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Framework for R&D decisions: A real options approach

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Industrial Economics and Technology Management
Submission date: June 2011
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Oppstartsdato **17. jan 2011**	Innleveringsfrist **13. jun 2011**
Oppgavens (foreløpige) tittel **Framework for R&D decisions: A Real Option Approach**	
Oppgavetekst/Problembeskrivelse Use the real options framework to evaluate R&D projects in a large industrial firm. Analyse to what extent different factors affect the optimal decision of the firm. 1. Analyse the R&D decision making problem and identify area(s) that are well suited for a real options approach. 2. Apply quantitative analyses on selected area(s), to illustrate the suitability of the real options framework.	
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4. Underskrift

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Partene er gjort kjent med avtalens vilkår, samt kapitlene i studiehåndboken om generelle regler og aktuell studieplan for masterstudiet.

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Oppgavens (foreløpige) tittel **Framework for R&D decisions: A Real Option Approach**

4. Bedømmelse

Kandidatene skal ha *individuell* bedømmelse ☐
Kandidatene skal ha *felles* bedømmelse ☒

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Framework for R&D decisions: A real options approach

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Master thesis
Norwegian University of Science and Technology

June 1, 2011

Executive summary

Hybrid real options

Statoil invests around NOK 2 billion in various R&D initiatives annually. Each year, they must evaluate higher versus lower priority projects and allocate funds as deemed necessary. Due to the highly uncertain nature of most R&D projects, it is essential they maintain a consistent assessment methodology in comparing the economical value of each project. This analysis therefore aims at providing such a framework for valuation of R&D projects utilizing a real options methodology. The framework is applied on Statoil's engagement in the Carbon Capture and Storage (CCS) technology.

Today, the three most commonly applied methodologies in assessing R&D projects are the Decision Analysis (DA), the financial option theory, and the traditional Net Present Value (NPV) approach. However, they all have flaws which make them inadequate for R&D valuation. For instance, DA is incapable of handling the varying discount rates that prevail over the lifetime of a project. The financial option theory, on the other hand, is too dependent on historical data that is generally unavailable for unique R&D projects. Finally, ordinary NPV lacks the ability to include active managerial decisions along the project's lifetime.

This paper proposes instead the use of the hybrid real options framework. The framework merges the benefits of DA and financial option theory by separating risk into project versus market risk. These risks are quantified by including experts' opinions and risk-neutral valuation, respectively. The latter is conducted through the Binomial Option Pricing Model (BOPM), where an asset traded on the market yields risk-neutral, probabilistic outcomes that through a regression analysis determines the market risk.

There are three main advantages with the hybrid real options framework:

1. It is a practical and effective approach, and still maintains a high level of accuracy.
2. The framework enables the use of the risk-free rate when discounting, as the project risk can be diversified and need no risk-premium. Similarly, the market risk neither needs any additional risk compensation as it is transformed with a risk-neutral valuation.
3. The separation of the project and market risks divide the valuation into a technical and financial part where the corresponding experts can apply their knowledge independently.

Hybrid real options methodology applied on CCS technology

The potential of CCS is large since it is, as of today, the only promising option for reduction of CO_2 emissions while still keeping consumption of fossil energy resources at current, or even increasing, levels. According to the International Energy Agency (IEA), CCS is expected to account for 4 Gt/yr of CO_2 abatement by 2035. EU shows their faith in CCS by investing EUR 13 billion over the next decade to development and deployment of the technology throughout their member states.

Statoil will benefit from the CCS technology through emission trading and avoided carbon tax, but the cost of the technology exceeds these benefits in the next 20 years. There is no doubt that the value of the technology, seen in isolation, is poor. However, it has the potential to be a door-opener for access to large amounts of new energy resources. Our analysis shows that a major, and increasing, part of this new production will be in the field of unconventional oil and gas. Opposed to conventional oil resources, the unconventional ones are usually associated with huge emissions of CO_2 in the extraction phase. This is where there will be a need for the CCS technology.

The hybrid real options framework values Statoil's CCS R&D project at best when Statoil continues development. Then the expected value is NOK 20 billion. Risk analysis gives a probability close to 50% that the project will yield a loss with similar magnitude (see Figure 1). The distribution of the CCS value is skewed to the left. When the result turns negative it is almost always with such an amount that the decision to abandon further development of CCS is most beneficial. In comparison to the traditional NPV methodology, the estimated expected value is nearly NOK 1 billion higher. Hence, the value of the inherent flexibility of this R&D project is significant. In this context, the difference in value represents the option value of the implementation decision - available through active management of the project.

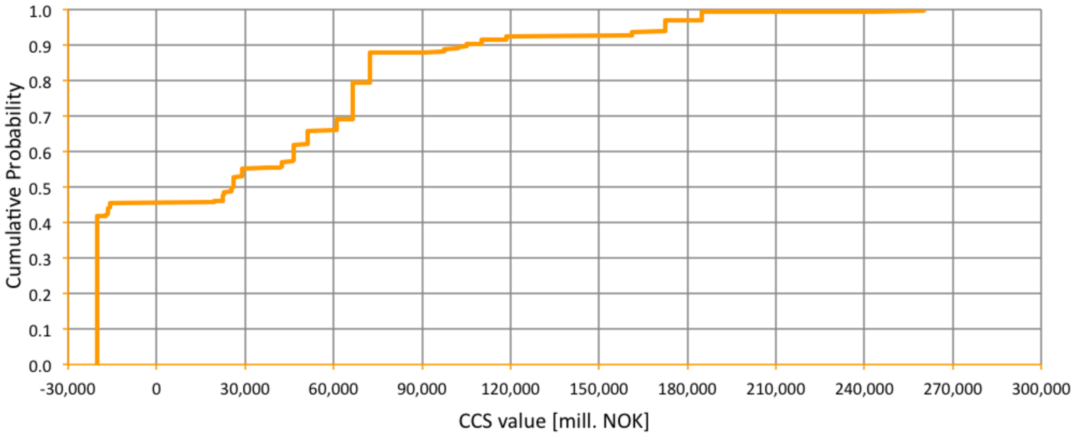

Figure 1: The cumulative distribution of the CCS technology value taking into account a variety of possibilities for the affecting factors. As displayed in the figure, 46% of the simulation runs return a negative expected value of NOK 20 billion for Statoil's CCS involvement - thus - it is no doubt CCS is a high risk project.

The *annual production growth* and the *share of unconventional oil in new production* are the most significant variables for the final CCS value (see the tornado diagram in Figure 2). This is quite intuitive as unconventional oil production yields high emissions that in turn is the main benefit driver for CCS. Given the assumptions in this analysis, Statoil's annual break-even production growth for the CCS technology is -0.14%. Thus, profitability of the CCS technology requires that Statoil at least maintains current production levels.

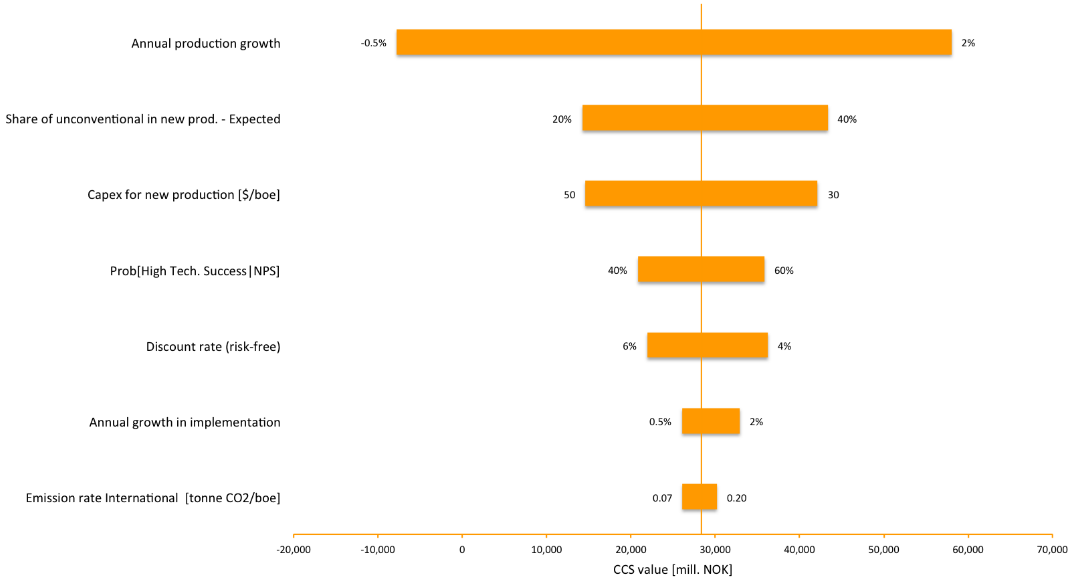

Figure 2: Tornado chart showing the factors having the most significant effect on the final CCS technology value for Statoil. The top-most variables has the highest relative importance, and the length of each bar represents the high and low limits of each variable. This is a one way sensitivity analysis. Thus, it returns the sensitivity for an input variable by letting it vary from a low to a high extreme, while all other variables are held fixed at their base value. On the horizontal axis below, the corresponding CCS value is displayed.

Merging the hybrid real options methodology with game theory

The framework is extended with simple game theory, where Statoil is confronted with the actions of the majority of its competitors. Both actors have the option to continue and defer further development, and are to decide without knowing the opponent's decision. The consideration of competitors action is essential and the strategic value was proven to be superior to the value of flexibility by more than NOK 50 billion. The game focuses on the first mover advantage which, in this valuation, is defined as access to new petroleum production.

The dominant strategy for Statoil is to continue further development of CCS, which is valued at NOK 48.1 billion. This is considerably higher compared to the original model and is due to the assumption of achievable benefits despite low level of technological outcome. This impacts the risk assessment as there is now a probability of less than 30% to achieve a negative return from the CCS R&D project, opposed to a probability of 50% in the first model.

Suggestions for further work

To make the framework more complete, further investigation of strategic values and other games should be considered. An interesting topic would be considerations of Statoil's relative importance for actual development of certain technologies - would CCS be developed without Statoil's involvement? In addition, other uses of the CCS technology should be considered to yield a more complete valuation.

Acknowledgements

We would like to thank our supervisor, Stein-Erik Fleten, from NTNU, Norway. With his helpful suggestions and precise feedback he has been important for the development of our thesis. Likewise, Per Ivar Karstad from Statoil ASA has been a key motivator and facilitator for our progress. With great enthusiasm he has answered all our questions and been truly helpful with suggesting and providing relevant data for the completion of our analysis. In addition, when finishing our studies, it is appropriate to direct a special thanks to the master programme for Industrial Economy and Technology Management at NTNU - for years of interesting lectures and enthusiastic professors.

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Chapter 1

Introduction

This thesis addresses the complex decision analysis required for conducting long-term R&D valuation. We aim at finding a framework that builds on the real options methodology, and we verify this framework by valuating Statoil's involvement in the development of the Carbon Capture and Storage (CCS) technology.

The framework we use was initially developed by Neely (1998) and is a synthesis of real options and decision analysis. A similar framework was suggested by Smith and Nau (1995), but this relies on hedging traded securities when quantifying the market uncertainty. As the CO_2 market suffers from significant "infant diseases", this approach is unsuited for the valuation task. Neely, on the other hand, includes the market uncertainty through a benefit driver that is not necessarily traded in a fully developed market. Thus, it is more applicable for an R&D project like a CCS development project.

As far as we are aware of, a methodology like this has never been applied on a company's involvement in CCS technology, nor for projects with a similar time-frame as is required here. In addition, we have extended the analysis to also include a simple level of game theory, where valuation of the first mover advantage have been considered.

It should be noted that we are not entering into knapsack problems, regarding how to pick the ideal projects among a huge variety of opportunities. We are forming a basis for valuating a single project, and optimal decision and valuation strategy for the project at hand.

The outline of this thesis is as follows: In Chapter 2 we start by reviewing the conventional capital budgeting tools. We build on this by introducing financial options, then real options evolve from this thinking. In Chapter 3 we address the problems with the ordinary options thinking and arrive at the hybrid real options framework. In Chapter 4 we give a brief overview of the CCS technology and its possible revenue drivers on a macro scale, then we continue in Chapter 5 with specific implications for Statoil. In Chapter 6 we move on with actually applying this framework and thus most of the chapter is devoted for outlining numbers and the analysis behind them. In Chapter 7 we extend the framework when valuating the first mover advantage through a simple game. Finally, we conclude the thesis Chapter 8. A reader who is unfamiliar with the many abbreviations commonly used for capital budgeting and in the oil and gas industry may find a list of abbreviations on page 68 helpful.

Chapter 2

Capital budgeting tools and financial options

This chapter focus on the framework needed for valuating complex projects with a long time horizon. We start out building a basis with some fundamental valuation concepts, needed for even the simplest capital budgeting problems. We move on to a more convoluted world when introducing the fiancial options framework.

2.1 Fundamental valuation concepts

Fundamental valuation concepts are necessary as a basis for understanding the more complex valuation methodologies. First we provide information on the Net Present Value (NPV) framework, then presents different theories for finding the correct or required discount rate, namely Weighted Average Cost of Capital (WACC) and Capital Asset Pricing Model (CAPM).

2.1.1 Net present value

The NPV approach is probably the most applied financial valuation concept that is used for making capital budgeting decisions. It is founded on the time-value-of-money principle, stating that money today is worth more than the same nominal amount of money in the future. This is because of the interest rate, and that you would receive a risk free return if you invested the money today - yielding a higher nominal value for the future.

The NPV is simply the sum of all future Cash Flow (CF) with the appropriate sign, discounted with the applicable discount rate,

$$NPV = -I_0 + \sum_{t=1}^{N} \frac{E(FCF_t)}{(1+r_i)^t}, \tag{2.1}$$

where I_0 is the initial investment at time 0, $E(FCF_t)$ is the expected CF from future revenues, r_i is the appropriate discount rate and N is the number of periods into the future

A NPV of zero forms a bottom threshold for a positive investment decision. The simple decision rule is that whenever the NPV is positive, you should accept the project as it adds value for the shareholders - and importantly - no mutually exclusive project has a higher NPV. If there is such a mutually exclusive project, this project should be chosen instead of the one at hand. A negative NPV project should not be accepted.

Unfortunately, there are still some major flaws with the NPV approach, where the most important include: What is the appropriate discount rate for our project? How to account for uncertainty in the future CF, if not all for them are equally uncertain? How to account for managerial flexibility?

2.1.2 Weighted-average cost of capital

Firms operating in a competitive market with multiple sources of financing need to select projects with an expected return greater than their financing liabilities. The WACC is the indicator that effectively finds this rate. Since financing can originate from a number of different sources, it could be quite tedious work to evaluate the WACC (Developed by Miles and Ezzell (1980)).

The general WACC formula, with N sources of financing is given as

$$\text{WACC} = \frac{\sum_{i=1}^{N} r_i MV_i}{\sum_{i=1}^{N} MV_i}, \tag{2.2}$$

where r_i is the required return for source i and MV_i is the respective Market Value. For a company whose financing arise from only equity and debt, the formula will simplify to the following

$$\text{WACC} = \frac{MV_e}{MV_d + MV_e} \cdot R_e + \frac{MV_d}{MV_d + MV_e} \cdot R_d \cdot (1 - \tau), \tag{2.3}$$

where subscript e and d represents equity and debt, respectively. One should keep in mind that debt, from the shareholder perspective of maximizing profits, is relatively more attractive as a source for financing because of the corporate tax rate, τ.

When using the WACC for a project within a given firm, the project needs to closely resemble the risk profile of the company. In addition, the formula requires a constant leverage ratio over the entire period considered. Thus, to maintain this ratio, the company need to issue more debt in “good” times, and retire debt in “worse” times.

Naturally, for the R&D projects we are considering later in the thesis, the risk profile seldom resembles that of the firms main operations. This weakness with the WACC leads to the CAPM model, which also includes the non-diversifiable market risk.

2.1.3 Capital asset pricing model

The CAPM model is relating the expected return of a proposed investment related to its amount of market risk. Opposed to project risk, that could be avoided by investing in a wide range of projects, market risk cannot be mitigated by diversifying the portfolio (although it can be hedged with other financial instruments). For a more elaborated walk-through of the CAPM model, see for instance Brealey et al. (2011).

The excess expected rate of return for an individual security is inflated by its covariance to the excess expected return of the overall market. Thus, we get

$$\frac{E(R_i) - R_f}{\beta_i} = E(R_m) - R_f, \tag{2.4}$$

where R_f is the risk-free return, $E(R_i)$ is the expected return of the individual security, $E(R_m)$ is the expected return of the market portfolio and β_i represents the covariance of the return of the individual security to the market portfolio, such that

$$\beta_i = \frac{Cov(R_i, R_m)}{Var(R_m)}. \tag{2.5}$$

When rearranging the initial CAPM formula an solving for what should be the expected return for an individual security given all other factors, we get

$$E(R_i) = R_f + \beta_i[E(R_m) - R_f]. \tag{2.6}$$

This formula is also the basis for constructing the security market line, that could be plotted with risk (β) on the x-axis versus expected asset return on the y-axis, usually forming a straight line.

2.2 Financial options

2.2.1 Fundamental concepts

Financial options are the foundation when developing the real options methodology.

In finance, an option is a contract between a buyer and seller regarding an underlying asset that are to be considered in future time. The buyer of the option will gain the right, but not the obligation, to engage in the transaction specified in the contract. The seller on the other hand are obligated to fulfill the transaction if this is requested by the buyer.

When the option gives the buyer the right to *buy* the underlying asset, it is defined as a *call* option. When the buyer of the option is given the right to *sell* the asset, it is called a *put* option. In the options contract it is specified at least the following specifications:

- **Option style** and whether it is a put- or a call option
- **Quantity of underlying asset** the option contract is valid for
- **The strike price,** K_T, is the price of the underlying asset the option can exercise upon at time of expiration, T. The actual price of the underlying is usually referred to as S_t.
- **The expiration date,** T, is the last date the option can be exercised

- **Settlement terms** defines how the contract is to be settled - typical whether it is a monetary transaction or a physical delivery

The most common style of options are *American* and *European.* They differ in how they can be exercised; American options can be exercised any trading day before maturity, whilst European options can only be exercised on expiration. Complex option contracts are often referred to as *exotic* options, while any option that is not exotic is regarded as *vanlilla* options.

Since the option do not obligate the buyer to exercise the transaction, the investor can avoid downside risk and limit the loss to the cost of acquiring the option. At the same time the investor can enjoy the upside risk with potentially unlimited gain for the call option. An unlevered put option has a maximum payoff of the strike price, K, for each individual contract. An illustration of the payoff diagram for plain call and put options are found in Figure 2.1.

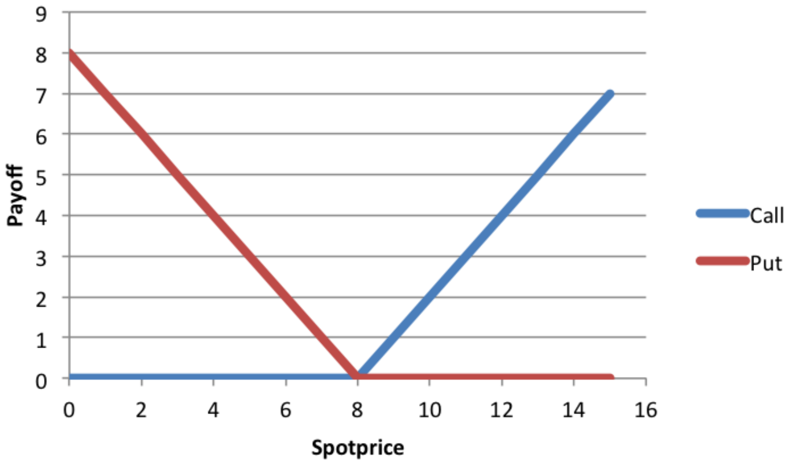

Figure 2.1: Payoff for put (red) and call (blue) options, both with strike price K=8. Maximum payoff for a put is limited by K, while call options has no such limit. The price of the option contract is not included here.

The most important factors that influence on the options value are the price and the volatility of the underlying asset, the strike price, the time to expiration, the risk-free interest rate, and the cash dividends. The value of a call (put) option increases (decreases) with the price of the underlying asset, and decreases (increases) as the strike price increases. Volatility represents the uncertainty and are the most important factor. As the volatility increases the upside payoff has a higher potential than the downside payoff, and thus the option value increases. Table 2.1 shows the most common options and their price reaction to changes in different underlying parameters.

2.2.2 Financial option valuation methods

When pricing options two important assumptions are taken:

1. No arbitrage opportunities can survive, and effectively they never exists.
2. Random fluctuation of stock price in a complete market, and more specifically, the price follows a Geometric Brownian Motion (GBM) and has a lognormal distribution.

Table 2.1: Different option styles and price sensitivities to an increase in underlying parameters, while keeping all others fixed. The table is slightly modified from Table 7.1 in Hull (1993).

		European style		American style	
Variable		Call	Put	Call	Put
Stock Price	S_t	+	-	+	-
Strike Price	K_T	-	+	-	+
Time to Expiration	$T-t$	Varies	Varies	+	+
Volatility	σ	+	+	+	+
Risk-free Rate	r_f	+	-	+	-
Dividends	q	-	+	-	+

Black-Scholes option pricing model

Black and Scholes (1973) presented a model that develops a solution for a Partial Differential Equation (PDE) to price a European option. The closed form solution of this PDE is known as the Black-Scholes formula and can be seen in Equation 2.7 and 2.8. A non-dividend paying underlying asset is among the models multiple assumptions. Merton (1973) extended the model of Black and Scholes by enabling valuation of an European option with cash dividend payment.

The formula for valuating the European non-dividend paying Call- and Put option value, are given as

$$C(S,t) = N(d_1)S - N(d_2)Ke^{-r(T-t)} \tag{2.7}$$

$$P(S,t) = N(-d_2)Ke^{-r(T-t)} - N(-d_1)S \tag{2.8}$$

respectively, where

$$d_1 = \frac{ln(\frac{S}{K}) + (r + \frac{\sigma^2}{2})(T-t)}{\sigma\sqrt{T-t}}$$

$$d_2 = d_1 - \sigma\sqrt{T-t}$$

and

- $N()$ is the cumulative distribution function of the standard normal distribution
- $T-t$ is the time to maturity
- S is the spot price of the underlying asset
- K is the strike price
- r is the risk free rate (annual rate, expressed in terms of continuous compounding)
- σ is the volatility of the returns from the underlying asset.

There has been a number of suggestions for extending the Black-Scholes formula: Hull and White (1987) suggested an extension with stochastic volatility to cope with what they claimed to be a flaw with the Black-Scholes formula, namely overpricing when using fixed volatility. Pindyck (1993) formulated a model that considers technical uncertainty and input cost uncertainty in an investment opportunity. Grenadier and Weiss (1997) investigated the options pricing for sequential investments in technological innovations. They allow innovations to be stochastic both in their arrival times and profitability.

Binomial option pricing model

This numerical method for options pricing was first proposed by Cox et al. (1979). The model uses, opposed to Black-Scholes Option Pricing Model (BS), discrete time when constructing the evolution of the underlying asset through a binomial lattice (tree). Each node in the lattice represents a possible price of the underlying at a given point in time. In general, Binomial Option Pricing Model (BOPM) does not provide closed-form solutions but can handle a huge variety of different exotic option styles.

The valuation lattice forms an iterative method that starts at each of the final nodes. From here it works backwards, through the lattice, ending up at the first node representing the valuation date. This process is performed in three steps.

Step 1: Generation of the lattice: The lattice is generated by moving from valuation date and towards expiration date. For every time step, it is assumed that the price, S, of the underlying asset can move up or down by a factor u and d, respectively. The factors u and d are defined in Equation 2.9.

$$
\begin{aligned}
u &= e^{\sigma\sqrt{t}} \\
d &= e^{-\sigma\sqrt{t}} = \frac{1}{u}
\end{aligned}
\tag{2.9}
$$

A practical feature about this method is that an up-and-down price movement will end up in the same node as a down-and-up movement. This reduces the number of nodes and thus the computational time needed.

Step 2: Calculation of option value at each final node: At each final node the option value is defined as

- $Max[S_n - K, 0]$ for a call option, and
- $Max[K - S_n, 0]$ for a put option

where K is the strike price, S_n is the current price of the underlying asset in period n.

Step 3: Sequential calculation of the option value at each preceding node: Calculation of the option value for the remaining nodes makes use of the risk-neutral valuation. By assuming risk neutrality[1], the price of a derivative is equal the expected value of its future discounted payoffs. Hence, the option value for a node is the expectation of the values from the two previous nodes. The values of the previous nodes are weighted with the probability p and $(1-p)$ for the up and down move, respectively. The risk-free rate is used when discounting the expected value.

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[1] For a more elaborated explanation on risk-neutrality, see for instance Gisiger (2009) or Hull (1993).

The following formula yields the expected value

$$C_{t-\Delta t,i} = e^{-r\Delta t}(pC_{t,i+1} + (1-p)C_{t,i-1}), \tag{2.10}$$

where $C_{t,i}$ is the option value for node i at time t. The probability p is given as

$$p = \frac{e^{(r-q)\Delta t} - d}{u - d}. \tag{2.11}$$

The probability for an up movement is constructed so the binomial distribution simulates the GBM of the underlying asset with parameters r and σ. q is the dividend yield of the underlying asset, and can be set equal to zero due to the fact that in an risk-neutral world the expected growth of future prices is assumed to be zero. An illustration of the different steps for constructing the binomial tree can be seen in Figure 2.2.

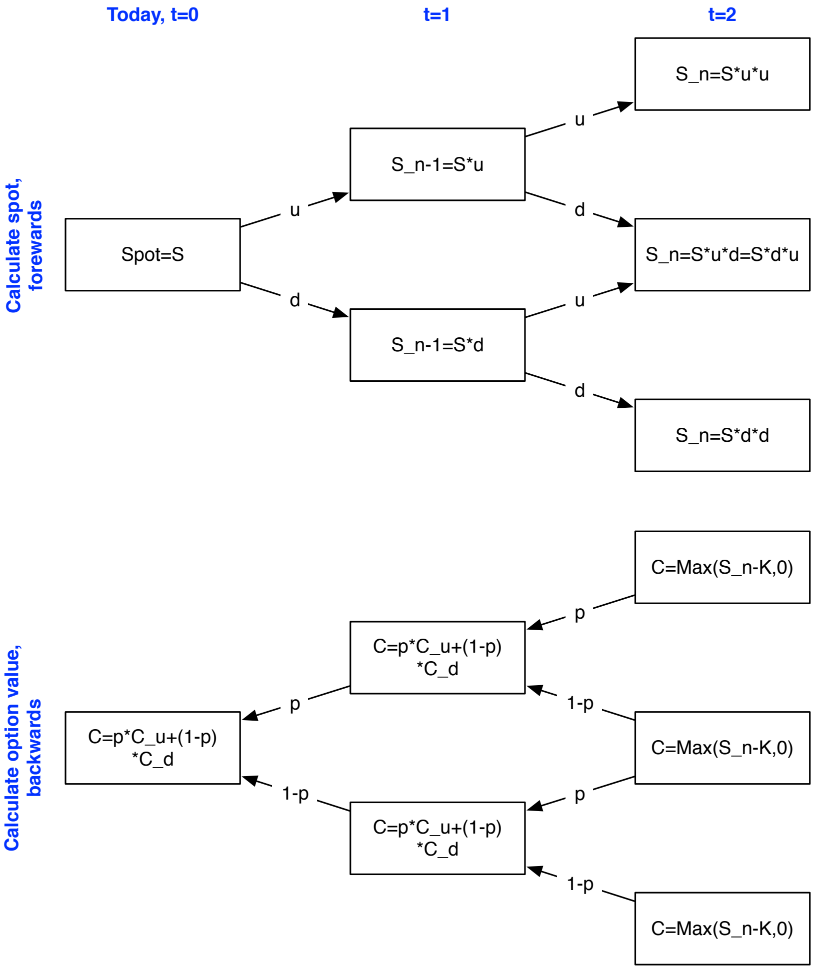

Figure 2.2: Structure of binomial option pricing model. Here it is illustrated by a European style call option with two time-steps.

Chapter 3

Real options for R&D valuation

Real options are associated with the flexibility inherent in a project. This flexibility is linked to active managerial decisions that will enhance the upside opportunities, and limit the potential downside losses. The flexibility is of various types, and Table 3.1 shows different real options that make the decision taker able to handle risk and uncertainty - and suggests associated industries where the real options typically are present.

Table 3.1: Real option types with associated examples, from Trigeorgis (1996), Table 1.1, with slight modifications.

Project options	Description	Examples
Deferral	The firm is able to defer its investment to gather information to wait for the best time to enter the market.	All natural resource extraction industries, real estate, farming.
Abandonment	The firm is able to abandon the current operations and permanently leave the position	New product penetration in uncertain markets, capital intensive industries, financial services.
Sequential/Staged	The firm can portion its investments, and rethink whether it is beneficial to leave the entire investment, or continue to invest in the next step.	All R&D intensive industries, long spanning capital intensive projects, start-up ventures.
Scaling	The firm can expand, contract or temporary close its operations regarding on how favourable the current market outlook seems.	Natural recourse industries, fashion apparel, consumer goods, commercial real estate.
Switching	If prices or demand changes, the firm can alter its production output (product flexibility). Alternatively, the same output can be produced from a different input (process flexibility).	*Output:* Consumer electronics, toys, machine parts, autos. *Input:* Feedstock-dependent facilities, power generation, chemicals, crop switching.
Growth	The firm can do prerequisite investments. The early entry and associated knowledge allow the firm to capture future opportunities.	All strategic industries, especially high-tech and R&D intensive industries, multinational operations, acquisitions.
Multiple Interaction	The firm holds multiple options in its projects. These options can be viewed as a basket of plain vanilla options and exotic options, and may interact in convoluted ways.	Real-life projects in most industries listed above.

3.1 Financial and real options

Real options follow financial options conceptually in the sense that there is still a right, not an obligation, to take a certain action. However, real options mainly distinguishes itself from financial options in two ways:

1. The underlying asset that drives the value of the financial option is not necessarily a financial asset for real options (e.g. market share, production output, production input, R&D projects). In order to apply the Black-Scholes formula or the binomial option pricing model, the price of the underlying asset is required to have a log-normal distribution.
2. The time to maturity for real options are significantly longer than for financial options. For financial options the maturity is usually no more than two years, whilst for a real option it might be decades. This has a major impact on the modeling of future value of the underlying as the historical data is seldom sufficient for estimating the project value.

Through comparison with a financial call option, the "optionlike" nature of investment opportunities was clarified by Dixit and Pindyck (1994). They emphasize the importance of irreversibility of investments and the prevailing uncertainty, and acknowledge the value of *waiting* in order to get more information.

Wang and De Neufville (2005) applied real options on engineering system designs, and conceptualized the difference between real options "on projects" and "in projects". Real options "on-projects" were defined as financial options applied on technology, where the technology itself is treated as a "black-box". Real options "in-projects" were options emerging from changing the actual design of the technical system. The latter requires deep understanding of the technology, which options analysts have not been in possession of, and thus most option valuations have been "on" projects.

Mitchell and Hamilton (2007) relate investments in R&D projects to financial call options and concluded that, given high uncertainty and the long time-frame of a typical R&D project, a real option model would be appropriate for the valuation. Mitchell and Hamilton use stock price of the underlying asset as the benefit driver, the implementation cost as the strike price, and the date of implementation as the time of maturity. They argue that investing in R&D is a way to create and identify future options.

From history, real options following the methodology of financial options have generally been applied on investments in natural resources. This is because historical market data of the underlying assets has been fairly easily available. Brennan and Schwartz (1985) considered a long-term supply contract in the copper mining industry and Siegel et al. (1987) looked into the suitability of option theory for valuating offshore oil features.

3.2 Decision analysis with "real options thinking"

Decision Analysis (DA), as a term, was first created by Howard (1966), and is conceptually a mapping of the possible decisions. Uncertainties are incorporated through discrete probabilities and probability distributions. The intention behind DA is to let the decision-maker choose the path that will maximize expected utility. Common graphical representations of a DA problem are decision trees and influence diagrams, which both illustrate how the decisions and the uncertainties are linked together. The decision tree is constructed by three different nodes:

1. The decision nodes representing the options and flexibility inherent in the problem.
2. The chance nodes representing events with uncertain outcomes.
3. The value nodes at the end-points represent the final value of each possible outcomes of the problem. The exact value is determined by the decisions that were made and the outcome of the previous events.

An example of a decision tree can be seen in Figure 3.1. The analysis builds upon a calculation of the expected value for every path leading from a decision node, and thus makes it easy for the decision-maker to see what path is most beneficial.

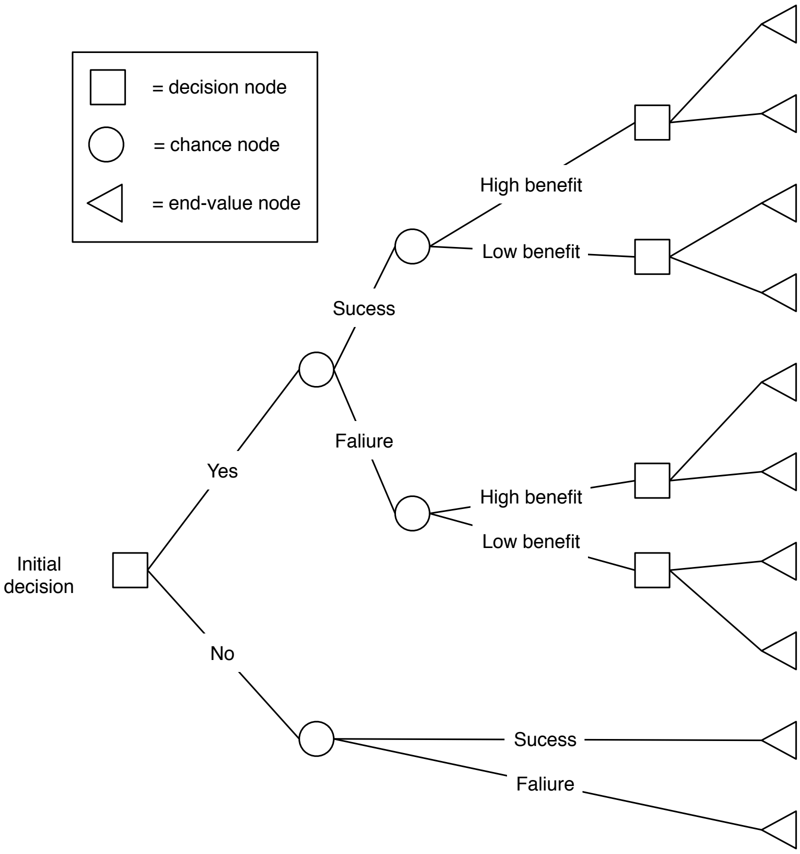

Figure 3.1: An example of a decision tree, with symbol explanation. Squares represent decision nodes, circles represent chance nodes and triangles represent end-points. The tree can be extended to include a vast number of events and choices, but this will harm the intuitiveness of the tree.

Faulkner (1996) emphasizes that option pricing theory provides a better basis for the valuation of R&D projects than the ordinary capital budgeting tools. However, he also argues that R&D managers need to be aware of the "options thinking" methodology, and the associated computational techniques. Through DA, Faulkner analyzes whether Kodak ought to continue its R&D programme for developing a new film product, and shows DA's potential as an *option think-*

ing valuation. DA does not yield an exact pricing of the option, but it gives a more intuitive understanding of the real options and how the flexibility is valued.

Similarly, Copeland and Tufano (2004) essentially suggest using decision trees for valuating real options as it “makes the math of options easier but also helps you make better decisions about exercising them”. They emphasize that most options embedded in managerial decisions are far more complex and ambiguous than financial options.

Sensitivity analysis

The project risk in a DA problem is quantified through discrete probabilities. There are two ways to establish these probabilities. The first is by interviewing people who possess special expertise, called “expert opinions”. Clemen and Reilly (1999) provide fundamental techniques for such an assessment. The other way is to use historic probabilities for similar projects, and use these directly.

The process of quantification is generally a matter of intuition, and even though it is accomplished by experts or by historical data, the probabilities could only be roughly estimated. Hence, sensitivity analysis becomes an important aspect of a DA problem in order to grasp the probabilities’ impact on the value of the project.

A tornado chart is commonly applied when conducting sensitivity analysis. It enables simultaneous comparison of a one-way sensitivity analysis for several input parameters. One-way analysis returns the sensitivity for an input variable by letting this variable vary from a low to a high extreme, while all other variables are held at their base value. A spider chart distinguishes itself from the tornado chart by showing how the model’s output depends on the percentage changes for each of the model’s input variables. Opposed to the tornado chart, the spider chart enables identification of nonlinear relationships.

The tornado and spider chart are limited to only give insight in the sensitivity for a variable when all others are fixed. In order to obtain a joint sensitivity for multiple factors, a two-way sensitivity analysis is required.

3.3 The flaws of financial options and decision analysis for valuation

Before presenting the flaws of the two most commonly applied valuation methods, it should be emphasized that the traditional NPV analysis fails conceptually as it assumes an unchangeable commitment to the expected cash flow specified when initiating a project. It ignores the inherent flexibility of projects that active managers are in control of. Consequently, projects are always assumed to be taken to the final stage even when early results are unfavorable for further development. The traditional NPV analysis fails mechanically as well by only considering a single stream of income and expenses, which implicates that the cash flows are assumed to be the average of a range of possible cash flows. This is generally incorrect as the probability distributions of the returns are most often asymmetric.

Mitchell and Hamilton (2007) conclude that ordinary NPV approaches tend to unjustly discriminate R&D projects with a high-risk and long time frame. Similarly, Faulkner (1996) concludes that conventional Discounted Cash Flow (DCF) methods tend to under valuate R&D projects, and that option theory often is more suitable for the valuation.

The financial options methodology developed by Merton (1973) and Black and Scholes (1973) was able to more correctly valuate ordinary option contracts. Their methodology utilizes a statistical measurement of the historical risk for the underlying asset the option contract is concerning. When applied on real option opportunities in for instance R&D projects, such historical data is usually unavailable. Thus, the financial options valuation method is inadequate.

DA fails in the sense that it is not able to handle the changing level of risk over time that is typical for large projects. DA assumes a fixed discount rate applied throughout the project's lifetime. According to the CAPM theory the discount rate should depend on the relative risk present at any time. If DA was to achieve a correct discounting, the discount rate would need to be altered every time a decision could be made, for all possible outcomes. This is not impossible, but rather unpractical.

3.4 Hybrid real options - the best of two worlds

Smith and Nau (1995) successfully merge the more intuitive DA approach and the options framework. They conclude that when applied correctly, DA and option theory are fully compatible and this is highlighted through their consistency theorem[1]. This is in contrast to some of the claims in the "real options" literature. Thus, it opens for using option theory for incomplete markets and makes the analysis of projects that can be partially hedged by traded securities easier. The framework was applied on oil and gas investments by Smith and McCardle (1999).

Similar to Smith and Nau, Neely (1998) combines the DA and the options theory in his *hybrid real options* framework. The value of flexibility is estimated by distinguishing two types of risks - project and market risks.

- **Project risks** are those associated with the project itself, and are thus unique to the project by definition. Hence, managers can protect themselves by diversifying their investments into different projects. An unexpected loss in one project, will be compensated by an unexpected gain in another. These projects can be analysed correctly by decision analysis with constant discount rate.
- **Market risk** appear from external markets, and cannot be diversified. Option theory handles the constantly varying discount rate by a process known as the *risk-neutral* valuation. This process requires statistical information for an asset that is related to the project.

Neely applies DA on project risks and option theory on market risks. Unlike Smith and Nau, who quantify the market uncertainty with a multiple of traded securities through the "contingent claims" approach, Neely includes the market uncertainty through a benefit driver that is not necessarily traded in a fully developed market. As the CO_2 emissions market suffers from

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[1] See Smith and Nau (1995) for more details on the consistency theorem.

"infant diseases" resulting in severe market instability, the framework of Neely is preferred over the framework of Smith and Nau.

3.4.1 Methodology of the hybrid real options framework

In his doctor dissertation Neely proposed a five-step approach to valuate risky projects:

Step 1: Scope of assessment identifies the potential uses of the R&D project, and focuses on potential applications, user segments and scenarios that have an impact on the value of the project.

Step 2: Project Data Collection collects the necessary data in order to value the project. Here, the timing and magnitude of costs and benefits are estimated, the different decisions to be made are identified, and the elated uncertainties are quantified.

Costs and benefits are fairly intuitive and will not be explained in more detail here. Regarding the different decision opportunities it is worth mentioning that trying to value multiple options is complicated since their values are not additive (Trigeorgis, 1995). The hybrid option framework can handle multiple options, but Neely advises to focus on what is considered the main project options.

Regarding uncertainties related to the project, there are two types that need to be quantified:

1. *Project specific uncertainties* have no relation to external markets. There are multiple methods for estimating discrete, probabilistic outcomes of these. Neely suggests two different approaches for enumeration of the specific values; subjective assessments or the use of a continuous distribution. The use of a continuous distribution has several advantages. First, it enables estimation of any number of outcomes. Second, it reduces the data collection requirements when there are many outcomes. Third, it should be more intuitive for a manager to define an expected value and an upper and lower limit opposed to defining all outcomes. The Extended Pearson-Tukey method and the Bracket Medians method are two alternatives for finding this continuous distribution. A review of them is found in Appendix B.
2. *Market specific uncertainties* are estimated in two stages. First, the revenue/benefit driver needs to be identified. Second, this driving factor must be related, typically through a regression model, to an externally priced asset.

Step 3: Transforming Project Data covers the transformation of complex benefits to monetary values and market uncertainties into risk-neutral quantities. The latter is done most easily with the binomial method described in Section 2.2.2 on page 7. This method will give the required set of risk-neutral prices with corresponding probabilities that are to be applied in the market uncertainty relation defined in Step 2.

Step 4: Valuing Technology Use performs the traditional decision tree evaluation process. The expected cash flows are inserted as conditional, probabilistic outcomes, then the decisions are evaluated for each of these outcomes. Finally the tree is traced back in order to find the expected value of the project. Present values of the dollar-based estimates of costs and benefits are found by use of traditional financial discounting. Due to the risk-neural transformation in Step 3, the risk-free rate can be used as the discount rate throughout the entire tree.

Step 5: Total Project Value calculates the total value as a weighted sum of the respective single use values. In order to find the value of the entire project, Step 2-4 has to be done for all uses of the R&D project found in Step 1.

3.4.2 Advantages of hybrid option valuation

There are three main advantages with hybrid real options. Firstly, hybrid real options is a practical and at the same time accurate approach. The lack of elegance from a theoretical point of view, is compensated by its simple effectiveness and perspicuity. Secondly, the framework allows the use of the risk-free rate as a consistent constant discount rate. This is possible because project risks can be diversified and thus require no risk-premium, and that market risks are transformed by the risk-neutral valuation process yielding that no compensation for risk is required. Finally, the valuation becomes organized in the sense that the process is divided into a technical and financial part. Hence, technical and financial experts can apply their knowledge independently.

Chapter 6 exemplifies the framework of Neely on Statoil's R&D engagement in the CCS technology.

Chapter 4

CCS technoogy - why do we need it?

This chapter will bring the reader up-to-date on the potential of CCS technology, with a special focus on areas we find most interesting for Statoil. The analysis and valuation will follow in the next chapters.

4.1 Global warming

Theories about human impact on the environment were put on the global agenda in the 1980s, and world-wide acceptance was reflected in the binding commitment from 1997 when the Kyoto agreement was ratified by most countries. Currently, 192 states has signed the protocol (United Nations Framework Convention on Climate Change, 2011). The major concern is related to emission of Green House Gases (GHG), where CO_2 is found to be of most importance.

According to the 2007 Fourth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007), there has been an increase in global surface temperature of 0.74 ± 0.18 °C during the 20^{th} century. The observed rise in temperature is mainly caused by increasing atmospheric concentration of greenhouse gases, which result from human activities, such as the burning of fossil fuel.

The implications of global warming are primarily concerned to rising sea level, changing precipitation patterns, and expansion of sub-tropical deserts. In addition, there is likely to be more frequent and intense extreme weather events, species extinctions, and changes in agricultural yields.

There has been presented future emission scenarios depending on the governments' climate policies. If business continues as usual, International Energy Agency (IEA) predicts that the emissions of CO_2 will grow at 1.4% per year on average, reaching 42.6 Gt in 2035. In order to reach the goal of limiting the increase in global temperature to 2°C, the emission of GHG needs to be reduced to 21.7 Gt pr year. The need for less carbon intensive energy sources is evident. (IEA, 2010)

4.2 Carbon Capture and Storage

4.2.1 What is CCS?

CCS is a three-step technology that reduces the emissions of CO_2 to the atmosphere. The technology aims at capturing roughly 90% of the emissions, and thus preventing it from reaching the atmosphere. This is achieved by transporting and storing it permanently once captured.

The net reduction depends on the fraction of CO_2 captured, and the increased CO_2 production from loss in overall efficiency due to the energy penalty imposed, see Figure 4.1. Because of this effect, a power plant with CCS equipment needs to be over-sized in order to deliver the same energy output as a plant without CCS.

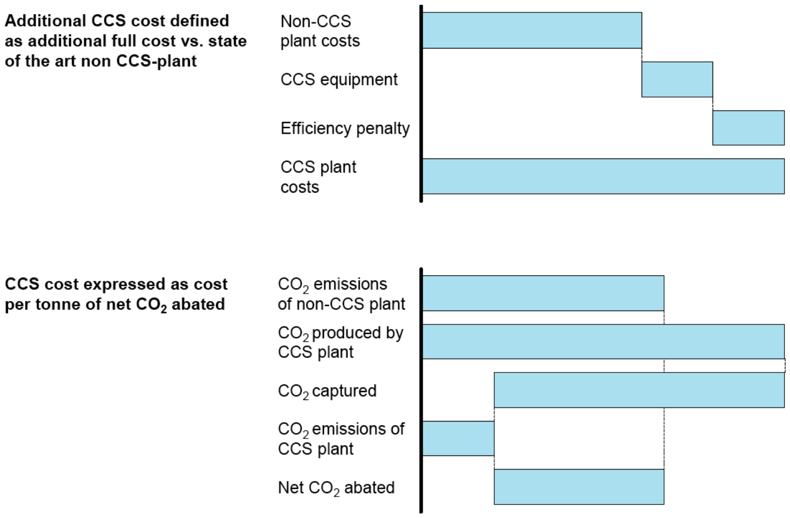

Figure 4.1: Conseptual scetch of energy penalty on a plant equipped with CCS technology versus an ordinary power plant. The plant equipped with CCS equipment need to be over-sized in order to deliver the required energy output. Source: McKinsey & Company (2008).

Today, there are three major capture technologies. They differ in time of capture and type of fuel:

- **Oxy-fuel combustion:** This process uses oxygen as fuel, which results in a flue stream of more concentrated CO_2 and water vapour. Nitrogen is removed from the process and thus the volumes of useless flue gas is reduced, and capturing is easier.
- **Post-combustion:** This process captures CO_2 from the exhaust gas by use of absorbing solvents, such as amine washing. As this technology can be retrofitted to existing power plants with limited impact on the existing process, it is by far the most popular one as of today.
- **Pre-Combustion:** This process pre-treat the fuel in order to achieve a stream of CO_2 and hydrogen, from where CO_2 is removed.

Transportation to a storage facility can be done through pipelines or by ship, though the former is preferred solution when considering large-scale transportation. Storage of CO_2 in geological formations is one of several possiblities. Depleted oil and gas fields together with saline aquifers is found to be the primary options. A principal sketch of the CCS technology can be seen in Figure 4.2.

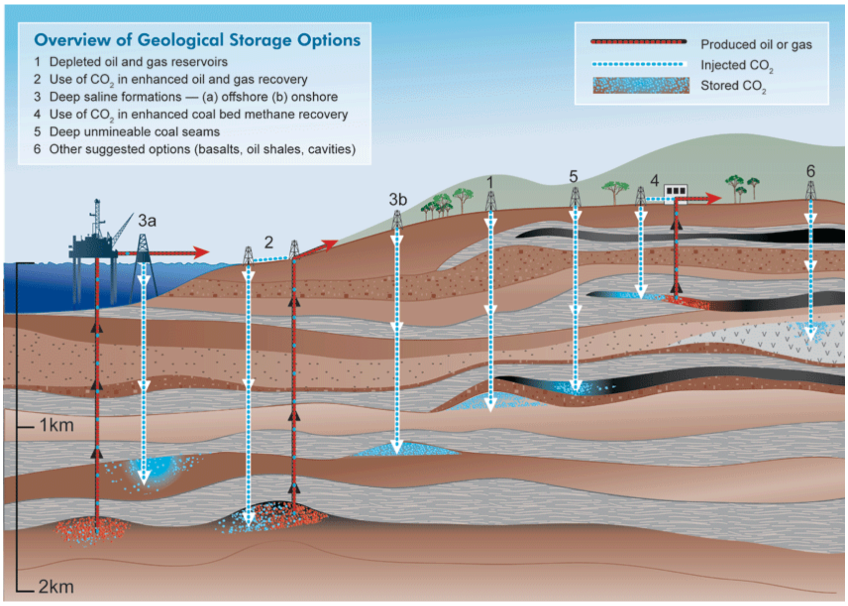

Figure 4.2: This is a conseptual scetch of the CCS technology as the layout of the process may differ significantly on different sites. Source: IPCC (2005), Figure SPM.4.

4.2.2 Potential of CCS

CCS has the potential to reduce overall mitigation costs and increase flexibility in achieving greenhouse gas emission reductions. The adoption of CCS depends on multiple factors. Among the most important are technical maturity, costs, diffusion, regulatory aspects, environmental issues and public perception.

Currently CCS is not commercially viable[1]. Transportation and storage of CO_2 are both technologies proven successful from the petroleum industry, where the former has been applied in Enhanced Oil Recovery (EOR) in central US for more than 30 years and the latter at Sleipner (Norway), Weyburn (Canada) and in Salah (Algeria) for at least 10 years. The capture step is based on technology applied already in chemical and refining industries, but demonstration in the context of power production on a large-scale is yet to be done.

Given today's energy mix, demand growth and energy security, fossil fuels will still dominate as energy source for decades to come - despite the increasing use of renewable energy. CCS is assumed to play a key role among abatement technologies accounting for nearly 4 Gt/yr of abatement (IEA, 2010). Other suggestions for the CO_2 abatement needed in 2030 are 1.5-4 Gt/yr globally (McKinsey & Company, 2008) and 3.6 Gt/yr (Enkvist et al., 2007).

In the last two years multiple governments[2] in addition to the European Commission have committed to facilitate deployment of large-scale CCS projects by substantial public funding.

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[1] It should be noted that CCS is commercially *available*, but is currently not commercially *attractive*.

[2] Australia, Canada, Japan, Norway, the Republic of Korea, the United Kingdom and the United States.

As of April 2010 there was announced launching of 19-43 projects with a funding of USD 27-36 billions (IEA, 2010).

Europe is especially eager to make CCS more attractive because of an energy security dilemma. Europe has vast amounts of coal reserves, but limited gas and liquid petroleum. By making coal fired power plants cleaner, they reduce dependency on gas and petroleum from politically unstable regions. Thus, Europe has been one of the primary driver of deployment of the CCS technology.

By the directive of 2008, EU presented its 2020 emission plan called the Strategic Energy Technology (SET) plan (European Commission, 2010). Here it suggests eight industrial initiatives, where CCS is one of them. The ultimate goal for the plan is to achieve commercial viability of CCS under the European Union Emission Trading Scheme (EU ETS) by 2020. In order to reach this goal, the plan aims for 12 industrial scale CCS by 2015. EU has estimated to spend EUR 13 billion over ten years from 2010-2020 for this CCS initiative (European Commission, 2010).

Today, CCS has the benefit of being the only technology that is able to capture emissions from existing CO_2-emitters, and many of the emitters can hardly avoid CO_2 emissions from their processes. Hence, CCS is the technology they have to rely on and invest in.

4.2.3 Capture

Capturing the CO_2 accounts for roughly 2/3 of the technology cost. There are two main cost drivers. The first is capital intensive equipment, for instance oxygen separation from air for a oxy-fuel plant or a CO_2 scrubber in the post-combustion. Secondly, there is a severe energy penalty for a plant equipped with CCS technology, usually from 8-12 percentage points (IEA, 2006). This drives an increase in fuel consumption and requires oversizing of the plant to ensure the same energy output.

Choice of capture technology impact the costs, but often is the impact of the characteristics and design of the overall power plant more important. For instance, a post-combustion capture system applied in Natural Gas Combined Cycle (NGCC)[3] plants is more difficult than in coal plants as the CO_2 concentration in the flue gas is lower (merely around 3-4%) (IEA, 2006). Due to the fact that there exists a large number of technical and economic factors related to the design and operation of both the CCS system and the corresponding power plant/industrial process that influence the overall costs, the reported cost estimates of CO_2 capture vary widely.

The capital cost for a capturing system generally includes the total expenditures needed for designing, purchasing and installing the system. There might be components not needed in the absence of CCS, for instance upstream gas purification system to protect the capture device. Hence, the total incremental cost of CO_2 capture for a given plant design is best determined as the difference in total cost between plants with and without CO_2 capture equipment, producing the same amounts of useful (primary) product, such as electricity.

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[3] Natural Gas Combined Cycle - a gas fired power plant with a steam boiler on the exhaust. The steam is used in a secondary cycle with a steam turbine to generate additional electricity.

The most widely studied systems are investments in new power plants based on coal combustion or gasification, see for instance Heydari et al. (2010).

4.2.4 Transportation

For transportation of the large amounts of CO_2 that is required with a world-wide roll-out of CCS technology, pipeline is the only alternative for transportation. Transportation by tanker and ship are very limited, and mainly utilized in the food and beverage industry. Although one can easily imagine tankers to be a more attractive solution for the future, the costs are highly uncertain and a pilot project is yet to be tested on the scale required for this scale of CCS. (Carbon Sequestration Leadership Forum, 2010)

The cost of pipelines can be categorized into construction costs, operation and maintenance cost, and other costs, where the contruction costs is of most interest.

The construction costs consists of material and equipment cost. First of all the material costs depends on the characteristics of the pipes (i.e. length, diameter, amount and quality of the CO_2 to be transported). Furthermore, the cost is dependent on the terrain. Onshore pipeline costs may increase with 50-100% when the route is congested and heavily populated. In general offshore pipelines operate with higher pressure and lower temperature, and are often found 40-70% more expensive compared to its onshore counterparts. The need for compressor stations would also impact the costs.

Economics of scale applies to the transportation cost, where collecting CO_2 from several sources into one pipeline is cheaper than separate infrastructure. For this reason, early movers will face a high transportation cost, and will be more sensitive to transportation distance than late movers.

4.2.5 Storage

Storage can be done in geological formations or in the ocean, while the former is considered most relevant due to the fact that ocean storage has not yet been deployed or thoroughly tested.

The major capital cost for geological storage is related to drilling wells and surrounding infrastructure. For enhanced oil, gas and coal bed methane options, additional facilities may be required for handling produced oil and gas. When reuse of infrastructure and wells is possible, it will reduce costs.

The storage costs are highly site-specific, and depend on the type of storage, location, terrain, depth and characteristics of the storage reservoir formation.

The unit costs are usually higher offshore, due the need for platforms or sub-sea facilities and higher operating costs, as shown in separate studies for Europe (Hendriks et al., 2002) and Australia (Bradshaw et al., 2002). For a more thorough treatment of the topic, see for instance IPCC (2005).

Chapter 5

Statoil and CCS

5.1 Statoil's CCS initiatives until now

For the G8 Summit in Muskoka, Canada in 2010, a report on the progress of the CCS technology was presented by IEA (2010). Out of the five commercial CCS projects in operation at that time, Statoil was participating in three of them:

- **The Sleipner project** extracts CO_2 from natural gas delivered from the offshore Sleipner gas field. The project began in 1995 after Statoil faced a government-imposed carbon tax equivalent to about USD 55 per tonne in 1991. The CO_2 is captured using a conventional amine process. Statoil is injecting more than 1 million tonnes of CO_2 per year under the North Sea into the Utsira saline formation located in close proximity to the natural gas field. The capacity of this formation is estimated to be about 600 billion tonnes of CO_2, and it is expected to receive injections long after natural gas extraction at Sleipner has ended.
- **At the LNG-plant Snøhvit,** Statoil captures CO_2 for injection and storage, when extracting natural gas. The separation is necessary since the CO_2 content in the gas is initially too high. Statoil captures about 700 000 tonnes of CO_2 per year at Snøhvit.
- **In Salah**, Statoil is invovled in an injection program in partnership with the Algerian national oil and gas company, Sonatrach and BP. The project injects CO_2 from gas extracted in the Sahara desert. The CO_2 is stored in the Krechba geological formation at a rate of 1 million tonnes per year.

5.1.1 Technology Center Mongstad

In 2006, Statoil agreed together with the Norwegian government to construct a full-scale carbon capture facility at Mongstad. At first stage, Technology Centre Mongstad (TCM) was established in partnership with Dong Energy, Vattenfall, Shell and Gassnova SF. South-African Sasol has later joined the partnership while Dong Energy and Vattenfall left. For five years, starting in 2012, TCM is intended to capture 100 000 tonnes CO_2 per year with two different technologies tested against each other. The second stage, CO_2 Capture Mongstad (CCM), includes a full-scale facility that will capture CO_2 from the Combined Heat and Power (CHP) station. The full-scale facility will capture approximately one million tonnes of CO_2 per year, and was initially planned to start up in 2014. Due to the uncertainty associated with the amine emissions to air and an associated health hazards, the planned start up is postponed to 2016.

5.2 How will Statoil benfit from CCS?

The benefits, and finally profits, of the CCS technology mainly originate from two different sources:

1. **Direct benefits** are benefits arising from the technology itself - on a primary level. It includes income from a CO_2-market, the Emission Trading Scheme (ETS) in Europe. In addition, we have included *avoided tax* and although this is not an income, it is a reduction of cost - and will yield a positive cash flow for Statoil.
2. **Indirect benefits** are hard to quantify, but these are the real upside for the CCS technology. Expert opinions from Statoil employees suggest that a lot of the future revenue potential arise from being ahead of competitors in the CCS field. Certain technologies and/or resources may also be available only with CCS applied. In addition, the somewhat unclear term *license to operate*[1] could be applicable to CCS, but it is uncertain to what extent this is simply a trendy buzz-word to avoid an explicit enumeration of possible values.

In the sections below both of these sources will be elaborated in more detail.

5.3 Direct benefits

5.3.1 Cap and Trade

Emission trading takes place in a market constructed by authorities that are suppose to control the pollution level by providing incentives for reduced emissions. Authorities will allocate or sell emission permits for the amount set by the cap. Businesses that are emitting more than allowed by their permits, will have to buy additional permits from businesses that are in surplus. In effect, the buyer is charged for a higher emissions level while the seller is rewarded for its lower emission level.

For GHG the largest trading program is the EU ETS. It was established in 2005 as a major pillar in the European Union (EU) climate policy. Norway joined the scheme from 2008, which brought Statoil into the emission trading (Regjeringen Stoltenberg II, 2007).

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[1] Defined by Fitch et al. (2000) as “Grant of permission to undertake a trade or carry out a business activity, subject to regulation or supervision by the licensing authority. Licenses are granted by state or federal agencies, and also by private concerns, as when a business authorizes another to use its name as a franchise operator. Licenses granted by government authority imply professional competence and ability to meet certain standards set by law or regulation.”

In its first phase (2005-2007) the EU ETS covered approximately 40% of the CO_2 emissions from the EU. This period suffered from over-allocation of permits, which resulted in a carbon price dropping to zero. The EU ETS is now in its second phase covering 2008-2012, and the emissions price development until now can be seen in Figure 5.1.

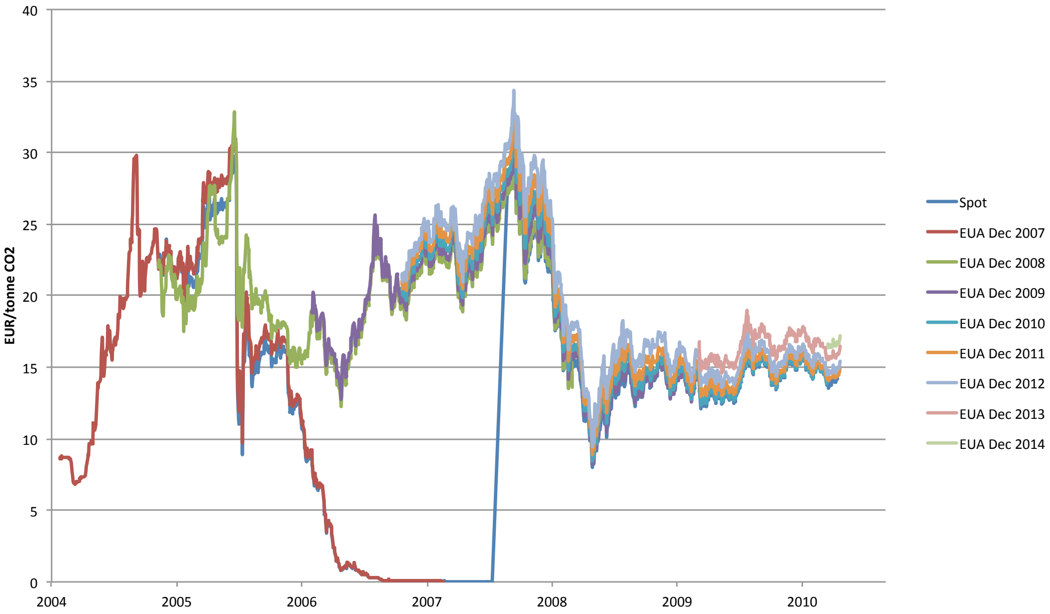

Figure 5.1: Development of the EU Emissions Trading Scheme. Source: Kjersti Ulset, Point Carbon/Thomson Reuters

The EU ETS has been criticized for both over-allocation and exessive price volatility. The problem of over-allocation vanishes as the cap tightens, which is already happening for the current phase and is proposed to be further tightened for the third phase (2012-2020) (The Committee on Climate Change, 2008). The price movements have been volatile and the viability of the trading scheme as a stable incentive for emitters has been questioned. Newbery et al. (2009) claimed EU ETS did not provide the stable carbon price necessary for long-term low-carbon investment, and suggested measures for stabilization by introducing a price-ceiling and floor. Still, in a market like the EU ETS, the considerable volatility is expected to continue. The carbon price behaviour, with its implied volatility, is in line with that of energy commodities generally.

For the third phase, proposed changes include a move from allowances towards an auctioning system.

5.3.2 Carbon tax

Carbon tax is charged by the government for emissions with carbon content. Several countries have made or are planning to make use of additional taxation of carbon emissions in order to achieve reductions in pollution. Among the international taxes, the Canadian is of most interest for Statoil as it in the beginning of 2011 started its production of the controversial oil sands in Alberta. Thus, the Canadian tax will be elaborated on together with the Norwegian.

Norwegian CO_2 tax: In 1991, the Norwegian government introduced a CO_2 tax differentiated on industries. The tax rate for the petroleum sector was NOK 257/tonne of CO_2, which was the highest among the Organization for Economic Co-operation and Development (OECD) countries. As seen from Figure 5.2, the Norwegian tax level is adjusted frequently. Usually, only a correction for inflation is added to the price. The most recent drop in prices was due to the fact that Norway joined the EU ETS, and adjusted the national tax so the tax and the carbon price together would reach the past tax level.

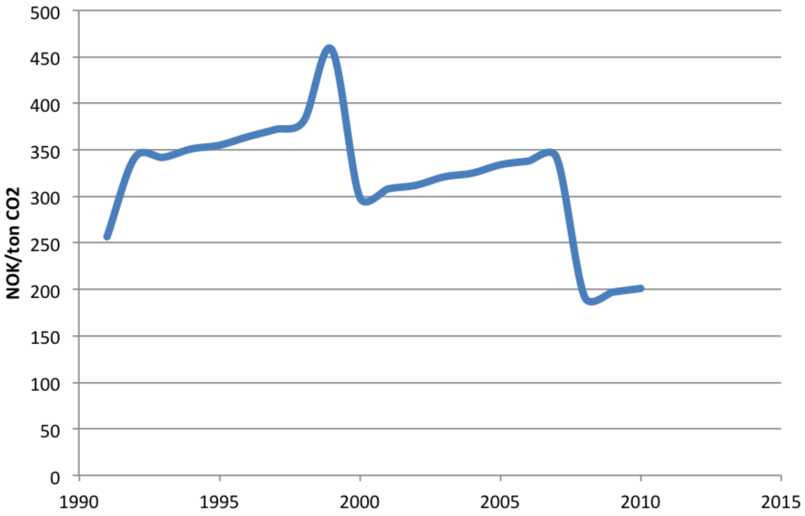

Figure 5.2: Development of the national CO_2 tax for the Norwegian Continental Shelf. The exact data is found in Table E.2. The growth rate after the last significant tax adjustment is 1.7%. Source: Marius Pilgaard, The Norwegian Ministry of Finance

Canadian CO_2 tax: Carbon tax only exists on a provincial level in Canada, and is implemented in Quebec, British Columbia and Alberta.

In 2007, the government of Alberta made companies with emissions exceeding 100 000 tonnes of GHG annually to either reduce the CO_2 emissions per barrel by 12%, contribute to a technology fund with US 15 per tonne, or to buy an offset in Alberta to apply against their total emissions.

5.4 Indirect benefits

As the most easily developable oil and gas fields are becoming increasingly scarce, most of Statoil's new production will be in fields with so called *unconventional* oil and gas. The term unconventional refers to oil and gas reserves that is extracted or produced with other techniques than the conventional method. These methods are less efficient and has has a higher carbon footprint, see Figure 5.3, and therefore they are by many considered somewhat controversial. CCS has the potential to play an important role for allowing Statoil to extract and produce unconventional oil and gas by reducing its associated emissions from the extraction phase.

IEA (2010) defines unconventional oil as:

- Oil sands

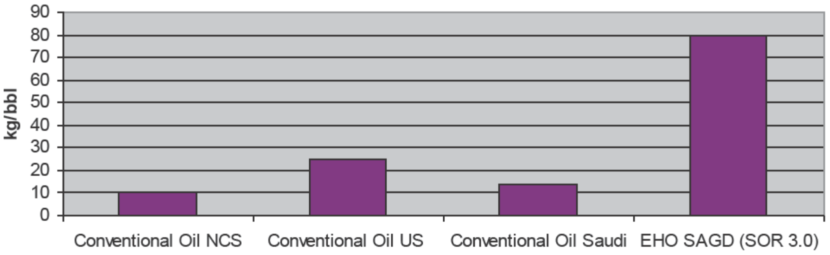

Figure 5.3: CO_2 emissions pr produced barrel from oil sands versus conventional fields. From left is conventional oil from the Norwegian Continental Shelf, conventional from the US, conventional Saudi and typical oil sands (EHO = Extra Heavy Oil) extracted with Steam Assisted Gravity Drainage (SAGD). Source: Statoil.

- Oil shales
- Coal-based liquid supplies
- Biomass-based liquid supplies
- Liquids from processing of natural gas, Gas To Liquid (GTL).

The IEA expects these sources to play a major role in 2035, potentially covering as much as 35% of oil demand. Primarily, oil sands in Canda and heavy-oil in Venezuela dominate, but also Coal To Liquid (CTL), GTL and to some extend oil shales contribute to growth. The expectation requires an assumption of technology development that reduces the oil prodution's impact on the environment, primarily its CO_2 emission.

Table 5.1: Unconventional oil supply by source and scenario, in mbbl/day. From Table 4.1 in IEA (2010). The scenarios concern the future climate policy, where the Current Policy Scenario and the 450 Scenario is the least and most stringent, respectively. For a detailed elaboration on the scenarios, see IEA (2010).

			New Policy Scenario		Current Policy Scenario		450 Scenario	
	1980	2008	2020	2035	2020	2035	2020	2035
Canadian oil sands	0.1	1.3	2.8	4.2	2.8	4.6	2.5	3.3
Venezuelan extra-heavy	0.0	0.4	1.3	2.3	1.3	2.3	1.3	1.9
Oil shales	0.0	0.0	0.1	0.3	0.1	0.5	0.1	0.2
Coal-to-liquids	0.0	0.2	0.3	1.1	0.4	1.6	0.3	1.0
Gas-to-liquids	-	0.1	0.2	0.7	0.3	1.0	0.2	0.5
Other*	0.0	0.4	0.6	0.9	0.7	1.0	0.6	0.6
Total	0.2	2.3	5.3	9.5	5.5	11.0	5.0	7.4

There are bitumen and extra-heavy oil deposits in countries other than Canada and Venezuela, see Table 5.1, but only Canada and Venezuela are likely to play a significant role in the exploitation of these resources in the timescale of IEAs projections.

5.4.1 Oil sands in Canada

Enormous reserves. Alberta's proven economically recoverable oil sands reserves amount to 173 billion barrels of oil equivalents (boe) (WWF, 2010), with estimates for bitumen in place between 1.7 and 2.5 trillion barrels, making it second only to Saudi Arabia in proven reserves. Production reached 1.3 million barrels per day (bpd) in 2008 and current projections place production between 2.5 and 4.5 million bpd by 2020, with production capacity possibly as high as 6.2 million bpd.

Production of oil sands can be done as mining or in-situ, where the former is limited to resources located near the surface (i.e. down to 75 meters depth). There are several in-situ production methods, but most of the oil sands require thermal methods due to high initial viscosity. By hot steam injection (250-350°C) the oil sands will become extractable. Cycling Steam Stimulation (CSS) and Steam-Assisted Gravity Drainage (SAGD) are two methods of steam injection, where the latter has become the most popular one. The production of hot steam is energy intensive, and currently fossil fuels is used as energy source.

Constraints on production are possibly many, but among the most noteworthy are:

- **CO_2 emissions** are probably seen as the biggest constraint from a Norwegian point of view. Unconventional oil emits more than three times as much compared to conventional oil production. Hence, there are forces wanting Canada to shut down its oil sands because of the CO_2 emission from the production phase (Montreal Gazette, 2011). It is assumed that levels of CO_2 emissions will reach an additional 40 kg/barrel compared to more easily extractable resources 2035. Ballpark figures for CO_2 emissions from the production is about 30kg/bbl for conventional oil, while unconventional is typically in the area 60-70kg/bbl. This gives an additional 60 million tonne more CO_2 annually. This is a significant increase compared to Canada's 550 million tonne/year as of today. Thus, it seems applicable to see this as a national challenge.
- **Water consumption** is the aspect devoted the most attention from the Canadian government. Water extraction from local rivers is regulated and limited to 3% of river flow (and less at times of low water flow); but even that amount is considered by some to be potentially damaging to the river ecosystems.
- **Land usage** is an emphasised problem when the extraction of the Canadian oil sands is conducted as open-pit mining. This consumes vast amounts of the boreal forrest.

CCS in Canada

Energy production is a corner stone in the Canadian economy, and oil sands represent a major income for the state. Due to the enormous reserves, it is highly unlikely that Canada will turn down its oil sands production. Instead, the government, both on the federal and provincial level, try to take its environmental responsibility by imposing stringent requirements for emission, and encourage use of CCS technology.

In 2007 the federal government released the regulatory framework, *Turning the Corner*, aiming at emission reduction of GHG and air pollution. The regulation suggests stringent emission targets, and it was stated that in order to meet those targets, oil sands plants will require to be equipped with CCS or equivalent technology by 2018.

Through the Alberta Climate Change Strategy, the provincial government states its belief in CCS as a significant contributor to reduce GHG emission, estimating up to 70% of Alberta's potential reductions. In late 2010, the Carbon Capture and Storage Statutes Amendment Act was passed, which comprises regulations and the disposition of rights for the injection and permanent storage of CO_2 in Alberta.

In March 2007, ecoEnergy CCS Task Force was established by the Alberta and Federal government. Its mandate is to advice on how industry and government can facilitate CCS opportunities (The ecoENERGY Carbon Capture and Storage Task Force, 2008).

A potential barrier for CCS to be deployed in Canada is the public opinion. Sharp et al. (2009) conducted two surveys which showed an increasing awareness of CCS among the Canadian people, and that their biggest concern is related to storage and leakage. Still, more than two-thirds agreed that CCS is a good short-term solution.

Statoil's situation in Canada

Estimated resources in 2007 when Statoil acquired North American Oil Sands Corporation was 2.2 billion barrels on site (DN.no, 2011a). In December 2010 Statoil decided to sell 40% of the shares in the oil sands project - Kai KOs Dehseh-license - to PTT Exploration and Production (PTTEP). A third party valued the resources to be in the range of 2.5-3.7 billion barrels, most probably around 3.1 billion barrels. The increase is due to new wells the last years, totally around 400. Hence, Statoil's reserves are today in the range 1.5-2.2 billion barrels.

Statoil has initiated a demonstration project at Leismer with an expected production of 20 000 bpd. The next step is Corner, which is planned to start up in 2016 and increase the capacity with 60 000 bpd (Statoil, 2011f).

At mid-2010, most new oil-sands projects are thought to be profitable at oil prices above \$65 to \$75 per barrel.

5.4.2 Heavy oil in Venezuela

The Orinoco Belt in Venezuela holds the second largest resources of extra heavy oil in the world, with an estimated amount of 1.3 trillions barrels in place (IEA, 2010). As of today thermal method, for instance CSS or SAGD, yields the highest recovery rate. Therefore, production in Venezuela is generally challenged with the same issues as in Canada concerning availability of energy, water usage and CO_2 emissions.

Statoil's situation in Venezuela

Statoil has been investing in Venezuela since 1994, and views its presence in a long-term perspective. In 2008 Statoil agreed in partnership with Total and Petroleos de Venezuela (PDVSA) on the Petrocedeno strategic association in the Orinoco Belt. The agreement is valid for 25 years, and as of today Statoil has a 9.67% share in the project that is one of the largest extra-heavy oil projects in the country. Its capacity is designed for approximately 200 000 bpd (Statoil, 2011g).

5.4.3 Oil shales in the US

Oil shales are fine sedimentary rocks containing kerogen from which oil can be produced. Extraction of oil shales are through thermal methods, since the kerogen needs to be heated (350-450° C) in order to transform it to liquid oil. As oil shales are the source rocks in most oil reservoirs, it exists in vast amounts, possibly more than 5 trillion barrels around the world, where about 20% is said to be technically recoverable. More than half of the recoverable resources are found in the US.

The production methods are similar to the ones for oil sands, and so are the expected environmental impact, though there has been fewer studies concerning extraction from oil shales. The energy requirements can reach 25% and 50% of the heating value of the produced oil for mining and in-situ projects, respectively. Hence, the CO_2 emissions from extraction are significant unless renewable energy is used as energy source. Brandt (2008) estimated the emission to reach 180-250 kg CO_2-equivalents per barrel of produced crude[2].

Statoil's situation in the US

In 2010 Statoil and Talisman agreed on developing and produce oil shale from the Eagle Ford resources in south-west Texas (Statoil, 2011d). Together, they have the option to buy as much as 22 000 additional acres in the area.

5.4.4 Gas-to-liquid

GTL is a mature technology, and has been known for decades. The interest for the technology was reborn in the early 2000s due to the increasing oil-gas-price ratio and technological advancements. The technology forms syngas by combining natural gas together with steam and oxygen, before transforming the syngas into liquid hydrocarbons by applying the Fischer-Tropsch synthesis.

As of today, GTL is only economically attractive on a large-scale, but there has been several attempts to accomplish profitable small-scale GTL. The small scale has an enormous potential since it will be able to utilize "stranded" gas, which is gas fields that have no way of bringing the gas to the market and still maintain profitability. In addition, small-scale GTL will be an alternative to flaring, which is equivalent to about 5% of the world's gas production.

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[2] One barrel is about 130 kg, the range translates into 1.38-1.92 kg CO_2 pr kg crude.

The disadvantage of the technology is the large environmental footprints in terms of CO_2 emission. During the process, approximately a quarter of the carbon in the natural gas is transformed to CO_2.

Statoil and GTL

Statoil began researching on the Fischer-Tropsch process and other gas conversion technologies already in 1986, and decided in 1999 to qualify the technology for commercialization. From 2002, Statoil has collaborated with PetroSA and Lurgi to build a commercial process demonstration Fischer-Tropsch plant in Mossel Bay, South Africa. The partnership was established through GTL.F1, and was awarded under the World GTL Summit in 2008 for its highly efficient technology (Statoil, 2011c).

Chapter 6

Valuation of CCS from Statoil's perspective

The valuation of CCS for Statoil will be based on the framework presented in Neely (1998). The building blocks from the hybrid real options theory will be applied on CCS technology and elaborated on before constructing the decision tree that provides the expected value of Statoil's R&D in the CCS field. For the entire valuation we assume that Statoil is a risk-neutral firm.

Step 1 of the framework (Scope of Assessment) has more or less been completed in Chapter 4 and 5. For now we consider CCS as being of one use only - mitigating emissions of CO_2 - and Step 5 is then redundant. This may change in the future, where there might be multiple uses of CO_2 other than storing it in the ground[1].

Throughout this chapter the specific value drivers for CCS will depend on what direction the climate policy will take. The analysis behind the choice of different scenarios will be elaborated under Section 6.1.4, but for simplicity we mention the main implications from each scenario beforehand:

- **Business As usual Scenario (BAS)** is a scenario where energy welfare and security are the major concerns. The revenue from the CO_2 tax is reinvested in renewable energy and CCS, which will be commercially available in 2015. This is the least stringent scenario.
- **New Policy Scenario (NPS)** introduces new measures, but in a cautious way. The scenario takes into account announced commitments for reducing GHG emission and fossil-energy subsidies, but they are not necessarily fully implemented. This is the most probable scenario.
- **450 Scenario (450)** aims at limiting the global temperature increase to 2°C by reducing the concentration of GHG in the atmosphere to 450 ppm of CO_2-equivalents. This is the most stringent scenario.

In addition to the possible policy scenarios, the different stages of the CCS R&D project will be

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[1] At TCM, a project in collaboration with industry is trying to make use of CO_2 in algea production for bio-fuels and chemical production, Technology Centre Mongstad (2011). This could pose a significant increase in the profitability of CCS technology.

outlined in the following list. For exact cost and benefit values associated with the respective stages, please consult the Excel file attached to the thesis.

- **R&D Stage I** consists of the initial R&D costs faced by Statoil at Mongstad. Thus, it includes preliminary R&D costs and qualifications costs of the TCM plant. These cash flows continue until 2016. At this point, we assume a full scale facility - CO_2 Capture Mongstad (CCM) - is built at Mongstad, with different cost projections linked to the possible policy scenarios.
- **R&D Stage II** consists of Capital Expenditures (CAPEX) for a possible new CCS technology, which span over ten years. In addition, associated alternative costs (labour) is added as they could provide a higher return elsewhere in Statoil. The background for these suggestions are found later in this chapter.
- **Broad implementation** of CCS is modelled to be decided upon by Statoil in 2020. From this point on, annual costs and benefits arise as an implication of the implementation throughout Statoil's operations.

6.1 Collecting and transforming project data

6.1.1 Decisions

Before any valuation can take place it is necessary to understand what kind of decisions that are to be made and what their implications are. As seen in Chapter 5, Statoil has agreed on full-scale CO_2 capture at Mongstad, and it is assumed that Statoil will fulfill its commitments that were agreed upon in the Collaboration Agreement (Statoil ASA and Staten ved Olje og Energidepartementet, 2006) with the Norwegian government. For that reason the unavoidable investments Statoil entails will be considered as initial cost in the R&D valuation, and are defined as R&D Stage I. These cost amount to 20% share of the total cost of TCM, which corresponds to an annual investment of NOK 250 million. Further, the initial cost includes the cost equivalent to Statoil's alternative cost if Mongstad was to be run without capture of CO_2 emissions. This cost is basically the applicable tax on the released emissions. In addition, the alternative costs in terms of labour resources also comprise the costs of Stage I as the labour resources invested in CCS could be utilized in other projects, yielding potentially a better return[2]. The man-labour years invested in Statoil's CCS project, is assumed to be 25, 120 and 100 in R&D, TCM and CCM, respectively (Statoil, 2011a). The latter is expected to reach 300 by 2015.

Statoil has already invested in CCS and needs to decide whether they should continue the R&D in CCS beyond Mongstad, and eventually whether it should be implemented on a broad scale throughout the company.

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[2] The average revenue per employee is set to the level of 2011. After the de-merger of Statoil Fuel & Retail in 2010 the number of employees in Statoil is approximately 20 000. From the first quarterly report of 2011 the cash flow provided by operating activities reached NOK 20.4 billion, which over a year sums up to NOK 81.6 billion. Hence, the average revenue per employee is NOK 4.1 million.

Decision 1: Continue R&D?

When choosing to continue R&D beyond Mongstad, Statoil moves on to what has been defined as R&D Stage II, and further R&D cost will be imposed. These costs are needed in order to prepare for a potential broad implementation, but the cost will also comprise research on other CCS solutions. Steam generation with oxy-fuel is by many considered to be a promising energy source for extraction of Extra Heavy Oil (EHO) in Canada. To accomplish this, a brand-new-concept investment similar to the amount invested in TCM is required (Statoil, 2011a). Hence, the annual investment costs for R&D Stage II are NOK 250 million.

The research on other CCS solutions, which is considered as a necessity when continuing the CCS development, is assumed to require a work force similar to the one utilized in the preliminary R&D and qualification stage at Mongstad, which adds up to 145 man-labour years.

Carbon Capture Journal (2011) reports that Statoil could benefit from a non-working emission trading schemes by profiting on a permit surplus. The EU has been given permits based on historical production levels and as these have been decreasing in the petroleum industry over the last years, a surplus of permits will possibly be given. Thus, Statoil is able to cover its emissions while still having permits to sell in the market. However, it is assumed that this will be an insignificant long-term effect as the scheme will improve and gradually move from allowances to auctioning (The Committee on Climate Change, 2008).

If Statoil chose to abandon further R&D in CCS, the initial costs from Mongstad will be lost, while the cost from R&D stage II are avoided.

Decision 2: Broad implementation?

Given that Statoil continued with R&D stage II, there will eventually - but no sooner than 2020 - be required a decision for whether or not to commence a broad implementation throughout the Statoil company. When choosing to implement CCS, costs and benefits will occur. Statoil should only implement if the benefits are larger than the sum of the implementation costs. These benefits and costs will be elaborated on in the next sections.

6.1.2 Cost

The costs of CCS is unquestionably the most crucial factors that the deployment of the technology depends on. As already mentioned there are several cost estimations for CCS due to the multiple influencing factors. When building this framework we will not go in detail on each of the three steps of CCS due to the uncertainty associated to cost estimation in general. Thus, we will deal with an overall cost development for the capture, transport and storage of CO_2.

McKinsey & Company (2008) estimated a cost development of CCS for the period 2009-2035 (see Figure 6.2). When assessing the economics of CCS, the technology cost was defined as all additional full cost (CAPEX, Operational Expenditures (OPEX)) for all three steps of the technology compared to a state-of-the-art non-CCS plant with the same net electricity output, using the same fuel. Further, McKinsey & Company defines three phases in the technology development: The *demonstration* projects are conducted from 2012-2015. After 2020 the *early full commercial scale* projects is running, which after 2030 becomes *mature commercial* projects.

For the demonstration projects, the cost is estimated to be EUR 60-90 per tonne abated. In comparison to Mongstad this is only 70% of the cost faced by Statoil and the Norwegian government. The high cost at Mongstad is due to certain unique circumstances[3] that is estimated by Statoil (Statoil, 2011a) to increase the cost by around 30%, compared to a plant built at a more favorable place.

The early full commercial scale projects experience a decrease in cost per abated tonne of CO_2 reaching EUR 35-50. Taking the the technology to the mature phase will bring down the costs even further. The abatement cost after 2030 depends on the degree of deployment. According to McKinsey & Company (2008) a roll-out of 80-120 projects in EU by 2030 will bring the cost down to EUR 30-45 per tonne abated CO_2. Another EUR 5 in reduction can be achieved both if the roll-out turns out to be five fold, and also if a technological breakthrough occurs in the capture phase.

Learning effects

The decrease in technology cost is due to learning effects and economics of scale. The learning effect estimated by McKinsey & Company (2008), Figure 6.1, is most dominant in the capture stage, where a 1% reduction of the efficiency penalty and 12% reduction of CAPEX costs for every doubled installed capacity can be expected. This rate of learning has been found for similar industries (Liquefied Natural Gas (LNG), 13%, capture system for SO_2 and NO_x, 12%).

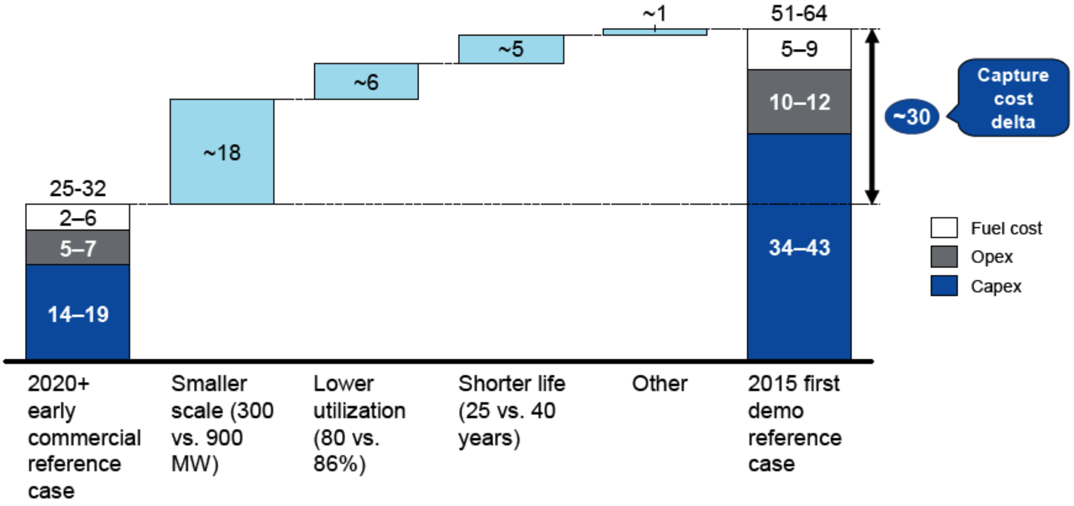

Figure 6.1: Cost of CCS with learning effects, estimated by McKinsey & Company (2008), measured in EUR/tonne CO_2 abated for capture. Please note that numbers in ranges may not add up due to interdependence of factors.

The expected learning rate is in line with prospects made of Riahi et al. (2004) for the CCS technology. He established a cost curve based on experience from controlling SO_2 emission. The

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[3] For instance; the close location to the refinery at Mongstad needs special precautions when designing and constructing.

estimated learning rate for the most common flue gas desulfurization (FGD) technology used at coal power plant for SO_2 capturing was 13%. Beceause of learning effects, a cost reduction of factor four could, according to Riahi et al., be expected within the 21^{st} century, ending up with a technology cost of USD 34-38/tonne carbon (C) abated. Riahi et al. assumed the policy scenario was limited to 550ppm CO_2 in the atmosphere.

For transportation and storage cost the learning effects are limited due to already known and applied technology. Cost of transportation will face reduction through scale and networks effects, but only when CCS is more broadly rolled out. Storage cost development will be driven by the mix of on- and offshore storage over time. The learning rates are from papers dated several years back in time. Since then there has been a stronger move towards renewables, so the rates may be overestimated.

The learning effect contributes to a successful penetration of CCS through interacting demand and supply activities. Limits of carbon concentration and increased returns from learning effects, drives the penetration of CCS from the demand and supply side, respectively.

For use in the model

We have chosen to measure cost of CO_2 in terms of amount captured. This makes it is easier to work with benefits, and easier to extend the model with directly usage of the captured CO_2, for instance with EOR. Another opportunity would be to measure cost by amount CO_2 avoided.

At the moment there are insignificant differences in cost between the three main capture technologies, and for that reason there will only be an overall technology cost development. The cost development can be seen in Figure 6.2 and are based on McKinsey & Company assessment. For the years not covered by their cost development, linear interpolation has been applied - see Table E.5.

In order to reach the early commercial phase McKinsey & Company assumed an installed capacity of 21-23GW to be required. To assume a similar cost development for a single company could be too optimistic. However, it was found to be in line with Statoil's own predictions (Statoil, 2011a) and will thus be applied in our model. The cost development from McKinsey & Company suggests the range of possible cost levels. This defines the high and low technology cost.

If demonstration projects start up in 2015, we assume 2020 to be the earliest the next phase can be reached.

6.1.3 Benefits

Benefits for the CCS technology can be divided into direct and indirect benefits. The former comprises benefits generated by the technology isolated, while the latter covers benefits that emerge as a consequence of having the technology available.

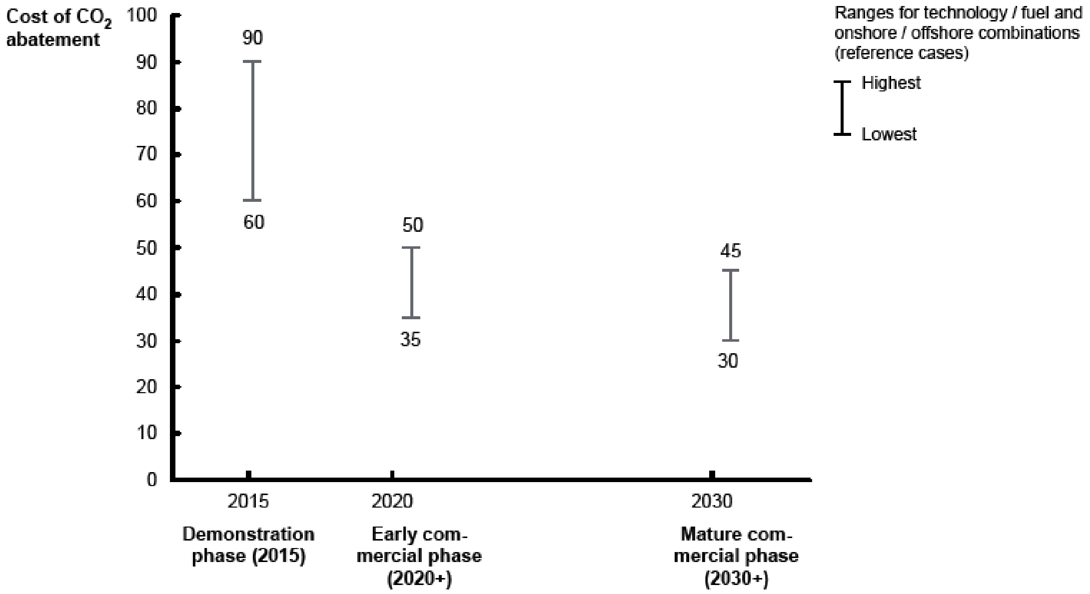

Figure 6.2: Cost development of CCS until 2030, estimated by McKinsey & Company (2008), measured in EUR/tonne CO_2 abated - rounded to the nearest EUR5. The ranges are representing combinations of technology/fuel and onshore/offshore combinations. This referece case is valid for a European rollout scenario, and cost of for instance retrofitting coal power plants and industry will vary.

Direct benefits

Today, there are two regulated monetary systems that will be beneficial for capturing CO_2 emissions. Firstly, the emissions trading offers a market where the captured CO_2 can be sold through permits and yield a profit. Secondly, capturing CO_2 will be beneficial in terms of avoided CO_2 taxation. These benefits are realized only if CCS is implemented.

Emission trading
The carbon price development is highly sensitive to the climate policy. Therefore, it will be necessary to operate with a price development for different policy scenarios. Our scenarios are based on IEA (2010) and Karstad (2009), and will be elaborated in more detail under Section 6.1.4. IEA has only estimated the carbon price for certain years, and for the remaining years a linear interpolation has been applied. The price development we assume for the modelling can be seen in Figure 6.3.

When using this price development in the model, we have assumed:

- a steadily increasing price
- that the market will develop freely without any restrictions; no floor, no ceiling
- that the development is valid for the whole world, at least where Statoil is operating.

Carbon tax
Due to the significant gap between the Norwegian tax and international taxes, we will operate with two taxes. The Canadian tax level is assumed to be applicable for all international emissions. In the same way as for the carbon price, there will be three carbon tax developments for

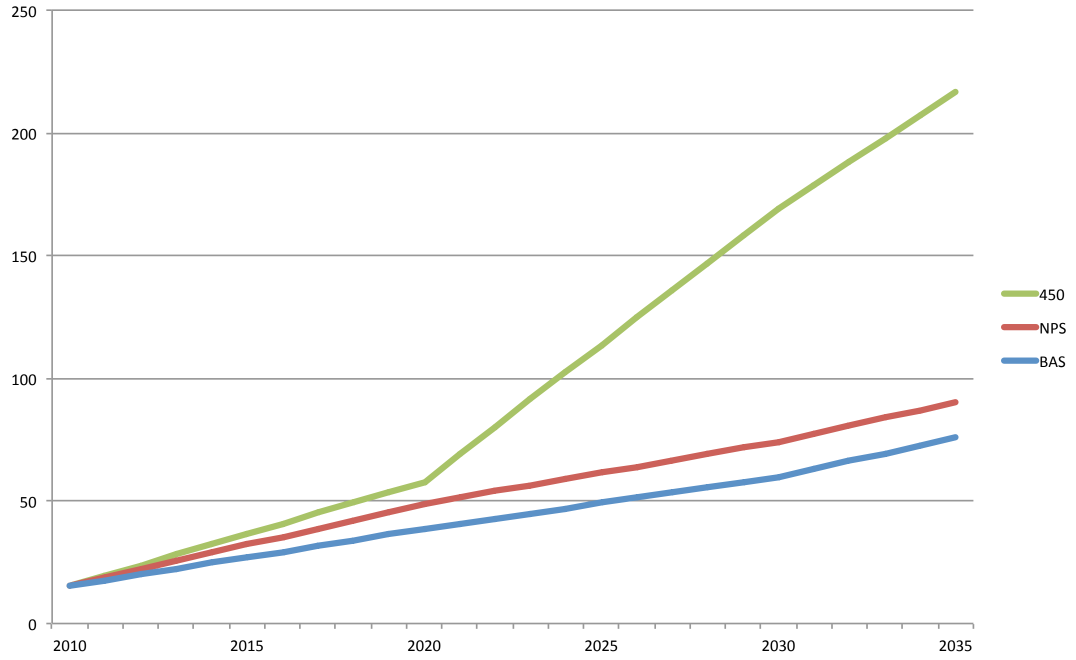

Figure 6.3: Assumed CO_2 quota price development in EUR/tonne CO_2 for the different scenarios (see Table **??**). After 2020 the prices in the 450 Scenario increases significantly compared to the others. The annual inflation is 2.30%.

each of the climate policy scenarios.

The growth rate of the tax level for the least stringent scenario (BAS) will follow the Norwegian rate that has been present after Norway joined the EU ETS in 2008 (see Figure 5.2). In the model a price development with an annual growth rate of 2% will be used. For the NPS and 450 scenario, the growth rates are assumed to be 20% and 100% higher compared to the rate in BAS, respectively. The percentage growth for the international tax is assumed to be similar to the Norwegian trend.

The initial tax level for use in model will be NOK 201 and USD 15 for Norwegian and international emissions, respectively. Even though the carbon tax in Norway is said to be abolished in favor of the EU ETS, it will for this valuation be assumed that the tax and emission trading will prevail side by side. Table E.3 in Appendix E contains the Norwegian and the international tax levels faced by Statoil in 2010-2035.

Indirect benefits

The indirect benefits include the benefits achieved by the possession of CCS knowledge. An obvious indirect benefit is gaining license and access to extract unconventional oil and gas with energy intensive extraction methods.

Access to unconventional production

CCS is expected to play an important part in sustaining Statoil's future production level by justifying extraction of controversial unconventional oil and gas. According to The Norwegian Oil

Directorate (Oljedirektoratet) (OD) (Oljedirektoratet, 2009) the production level on the Norwegian Continental Shelf (NCS) will remain stable at approximately 235 million Sm^{3}oil equivalents per day (oepd) until 2020, and then decline steadily for ten years reaching 150mSm^{3}oepd, see Figure 6.4.

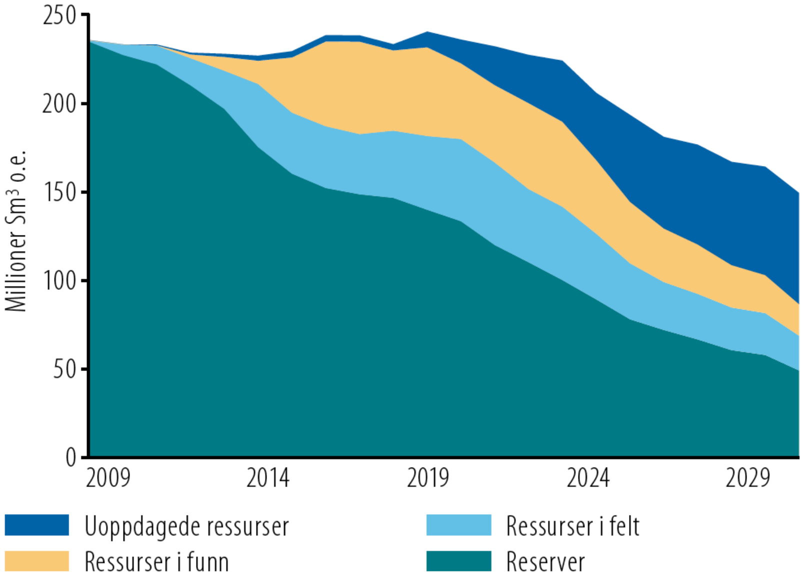

Figure 6.4: Estimated petroleum production from the NCS 2009-2030. Source: Oljedirektoratet (2009), Figure 4.19. The exact data can be found in Table A.12.

Statoil has stated that it aims to keep its production level on the NCS stable until 2020 (DN.no, 2011b), in addition to achieving an annual growth in its overall production of 1% (Statoil, 2011a). This will be assumed correct throughout the analysis. Furthermore, we assume that Statoil will keep its 40% share on the NCS as of today for this valuation's time frame, and thus Statoil will experience a decline in production corresponding to the estimations stipulated by OD. For the last five years of the the valuation's time frame that is not covered by the predictions of OD, we assume that the production level will stabilize on the 2030-level.

We are only interested in the need for new production after 2020 as this is the point when Statoil, at the earliest, can possess commercially viable CCS technology that will have an impact on the potential benefits.

The decline in production on the NCS and the goal of overall growth will require Statoil to increase ownership in international production fields. The loss of production on the NCS in the period 2020-2035 amounts to a total of 1.7 billion boe. For the same time period, the overall expansion goal will require an additional 1.9 billion boe of new production. Figure 6.5 illustrates the need for new production.

As the most easily extractable resources are not available, Statoil is forced to look into the field of unconventional oil and gas. For use in the model, it is expected that 30% of the new international production Statoil needs can be classified as unconventional oil and gas that require CCS technology to be socially acceptable. 60% is assumed to be the upper level.

The value of this new production is assessed through the oil-gas production ratio outside Norway, the production cost outside Norway and the price development of oil and gas. The latter depends

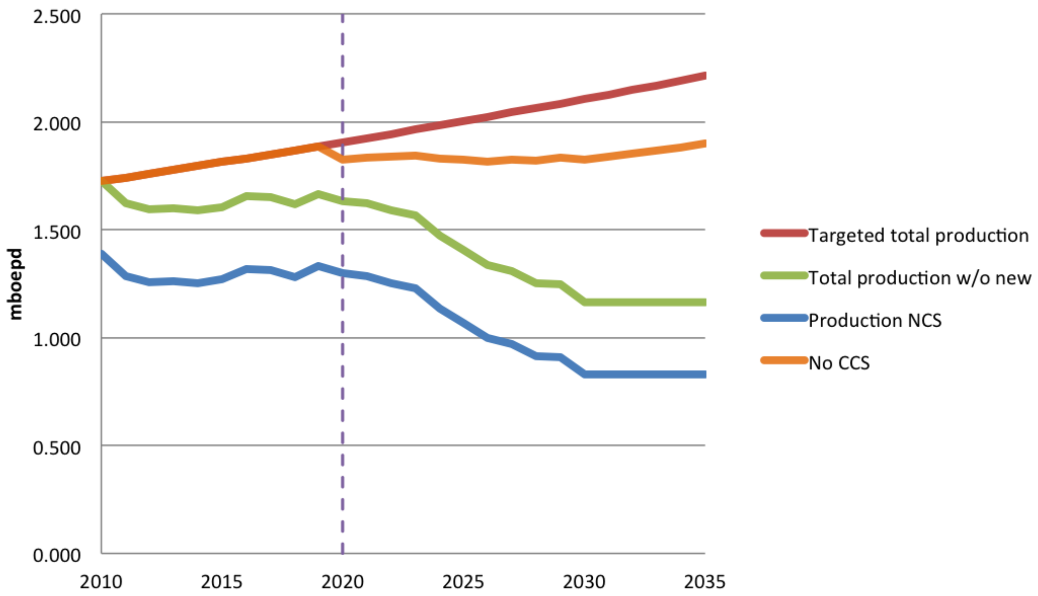

Figure 6.5: Statoil's need for new production to obtain its stated goal for future growth, is the area between *Targeted total production* (red) and *Total production w/o new production* (green). *No CCS* (yellow) is a 30% reduction from *Targeted total production*, and represents Statoil's production if Statoil chooses not to develop CCS. Thus, the area confined by *Targeted total production* and *No CCS* represents Statoil's benefical production when developing CCS

on the demand for the respective energy source. Predictions of the demand for oil and gas are given by IEA for each of the climate policy scenarios and are seen in Figures 6.6 and 6.7, respectively. The oil and gas prices are expected to increase with increasing demand in the IEAs Current Policy Scenario and NPS due to population and economical growth. In the 450 scenario the prices are expected to fall as a response to declining demand due to the effects of drastic policy actions to mitigate fossil energy consumption.

Today, Statoil's oil-gas production ratio outside Norway is 80%, and has been stable on this level for the last five years (Table A.9). At the end of 2010, Statoil's reserves outside Norway are distributed with a share of 75% in oil and 25% in gas. For simplicity, we will continue using an oil-gas production ratio of 80% until 2035.

Statoil's production costs are measured in NOK/boe, and has experienced an average annual growth of 4.1% on the NCS the last decade, increasing from NOK 23.70 in 1998 to NOK 40.6 in 2010 (see Table A.11). The production cost outside Norway is considerably higher, and averaged NOK 52.4 in 2010. The growth of the international production cost has been larger than on the NCS. Both trends are expected to accelerate due to more difficult extractable resources, but for the model we assume the trend to be in line with historical data. We will use the growth rate on the NCS for the development of the international production cost due to lack of international historical data.

Statoil's Senior Vice President in Strategy and Commercial Affairs in Canada, Robert Skinner, said in June 2010 that break-even for oil sands in Canada is in the range of USD 65-75/boe (Bloomberg, 2011). However, projects in near future are estimated by Statoil to run, on average, break-even with approximately USD 50/boe, as seen in Figure 6.8. After excluding today's

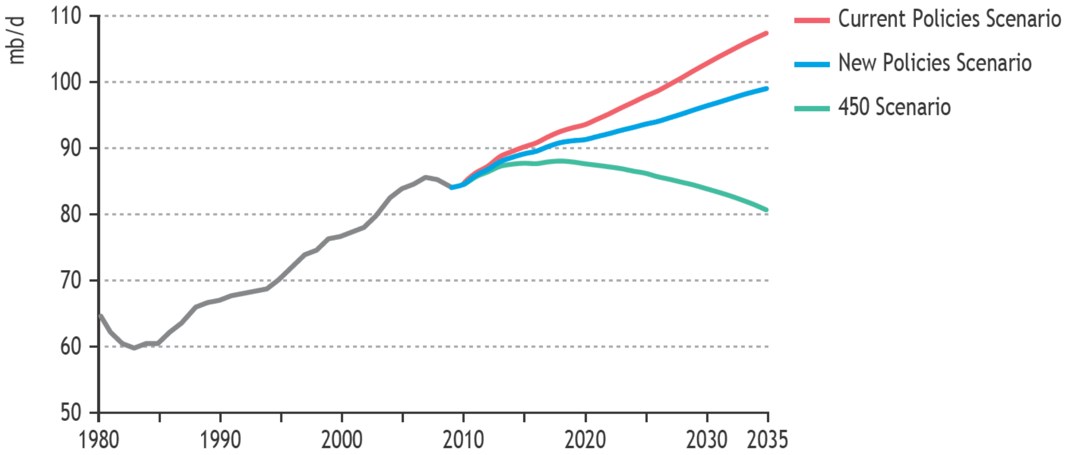

Figure 6.6: Future oil demand. In the Current Policy Scenario, the demand is expected to continue steady growth. This is attributed to increasing population and economic growth. The same argument is valid for the NPS, just to a smaller scale. The policy implications in the 450 Scenario causes the demand to fall. Source: IEA (2010), Figure 3.1.

production cost on the NCS of USD 10, the remaining USD 40 of the average break-even price is used as an annual measure for the capital expenses required to access new production fields for this valuation's time frame. Thus, the annual increasing break-even cost is a result of increasing operational costs.

Table 6.1 gives the estimated benefits from accessing unconventional production for the respective climate policy scenarios.

Table 6.1: Estimated indirect benefits. The BAS yields the largest indirect benefits as a result of high oil and gas prices.

Unconventional share		Benefits [bill. NOK]		
		BAS	NPS	450
Expected	30%	141	102	60
High	60%	283	204	120

For explicit considerations of the indirect and direct benefits utilized in the model, see the tables in Appendix A.

6.1.4 Uncertainties

Statoil's costs and benefits are dependent on several uncertainties. The most dominant are the uncertainties related to climate policy and degree of technological success.

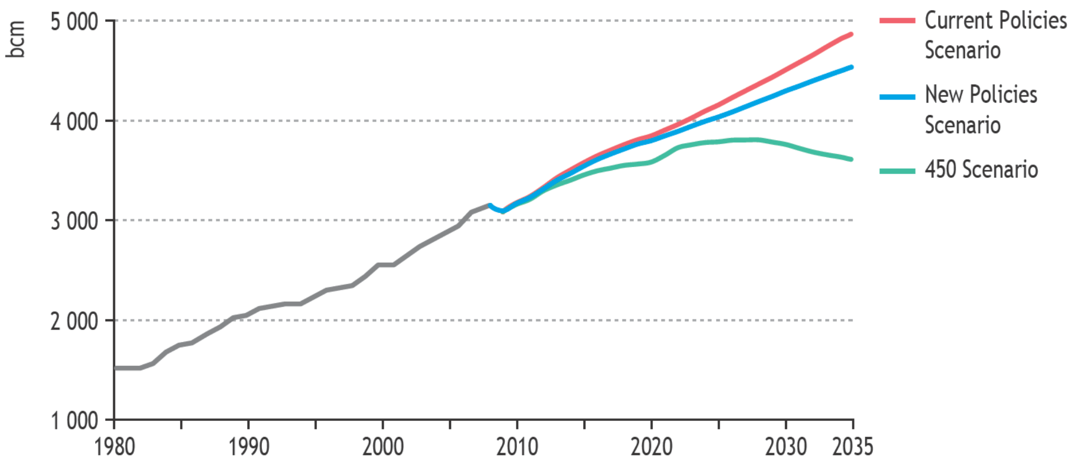

Figure 6.7: Future gas demand. The explanation here is similar to the one in Figure 6.6, but generally, gas is still assumed to have a steady growth in all scenarios apart from the 450 scenario, where the demand is flat after 2020. Gas is still readily available as an energy source, and this fact, together with a lower carbon footprint compared to oil, is the reason for the steady growth. Source: IEA (2010), Figure 5.1.

Climate Policy

Statoil's decision on whether to take its CCS development a step further is influenced by the climate policy the next 30-50 years. The policy will impact Statoil's ability to make a profit, both directly in terms of price levels (i.e CO_2, hydrocarbon resources) and indirectly through requirements for being licensed to operate.

In order to handle the uncertain future the model will operate with three scenarios that differ in climate policy stringency. These scenarios are based on the scenarios defined by Karstad (2009) and IEA (2010).

The methodology of Karstad for scenarios applies a trilemma, illustrated in Figure 6.9, to cover economic growth and development, security of energy supply, and environmental impact of energy consumption. The scenarios are then defined after which two aspects that dominates the climate policy. The time frame is 2009-2100.

Karstads' scenarios are as follows:

1. **Business As usual Scenario (BAS)** is when energy welfare and security are the major concerns. The revenue from the CO_2 tax is reinvested in renewable energy and CCS, which will be commercial available in 2015.
2. **Nationalisation** scenario is concerned about energy security and environment. Domestic energy sources are given a highly strategic value, and thus there will be no investments in the energy export infrastructure after 2015. CO_2 taxes exist, but varies significantly between continents.
3. **Global cooperation** is emphasizing environmental concern and economic welfare. There will be a significant transfer of technology, which lifts the capacity of CCS in Europe and Asia. A global CO_2 tax is established in 2015.

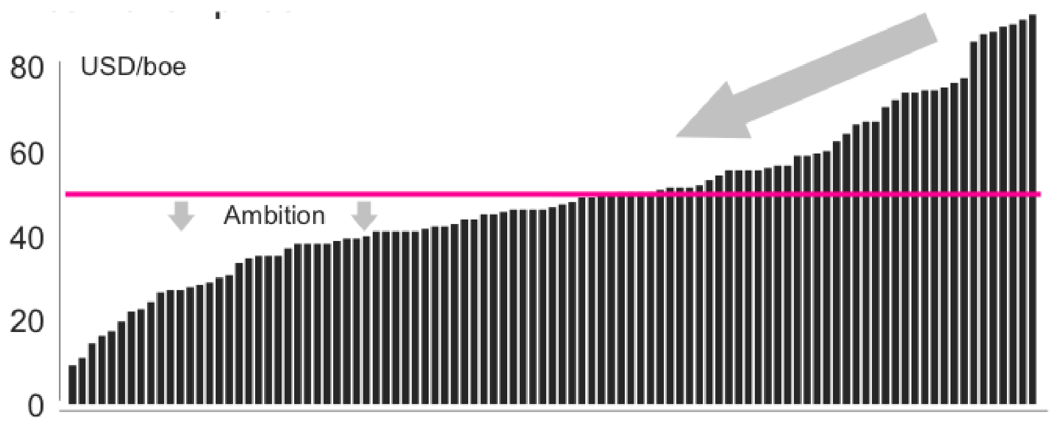

Figure 6.8: Statoil's expected break-even prices for future projects. The projects with lowest break-even price are usually developed first, and are most often found in Norway. The higher break-even prices are therefore more of interest for this valuation as the indirect benefits is based on international production Statoil (2011e).

The IEA has defined three scenarios, the Current Policy Scenario, the New Policy Scenario, and the 450 Scenario:

1. **Current Policy Scenario** takes into account all measures agreed upon by mid of 2010, but no further measures are assumed adopted in the future. It is a reference scenario and is intended as a base-line for the two other scenarios. IEA emphasizes that it is highly unlikely that the policy will stay unchanged, and thus the scenario should not be given significant attention.
2. **New Policy Scenario (NPS)** introduces new measures, but in a cautious way. The scenario takes into account announced commitments for reducing GHG emission and fossil-energy subsidies, but they are not necessarily fully implemented. Due to uncertainty in the power of governmental actions, the lower end of announced target ranges are adopted. Most of the national commitments expire before 2020, but the trend of declining carbon intensity is assumed for the remaining period of the time frame. The OECD countries establish targets for emissions reduction for all sectors of the economy, while non-OECD countries are assumed for the first period of the time frame to maintain the pace of reduction of domestic carbon intensity.
3. The **450 Scenario (450)** aims at limiting the global temperature increase to 2°C by reducing the concentration of GHG in the atmosphere to 450 ppm of CO_2-equivalents. To achieve this, the high end of the announced target ranges are adopted and it is assumed a full implementation of the Copenhagen Accord. Further OECD and Other Major Economies (defined by IEA as Brazil, China, Russia, South Africa and the countries of the Middle East) (OME) establish separate carbon markets, and buy offsets in other countries, resulting in one system beyond 2020. This is in line with Karstad's global cooperation scenario.

Assigning scenario probabilities

In the model we will use the scenario names presented by IEA (2010) with exception of the Current Policy Scenario (CPS) that will be referred to as Business As Usual (BAS).

Since the Kyoto agreement in 1997, environmental issues has been on the international agenda

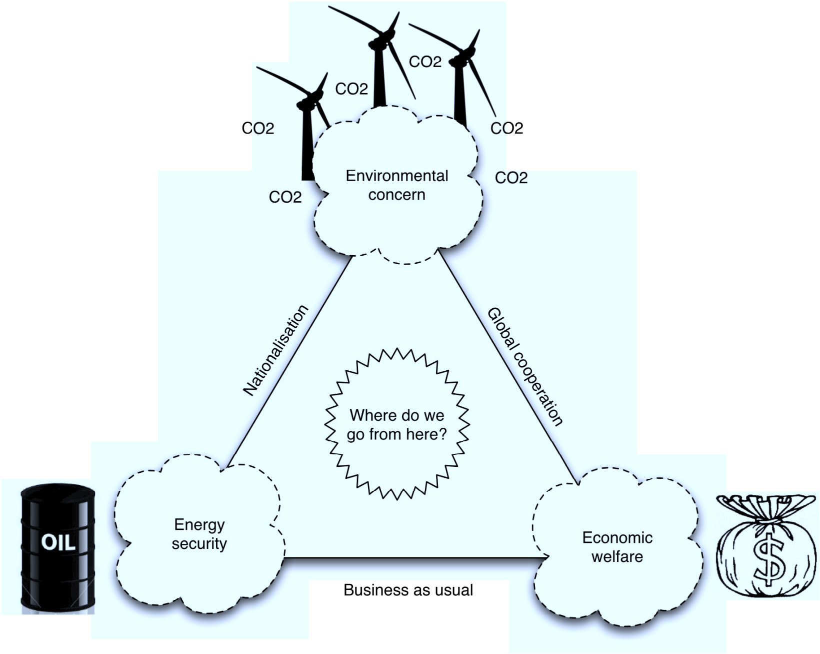

Figure 6.9: Trilemma triangle for scenario development. Source: Slightly modified from Figure 55 in Karstad (2009).

and there exists a global willingness to reduce emissions of GHG. Thus, it is likely that the climate policy will take a more stringent path in the near future. However, there has been lack of agreement in terms of responsibility, where developed countries requires the developing countries to participate in a larger extent than today. There is yet to be found a successor to the Kyoto agreement that ends in 2012. Due to the prevailing reluctance to take abatement measures the BAS is assigned a probability of 10%, despite IEA's lack of faith in this scenario.

The 450 scenario requires a global cooperation, and is found ambitious for various reasons. Firstly, it is an expensive path. IEA (2010) estimates additional spending in low-carbon energy technology in the period 2010-2035 to be USD 18 trillion (year-2009 dollar) and USD 13.5 trillion more than in the BAS and NPS, respectively. Enkvist et al. (2007) developed a cost curve that showed annual cost of the 450 scenario in 2030 to be around EUR 500 billion. Currently, there are disagreements on how to allocate the costs among countries. Secondly, climate risks and energy security challenge the world society to unite due to conflicting interest on national level. The energy situation in Asia, Europe and North America will become more constrained after 2015 due to increasing domestic energy demand in energy exporting regions such as the Middle East, the Caspian and Russia (Karstad, 2009; Gately, 2007). In addition, geopolitical instability in Middle East makes global cooperation even harder. Therefore, the 450 scenario is assigned a probability of 10%.

Thus, the remaining 80% probability will be assigned to the NPS. For a complete overview, see Table 6.2.

Table 6.2: Probabilities for climate scenario outcome with emphasis on the verbal considerations in IEA (2010).

Scenario		Probability
Business As usual Scenario	BAS	10%
New Policy Scenario	NPS	80%
450 Scenario	450	10%

Technology

The technical uncertainty yields outcomes with different level of technological success. The handling of this uncertainty needs to be facilitated by Statoil due to the company specific nature of the uncertainty.

As the CCS technology already has been proven working, there will be no failure outcome, only high and low success. The level of success will impact the abatement cost and the capture rate. A 30% cost reduction is expected for the high success outcome compared to the low outcome (Statoil, 2011a). For this reason, the high success outcome will be assigned to the lower end of the cost range presented in Section 6.1.2, while low success outcome will be modelled with the high end of the range. Further, a capture rate of 90% is assigned to the high success outcome, while the lower level of success will achieve only a 70% capture rate, after conferring with Statoil (Statoil, 2011a).

The probability for the technology outcomes is conditional on the climate policy scenario. With an increasing stringency of the international climate policy, the more likely is a highly successful technological outcome (Stern, 2006). This is due to the fact that Statoil (and others) will, with increasing stringency in its surroundings, put more effort into making CCS commercially attractive. The goal of accomplishing CCS becomes more integrated in the company's policy.

The probabilities for the technological outcomes result from interviewing Statoil employees (Statoil, 2011a), and are given in Table 6.3:

Table 6.3: Probabilities for technological outcome. The high estimate refers to a capture rate of 90%, while the low estimate refers to a capture rate of 70%.

Scenario		High estimate	Low estimate
Business As usual Scenario	BAS	30%	70%
New Policy Scenario	NPS	50%	50%
450 Scenario	450	80%	20%

Benefits

The uncertainty related to the indirect benefits of accessing unconventional petroleum production is set to yield three discrete probabilistic outcomes. Three outcomes are chosen due to simplicity of the decision tree. In addition, it enables the use of the extended Pearson-Tukey method when establishing the probabilities, which is convenient as there is only need for assessing the expected value and a maximum value. For more probabilistic outcomes the Median Bracket method could be applied. See Appendix B for a more detailed walk-through of these methodologies.

As it is assumed that successful development always will have an unlimited potential with benefits greater than zero, the indirect benefits are assumed to be lognormal. The three benefit outcomes, low, medium and high represent the 5%, 50% (median) and 95% quantile of the lognormal distribution.

The indirect benefits are characterizied by an expected value and an upper limit value (see Table 6.1), where the latter is the high benefit outcome (95% quantile). A standard deviation can be constructed by Equation 6.1.

$$\sigma_b = \frac{\ln(\frac{UpperLimit}{Expected})}{1.645} \tag{6.1}$$

The value for the low and high benefit outcome, and medium benefit outcome are then calculated as shown in Equations 6.2 and 6.3, respectively.

$$Benefit\,Outcome_i = E[Benefit]e^{Z_i \sigma_b}, \tag{6.2}$$

where Z is the quantile corresponding to the i^{th} outcome, and $i = \{low, high\}$. Since the distribution is lognormal, the following relationship is valid

$$\begin{aligned} E[X] =& e^{Y_{ave}+\frac{1}{2}\sigma^2} \\ \text{Median}[X] =& e^{Y_{ave}} \\ X =& \ln(Y) \end{aligned}$$

resulting in

$$\text{Benefit Outcome}_{medium} = \frac{E[\text{Benefit}]}{e^{\frac{1}{2}\sigma_b^2}}, \tag{6.3}$$

when X is the indirect benefits.

Following the extended Pearson-Tukey method, the high and low benefit outcomes and the medium benefit outcome are assigned a probability of 0.185 and 0.63, respectively.

Market

The estimated benefits of the CCS technology assumes that Statoil accomplishes its stated strategies as of today. How well Statoil meets the future challenges, which go beyond succeeding in CCS (e.g. environmental issues, decreasing level of reserves) is uncertain, and is covered by the market uncertainty. In order to link Statoil's future market position with the valuation of R&D projects, benefit drivers for the projects needs to be established. As Statoil's production increases so does its associated emissions, and therefore the production level can be viewed as a benefit driver for the CCS project.

Thus, the market uncertainty in this valuation covers the variation in Statoil's future production.

Regression models
The growth or decline in future expected operations are assumed to be reflected in the company's stock price, and thus the stock is chosen as the underlying asset[4]. By modelling a relationship between level of production and the stock price, probabilistic future production levels can be found through a risk-neutral valuation of the stock price. However, the direct link between level of production and stock price was not very statistically significant. In addition, as Statoil was listed on the stock exchange as late as 2001, there is lack of stock price data to capture a time lag of ten years. This would have been necessary in the risk-neutral valuation if level of production was to be obtained directly.

Regression results shows that the relationship between reserve level and stock price is stronger than between production and stock price. As reserve level can be seen as prediction of future production, the reserve level will be used as an intermediate stage for finding the probabilistic future production levels.

Equation 6.4 yields a linear regression model relating the logarithmic transformation of the percentage change in the stock price with the logarithmic transformation of the percentage change in reserve level.

$$R_{t+m} = R_t \, e^{A+B\ln(\frac{S_{t+m}}{S_t})}, \tag{6.4}$$

where R_t and R_{t+m} are the reserve levels at time t and $t+m$, S_t and S_{t+m} are the prices of the stock at time t and $t+m$, and A, B and m are constants. m represents the time lag for the calculation of the percentage change in the stock price and reserve level, and thus the number of years into the future the reserve level is predicted. From the reserve levels, future production levels will be given by the linear regression model found in Equation 6.5.

$$P_{t+n} = e^{C+D\ln(R_t)}, \tag{6.5}$$

where P_{t+n} is the production level at time $t+n$, R_t is the reserve level at time t, and C, D and n are constants. n represents the time lag for a reserve level to reach production.

The present time ($t = 0$) for this valuation is 2010. We are interested in the production level in 2020 ($t = 10$) when the implementation decision is to be made, in order to say something about Statoil's situation. Thus, m and n together need to cover this time period.

An appropriate combination of m and n is determined by regressing the reserve and production model with various values of m and n, respectively. The adjusted R-squares are found in Table C.1. $n = 7$ gave the best fit in the production model, while the reserve model experienced significant improvement of fit with increasing value of m. As the time lag in real-life for a reserve level to be in production (n) is approximately 10 years (Statoil, 2011a), m and n are chosen to reflect this reality at its best while at the same time yielding a good fit. m and n are selected 4 and 6, respectively. The resulting R-square values for the reserves versus stock and production versus reserves, are 0.89 and 0.44, respectively. All the coefficients except C are statistically significant at 3% significance level. The R-squares indicate that the relationship

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[4] Intuitively, the CO_2 appears to be a potential benefit driver as well, and could act as the underlying asset. However, the fundamental assumptions justifying the analysis of options concern the possibility of creating a replicating portfolio of assets and loans that counterbalance the option. This requires a market for the assets over the valuation period for the option. Since it is uncertain whether there will be a market for CO_2 over the options life time, it is not suitable as an underlying asset.

between reserves and production should be modelled differently to yield a better fit. However, the regression is satisfactory for the purpose of this paper. The exact regression results are found in Tables C.2 and C.3.

Constructing risk-neutral distribution
When constructing the risk-neutral distribution the binomial method described in Section 2.2.2 will be applied. In order to make use of risk-neutral valuation procedures, it is assumed that the underlying stock captures all of the market risk. The stock price is further assumed to be log-normally distributed, which is a common assumption for market traded assets. Thus, the calculation of the volatility will follow the method of Cox and Rubinstein (1985), and can be seen in Table C.4. The annual growth and volatility of the stock price are estimated from data dated only two years back in time and are found to be 2.89% and 17.34%, respectively. The short time period of data is chosen in order to avoid the collapse of the stock market in late 2008, which would give a non representative volatility.

Risk-neutral probabilistic outcomes of the future stock price with corresponding production levels are found in Table 6.4.

Table 6.4: Probabilities for market outcome with corresponding stock prices and production levels. As the production today is 620 mboe, the market uncertainty will adjust the benefits down for all outcomes as seen in Equation 6.6.

Market outcome	Probability	Stock Price [NOK]	Production [mboe]
High	39%	185.62	528.64
Medium	47%	124.38	498.20
Low	14%	83.34	469.52

Once the future production levels are established, the market uncertainty yields outcomes that are calculated as shown in Equation 6.6. Basically, the market uncertainty adjusts the benefits outcomes according to the ratio of future and present production.

$$\text{Market Outcome}_i = \text{Benefit Outcome} \times \frac{\text{Future Production}_i}{\text{Present Production}} \tag{6.6}$$

where $i = \{low, medium, high\}$.

The details of the risk-neutral distribution are given in Appendix C.

6.2 Valuing the project

The value of the project consists of four elements; the costs of R&D Stage I, the costs of R&D Stage II, the direct economics and the indirect benefits.

The calculations of the first three elements are found in Appendix A in Tables A.1 to A.6:

- ***CO_2 emissions before capture*** is constructed from the targeted production level and an emission rate. The emissions are divided in Norwegian and international with emissions of CO_2 per boe being 0.026 and 0.142, respectively. The former may seem high, but it comprise both on- and offshore emission. The rates are found through emission and production from Statoil (2010).

- ***CO_2 captured*** is considered for the TCM, CCM and the potential implementation stage. The two former are given from the Collaboration Agreement (Statoil ASA and Staten ved Olje og Energidepartementet, 2006) with the Norwegian government, while the amount of CO_2 captured from the implementation stage depends on the implementation rate and the capture rate. The initial broad implementation rate is 2% with a annual increase of 1 percentage point. The capture rate depends on the level of technology success, and are 70% and 90% for low and high success, respectively.
- ***Costs*** are broken down to every stage of the development process. In the R&D Stages, the cost of the TCM and *New Concept CAPEX* is the fixed annual investment of NOK 250 million, while the cost of CCM is the equivalent amount of taxes Statoil would had to pay as an alternative cost if it did not do CCS. In both R&D Stages the alternative labour cost is included. For the implementation, the cost development established in Section 6.1.2 are applied.
- ***Direct Benefits*** are established from the CO_2 tax and the CO_2 quota price development.

The *direct economics* are defined as the net value of direct benefits from emissions trading and avoided tax, and the implementation costs. As the implementation costs together with the direct benefits are influenced by the production level, the direct economics need to be treated under the market uncertainty together with the indirect benefits in the *benefit tree.*

Benefit tree

The benefit tree is an intermediate calculation stage, where the terminal values for the direct economics and indirect benefits for the different scenarios are found by applying the equations presented in previous sections, as seen in Tables A.15 - A.17. The tree structure captures the possible outcomes in a compact and efficient way.

LOG SD is the standard deviation of the lognormally distributed benefits, and is calculated by Equation 6.1.

The *Indirect Benefit Outcome* in the above mentioned tables is given by Equations 6.2 and 6.3, where the *PV E[Indirect Benefits]* are given by Table 6.1. *P[Indirect Benefits]* is given by the extended Pearson-Tukey method. Further, the *Market Outcomes* for both the indirect benefits and direct economics are found trough Equation 6.6. *P[Market]* is the probabilities from the risk-neutral valuation.

The *Market Outcome* is then combined with the corresponding cost values from the two R&D stages in the the terminal values of the decision tree.

These values have all been discounted with the risk-free rate, r_f, and are therefore present values.

The value of the CCS technology isolated

For the isolated case, the indirect benefits comprising 30% of the new production is excluded. This only affects Statoil's international emissions as all new production is assumed to be outside Norway. It should be noted that these accumulated cash flows are not adjusted for the benefit and market risks.

Accumulated cash flow for the technology isolated for the three scenarios with a high and a low level of technology success is found in Figure 6.10 and 6.11, respectively. As seen from the figures, the isolated value of the technology is negative regardless of level of technological success and climate policy scenario. However, the accumulated cash flow has a promising trend in the 450 Scenario with positive cash flow occurring in 2027, yielding a loss of 8.4 billion over the valuation's time frame when a high level of success is achieved.

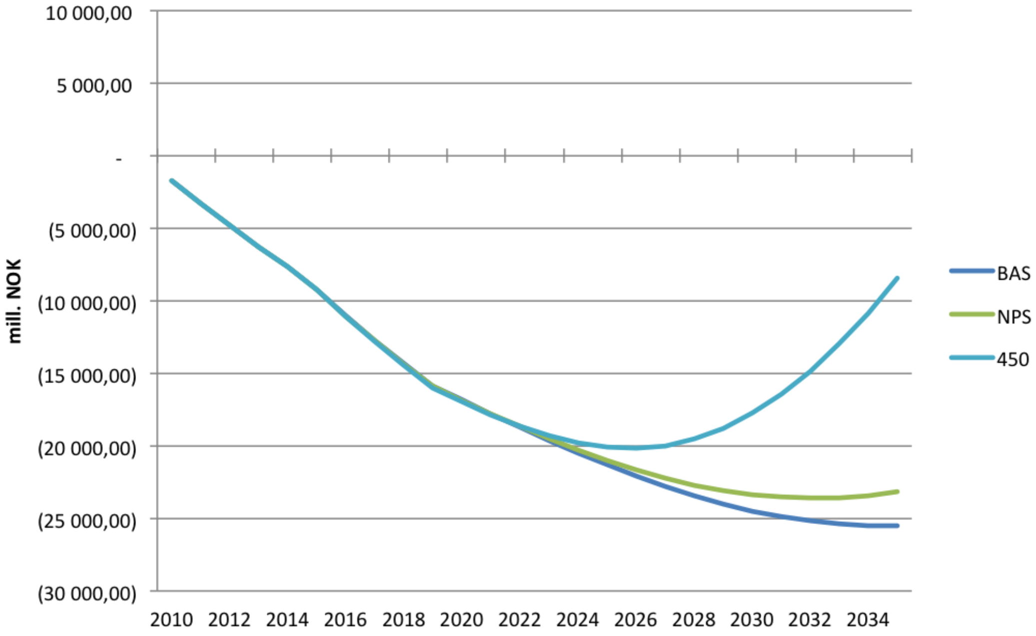


Figure 6.10: Accumulated cash flow from the CCS technology for Statoil when assuming a high technological success. The 450 Scenario yields a negative accumulated cash flow of NOK 8.4 billion, but achieves positive cash flow with strong growth after 2027. The NPS achieves a positive cash flow at the end of the valuation period, while BAS is close to breaking even in the last year of the time-frame. NPS and BAS both yield a negative accumulated cash flow above NOK 20 billion.

For comparison, the accumulated cash flow when indirect benefits are included is seen in Figure 6.12 and it is obvious that the indirect benefits are crucial in order to see the real value of the CCS technology. It should be emphesized that this accumulated cash flow are calculated with the assumption of 30% share of new production that requires CCS to be available. The accumulated cash flow is only shown for the high level of technology success as the indirect benefits are not realized for the low level.

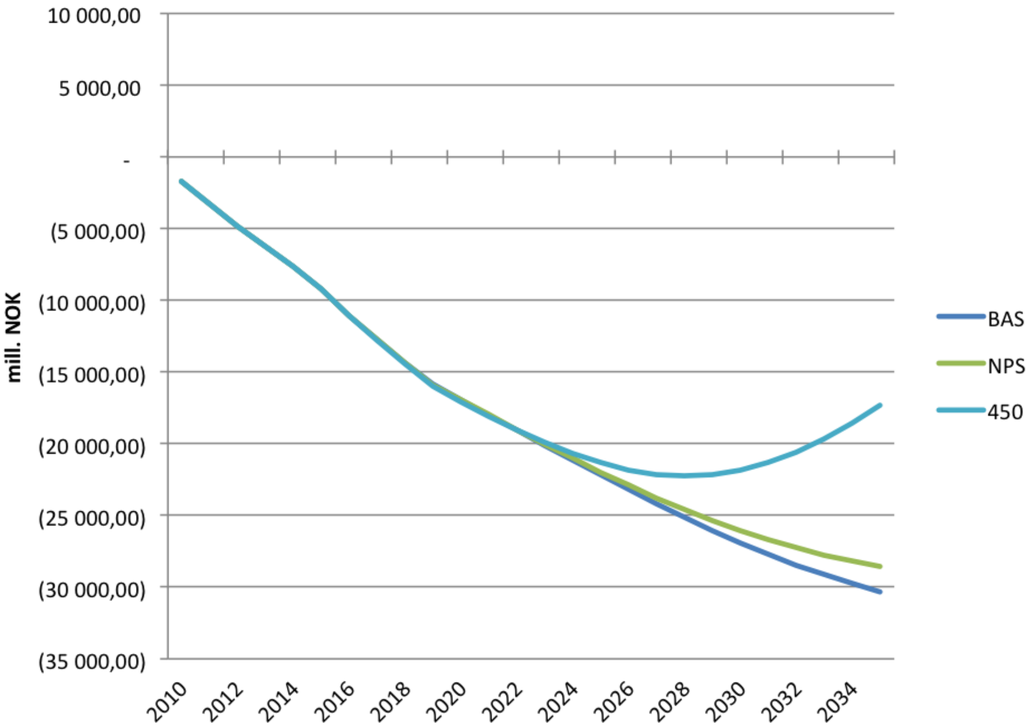


Figure 6.11: Accumulated cash flow from the CCS technology for Statoil when assuming a low technological success.The 450 Scenario yields a negative accumulated cash flow of NOK 17.3 billion, but achieves positive cash flow with strong growth after 2028. Both the BAS and NPS yields negative cash flow at the end of the valuation period, and the accumulated negative cash flow reach approximately NOK 30 billion.

6.2.1 Decision tree and CCS value

Based on the previous mentioned decisions and uncertainties the decision tree is build as shown simplified in Figure 6.13. The tree yields a total of 111 outcomes, which is on the verge to become too comprehensive to be useful. The range of the possible outcome's value is NOK 291 billion with a maximum of NOK 260 billion and minimum of NOK -31 billion. The most favorable outcome is achieved in the BAS due to the high indirect benefits as the oil and gas prices are highest in this scenario.

The hybrid real options framework yields an expected value of CCS at NOK 28.4 billion when continuing further development is decided, while ordinary NPV methodology yields NOK 27.5 billion. Hence, the option of abandoning the implementation has a value of NOK 860 million.

If the CCS technology was valued without the indirect benefits, the expected value when continuing development would be NOK -23.2 billion. Thus, one would chose to abandon further R&D beyond Mongstad and then limiting the loss to NOK 20.5 billion. The NPV valuation would value CCS isolated at NOK -23.8 billion, and the option value of abandoning further R&D is then NOK 3.3 billion.

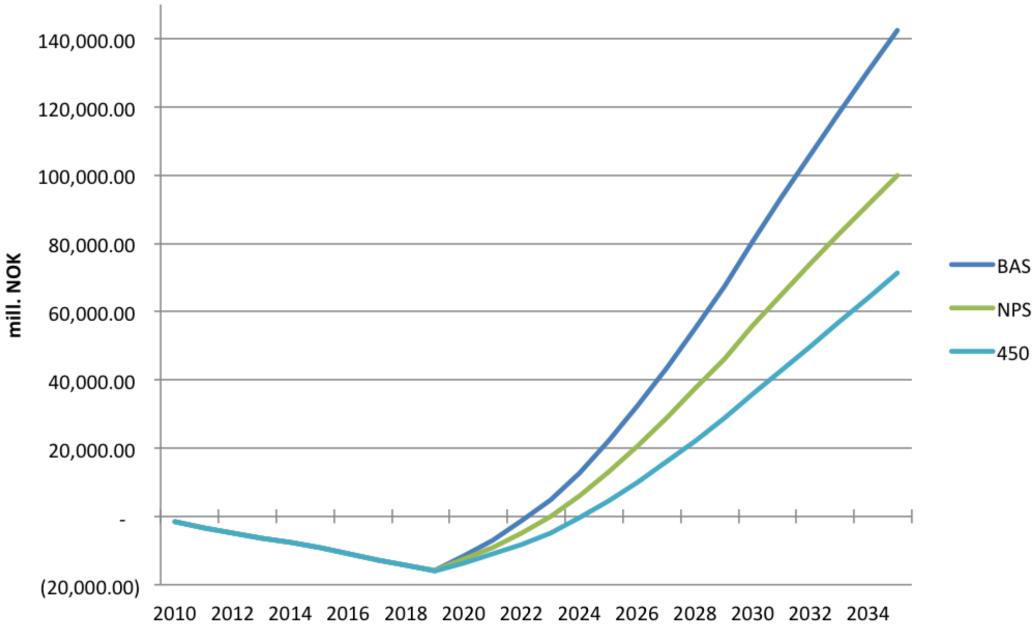


Figure 6.12: Accumulated cash flow from the CCS technology for Statoil when assuming a high technological success and inclusion of indirect benefits. The cash flow turns positive for all scenarios when the technology is implemented. The accumulated cash flows break even 3-5 years after implementation. The BAS yields the best result with NOK 143 billion over the valuation period, which is explained by the expected higher demand and prices for oil and gas in this scenario.

6.2.2 Risk analysis

The risk analysis is conducted with a Monte Carlo simulation. A random variable for each of the uncertainties is generated, and by using random inputs the deterministic model turns into a stochastic model. The simulation comprise of 10 000 runs, and the statistics are summarized in Table 6.5. The results are displayed both in a histogram (Figure 6.14) and in a cumulative distribution chart (Figure 6.15).

Table 6.5: Summary of Statistics from the risk analysis (Monte Carlo simulation). Total number of trials is 10 000.

Variable	Unit	Value
Mean	[mill. NOK]	31 337
St. Dev.	[mill. NOK]	58 701
Mean St. Error		587,01
Minimum	[mill. NOK]	-20 324
First Quartile	[mill. NOK]	-20 324
Median	[mill. NOK]	25 656
Third Quartile	[mill. NOK]	66 490
Maximum	[mill. NOK]	260 119
Skewness		1,1209

The CCS technology value has a mean and median close to NOK 31 billion and 26 billion, respectively. The distribution is skewed to the left with significant loss outcomes. There is a probability of 42% where abandoning further CCS development is the favorable decision, which

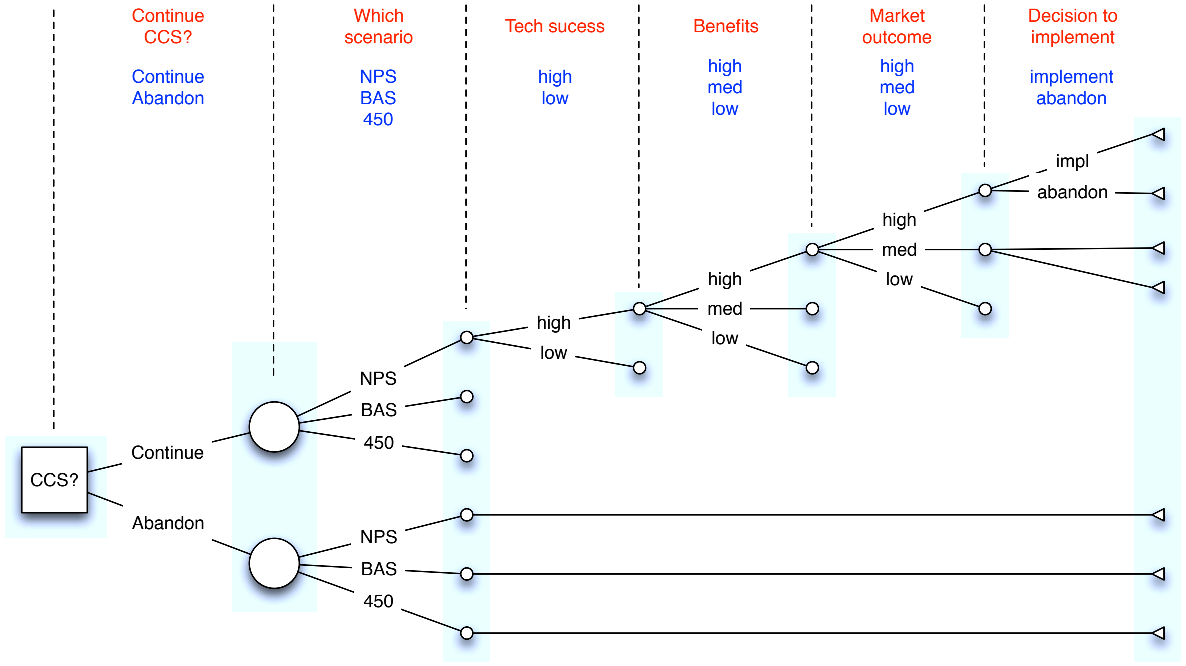


Figure 6.13: A somewhat simplified decision tree for Statoil's CCS R&D project. The complete tree is not shown due to a vast number of branches that hampers readability. Thus, all branches not ending with an end-point (triangle) have been cut, but are identical to the ones that are fully outlined.

means a negative NPV of the CCS involvement of approximately NOK 20 billion. Further, there is a probability of 4% where continuing R&D beyond Mongstad is the economical reasonable action, but still yielding a loss value of CCS in the range NOK 15-17 billion. Hence, there is a probability close to 50% where the CCS R&D project turns into a tremendous loss.

6.2.3 Sensitivity analysis

In order to compare the relative importance of the variables affecting the expected value of the CCS technology, a tornado and a spider chart have been utilized. For both analyses, a base value together with a high and low extreme, that yields the range of the variable's value, is required. The end points of the ranges are established by experts opinions. For the sensitivity analyses there are totally 16 variables, and the details of the analyses are found in Appendix D.

Tornado chart

Figure 6.16 shows the tornado chart for the CCS value, where only the seven most affecting variables for the final value are included.

The annual increase in production is clearly the most important variable with its low and high extreme being -0.5% and 2%, respectively. The lower end of the range, which means a decline of today's production level, would yield an expected loss of NOK 7.8 billion. Figure 6.17 shows that the annual break-even production growth for the CCS technology is -0.14%. Hence, given

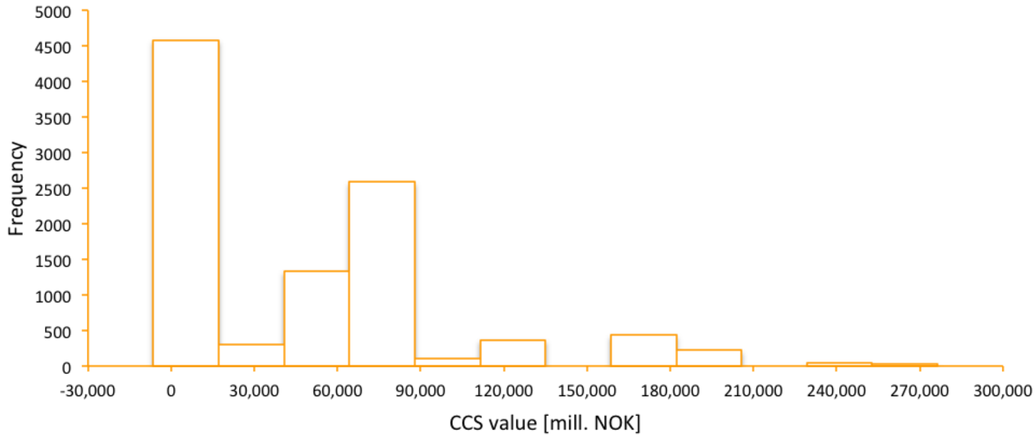


Figure 6.14: Risk analysis (Monto Carlo simulation) displayed as a histogram of the CCS value. It is obvious that the distribution is skewed to the left. Total number of trials is 10 000.

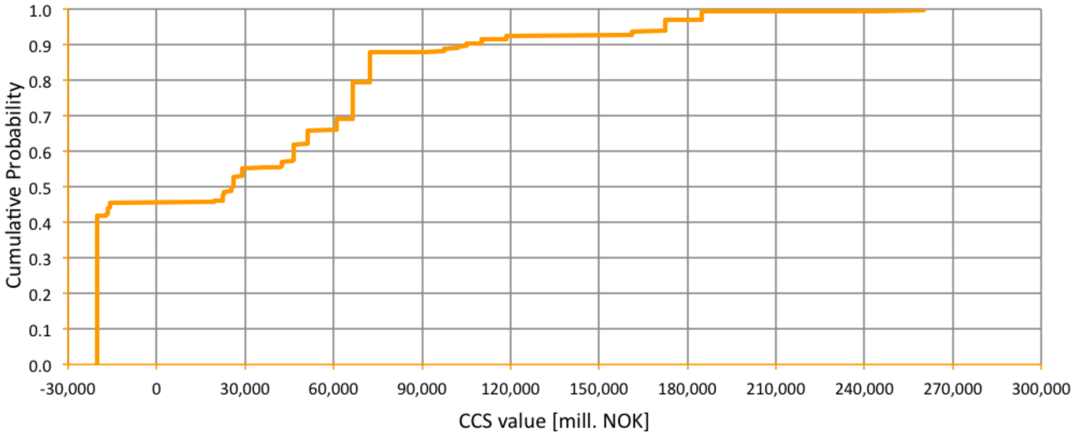


Figure 6.15: Risk analysis (Monto Carlo simulation) displayed as the cumulative distribution of CCS value. As sen from the chart the CCS project is considered risky as there is a probability close to 50% where the CCS R&D project turns into a tremendous loss. Total number of trials is 10 000.

the base level of the other variables, Statoil is required to stabilize its production in order to make CCS beneficial.

The second most important variable is the *share of new production* that requires CCS to be extractable. As the Norwegian state is a major shareholder of Statoil, it could potentially decide where and to what extend CCS will be required for Statoil. The Norwegian government has so far said it has no plans for such an intervention Petro.no (2011).

Spider chart

On the spider chart, the slope of the lines indicate to what degree a small percentage change in the variable compared to its base value affect the output value. Variables with a steeper slope indicates that the respective variable is relatively more sensitive for the final CCS value. Figure

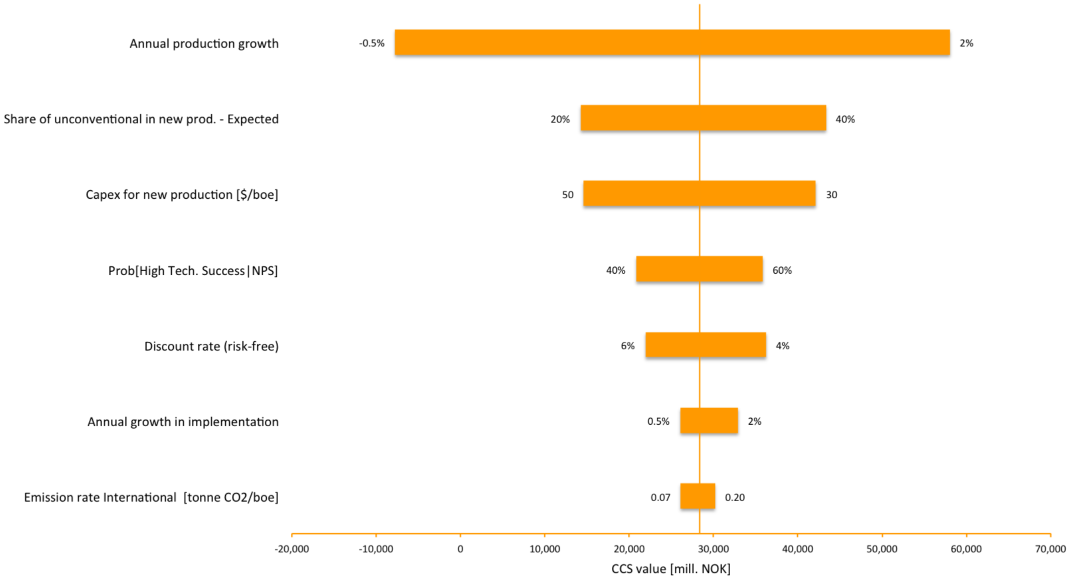


Figure 6.16: Tornado chart for the seven most important variables for the CCS value. The annual production growth is by far the most important variable.

6.18 displays the spider chart for the same seven variables shown in the tornado chart in Figure 6.16. The most sensitive variable is *CAPEX for new production*. For every percentage increase in this variable from its base value, the value of CCS technology decreases by NOK 0.55 billion.

The annual increase in production, which was the dominating variable in the tornado chart, rank only as number five in the spider chart. Still, the variable is considered the most important as the overall performance in the two charts need to be assessed to make final conclusions.

Two-way sensitivity analysis

Figure 6.19 shows a two-way sensitivity chart for the two most important variables found from the one-way sensitivity analyses - *the annual production growth* and *the share of unconventional recources* in new production. When varying these two variables at the same time, the value of the CCS technology spans from a loss of NOK 12.3 billion to a profit of NOK 81.4 billion. This range is nearly NOK 30 billion larger than the largest range found in the tornado chart. Hence, a two-way sensitivity charts yields a more complete picture of the sensitivity for the final CCS value.

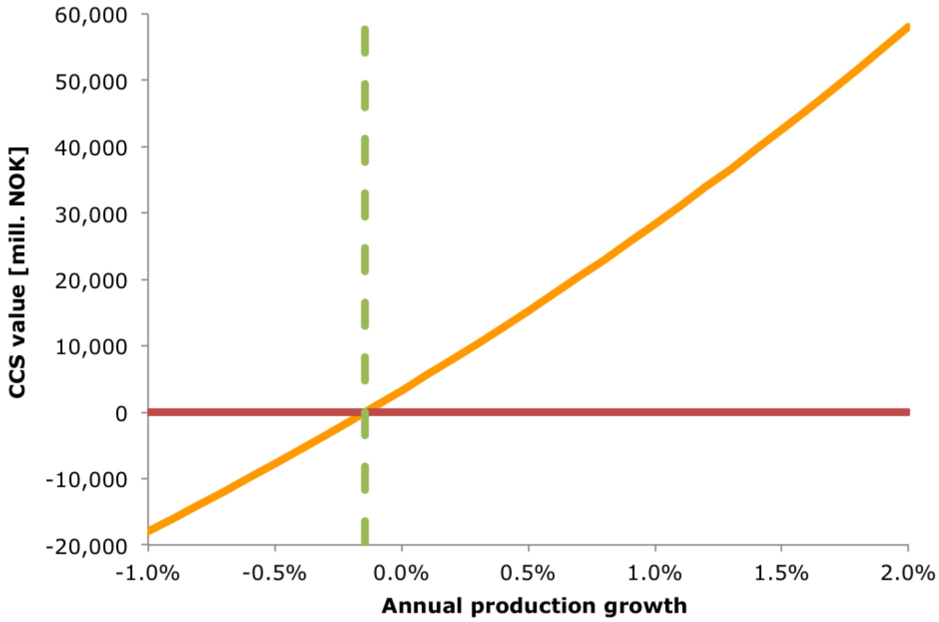


Figure 6.17: Statoil's annual break-even production growth for its CCS technology is -0.14%. This result is a direct consequence of the amount of new unconventional production and the assumption that this actually requires CCS technology to allow extraction.

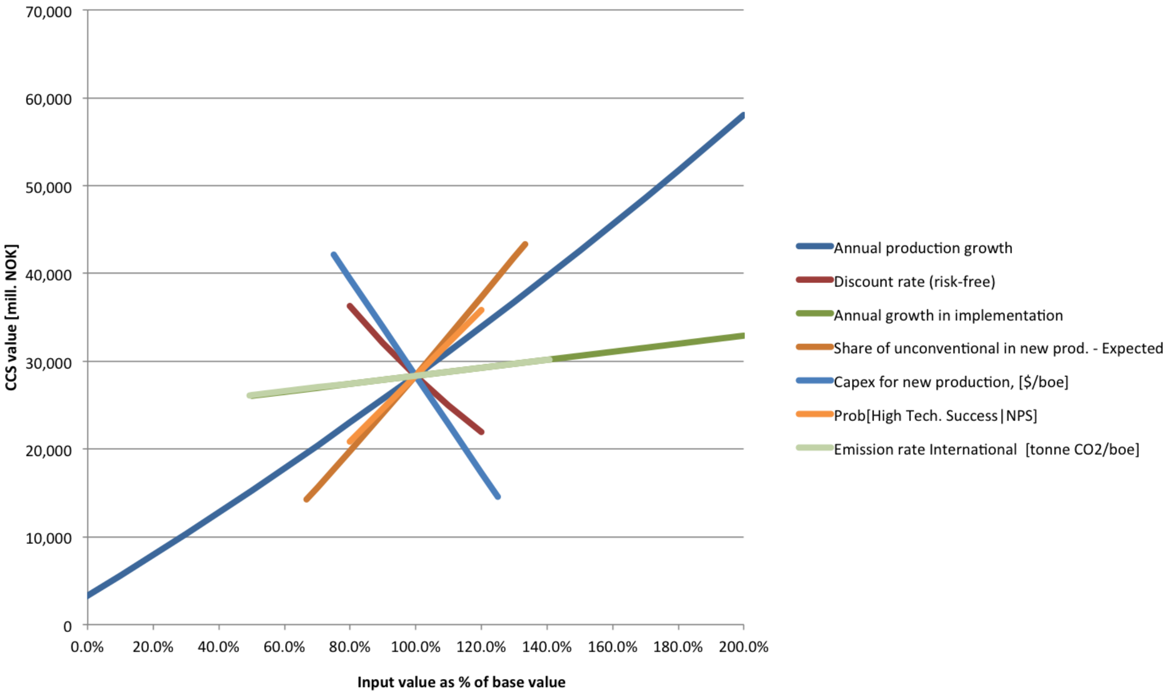


Figure 6.18: Spider chart for the seven most important variables for the CCS value. The slope of the lines indicate to what degree a small percentage change in the variable affect the output value. Variables with a steeper slope indicates that the respective variable is relatively more sensitive for the final CCS value. The most sensitive variable is *CAPEX for new production*. Every percentage increase in this variable from its base value, decreases the value of CCS technology with NOK 0.55 billion.

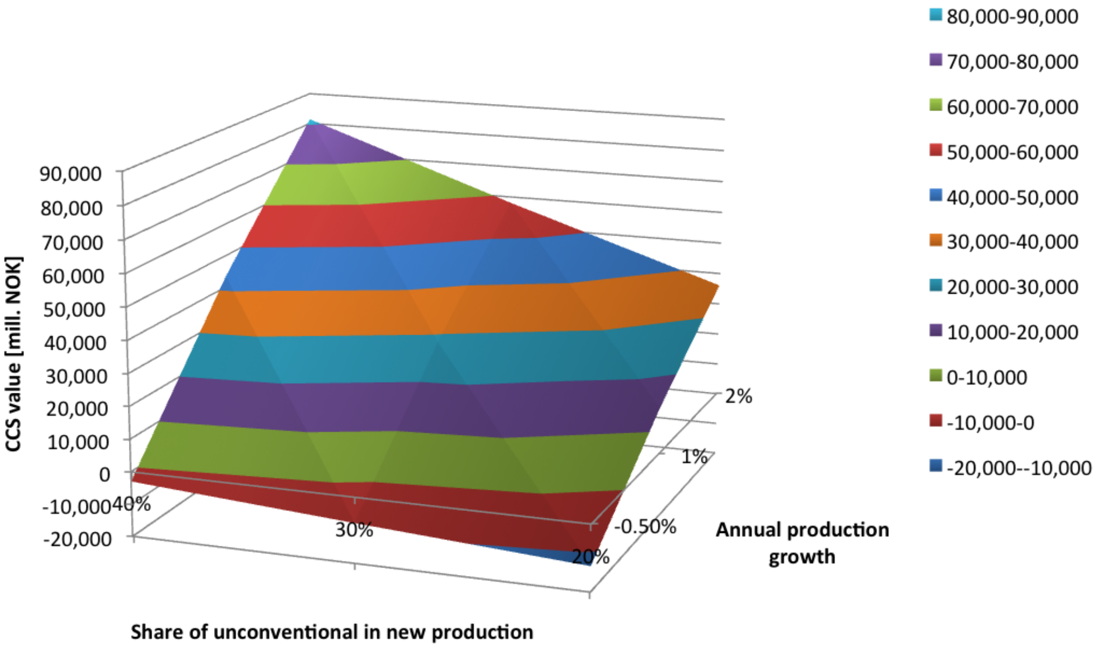


Figure 6.19: A two-way sensitivity chart for the *share of unconventional in new production* and *the annual production growth* - the two most important variables for the final CCS value. When varying these two variables at the same time, the value of the CCS technology spans from a loss of NOK 12.3 billion to a profit of NOK 81.4 billion.

Chapter 7

Valuation of CCS with game theory

Until now we have modelled an option to continue or abandon further development of CCS (R&D Stage II), and given further development an option to conduct or abandon a broad implementation of CCS technology throughout Statoil.

In the previous model, indirect benefits were achieved when granted unconventional reserves by governments, regardless of action from competitors in the CCS field. As Statoil faces fierce competition for access to new reserves, any competitive advantage arising from the CCS technology would result in a major valuation difference.

7.1 Merging real options and game theory

As mentioned in earlier parts, the amount of literature concerning the real options valuation framework, and the value of an option to wait, has increased tremendously during the last two decades. Although they focus on an important part of business strategy, the value of waiting can be eroded by strategic considerations when facing competitors. Real options analysis emphasises the option of waiting for more information for a project that is currently *out of the money*, while game theoretic and strategic considerations may find it appropriate to invest earlier to gain a competitive advantage. An early investment commitment must be weighted against this loss of flexibility.

The game theoretic addition to real options analysis is particularly appropriate for R&D valuation, also taking into account the "winner-takes-all" nature of the patent system. Smit and Trigeorgis (2006) includes the strategic commitment value to the real options valuation framework as seen in the following equation

$$\begin{aligned}\text{Expanded (strategic) NPV} &= \text{direct (passive) NPV}\\ &\quad + \text{strategic (commitment) value} \\ &\quad + \text{flexibility value.}\end{aligned} \tag{7.1}$$

We will include the strategic value by redefining what previously was called indirect benefits to *strategic benefits*.

Smit and Trigeorgis suggests different games, some of them outlined in Table 7.1. They illustrate these games with varieties of symmetric and asymmetric decisions made by comparable firms, sequential R&D investments with complete and incomplete information, and finally a game of R&D competition versus collaboration with joint ventures and strategic alliances.

Table 7.1: Real options and strategic games, overview of the different games and their implications for the ones involved.

Game	Description
Prisoner's Dilemma	Firms have an incentive to invest immediately to avoid being pre-empted by competitors. The sum of the earnings would be greatest if all followed a wait-and-see strategy.
Grab the Dollar	Similar to Prisoner's Dilemma, but here all firms receive a negative pay-off if investing simultaneously. Only the first firm captures "the dollar" (e.g. a patent).
Burning the Bridges	A firm with the First Mover Advantage can use the threat of a battle and can make the first investment commitment and thus capture a large portion of the market.
Battle of the Sexes	The game is applicable in cases where firms have incentives to align their strategies and cooperate.

The variety of games like this is only limited by creativity, and the game outlined in the following section is not exactly like any of the above mentioned games. We find it more appropriate to design a game that seems to fit the case optimally.

7.2 Applying game theory on Statoil's CCS engagement

There will be two actors in the game: 1) Statoil and 2) the majority of Statoil's competitors. The actors have the option to continue or to defer further development of CCS, and are to decide without knowing the opponents decision.

As a first mover you will be rewarded with a First Mover Advantage (FMA). In this valuation an obvious FMA is the higher possibility of winning new contracts as governments issuing production licenses after 2020 is assumed to require some kind of CO_2 treatment in the extraction process. In addition, the first technology that is viable could become an industry standard. Hence, there might also be a potential advantage in licensing the technology, but that will not be considered here.

A deferral decision is assumed to delay the development by five years, and over this period 30% of the targeted production will be lost due to the assumed requirement of implemented CCS technology. Once implementation is initiated, the future production will follow the growth of the originally targeted production (see Figure 7.1).

The expected benefit when continuing development is named benefit X and is represented by

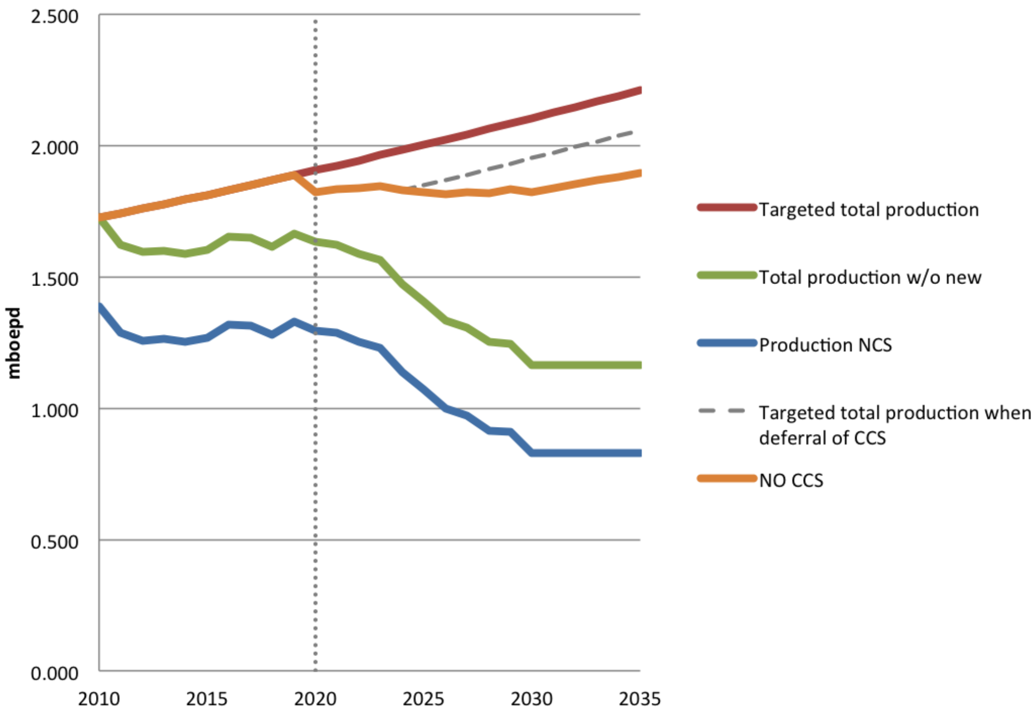


Figure 7.1: Production with a deferral option of the CCS investment. After 2020 Statoil receives a lower production if deferral of further development is deceided. The *targeted total production with deferral of CCS* (dashed grey) growth projection represent Statoil's production once the deferred implementation of CCS is chosen. Thus, the area between the *targeted total production* (red) and the *targeted total production with deferral of CCS* represent the loss of production when deferring further development.

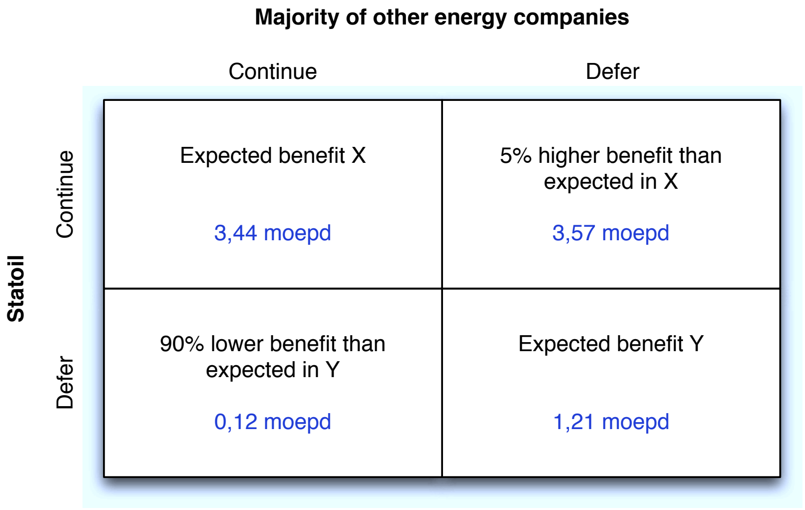
the area constrained by the targeted production and the case of no CCS development. The expected benefit when deferring development is named benefit Y, and is represented by the area constrained by the production with deferral and the case of no CCS.

If Statoil chooses to defer its development of the CCS technology, it would still be exposed to the risk of a low technological success. However, the risk is highly reduced due to a learning effect. Thus, for simplicity reasons we assume that Statoil achieves a high technological success with certainty when the CCS development is postponed five years.

- *The flexibility value of waiting* comprise of lower technology costs and higher prices for the direct benefits (i.e. emission trading, avoided tax). However, if the direct economics already was positive, this value will then be lost when deferring the development. In addition, the cost and benefits will face a larger discount factor, which yields a lower present value of them both.
- *The strategic value of continuing* is the additional benefits from accessing new production compared to when deferring development. When continuing, Statoil is in position to acquire a larger share of new unconventional recources. The strategic value must be weighted against the value of lost flexibility.

The game outcomes for Statoil are explained below, and summarized in Figure 7.2.

From Statoil's previous engagements in the CCS field (see Section 5.1) it seems fair that it has



		Majority of other energy companies	
		Continue	Defer
Statoil	Continue	Expected benefit X 3,44 moepd	5% higher benefit than expected in X 3,57 moepd
	Defer	90% lower benefit than expected in Y 0,12 moepd	Expected benefit Y 1,21 moepd

Figure 7.2: Achieved new production for CCS valuation with game theory. The blue numbers in each cell represent Statoil's benefit production related to Statoil's and the majority of other energy companies choice.

gained a more thorough understanding of CCS than their competitors. This can be beneficial for an eventual further development process of the technology, and could give Statoil competitive advantages.

Statoil chooses *Continue* and…

… the majority chooses *Continue*: With a high technological success, Statoil will achieve the full benefits X as its previous history in CCS development have been of advantage in developing a leading technology. In the case of a low level of technological success, Statoil will lose all its potential benefits X to competitors because of an inferior technology.
… the majority chooses *Defer*: Statoil becomes one of the very first movers. With high technological success it is able to increase the full benefits of X by 5% as it gains contracts at the expense of its competitors. Even with low level of technological success, Statoil will achieve benefits, but it is limited to X.

Statoil chooses *Defer* and…

… the majority chooses *Continue*: Statoil is lagging behind and 90% of the benefits of Y are taken by competitors.
… the majority chooses *Defer*: As the early movers are few it is assumed that there will be technologies with flaws that are unable to quickly absorb "infant diseases". Thus, Statoil is competitive when entering the market five years later, and will realize the full benefits of Y.

The dominant strategy for both actors is to develop without any postponement when assuming that the majority of Statoil's competitors are experience the same benefit payoff as Statoil. Thus, it is more likely for the majority of Statoil's competitors to develop right away and it is assigned probability of 60% when implemented in the model.

The strategic value is found to be NOK 54.6 billion and is superior to the flexibility value at only NOK 0.743 billion.

It is clear that Statoil has no incentives to defer development as a deferral would result in severe loss in strategic benefits, which would never be compensated by improved direct benefits as seen from the flexibility value's inferiority to the strategic value. Thus, the game presented here is not similar to the most common ones from theory. However, if the assumption of required implemented CCS in 2020 is relaxed to only requiring an *ongoing* CCS R&D process in 2020, the game would turn into the classic *prisoner's dilemma*[1] as postponement of the development would yield the best outcome for all seen together. This is because when both parts defer, Statoil achieves the same strategic benefits as when both continue, while the the flexibility value will only be valid when both defer, making it the best outcome.

Results from extended model

The hybrid real options model is extended with a new event related to the uncertainty in the share of early movers among Statoil's competitors. The corresponding extended decision tree is seen in Figure 7.3. The model yields an expected value of CCS of NOK 48.1 billion and NOK -5.9 billion when deciding to continue and defer further development, respectively. The value of the CCS technology when continuing is nearly doubled compared to the previous model. This is explained by the new assumptions of achievable benefits despite a low level of technological success.

The risk simulation of the new model is summarized in Table D.4. The distribution is still skewed to the left, but the shift is less significant compared to the case without game theory. As seen from the cumulative distribution in Figure 7.4 there is a probability of more than 70% for obtaining a positive value for the CCS engagement.

The most important variables from the first model are still applicable. In addition, the variable *Prob[Large share of early movers]* introduced in the new model is essential as it reduces the value of the CCS project by NOK 300 million for every percentage increase in the variable from its base case value of 60%.

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[1] "In the classic prisoners' dilemma, two prisoners accused of a crime would be worse off if they both confess than if they do not, but the fear of the other prisoner confessing puts pressure for both to do so even though not confessing would have been preferable for both." Source: Smit and Trigeorgis (2006).

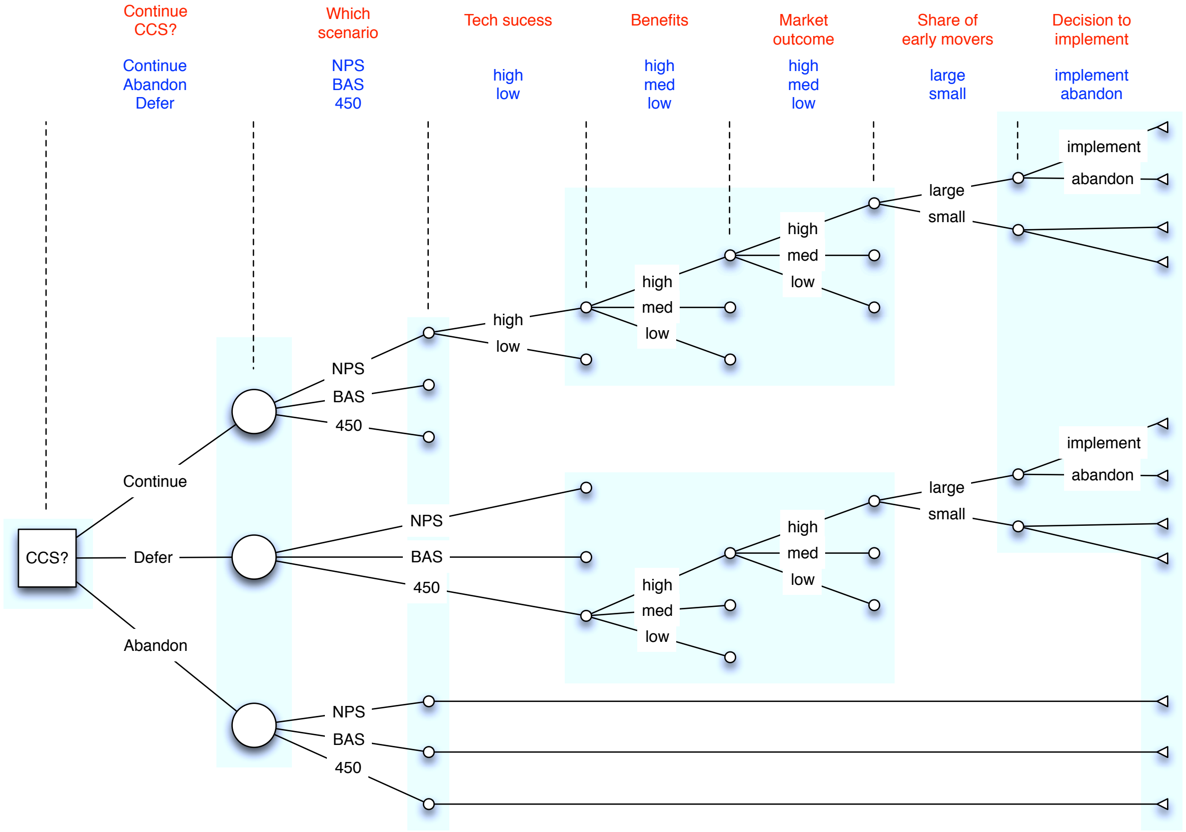

Figure 7.3: A simplified decision tree with game theory. This tree has, compared to the tree without a game theoretic point of view (Figure 6.13) an additional "Defer" branch. In this branch the possibility for a low technological success has been removed, and throughout the tree a new chance node for "share of early movers" has been added. The whole tree is not shown due to a vast number of branches that hamper readability.

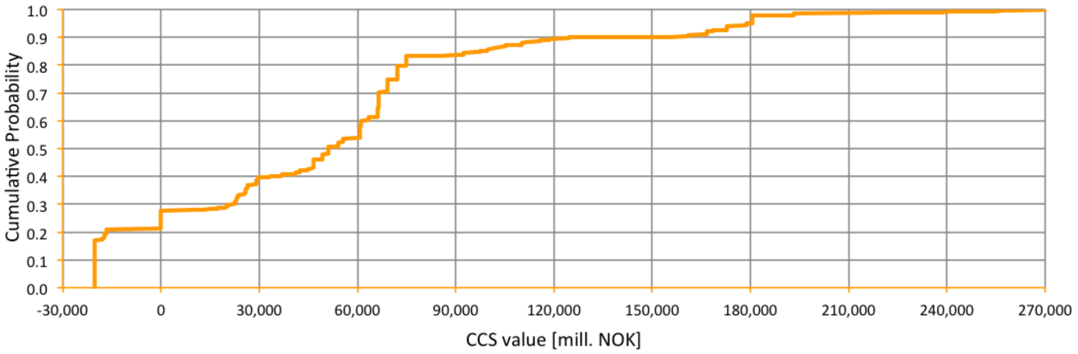

Figure 7.4: Cumulative CCS value with inclusion of game theory in the valuation process. There is a probability of about 70% that the CCS engagement will return a positive value. The risk analysis has been done with Monte Carlo simulation with 10 000 trials.

Chapter 8

Conclusions

This thesis proposes the use of the hybrid real options framework presented by Neely (1998) to facilitate valuation of, and decision making in, R&D projects. The framework combines the favorable benefits from Decision Analysis (DA) and financial option theory, which are the two most commonly applied methodologies for real option assessments. The combined framework addresses the DA's incapability for handling a fluctuating discount rate in a practical way, and the financial option theory's requirement of historical data, that is generally unavailable for unique R&D projects. The value of flexibility is estimated by distinguishing two types of risks; project and market risks, where DA and option theory are applied, respectively.

The hybrid real options is a practical and at the same time accurate approach. It allows the use of the risk-free rate as a consistent constant discount rate. In addition, the valuation becomes organized in the sense that the process is divided in a technical and financial part. Hence, technical and financial experts can apply their knowledge independently. However, the framework's use of a decision tree restricts the complexity of the model as it could turn too comprehensive to be applicable in an assessments context.

When exemplifying the framework, an option to continue or abandon further development of CCS is modelled. The framework values the CCS project - at best - when continuing the development. This returns an expected profit of NOK 28 billion. However, risk analysis yields a probability close to 50% that the project returns a loss of similar magnitude. The estimated expected value is NOK 860 million higher compared to the traditional Net Present Value methodology. Hence, the value of including the inherent flexibility of an R&D project is significant. In this context, this difference represents the option value in the decision of whether to implement or not.

The sensitivity analysis concludes that the *annual production growth* stand out as the most important variable for the expected value of Carbon Capture and Storage (CCS). This is rather intuitive as new production yields possibly large emissions of CO_2, which is the main benefit driver for the CCS technology. In addition, the *share of unconventional oil* in new production, that we assume would require CCS, is essential.

We extend the framework of Neely (1998) by incorporating simple game theory, which proved to introduce a significant value change because of the possible strategic advantages of a CCS involvement. The game considered only a valuation of the First Mover Advantage (FMA) and showed that the strategic value is superior to the flexibility value by more than NOK 50 billion. The dominant strategy is to continue further development of CCS, which then values the project at NOK 48.1 billion. Now, risk analysis concludes that there is a probability of more than 70% to achieve a positive return from the CCS R&D project.

For further work, a more detailed consideration of game theory is suggested. An interesting topic would be Statoil's impact on its own technology supply environment - does it *really* make a difference that Statoil is engaged in the CCS field, or should it let others do the hard work? In addition, inclusion of other uses of the CCS technology would yield a more complete valuation.

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Abbreviations

boe barrels of oil equivalents.
BOPM Binomial Option Pricing Model.
bpd barrels per day.
BS Black-Scholes Option Pricing Model.

CAPEX Capital Expenditures.
CAPM Capital Asset Pricing Model.
CCM CO_2 Capture Mongstad.
CCS Carbon Capture and Storage.
CF Cash Flow.
CHP Combined Heat and Power.
CSS Cycling Steam Stimulation.
CTL Coal To Liquid.

DA Decision Analysis.
DCF Discounted Cash Flow.

EHO Extra Heavy Oil.
EOR Enhanced Oil Recovery.
ETS Emission Trading Scheme.
EU European Union.
EU ETS European Union Emission Trading Scheme.

FGD flue gas desulfurization.
FMA First Mover Advantage.

GBM Geometric Brownian Motion.
GHG Green House Gases.
GTL Gas To Liquid.

IEA International Energy Agency.
IPCC Intergovernmental Panel on Climate Change.

LNG Liquefied Natural Gas.

NCS Norwegian Continental Shelf.
NGCC Natural Gas Combined Cycle.
NPV Net Present Value.

OD The Norwegian Oil Directorate (Oljedirektoratet).
OECD Organization for Economic Co-operation and Development.
oepd oil equivalents per day.
OME Other Major Economies (defined by IEA as Brazil, China, Russia, South Africa and the countries of the Middle East).
OPEX Operational Expenditures.

PDE Partial Differential Equation.

SAGD Steam-Assisted Gravity Drainage.

TCM Technology Centre Mongstad.

WACC Weighted Average Cost of Capital.

Appendix A

Quantifying benefits

In the following pages, exact values of benefit drivers for the CCS technology are given. Many of the tables are presented in landscape mode, and some are even spread over several pages.

The data files attached to the thesis should be examined for a more easy understanding of the different data and the analysis behind.[1]

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[1] The relevant files can be obtained by contacting the authors.

Table A.1: Direct economic benefits, high technological success (table 1 of 3).

Year	Broad Impl. Rate	CO$_2$ emission before capture [mill. ton]			CO$_2$ captured [mill. ton]				
		Norway	Int.	Total	R&D Stage 1		Broad Implementation		
					Qualification, TCM	First Facility, CCM	Norway	Int.	Total
2010	0 %	13,2	17,4	30,6	0,1	0			
2011	0 %	12,2	23,7	35,9	0,1	0			
2012	0 %	11,9	26,0	37,9	0,1	0			
2013	0 %	12,0	26,6	38,6	0,1	0			
2014	0 %	11,9	28,1	40,0	0,1	0			
2015	0 %	12,0	28,2	40,2	0	1,17			
2016	0 %	12,5	26,6	39,1	0	1,17			
2017	0 %	12,5	27,8	40,3	0	1,17			
2018	0 %	12,1	30,5	42,6	0	1,17			
2019	0 %	12,6	28,9	41,5	0	1,17			
2020	2 %	12,3	31,6	43,9	0	1,17	0,2	0,6	0,8
2021	3 %	12,2	33,1	45,3	0	1,17	0,3	0,9	1,2
2022	4 %	11,9	35,8	47,7	0	1,17	0,4	1,3	1,7
2023	5 %	11,7	38,0	49,7	0	1,17	0,5	1,7	2,2
2024	6 %	10,8	43,9	54,6	0	1,17	0,6	2,4	3,0
2025	7 %	10,2	48,3	58,5	0	1,17	0,6	3,0	3,7
2026	8 %	9,5	53,1	62,6	0	1,17	0,7	3,8	4,5
2027	9 %	9,2	55,6	64,8	0	1,17	0,7	4,5	5,2
2028	10 %	8,7	59,5	68,2	0	1,17	0,8	5,4	6,1
2029	11 %	8,6	60,8	69,5	0	1,17	0,9	6,0	6,9
2030	12 %	7,9	66,2	74,1	0	1,17	0,8	7,1	8,0
2031	13 %	7,9	67,3	75,1	0	1,17	0,9	7,9	8,8
2032	14 %	7,9	68,4	76,2	0	1,17	1,0	8,6	9,6
2033	15 %	7,9	69,5	77,4	0	1,17	1,1	9,4	10,4
2034	16 %	7,9	70,6	78,5	0	1,17	1,1	10,2	11,3
2035	17 %	7,9	71,8	79,6	0	1,17	1,2	11,0	12,2

Table A.2: Direct economic benefits, high technological success (table 2 of 3).

Year	Cost [mill NOK]							
	R&D Stage 1					R&D Stage 2		Broad Impl.
	R&D	Qualification (TCM)	First Facility, CCM			New Concept Capex	Alt. Cost (Labour)	Tech.
			BAS	NPS	450			
2010	102,00	739,60	-	-	-	250,00	591,60	-
2011	97,14	704,38	-	-	-	238,10	563,43	-
2012	92,52	670,84	-	-	-	226,76	536,60	-
2013	88,11	638,89	-	-	-	215,96	511,05	-
2014	83,92	608,47	-	-	-	205,68	486,71	-
2015	79,92	579,50	226,04	230,51	249,09	195,88	463,53	-
2016	76,11	-	1 132,95	1 138,17	1 160,09	186,55	441,46	-
2017	-	-	1 083,19	1 089,11	1 114,24	177,67	420,44	-
2018	-	-	1 035,67	1 042,26	1 070,49	169,21	400,42	-
2019	-	-	990,30	997,52	1 028,74	161,15	381,35	-
2020	-	-	946,98	954,78	988,88	-	-	223,83
2021	-	-	905,61	913,96	950,84	-	-	373,74
2022	-	-	866,10	874,97	914,52	-	-	493,27
2023	-	-	828,37	837,73	879,85	-	-	603,14
2024	-	-	792,34	802,15	846,74	-	-	748,50
2025	-	-	757,93	768,16	815,13	-	-	878,03
2026	-	-	725,06	735,68	784,93	-	-	1 008,37
2027	-	-	693,66	704,64	756,10	-	-	1 103,25
2028	-	-	663,67	674,99	728,55	-	-	1 211,48
2029	-	-	635,02	646,65	702,24	-	-	1 275,10
2030	-	-	607,65	619,57	677,10	-	-	1 391,89
2031	-	-	581,50	593,68	653,07	-	-	1 445,67
2032	-	-	556,52	568,94	630,12	-	-	1 492,46
2033	-	-	532,65	545,29	608,18	-	-	1 532,70
2034	-	-	509,84	522,67	587,20	-	-	1 566,82
2035	-	-	488,04	501,06	567,15	-	-	1 595,23
Total	619,72	3 941,68	15 559,09	15 762,48	16 713,26	2 026,96	4 796,59	16 943,47

Table A.3: Direct economic benefits, high technological success (table 3 of 3).

Year	Direct benefits [mill NOK]								
	Tax Avoided						Emission Trading		
	Norway			International					
	BAS	NPS	450	BAS	NPS	450	BAS	NPS	450
2010	-	-	-	-	-	-	-	-	-
2011	-	-	-	-	-	-	-	-	-
2012	-	-	-	-	-	-	-	-	-
2013	-	-	-	-	-	-	-	-	-
2014	-	-	-	-	-	-	-	-	-
2015	-	-	-	-	-	-	-	-	-
2016	-	-	-	-	-	-	-	-	-
2017	-	-	-	-	-	-	-	-	-
2018	-	-	-	-	-	-	-	-	-
2019	-	-	-	-	-	-	-	-	-
2020	33,31	34,64	40,45	38,26	39,79	46,46	112,05	141,93	168,07
2021	48,13	50,25	59,59	58,51	61,08	72,44	174,44	220,36	295,92
2022	60,74	63,66	76,67	81,99	85,93	103,50	245,36	309,19	459,64
2023	72,45	76,23	93,26	105,54	111,05	135,84	319,00	401,09	648,73
2024	78,02	82,41	102,39	142,07	150,07	186,45	420,09	527,11	915,58
2025	83,27	88,31	111,43	177,38	188,10	237,35	521,94	653,70	1 207,17
2026	86,25	91,83	117,68	216,30	230,28	295,12	633,83	792,48	1 543,48
2027	91,66	97,96	127,51	247,43	264,45	344,20	732,18	913,99	1 865,43
2028	93,31	100,12	132,35	285,90	306,77	405,52	847,70	1 056,66	2 247,98
2029	99,11	106,76	143,33	312,47	336,59	451,89	939,54	1 169,55	2 582,09
2030	95,48	103,26	140,79	360,36	389,70	531,38	1 078,76	1 341,16	3 061,33
2031	100,48	109,09	151,07	385,49	418,51	579,57	1 190,80	1 465,29	3 384,83
2032	105,12	114,57	161,14	409,88	446,74	628,33	1 303,13	1 588,56	3 709,63
2033	109,41	119,72	171,01	433,55	474,39	677,65	1 415,29	1 710,55	4 034,29
2034	113,37	124,54	180,67	456,51	501,47	727,52	1 526,82	1 830,88	4 357,51
2035	117,01	129,04	190,14	478,76	527,97	777,93	1 637,34	1 949,21	4 678,10
Total	1 387,13	1 492,38	1 999,49	4 190,38	4 532,88	6 201,15	13 098,27	16 071,71	35 159,79

Table A.4: Direct economic benefits, low technological success (table 1 of 3).

Year	Broad Impl. Rate	CO_2 emission before capture [mill. ton]			CO_2 captured [mill. ton]				
		Norway	Int.	Total	R&D Stage 1		Broad Implementation		
					Qualification, TCM	First Facility, CCM	Norway	Int.	Total
2010	0 %	13,2	17,4	30,6	0,1	0			
2011	0 %	12,2	23,7	35,9	0,1	0			
2012	0 %	11,9	26,0	37,9	0,1	0			
2013	0 %	12,0	26,6	38,6	0,1	0			
2014	0 %	11,9	28,1	40,0	0,1	0			
2015	0 %	12,0	28,2	40,2	0	0,91			
2016	0 %	12,5	26,6	39,1	0	0,91			
2017	0 %	12,5	27,8	40,3	0	0,91			
2018	0 %	12,1	30,5	42,6	0	0,91			
2019	0 %	12,6	28,9	41,5	0	0,91			
2020	2 %	12,3	31,6	43,9	0	0,91	0,2	0,4	0,6
2021	3 %	12,2	33,1	45,3	0	0,91	0,3	0,7	1,0
2022	4 %	11,9	35,8	47,7	0	0,91	0,3	1,0	1,3
2023	5 %	11,7	38,0	49,7	0	0,91	0,4	1,3	1,7
2024	6 %	10,8	43,9	54,6	0	0,91	0,5	1,8	2,3
2025	7 %	10,2	48,3	58,5	0	0,91	0,5	2,4	2,9
2026	8 %	9,5	53,1	62,6	0	0,91	0,5	3,0	3,5
2027	9 %	9,2	55,6	64,8	0	0,91	0,6	3,5	4,1
2028	10 %	8,7	59,5	68,2	0	0,91	0,6	4,2	4,8
2029	11 %	8,6	60,8	69,5	0	0,91	0,7	4,7	5,3
2030	12 %	7,9	66,2	74,1	0	0,91	0,7	5,6	6,2
2031	13 %	7,9	67,3	75,1	0	0,91	0,7	6,1	6,8
2032	14 %	7,9	68,4	76,2	0	0,91	0,8	6,7	7,5
2033	15 %	7,9	69,5	77,4	0	0,91	0,8	7,3	8,1
2034	16 %	7,9	70,6	78,5	0	0,91	0,9	7,9	8,8
2035	17 %	7,9	71,8	79,6	0	0,91	0,9	8,5	9,5

Table A.5: Direct economic benefits, low technological success (table 2 of 3).

Year	Cost [mill NOK]							
	R&D Stage 1					R&D Stage 2		Broad Impl.
	R&D	Qualification (TCM)	First Facility, CCM			New Concept Capex	Alt. Cost (Labour)	Tech.
			BAS	NPS	450			
2010	102,00	739,60	-	-	-	250,00	591,60	-
2011	97,14	704,38	-	-	-	238,10	563,43	-
2012	92,52	670,84	-	-	-	226,76	536,60	-
2013	88,11	638,89	-	-	-	215,96	511,05	-
2014	83,92	608,47	-	-	-	205,68	486,71	-
2015	79,92	579,50	226,04	230,51	249,09	195,88	463,53	-
2016	76,11	-	1 132,95	1 138,17	1 160,09	186,55	441,46	-
2017	-	-	1 083,19	1 089,11	1 114,24	177,67	420,44	-
2018	-	-	1 035,67	1 042,26	1 070,49	169,21	400,42	-
2019	-	-	990,30	997,52	1 028,74	161,15	381,35	-
2020	-	-	946,98	954,78	988,88	-	-	295,09
2021	-	-	905,61	913,96	950,84	-	-	428,69
2022	-	-	866,10	874,97	914,52	-	-	564,03
2023	-	-	828,37	837,73	879,85	-	-	687,45
2024	-	-	792,34	802,15	846,74	-	-	850,31
2025	-	-	757,93	768,16	815,13	-	-	994,06
2026	-	-	725,06	735,68	784,93	-	-	1 137,61
2027	-	-	693,66	704,64	756,10	-	-	1 240,15
2028	-	-	663,67	674,99	728,55	-	-	1 356,72
2029	-	-	635,02	646,65	702,24	-	-	1 422,45
2030	-	-	607,65	619,57	677,10	-	-	1 546,54
2031	-	-	581,50	593,68	653,07	-	-	1 621,85
2032	-	-	556,52	568,94	630,12	-	-	1 690,65
2033	-	-	532,65	545,29	608,18	-	-	1 753,26
2034	-	-	509,84	522,67	587,20	-	-	1 809,97
2035	-	-	488,04	501,06	567,15	-	-	1 861,10
Total	619,72	3 941,68	15 559,09	15 762,48	16 713,26	2 026,96	4 796,59	19 259,93

Table A.6: Direct economic benefits, low technological success (table 3 of 3).

Year	Direct benefits [mill NOK]								
	Tax Avoided						Emission Trading		
	Norway			International					
2010	-	-	-	-	-	-	-	-	-
2011	-	-	-	-	-	-	-	-	-
2012	-	-	-	-	-	-	-	-	-
2013	-	-	-	-	-	-	-	-	-
2014	-	-	-	-	-	-	-	-	-
2015	-	-	-	-	-	-	-	-	-
2016	-	-	-	-	-	-	-	-	-
2017	-	-	-	-	-	-	-	-	-
2018	-	-	-	-	-	-	-	-	-
2019	-	-	-	-	-	-	-	-	-
2020	25,91	26,95	31,46	29,76	30,95	36,14	87,15	110,39	130,72
2021	37,44	39,08	46,35	45,51	47,51	56,34	135,68	171,39	230,16
2022	47,24	49,51	59,63	63,77	66,84	80,50	190,84	240,48	357,50
2023	56,35	59,29	72,53	82,08	86,37	105,65	248,11	311,96	504,57
2024	60,68	64,10	79,64	110,50	116,72	145,01	326,73	409,98	712,12
2025	64,77	68,68	86,66	137,96	146,30	184,61	405,96	508,43	938,91
2026	67,08	71,42	91,53	168,24	179,11	229,54	492,98	616,37	1 200,49
2027	71,29	76,19	99,17	192,44	205,68	267,71	569,47	710,88	1 450,89
2028	72,57	77,87	102,94	222,37	238,60	315,40	659,33	821,85	1 748,43
2029	77,08	83,04	111,48	243,03	261,79	351,47	730,75	909,65	2 008,29
2030	74,26	80,31	109,51	280,28	303,10	413,29	839,03	1 043,12	2 381,04
2031	78,15	84,85	117,50	299,82	325,51	450,78	926,18	1 139,67	2 632,65
2032	81,76	89,11	125,33	318,80	347,46	488,70	1 013,55	1 235,55	2 885,27
2033	85,10	93,11	133,01	337,21	368,97	527,06	1 100,78	1 330,43	3 137,78
2034	88,18	96,86	140,52	355,06	390,03	565,85	1 187,53	1 424,02	3 389,17
2035	91,01	100,37	147,88	372,37	410,64	605,06	1 273,48	1 516,05	3 638,52
Total	1 078,88	1 160,74	1 555,16	3 259,18	3 525,58	4 823,12	10 187,54	12 500,22	27 346,50

Table A.7: Accumulated CF for the CCS technology isolated (high technological success).

Year	Cash flow [mill. NOK]			Acc. Cash flow [mill. NOK]		
	BAS	NPS	450	BAS	NPS	450
2010	(1 683,20)	(1 683,20)	(1 683,20)	(1 683,20)	(1 683,20)	(1 683,20)
2011	(1 603,05)	(1 603,05)	(1 603,05)	(3 286,25)	(3 286,25)	(3 286,25)
2012	(1 526,71)	(1 526,71)	(1 526,71)	(4 812,96)	(4 812,96)	(4 812,96)
2013	(1 454,01)	(1 454,01)	(1 454,01)	(6 266,97)	(6 266,97)	(6 266,97)
2014	(1 384,77)	(1 384,77)	(1 384,77)	(7 651,74)	(7 651,74)	(7 651,74)
2015	(1 544,88)	(1 549,34)	(1 567,92)	(9 196,62)	(9 201,09)	(9 219,67)
2016	(1 837,08)	(1 842,30)	(1 864,22)	(11 033,70)	(11 043,39)	(11 083,88)
2017	(1 681,30)	(1 687,22)	(1 712,35)	(12 715,00)	(12 730,61)	(12 796,24)
2018	(1 605,30)	(1 611,89)	(1 640,12)	(14 320,29)	(14 342,50)	(14 436,36)
2019	(1 532,80)	(1 540,02)	(1 571,24)	(15 853,10)	(15 882,51)	(16 007,60)
2020	4 282,24	3 277,77	2 367,87	(11 570,86)	(12 604,74)	(13 639,73)
2021	4 709,85	3 586,55	2 551,79	(6 861,00)	(9 018,19)	(11 087,94)
2022	5 553,04	4 226,89	3 004,18	(1 307,96)	(4 791,30)	(8 083,76)
2023	6 159,12	4 673,28	3 318,45	4 851,15	(118,03)	(4 765,31)
2024	7 970,11	6 047,53	4 300,59	12 821,26	5 929,51	(464,72)
2025	9 218,13	6 968,85	4 951,95	22 039,39	12 898,36	4 487,23
2026	10 491,49	7 852,32	5 608,12	32 530,88	20 750,68	10 095,35
2027	10 989,97	8 137,80	5 866,59	43 520,85	28 888,48	15 961,94
2028	11 876,49	8 705,56	6 332,12	55 397,34	37 594,04	22 294,06
2029	11 962,48	8 680,31	6 415,05	67 359,82	46 274,36	28 709,11
2030	13 149,71	9 449,95	7 045,70	80 509,53	55 724,30	35 754,81
2031	12 898,71	9 242,58	7 047,40	93 408,24	64 966,89	42 802,20
2032	12 649,80	9 038,71	7 060,82	106 058,04	74 005,60	49 863,02
2033	12 402,60	8 837,84	7 084,23	118 460,64	82 843,43	56 947,25
2034	12 156,75	8 639,52	7 116,04	130 617,38	91 482,95	64 063,29
2035	11 911,93	8 443,35	7 154,75	142 529,31	99 926,30	71 218,04
Total	142 529,31	99 926,30	71 218,04			

Table A.8: Accumulated CF for the CCS technology isolated (low technological success).

Year	Cash flow [mill. NOK]			Acc. Cash flow [mill. NOK]		
	BAS	NPS	450	BAS	NPS	450
2010	(1 683,20)	(1 683,20)	(1 683,20)	(1 683,20)	(1 683,20)	(1 683,20)
2011	(1 603,05)	(1 603,05)	(1 603,05)	(3 286,25)	(3 286,25)	(3 286,25)
2012	(1 526,71)	(1 526,71)	(1 526,71)	(4 812,96)	(4 812,96)	(4 812,96)
2013	(1 454,01)	(1 454,01)	(1 454,01)	(6 266,97)	(6 266,97)	(6 266,97)
2014	(1 384,77)	(1 384,77)	(1 384,77)	(7 651,74)	(7 651,74)	(7 651,74)
2015	(1 544,88)	(1 549,34)	(1 567,92)	(9 196,62)	(9 201,09)	(9 219,67)
2016	(1 837,08)	(1 842,30)	(1 864,22)	(11 033,70)	(11 043,39)	(11 083,88)
2017	(1 681,30)	(1 687,22)	(1 712,35)	(12 715,00)	(12 730,61)	(12 796,24)
2018	(1 605,30)	(1 611,89)	(1 640,12)	(14 320,29)	(14 342,50)	(14 436,36)
2019	(1 532,80)	(1 540,02)	(1 571,24)	(15 853,10)	(15 882,51)	(16 007,60)
2020	(1 063,29)	(1 051,01)	(1 061,01)	(16 916,38)	(16 933,52)	(17 068,61)
2021	(1 065,09)	(1 042,51)	(1 020,06)	(17 981,47)	(17 976,03)	(18 088,67)
2022	(1 063,34)	(1 029,34)	(958,54)	(19 044,81)	(19 005,37)	(19 047,20)
2023	(1 053,08)	(1 007,30)	(874,27)	(20 097,90)	(20 012,67)	(19 921,47)
2024	(1 051,82)	(990,65)	(770,51)	(21 149,71)	(21 003,33)	(20 691,98)
2025	(1 038,91)	(962,31)	(640,72)	(22 188,62)	(21 965,63)	(21 332,70)
2026	(1 020,75)	(927,44)	(485,86)	(23 209,37)	(22 893,07)	(21 818,56)
2027	(985,77)	(877,55)	(313,01)	(24 195,14)	(23 770,63)	(22 131,58)
2028	(950,29)	(824,97)	(115,65)	(25 145,43)	(24 595,59)	(22 247,22)
2029	(897,81)	(758,45)	87,22	(26 043,23)	(25 354,04)	(22 160,01)
2030	(854,96)	(695,50)	332,41	(26 898,19)	(26 049,54)	(21 827,59)
2031	(802,26)	(633,62)	519,22	(27 700,45)	(26 683,16)	(21 308,37)
2032	(746,50)	(569,24)	710,45	(28 446,95)	(27 252,40)	(20 597,92)
2033	(688,11)	(502,75)	905,11	(29 135,06)	(27 755,15)	(19 692,81)
2034	(627,52)	(434,55)	1 102,26	(29 762,58)	(28 189,70)	(18 590,55)
2035	(565,10)	(364,99)	1 301,07	(30 327,68)	(28 554,69)	(17 289,48)
Total	(30 327,68)	(28 554,69)	(17 289,48)			

Table A.9: Statoil's entitlement production of oil and gas with regional share. The values are for the year ended 31. December. Source: Statoil annual reports obtained (`www.statoil.com`).

	2010	2009	2008	2007	2006
Norway					
Crude oil (mmbbls)	256	279	302	299	315
Natural gas (bcf)	370	1 367	1 348	1 238	1250
Natural gas (bcm)	38,8	38,7	38,2	35,1	35,4
Combined oil and gas (mmboe)	500	523	542	519	539
Eurasia excluding Norway	22,3%	21,5%			
Crude oil (mmbbls)	18	19	n/a	n/a	n/a
Natural gas (bcf)	51	49	n/a	n/a	n/a
Natural gas (bcm)	1,4	1,4	n/a	n/a	n/a
Combined oil and gas (mmboe)	27	28	n/a	n/a	n/a
Africa	49,6%	56,2%			
Crude oil (mmbbls)	53	63	n/a	n/a	n/a
Natural gas (bcf)	41	54	n/a	n/a	n/a
Natural gas (bcm)	1,2	1,5	n/a	n/a	n/a
Combined oil and gas (mmboe)	60	73	n/a	n/a	n/a
America	28,1%	22,3%			
Crude oil (mmbbls)	26	20	n/a	n/a	n/a
Natural gas (bcf)	47	48	n/a	n/a	n/a
Natural gas (bcm)	1,3	1,4	n/a	n/a	n/a
Combined oil and gas (mmboe)	34	29	n/a	n/a	n/a
Outside Norway total					
Crude oil (mmbbls)	97	102	85	92	70
Natural gas (bcf)	139	151	121	114	84
Natural gas (bcm)	3,9	4,3	3,4	3,2	2,4
Combined oil and gas (mmboe)	121	130	106	112	85
Overall total					
Crude oil (mmbbls)	352	381	386	391	385
Natural gas (bcf)	1 509	1 519	1 469	1 352	1335
Natural gas (bcm)	42,8	43	41,6	38,3	37,8
Combined oil and gas (mmboe)	621	652	648	632	624
Oil/gas production ratio	2010	2009	2008	2007	2006
Norway	51 %	53 %	56 %	58 %	58 %
Outside Norway	80 %	78 %	80 %	82 %	82 %

Table A.10: Statoil's proven reserves of oil and gas. Source: Statoil Annual Report 2010 (`http://www.statoil.com/AnnualReport2010`).

Developed	Oil and NGL (mmbbls)	Natural Gas (bcf)	Total oil and gas (mmboe)
Norway	950	13721	3394
Eurasia excluding Norway	99	421	174
Eurasia	1 048	14 142	3 568
Africa	192	221	231
America	116	336	176
Undeveloped			
Norway	291	2622	758
Eurasia excluding Norway	71	214	109
Eurasia	362	2 836	868
Africa	121	300	175
America	284	130	307
Total proved reserves	2 124	17 965	5 325

Table A.11: Statoil's historical production costs for the Norwegian and international resources. The availability of public data for the international production costs are limited. Source: Statoil annual reports (`www.statoil.com`).

Year t	Prod. Cost, P [NOK/boe]		$\ln \frac{P(t+1)}{P(t)}$	
	Norway	International	Norway	International
1998	23,70	n/a		
1999	26,38	n/a	0,107	
2000	27,12	n/a	0,028	
2001	23,91	n/a	-0,126	
2002	22,85	n/a	-0,045	
2003	22,30	n/a	-0,024	
2004	30,92	n/a	0,327	
2005	25,14	n/a	-0,207	
2006	28,40	n/a	0,122	
2007	43,30	34,40	0,422	
2008	37,30	42,20	-0,149	0,204
2009	36,90	45,00	-0,011	0,064
2010	40,60	52,40	0,096	0,152
Average annual growth			4,5%	14,0%

Table A.12: Predicted production on the NCS 2009-2030. Data obtained directly from Tom Andersen in Oljedirektoratet, and is the underlying data for constructing Figure 4.19 in Oljedirektoratet (2009). The figure is also displayed earlier in the thesis, see Figure 6.4.

Year	Production of resources [mSm^{3}oe]				Total production	
	Reserves	Fields	Discoveries	Undiscovered	[mSm^{3}oe]	[mboepd]
2009	235	1	0	0	236	4,07
2010	227	6	0	0	233	4,02
2011	222	11	0	0	233	4,02
2012	210	15	2	1	228	3,93
2013	197	22	8	2	229	3,95
2014	175	36	13	3	227	3,91
2015	160	35	31	4	230	3,97
2016	152	35	48	4	239	4,12
2017	148	34	52	4	238	4,10
2018	146	38	45	3	232	4,00
2019	140	42	50	9	241	4,16
2020	133	46	43	13	235	4,05
2021	120	47	44	22	233	4,02
2022	110	41	49	27	227	3,91
2023	100	41	48	34	223	3,84
2024	89	37	42	38	206	3,55
2025	78	32	35	49	194	3,34
2026	72	27	30	52	181	3,12
2027	66	26	28	56	176	3,03
2028	60	24	24	58	166	2,86
2029	58	24	22	61	165	2,84
2030	49	20	18	63	150	2,59

Table A.13: Statoil's production loss on the NCS and needed international compensation to maintain stated growth targets until 2035. All values are measured in mboepd.

Year	Statoil's prod on NCS	Dev. 2020 level	Statoil's target total prod	Dev. 2010 level	Total int. prod.	Total prod w/o new	No CCS
2010	1,389	-	1,725	0,000	0,336	1,725	1,725
2011	1,286	-	1,742	0,017	0,457	1,622	1,742
2012	1,258	-	1,760	0,035	0,502	1,594	1,760
2013	1,263	-	1,777	0,052	0,514	1,600	1,777
2014	1,252	-	1,795	0,070	0,543	1,589	1,795
2015	1,269	-	1,813	0,088	0,544	1,605	1,813
2016	1,319	-	1,831	0,106	0,513	1,655	1,831
2017	1,313	-	1,849	0,124	0,536	1,649	1,849
2018	1,280	-	1,868	0,143	0,588	1,616	1,868
2019	1,330	-	1,887	0,162	0,557	1,666	1,887
2020	1,297	-	1,905	0,180	0,609	1,633	1,824
2021	1,286	0,011	1,925	0,200	0,639	1,622	1,834
2022	1,252	0,044	1,944	0,219	0,691	1,589	1,837
2023	1,230	0,066	1,963	0,238	0,733	1,566	1,844
2024	1,137	0,160	1,983	0,258	0,846	1,473	1,830
2025	1,070	0,226	2,003	0,278	0,932	1,406	1,824
2026	0,999	0,298	2,023	0,298	1,024	1,335	1,816
2027	0,971	0,326	2,043	0,318	1,072	1,307	1,822
2028	0,916	0,381	2,063	0,338	1,147	1,252	1,820
2029	0,910	0,386	2,084	0,359	1,174	1,246	1,833
2030	0,828	0,469	2,105	0,380	1,277	1,164	1,822
2031	0,828	0,469	2,126	0,401	1,298	1,164	1,837
2032	0,828	0,469	2,147	0,422	1,320	1,164	1,852
2033	0,828	0,469	2,169	0,444	1,341	1,164	1,867
2034	0,828	0,469	2,190	0,465	1,363	1,164	1,882
2035	0,828	0,469	2,212	0,487	1,385	1,164	1,898

Table A.14: Statoil's benefit production: Needed international production for Statoil to obtain targeted growth, with profits linked to the different climate policy scenarios.

Year	Benefit production	Oil/gas ratio	Disc. factor	Prod.cost	Benefit [mill. NOK]		
	[moepd]			[NOK/boe]	BAS	NPS	450
2011	-	0,8	0,952	54,75	-	-	-
2012	-	0,8	0,907	57,21	-	-	-
2013	-	0,8	0,864	59,78	-	-	-
2014	-	0,8	0,823	62,46	-	-	-
2015	-	0,8	0,784	65,26	-	-	-
2016	-	0,8	0,746	68,19	-	-	-
2017	-	0,8	0,711	71,25	-	-	-
2018	-	0,8	0,677	74,44	-	-	-
2019	-	0,8	0,645	77,79	-	-	-
2020	0,08	0,8	0,614	81,28	5 269	4 240	3 326
2021	0,09	0,8	0,585	84,92	5 708	4 543	3 448
2022	0,11	0,8	0,557	88,73	6 524	5 136	3 772
2023	0,12	0,8	0,530	92,72	7 094	5 526	3 924
2024	0,15	0,8	0,505	96,88	8 871	6 839	4 691
2025	0,18	0,8	0,481	101,22	10 072	7 685	5 089
2026	0,21	0,8	0,458	105,76	11 289	8 482	5 445
2027	0,22	0,8	0,436	110,51	11 716	8 669	5 389
2028	0,24	0,8	0,416	115,47	12 525	9 128	5 486
2029	0,25	0,8	0,396	120,65	12 521	8 989	5 215
2030	0,28	0,8	0,377	126,06	13 615	9 627	5 381
2031	0,29	0,8	0,359	131,72	13 249	9 289	5 031
2032	0,30	0,8	0,342	137,63	12 881	8 950	4 684
2033	0,30	0,8	0,326	143,81	12 510	8 611	4 342
2034	0,31	0,8	0,310	150,26	12 137	8 272	4 004
2035	0,31	0,8	0,295	157,00	11 762	7 933	3 671
Total	3,44				167 741	121 920	72 899

Table A.15: Terminal values for the Direct Economics and Indirect Benefits, given for the Business as Usual scenario. (Similar tables for the two other scenarios can be found in Table A.16 (NPS) and Table A.17 (450)).

Tech. Success	High	Low
Expected benefit	141 334,70	0
Upper limit benefit	282 669,40	-
LOG SD	42,14 %	0,00 %

						Market Outcome	
P[Tech Success]	PV E[Indirect Benefits]	P[Indirect Benefit]	Indirect Benefit Outcome	PV E[Direct Economics]	P[Market]	Indirect Benefits	Direct Economics
0,3	141 334,70	0,185	282 669,40	1 732,30	0,39	240 630,01	1 474,67
					0,47	226 774,15	1 389,76
					0,14	213 716,12	1 309,73
		0,63	129 328,56	1 732,30	0,39	110 094,45	1 474,67
					0,47	103 755,04	1 389,76
					0,14	97 780,65	1 309,73
		0,185	70 667,35	1 732,30	0,39	60 157,50	1 474,67
					0,47	56 693,54	1 389,76
					0,14	53 429,03	1 309,73
0,7	-	0,185	-	-4 734,33	0,39	-	-4 030,23
					0,47	-	-3 798,16
					0,14	-	-3 579,46
		0,63	-	-4 734,33	0,39	-	-4 030,23
					0,47	-	-3 798,16
					0,14	-	-3 579,46
		0,185	-	-4 734,33	0,39	-	-4 030,23
					0,47	-	-3 798,16
					0,14	-	-3 579,46

Table A.16: Terminal values for the Direct Economics and Indirect Benefits, given for the New Policy Scenario. (Similar tables for the two other scenarios can be found in Table A.15 (BAS) and Table A.17 (450))

Tech. Success	High	Low
Expected benefit	102 079,89	0
Upper limit benefit	204 159,79	-
LOG SD	42,14 %	0,00 %

						Market Outcome	
P[Tech Success]	PV E[Indirect Benefits]	P[Indirect Benefit]	Indirect Benefit Outcome	PV E[Direct Economics]	P[Market]	Indirect Benefits	Direct Economics
0,5	102 079,89	0,185	204 159,79	5 153,50	0,39	173 796,57	4 387,06
					0,47	163 789,08	4 134,44
					0,14	154 357,84	3 896,37
		0,63	93 408,38	5 153,50	0,39	79 516,43	4 387,06
					0,47	74 937,74	4 134,44
					0,14	70 622,71	3 896,37
		0,185	51 039,95	5 153,50	0,39	43 449,14	4 387,06
					0,47	40 947,27	4 134,44
					0,14	38 589,46	3 896,37
0,5	-	0,185	-	-2 073,40	0,39	-	-1 765,04
					0,47	-	-1 663,40
					0,14	-	-1 567,62
		0,63	-	-2 073,40	0,39	-	-1 765,04
					0,47	-	-1 663,40
					0,14	-	-1 567,62
		0,185	-	-2 073,40	0,39	-	-1 765,04
					0,47	-	-1 663,40
					0,14	-	-1 567,62

Table A.17: Terminal values for the Direct Economics and Indirect Benefits, given for the 450 Scenario.)Similar tables for the two other scenarios can be found in Table A.15 (BAS) and Table A.16 (NPS))

Tech. Success	High	Low
Expected benefit	59 852,16	0
Upper limit benefit	119 704,32	-
LOG SD	42,14 %	0,00 %

						Market Outcome	
P[Tech Success]	PV E[Indirect Benefits]	P[Indirect Benefit]	Indirect Benefit Outcome	PV E[Direct Economics]	P[Market]	Indirect Benefits	Direct Economics
0,8	59 852,16	0,185	119 704,32	26 416,96	0,39	101 901,55	22 488,15
					0,47	96 033,90	21 193,25
					0,14	90 504,11	19 972,91
		0,63	54 767,82	26 416,96	0,39	46 622,60	22 488,15
					0,47	43 937,99	21 193,25
					0,14	41 407,97	19 972,91
		0,185	29 926,08	26 416,96	0,39	25 475,39	22 488,15
					0,47	24 008,47	21 193,25
					0,14	22 626,03	19 972,91
0,2	-	0,185	-	14 464,85	0,39	-	12 313,59
					0,47	-	11 604,56
					0,14	-	10 936,35
		0,63	-	14 464,85	0,39	-	12 313,59
					0,47	-	11 604,56
					0,14	-	10 936,35
		0,185	-	14 464,85	0,39	-	12 313,59
					0,47	-	11 604,56
					0,14	-	10 936,35

Appendix B

Estimating discrete probabilistic outcomes

Here, two methods that utilize assumption of a probability distribution for an uncertain variable will be presented. Although these methods still are somewhat reliant on subjective asessments, the advantage over interviewing expert is that data collection efforts are minimized.

B.1 Extended Pearson-Tukey method

Keefer and Bodily (1983) found an extended method of Pearson and Tukey to yield the best accuracy when evaluating three-point approximations for continuous random variables. The method allocate discrete probabilities of 0.185 to the 5% and 95% quantiles, and 0.63 to the median. A disadvantage of this method is the requirements of estimation of the 5% and 95% quantile, which can be more difficult than points closer to the centre. If this is an issue, Keefer and Bodily suggest the extended Swanson and Megill approximation, that was considered second best, as it utilizes the 10% and 90% quantiles in addition to the median. The limitations of both these methods is that they can only handle three outcomes, which could be insufficient in many problems.

B.2 Bracket Medians method

After Clemen (1996): The method defines an upper and lower limit (a, b) for an uncertain parameter X, the interval bounded by a and b defines a bracket. A value m is found such that $P(a < X < m) = P(m < X < b)$, and thus is the median of the bracket. Given that the cumulative probabilities for the limits a and b are p and q, respectively, the cumulative probability for the value m is $(p + q)/2$. The m value represents an outcome and is associated with a probability of $1/n$, where n is the number of equally likely brackets. As opposed to the Extended Pearson-Tukey method, The Bracket Medians method does not have any limitations concerning number of outcomes, but as the outcomes increases so does the data collection effort.

Appendix C

Transforming market uncertainties into risk-neutral quantities

C.1 Regression models

In order to transform the market uncertainty, which in Statoil's case is assumed to be its level of production, a relationship between production and an external market are established through regression models. The equations concerning the regressions are found in Equation 6.4 and 6.5. The regression results are seen in Table C.2 and C.3. The stock price is assumed to capture all the market risk, and will be used as the underlying, externally priced asset.

Table C.1: Adjusted R-square results by regressing the reserve and production model with various values of of the time lags m and n, assigned to the respective models. The associated Equations are 6.4 and 6.5 found in Chapter 6.

Time lag, m (years)	Adjusted R-square	Time lag, n (years)	Adjusted R-square
1	0.26308	9	0.32404
2	0.45504	8	0.34089
3	0.57866	7	0.40554
4	0.84528	6	0.34576
5	0.92406	5	0.30855

C.2 Calculating volatility of the stock price

The annual growth and volatility are found to be 2.89% and 17.34%, respectively. The calucu-lations are found in Table C.4.

The data is only dated two years back in time, and is chosen this way to avoid the collapse of the stock market in late 2008, which would yield a non representative volatility.

Table C.2: Regression results for stock price and reserve level, time lag $m = 4$. The regression model is found in Equation 6.4. Both the intercept A and the coefficient B is significant at a 2% significance level. A coefficient of 0.158 yields that a 1% increase in the percentage change in stock price over four years will give a 0.16% increase in the percentage change of the reserve level over 4 years.

Regression Statistics							
R	0,94019						
R Square	0,88396						
Adjusted R Square	0,84528						
S	0,03772						
Observations	5						
0.0042 =- 0.1342 + 0.1584 * 0.9843							
ANOVA							
	d.f.	SS	MS	F	p-level		
Regression	1,	0,03251	0,03251	22,85248	0,0174		
Residual	3,	0,00427	0,00142				
Total	4,	0,03678					
	Coefficients	Standard Error	LCL	UCL	t Stat	p-level	H_0 (2%) rejected?
Intercept	-0,1342	0,01933	-0,22197	-0,04643	-6,9426	0,00613	Yes
LN	0,15839	0,03313	0,00794	0,30884	4,78043	0,0174	Yes
T (2%)	4,5407						
LCL - Lower value of a reliable interval (LCL)							
UCL - Upper value of a reliable interval (UCL)							
Residuals							
Observation	Predicted Y	Residual	Standard Residuals				
1	0,03367	-0,01326	-0,40583				
2	-0,02642	0,02666	0,81617				
3	-0,12188	0,01104	0,33789				
4	-0,18542	0,02626	0,80382				
5	-0,14527	-0,0507	-1,55205				

It is worth keeping in mind that these results will change for different time periods.

C.3 Constructing a risk-neutral distribution of the stock price

When constructing the risk-neutral distribution the binomial method described in Section 2.2.2 is applied. The risk-free rate is assumed to be 5% and the volatility is given from above as 17.34%.

As implementation of CCS is to be decided upon in 2020, the time period, T, is 10 years, and will be broken in two equal intervals in order to yield three probabilistic outcomes. Three outcomes are chosen purely for simplicity of the decision tree, and if desirable any number of outcomes is possible.

The size up and down movement (see Equation 2.9) of the lattice is given as

$$u = e^{0.1734\sqrt{5}} = 1.222$$

$$d = 1/u = 0.819.$$

Table C.3: Regression results for reserve level and production rate, time lag $n = 6$. The regression model is found in Equation 6.5. The intercept C is insignificant on a high level, while the coefficient D is significant at a 3% level. Due to the logarithmic transformation, a 1% increase in the reserve level yields a 0.94% increase in the production level in six years

Regression Statistics

R	0,66408
R Square	0,44101
Adjusted R Square	0,37889
S	0,06027
Observations	11

5.8143 =- 1.8133 + 0.9352 * 8.2862

ANOVA

	d.f.	SS	MS	F	p-level
Regression	1,	0,02579	0,02579	7,10033	0,02585
Residual	9,	0,03269	0,00363		
Total	10,	0,05848			

	Coefficients	Standard Error	LCL	UCL	t Stat	p-level	H_0 (2%) rejected?
Intercept	-1,81327	2,93005	-10,08021	6,45368	-0,61885	0,55135	No
LN(reserve level)	0,93521	0,35097	-0,05503	1,92545	2,66465	0,02585	No
T (2%)	2,82144						

LCL - Lower value of a reliable interval (LCL)
UCL - Upper value of a reliable interval (UCL)

Residuals

Observation	Predicted Y	Residual	Standard Residuals
1	5,94543	-0,07909	-1,38342
2	5,93984	-0,03496	-0,61143
3	5,91758	-0,01071	-0,18725
4	5,9478	0,02349	0,41089
5	6,02255	-0,04569	-0,79915
6	6,07839	-0,07775	-1,35983
7	6,05586	0,00018	0,00322
8	6,01475	0,01318	0,23048
9	6,00605	0,04098	0,71683
10	6,00386	0,08031	1,40472
11	6,0032	0,09004	1,57493

Together with Equation 2.11 this yields a risk-neutral probability of $p = 0.621$.

Before establishing the lattices, the stock price needs to be adjusted for the dividend payments, and is done by the following equation $S_d = S(1 - \delta)^T$.

When the initial stock price is set to be NOK 150, the dividend-adjusted starting price will be NOK 124.38. The probability and stock price lattice are then given in Table C.5.

Table C.4: Calculation of Statoil's stock volatility. The stock price is assumed to be log-normally distributed, which is a common assumption for market traded assets. Thus, the calculation of the volatility will follow the method of Cox and Rubinstein (1985).The data comprise stock prices for the last two years realized the first trading day after the quarter reports have been published. The quarter dividend is an average of the annual one presented by Statoil (Statoil, 2011b). Dividend needs to be considered, since it reduces the value of the share. When estimating the average growth rate, this decline in value must be factored back into the share price as the average growth rate impacts on the estimation of the volatility.

Date (t)	Stock Price S(t)	Quarterly Dividends D(t)	Quaterly Dividends	$[S+D](t)$	$X = \frac{S(t)}{[S+D](t-1)}$	$\ln(X)$	$Y = (\ln(X) - \ln(X)_{avg})^2$
17.02.2009	118,60	1,50	1,26 %	120,10	0,861	-0,150	0,025
11.05.2009	137,70	1,50	1,09 %	139,20	1,147	0,137	0,017
04.08.2009	134,52	1,50	1,12 %	136,02	0,966	-0,034	0,002
04.11.2009	138,90	1,50	1,08 %	140,40	1,021	0,021	0,000
11.02.2010	129,80	1,50	1,16 %	131,30	0,925	-0,079	0,007
05.05.2010	138,40	1,50	1,08 %	139,90	1,054	0,053	0,002
29.07.2010	126,00	1,50	1,19 %	127,50	0,901	-0,105	0,013
03.11.2010	122,40	1,50	1,23 %	123,90	0,960	-0,041	0,002
09.02.2011	137,70	1,50	1,09 %	139,20	1,111	0,106	0,010
			Dividends			Growth	Variance
Average Quaterly			1,14 %			0,72 %	0,008
			Dividends			Growth	Volatility
Average Annual			4,58 %			2,89 %	17,34 %

Table C.5: The probability and stock price lattice are calculated from the methodology described in Section C.3. The right-most column is year 2020 where the possible implementation of CCS is decided. Thus, the time steps are five years.

Probability Lattice		
2010	2015	2020
1.00	0.62	0.39
	0.38	0.47
		0.14

Stock Price Lattice		
2010	2015	2020
124.38	151.94	185.62
	101.81	124.38
		83.34

Appendix D

Sensitivity analysis

In this section, the exact values for the sensitivity analysis are given. The first graphs and tables are concerning the sensitivity analysis for the real options analysis (without game theory), while the later tables are concerning the game theoretic values. As mentioned before, please refer to the attached Excel files.

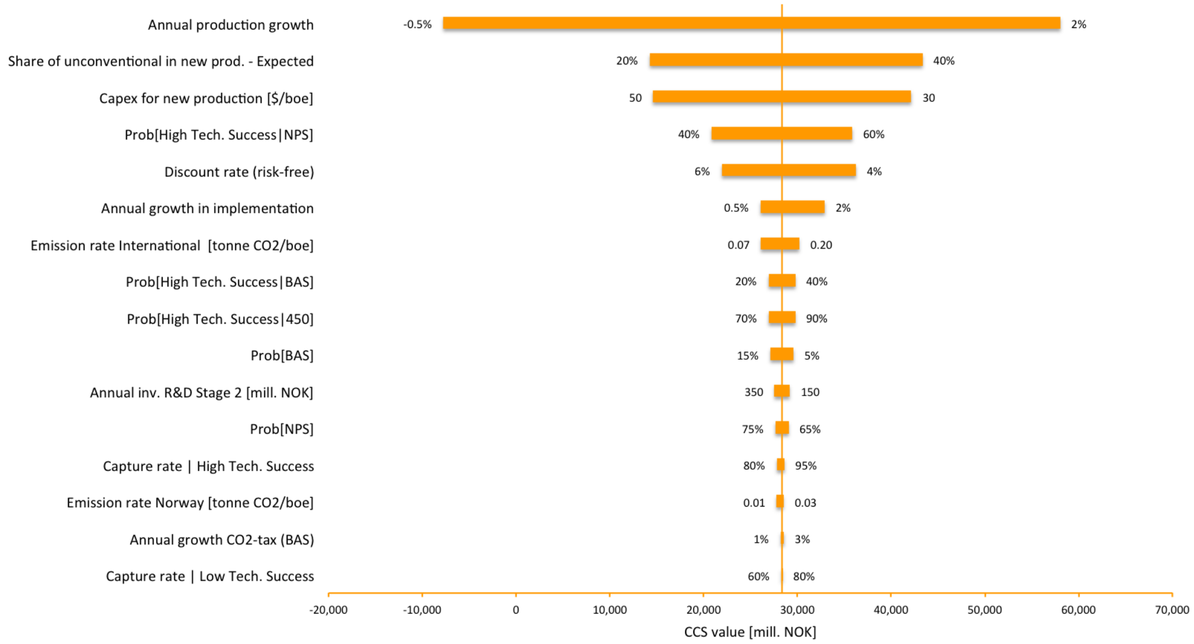

Figure D.1: Tornado chart of all the input variables. For exact values, see Table D.1.

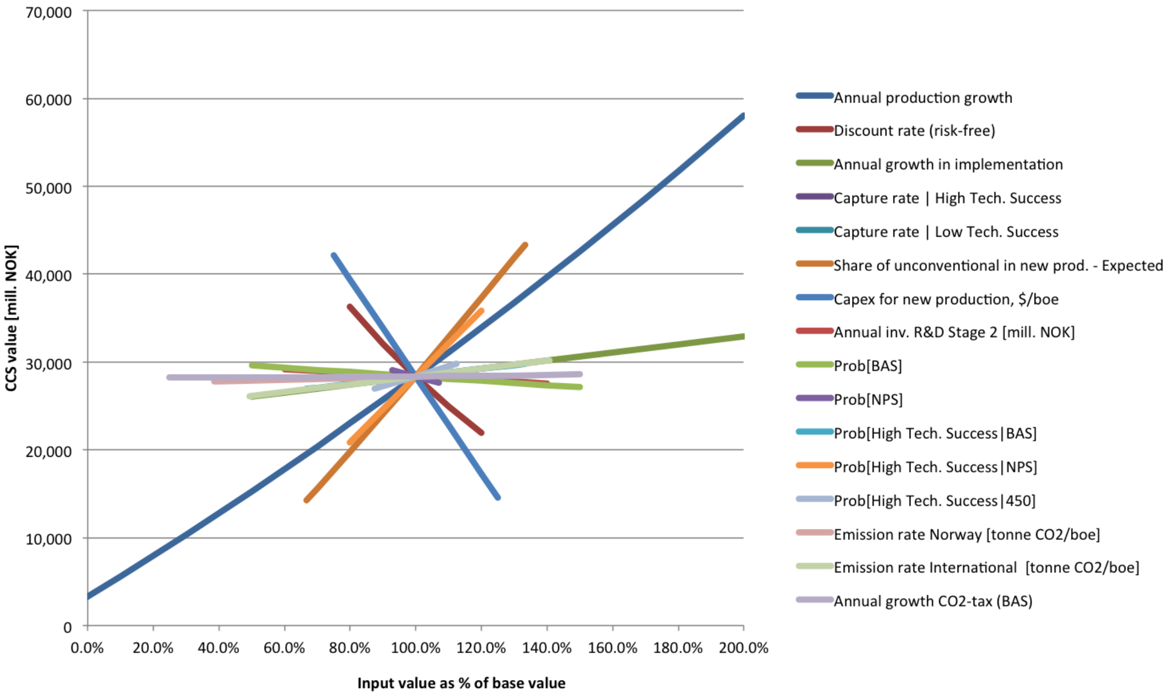

Figure D.2: Spider chart of all the input variables. For exact values, see Table D.2.

Table D.1: Data values for the tornado chart. For a graphical illustration, see Figure D.1.

	Corresponding Input Value			Output Value				
Input Variable	Low Output	Base Case	High Output	Low	Base	High	Swing	$(\text{Swing})^2$
Annual growth in production	0 %	1 %	2 %	-3 836,17	20 037,60	48 419,03	52 255,20	67,6%
Share of unconventional in new prod. - Expected	20 %	30 %	40 %	8 260,63	20 037,60	32 561,23	24 300,60	14,6%
Capex for new production, [USD/boe]	50	40	30	8 515,47	20 037,60	31 559,74	23 044,28	13,2%
Prob[High Tech. Success|NPS]	40 %	50 %	60 %	13 696,48	20 037,60	26 378,73	12 682,25	4,0%
Discount rate (risk-free)	6 %	5 %	4 %	14 709,29	20 037,60	26 643,89	11 934,60	0,1%
Annual growth in implementation	1 %	1 %	2 %	17 747,25	20 037,60	24 618,31	6 871,06	0,1%
Emission rate International [tonne CO_2/boe]	0,070	0,142	0,200	17 776,97	20 037,60	21 858,67	4 081,70	0,1%
Prob[High Tech. Success|BAS]	20 %	30 %	40 %	18 827,38	20 037,60	21 247,82	2 420,44	0,1%
Prob[High Tech. Success|450]	70 %	80 %	90 %	18 829,84	20 037,60	21 245,37	2 415,53	0,1%
Prob[BAS]	15 %	10 %	5 %	18 906,01	20 037,60	21 169,20	2 263,20	0,0%
Share of unconventional in new prod. - High	50 %	60 %	70 %	19 258,57	20 037,60	20 994,26	1 735,69	0,0%
Annual inv. R&D Stage 2 [mill. NOK]	350	250	150	19 226,82	20 037,60	20 848,39	1 621,56	0,0%
Prob[NPS]	75 %	70 %	65 %	19 345,19	20 037,60	20 730,01	1 384,82	0,0%
Capture rate | Low Tech. Success	80 %	90 %	95 %	19 487,12	20 037,60	20 312,85	825,73	0,0%
Capture rate | High Tech. Success	0,01	0,026	0,03	19 442,41	20 037,60	20 186,40	744,00	0,0%
Annual growth CO_2-tax (BAS)	0,005	0,02	0,03	19 903,96	20 037,60	20 259,05	355,09	0,0%
Emission rate Norway [tonne CO_2/boe]	0,6	0,7	0,8	19 970,28	20 037,60	20 104,93	134,65	0,0%
450, Positive Deviation from BAS	0,7	1	1,3	19 975,25	20 037,60	20 109,27	134,03	0,0%
NPS, Positive Deviation from BAS	0,3	0,2	0,1	20 030,67	20 037,60	20 044,83	14,17	0,0%

Table D.2: Data values for the spider chart. For a graphical illustration, see Figure D.2. (The columns with corresponding input values are omitted because of space limitations - they equal to the ones in Table D.1.)

	Input Value as % of Base			Output Value				Slope
Input Variable	Low %	Base %	High %	Low	Base	High	Swing	[bill. NOK/1% change]
Annual growth in production	0,0%	100,0%	200,0%	-3 836,17	20 037,60	48 419,03	52 255,20	261,28
Share of unconventional in new prod. - Expected	66,7%	100,0%	133,3%	8 260,63	20 037,60	32 561,23	24 300,60	364,51
Capex for new production, USD/boe	125,0%	100,0%	75,0%	8 515,47	20 037,60	31 559,74	23 044,28	-460,89
Discount rate (risk-free)	120,0%	100,0%	80,0%	14 709,29	20 037,60	26 643,89	11 934,60	-298,37
Annual growth in implementation	50,0%	100,0%	200,0%	17 747,25	20 037,60	24 618,31	6 871,06	45,81
Emission rate International [tonne CO_2/boe]	49,3%	100,0%	140,8%	17 776,97	20 037,60	21 858,67	4 081,70	44,58
Share of unconventional in new prod. - High	83,3%	100,0%	116,7%	19 258,57	20 037,60	20 994,26	1 735,69	52,07
Capture rate | High Tech. Success	88,9%	100,0%	105,6%	19 487,12	20 037,60	20 312,85	825,73	49,54
Emission rate Norway [tonne CO_2/boe]	38,5%	100,0%	115,4%	19 442,41	20 037,60	20 186,40	744,00	9,67
Annual growth CO_2-tax (BAS)	25,0%	100,0%	150,0%	19 903,96	20 037,60	20 259,05	355,09	2,84
Capture rate | Low Tech. Success	85,7%	100,0%	114,3%	19 970,28	20 037,60	20 104,93	134,65	4,71
450, Positive Deviation from BAS	70,0%	100,0%	130,0%	19 975,25	20 037,60	20 109,27	134,03	2,23
NPS, Positive Deviation from BAS	150,0%	100,0%	50,0%	20 030,67	20 037,60	20 044,83	14,17	-0,14
Prob[High Tech. Success|NPS]	80,0%	100,0%	120,0%	13 696,48	20 037,60	26 378,73	12 682,25	317,06
Prob[High Tech. Success|BAS]	66,7%	100,0%	133,3%	18 827,38	20 037,60	21 247,82	2 420,44	36,31
Prob[High Tech. Success|450]	87,5%	100,0%	112,5%	18 829,84	20 037,60	21 245,37	2 415,53	96,62
Prob[BAS]	150,0%	100,0%	50,0%	18 906,01	20 037,60	21 169,20	2 263,20	-22,63
Annual inv. R&D Stage 2 [mill. NOK]	140,0%	100,0%	60,0%	19 226,82	20 037,60	20 848,39	1 621,56	-20,27
Prob[NPS]	107,1%	100,0%	92,9%	19 345,19	20 037,60	20 730,01	1 384,82	-96,94

Table D.3: Complementary table for Figure 6.17: Break-even for annual production growth. The CCS value breaks even with an annual increase in production of -0.14%.

Increase	CCS value
-1,0%	-17 935
-0,9%	-15 973
-0,8%	-13 977
-0,7%	-11 947
-0,6%	-9 883
-0,5%	-7 784
-0,4%	-5 649
-0,3%	-3 477
-0,2%	-1 269
-0,1%	977
0,0%	3 260
0,1%	5 583
0,2%	7 946
0,3%	10 348
0,4%	12 792
0,5%	15 277
0,6%	17 804
0,7%	20 374
0,8%	22 989
0,9%	25 647
1,0%	28 351
1,1%	31 102
1,2%	33 899
1,3%	36 744
1,4%	39 637
1,5%	42 579
1,6%	45 572
1,7%	48 616
1,8%	51 712
1,9%	54 861
2,0%	58 064
2,0%	58 064

Table D.4: Summary of Statistics from the risk analysis (Monte Carlo simulation) for the valuation with inclusion of game theory. Total number of trials is 10 000.

Variable	Unit	Value
Mean	[mill. NOK]	50 754
St. Dev.	[mill. NOK]	58 759
Mean St. Error		587,59
Minimum	[mill. NOK]	-20 324
First Quartile	[mill. NOK]	-
Median	[mill. NOK]	51 176
Third Quartile	[mill. NOK]	72 211
Maximum	[mill. NOK]	274 398
Skewness		0,9737

Appendix E

Detailed data description

In this part, we will present in detail the input data used for the valuation and modelling of the CCS-technology values. Specifically, we enumerate all the input variables, and specific values for different prices; technology, crude- and gas price, national and international tax development and evolvement of the CO_2 quota market. Also here we refer to the attached Excel file.

Table E.1: Input data used in the model. Variables suitable for sensitivity analysis are given two extreme values in addition to their base value.

Captured at TCM [mill ton/yr]	0,1
Emission CCM [mill ton/yr]	1,3
Labour resources invested	
R&D [units/yr]	25
TCM [units/yr]	120
CCM [units/yr]	300
Revenue Statoil 2011 [mill. NOK]	81 600
Employees Statoil 2011	20 000
Avg. Revenue per employee (2010) [mill. NOK]	4,08
Base case specific data	
Present year	2010
Implementation year	2020
Discount rate (risk-free)	5 %
Initial Broad Impl. Rate	2 %
Annual growth in implementation	1 %
Emission rate	
Emission rate Norway [tonne CO_2/boe]	0,026
Emission rate International [tonne CO_2/boe]	0,142
CO_2 Capture rate	
Capture rate | High Tech. Success	90 %
Capture rate | Low Tech. Success	70 %
Exchange rate	
NOK/EUR	8
NOK/USD	6
CO_2-tax development	
Annual growth CO_2-tax (BAS)	2 %
NPS, Positive Deviation from BAS	20 %
450, Positive Deviation from BAS	100 %
Benefit	
Annual growth in prod.	1 %
Share of unconventional in new prod. - Expected	30 %
Share of unconventional in new prod. - High	60 %
Capex for new production, USD/boe	40
Annual Investments	
Annual inv. R&D Stage 1 [mill. NOK]	250
Annual inv. R&D Stage 2 [mill. NOK]	250
Scenario probabilities	
Prob[BAS]	10 %
Prob[NPS]	70 %
Prob[450]	20 %
Scenario probabilities given high tech. success	
Prob[High Tech. Success|BAS]	30 %
Prob[High Tech. Success|NPS]	50 %
Prob[High Tech. Success|450]	80 %

Table E.2: Norwegian CO_2 tax growth rate. Data is split in two sections to adjust for major corrections in tax level. The plot of the data are shown in Figure 5.2. Data source: Marius Pilgaard, The Norwegian Ministry of Finance

Year	Tax, P [NOK]	$X = P(t)/P(t-1)$	$\ln(X)$
1992	342		
1993	342	1,000	0,000
1994	351	1,026	0,026
1995	355	1,011	0,011
1996	364	1,025	0,025
1997	372	1,022	0,022
1998	381	1,024	0,024
Avg. annual growth 1992-1998=0,018			
2001	308		
2002	312	1,013	0,013
2003	321	1,029	0,028
2004	325	1,012	0,012
2005	334	1,028	0,027
2006	338	1,012	0,012
2007	342	1,012	0,012
Avg. annual growth 1992-1998=0,017			

Table E.3: Norwegian and international CO_2 tax development used in the calculations

	Norway [NOK/tonne]			International [USD/tonne]		
Year	BAS	NPS	450	BAS	NPS	450
2010	201,0	201,0	201,0	15,0	15,0	15,0
2011	205,0	205,8	209,0	15,3	15,4	15,6
2012	209,1	210,8	217,4	15,6	15,7	16,2
2013	213,3	215,8	226,1	15,9	16,1	16,9
2014	217,6	221,0	235,1	16,2	16,5	17,5
2015	221,9	226,3	244,5	16,6	16,9	18,2
2016	226,4	231,7	254,3	16,9	17,3	19,0
2017	230,9	237,3	264,5	17,2	17,7	19,7
2018	235,5	243,0	275,1	17,6	18,1	20,5
2019	240,2	248,8	286,1	17,9	18,6	21,3
2020	245,0	254,8	297,5	18,3	19,0	22,2
2021	249,9	260,9	309,4	18,7	19,5	23,1
2022	254,9	267,2	321,8	19,0	19,9	24,0
2023	260,0	273,6	334,7	19,4	20,4	25,0
2024	265,2	280,2	348,1	19,8	20,9	26,0
2025	270,5	286,9	362,0	20,2	21,4	27,0
2026	275,9	293,8	376,5	20,6	21,9	28,1
2027	281,4	300,8	391,5	21,0	22,4	29,2
2028	287,1	308,0	407,2	21,4	23,0	30,4
2029	292,8	315,4	423,5	21,9	23,5	31,6
2030	298,7	323,0	440,4	22,3	24,1	32,9
2031	304,6	330,7	458,0	22,7	24,7	34,2
2032	310,7	338,7	476,4	23,2	25,3	35,5
2033	317,0	346,8	495,4	23,7	25,9	37,0
2034	323,3	355,1	515,2	24,1	26,5	38,4
2035	329,8	363,7	535,8	24,6	27,1	40,0

Table E.4: Quota market, price development used in the model. Measured in USD_{2009} per tonne CO_2.

	Quota market [USD_{2009} per tonne CO_2]		
Year	BAS	NPS	450
2010	15,3	15,3	15,3
2011	17,7	18,7	19,6
2012	20,0	22,0	23,8
2013	22,3	25,4	28,1
2014	24,6	28,7	32,3
2015	26,9	32,1	36,6
2016	29,3	35,4	40,8
2017	31,6	38,8	45,1
2018	33,9	42,1	49,3
2019	36,2	45,5	53,5
2020	38,5	48,8	57,8
2021	40,6	51,3	68,9
2022	42,8	53,9	80,1
2023	44,9	56,4	91,2
2024	47,0	58,9	102,4
2025	49,1	61,5	113,5
2026	51,2	64,0	124,7
2027	53,3	66,5	135,8
2028	55,4	69,1	147,0
2029	57,5	71,6	158,1
2030	59,6	74,2	169,3
2031	62,9	77,4	178,8
2032	66,1	80,6	188,3
2033	69,4	83,8	197,8
2034	72,6	87,1	207,2
2035	75,9	90,3	216,7

Table E.5: Technology price development used in the model. Measured in EUR_{2008} per tonne CO_2 captured.

	Technology Cost [EUR_{2008} per tonne CO_2 captured]	
Year	low	high
2010	150,0	150,0
2011	134,1	141,1
2012	118,1	132,2
2013	102,2	123,3
2014	86,3	114,4
2015	70,4	105,5
2016	69,5	104,0
2017	68,7	102,5
2018	67,8	100,9
2019	67,0	99,4
2020	66,1	97,8
2021	65,3	96,3
2022	64,5	94,8
2023	63,6	93,2
2024	62,8	91,7
2025	61,9	90,1
2026	61,1	88,6
2027	60,2	87,1
2028	59,4	85,5
2029	58,6	84,0
2030	57,7	82,5
2031	57,3	82,6
2032	56,8	82,7
2033	56,3	82,9
2034	55,9	83,0
2035	55,4	83,1

Table E.6: Crude price and gas price development. Source: IEA (2010)

	Crude oil Price [USD/barrel]			Natural Gas import price (Europe) [USD/MBtu]		
Year	BAS	NPS	450	BAS	NPS	450
2010						
2011						
2012						
2013						
2014						
2015	94,0	90,4	87,9	10,7	10,6	10,4
2016	97,2	92,1	88,3	11,0	10,8	10,4
2017	100,4	93,8	88,7	11,3	11,0	10,5
2018	103,6	95,6	89,2	11,5	11,2	10,5
2019	106,8	97,3	89,6	11,8	11,4	10,6
2020	110,0	99,0	90,0	12,1	11,6	10,6
2021	112,0	100,2	90,0	12,3	11,7	10,6
2022	114,0	101,4	90,0	12,4	11,9	10,6
2023	116,0	102,6	90,0	12,6	12,0	10,7
2024	118,0	103,8	90,0	12,7	12,2	10,7
2025	120,0	105,0	90,0	12,9	12,3	10,7
2026	122,0	106,0	90,0	13,1	12,4	10,7
2027	124,0	107,0	90,0	13,3	12,5	10,8
2028	126,0	108,0	90,0	13,5	12,7	10,8
2029	128,0	109,0	90,0	13,7	12,8	10,9
2030	130,0	110,0	90,0	13,9	12,9	10,9
2031	131,0	110,6	90,0	14,0	13,0	10,9
2032	132,0	111,2	90,0	14,1	13,1	10,9
2033	133,0	111,8	90,0	14,2	13,1	11,0
2034	134,0	112,4	90,0	14,3	13,2	11,0
2035	135,0	113,0	90,0	14,4	13,3	11,0