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ScienceDirect

Energy Procedia 63 (2014) 7836 – 7843

Energy Procedia

GHGT-12

The economic value of CO_2 for EOR applications

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Abstract

While most works on CCS in connection with CO_2 EOR credit all the benefit of the additional oil production to the CCS entity, this work investigate the impact of alternative EOR methods on the valuation on CO_2 EOR storage. Based on a generic model suitable for CO_2 EOR in Norwegian oil fields, EOR production with CO_2 injection is compared to the EOR production with chemical EOR for different scenarios.

The comparison shows that depending on the scenario combination considered the added value of using the CO_2 EOR method instead of the chemical EOR method varies from -4 to 33 €/$bbl_{produced}$ equivalent to -4 to 56 €/$tCO_{2,avoided}$. In most of the cases considered, the CO_2 EOR method would therefore be preferred with however more or less value creation depending on the case. The evaluation shows that for an oil price minus the normal production costs equal to 50 €/bbl, the oil value which shall be considered for CO_2 EOR application varies between 8 and 41 €/bbl, which can therefore be significantly lower than the 50 €/bbl which shall be considered if chemical EOR is not an alternative. The value one would be willing to pay to have CO_2 delivered at a field varies between -4 and 56 €/t_{CO2} depending on the scenario combinations considered and can therefore also be significantly lower than in cases in which chemical EOR is not an alternative. For example, in the medium CO_2 EOR scenario, the CO_2 value is between 27 and 60% lower if chemical EOR is considered as an alternative option for EOR. As a consequence, a CCS chain including CO_2 EOR would overestimate its benefits if it does not considered chemical EOR as an alternative to CO_2 EOR for Oil & Gas companies. Finally, the sensitivity analyses identify the factors having the largest influence on the value one would be willing to pay to have CO_2 delivered at its field.

Peer-review under responsibility of the Organizing Committee of GHGT-12

Keywords:Carbon Capture and Storage (CCS); CO2 EOR storage; Cost evaluation; Chemical EOR; Enhanced Oil Recovery.

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Peer-review under responsibility of the Organizing Committee of GHGT-12
doi:10.1016/j.egypro.2014.11.818

1. Introduction

CO_2 capture, transport and storage in connection with Enhanced Oil Recovery (EOR) is often considered to be a promising way to ensure cost-efficient avoidance of CO_2 emissions to atmosphere [1]. Indeed even if different methods for CO_2 capture and utilization exist, CO_2 EOR has two major advantages: first it is a technology which has already been implemented in the oil and gas industry and second, it can generate a product with a strong economic value.

While the industrial experience regarding the use of CO_2 for EOR has been available since the 70's from an oil production perspective, the business model can be expected to be different in the case of CCS with EOR storage. If the CO_2 capture and transport is handled by a different entity than the oil field operator, the two entities can be expected to have different and possibly competitive objectives. The oil production company may aim at maximizing its oil production revenues with low associated production costs while the CCS business entity may aim at lowering its costs to capture, transport and store CO_2 in order to have a full cost below the carbon emission credit (tax or quota). The frontier between the two entities is crucial to understand the "realistic" economic value of CO_2 for EOR applications. It is therefore important to also consider the objectives of oil production companies when considering CCS chains with EOR storage.

Most studies consider that all the benefit from additional oil production will offset the cost of CCS chains combined with EOR CO_2 [2-4]. However other methods can be used to recover, at least partly, the additional oil production which would have been obtained using CO_2 storage as EOR technique. Considering that other potentially cheaper options than CO_2 injection can be used for enhanced oil recovery, the full benefits from the additional oil production cannot be credited solely to the CCS chain. It is therefore important to consider the other EOR alternatives of Oil and Gas companies to determine the economic value creation associated with CO_2 EOR and thereby the value that one would be willing to pay for CO_2 available at an oil production field.

This paper will indicate the economic value of CO_2 for EOR based on generic models [5] for Norwegian oil fields suitable for CO_2 EOR. The methodology including scenarios, technical assessments and economic evaluation of the two options is first presented. The results of the assessments, the oil value which shall be considered for valuation of CCS project with CO_2 EOR, as well as the value one would be willing to pay for CO_2 available at an oil field are then presented. Sensitivity analyses are finally presented in order to address and quantify the impact of several factors on the results.

2. Methodology

2.1. Technical assessment

The following section presents the technical data and hypotheses considered for the assessment of the CO_2 EOR and chemical EOR options. For both technologies, three scenarios (high, medium and low) are built in order to represent a range of possible responses of the oil field to the EOR methods considered.

2.1.1. CO_2 flooding EOR

Predictions of the oil production response to CO_2 flooding are based on work presented in [5, 6]. Simulations are run on a set of generic reservoir models, with properties representative for North Sea oil reservoirs, to find representative CO_2 EOR responses. Predictions of oil, water and gas production profiles for any given real oil reservoir can be obtained by entering the reservoir specific properties (such as pressure, temperature, oil density and viscosity, permeability) into a response-surface model fitted to the simulation results [6] or by scaling the results from the generic simulation with the best match to the reservoir properties [5]. For this work, generic results are generated using typical North Sea reservoir and oil properties. It is assumed that the reservoir originally contained 90 MSm^3 of oil (570 Mbbl) and that it has been water flooded at a rate of 79 000 bbl/day for 24 years prior to the start-up of CO_2 flooding. It is assumed that CO_2 flooding is performed at the same volumetric rate as the preceding water flooding [5, 6], which for the modelled reservoir corresponds to an injection rate of 4.79 million tonnes CO_2

per year[†]. The model-generated results give an additional oil recovery of 9% of the original oil in place (OOIP). This is used as the *medium* scenario. *Low* and *high* scenarios are obtained by scaling of the medium scenario to obtain additional recoveries of about 5 and 15% of OOIP.

Based on the CO_2 injection and the EOR oil production profiles, the technical characteristics of the CO_2 EOR storage (wells and oil production plateau) are assessed using the BIGCCS storage module [7] based the ZEP methodology [8] and Holt et al. [9]. The following considerations are therefore assumed to determine the required number of wells of each category:

1) No new exploration wells are required as the data have already been acquired during the normal development and production of the oil field;
2) No observation well is considered for offshore cases;
3) The number of injection wells is calculated based on typical capacity for injection wells and the required total injection rate;
4) The number of contingency wells is assumed to be 10% of the number of injection wells, with a minimum of 1 contingency well;
5) The oil production wells are considered to be existing and therefore their costs are not included in the costs of CO_2 EOR.

2.1.2. EOR using chemical flooding

Chemical EOR such as alkaline-surfactant-polymer (ASP) flooding schemes are reported to give quite high (up to 30% or more) additional oil recoveries in laboratory core flooding experiment and small-scale on-shore field pilots [10-12]. With beneficial sweep patterns (such as line-drive) the production profile is characterized by an initial delay before the oil production response is seen in the production well, followed by a steady production as the oil bank mobilized by the chemical flooding is produced. Reservoir modelling of chemical EOR has not been performed for the discussion in the present paper. Rather, a set of generic EOR profiles are constructed based on other reported work. More moderate total additional recovery is assumed for offshore fields, based on the following reasoning: the remaining oil after water flooding in the reported cases is typically a high fraction of OOIP (due to unfavorable conditions for water flooding), the well to well distance is much smaller than what can realistically be obtained offshore, and the flooding pattern (five-spot or line-drive) is more optimal due to the lower well cost. Additional oil recoveries of 10, 7 and 5% are therefore assumed for the high, medium and low scenarios, respectively. As for the CO_2 EOR case, the injection rate for the chemical flooding is taken to be the same as for the water flooding phase preceding the EOR operation.

2.2. Economic assessment

The evaluation of the two options is based on a Net Present Value (NPV) approach accounting for both EOR oil production revenues as well as production costs. Two methodologies are used in order to evaluate the costs associated with CO_2 and chemical EOR methods.

2.2.1. CO_2 EOR storage cost evaluation

The cost model for CO_2 EOR storage is assessed using the BIGCCS storage module based on the ZEP methodology [8] to represent the cost associated with the CO_2 storage in a Depleted Oil and Gas Field, and Holt et al. [6] to represent the costs and benefits associated with the CO_2 EOR production..

The costs consist of six phases over the project lifetime:

1) Pre-FID which include the cost of modelling/logging, inject test and permitting;
2) The platform costs which include the costs associated with the modification of the oil production process and costs associated with recompression of CO_2.

[†] It is important to note that even if the yearly amount injected remains constant over the project duration, the amount of CO_2 imported (i.e. avoided) decreases over the duration in order to accommodate the excess break-through CO_2 produced by the oil field and which shall be reinjected.

3) Injection wells which include the cost of new injection wells, legacy well remediation of reused wells and contingency wells;
4) Operating cost which include costs associated with operation and maintenance of the installation;
5) Monitoring, Measuring and verification which include the costs of recurring MMV, new observation wells, post-closure monitoring, the baseline seismic survey and final seismic survey;
6) Close-down which include the cost associated with decommissioning of all wells and platform 20 years after closure and the liability cost.

As an illustration of the methodology, the unitary costs of offshore depleted Oil & Gas field (DOGF) and saline aquifer (SA) are presented in Table 1 for three cost scenario (low, medium and high).

Table 1: Offshore CO_2 storage cost (€$_{2009}$/t$_{CO2}$) scenarios characteristics [7]

Type of storage	Legacy wells	Low cost scenario	Medium cost scenario	High cost scenario
DOGF	Yes	2.1	7.4	10.6
DOGF	No	2.7	9.9	13.7
SA	No	4.7	14.2	20.2

2.2.2. EOR using chemical flooding cost evaluation

A wide range of cost for chemical EOR is available in the literature and these costs are often representative of onshore North American conditions and might be expected to be higher for offshore locations in the Norwegian continental shelf. As a consequence a unitary cost of production of 20 €/bbl of oil produced by chemical EOR is assumed (which correspond to 26 $/bbl [13]) . This cost is expected to account for:

1) Investments required for the overall chemical EOR infrastructure such as multiple mixing tanks for chemicals, equipment for optimization of water composition, transport infrastructure for chemicals, treatment of produced water, treatment of produced oil;
2) Operating expenses such as operation and maintenance, labor, expenses associated with injected chemicals and chemicals for post-treatment of water and oil

As the unitary cost of production using chemical EOR is an uncertainty, sensitivity analyses include this parameter in order to quantify its impact on the Key Performance Indicator.

2.2.3. EOR production revenues

The revenues associated with the EOR oil production are calculated based on the EOR annual production profile of each of the two EOR options, as well as the oil price:

$$\text{Annual EOR Revenue}\,(€) = \text{Annual EOR oil production (bbl)} \cdot \text{Oil valuation}\,(€/\text{bbl}) \quad (1)$$

The oil valuation considered is the oil barrel FOB (Free On Board) price in Rotterdam minus costs which are not included in the EOR production costs, such as normal production costs as well as transport from the oil platform (in the North Sea) until Rotterdam. This price assumed to be equal to 50 €/barrel corresponding to the average price of oil 90$\$_{2013}$/barrel [14] minus a production cost of 25$/barrel [15].

2.2.4. Project valuation and value creation

The economic evaluation of each of the two options is made using the Net Present Value with is the discounted cashflow of project revenues minus the project costs. The NPV are calculated assuming a real discount rate of 8%[‡] and an economic lifetime of 25 years [16, 17].

[‡] This real discount rate of 8 % corresponds to a nominal discount rate around 10% if an inflation rate of 2% is considered.

The unitary value creation (€/bbl or €/$t_{CO2,avoided}$) associated with CO_2 EOR compared to EOR using chemical flooding is obtained by dividing the differences in NPVs by either the discounted amount of EOR oil produced or the discounted amount of CO_2 avoided as shown in equation 2.

$$\text{Unitary } CO_2 \text{ EOR value creation} = \frac{NPV_{CO2\ EOR\ storage} - NPV_{Surfactant\ flooding\ EOR}}{\sum_{\text{project duration}} \frac{\text{Amount of CO2 EOR oil produced or Amount of CO2 avoided}_k}{(1+\text{discount rate})^k}} \quad (2)$$

The unitary oil value which shall be considered to evaluate CCS projects with CO_2 EOR can then be calculated considering that one would be willing to pay the oil price minus the production cost for the CO_2 EOR oil production above the chemical EOR one and only the chemical EOR unitary production cost below, divided by the discounted production. In the same way, the value someone would be willing to pay to have CO_2 delivered at its field, considering chemical EOR as an alternative, follows the same equation considering also the CO_2 EOR storage costs and with the discounted amount of CO_2 avoided at the denominator. The "oil value" and "CO_2 value" can therefore be written as illustrated respectively in equation 3 and 4.

$$\text{Oil value (€/bbl)} = \frac{\left(\sum \frac{\text{EOR production}_{CO2\ EOR}}{(1+\text{discount rate})^k} - \sum \frac{\text{EOR production}_{Chemical\ EOR}}{(1+\text{discount rate})^k}\right) \cdot (\text{Oil price} - \text{Production cost})}{\sum \frac{\text{Amount of CO2 EOR oil produced}_k}{(1+\text{discount rate})^k}} + \frac{\sum \frac{\text{EOR production}_{Chemical\ EOR}}{(1+\text{discount rate})^k} \cdot \text{Chemical EOR unitary production cost}}{\sum \frac{\text{Amount of CO2 EOR oil produced}_k}{(1+\text{discount rate})^k}} \quad (3)$$

$$CO_2 \text{ value (€/}t_{CO2,avoided}) = \frac{\left(\sum \frac{\text{EOR production}_{CO2\ EOR}}{(1+\text{discount rate})^k} - \sum \frac{\text{EOR production}_{Chemical\ EOR}}{(1+\text{discount rate})^k}\right) \cdot (\text{Oil price} - \text{Production cost}) - Investment - \sum \frac{OPEX_k}{(1+\text{discount rate})^k}}{\sum \frac{\text{Amount of CO2 avoided}_k}{(1+\text{discount rate})^k}} + \frac{\sum \frac{\text{EOR production}_{Chemical\ EOR}}{(1+\text{discount rate})^k} \cdot \text{Chemical EOR unitary production cost}}{\sum \frac{\text{Amount of CO2 avoided}_k}{(1+\text{discount rate})^k}} \quad (4)$$

Finally, sensitivity analyses are performed in order to address and quantify the impact of a range of important uncertainties on the value someone would be willing to pay to have CO_2 delivered at its field.

3. Results and discussion

3.1. Technical results

As shown in Figure 1, the general shape of the additional oil production profile for both CO_2 EOR and chemical EOR is characterized by an initial delay after the start of the EOR operation. The CO_2 EOR profile is based on reservoir simulations as described above. The profile for chemical flooding is generated as Beta distribution functions with lower and upper limits set to 0.1 and 2 PV injected, and with α and β parameters equal to 2 and 6. This gives the characteristic delay before EOR oil response and a higher oil rate early in the EOR period. The

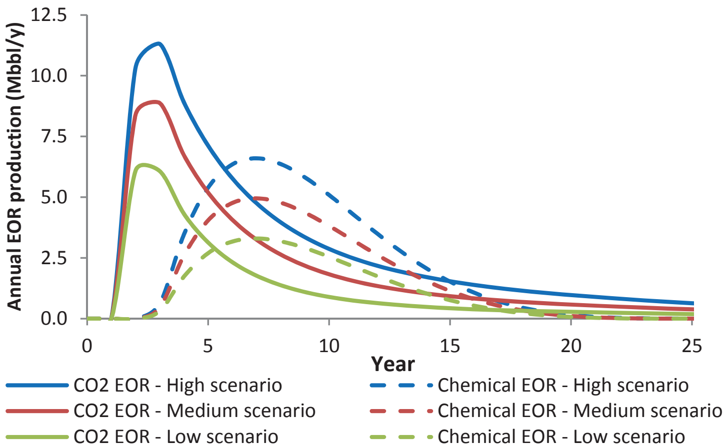

Figure 1: Annual EOR oil production scenarios for the two EOR methods and the three production scenarios

initial delay is assumed to be longer for chemical EOR, due to the more favourable mobility ratio of the injected fluids and corresponding longer time for breakthrough. It should again be noted that the chemical EOR profiles should not be taken as categorical values, since it is used in this work to illustrate a principle related to the valuation of CO_2 for EOR.

3.2. Economic results

The results of the economic comparison between the use of the CO_2 EOR method and the chemical EOR method are given in Table 2. The comparison, including respective EOR productions and associated costs, shows that depending on the scenario combination the added value of using the CO_2 EOR method instead of the chemical EOR method varies from -4 to 33 €/bbl$_{produced}$ equivalent to -4 to 56 €/t$CO_{2,avoided}$. The CO_2 EOR method would therefore be preferred in most of the cases considered, except in the high chemical EOR and low CO_2 EOR scenario combination, with however more or less value creation depending on the case considered.

Table 2: Value creation associated with the use of CO_2 EOR instead of chemical EOR (a) in €/bbl$_{produced}$ (b) in €/t$_{CO2, avoided}$

(a)

		Chemical EOR Scenario		
		High	Medium	Low
CO_2 EOR Scenario	High	23	28	33
	Medium	15	21	28
	Low	-4	5	16

(b)

		Chemical EOR Scenario		
		High	Medium	Low
CO_2 EOR Scenario	High	40	48	56
	Medium	18	26	34
	Low	-4	4	12

Based on the fact that chemical EOR can be an alternative to CO_2 EOR, the oil value which shall be considered for valuation of CCS project associated with CO_2 EOR and the value one would be willing to pay to have CO_2 delivered at its field are calculated and presented in Figure 2. Figure 2 also presents the value someone would be willing to pay for CO_2 delivered at its field if chemical EOR is not an option. The evaluation shows that for an oil price minus the normal production costs equal to 50 €/bbl, the oil value which shall be considered for CO_2 EOR application varies between 8 and 41 €/bbl, which can therefore be significantly lower than the 50 €/bbl which shall be considered if chemical EOR is not an alternative. It is worth noting that in cases in which CO_2 EOR is more profitable than chemical EOR, the oil value is comprised between the chemical EOR cost and the oil price minus normal production costs depending on the difference in production between the two EOR methods. On the other hand, in cases in which the chemical EOR is more profitable than CO_2 EOR, the oil value which shall be considered will be below the chemical EOR production costs and might be lower than zero in cases in which the EOR oil production associated with CO_2 EOR is significantly below the chemical EOR one.

The evaluation of the different scenarios shows that the value one would be willing to pay to have CO_2 delivered at its field[§] varies between -4 and 56 €/t$_{CO2,avoided}$ depending on the scenario combination considered and can therefore also be significantly lower than in cases in which chemical EOR is not an alternative. For example, in the medium CO_2 EOR scenario, the CO_2 value is between 27 and 60% lower if chemical EOR is considered as an alternative option. As a consequence, a CCS chain including CO_2 EOR would overestimate its benefits if it does not considered chemical EOR as an alternative to CO_2 EOR for Oil & Gas companies.

The sensitivity analyses on the value one would be willing to pay to have CO_2 delivered at a field is illustrated in Figure 3 for the combination of medium scenarios. The sensitivity analyses show that the four factors with the highest impact are the CO_2 EOR scenario, the chemical EOR scenario, the oil price and the chemical EOR cost scenario as they are directly linked to the CO_2 value defined in section 2.2.4. On the contrary, the discount rate and the CO_2 EOR cost scenario have a smaller influence.

[§] It is however important to keep in mind that this cost includes only the costs linked to the storage of the amount of CO_2 imported to the EOR storage while the costs associated with capture, transport of the imported CO_2, as well as the storage of the remaining CO_2 in an additional reservoir are not included.

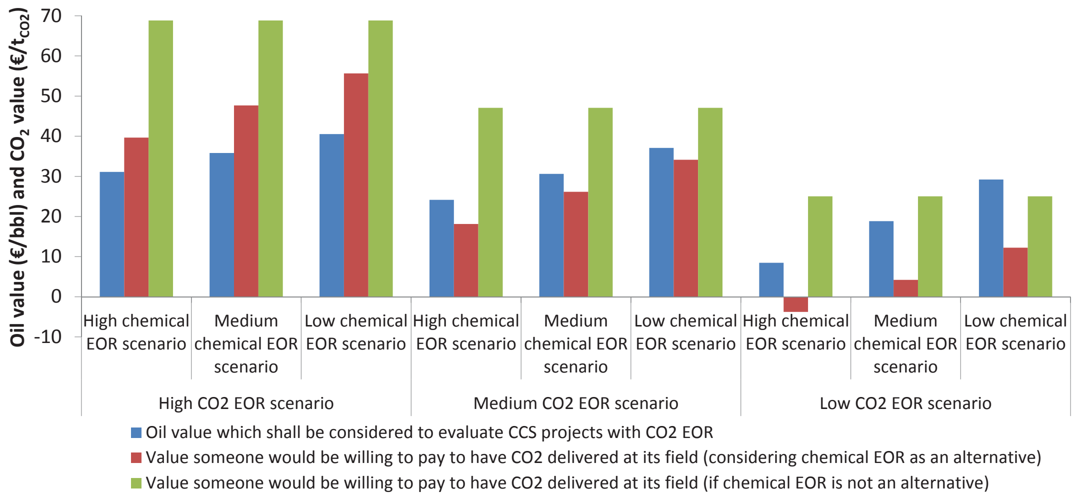

Figure 2: Oil value which shall be considered in CCS project associated with CO_2 EOR (€/bbl) and values one would be willing to pay to have CO_2 delivered at its field (€/$t_{CO2,avoided}$)

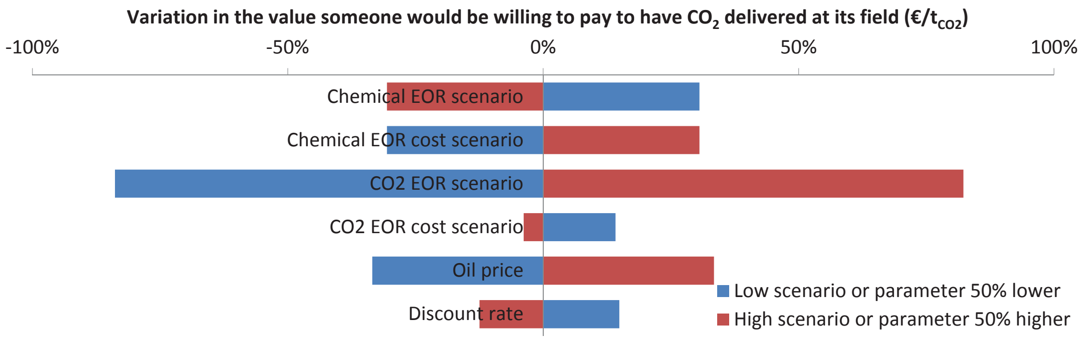

Figure 3: Sensitivity analyses on the value someone would be willing to pay to have CO_2 delivered at its field for the combination of the medium CO_2 EOR and medium chemical EOR scenarios

4. Conclusions

While most works on CCS in connection with CO_2 EOR credit all the benefits of this additional oil production to the CCS entity, this work investigate the impact of alternative EOR methods on the valuation on of CO_2 EOR in connection with CO_2 EOR. Based on a generic model suitable for CO_2 EOR in Norwegian oil fields, the EOR productions of CO_2 injection is compared to the EOR production of chemical EOR for different CO_2 EOR and chemical EOR scenarios.

The comparison shows that depending on the scenario combination considered the added value of using the CO_2 EOR method instead of the chemical EOR method varies from -4 to 33 €/$bbl_{produced}$ equivalent to -4 to 56 €/$tCO_{2,avoided}$. In most of the cases considered, the CO_2 EOR method would be preferred with however more or less value creation depending on the case. The evaluation shows that for an oil price minus the normal production costs equal to 50 €/bbl, the oil value which shall be considered for CO_2 EOR application varies between 8 and 41 €/bbl, which can therefore be significantly lower than the 50 €/bbl which shall be considered if chemical EOR is not an option. The value one would be willing to pay to have CO_2 delivered at its field varies between -4 and 56 €/t_{CO2}

depending on the scenario combinations considered and can therefore also be significantly lower than in cases in which chemical EOR is not an alternative. For example, in the medium CO_2 EOR scenario, the CO_2 value is between 27 and 60% lower if chemical EOR is considered as an alternative option. Finally, the sensitivity analyses show that the four factors with highest impact on the value one would be willing to pay to have CO_2 delivered at its field are the CO_2 EOR scenario, the chemical EOR scenario, the oil price and the chemical EOR cost scenario.

While specific cases would be required to obtain more accurate results, the methodology and results presented in this paper provide support to help to identify the range of costs which could be expected for CCS chains with EOR and therefore also the range of the emission penalty cost (CO_2 quota or tax) which would be necessary to make these chains viable. Indeed by crediting all the benefits of the additional oil production to the CCS entity, the emission penalty required is underestimated, therefore potentially giving the wrong indications to policy makers, CCS actors, as well as researchers on the correct value of CO_2 for EOR applications.

Acknowledgements

This publication has been produced with support from the BIGCCS Centre, performed under the Norwegian research program Centres for Environment-friendly Energy Research (FME). The authors acknowledge the following partners for their contributions: ConocoPhillips, Gassco, Shell, Statoil, TOTAL, GDF SUEZ and the Research Council of Norway (193816/S60).

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