Value chains for carbon storage and enhanced oil recovery: optimal investment under uncertainty

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Abstract Carbon capture and sequestration is a possible technology for abating carbon dioxide emissions. This is costly and requires investment in capture, transportation and storage facilities, and compensation for possibly substantial operational cost at these facilities. On the other hand, this option avoids buying carbon offsets, and the CO₂ may in some cases be used for enhanced oil recovery. Stochastic dynamic programming is applied to perform the underlying investment analysis, that is, to decide whether investment on a CO₂ value chain is profitable, and if so, then when the decisions should be taken. The oil and CO₂ prices are modelled as stochastic processes. As a case study we consider possible CO₂ value chain investments on the Norwegian Continental Shelf.

Keywords CO₂ value chain · Carbon capture and storage · Enhanced oil recovery · Dynamic programming · Greenhouse gas abatement · Energy price uncertainty

1 Introduction

The abatement of carbon dioxide emissions is high on the agenda of politicians, researchers and main CO₂ emitters. In 2007, the European Union leaders committed Europe to transforming itself into a highly energy-efficient, low-carbon economy. The main goals are known as the 20-20-20 targets, that is in 2020, a reduction in greenhouse gas emissions of at least 20% compared to 1990 levels, to produce 20% of the energy consumed from renewable sources and a 20% reduction in primary

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energy use, to be achieved by improving energy efficiency. This climate and energy package became law in June 2009. The core of the package is composed of four main points: an improvement of the Emissions Trading System (EU ETS) so it becomes the driver for cutting emissions cost-effectively, an “Effort Sharing Decision” that covers other sectors not included in the EU-ETS, targets for renewable energy, and a legal framework to promote the development and safe use of carbon capture and storage (CCS).

The promotion of CCS is based on the observation that fossil fuels will remain the primary source of energy worldwide for the decades to come. The carbon emissions reduction target will never be met unless the energy production coming from fossil fuels can be exploited without ballooning emissions. Clearly CCS has the potential to contribute to the EU’s climate goals [12].

Carbon capture and geological storage is a technique for trapping carbon dioxide from large emitters by separating the CO₂ from the flue gas, conditioning it, compressing it, and transporting it to a suitable storage site (such as aquifers) where it is injected for a safe and long-term storage. Although the components of CCS are all known, the integration into one system is new. One of the main challenges for CCS is the economic burden. Significant up-front investments are required, and the energy penalty during capture is high (in the order of 10–40% [11]). If the geographical situation is favourable or infrastructure is in place, then CO₂ can be used for improving the recovery of oil. When oil production with conventional methods declines, enhanced oil recovery (EOR) methods allow additional oil to be extracted economically from the reservoir and increase the producer’s revenues. In some oil fields, CO₂ can be used to displace additional oil that otherwise would remain in the reservoir.¹

Within Europe large CO₂ emitters need to hold emission rights for each tonne of CO₂ emitted. When a company emits more CO₂ than the amount of allowances owned, the company has to offset the exceeded carbon emissions by for example buying emission rights in the Emissions Trading Scheme (EU-ETS) [1], a market where companies can trade CO₂ allowances.

CO₂ producers within the EU have the choice between buying carbon allowances and investing in carbon capture and storage (CCS) facilities. In this paper, we examine an investment opportunity for CCS with EOR. We focus on upstream investment decisions regarding CO₂ storage and use for EOR. We assume that a gas power plant has recently been installed, and we consider three possibilities regarding the treatment of the CO₂. One is to vent the CO₂ and, therefore, CO₂ allowances are required. The second possibility is to invest in a CCS value chain, where the CO₂ is stored in a nearby aquifer. The third option is to invest in CCS and also in EOR. This latter option is the one that requires more investment, but there are additional revenues from the extra oil recovered. The analysis can be viewed as an application of real options theory; however, we apply a traditional dynamic programming approach instead of state-contingent (risk neutral) pricing.

Several authors have studied the profitability of investments in CCS. Abadie et al. [2] analyse a coal-fired power plant that has the option to invest in a CCS

¹ The emissions due to the extra oil recovered are not considered in this study.

unit. A real options analysis is used to determine the price of CO₂ that triggers investment in CCS. Their conclusion is that, with current carbon prices and projected variability, the best practice is to wait for higher CO₂ prices. Fuss et al. [5] illustrate how uncertainty around the carbon price due to market and policy fluctuations delays the decision to invest in CCS. Both papers model the CO₂ allowance price and the electricity price as two correlated stochastic processes, and the main conclusion is that current CO₂ prices do not promote investment in CCS. Heydari et al. [6] study the option to retrofit a coal power plant with full or partial CCS. The coal and the allowances prices evolve as correlated geometric Brownian motion processes. A real option analysis is performed to conclude that, with current market data, the best option in the near term is to wait. In order to increase the chances of having a profitable investment, we extend the value chain with the possibility of EOR.

Gaspar et al. [13] develops a techno-economical model to assess the feasibility of CO₂ sequestration in EOR operations. Their conclusion is that EOR with CO₂ is economically sound, and that, at the same time, large amounts of CO₂ can be stored. While their study focuses on the profitability of CO₂-EOR, we look into a complete value chain, with decisions on whether and when to capture and how to store the CO₂. Timing of investment is an important property of our analysis. Klock et al. [9] present a deterministic multiperiod investment model for designing an optimal deployment of a large CCS infrastructure (including EOR). Their model assumes that a fixed set of CO₂ producers will install the capture facilities at the beginning of the planning period, and the model chooses the best candidates (either aquifers or oil fields for EOR) for storing the CO₂ and the pipelines used. In our model, investing in carbon capture is a possibility that happens only if it is more profitable than venting. In addition to the flexibility on the investment in capture, we treat the future oil and CO₂ allowance price as stochastic processes. Our contribution is a stochastic dynamic analysis for CO₂ value chains where the use of CO₂ for EOR is a possibility in addition to the storage in an aquifer.

A base case is used in order to illustrate how uncertainty in future prices and the flexibility in postponing an investment affects its overall profitability. We consider a natural gas-fired power plant in Norway, which has the possibility of retrofitting the plant with a capture unit and storing the CO₂ in a nearby aquifer or using the CO₂ for EOR. We assume that the power plant starts its operation in 2012 and has a lifetime of 25 years.

The paper is organised as follows. Section 2 presents the theoretical framework used to perform the investment analysis. Section 3 describes the test case and the parameters used. It concludes with the analysis of the results and main findings.

2 Dynamic programming framework

In this paper, we evaluate timing decisions on whether and when a CO₂ producer should invest in CCS facilities. We put special emphasis on how the use of CO₂ for EOR influences the profitability of CCS and on the timing of investment in the various elements of the CO₂ value chain. This section presents the modelling and solution approach.

Fig. 1 Representation of the binomial lattice used to represent the stochastic processes in discrete time, $\xi_t^k = (P_t^{\text{oilk}}, P_t^{\text{CO}_2k})$

The model considers investment in CCS (with EOR) based on two economic incentives. One is the savings in CO₂ allowances, and the other is the extra income due to producing and selling additional oil. In our analysis, CO₂ and oil prices are treated as stochastic processes. The price dynamics of commodities may be classified into short-term and long-term factors [14]. The former are transitory and affect current supply and demand, but without a permanent effect on them. Long-term factors, by contrast, are persistent and cause supply and demand changes that last for a long time. The latter phenomenon is usually modelled using a random walk process. Because this analysis deals with strategic investment decisions with a time frame of 25 years, it is assumed that only the long-term uncertainties drive the investment decisions (thus ignoring mean-reverting short-term effects), and the price developments are modelled following a geometric Brownian motion (GBM).

The GBM stochastic process occurs in continuous time and is represented by (1), where P_t is the price that changes with the time, μ is the expected percentage drift, σ is the percentage volatility and Z_t is a standard Brownian motion process. Given the current price P_0 , P_t follows a log-normal distribution [3]. Both the oil price, P_t^{oil} , and the CO₂ price, $P_t^{\text{CO}_2}$, are modelled as correlated GBMs, i.e., $dZ_t^{\text{oil}}dZ_t^{\text{CO}_2} = \rho dt$.

$$\frac{dP_t^i}{P_t^i} = \mu^i dt + \sigma^i dZ_t^i, \quad i = \text{oil}, \text{CO}_2 \quad (1)$$

An approximation to the GBM process in discrete time is through a binomial lattice (see Fig. 1). Let ξ_t be the random variable with the oil and CO₂ prices pair $(P_t^{\text{oil}}, P_t^{\text{CO}_2})$. Each node in the lattice is related to one price state in one specific point in time, ξ_t^k , where t represents the time period and k a particular realization of the uncertainty $(P_t^{\text{oilk}}, P_t^{\text{CO}_2k})$. In this analysis, the time step used is one year. Because the two commodities are correlated, the prices are modelled using a Rubinstein non-rectangular lattice [8], where for a given time period the mean and variance of the lattice are the right values (with respect to the mean and variance implied by (1)) and the prices of the two commodities are related through the parameter ρ , where $dZ_t^{\text{oil}}dZ_t^{\text{CO}_2} = \rho dt$.

The owner of the value chain faces the decision of how to treat the CO₂ produced and wishes to maximise the sum of discounted expected future profits by taking the best decision at the right moment. Dynamic programming (DP) is well suited to solving optimisation problems that combine time, uncertainty and can be decomposed into subproblems. DP defines two types of variables: state variables and decision

variables. The state variables at each node k , s_t^k , define the state of the system at time t : oil and CO₂ prices, ξ_t^k , and level of investment. Here there are two possible states regarding the treatment of the CO₂: to vent or to capture the CO₂; and three possible states regarding the storage of CO₂: no storage, storage in an aquifer, or using the CO₂ for EOR. The decision variables, x_t^k , are the set of possible actions that can be taken: to invest in CO₂ capture, to invest in storage in the aquifer or to invest in EOR activity.

At each period t , some choices are available to the firm, so a transition matrix, τ_t , is used to determine how the system can evolve from period t to period $t + 1$. Also the state and decision variables at time t , s_t^k and x_t^k , affect the probability distribution of future states. Let $\phi_t^k(s_{t+1}|s_t^k, x_t^k)$ denote the probability density function of the state next period, conditional upon the current information. This function is built from the transition matrix, τ_t , and the representation of the stochastic components, ξ_t^k .

Given a realization of the uncertainty at time t , ξ_t^k , the immediate profit $\pi_t(s_t^k, x_t^k)$ can be calculated. The yearly profits of the owner of the value chain with respect to the treatment of the CO₂ (2) are composed of the oil revenues minus the cost of buying CO₂ allowances minus variable costs for operating the CCS system (with EOR) minus the investment costs faced in this period.

$$\pi_t(s_t^k, x_t^k) = P_t^{\text{oil}k} q_t^{\text{oil}}(s_t^k) - P_t^{\text{CO}_2k} q_t^{\text{CO}_2}(s_t^k) - c_t^{\text{op}}(s_t^k) - c_t^{\text{inv}}(x_t^k) \quad (2)$$

$P_t^{\text{oil}k}$ and $P_t^{\text{CO}_2k}$ are the prices of CO₂ and oil in state s_t^k , $q_t^{\text{oil}}(s_t^k)$ is the amount of oil produced, $q_t^{\text{CO}_2}(s_t^k)$ is the amount of CO₂ emitted and $c_t^{\text{op}}(s_t^k)$ are the operational costs. These quantities are different depending on the state of the system. The quantity $c_t^{\text{inv}}(x_t^k)$ corresponds to the investment costs incurred by making decision x_t^k .

Let $F_t(s_t^k)$ express the expected net present value (NPV) of all cash flows of being in state s_t^k , when all decisions from time t onwards are made optimally:

$$F_t(s_t^k) = \max_{x_t^k} \left\{ \pi_t(s_t^k, x_t^k) + \frac{1}{1+r} \mathbb{E}_t[F_{t+1}(s_{t+1})] \right\} \quad (3)$$

where $r = 0.055$ is the discount rate. Since we are in a stochastic setting the set of optimal decisions at time $t + 1$ will yield $F_{t+1}(s_{t+1})$, which is a random quantity from the perspective of period t . Therefore the expected value (4) is taken.² This expected value is called continuation value, and it has to be discounted to time t . The owner of the value chain will choose the decision x_t that maximises (3).

$$\mathbb{E}_t(F_{t+1}(s_{t+1})) = \sum_{l=1}^4 \phi_t^k(s_{t+1}^l | s_t^k, x_t^k) F_{t+1}(s_{t+1}^l) \quad (4)$$

Equation (3) is applied recursively from the last period, T , to the first period. The decision to be made in the last stage, x_T^k , is already known, which is to stay

²The expression given here for the expected value is adapted for our problem. The general form is: $\mathbb{E}_t(F_{t+1}(s_{t+1})) = \int F_{t+1}(s_{t+1}) d\Phi_t(s_{t+1}|s_t^k, x_t^k)$ where $\Phi_t(s_{t+1}|s_t, x_t)$ is the cumulative distribution function of $\phi_t(s_{t+1}|s_t, x_t)$ and the range of integration is the support of $\Phi_t(s_{t+1}|s_t, x_t)$.

in the same state as nothing else will occur. Therefore $F_T(s_T^k)$ is known: $F_T(s_T^k) = \pi_T(s_T^k, x_T^k)$. From there the value $F_{T-1}(s_{T-1})$ can be computed with (3). Backward induction is employed until the first period (see [3] for a formal description). The solution procedure in pseudo-code is:

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for all nodes of the lattice that belong to period  $T$  and state  $k$  do
  Compute  $F_T(s_T^k) := \pi_T(s_T^k, x_T^k)$ 
end for
for  $t = T - 1$  until 1 do
  for all nodes that belong to period  $t$  do
    Compute  $\mathbb{E}_t(F_{t+1}(s_{t+1}))$  as in (4)
    for each possible decision  $x_t^k$  that can be taken from state  $s_t^k$  do
      Compute the current profit  $\pi_t(s_t^k, x_t^k)$  as in (2)
    end for
    Compute  $F_t(s_t^k)$  as in (3)
  end for
end for

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The information obtained from the DP solution is a matrix containing the optimal decision, x_t^k , for every time period t , state s_t^k , and pair of price instances (P_t^{oilk} , $P_t^{\text{CO}_2k}$). The solution $F_1(s_1^1)$ is the expected NPV when the investor will follow the strategy (set of optimal decisions at each node of the lattice and state) found by DP.

3 Case description

Suppose that a natural gas power plant of 400 MW without capture will be built by 2012. If the power plant is retrofitted with a capture module then 2 tonnes of CO₂ per year will be captured.³ The study starts in 2012 and we assume that the remaining lifetime of the plant is of 25 years.

The investment possibilities, which define the investment costs $c_t^{\text{inv}}(x_t^k)$ and the subsequent operational costs $c_t^{\text{op}}(s_t^k)$, are:

- CCS system: to install a capture unit that separates, conditions and pressurizes the CO₂. The CO₂ is transported in a 14" pipeline to an aquifer 330 km away from the power plant. The aquifer needs to be prepared for CO₂ injection.
- CCS + EOR: On top of the CCS system, the investment can be extended for CO₂-EOR. The oil field has to be adapted for CO₂ injection and a separation plant (with technology similar to the capture plant) has to be installed. If EOR would be the first choice, then the investment in the aquifer might be postponed until the end of the EOR activity. As of today, it is not clear that CO₂ for EOR would earn credits for units of CO₂ sequestered. However, we assume that this will be the case as long as it can be proved that the CO₂ is sequestered. Therefore, having the aquifer

³We assume a capture rate of 85%. Remaining emissions will need to be covered by emission permits in any case.

Fig. 2 In state 1 the option is to vent the CO₂, in state 2 the option is to invest in CCS and then jump to state 4 which is to store the CO₂ in an aquifer. State 3 invests in CCS + EOR at the same time, and then switches to a state where EOR is done for at most 10 years (from state 6 to state 13). In state 5 we are already storing the CO₂ in the aquifer and then we invest in EOR. States 6 to 13 represent EOR starting from 2016 to 2023

Table 1 Investment and operational costs (in 2005 NOK)

	CAPEX (MNOK)	OPEX (MNOK/year)
CCS system		
Capture plant [15]	3370	600
Pipeline [10]	2000	20
Aquifer [15]	350	5
Additional costs for EOR		
Oil field adequacy [15]	3458	604

available for use from the beginning is considered to be a backup mechanism to ensure continued sequestration.

- Venting: The alternative of not investing in CCS is also possible. In this case, carbon allowances have to be purchased.

See Fig. 2 for the representation of the different states of investment, and of capture and storage of CO₂. The transition matrix τ_t is based on this information.

Table 1 shows the costs used in our analysis, which are obtained from studies on Tjeldbergodden (a projected gas power plant in Norway). The values have been updated to 2012 currency units, using the CEPCI index until 2008 and a estimated inflation rate (2.5%) for the rest of the years.

The technology for large-scale CO₂ capture is still being developed. Investment costs for CO₂ capture are expected to be lower as the technology becomes more mature, and a yearly reduction of 2% is assumed. Technology for CO₂ transport is very similar to the natural gas transport, which has been used for many years and is a well established and mature technology. Also, technology for CO₂ injection, either in an aquifer or in an oil field, can be transferred from the oil and natural gas industry. Construction costs are attributed to the year in which the facility begins operation, although in reality construction may take more years, and costs would be

spread across the construction period. In doing so, we are slightly overestimating the construction costs.

All the values presented are adjusted by the inflation, which we assume to be 2.5% as this is the goal of the Norwegian Government's monetary policy.

3.1 EOR model

Oil recovery methods can be grouped into conventional and enhanced methods. Conventional recovery involves production of oil through natural reservoir pressure or by waterflooding, where water is injected into the reservoir to maintain reservoir pressure and displace the oil. Conventional recovery ceases when the oil production rate is too low to offset the cost of operating the field. At this point, typically 40% to 60% of the original oil in place remains trapped in the reservoir. Enhanced oil recovery methods allow additional oil to be extracted economically from the reservoir. One of the possible EOR methods is the injection of CO₂, where the CO₂ dissolves in the oil and improves oil displacement into the production wells. The exact response to CO₂ flooding varies for each specific field. Recovery rates of additional oil can be only estimated through specific simulation models that involve technical details of the particular reservoir. In this case, the recovery ratio (the number of additional barrels of oil produced for each tonne of CO₂ injected) shown in Fig. 3 (above) is an estimate taken from [7]. As can be observed, the recovery ratio is low the first years before peaking and then starts declining.

Shortly after the CO₂ injection starts, the CO₂ will break through and some of the CO₂ injected will slip to the surface. CO₂ then is separated, conditioned and reinjected into the reservoir; therefore, the amount of CO₂ injected increases with the time. Figure 3 (below) shows the CO₂ re-cycling ratio: tonnes of CO₂ that resurface for each tonne of CO₂ injected. The injection of CO₂ ceases after 10 years and before 2030 (year when the field is projected to shut down).

Since the injection of CO₂ cannot start too early and cannot be delayed too much because the field may be decommissioned before the EOR investment is paid back,

Fig. 3 CO₂-EOR profile—(above) EOR ratio is the number of extra barrels of oil produced for each tonne of CO₂ injected; (below) CO₂ re-cycling ratio is the amount of CO₂ that re-cycles for each tonne of CO₂ injected

Table 2 Value of the parameters of (1) for the oil and the CO₂ price. The correlation is $\rho = 0.87$

	P_{2012}	μ	σ
Oil	70 USD/bbl	0.0111	7.75%
CO ₂	14 EUR/tonne	0.0093	7.75%

Fig. 4 Oil and CO₂ samples from the binomial lattice

the injection of CO₂ for EOR has a specific time window. For the oil field used in our study, CO₂-EOR cannot start before 2016 and no later than 2023.

3.2 Uncertainty representation

Oil and carbon prices are modelled by means of a binomial lattice representing the two correlated variables. Table 2 presents the values used.⁴ The price in 2012 is based on the observed prices from April 2009 to March 2010. The expected drift has been calculated from the forecasts in the Baseline scenario used by the European Commission [4].⁵ The annual price volatility estimates and the correlation between the two commodities are from Yang et al. [16].

Figure 4 shows a sample from the binomial lattice of the oil and CO₂ price paths. The central white dots depict the expected value of the price at each time period. The scatter plot in the bottom plots the CO₂ price against the oil price where it is appreciated the high correlation between the two commodities.

4 Results and sensitivity analysis

By analysing the results of the base case presented, we wish to understand how the use of CO₂ for EOR influences the profitability and timing of a CCS project and what are the main drivers of the expected NPV.

⁴The currency of the model is MNOK. When it is required, a fixed rate of 8 NOK/EUR and 6.5 NOK/USD is used.

⁵Forecasts are only until 2020, and the same drift was assumed to be valid until 2036.

Table 3 Expected NPV (in MNOK) for the given choices

Decision	$E(NPV)$
Always vent CO_2	-4472
Invest in CCS from $t = 1$	-19807
Invest in CCS + EOR (DP solution)	-477

Fig. 5 Probability of being at each state in each time period (above) and oil and price distribution in 2019 (below)

Table 3 shows the expected NPV when the only choice is to vent the CO_2 . During the 25 years, the power plant would spend on average 4472 million NOK on emission permits. The investment in CCS is even more unfavourable, thereby meaning that the (estimated) level of the CO_2 price by itself does not promote investment in CCS. The focus shifts when there is the option to use the CO_2 for EOR, where the losses are reduced to -477 (according to the solution found by DP). However, the profits obtained from the oil are not sufficient for producing a positive NPV.

Given the underlying uncertainty in the oil and CO_2 prices and the results from the DP solution, we can compute the probability of being in a particular state at each time period. Figure 5 (above) plots these probabilities (see Fig. 2 for an explanation of the states). The strategy to follow looks clear. The power plant emits CO_2 until 2020 when, with a probability of 77%, it invests in CCS + EOR and in 2021 starts capturing the CO_2 and using it for EOR. Year 2021 is the last year where there will

be 10 years of EOR. After 10 years of CO₂-EOR operations, the CO₂ is stored in the aquifer.

The question that arises with this picture is why the investment in CCS does not happen earlier (if the investment is done in 2020 anyhow). The inflation and the discount rate play a role in hiding some of the effects, as well as the learning curve used for the capture costs. However, if we inspect the results closely then we see that the main difference is due to the high operating cost of the CCS. The savings from not buying CO₂ allowances do not compensate for the operating costs of the capture plant.

Figure 5 (below) shows the oil and CO₂ price distribution that encourages investment in CCS + EOR. The size of the dot is proportional to the probability of being in such a price pair. The rule observed is that for low oil prices, the optimal decision is to keep on venting the CO₂, while for higher oil prices (from around 65 USD on) the best decision is to invest in CCS + EOR. Since the range of the CO₂ price does not change the investment decision rule, we conclude that the CO₂ price does not to affect the decision.

In order to see the effect that price uncertainty has over the profitability of the value chain, we examine the distribution of the NPV. Given the oil and CO₂ price distributions, computing the exact variance of the model is prohibitive due to the exponential number of possible paths that the prices can follow. We have sampled 50000 price paths from the lattice. Each price path is a sequence of price pairs (oil and CO₂) for each time period. At each point, the decisions made are the ones obtained from the DP solution. In order to analyse statistically the distribution of the NPV, the sampling process has been repeated 100 times (see Fig. 6 (above)). It is a non-symmetric distribution, strongly skewed to the right. The shape clearly suggests that the distribution is a combination of two underlying distributions, which are plotted below. One corresponds to the NPV distribution when investment in CCS + EOR occurs (77% of the cases), and the other for the situation where there is no investment. We can see that the NPV distribution when investment happens has more variability than for the non-investment one. However, values are more spread to the positive

Fig. 6 NPV distribution according to the underlying oil and CO₂ price distribution and the strategy set by the DP solution

Fig. 7 $\mathbb{E}(\text{NPV})$ (left) and probability of not investing (right), when varying the annual volatility (σ)

part than for the negative one. This indicates that, although the risk is high, there are possibilities of making large profits.

4.1 Sensitivity analysis

In this section, we focus on how the analysis performed in the previous sections may vary when some of the data change. We start by looking at the effect of volatility. Figure 7 (left) displays the expected NPV solution when the annual volatility changes. The expected NPV solution is higher when the volatility grows, as the chances for increasing revenues are also higher. However, this increase is at the expense of reducing the probability of investing in CCS. The effect of the volatility of the CO_2 and oil price are unequal. Observe that the increase in the oil volatility delays the finding of a solution with positive expected NPV more than for the CO_2 volatility. Therefore, the driver for investing in CCS (+EOR) is the income and not the avoided costs due to CO_2 emissions.

On the other hand, the higher the values of the volatility of the CO_2 price the higher is the probability of venting the CO_2 for the whole period. This result suggests that uncertainty around the CO_2 price leads to a postponement of the investment in CCS. Given that the CO_2 price it is not only driven by market rules but also by political decisions, governments should give clear signals about their environmental policy in order to reduce the sources of uncertainty. Note that for the deterministic case (when volatility is equal to 0) the probability of investing is 1 although the $\mathbb{E}(\text{NPV})$ has its lowest value (but still higher than the option of not investing in CCS or only in CCS with aquifer storage).

Another component that defines the price is the drift. Figure 8 (left) displays how the expected NPV changes with the drift and the probability of never investing in CCS (right).⁶ Starting always as indicated in Table 2, the price at the last period varies from 20 to 140 USD for the oil, and from 0 to 60 EUR for the CO_2 . Since a higher drift implies higher future prices, we observe that higher CO_2 prices delay positive

⁶Note the reverse axis in this plot.

Fig. 8 $\mathbb{E}(\text{NPV})$ (left) and probability of not investing (right), when varying the annual drift (μ)

NPV investments, although the probability of investing increases with higher prices. In the extreme case that the CO_2 price goes to zero, the NPV is rather small due to the low costs of the carbon permits (the probability of investment is 0). However for final prices greater than 35 USD ($\mu^{\text{oil}} = -0.026$) the probability of investing in CCS + EOR starts to increase. Analysing the distribution of the probability of not investing, it is seen that for low prices CCS investment will never happen, and that for high prices investment will always occur.

The sensitivity analysis of the correlation between both commodities shows that a change in this parameter influences the final outcome very little, although the higher the correlation the better is the expected NPV. The expected NPV changes linearly from -610 MNOK when $\rho = 0$ to -459 MNOK when $\rho = 1$.

5 Conclusion

In this paper we have investigated the profitability of several value chains for large CO_2 producers. The alternatives to venting the CO_2 and buying (from 2012 on) CO_2 allowances are: to invest in a CCS system with storage in an aquifer; or to extend the CCS investment with EOR. The use of CO_2 for EOR is plausible for oil producer countries (such as the North Sea area), or if there is an adequate infrastructure for CO_2 transport and regulations support this.

The main conclusion is that the combination of CCS with EOR will result in a situation more profitable (although still with negative expected NPV) than venting the CO_2 or investing and running only the CCS infrastructure. There is a time window for initiation of EOR, and the results indicated that the optimal timing for investing will most likely be around 2020, the last period where EOR will last for 10 years (maximum number of years allowed for the base case used). It is clear also that oil revenues from EOR are the main driver for CCS + EOR implementation. Due to the high operating costs of the capture plant, avoided costs for CO_2 allowances do not pay off an earlier investment on the CCS part.

The analysis of investment includes uncertainty in the CO_2 allowance price and in the oil price. Higher volatility in the prices shows a major potential for a positive expected net present value, but at the expense of postponing the investment in the

mitigation technology. On the other hand, higher drift rates increases the chances of investing in CCS + EOR and having positive expected NPV.

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