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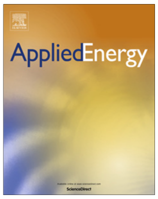

Considering economic and geological uncertainty in the simulation of realistic investment decisions for CO_2-EOR projects in the North Sea

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HIGHLIGHTS

- PSS IV, a techno-economic model for simulating CO_2-EOR projects, is presented.
- Investment risk and uncertainty play a central role in our methodology.
- A North Sea case study for the Claymore and Scott field is developed.
- Case study results show a 30% value increase for the cluster approach.

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ABSTRACT

The use of anthropogenic CO_2 for enhancing oil recovery from mature oil fields in the North Sea has several potential benefits, and a number of assessments have been conducted. It remains, however, difficult to realistically simulate the economic circumstances and decisions, while including the economic uncertainties that surround the relevant markets and policies, and the geological and technological uncertainties that are inherent to dealing with reservoirs and novel technologies in a challenging environment. A new method is proposed here introducing a unique combination of innovations, that include true limited foresight, project flexibility, and the consideration of realistic investment risk. The value of project is here expressed as the Net Present Value (NPV). These elements are combined in the PSS IV simulator. This is a techno-economic simulator for CO_2-enhanced oil recovery (CO_2-EOR), which applies limited foresight and Real Options Analysis to make realistic investment decisions on projects with significant uncertainties and thus risk. Consecutive project decisions are taken based on a decision tree. Multiple oil fields can be approached as a single cluster project, which can provide a lower investment hurdle. In a first test case for PSS IV, the Claymore and Scott oil fields are assessed, and it is shown that economic simulations where EOR projects are regarded as a sum of the individual field assessments will undervalue projects. Simulation results show that results are in a realistic range compared to published numbers, with individual project values for the Claymore field on average of 15.8 €/barrel (bbl; standard deviation SD = 8.3) and for the Scott field of 14.3 €/bbl (SD = 8.6). Due to the inclusion of uncertainties and the application of limited foresight, results range from −6 €/bbl (loss) to over 30 €/bbl. In a cluster configuration 5 €/bbl of additional value is created.

1. Introduction

Large-scale reduction of anthropogenic CO_2 emissions by geological storage of CO_2 (CO_2 capture and storage, CCS) is a necessary measure to mitigate global climate change [1,2]. At the latest UNFCCC Conference of Parties in Paris (COP21), it was agreed to keep global temperature increase well below 2 °C above pre-industrial levels, and even pursue a 1.5 °C target [3]. Although explicitly excluded from the substances categorised as "waste" by the EU CCS directive (Directive 2009/31/EC), CO_2 is still generally treated as-such by emitting it into the atmosphere. It can however be turned into a useful product but there are a very limited number of possible applications that can cope with the large amounts of CO_2 produced by industrial installations – up to several

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million tonnes per year for a single installation. Considering these volumes, CCS is the best option, including CO_2-enhanced oil recovery (CO_2-EOR). Enhanced oil recovery (EOR) is a well-known and frequently applied technique to increase oil recovery from mature reservoirs [4]. CO_2 has a number of advantages as a working fluid for EOR [5–7]. Most importantly, CO_2 reduces the oil's viscosity, enabling a more efficient reservoir sweep. CO_2-EOR has been used for over 40 years in oil fields in the United States. It was first applied in Scurry County, Texas in 1972 [8,9]. Globally, there were 152 CO_2-EOR projects active in 2013 [10]. Onshore CO_2-EOR is a proven technology, extensively covered by research [11–13] and commercially applied [14].

The majority of CO_2-EOR projects uses CO_2 from natural sources [13,15]. However, some onshore CO_2-EOR projects (e.g., the Weyburn project; [16]) use CO_2 from industrial sources [4,11,12,17]. In the last years, there has been increasing interest in applying CO_2-EOR in the North Sea. Several techno-economic studies confirm the profitability of North Sea CO_2-EOR [18], but actual projects are not yet started due to the higher risk and cost for offshore installations compared to an onshore environment, and the current absence of affordable CO_2 sources [19]. A large number of oil fields in the North Sea are considered suitable for EOR because they are in their mature phase. A more efficient sweep of the oil reservoir is also attractive for both better use of this resource and energy security. Increasing oil production from fields in the North Sea could reduce the importation of fossil fuels from abroad, also from politically unstable regions. Last, CO_2-EOR is seen as a possible business case and catalyser for the commercial-scale deployment of CO_2 geological storage. There can also be a knowledge and experience spillover to several CCS-related activities such as CO_2 capture, transportation, monitoring and legal framework, while covering initial investments and capturing part of the steep learning and cost reduction curves. Moreover, offshore storage of CO_2 is better accepted by the public compared to onshore storage (see e.g. [20]). Despite the interest and potential advantages, there have been no commercial applications yet of CO_2-EOR in the North Sea. Techno-economic modelling can help identifying potential bottlenecks and provide decision support for potential projects. We will show that, although much work has been done, improvement of the simulation methodology is possible and necessary to make accurate investment risk assessments.

2. State-of-the-art of techno-economic CCS and CO_2-EOR modelling

A number of economic simulations have been performed to identify the drivers of CO_2-EOR in the North Sea, and several models for techno-economic calculations on CO_2-EOR have been developed. A number of studies focus on the economics of a single reservoir approach, including Gozalpour et al. [21], Tzimas et al. [22], McCoy [23], Gaspar Ravagnani et al. (2012), Roussanaly and Grimstad [24], and Wei et al. [25]. Noteworthy is the study by Kemp and Kasim [26] that investigates several fiscal incentives for the purpose of speeding up the commercial introduction of CO_2-EOR in the offshore UK. It is, however, expected that creating a CO_2-EOR network or cluster is more cost-effective, because of additional flexibility and economies of scale, and thus a more realistic approach for the development of a CO_2 value chain.

In most cases, techno-economic CO_2-EOR models are spreadsheet-based models with or without linear optimization. The Net Present Value (NPV) is calculated as a discounted cash flow, incorporating the various investment and operational costs, taxes, CO_2 transfer cost and income from additional oil sales. Often these studies do not take into account the cost of risk and risk assessment. Holt et al. [27,28] developed such a techno-economic spreadsheet tool to investigate the potential of the North Sea for CO_2-EOR. Hustad [29], Middleton et al. [30], Pershad et al. [18], Kemp and Kasim [31] and King et al. [13] used a similar methodology. Klokk et al. [32] presented a model for optimizing a CO_2-EOR value chain network, applied to the Norwegian continental shelf. In contrast to previous papers, the latter authors considered a window of opportunity for EOR deployment wherein timing can be optimized. Mendelevitch [33] stated that all of the previously mentioned studies assume a central planner for optimization. To get a more realistic picture, the author introduces a CO_2 trader as a governmental entity that regulates the CO_2 market, but does not take investment decisions regarding CO_2 capture or EOR.

Simulating a CCS network with the SimCCS model, Keating et al. [34] observed that reservoir uncertainty has a large influence on the development of CCS infrastructure. It can be expected that other sources of uncertainty also have a significant influence, and that in the development of CO_2-EOR infrastructure, uncertainties play a similar and maybe even a key role due to the additional dimension of oil production. In addition, the scope of the current research focusses on the North Sea area. Gozalpour et al. [21] mentioned the challenges of pursuing CO_2-EOR in this area because of a number of uncertainties. Most of the experience on CO_2-EOR has been gained in North America [14]. Costs will inherently be higher to perform similar operations in the North Sea as indeed drilling costs are higher in Europe compared to the US, and offshore operations are more expensive. The North Sea is a challenging offshore environment, and materials need to be suitable to withstand harsh conditions. Additionally, uncertainties are larger because field development and monitoring is more difficult [35], and a less efficient reservoir sweep by EOR operation can be expected, as the well density is likely to be lower. Summarizing, there are several sources of uncertainty that influence the feasibility and profitability of a CO_2-EOR project in the North Sea including geological uncertainty, technological uncertainties (including the development and performance of CO_2 capture technologies), and uncertainties inherent to forecasting, such as the oil and CO_2 market prices (market uncertainty). Although these uncertainties are acknowledged, a traditional sensitivity analysis is insufficient to fully address their impact because of the complexity of real investment decisions.

All of the studies mentioned before in this section use the NPV methodology, which is a standard methodology for evaluating projects using future cash flows. Since the 1980's, however, awareness has grown on the limitations of the NPV to deal with uncertainty, flexibility and irreversibility of an investment decision. Apart from including a sensitivity analysis such as a Monte Carlo calculation, the traditional NPV methodology does not consider uncertainties. Under market uncertainty for example, there is an opportunity cost when investing immediately or waiting until uncertainty is (partly) resolved. Dixit and Pindyck [36] showed that this opportunity cost has a significant value as part of a company's investment decision. To explicitly address this, methodologies have been developed to include this opportunity cost in the economic analysis. Fleten et al. [37] applied, for instance, Real Options Analysis to account for the economic value of uncertainty on the evolution of CO_2 and oil prices. They showed that the volatility and drift of the CO_2 and oil price influenced the optimal timing and NPV of CCS and CO_2-EOR projects on the Norwegian Continental Shelf, and that the oil revenues are the main driver for investing in EOR. Geological and technological uncertainties were not considered in their study. Compernolle et al. [38] also show that a fixed carbon tax provides a necessary lowering of the investment threshold for EOR.

The methodologies just discussed show that there are still several opportunities for improving forecasting CO_2-EOR projects. There is a need to develop techno-economic forecasting tools for CO_2-EOR that models all processes as realistically as possible, by including geological, economic, and technological uncertainties. Additionally, in most models that are cited above, actual decision-making and the development of infrastructure over time (e.g. addressing different oil fields over time) is not included. Summarizing, there are three main research gaps that we identified in literature, that are closely intertwined: the influence of different kinds of uncertainties; project flexibility in both space and time; and the investment risk associated with the two previous bullet points.

In this paper a new techno-economic forecasting simulator is presented. This simulator aims to assess the viability of offshore CO_2-EOR in the North Sea. The simulator is based on a techno-economic simulator, developed for making forecasts on the deployment of CCS, called PSS (Policy Support System; [39]). The concept of a forecasting simulator was chosen for its ability to incorporate different kinds of uncertainties and generate realistic results. The new methodology includes the following main innovations: a more realistic approach on geological and economic uncertainty, including true limited foresight; the consideration of project flexibility as yearly decision moments for investment or abandonment, and decisions are made for fields in a cluster; and investment decisions are based both on project value and realistic investment risk through the uncertainties and project flexibility. To illustrate the use of the methodology, a case study in the North Sea, addressing the Claymore and Scott oil fields, is presented. This case study will also be used to demonstrate the influence of considering project flexibility in the analysis.

3. Methodology development

3.1. PSS version history

The techno-economic simulator PSS (Policy Support System) was generated as part of the national Belgian PSS-CCS projects (Policy Support System for Carbon Capture and Storage). PSS (version I) was built as an ad-hoc, bottom-up techno-economic CCS simulator for policy support for the electricity-producing sector [39]. During the second project phase (2009–2011) the simulator was improved and expanded, adding realistic investment decision algorithms and different CO_2-emitting industries as CO_2 sources in each region evaluated by the simulator [40,41]. The PSS version III simulator is a further evolution, which includes several updates such as renewable energy production. This version was used for studies in Kazakhstan [42] and Austria Welkenhuysen et al. [43].

While the socio-political environment can be a major decisive factor in the development of CO_2 storage and EOR, these issues will not be taken into account in the present study. The PSS simulator is a techno-economic simulator and therefore socio-political issues, such as the NIMBY (Not In My Back Yard) syndrome are taken into account at scenario level.

The PSS III simulator simulates realistic investment decisions by considering geological, technological and economic uncertainties. Its building blocks are designed for addressing the specific nature of a geological reservoir and are well suited for coping with the challenges of assessing potential CO_2-EOR projects. The PSS simulator is therefore used as a basis to build an advanced and new simulation tool for CO_2-EOR. In practice, the new tool is added as a second mode to the PSS simulator, together constituting version IV. The concept of how a CO_2-EOR project is modelled and evaluated in PSS IV is elaborated in Fig. 1. From an onshore CO_2 hub/-source, where a certain quantity of CO_2 can be obtained at a certain price, an offshore trunk pipeline transports the CO_2 to a single oil field or field cluster. In case of the latter, local pipelines handle CO_2 transport to the different injection locations. CO_2 is injected into the reservoir which pushes out additional oil. With CO_2-EOR, CO_2 breakthrough comes early as CO_2 mixes with the oil for a maximum reservoir sweep [18]. After breakthrough, both CO_2 and oil are produced. The CO_2 and oil are separated, the recycled CO_2 is reinjected, and the crude oil is sold.

3.2. CO_2 supply

CO_2 capture is a costly and energy-intensive process, but it is not separately considered in this paper. Here, it is assumed that a continuous stream of CO_2 is available from an onshore hub/central location. As there are different capture processes for different facilities that can feed into this hub, the CO_2 price can change depending on CO_2 demand. Fig. 2 shows an example of a CO_2 cost input curve for the industrial region of the port of Antwerp (Belgium). It is possible to choose from different locations, based on an overall least-cost combination for supply and transport to the oil fields. The cost of fresh CO_2 supply to a CO_2-EOR project is the balance between the CO_2 capture cost in Fig. 2 and the potential CO_2 emission revenues (e.g. from the EU Emission Trading System; ETS). The CO_2 capture cost will remain equal during a project, as the supply of fresh CO_2 remains constant. The emission cost however might change, introducing additional uncertainty on the investment and operation of a CO_2-EOR project.

3.3. CO_2 transport

The PSS IV simulator relies on the pipeline model presented by Vandeginste et al. [44]. This model is integrated in a least-cost pipeline routing module, present in earlier versions of the PSS simulator [39,40]. Least-cost pipeline routes are calculated based on a 32-direction raster. The cost factors (labour, material, right of way and miscellaneous costs) are determined by terrain factor grids (soil type, topography, land use and a regional factor), and by the number of vector object crossings (roads, railways and waterways). A methodology for calculating pipeline networks is also present in PSS IV.

If CO_2 is required in a PSS IV simulation, a least-cost pipeline route is calculated from the onshore, seaside hub to the centre of the oil field cluster. Smaller pipelines are calculated from this centre point to the individual fields. A cost item that was added for offshore transport relates to the cost to make the transition from an onshore to an offshore environment (i.e., a beach landing). Thus, except for CO_2 source and the pipeline beach landing, all pipelines and facilities are assumed to be offshore.

The implications and trade-offs are different for offshore pipelines compared to onshore pipelines. While an offshore pipeline might encounter less socio-political resistance, construction and maintenance become significantly more difficult and thus more expensive [45]. The transport of CO_2 by ship has also been discussed for offshore CO_2-EOR [46,47]. The possibility of adding this transport method at a later stage has been foreseen in the PSS IV architecture.

3.4. Modelling oil production

3.4.1. Primary production

A typical oil production curve starts with low production values that build up to a peak or plateau. Thereafter, production declines until the field is abandoned. This decline curve has been modelled in different ways (e.g. [48–50]). When analysing different oil production curves from the North Sea oil fields, it becomes apparent that many of them approach a lognormal distribution. A lognormal curve can conveniently be described with just two parameters (μ and σ, mean and standard deviation of the normal distribution). Fig. 3 shows a real lognormal distribution in orange, and the normalized true production curves of ten oil fields in the central North

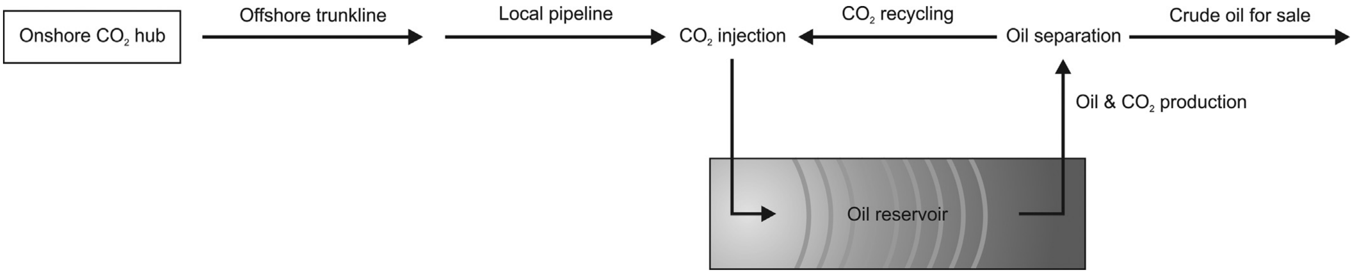


Fig. 1. General concept of a CO_2-EOR value chain in PSS IV with indication of the oil and CO_2 flows. The offshore trunk line can feed into multiple local pipelines to feed a cluster of oil fields.

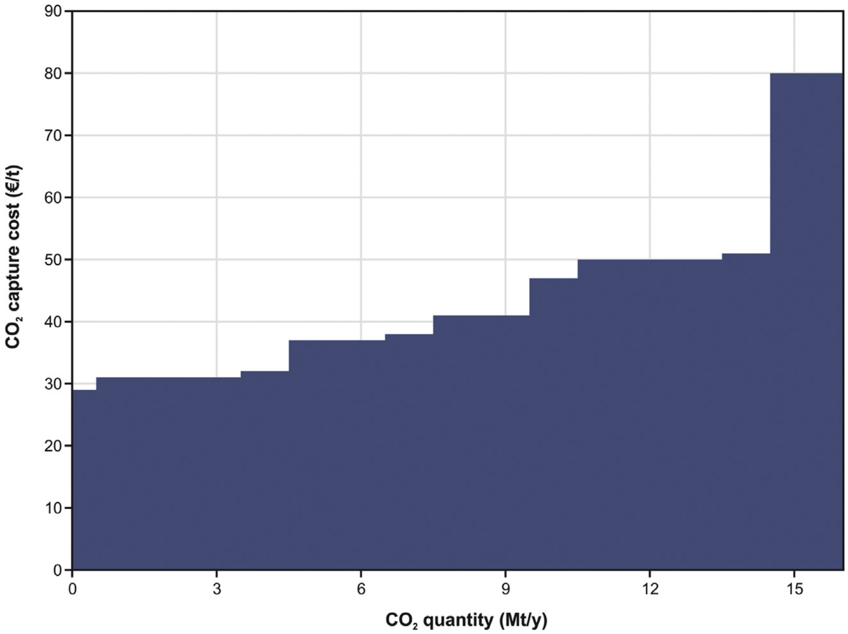


Fig. 2. Example of a CO_2 supply curve of a CO_2-hub. Smaller amounts of CO_2 are available at low cost (so-called low-hanging fruits for capture). If larger volumes are needed, CO_2 capture would be considered in sources that have a more expensive capture process. The source of the shown data refers to the PSS II database [40].

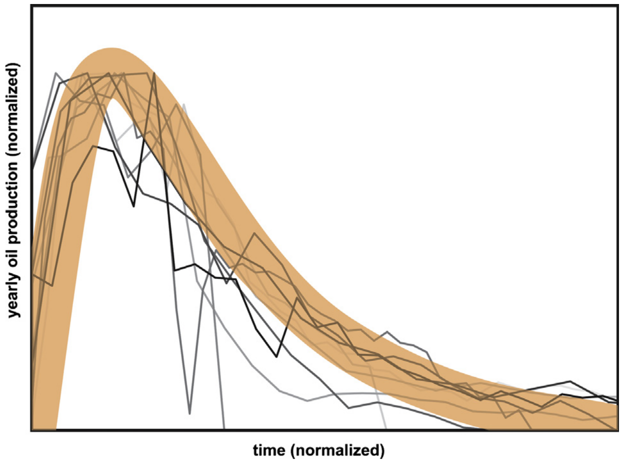


Fig. 3. Production profiles of the Alba, Brae North, Brae South, Buzzard, Claymore, Forties, Miller, Nelson, Scott and Tartan oil fields [51], and a real lognormal curve (orange). The production curves are normalized by linearly sizing the x and y axis to make them coincide, but the shape of the curves is retained. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Sea which are potential targets for CO_2-EOR: the Alba, Brae North, Brae South, Buzzard, Claymore, Forties, Miller, Nelson, Scott and Tartan oil fields [51]. The production numbers were normalized for the curves to coincide. Specific for the oil production in this region, the plateau phase of production is relatively short in comparison with the decline phase; the lognormal fit is therefore still a good approach for the real production curve. Moreover, for EOR, the decline phase is most important, as it is in this phase that production enhancing techniques will be applied. The oil production in PSS IV was modelled using a lognormal curve (see Eq. (1)). This also implies that a continuous production is assumed, without disruptions caused by operational issues. For simplicity, and because water injection in North Sea oil reservoirs is usually done very early in the production phase, the term ‘primary production’ encompasses both primary and secondary oil production in this paper. In Eq. (1) the standard formula for a lognormal distribution is given.

$$y = \frac{1}{x\sigma\sqrt{2\pi}} * e^{-\frac{(\ln x-\mu)^2}{2\sigma^2}} \tag{1}$$

where μ and σ are the mean and standard deviation of the normal distribution.

Eq. (1) is evolved to represent the primary oil production. X is substituted by time, while y is the resulting yearly production. Because the area beneath a lognormal function is by definition equal to 1, a scale factor can simply be used to represent the total amount of oil recovered. This scale factor is equal to the Oil Originally In Place (OOIP) multiplied by the recovery factor. The primary oil production in year y is then given by Eq. (2). In further formulas, y represents the current year of calculation, Y represents a different year, defined by its subscript, and T represents a certain relative period in time.

$$PrimProd_y = OOIP * R_{Prim} * \frac{1}{(y - Y_{PrimStart})\sigma_{Prim}\sqrt{2\pi}} * e^{-\frac{(\ln(y - Y_{PrimStart}) - \mu_{Prim})^2}{2\sigma_{Prim}^2}} \tag{2}$$

where OOIP is the Original Oil In Place [bbl, barrels], R_{Prim} is the primary production recovery factor, μ_{Prim} is the primary production μ, σ_{Prim} is the primary production σ, and $Y_{PrimStart}$ is the start year of primary production. A modelled lognormal production curve can be fitted to the historic production data and it allows future projections. The maximum value represents peak oil production, and the shape of the curve can be altered using the parameters for μ and σ.

3.4.2. EOR production

Real, representative production data from CO_2-EOR projects is not widely available in open literature. Azzolina et al. [52] analysed 31 CO_2-EOR project in the US, and fitted log-logistic functions to the production data (these resemble lognormal distributions, but with a heavier tail). Recovery curves from other studies approach a lognormal distribution (e.g. [24,28,32]). The more conservative lognormal production curve, with slightly lower production in the tail of the curve, is used here for modelling the incremental enhanced oil recovery. This incremental production by EOR in year y is given by Eq. (3).

$$EORProd_y = OOIP * R_{EOR} * \frac{1}{(y - Y_{EORStart})\sigma_{EOR}\sqrt{2\pi}} * e^{-\frac{(\ln(y - Y_{EORStart}) - \mu_{EOR})^2}{2\sigma_{EOR}^2}} \tag{3}$$

where the OOIP is the Original Oil In Place [bbl], R_{EOR} is the EOR production recovery factor, μ_{EOR} is the EOR production μ, σ_{EOR} is the EOR production σ and $Y_{EORStart}$ is the start year of EOR production. This enhanced production curve is superimposed on the primary production curve to obtain the total oil recovery (Fig. 4). Note the delay between the start of CO_2 injection and the first effect in production of the EOR.

3.4.3. Extended primary oil production

If CO_2-EOR starts in the final stages of primary production (as is often expected to happen), the lifetime of the oil field is extended, and so is the primary production (Fig. 4). The revenues that are obtained from selling this additional primary oil are considered revenues from implementing CO_2-EOR. This extended primary oil ($PrimProdExt_y$) is calculated in the same way as shown in Eq. (2).

3.5. CO_2 injection and recycling

CO_2 delivered at the EOR field is injected into the reservoir, where it forms a miscible or immiscible flow to push and drag along the oil, which is then produced at the production wells. CO_2 will be produced together with the oil after a certain time (months to years, depending on reservoir structure, well configuration and injection rates). To reduce cost, the CO_2 is separated and re-injected. In PSS IV, the CO_2 flow and oil production are exogenously matched, and decoupled during the simulation itself. This means that in the simulator there is no EOR performance formula, which would state the amount of additional oil production as a function of the amount of injected CO_2. This relation is fixed on beforehand in the EOR production curve parameters and the CO_2 injection parameters that are discussed hereafter. The model itself is based on several models (including those discussed in [18,32]), and the CO_2 flows are modelled as follows. It is assumed that the reservoir can accept a certain maximum amount of CO_2, which is the sum of both newly supplied and recycled CO_2 (Eq. (7)). The CO_2 supply is assumed to be constant over time. The recycling rate rises over time and stabilises when the equilibrium between CO_2 injection and production is reached after a predefined time ($T_{RecycMax}$; Fig. 5). The parameters and values presented here are assumed to be the sum of all wells in a single field.

Eq. (4) shows the amount of CO_2 that is re-produced and recycled for injection in year y.

$$CO_2Recyc_y = CO_2Inj_y * RecycFact_y \tag{4}$$

where CO_2Inj_y is the amount of CO_2 injected in year y [tCO_2] and $RecycFact_y$ is the CO_2 recycling factor in year y. CO_2 breakthrough and recycling start after a certain amount of time ($T_{RecycDelay}$). The

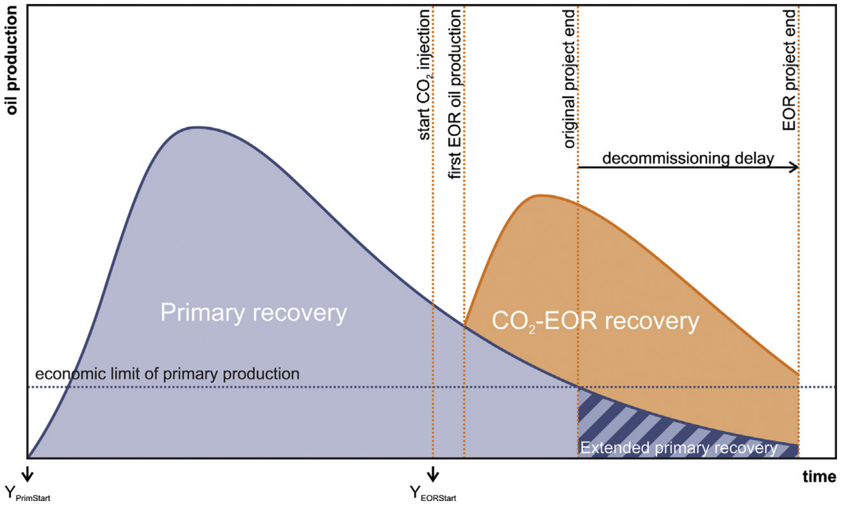


Fig. 4. Schematic illustration of modelled oil production in PSS IV. With CO_2-EOR, oil production is prolonged, and the extended primary oil production is an additional benefit from investing in EOR.

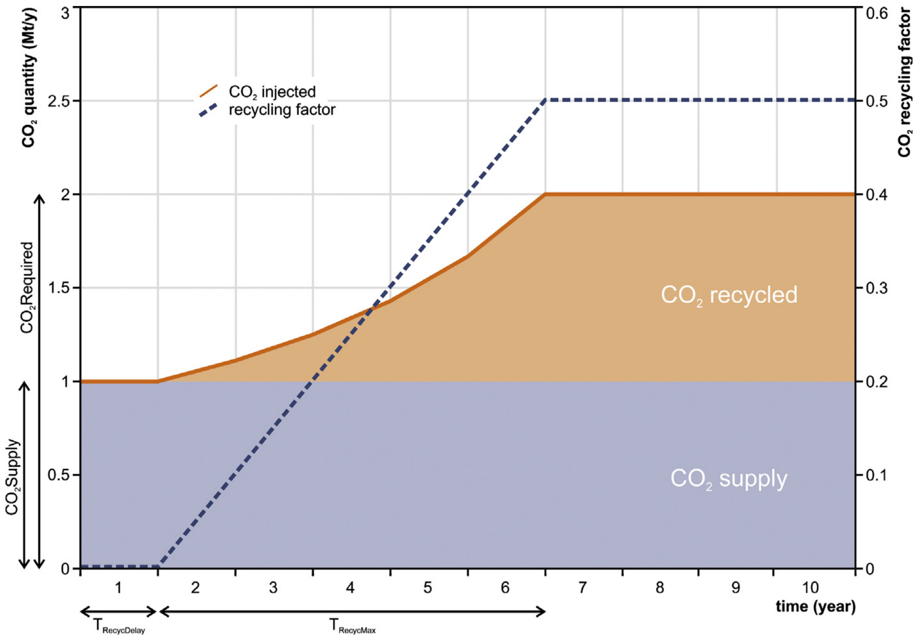


Fig. 5. Example of the CO_2 injection (orange line, total, left scale) and recycling operations through time. A constant stream of CO_2 is supplied. The recycling factor (dashed line, right scale) increases over time until the equilibrium is reached between injected and re-produced CO_2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

recycling factor rises until equilibrium is reached at $T_{RecycDelay} + T_{RecycMax}$, corresponding to the time after the start of EOR operations at which the maximum amount of CO_2 is injected. The CO_2 recycling factor in year y is given by Eq. (5).

$$
RecycFact_y = \begin{cases} 0, \text{ for } y < Y_{EORStart} + T_{RecycDelay} \\ \frac{RecycFactMax}{T_{RecycMax}}(y - Y_{EORStart} - T_{RecycDelay}), \text{ for } Y_{EORStart} + T_{RecycDelay} \leqslant y > Y_{EORStart} + T_{RecycDelay} + T_{RecycMax} \\ RecycFactMax, \text{ for } y \geqslant Y_{EORStart} + T_{RecycDelay} + T_{RecycMax} \end{cases} \quad (5)
$$

where RecycFactMax is the maximum CO_2 recycling factor, attained at $T_{RecycMax}$, $Y_{EORStart}$ is the start year of CO_2 injection, $T_{RecycDelay}$ is the time after $Y_{EORStart}$ at which CO_2 breaks through at the production wells and $T_{RecycMax}$ is the time after CO_2 breakthrough at which RecycFactMax is attained.

The amount of CO_2 injected in year y, in [tCO2/y], is given by Eq. (6), which is the sum of the freshly supplied CO_2 and the recycled CO_2.

$$
CO_2Inj_y = \frac{CO_2Supply}{(1 - RecycFact_y)} \quad (6)
$$

where CO_2Supply is the amount of fresh CO_2 supplied to the oil field (fixed yearly amount) [tCO_2] and $RecycFact_y$ is the CO_2 recycling factor in year y.

The fixed amount of CO_2 that is yearly supplied to the oil field, in [tCO2/y], is given by Eq. (7).

$$
CO_2Supply = CO_2Required * (1 - RecycFactMax) \quad (7)
$$

where CO_2Required is the maximum yearly amount of CO_2 required for injection [tCO_2] and RecycFactMax is the maximum CO_2 recycling factor, attained at $T_{RecycMax}$.

3.6. Cost calculation

3.6.1. Expenses

The expenses of a project are modelled in PSS IV as follows.

$$
Expenses_y = INV + Decom + FOM_y + (VOM_y * CO_2Inj_y) + (CO_2Cost_y * CO_2Supply) \quad (8)
$$

where INV is the total investment cost [€], Decom is the decommissioning cost [€], FOM_y is the fixed operations and maintenance cost [€/y], VOM_y is the variable operations and maintenance cost (for PSS IV: cost of injection) [€/tCO_2], CO_2Inj_y is the amount of CO_2 injected in year y, from Eq. (6) [tCO_2], CO_2Cost_y is the cost of fresh CO_2 purchase [€/tCO_2] and CO_2Supply is the amount of fresh CO_2 supplied [tCO_2]. The investment cost and decommissioning cost parameter are zero for years without investment or decommissioning, as explained further on.

3.6.2. Revenues

The main positive cash flow from a CO_2-EOR project is generated from selling additional oil. A delay on the oil field's decommissioning by extending its lifetime can potentially also create revenues.

$$
Revenues_y = OilPrice_y * (EORProd_y + PrimProdExt_y) + DecomDelay_y \quad (9)
$$

where $OilPrice_y$ is the average oil price in year y [€/bbl], $EORProd_y$ is the EOR oil production in year y (Eq. (3)) [bbl], $PrimProdExt_y$ is the primary extended oil in year y [bbl] (Fig. 4) and $DecomDelay_y$ is the possible income obtained from delaying the oil field decommissioning [€] [18].

3.6.3. Decommisioning

When shutting down operations at an oil field, significant costs needs to be made to properly leave the site as required by law, i.e. the decommissioning cost. If, by applying EOR, the lifetime of the field is extended (see Fig. 4), it is possible that the compound interests on the decommissioning cost, by re-investing the decommissioning sum for the time period of the decommissioning delay, generate a surplus. This surplus is regarded as a positive cash flow from the EOR project, and may amount to several million euro.

3.6.4. Taxes

Countries with North Sea territory levy taxes on the profits from oil production. An overview is given in Pershad et al. [18]. Because of the complexity and differences between countries, at this moment, a single flat rate tax on profit is applied in PSS IV. Profit is calculated as the yearly difference between revenues and expenses. It is possible that the real cash flows that are incurred and those used for calculating taxes differ from each other. This may be the case e.g. when investments are written off over several years. PSS IV allows for such distinctions. Also more specific and advanced tax rules can be implemented, which is needed when simulating specific fields in a non-generic context.

3.6.5. Project value

The overall cost balance of a certain project in PSS IV is calculated as a rate of return. It is the ratio between the sum of the discounted yearly revenues and the expenses, as given by Eq. (10).

$$Rate\ of\ Return = \frac{\sum_{y=0}^{T}\frac{1}{(1+r)^{y}}(Revenues_{y}) - \sum_{y=0}^{T}\frac{1}{(1+r)^{y}}(Expenses_{y}+Taxes_{y})}{\sum_{y=0}^{T}\frac{1}{(1+r)^{y}}(Expenses_{y}+Taxes_{y})} \tag{10}$$

where $Revenues_y$ are all positive cash flows in year y [€], $Expenses_y$ are all negative cash flows in year y [€], $Taxes_y$ are the taxes to be paid in year y [€], r is the discount rate and T is the project lifetime.

The rate of return provides an indication on the efficiency of the expenses to generate income. Therefore, the amount of value created per unit of expenses is quantified to include negative cash flows and additional investments in the project lifetime. This method is a modification of the profitability index (PI), which is the ratio between the present value of future cash flows (excluding the initial investment) and the initial investment. The PI quantifies the amount of value created per unit of investment. In our approach, however, the investment cost is integrated in the expenses, with the resulting ratio being the value created per unit of total expenditure.

3.7. Economic principles and algorithms

In this section, the different algorithms used for analysing and evaluating potential CO_2-EOR projects are discussed. While most of these algorithms are commonly used (except for limited foresight), and some of them have been applied individually for assessing CO_2-EOR projects (e.g. Real Options Analysis by [37]), it is their combination which makes PSS IV unique.

3.7.1. Parameter uncertainty

A simple but robust methodology to deal with parameter uncertainty is the Monte Carlo methodology with stochastic parameters. Monte Carlo uses a random sampling within the uncertainty ranges of these stochastic parameters to obtain differing outcomes. In PSS IV, two sets of parameters are stochastic by default, although any technical or geological parameter can be run stochastically. The first set is the oil and CO_2 emission market price (EU ETS or equivalent). The envelope of minimum and maximum prices reflect parameter uncertainty (Fig. 6).

The second set of stochastic parameters are the EOR oil production curves. The oil production in PSS IV is simulated using lognormal curves, of which the shape is defined by μ, σ, OOIP and the recovery factor. The σ parameter is kept fixed to define a certain reservoir characteristic. μ defines the position of the peak or mode, which is considered here as a reservoir performance indicator: fast response corresponds to an early and high peak, where oil will be produced fast with a short tail. In case of a slow reservoir, peak oil

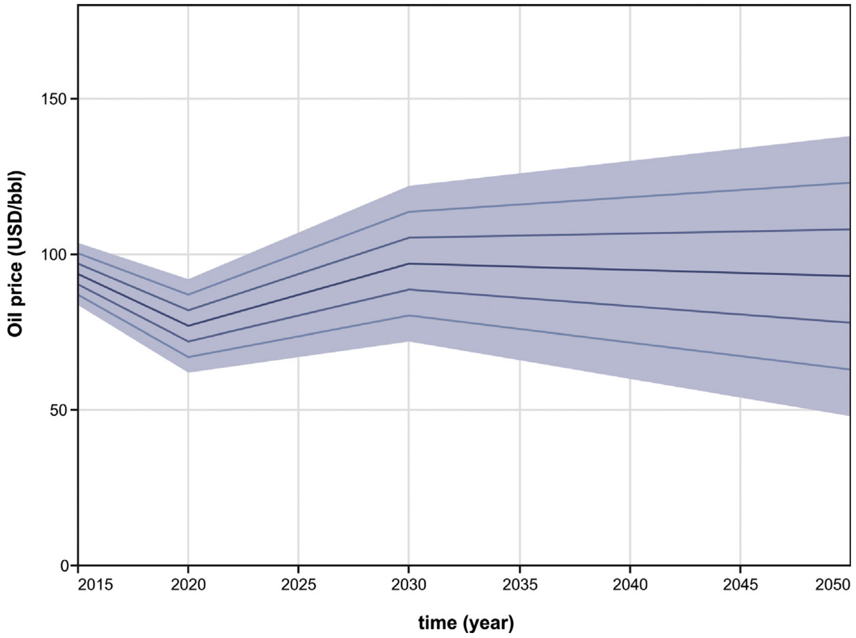


Fig. 6. Example of the parameter uncertainty of the CO_2 price. In a Monte Carlo calculation, different price paths are randomly chosen (5 are drawn here). The oil price path shown here is based on the IEA predictions of the crude oil import price under the 2DS scenario [72].

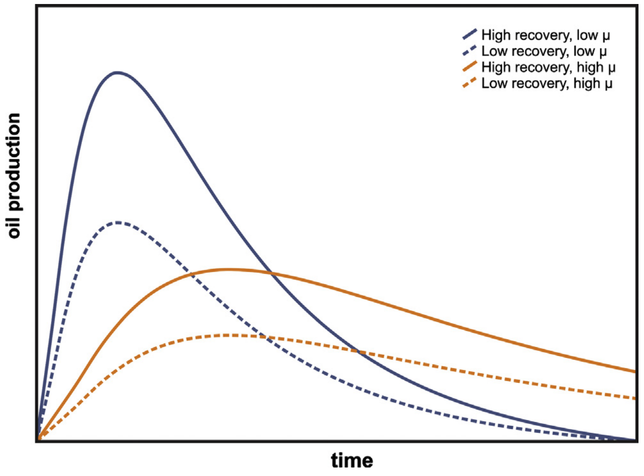


Fig. 7. Oil production curve variations, obtained through varying stochastic μ and recovery factor parameters.

will come later but the oil production will last longer. The recovery factor defines the surface below the lognormal production curve, and therefore the fraction of the OOIP recovered by EOR. By varying both μ and the recovery factor, a range of possible production curves is obtained that reflects reservoir uncertainty (Fig. 7).

3.7.2. Real options analysis

Dixit and Pindyck [36] state that having the option to change or reverse an investment after the initial investment decision can have a significant part in the value of an investment, because of the possibility of changing the investment decision following new information in the future. The monetary value of this option is called the Real Options Value. Dixit and Pindyck [36] developed an analytical methodology for calculating the Real Options Value of an investment, based on the possible future variation of a parameter. The calculations in PSS IV are complex, and include several stochastic parameters. This makes it impossible to apply this analytical approach. A brute force approach to uncertainties, such as a Monte Carlo calculation, is therefore preferred. The Datar-Matthews method [53] for example uses the Monte Carlo method for calculating the Real Options Value of investments. PSS IV also relies on Monte Carlo, in combination with a decision tree: a possible investment decision in a certain time step is evaluated with several Monte Carlo iterations.

Real Options Analysis starts with building an option tree with potential current and future technology options/decisions, including project abandonment. Every branch on this tree represents a different future, where different project decisions are taken (Fig. 8). In the project evaluation, each of these branches is evaluated for production, cost and revenues. Specifically for CO_2-EOR projects, several oil fields can be active in a network or cluster. In order to simulate all possible networking options, a multidimensional technology tree is made. If a technology tree is considered as a set of branches, a Cartesian product is made: every branch of a single technology tree is linked to every branch of every other technology tree to create clusters (Fig. 9). Thus, a cluster in PSS IV contains a combination of technology options for every oil field. The clusters are grouped by their next year's technology, which depends on the combination of the branches. As such, the different investment choices for next year are formed, which will be used for evaluation (3.7.3 Project evaluation).

Limited foresight is a more realistic way of simulating investment decisions compared to traditional, perfect foresight models [54]. With limited foresight, future values of cost and performance parameters are not exactly known at the moment of decision-making. This results in an investment decision that is less than optimal. In Real Options Analysis as applied by Dixit and Pindyck [36] and Fleten et al. [37], limited foresight is introduced by the geometric Brownian motion of stochastic parameters. A brief overview of the principle of limited foresight as applied in PSS IV is given hereafter. PSS IV relies on stochastic parameters and a Monte Carlo methodology to handle uncertainties. The values set in one of these (primary) Monte Carlo iterations are regarded as reality by the simulator. In order to create a realistic outlook towards the future, i.e. a growing uncertainty, a second level of stochastic parameters is added: the outlook parameters. The uncertainty envelope starts off from what is considered by the simulator as today and the real value (set in the primary Monte Carlo), and grows towards the future in a funnel-shaped envelope (Fig. 10). A number of secondary Monte Carlo iterations is performed using outlook parameter values as a random walk within this envelope. Decisions are taken using results from calculations with these outlook parameters. Actual project performance and cost are calculated with the parameters from the primary Monte Carlo. The values of the outlook parameters differ from those in the primary Monte Carlo level, and thus the decisions taken are near-optimal for the simulated scenario, instead of truly optimal.

The result of this methodology differs slightly from the analytical model developed by Dixit and Pindyck [36]. In the latter methodology, the average value for calculations is the centre or expected value of the uncertainty envelope created by the geometric Brownian motion. In PSS IV, the number of Monte Carlo iterations within the outlook envelope is deliberately limited (25 by default), which on average produces results that slightly differ from the expected value, which is a means to simulate imperfections in actual decision taking to add more realism to the projection. Simulated project decisions taken based on this information will therefore be near-optimal.

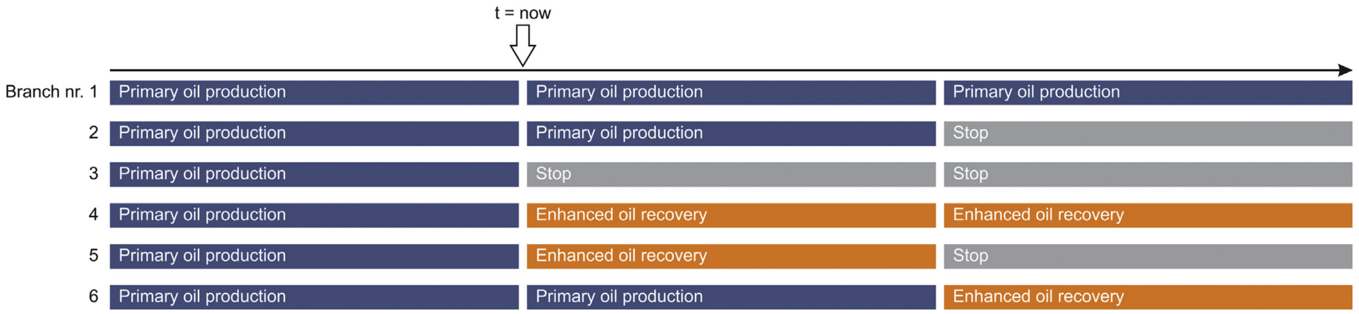
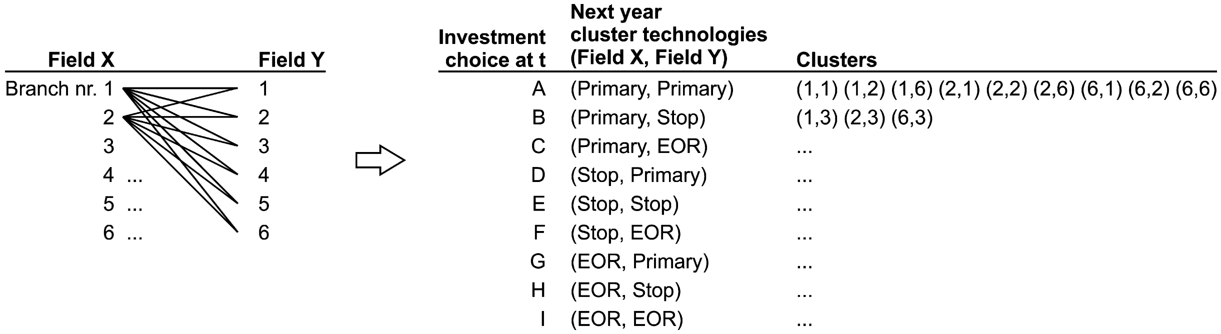


Fig. 8. Example of technology tree starting from current primary oil production. Choices for the next time steps are to continue primary production, switch to enhanced production, or stop all production. This defines the potential choices for the following time step, and so on. In some cases this quickly results in extensive technology trees, even for a limited number of technology choices. In our example, and in the case study presented further on, only CO_2-EOR and project abandonment are possible options. In reality, a wide range of options is available, including natural gas storage and geothermal energy production, with potential conflicts or synergies [73]. Although it is technically feasible to add these options in PSS IV, it lies beyond the scope of the research presented here.



Investment choice at t	Next year cluster technologies (Field X, Field Y)	Clusters
A	(Primary, Primary)	(1,1) (1,2) (1,6) (2,1) (2,2) (2,6) (6,1) (6,2) (6,6)
B	(Primary, Stop)	(1,3) (2,3) (6,3)
C	(Primary, EOR)	...
D	(Stop, Primary)	...
E	(Stop, Stop)	...
F	(Stop, EOR)	...
G	(EOR, Primary)	...
H	(EOR, Stop)	...
I	(EOR, EOR)	...

Fig. 9. Illustration of combination of option tree branches into clusters and investment choices. The branches of all fields are combined with each other in clusters in a Cartesian product (left). These clusters are grouped according to their next year's technology/ investment choices (A, B, … I).

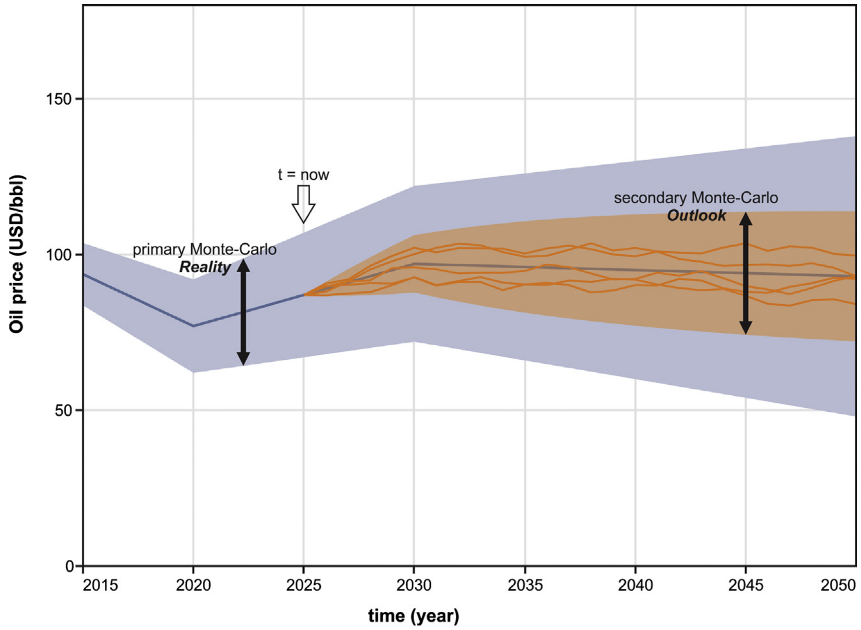


Fig. 10. Example of the principle of limited foresight, as applied in PSS IV, applied to the IEA predictions of the crude oil import price under the 2DS scenario [72]. The "outlook" values (orange) are used for decision-making, but may differ from what is considered by PSS IV as "reality" (blue), leading to near-optimal solutions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.7.3. Project evaluation

The investment decision is made from the point of view of the oil field operator. Investment decisions are modelled as decisions that are made for the next year (Fig. 11). This decision has consequences over a certain number of years to come. At the start of every inner Monte Carlo iteration, the stochastic parameter values for this iteration are set (step 1). These values are used until step 9, when the next Monte Carlo iteration is initiated. The values that are set in step 1 are a random walk as shown by the orange lines in Fig. 10, for all stochastic parameters. The random walks of different parameters are not correlated. For every oil field, every possible technology branch with different future decisions is analysed. Oil production, CO_2 use and cost calculations are made for every time step in the technology branch (step 2), using the formulas previously discussed.

In the second part of the Monte Carlo iteration, the combinations of every technology branch of every oil field with each other (here called "cluster") are analysed. Next, the best CO_2 supply chain is calculated in step 3. The costs and revenues for every field and every year (step 4) are used to calculate the yearly taxes (step 5). Then, the CO_2 supply and transport costs for the cluster are added in step 6, and discounting is applied (step 7) which results in the project's rate of return (step 8) as calculated with Eq. (10). Here ends the inner Monte Carlo iteration in the model. The best cluster is remembered for every Monte Carlo iteration (step 9). As a result, there are a number of best clusters (equal to the number of Monte Carlo iterations). The decision that needs to be taken now is which technology option is deployed in each field next year. Therefore the best clusters are grouped according to their technology choice for next year (step 10; Fig. 9: A, B, C, …). For each of these technology groups, expected value (mean profit rates) and risk (variance of the return rates) are calculated (step 11). The division of the return by the risk provides the return versus risk rate. The technology group with the highest risk versus return rate is activated for the next year (step 12). Note that this "activation" may be the continuation of current operations. The combination of calculations that lead to an evaluation including investment risk is a first of its kind for the assessment of CO_2-EOR projects.

4. Claymore and Scott case study

4.1. Input & scenario

A case study was developed to investigate the profitability of two oil fields in the North Sea: the Claymore and Scott oil fields. This case study is also used to demonstrate part of the newly proposed methodology: a comparison will be made between an indi-

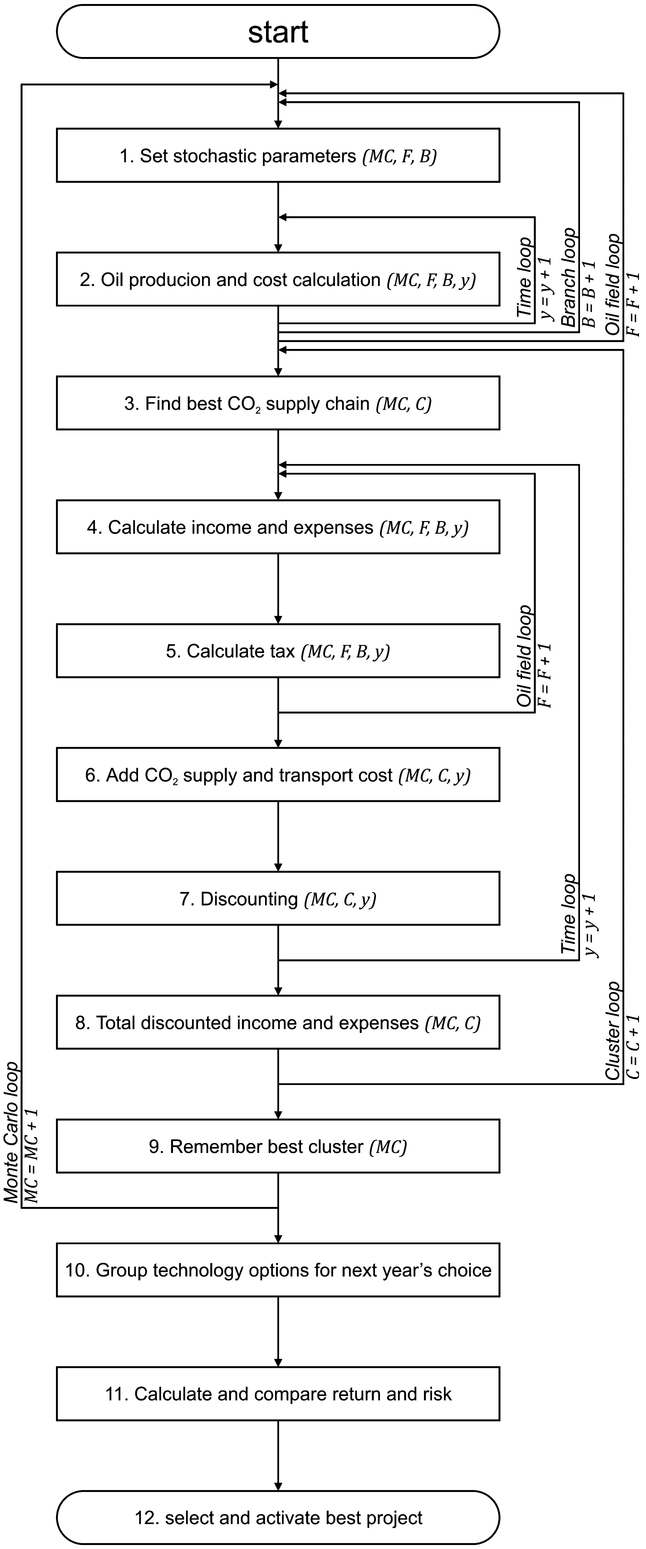


Fig. 11. Flow chart of the CO_2-EOR project evaluation in PSS IV. A Monte Carlo calculation is first performed for all clusters. Every Monte Carlo iterations results in a best cluster, which are grouped for their next year's technology choice (see Fig. 9). The investments' return and risk are compared, and the best investment is chosen to be activated. Parameter dimensions are indicated (MC: Monte Carlo; F: field; y: time; C: cluster; B: technology branch for field).

vidual and a cluster assessment. The Claymore field, which started production in 1977, is currently operated by Talisman Energy Inc. The field's OOIP is estimated at 1455 MMbbl. The Scott field, operated by Nexen Petroleum UK Limited, has been in production since 1993, and has an estimated OOIP of 646 MMbbl [51,55,56]. Both fields are located in the UK offshore sector of the North Sea, about 160 km east of Aberdeen, and are potential targets for CO_2-EOR [18]. Four parameters were treated as stochastic, with uncertainties for the primary (reality) and secondary (outlook) Monte Carlo calculation: the oil price ($OilPrice_y$), CO_2 cost (CO_2Cost_y), EOR recovery factor (R_{EOR}) and EOR μ (μ_{EOR}). In the primary Monte Carlo, the long-term oil price can vary between 50 and 120 €/bbl, the CO_2 cost between −10 and 10 €/t, which is in line with the −10 to 10 GBP/tCO_2 used in Pershad et al. [18]. The CO_2 cost range implies that CO_2 is either payed by the oil field operator, or they receive payments to dispose the CO_2 underground. For this case study it was assumed that sufficient CO_2 would be available. In reality, this is one of the practical bottlenecks that hamper the commercial introduction of CCS and CO_2-EOR. The tax rate was set to a 50% flat rate tax on profit, which assumes that the higher Petroleum Revenue tax (PRT) for fields established before 1993 is abolished. A 100% First Year Allowance (FYA) is also available, which enables a tax relief on investments in the year of incurrence. These scenario parameters are also given in Table 1.

A range of numbers are available in literature for the EOR recovery factor, averaging around 10% (e.g. [18,22,57,58]). The uncertainty ranges for the EOR recovery factor and EOR μ were chosen between 8 and 12%, and between 1.9 and 2.1 respectively. These and all other oil field parameters are given in Table 2. Parameter definitions can be found in the methodology section of this paper.

Oil field data and data concerning primary and CO_2-EOR production were collected from different sources and combined to obtain a coherent set of values for all PSS IV parameters, which required some assumptions by the authors (especially for the uncertainty ranges). Primary oil production curves were fitted on production data from the DECC [51]. OOIP and recovery factor data were collected from Tzimas et al. [22] and Sandrea and Sandrea [57]. Other data regarding EOR performance were combined from these previous sources, as well as data from Holt et al. [28], Klokk et al. [32], Pershad et al. [18], and Kemp and Kasim [31].

Same as for the production data, the cost data was collected from different sources and combined to obtain a coherent set of values for all PSS IV parameters for the Claymore field. These values were then scaled for the Scott field. The main sources for these cost data are Gozalpour et al. [21], BERR [59], NOGEPA [60], Pershad et al. [18] and Mendelevitch [33].

4.2. Results

Simulations with PSS IV were run for multiple days, and resulted in 685 Monte Carlo iterations (MC's) for the Claymore field simulations, 747 MC's for the Scott field, and 665 MC's for the cluster configuration of both oil fields. Activated CO_2-EOR projects received a positive evaluation and investment decision. Of the positively evaluated and consequently activated projects, a net present value is calculated after decommissioning. PSS IV produces a multitude of output parameters. Here, the NPV and NPV per barrel of additionally produced oil are shown, to be able to compare the single-field to the cluster approach.

Table 1
Scenario parameters and values for Claymore and Scott case study. The tax rate is not treated as stochastic, thus it has no uncertainty range.

Parameter	Unit	Value/range
Oil price	€/bbl	50–120
CO_2 purchase cost	€/t	−10 to 10
Tax rate	%	50

Table 2
Field-specific parameters and values for the Claymore and Scott oil fields.

Parameter	Unit	Value Claymore	Value Scott	Reference
OOIP	MMbbl	1455	946	Tzimas et al. [22]
$Y_{PrimStart}$	y	1977	1993	DECC [51]
R_{Prim}	–	0.46	0.46	Tzimas et al. [22], Sandrea and Sandrea [57]
μ_{Prim}	–	2.6	1.65	Own calculation, based on DECC [51]
σ_{Prim}	–	0.98	1.2	Own calculation, based on DECC [51]
R_{EOR}	–	0.08–0.12	0.08–0.12	Based on several sources
μ_{EOR}	–	1.9–2.1	1.9–2.1	Own estimate, based on Pershad et al. [18]
σ_{EOR}	–	0.65	0.65	Own estimate, based on Pershad et al. [18]
CO_2Required	Mt/y	7	4.6	Own estimate, based on several sources
$T_{RecycMax}$	y	5	5	Tzimas et al. [22]
RecycRateMax	–	0.75	0.75	[32]
$T_{RecycDelay}$	y	2	2	Tzimas et al. [22]
INV	M€	791	514	[76]
Decom	M€	119	77	15% of INV, Pershad et al. [18]
VOM_y	€/tCO_2	26	26	[76]
FOM_y	M€/y	65.6	42.6	[76]

The development probability, or the ratio of Monte Carlo iterations in which an actual CO_2-EOR project is activated over the total number of iterations, is 100% in all cases. Thus, in every MC for every field or cluster, EOR was applied at some time. This is mainly due to the relatively high oil prices of 50–120 €/bbl. This presumption is confirmed when comparing to published numbers by e.g. Klokk et al. [32], where a 0 NPV threshold is found at about 45 USD/bbl and a CO_2 cost of 0. This means that at higher oil prices, CO_2-EOR becomes a very interesting option.

Fig. 12 shows the Net Present Value (NPV) in function of the oil and CO_2 price, for the cluster configuration of the Claymore and Scott fields. Every dot represents the NPV of a cluster project in a single primary Monte Carlo iteration, with a randomly chosen oil and CO_2 price. The NPV ranges between 49 and 3863 M€. The main driver is clearly the oil price and by comparison the variation in NPV caused by the CO_2 price is only minor. Note however the comparatively small uncertainty range of the CO_2 price. Still, the correlation between NPV and oil price is about 5 times larger than the correlation between NPV and CO_2 price.

Although there is a clear trend observable, the NPV results (size of the dots) are not perfectly sorted. A first reason is the fact that there are two more stochastic parameters that influence uncertainty: the EOR recovery factor and the μ of the EOR oil production curve. The second reason is the PSS IV methodology of limited foresight and optionality. The investment decisions are taken based on imperfect information, and reality (i.e. the oil and CO_2 prices in this graph) may differ from what was anticipated. Imperfect decisions lead to project's NPV that may turn out lower than foreseen. Moreover, the multi-period decision scheme introduced by the Real Options Analysis can cause small variations to result in significant changes in the final result. A statistical analysis allows to define average threshold levels for NPV values black lines in Fig. 12. The

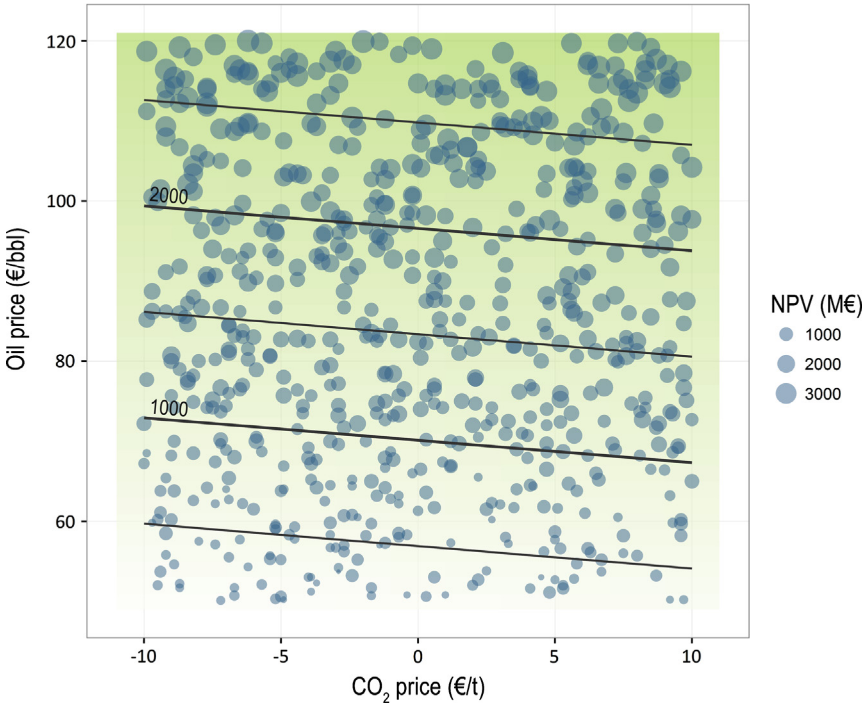


Fig. 12. Net Present Value (NPV) results of the cluster configuration, in function of the stochastic oil and CO_2 prices of the primary Monte Carlo. The average threshold level lines were calculated using kriging of the gstat package in R [74,75].

zero-NPV level is not visible within this range of oil and CO_2 prices. Over an oil price of 70 €/bbl, most CO_2-EOR projects attain an NPV of 1000 M€ or more.

This also illustrates the main difference and advantage of the PSS IV methodology over other EOR calculation schemes. Traditional NPV calculations show the result of decisions with perfect foresight. The traditional NPV result therefore is a theoretical value which does not entirely reflect reality. This is usually complemented by a sensitivity analysis to cover possible variations in relevant parameters separately. With PSS IV, the variation of all stochastic parameters, and therefore also their mutual influences, are taken into account at the same time. Especially for multi-period investment decisions that are influenced by optionality, this is the only way of incorporating the real influence of the uncertainties. The project NPV's obtained through PSS IV are therefore more realistic than those found by a traditional NPV calculation. Moreover, instead of a single threshold level, results as shown in Fig. 12 provide the whole field of possible outcomes.

Fig. 13 shows, for the Claymore field, a probability histogram of the NPV (Net Present Value) per barrel. The average value of a CO_2-EOR project at the Claymore field is 15.8 €/bbl (standard deviation SD = 8.3), with a total range of marginally negative project values to higher ranges of about 35 €/bbl. Fig. 14 shows the same probability histogram for the Scott field. The average value of a CO_2-EOR project is here 14.3 €/bbl (SD = 8.6), which is about 10% lower than for the Claymore field. Also the range of results is lower, with a more negative NPV result. Fig. 15 shows the probability histogram for the cluster configuration. The average project value of the cluster is 20.3 €/bbl, which is clearly higher than for the individual fields. The standard deviation is also higher (SD = 9.9), and the range is strictly positive, from 0 to over 40 €/bbl.

The results shown in these histograms show both a profitability assessment for these fields and the added value of the PSS IV methodology. A first observation is that the value per barrel of oil for the Claymore field on average is higher than the Scott field. Although some scale effects are neutralized by presenting the results as per barrel, this difference is still primarily explained by scale effects due to a higher OOIP for the Claymore field. A second observation is that, although a profitability evaluation was made before activating projects, negative project values can still occur. This is due to the limited foresight: there is a difference between values of the stochastic parameters in the evaluation (outlook, secondary MC) and the simulator's reality (primary MC). If circumstances turn out to be worse than expected, this may results in negative 'real' project values.

The most notable result is the difference between the individual field simulations and the cluster approach. There is a 5 €/bbl (~30%) value increase when the fields are produced as a cluster. Moreover, the probability on a negative project value is zero. Because scale effects are mostly neutralized by presenting the results as per barrel, there are other mechanisms causing this value increase. First is the possibility of sharing investment costs, such as a single CO_2 transport pipeline for supplying multiple fields. Second is the additional project flexibility, introduced by Real Options Analysis. Project decisions are taken based on an increased number of (future) options: fields can be addressed one after another, in parallel, and with a flexible timing, based on market and reservoir behavior. This reduces the investment risk and ultimately increases overall project value.

To put the 5 €/bbl value increase into perspective, a simplified calculation indicates that for a combined OOIP of about 2400 MMbbl and an average EOR recovery factor of 10%, over one billion Euro of additional value is created. As a consequence, economic simulations where EOR projects are regarded as a sum of the individual field assessments will undervalue projects.

This comparison of CO_2-EOR as single projects and in a cluster is a first in its kind. Moreover, the use of the value per barrel of additionally produced oil is only occasionally found in literature. It is therefore difficult to make a direct comparison to published numbers. Wei et al. [25] have calculated a net income after taxes for oil fields in China of up to 25 USD/bbl for the most profitable fields, at a discount rate of 10%, and depending on the number of oil fields included (fields less fit for EOR represent the negative range). Gaspar Ravagnani et al. [61] obtain a lower result of 1.91 USD/bbl after

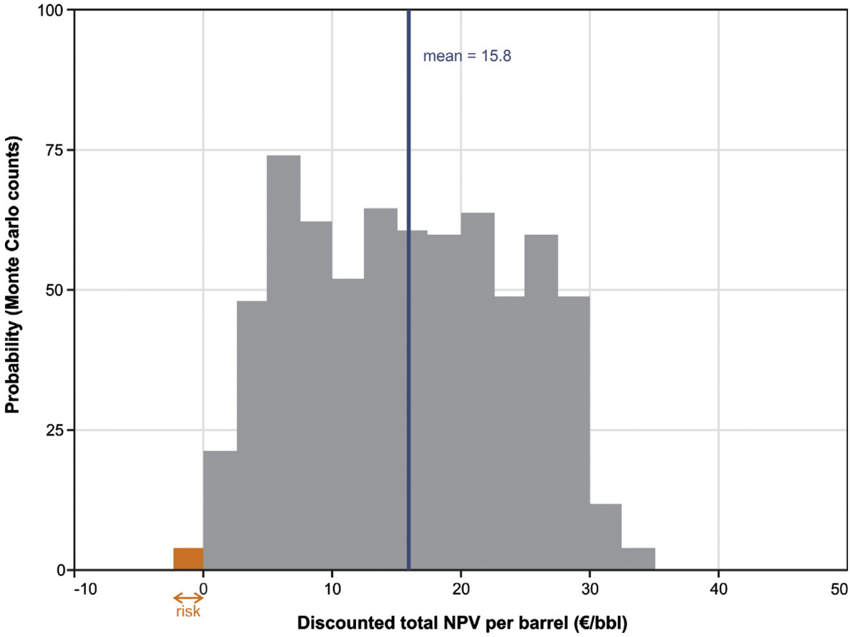


Fig. 13. Probabilistic histogram of the discounted NPV per barrel of additional oil produced for activated CO_2-EOR projects at the Claymore oil field. The probability is expressed as the number of MC iterations.

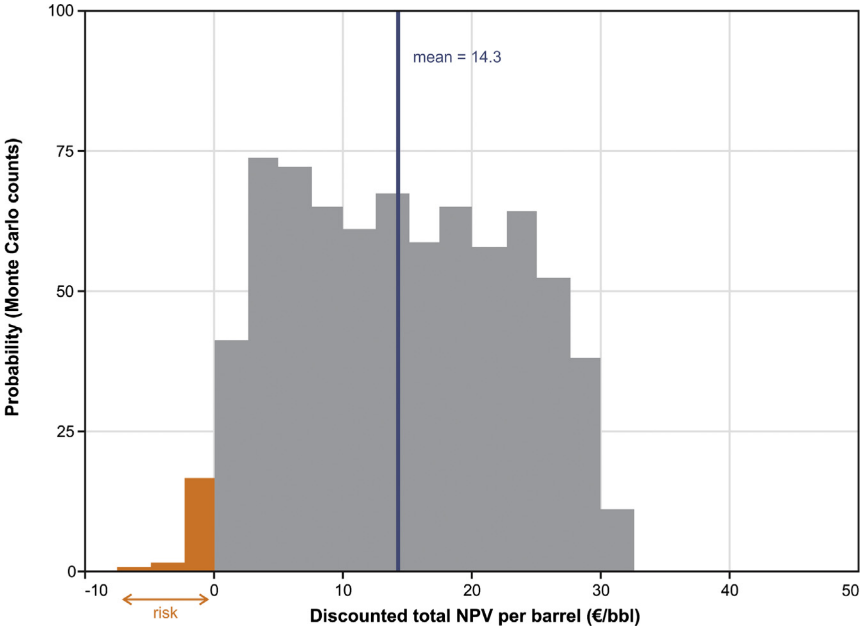


Fig. 14. Probabilistic histogram of the discounted NPV per barrel of additional oil produced for activated CO_2-EOR projects at the Scott oil field. The probability is expressed as the number of MC iterations.

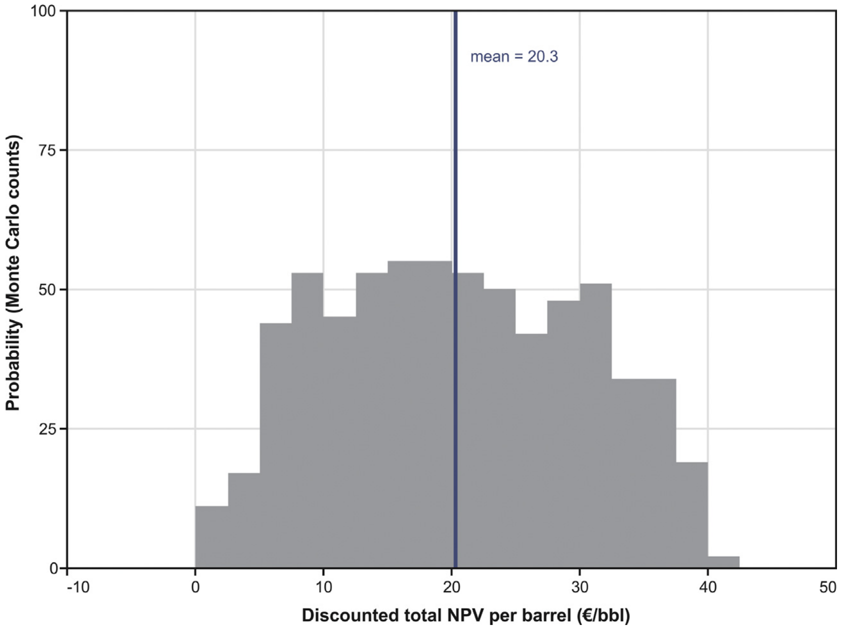


Fig. 15. Probabilistic histogram of the discounted NPV per barrel of additional oil produced for activated CO_2-EOR projects in a cluster configuration of the Claymore and Scott fields. The probability is expressed as the number of MC iterations.

taxes for a Brazilian oil field, at a discount rate of 12%. These settings are of course completely different from our North Sea case, which is a first explanation for differences in the numbers. The highest project values of Wei et al. [25] of up to 25 USD/bbl are higher than the average project values presented here, but still fall within the ranges presented here. The value of 1.91 USD/bbl by Gaspar Ravagnani et al. [61] is significantly lower, at the bottom end of our range of results. The differences are also explained by the oil prices used in the simulations, with Wei et al. [25] using an average oil price of 90 USD/bbl (~80 €/bbl), which falls within our own simulation range, and Gaspar Ravagnani et al. [61] one of only 35 USD/bbl (~30 €/bbl), outside of the range assumed in our study. Pershad et al. [18] used a cluster approach for evaluating CO_2-EOR projects in the North Sea, including the Claymore and Scott fields. In the most optimal scenario, with oil prices rising well over 100 €/bbl, the NPV per barrel after taxes for the Claymore field is 3.60 GBP/bbl (~4.60 €/bbl), and 6.50 GBP/bbl (~8.30 €/bbl) for the Scott field. There are several possible reasons for the gap between these numbers and the PSS IV results. In the PSS IV case study, it is assumed that the PRT is abolished, lowering the tax rate from 81% to 50%. The optionality in PSS IV also adds the Real Options value to the total project value. Lastly, as this application is a first case study to demonstrate the PSS IV methodology, the costs might be underestimated. These issues need to be addressed in future research.

5. Discussion

5.1. PSS IV strengths and limitations

The development of PSS IV as an investment decision support tool for CO_2-EOR projects was started to address three main issues in techno-economic modelling: uncertainty, flexibility and investment risk. In these fields, PSS IV has several advantages over other tools. On parameter level, the possibilities to add uncertainty are virtually unlimited. Almost every parameter can be defined with its own stochastic range. An important development is the integration of geological uncertainties in techno-economic modelling, which allows to retain the geological uncertainties throughout the whole value chain and simulation process. The project flexibility generated by the technology tree and cluster capability is combined with true limited foresight. This allows for making more realistic investment decisions compared to other tools, by considering a more realistic investment risk and the consequences of optionality (such as excluding certain future pathways). The technology tree can also be expanded with other options for using (nearly) depleted oil fields, such as energy storage and geothermal energy production. The possibility of adding CO_2 storage is discussed in Section 5.5.

Because of these combined elements, the PSS IV simulator is unique in its kind and results provide better support to the investment decisions of CO_2-EOR projects. While most models apply a single-parameter sensitivity analysis, PSS IV makes simulations with multiple stochastic parameters in a multi-period real options analysis. The result of this interaction of uncertainties is impossible to grasp with a standard sensitivity analysis. The primary field of application of PSS IV is as decision support system for oil companies, where it can be applied to make more accurate analyses of oil fields with CO_2-EOR potential. A second field of application are governments wanting to stimulate either oil production or CO_2 storage through e.g. tax incentives.

As PSS IV is a computer simulator, there are also a number of limitations to consider. First of all, generalizations were made regarding the geotechnical model for CO_2 injection and oil production. Although the current analytical model of the reservoirs and the CO_2-EOR process results in realistic predictions, a number of simplifications, including the decoupling of the CO_2 injection and incremental oil production, cause that not all aspects of the reservoir response can be captured. Also the possibility of leakage is currently not taken into account. While Narita and Klepper [62] show in a Real Options Analysis that the effect of potential leakage on the investment threshold is only minor, this is strongly reservoir-dependent and could be included to obtain a more realistic risk. An adjusted analytical model can therefore be considered, with benchmarking against numerical reservoir models.

Another generalization was made concerning the stochastic outlook parameters. For generating an outlook for making investment decisions, PSS IV uses the random walk stochastic process for all stochastic parameters. The random walk is suited for simulating market behavior, but is not ideal for describing geotechnical parameters. While the uncertainty range of a random walk grows towards the future, this is not the case when applied to reservoir exploration and exploitation, where information is gained and uncertainty reduced over time. This too can be considered as a simplification of the geotechnical model.

Because PSS IV is a techno-economic simulator, socio-political evolutions cannot be simulated directly. These can however become very important influences on CO_2 injection activities, as seen from many real-world examples (e.g. the cancellation of the Barendrecht project due to local opposition; [20]). In PSS IV, these parameters are included at scenario level, where oil and CO_2 prices are defined, and certain areas or reservoirs can be in- or excluded for injection of CO_2.

A final limitation of the PSS IV methodology is the number of possible options generated by the technology tree and the nested Monte Carlo approach. Therefore calculation time in the current set-up can become problematic, as discussed in Section 5.4.

5.2. ETS and revenue distribution

In the presented methodology of PSS IV, it is assumed that an agreement is made between an onshore CO_2 supplier and an oil field operator, and that potential benefits from the Emission Trading System (ETS) are all accredited to the oil field operator. In practice, CO_2 used solely for enhanced oil recovery falls outside of the scope of the CCS Directive [63], and cannot therefore benefit from the ETS [64,65]. In case CO_2 is used and eventually stored permanently, e.g. when an EOR project is closed and injected CO_2 is left in place, the CCS directive does apply, and the stored CO_2 is then eligible for the ETS. Our model currently does not make this legal distinction, and considers injected CO_2 as stored and eligible for ETS credits. However, the current ETS market price is very low (<5 €/tCO_2, summer 2016; [66]) and insufficient to offset capture costs [67].

Models from other authors also explicitly include capture and a central regulator which either makes whole-chain decisions, or regulates the throughput and distribution of CO_2 via its transport infrastructure. Mendelevitch [33] suggested that the latter option is more realistic, and it is likely that a government will take over this role. This also means that there will be CO_2 transfer price negotiations between the CO_2 producer, the regulator and the oil field operator, which will depend on factors such as the quantity of CO_2, ETS price, capture cost and oil field operations (Compernolle et al. [38]).

5.3. Investment decision criterion

The Net Present Value (NPV) and internal rate of return (IRR) are the two most widely used investment criteria today [68]. PSS IV uses a custom rate of return for ranking investment options, based on the ratio between income and expenses. Although the basis of this approach is sound, it is not an industry standard, and asks for an evaluation of other criteria in use today. The NPV is a measure for the total project value today, without considering risk or efficiency. The IRR shows at which discount rate the NPV is zero. Therefore, it is a measure of investment efficiency, but the total project value is not shown. By applying a hurdle rate (minimum required discount rate), risk can be considered as well. Riskier projects will e.g. require a return in a shorter time, i.e. a higher discount rate. There are several issues regarding the use of IRR, most importantly its failure to provide a single value in case of negative cash flows (which is e.g. the case in decision trees with multiple investments). Additionally, the IRR generally overestimates the value of an investment, as it assumes that value generated over the course of a project is re-invested in that project, which in practice is rarely the case. Several modifications have therefore been proposed [68,69]. Introducing an IRR-related investment option ranking in PSS IV could be a viable alternative to implement in a future version and would provide a closer match to reality.

5.4. Calculation speed

An issue regarding the PSS IV calculations is the calculation time, which increases exponentially when adding oil fields to a cluster configuration. This is partly due to the brute-force approach inherent to the nested Monte Carlo calculations, and partly to the large number of potential future pathways in a cluster of oil fields. Assuming a simulation timeframe of 40 years, with possible technology changes every year for a three-oil-field-cluster, and a possibility to choose between three "technologies" (primary, EOR and project stop), there are 40^2 branches per field; combining three oil fields, this provides $(40^2)^3$ = 4E9 cluster possibilities. Calculation speed thus becomes a bottleneck for simulations, especially when adding several hundred Monte Carlo iterations to this number. A possible amelioration is to apply an analytical approach instead of Monte Carlo iterations, such as the Real Options approach by Dixit & Pindyck [36]. When calculations involve one or two stochastic parameters, such an analytical approach to uncertainty should be possible. PSS was, however, designed to be able to treat almost any parameter as stochastic, and therefore address problems that correspond to analytically unsolvable higher-order differential equations unsolvable. A second problem with an analytical approach is the way in which limited foresight is applied in PSS IV. Now, the limited number of inner Monte Carlo iterations results in an average project value that is not necessarily the "expected value" or centre line in the outlook envelope, which renders investment decisions less than optimal. This is not the case in the analytical Real Options approach by Dixit & Pindyck [36], where it is assumed that the amount of uncertainty is exactly known. The near-optimal character of the investment criteria adds to the realism of the simulations because in reality, the range of uncertainty is generally not precisely known. A possibility for reducing the calculation time is the application of an evolutionary algorithm to find the best sequence of investment decisions, where timing and technology options are varied based on biological evolutionary processes as an optimization [70].

5.5. CO_2 storage and EOR

It is likely that CO_2-EOR and CO_2 storage projects will be integrated in the same value chain, where revenues from the ETS potentially offset operational costs. A number of studies have addressed this combination, in different forms. In most of them, parallel projects are evaluated (e.g. [18,32,33]). Ettehadtavakkol et al. [71] specifically addressed coupled CO_2-EOR and storage. Economic analysis shows it is an attractive option with significant benefits for both operator and government. This option provides lower risk through the additional flexibility throughout the whole CO_2 value chain. A second possibility, which is less well documented, is the consecutive storage of CO_2 after oil production has ended. This is in essence storage in a depleted oil field, but with the opportunity of re-using the existing equipment. Although these storage options are not included in our analysis, the structure of PSS IV is foreseen for them to be added next to the enhanced oil production technology option.

6. Conclusions

The prospects for CO_2-EOR in the North Sea look promising. For this mature oil producing region, it is both an economic opportunity to extend the lifetime of "domestic" European production, and a possible business case for the permanent storage of CO_2 as a climate change mitigation measure. In this paper a simulation tool for CO_2-EOR projects, called PSS IV, is presented. PSS IV is a techno-economic simulator, which integrates several uncertainties and simulates realistic, near-optimal investment decisions for potential CO_2-EOR oil fields. In particular, geological uncertainties are integrated with technological and market uncertainties in a Monte Carlo calculation. Real Options Analysis is applied to further quantify investment risk and allow for investment flexibility in both space and time for single oil fields or clusters. Realistic, near-optimal investment decisions are simulated with limited foresight. PSS IV is unique in this combination of uncertainties, decision-making and project flexibility.

A case study for the Claymore and Scott oil fields in the North Sea has demonstrated the use of PSS IV. The cluster approach shows a higher project value compared to a single-field analysis. The latter methodology likely underestimates the project profitability. A comparison of the results of our case study with published numbers indicates that the results lie in a realistic range. A cost calibration is necessary though, and the true interactions within the model should be investigated in detail in a more in-depth case study. Simulation results show that at oil prices over 50 €/bbl CO_2-EOR can be a viable investment option.

A logical extension of this model is the inclusion of CO_2 storage without oil production, as a climate mitigation option. This is expected to reduce investment risk with added flexibility, although apart from ETS credits, this option provides no direct revenues. Adding technology options will, however, also affect calculation speed dramatically, a result from the brute force Real Options Analysis of the cluster. Other useful extensions to PSS IV include a body that manages the CO_2 distribution, an industry-standard investment decision criterion, such as the IRR, and the option of parallel or consecutive CO_2 storage.

Summarizing, the PSS IV simulator model goes much further than a traditional spreadsheet-based NPV calculation or sensitivity analysis. With the integration of different uncertainties in a Real Options calculation, this methodology leans closer to reality, and it is expected that more realistic assessments of the profitability of potential CO_2-EOR projects can be made. This adds to the credibility of these assessments and of possible CO_2 storage projects that might follow.

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