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A profitability study of CO_2-EOR and subsequent CO_2 storage in the North Sea under low oil market prices

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Abstract

A wide-scale application of CO_2-enhanced oil recovery (CO_2-EOR) in North Sea oil fields can have many advantages, especially when followed by CO_2 geological storage. Under the current low oil prices though, even maintaining basic oil production is challenging. A techno-economic assessment is made of the Claymore oil field with the PSS IV simulator, focusing on uncertainty and investment risk. For a stochastic oil price ranging between 10 and 70 €/bbl, a stochastic CO_2 revenue of -10 to 70 €/t and stochastic reservoir parameters, an average NPV of almost 500 M€ is obtained with a 73% chance on a positive NPV if the investment is made. Disregarding uncertainty relating to the underground by fixing the stochastic reservoir parameters, leads remarkably, but also erroneously, to a lower average NPV. Results also show that geological uncertainty is an important factor for determining the economic threshold level of an EOR project, and a proper assessment of the real uncertainties can make the difference between profit and loss. In case of assuming a fixed CO_2 revenue at 30 €/t, the probability of implementing EOR becomes higher, but the average NPV and project success rate are significantly lower, at 300 M€ and 63% respectively. This demonstrates that a fixed CO_2 tax is not a generic CGS enabling solution. It not well-weighted, it can hamper the deployment of certain technologies. A phase of CO_2 geological storage (CGS) after oil production becomes economically interesting from a CO_2 revenue of 17€/t. If such a price level can be guaranteed, then continuation of CO_2 injection can reduce investment risk for both the EOR and CGS investment, reduces the investment hurdle, and can be a catalyzer for large-scale and widespread CO_2 storage in Europe.

Peer-review under responsibility of the organizing committee of GHGT-13.
Keywords: CO_2-enhaced oil recovery, CO_2 geological storage, techno-economoic simulation

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1. Introduction

In periods of low oil prices with forecasts of stable or even decreasing prices, maintaining oil production from the North Sea area is challenging. Justifying additional investments in enhanced (tertiary) oil recovery techniques is therefore even more difficult. There are different techniques available for enhancing production. CO_2 enhanced oil recovery (CO_2-EOR) has proven to be the most efficient tertiary recovery technique [1] and has been demonstrated mainly onshore and in North America. Based on these experiences, an additional 5-15% of oil can be recovered [2]. The potential wide-scale deployment of CO_2-EOR in the North Sea holds other, long-term advantages as well. The CO_2 utilized for EOR is prevented from entering into the atmosphere, and part of the infrastructure can possibly be reused for geological storage of CO_2 when oil production has finished. Developing a CO_2-EOR network in the North Sea area can also aid the wide-scale deployment of CCS through knowledge spill-over and sharing of infrastructure.

Compared to the experience built in North America, the offshore environment of the North Sea is from both economic and practical point more challenging. Moreover, CO_2 is not readily available in sufficient quantities. No investments for CO_2-EOR projects have therefore been made in the North Sea area. Especially the current low oil and CO_2 emission allowance prices provide little incentive for such investments. These oil fields are also mostly highly mature, leaving only a limited window of opportunity in which conversion to CO_2-EOR is feasible. It is therefore plausible that first projects will need to be realized during a period of low oil and ETS prices.

Most studies regarding the techno-economic feasibility of CO_2-EOR in the North Sea use a fairly high oil price (>70€/bbl or 90$/bbl; [3,4,5]. Here we investigate the profitability and investment thresholds for CO_2-EOR and subsequent CO_2 storage for the North Sea under low oil market price conditions, while integrating different uncertainties. The Claymore oil field in the UK sector of the North Sea is used as a case study.

2. Methodology and scenario

To investigate the profitability of potential CO_2-EOR projects, the PSS IV techno-economic simulator was used [6,7]. PSS IV is a techno-economic decision support system extended for evaluating the potential of CO_2-EOR and consecutive CO_2 storage in nearly depleted oil fields. Realistic investment decisions are simulated with limited foresight by using nested Monte Carlo calculations. Yearly investment decisions are made based on the Modified Internal Rate of Return (MIRR; [8]) and the investment risk. PSS IV is not an optimization tool; instead it makes a succession of realistic investment decisions on one or a cluster of oil fields. PSS IV results are therefore based on evaluations, and because of the limited foresight, project evolution and final value might turn out significantly different than anticipated. Positively evaluated projects may for example turn out to make a loss when actually implemented. As a result of the stochastic approach and the yearly evaluation of (potential) EOR projects, the timing and duration of the different phases of a project (primary production, CO_2-EOR and CO_2 storage) will vary. This process of realistic decision-making in a techno-economic simulator, and the possibility to integrate different kinds of uncertainties, is what sets PSS IV apart from other techno-economic assessment tools.

A CO_2-EOR project in PSS IV consists of an onshore CO_2 supply, offshore CO_2 pipeline transport, and an offshore oil field. When it is decided to stop oil production, CO_2 can be continued to be supplied and injected for the purpose of permanent storage (CO_2 geological storage, CGS). Different capital and operational costs apply, and revenues are generated through the sale of incremental oil. The supply of fresh CO_2 can be either a cost or a revenue, depending on the market price. Oil production curves are simulated with a lognormal function (Figure 1). The surface below the curve represents the total oil recovered, and is determined by the OOIP of the field and the EOR recovery factor. The shape of the curve is determined by the mean of the normal distribution (μ). A low μ results in a fast reservoir response, with a high oil production peak. A high μ results in a slow response with a broad but low peak.

The goal of this simulation is to determine the profitability and threshold levels for CO_2-EOR and subsequent CGS under low oil prices. A Reference scenario was therefore built with a stochastic oil price ranging between 10 and 70€/bbl and a fresh CO_2 revenue ranging between -10 and 70€/tCO_2 (negative is cost to the oil field operator). The EOR recovery factor and μ of the production curve range between 0.05-0.15 and 1.9-2.1 respectively. Specifically for the simulated Claymore field, it is assumed that the Petroleum Revenue Tax is replaced by a lower flat rate tax on profit of 50%. A discount rate of 10% is used, and evaluated projects are subjected to a 10% hurdle rate on the MIRR. Other parameter values on cost and performance are taken from Welkenhuysen et al. (2015) [6].

The influence of stochastic parameters in a simulation process which includes limited foresight and a number of decision steps is not possible to unravel in a classical sensitivity analysis. In other words, fixing all stochastic parameters at their mean values will not necessarily produce the mean result of the Reference scenario. Instead, to better understand the influence of key parameters, two additional scenarios were built. In the GeoFix scenario, the two 'geological' parameters for oil recovery are fixed at their mean values, 0.1 for the recovery factor and 2.0 for the μ of the lognormal production curve. In the CO_2Fix scenario, the CO_2 revenue is fixed at its mean value, 30€/tCO_2. The scenario-specific parameters can be found in Table 1.

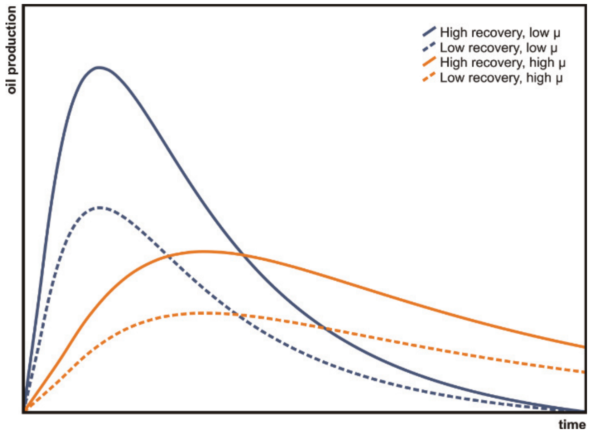

Figure 1. Variation of the modelled lognormal oil production curve, with stochastic recovery factor and μ parameters.

Table 1. Stochastic parameters for scenario definitions.

Parameter	Unit	GeoFix	CO_2Fix	Reference
Oil price	€/bbl	10-70	10-70	10-70
CO_2 revenue	€/tonne	-10-70	30	-10-70
EOR recovery factor	%	10	5-15	5-15
EOR μ	-	2.0	1.9-2.1	1.9-2.1

3. Results and discussion

3.1. Development probability and project value

PSS IV relies on Monte Carlo calculations, which is why results are presented in group or as probabilities. The main indicator of project success is the discounted Net Present Value (NPV), while project decisions are taken based on the Modified Internal Rate of Return. In Figure 2 probabilities on project success are presented.

In the Reference scenario, an investment in EOR is made in 75% of the cases. In 55% of the cases this also leads to a positive NPV (i.e. a 73% success rate after EOR decision). In 77% of the EOR cases EOR is followed by CGS, which has an 81% probability on a positive NPV. In case EOR is not followed by CGS, there is only a 47% chance on a positive NPV.

In the GeoFix scenario, the probabilities are very similar. It is marginally less likely that after an EOR project CO_2 is continued to be stored. It is the CO_2Fix scenario that shows a very different image. Firstly, removing uncertainty on the CO_2 revenue increases the chance of project development by 5% to 80%. The certain and sufficiently high CO_2 revenue of 30€/t, ensures that there is always a CGS phase after EOR. However, in absolute terms the chance of project failure (negative NPV) has increased from 20% to 30%, and the success rate after the EOR investment has decreased from 73% to 63%.

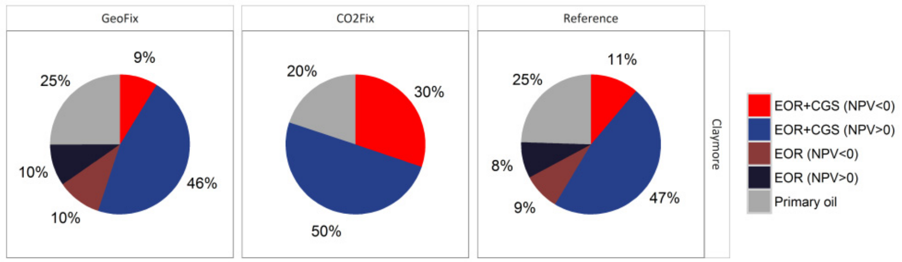

Figure 2. Development probability of EOR and EOR+CGS projects for the different scenarios.

A closer look at the distribution of the project NPV's shows that for all scenarios the mean value is positive (Figure 3). In the Reference scenario, the NPV ranges from -600 to +3000 M€, with a mean value of almost 500 M€. The asymmetric distribution is caused by the combination of exceptionally good parameter values on the positive side, and a Real Options approach and hurdle rate to prevent lossmaking projects from being activated or continued on the negative side. In the GeoFix scenario, the distribution remains somewhat asymmetrical, although the long tail extending above 2000 M€ is absent. This is directly caused by the reservoir parameters being fixed at their mean value: combinations of exceptionally good reservoir parameters with high oil and CO_2 prices result in very high NPV's in the Reference scenario. The average NPV is therefore 62 M€ lower compared to the Reference scenario.

At a fixed CO_2 revenue of 30€/t (CO_2Fix scenario), the NPV distribution gets pushed towards the negative side, with the mode of the distribution dropping below zero. The mean NPV is almost 200 M€ lower compared to in the Reference scenario.

The remarkable conclusion here is that a fixed CO_2 revenue does not necessarily encourage EOR investments, although this is often stated as an absolute truth. The underlying cause is that a CO_2 revenue which is insufficiently high will exclude certain options which might have been available under a variable price. Notice that the average CO_2 revenue should, at least in this example, be considered as insufficiently high.

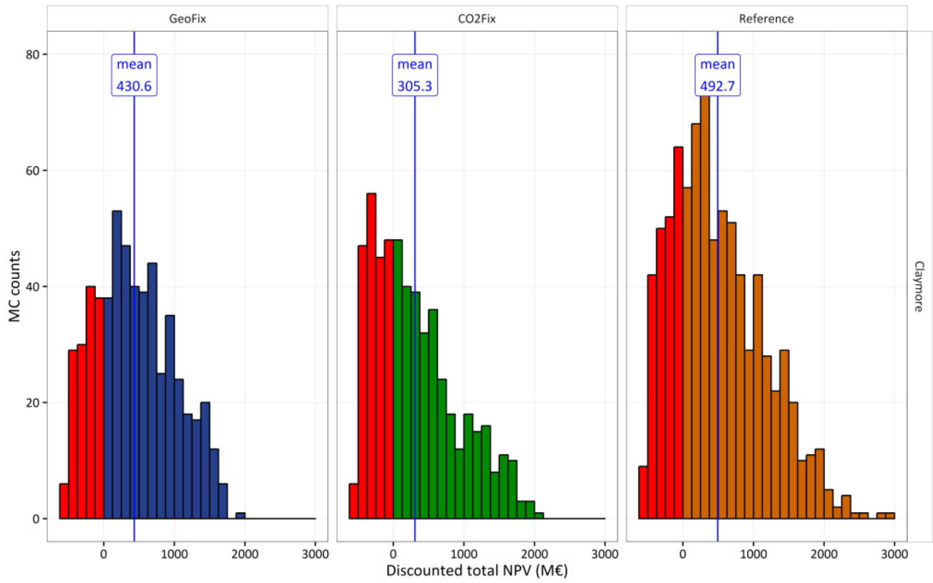

Figure 3. Discounted Net Present Value (NPV) histograms for activated EOR and EOR+CGS projects in the three scenarios, with indication of the mean value.

In Figure 4, the different threshold levels in function of the oil and CO_2 revenue are shown for the Reference scenario. Every dot represents a single Monte Carlo iteration with an investment in EOR or EOR+CGS. The minimum oil price for continuing oil production lies at 16 €/bbl. The minimum CO_2 revenue for starting CGS after the EOR phase is 17 €/bbl.

At the average Brent oil price in 2015 of about 45 €/bbl, the CO_2 revenue should be over +10 €/t. Assuming a capture cost of 30 €/t [9], this means that an ETS price of at least 40 €/t is needed for a profitable EOR project. At the time of writing, the ETS was 4.36 €/t, which would require a substantially higher oil price if no other incentives are available.

Even when the oil price and CO_2 revenue levels are sufficiently high to initiate an EOR project, there remains a risk that the NPV will turn out to be negative. This is primarily caused by the uncertainty in the reservoir parameters. No projects are activated that can result in an NPV lower than about -700 M€ (Figure 4). This still represents a substantial loss. In many cases, these lossmaking projects are not prematurely shut-down because of the loss-reducing strategy inherently applied by PSS. If revenues are even only marginally larger than operational costs, operation is continued to reduce the loss made by the sunken capital cost. A hurdle rate higher than 10% would reduce this investment risk, but at the same time reduce the number of projects resulting in a positive NPV. Determining the optimal hurdle rate is an interesting discussion, but out-of-scope of this paper.

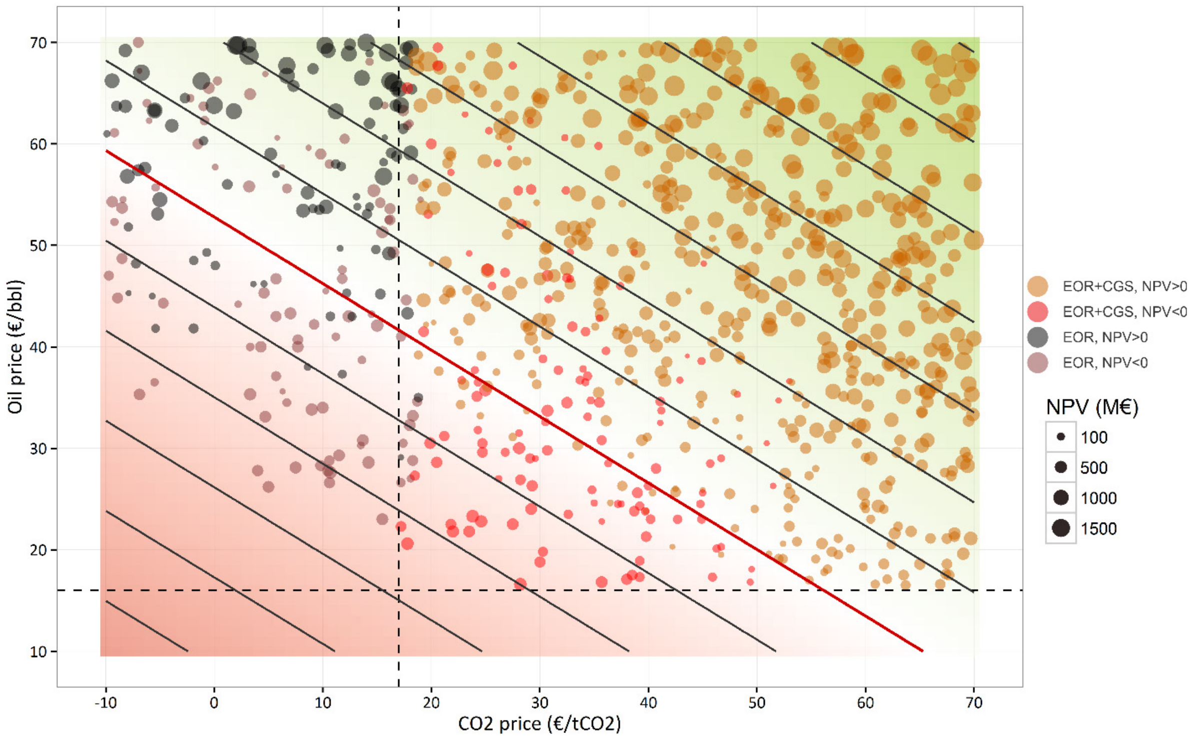

Figure 4. Cross-plot of the CO_2 revenue and oil price, in function of the Net Present Value (NPV) for the Reference scenario. Dots represent Monte Carlo iterations with activation of EOR or EOR+CGS, the size of the dots represent the NPV (absolute value for negative NPV). A horizontal oil price limit (dashed line) shows the minimum oil price for producing the Claymore field. A vertical CO_2 revenue threshold (dashed line) shows the minimum CO_2 revenue to continue CGS after oil production through EOR has stopped. The slanted solid lines represent average NPV levels with an interval of 250 M€, the red line is the average break-even point (NPV=0). The threshold values for oil and CO_2 price are manually estimated; the average NPV levels are calculated with the kriging function of the gstat R package [10].

3.2. Sensitivity analysis

In order to understand the influence of the different stochastic parameters, the NPV results of the three scenarios are plotted in function of the stochastic parameters separately as boxplots. Figure 5 shows the sensitivity of the NPV to the oil price. For the Reference scenario, there is a clear relation between the oil price and the upward extension of the NPV, while the minimum NPV value remains equal at around -500 M€. The project loss is limited to this minimum because of the 100% tax relief on investments (100% First Year Allowance, FYA), which reduces the total loss to 50% for investment costs.

When removing uncertainty by fixing one of the parameters, the bottom NPV value increases as well between 40 and 50 €/bbl. A combination of a sufficiently high oil price and a fixed CO_2 revenue can avoid negative NPV's. Similarly in the GeoFix scenario, the NPV range for oil prices around 70 €/bbl is even more pronounced positive. This observation highlights the importance of proper reservoir characterization for EOR.

The CO_2 revenue has a different influence on the total project value compared to the oil price (Figure 6). In the Reference scenario, the NPV range starts rising from a CO_2 revenue between 30 and 40€/t. During EOR, both the oil and CO_2 can generate revenues, while for CGS the oil price is not relevant. This cumulative effect leads to exclusively positive project values at a CO_2 revenue of over 50 €/t.

A clear relation exists between the EOR recovery factor and the NPV range (Figure 7). Similar to the relation with the oil price, the lower limit of the NPV does not increase with an increasing recovery factor for the Reference scenario. In the CO_2Fix scenario however, the lower NPV limit starts increasing at a recovery factor of 15%.

The NPV is relatively insensitive to changes in the μ of the lognormal EOR production curve (Figure 8). As it determines the shape of the production curve, it has an influence on project timing and duration. Shorter projects, with a lower μ, have a slightly higher NPV. This is mainly due to the effect of discounting and uncertainty towards the future: fast and high revenues are preferred over gradual and longer-lasting returns. Because the recovery factor is also fixed at its mean value in the GeoFix scenario, the range of results is somewhat smaller compared to the range of the $\mu \approx 2$ results in the Reference scenario.

The NPV result distributions in function of the CO_2 revenue (Figure 6) and in lesser amount those in function of the μ (Figure 8) are strongly skewed in the Reference and CO_2Fix scenarios, with a long tail at the upper end. If geological uncertainty is removed in the GeoFix scenario, a large part of this asymmetry disappears. Thus, a major part of the asymmetry and the exceptionally high NPV's is caused by the stochastic reservoir parameters. As a result, an oil field with good EOR potential can generate proportionally more revenue than expected from linear extrapolation. Because the NPV distributions in function of the oil price (Figure 5) are quite symmetrical, oil price is a second factor that causes the asymmetric distribution.

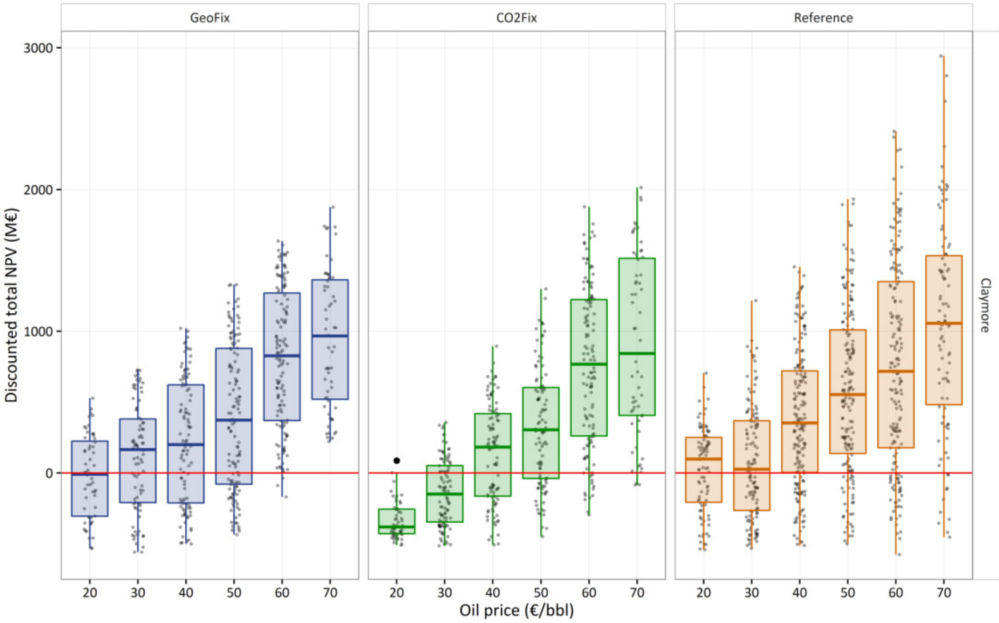

Figure 5. Boxplot of the Net Present Value (NPV) in function of the oil price. Actual data points are plotted as grey jitter points.

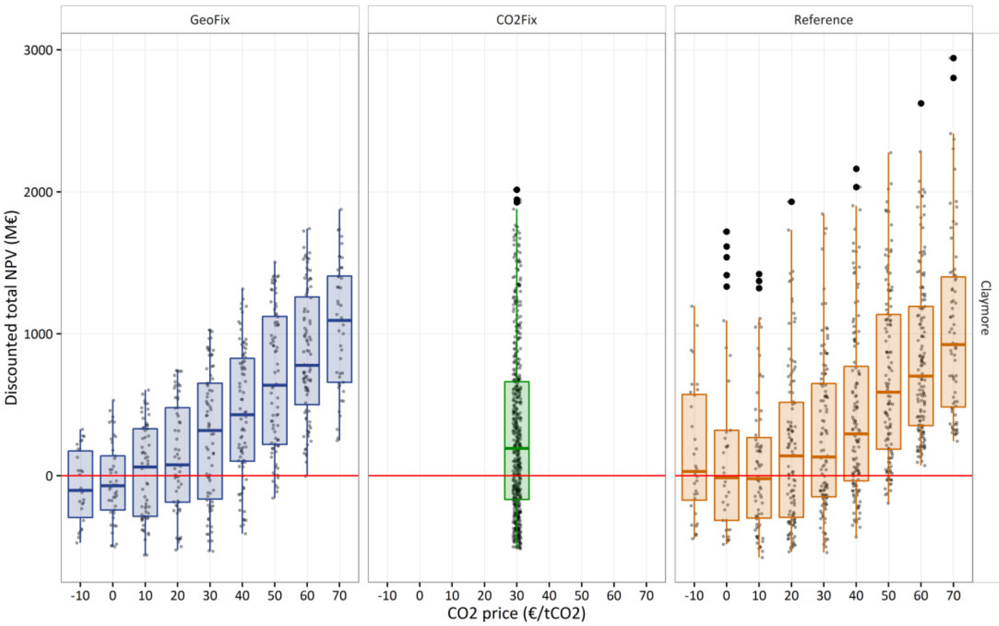

Figure 6. Boxplot of the Net Present Value (NPV) in function of the CO_2 revenue. Actual data points are plotted as grey jitter points, black dots are outliers.

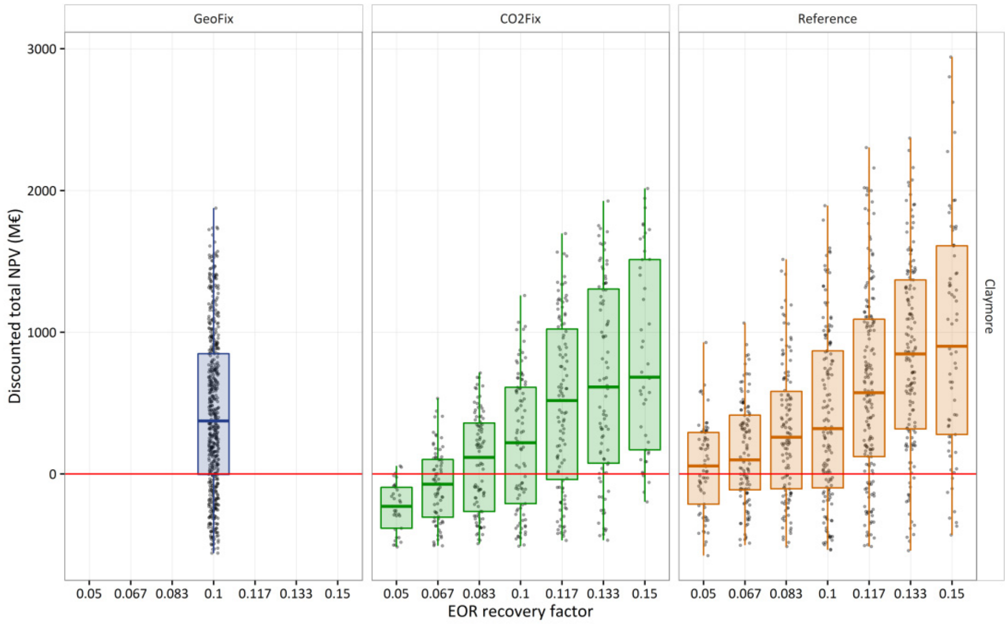

Figure 7. Boxplot of the Net Present Value (NPV) in function of the EOR recovery factor. Actual data points are plotted as grey jitter points, black dots are outliers.

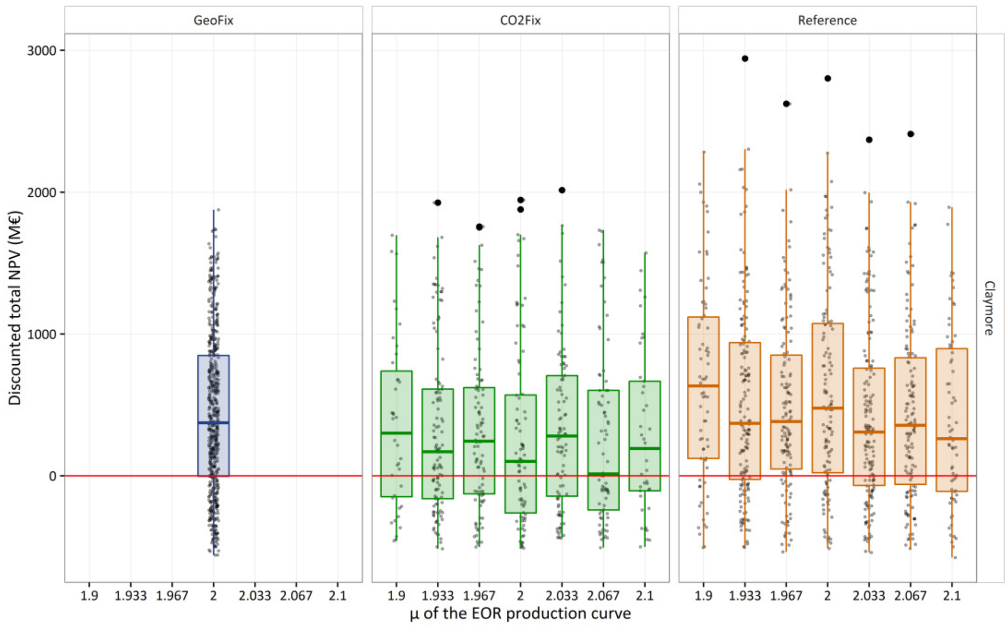

Figure 8. Boxplot of the Net Present Value (NPV) in function of the μ of the EOR production curve. Actual data points are plotted as grey jitter points, black dots are outliers.

4. Conclusions

CO_2-EOR is at this moment not applied in the North Sea oil fields, and especially with the current low oil prices, the profitability of such projects is questioned [11]. With this study, the viability of CO_2-EOR and consecutive CGS in the Claymore oil field is investigated under such circumstances, considering different sources of uncertainty that generate investment risk. Clearly the dynamics that play in CO_2-EOR projects with consecutive storage are not always straightforward, and uncertainty certainly plays a complicated role in this.

In general, CO_2-EOR projects, especially when joined with CGS, can be profitable at low oil prices. Oil price is however not the only determining factor. With oil prices below 40-50 €/bbl, a fairly high CO_2 revenue is necessary to enable EOR. The CO_2 revenue has only a minor influence on the EOR phase itself, but when followed by CGS, a sufficiently high CO_2 revenue can result in an almost risk-free investment. At a CO_2 revenue of 17€/t, a CGS phase after oil production has ceased becomes economically interesting.

Comparing the scenarios, it becomes apparent that a fixed CO_2 price increases the chance of project investment, but decreases the project's success rate. A variable CO_2 price means additional risk, but it also offers the outlook of a potential significant increase over the fixed value. This provides an additional perspective to the ongoing discussion of the efficiency of the European ETS market and whether or not a fixed CO_2 emission price is the best way for achieving sufficient emission reductions.

The current results are obtained through project evaluation with a hurdle rate of 10%, equal to the discount rate. There is however a large probability that the NPV is negative, depending on the scenario parameters. For an actual investment decision, a higher hurdle rate is recommended to reduce investment risk.

Geological uncertainty also adds an important factor, which is overlooked in many feasibility studies. Specifically the variation in the amount of incremental oil recovered with EOR has an important influence. Oil price and recovery factor both have a nonlinear relation with the NPV, and a combination of high values for both parameters can lead to exceptionally high project values of over 2000 M€. Without considering the geological uncertainties that are inherently associated with reservoirs, project values and risks cannot be correctly assessed. At the economic cut-off level, uncertainties become especially important, because the amount of reservoir uncertainty determines the economic threshold level at low oil prices.

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