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ABSTRACT

Production of mature oil fields emits significant amount of CO_2 related to circulation and handling of large volumes of gas and water. This can be reduced either by (1) using a low-carbon energy source and/or (2) reducing the volumes of the non-hydrocarbon produced/injected fluids. This paper describes how improved oil recovery techniques can be designed to reduce CO_2 intensity (kgCO_2/bbl oil) of oil production by efficient use of the injectants. It is shown that CO_2 emissions associated with injection of chemicals is strongly influenced by water cut at the start of the project, extent of the water cut reduction, and chemical utilization factor defined as the volume of produced oil per mass or volume of the injectant. As an example, for the oil field considered in this study, 3–8% reduction in water cut can result in 50–80% reduction in its CO_2 intensity. In addition to the incremental oil production with lower CO_2 intensity, the earlier implementation of enhanced oil recovery methods can extend the lifetime of the mature fields if carbon emission cut-offs are applied. In case of CO_2 enhanced oil recovery (EOR), the large storage potential for CO_2 can significantly reduce the overall CO_2 emissions of oil, albeit at a large energetic cost. For CO_2 EOR using CO_2 captured from gas power plants, improving the utilization factor from 2 bbl/tCO_2 to 4 bbl/tCO_2 can reduce the CO_2 intensity of the produced oil from 120 kgCO_2/bbl to 80 kgCO_2/bbl (33% reduction).

1. Introduction

Production of oil and gas requires a large amount of energy from the exploration stage to the final transport and refining of the extracted fuel. Therefore, emissions from hydrocarbon extraction account for significant shares of domestic emissions in many oil and gas exporting countries. This amounts to more than 20% of the total emissions of countries like Russia, Norway, and Canada (Brandt et al., 2018; Masnadi and Brandt, 2017). The large fraction of greenhouse gas emissions in the upstream oil and gas industry is associated with power generation for mechanical equipment and consumption, production processes such as oil and water treatment, fuel gas for onsite equipment such compressors, gas flaring, venting, fugitive emissions (i.e., leakage) and transportation (MacKay et al., 2021).

As the hydrocarbon fields mature, the energy requirement for the production and processing of the oil significantly increases (Masnadi and Brandt, 2017). First, the natural pressure of the reservoir is not sufficient to produce the fluids. This results in additional pumps to lift the fluids from the producing wells (Farajzadeh, 2019). An alternative to limit lifting is to maintain pressure by injection of large volumes of external fluids, use of downhole or surface lift pumps and gas lift, which are among the energy-intensive measures to extract oil. Nevertheless, the produced oil comes out with a large fraction (often >90%) of water (and/or gas). When chemicals are injected to enhance the oil production, breakthrough of the chemicals in the production stream can add to the energy burden of the production site. The separation of oil and water emulsion and the subsequent treatment and reinjection of the produced water are relatively energy-intensive processes (Al-Shidi et al., 2018). As shown in Fig. 1, pumping, compression, and treatment units are usually electricity-driven, with electrical energy that is supplied by a gas turbine

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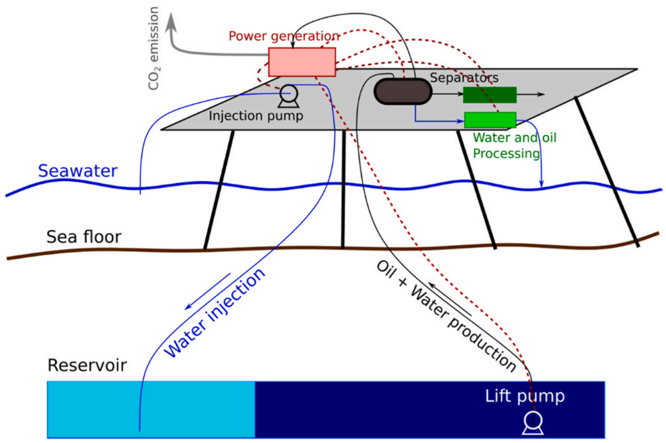

Fig. 1. A schematic of the major energy consumer units on an offshore platform that injects water and processes the produced oil and water.

or a diesel generator. The limited space on the (offshore) production platforms or remote field location prevents heat integration and imposes constraints on more efficient use of high pressure and temperature material streams.

There are different approaches to reducing carbon dioxide (CO_2) emission from a platform. Several fields in offshore Norway are already fully driven by electricity mostly provided from onshore renewable resources. An integrated study showed that under certain circumstances, the CO_2 emission would be reduced by 90%, even though the long-term economic feasibility of the electrification is questionable considering the future carbon tax that is countered by the high electricity prices (Riboldi et al., 2019). Increasing the efficiency of the units with the largest energy demand is another approach that can reduce the energy consumption and the CO_2 emission of the platform. Exergy analysis of a Norwegian offshore platform showed that the largest energy consumption occurs in the gas recompression and reinjection compressors (Voldsund et al., 2013). The same study showed that the maximum exergy loss, i.e., loss of the potential of the high-pressure fluid stream that can be converted to work, occurred in the production manifold (Voldsund et al., 2013). Exergy is the maximum "useful" work that can be obtained from an energy stream when brought in equilibrium with the reference environment with well-defined thermodynamic conditions called dead state (Szargut and Morris, 1987). Another study showed that the high pressure and temperature of the produced fluids can be converted to electricity in an expander (Nguyen et al., 2016). Those analyses, however, could not come up with a unique procedure for increasing the efficiency (and reducing the energy demand) of a production platform. Generally, increasing the efficiency of the specific equipment can only be realized marginally and identifying and utilizing the energy losses on the platform can achieve better results.

The other approach to reduce energy consumption in the field is (1) to reduce the volume of the injected fluids, often water (with and without added chemicals) and gas and/or (2) to reduce the production of the liquids, particularly the produced water and gas volumes. In most mature oil reservoirs, the production stream consists of water with a small volumetric oil fraction (Masnadi and Brandt, 2017; Battashi et al., 2022). Produced water and gas are usually re-injected into the reservoir after some treatment. Controlling the mobility of the injected water by adding, e.g., polymers and improving its microscopic sweep efficiency, for instance, by adding surfactants could result in additional oil in the producing wells (Lake et al., 2014; Bedrikovetsky, 1993; Farajzadeh, 2019). Such an approach should consider the additional energy required to produce the oil. The focus of this paper is to discuss this approach in detail.

The anthropogenic or captured CO_2 can be utilized in several processes and industries (see Peter, 2018 for example) to mitigate its negative environmental impact. However, the techno-economic risks and uncertainties has slowed down the progress of utilization of CO_2 (Tapia et al., 2018). Enhanced oil recovery using CO_2 is a mature technology that can lead to reduction of net emissions of CO_2 from conventional (Azzolina et al., 2017) and unconventional hydrocarbon reservoirs (Tapia et al., 2018; Syed et al., 2022). The injected CO_2 can replace the produced fluids and be permanently stored in the reservoir. CO_2 EOR has the potential to finance the cost of large-scale CCS while simultaneously reducing the carbon footprint of oil production (Middleton, 2013). Tapia et al. (2018) developed a methodology to optimize the CO_2 allocation and scheduling for EOR operations involving multiple fields. During production of unconventional reservoirs, especially in a low gas-price environment and when the infrastructure for gas transportation is unavailable, produced natural gas is commonly flared or vented. According to U.S. Energy Information Administration, more than 270 billion cubic feet of natural gas was flared or vented in 2015 (Energy Information Administration, 2015). Re-injection of the produced gas or resulting CO_2 from flaring can therefore limit the amount of flared or vented gas and simultaneously increase the oil production from these reservoirs (Du and Nojabaei, 2019). CO_2 huff-n-puff has been also suggested is an efficient technique to trap CO_2 in unconventional fields (Syed et al., 2022).

While the body of the literature has focused on utilizing CO_2 as an EOR agent, this study extends the previous work by Farajzadeh et al. (2021) to provide additional insights into impact of I/EOR methods on cleaner production of hydrocarbon fields. The developed correlations can be used to quantify CO_2 intensity of produced oil from water-based I/EOR methods. CO_2 intensity in this paper is defined as the mass of CO_2 emitted to the atmosphere per unit volume of oil produced (kg-CO_2/m^3 oil or kg-CO_2/bbl oil). Moreover, field data and ensuing analyses for two reservoirs in the Middle East in which polymer is injected for improving oil recovery is included in the paper. Finally, the method is extended to gas EOR to study the impact of different gas types on the exergetic efficiency of the process. The special case of CO_2 EOR is discussed in more details.

2. Methodology

To quantify overall CO_2 footprint or CO_2 intensity of a given EOR technique, the exergy consumed in the process should be calculated. The invested exergy is in the forms of electricity and material. While a direct relation between electricity and CO_2 emission can be assumed (considering the source of electricity), the CO_2 emission from material part is not as straightforward. A generic schematic of the main elements of the EOR processes and the methodology to calculate CO_2 intensity of the oil are given in Fig. 2. It considers the exergy required to manufacture the injectant (such as gas or chemicals) and its shipment to the field. The injectants are typically treated or mixed with water before injection. The produced oil and gas are the exergy sources, which are lifted from the producing wells using pumps. The produced water or gas can either be re-injected, disposed or sold to the market. In case injectant is gas, the produced gas is recompressed before injection. For EOR projects involving injection chemicals like polymer and/or surfactant, this study follows the procedure and calculations already described in Farajzadeh et al. (2021).

In summary, to calculate the CO_2 intensity of the produced oil for every I/EOR method the history of the produced oil and the exergy invested to produce the oil are required. The oil production history can be obtained either directly from field (Fig. 8) or from numerical/analytical simulations (Figs. 9 and 12). To calculate the exergy required to produce the oil, the work streams should be identified for each oil-recovery method. For example, for the chemical EOR processes, the work streams that are considered in this study include manufacturing of chemicals and their shipment, water treatment, water injection, polymer injection, lift of liquids, heating of oil, and processing of the fluids at the surface. The exergy required in each work stream is calculated from the

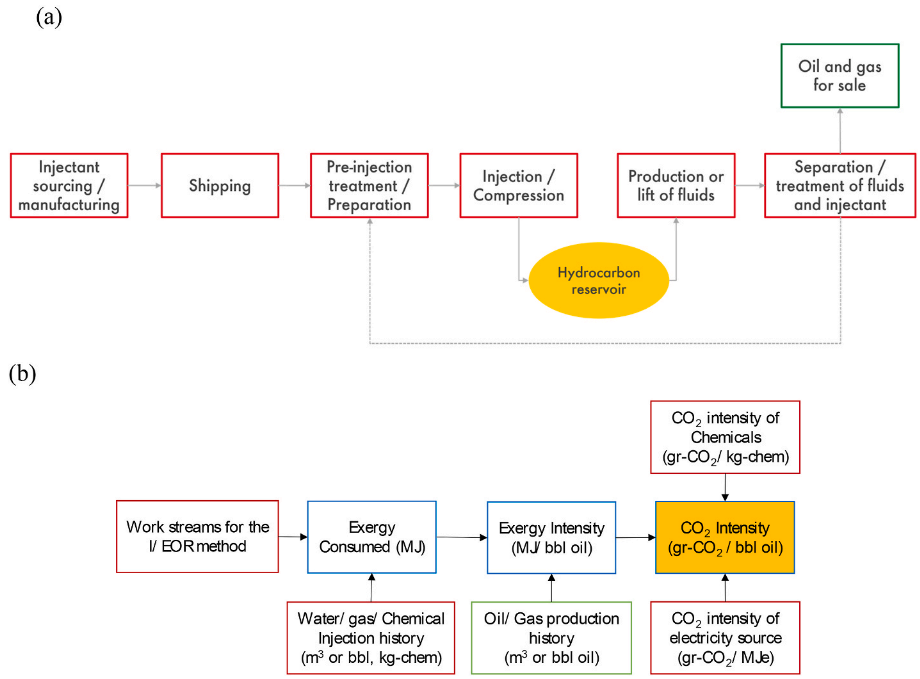

Fig. 2. A generic schematic of main components of an EOR process (a) and flowchart for calculation of the CO_2 intensity (b).

correlations provided in Table 1. For gas EOR processes, the work streams and the ensuing calculations are explained in section 3.5. The conversion of the exergy intensity (MJ/bbl) to CO_2 intensity (gr-CO_2/bbl or tCO_2/tHC) requires the specific CO_2 emission of the electricity source (gr-CO_2/MJe). Here, the assumption is that the electricity is supplied from a gas-fueled power plant with an average CO_2 intensity of 55 g-CO_2/MJe. The contribution of the chemicals is considered by adding CO_2 intensity of their manufacturing and shipment and chemical utilization factor in each time step.

3. Results and discussion

3.1. CO_2 intensity of oil production by water injection

It has already been shown (Farajzadeh, 2019; Farajzadeh et al., 2019a,b) that CO_2 intensity of the oil produced by water injection strongly depends on the water utilization factor w_{UF} (m^3-water/m^3-oil), which is defined as the volume of the injected water to produce one unit volume of oil. Assuming that the volume formation factors of water and oil are 1, no gas is produced, and the produced liquid volume is replaced by the injected water, i.e., a voidage replacement ratio (VRR) of 1, one can obtain Equation (1)

$$w_{UF} = \frac{q_{w,inj}}{q_{o,prod}} = \frac{q_{o,prod} + q_{w,prod}}{q_{o,prod}} = \frac{1}{1 - f_w} \tag{1}$$

where water fractional flow or water cut, f_w, is defined as Equation (2)

$$f_w = \frac{q_{w,prod}}{q_{o,prod} + q_{w,prod}} \tag{2}$$

Fig. 3 shows the correlation between water cut and the CO_2 intensity of oil production (kg-CO_2/bbl oil) for a mature field in the Middle East. The details of calculations can be found in Farajzadeh et al., (2021). For a waterflood project, the largest fraction of energy consumption is associated with operating injection and lift pumps (see for example

Table 1
Correlations to calculate the required exergy for chemical EOR processes (Farajzadeh et al., 2021).

Work Stream	Specific Exergy [kJ/kg]
Injection pump ($\dot{Ex}_{liquid}^{pr,pump}$)	$\dot{Q}\Delta P/\eta$
Artificial lift ($\dot{Ex}_{liq}^{th,lift}$)	$[\dot{Q}(f_w\rho_w + (1 - f_w)\rho_o)gh]/\eta$
Water treatment	18 (5 kWh/m^3)
Heating of crude oil (($\dot{Ex}_{oil}^{heating}$)	$\dot{m}_{oil}c_p\Delta T$
Transport of oil to refinery	188 J/kg-km
Other surface processes	20% (10%) of the total exergy for polymer/surfactant (water)
Polymer manufacturing	123600
Surfactant manufacturing	62000

$\dot{Ex}$ (kJ/kg): specific exergy, $\dot{Q}$ (m^3/s): flow rate, ΔP (Pa): pressure, η (−): pump efficiency, ρ (kg/m^3): density, g (m/s^2): acceleration due to gravity, h (m): reservoir depth, $\dot{m}_{oil}$ (kg/s): mass rate of produced oil, c_p (kJ/kg/K): heat capacity, ΔT (K): temperature difference between reservoir and transportation pipeline.

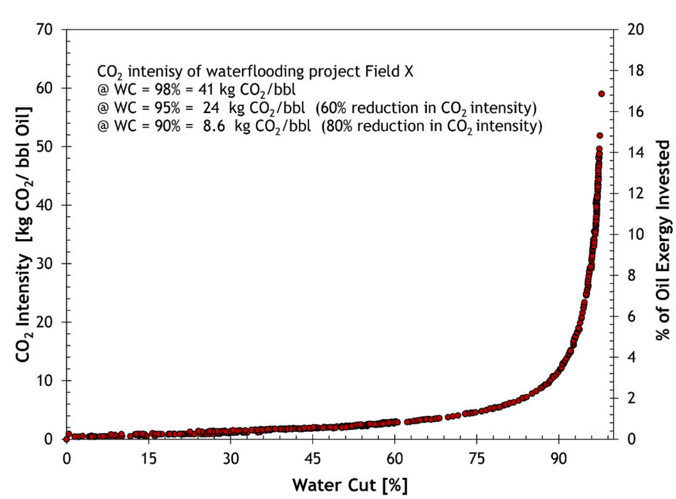

Fig. 3. Correlation between the CO_2 intensity of oil production vs. the water cut for a waterflood project.

Farajzadeh et al., 2019a,b). In the calculations, it has been assumed that the electricity required to drive the electrical components are supplied from a gas-fueled power plant with CO_2 intensity of 200 kg-CO_2/MWhe.

Below $f_w = 80\%$, little CO_2 is generated; however, when $f_w > 90\%$ a slight increase in the water cut leads to a significant increase in CO_2 emissions per barrel of oil produced. This emphasizes the importance of water management in water drive recovery of oil. Similarly, as the water cut increases, a significant fraction of gained energy from oil is "wasted" for its production as exceedingly more energy is spent on the circulation of water.

Fig. 4 plots the CO_2 intensity of oil production as a function of water utilization factor, $e_{CO_2,WF}$, which exhibits a linear behavior. Therefore, one can write Equation (3) to describe this behavior:

$$e_{CO_2,WF} = aw_{UF} + b = \frac{a}{1-f_w} + b \tag{3}$$

The factor b (kg-CO_2/m^3-oil) is the CO_2 resulting from the activities and processes that are not directly related to water injection. Examples include oil/water separation, chemicals, oil transportation to the refinery, crude oil heating, etc. For light oils (example shown in Fig. 3) and especially for water cuts larger than $f_w > 0.90$ it can be assumed that $b \ll \frac{a}{1-f_w}$. Therefore, Equation (3) simplifies to Equation (4):

$$e_{CO_2,WF} \approx \frac{a}{1-f_w} \tag{4}$$

The factor a (kg-CO_2/m^3-water) is the CO_2 emission related to the handling of a unit volume of water in the operations and can be calculated from the energy spent on water handling (MJ/m^3-water) and CO_2 intensity of the source of energy. Typical values are in the range of 20–40 MJ/m^3-water (Farajzadeh et al., 2019a).

3.2. Impact of chemical enhanced oil recovery on CO_2 intensity of oil production

Fig. 3 suggests two possible ways to reduce CO_2 emissions from mature fields with high water cut. The first method is to switch the power supply to low-carbon sources, which requires investment in the infrastructure and some modifications in the equipment. The second method relies on reducing the circulation of fluids and efficient utilization of the injectants, which is the focus of I/EOR methods. Chemical EOR methods such as polymer and surfactant injection are mature technologies currently applied in some fields around the globe. The application of these methods can reduce CO_2 intensity of mature oil fields with high water cuts (Farajzadeh et al., 2021). Here, a simple correlation to quantify the CO_2 intensity of chemical EOR projects is developed.

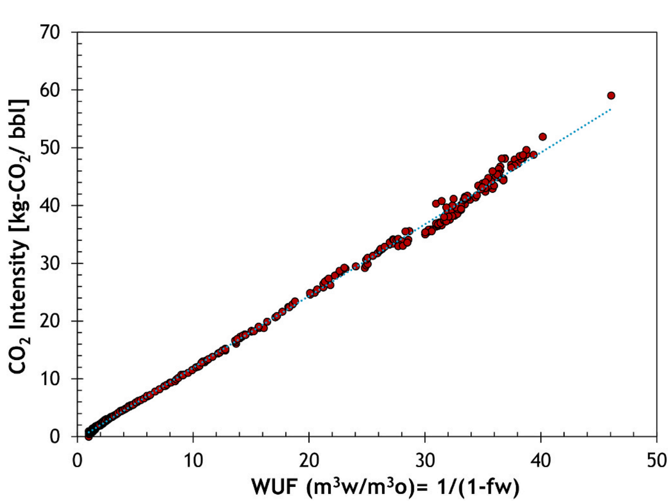

Fig. 4. The linear correlation between the CO_2 intensity of oil production and water utilization factor for waterflood projects.

To calculate the total CO_2 intensity of oil produced by chemical EOR, the CO_2 emitted from manufacturing and shipment of the chemicals ($e_{CO_2,chem}$, kg-CO_2/kg-chemical) should be added to Equation (1) to obtain Equation (5):

$$e_{CO_2,cF} = aw_{UF} + e_{CO_2,chem}c_{UF} \tag{5}$$

where, the chemical utilization factor, c_{UF} (kg-chemical/m^3-oil), is defined as the mass of the chemical(s) injected to produce one unit volume of oil. If c_{UF} is not known, Equation (6) can be written as

$$e_{CO_2,cF} \approx \frac{1}{1-f_w}\left(a + c_{m,chem}\rho_S e_{CO_2,chem}\right) \tag{6}$$

where, c is the mass concentration of the chemical in the formulation, and ρ_S is the mass density of the injected solution. If more than one chemical is injected Equation (6) can be expanded to Equation (7)

$$e_{CO_2,cF} \approx \frac{1}{1-f_w}\left(a + \sum_{c=1}^{n}\rho_{S,c}c_{m,c}e_{CO_2,c}\right) \tag{7}$$

The difference between the CO_2 intensity of the water flood and chemical EOR processes (EOR-CO_2 saving) can be calculated from Equation (8)

$$\Delta e_{CO_2,cF} = e_{CO_2,wF} - e_{CO_2,cF} = a\left(w_{UF,ini} - w_{UF,c}\right) - e_{CO_2,chem}c_{UF} \tag{8}$$

which can be re-written as Equation (9)

$$\Delta e_{CO_2,cF} = a\left(\frac{1}{1-f_{w,ini}} - \frac{1}{1-f_{w,c}}\right) - e_{CO_2,chem}c_{UF} \tag{9}$$

Or Equation (10),

$$\Delta e_{CO_2,cF} = \frac{a\Delta f_w}{\left(1-f_{w,ini}\right)\left(1-f_{w,c}\right)} - e_{CO_2,chem}c_{UF} \tag{10}$$

where $\Delta f_w = f_{wi} - f_{w,c}$ is the water-cut reduction due to injection of chemicals. Equation (10) indicates that the efficiency of chemical EOR in reducing CO_2 intensity of oil production depends on the magnitude of the water-cut reduction and the water cut at the start of the chemical injection. Fig. 5 shows the CO_2 saving for a polymer EOR project with polymer utilization factor of 2 kg-polymer/bbl-oil as a function of the water-cut reduction. The subsurface efficiency of a chemical EOR project is usually measured by the magnitude of the water-cut reduction after injection of the chemicals. The larger the water cut reduction, the more efficient the injected chemicals and hence better economics and chemical utilization factor. Naturally, when the water cut is very high, the amount of CO_2 emitted during oil production is also very high; consequently, a small reduction in the water cut can significantly reduce the CO_2 intensity. As shown in Fig. 5 the reduction of water cut from 98% (which is typical for a mature oil field) to 96% results in the reduction of CO_2 intensity by almost 25 kgCO_2/bbl of oil. For lower initial water cut, CO_2 intensity is also reduced, albeit at a lower rate. In the left plot in Fig. 4, CO_2 intensity does not include CO_2 emissions from manufacturing of the chemicals (Scope 3 emissions). For the right plot, the Scope 3 CO_2 emissions of 3.5 kg-CO_2/kg-chemical has been assumed, hence the negative values on y-axis.

In Fig. 6 the effect of polymer flood efficiency defined by the PUF on CO_2 intensity reduction is shown as a function of water cut reduction for an initial water cut of 94%. As expected, more efficient polymer floods demonstrate a more significant reduction of CO_2 intensity with the reduction of water cut. This especially matters if Scope 3 emissions associated with the polymer manufacturing and shipment are considered. In other words, when Scope 3 emissions are included, there is a threshold or break-even Δf_w beyond which implementation of chemical EOR leads to reduction of CO_2 intensity of oil production. This depends on the f_w before injection of chemicals, arrival time of the created oil

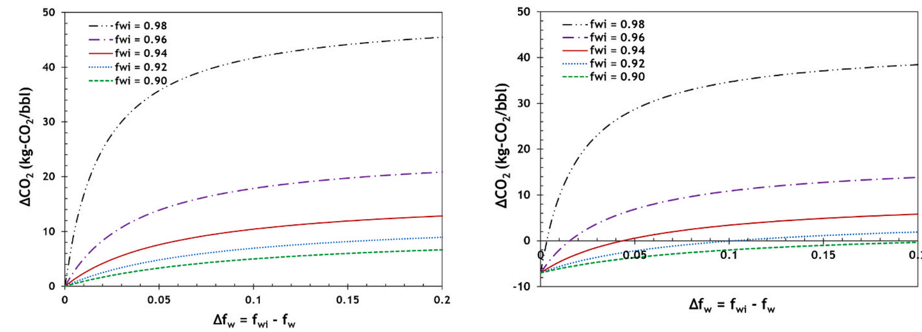

Fig. 5. Extent of CO_2 intensity reduction by chemical EOR with CUF = 2 kg-c/bbl as a function of water cut reduction. The left plot does not include the CO_2 emissions from chemical manufacturing. In the right plot, CO_2 intensity of chemical manufacturing has been assumed to 3.5 kg-CO_2/kg-chemical.

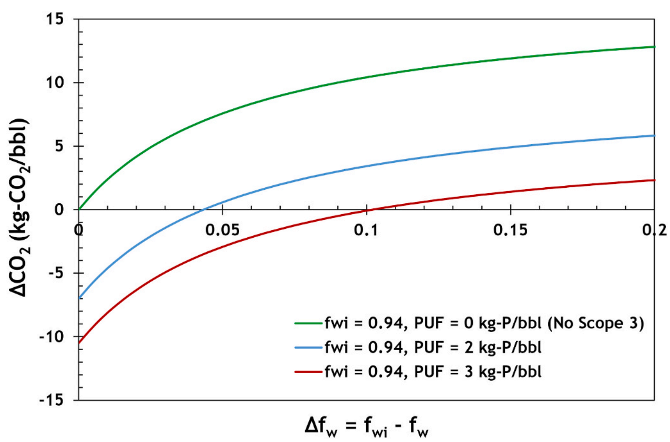

Fig. 6. Impact of polymer utilization factor on extent of CO_2 intensity reduction.

bank to the producers, chemical utilization factor and the magnitude of Scope 3 CO_2 emissions. As an example, the relation between the break-even Δf_w and the initial water cut is shown in Fig. 7.

3.3. Examples of field applications

Fig. 8 shows the CO_2 intensity of a polymer project in the Middle East. The polymer injection in the reservoir containing oil with a

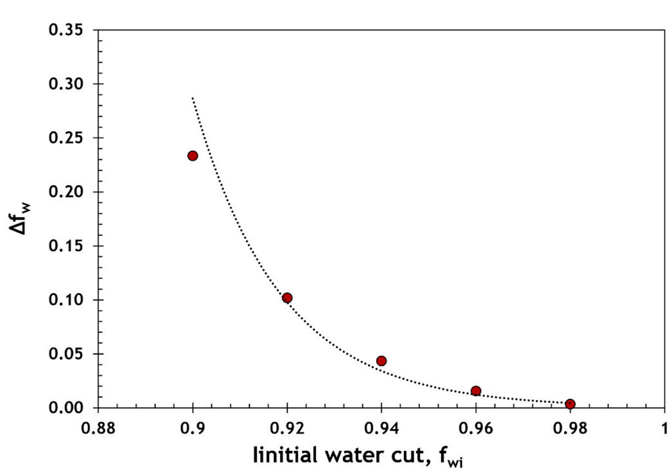

Fig. 7. *The relationship between the water cut before injection of chemicals and the threshold or break-even* Δf_w beyond which injection of chemicals reduces CO_2 intensity of oil production, when Scope 3 emissions are included (PUF = 2 kg-P/bbl oil, $e_{CO_2,polymer}$ = 3.5 kg-CO_2/kg-P).

viscosity of ~100 cP started in the middle of 2010 with a polymer viscosity of ~15 cP. The details of the calculation can be found in Farajzadeh et al., (2021). The dashed line shows the estimated CO_2 intensity if water injection had continued beyond 2010. In the absence of actual data for waterflooding, the average field behavior has been used to perform the calculations. The ups and downs in the line (and data) are related to the field activities such as temporary shut-down of facilities and/or wells or drilling of new wells. Fig. 8 indicates that polymer injection has reduced the CO_2 intensity of this field by more than 50%. During the injection of the polymer, the CO_2 intensity has remained below the cut-off value of the 0.15 tCO_2/tHC, above which production of oil is deemed to be unacceptable from an environmental point of view for waterflood projects. This indicates that, if the cut-off threshold had been imposed, waterflood project had to be stopped in 2015. In other words, injection of polymer extends the lifetime of the reservoir in this case.

Under certain conditions, the CO_2 intensity of produced hydrocarbons for an oil field under primary depletion could also be reduced through polymer flooding. An example is a reservoir in the Middle East with permeability up to 5 D, medium-heavy crude with a viscosity in the range of 250–700 cP, and a strong bottom aquifer (Mjeni et al., 2022). The field is currently under depletion and developed through infill drilling. The combination of a strong bottom aquifer, reservoir heterogeneity, high rock permeability, and unfavorable mobility ratio between water and oil resulted in the rapid development of water coning, restricting oil production. The main challenge for the future field development is to extract significant remaining oil reserves in a way that is both cost and carbon-efficient. Polymer flooding has been identified as a technology that can address such a challenge. The figure below compares the CO_2 intensity of polymer flooding and primary depletion (NFA). As it can be seen for the ten years of project duration, a significant 10% reduction of water cut (from 98% to 88%) due to viscous oil being mobilized by the injected polymer solution would result in the lower averaged CO_2 intensity. Even though energy consumption during polymer flooding is higher due to the energy invested in manufacturing, preparation, and injection of significant volumes of polymer solution (here VRR = 1), the CO_2 intensity of produced oil is lower than that of the primary depletion. During the first year of polymer injection, the CO_2 intensity is higher due to a one-year delay in the arrival of a mobilized oil bank.

In Fig. 10, the contribution from different sources of CO_2 emission is shown for the case of polymer flooding whose CO_2 intensity is shown in Fig. 9. The Water Supply emission is associated with the energy required to lift the necessary volume of water from the deep aquifer water. Similarly, the Artificial Lift is related to the energy spent lifting the expected volume of liquid (oil and water) from the target reservoir depth (~800m). The emission related to the treatment of the produced fluid, i.e., oil-water separation and preparation of the oil to the export specifications, correspond to the Water Treatment and Oil Heating, respectively. The Injection Pumps emission is associated with the energy

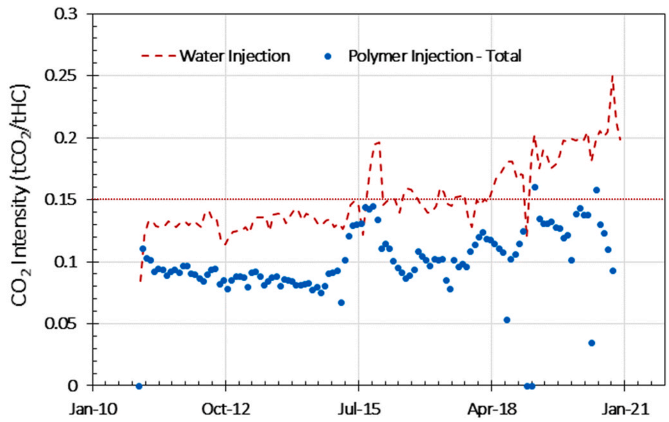

Fig. 8. CO_2 intensity of oil production by injection of polymer for a field in the Middle East. The dashed lines shows the predicted baseline (water flooding) based.

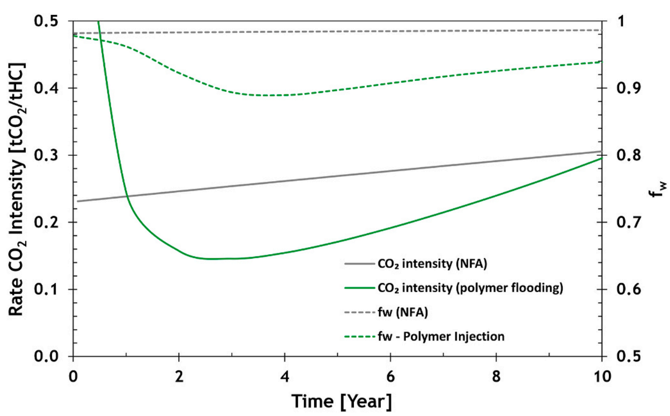

Fig. 9. CO_2 intensity and water cut for the primary depletion (NFA) and polymer flooding field development options.

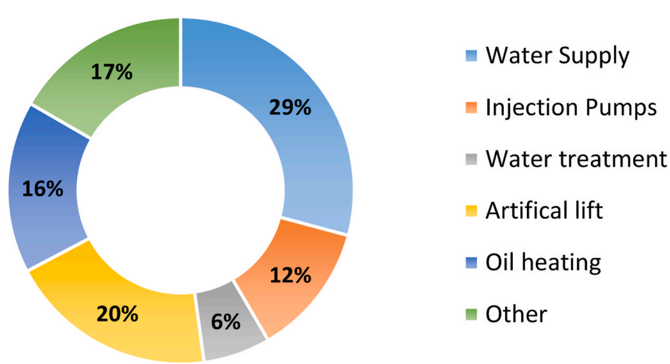

Fig. 10. Contribution from different sources of CO_2 emission for the polymer project.

required to operate the polymer injection facilities (i.e., pumps). Finally, the CO_2 emission related to the remaining energy consumption of the project (up to 20% of the total value) is lumped into the Other category. The details of these calculations are described in Farajzadeh et al. (2021). It is noted that the sources associated with the polymer injection i.e., water supply, treatment, and injection (including preparation of polymer solution), account for almost half of the total CO_2 emission. The base case polymer flooding, which is discussed in Figs. 9 and 10, assumes the use of a deep aquifer as a source of water to prepare the polymer solution and lifting of water from such an aquifer costs almost 30% of the total energy demand of the process. It was proposed to consider produced water as an alternative source of water for the polymer project to eliminate this cost.

Fig. 11 demonstrates the CO_2 intensity of the polymer flood using two different water sources: deep aquifer water (base case) and produced water. In this case, use of produced water is less favorable compared to the aquifer water because produced water requires more thorough treatment than deep aquifer water. More strict makeup water specifications are imposed to avoid injectivity issues observed in the field trial (Mjeni et al., 2022). Complex water treatment surface facilities are also required to meet these specifications in case of produced water. Operating these facilities would result in higher energy consumption compensating and even exceeding the energy-saving due to the elimination of water lifting from the deep aquifer. In addition, CAPEX associated with such water treatment facilities is significantly higher than that associated with drilling, completing and hooking-up the aquifer water source wells. However, the decision about the water source for the project like this is more complex and must consider the environmental and regulatory aspects.

3.4. Field life perspective

One of the upsides of polymer flooding is the acceleration of oil recovery. In case a field development plan results in a certain Estimated Ultimate Recovery (EUR) through waterflood in a period of 25 years, the same EUR can be reached in a shorter period when a polymer flood scheme is implemented. This is currently very attractive because hydrocarbon recovery needs to be phased out to reduce global CO_2 emissions before 2030 and 2050. Projects with large green-house gas (GHG) intensity are expected to be reviewed and early field abandonment or divestments are likely to be carried out. It implies that not all oil may be produced and hence investments might devaluate.

A comparing study between waterflood and polymerflood projects based on a Argonauta O-North reservoir in the BC-10 field located offshore Brazil (Souza et al., 2011) was performed. The waterflood has started in 2013 and is currently ongoing. The study was based on a semi-analytical model (Zijlstra et al., 2014) to forecast both the waterflood and polymer flood EUR. The parameters included an end of field life in 2038, floodable initial volumes of 390 MMBoe, an oil viscosity of 27 cp, typical relative permeability curves for higher viscous oil clastic reservoirs, a Dijkstra Parsons coefficient of 0.55 and a water viscosity of 0.55 cp. Fig. 12 shows the results of the study. The waterflood results in an EUR of 100.8 MMBoe using 0.84 PV of water injected in the 25 year period. A 5-year long polymer flood using a 13 cP polymer solution with start date in 2022 followed by a water chase exceeds the expected EUR from waterflood in 2028. There is a long tail production till 2038

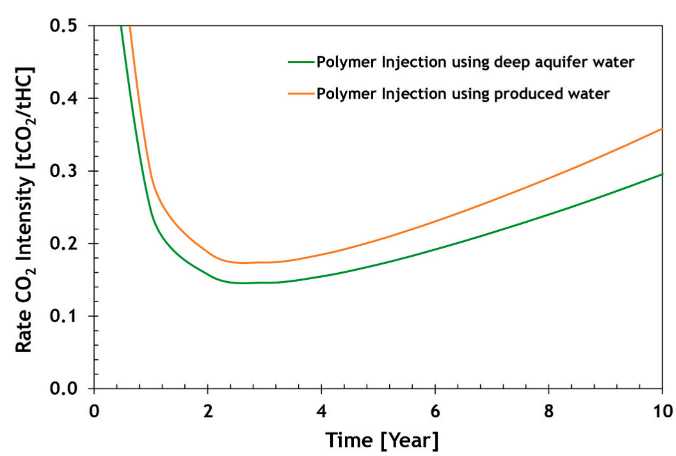

Fig. 11. Comparison of CO_2 intensity for polymer flooding using two sources of water: deep aquifer and produced water.

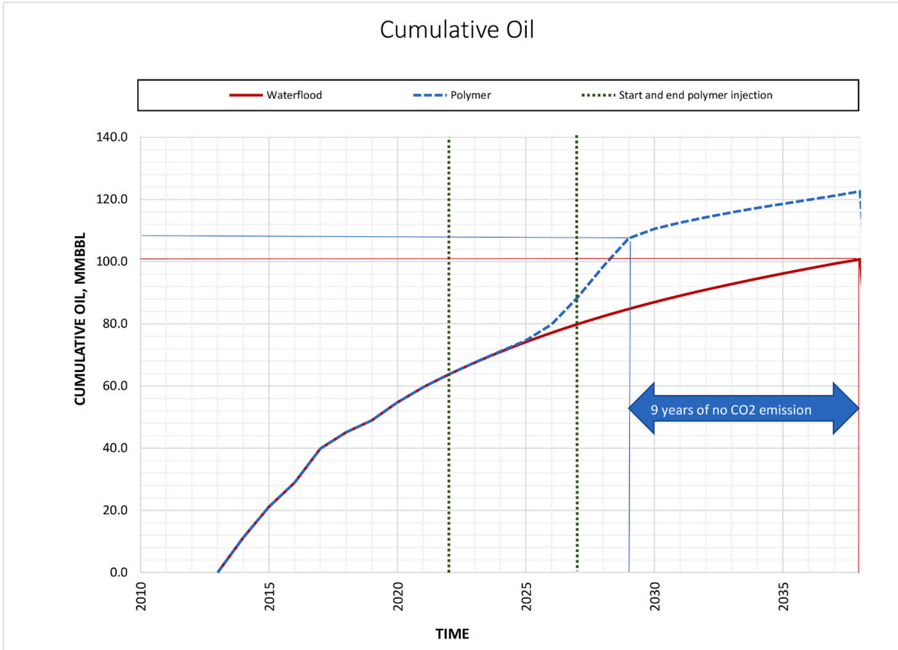

Fig. 12. Comparing cumulative oil vs time for waterflood (curve in red) with a polymer flood (curve in blue) starting in 2022. To obtain the recovery factors for water- and polymerflood projects the method developed by Zijlstra et al. (2014) has been used.

resulting in 122.6 MMBoe total, an additional 21.8 MMBoe. The polymer flood could be further optimized through longer polymer injection and has the potential for substantial accelerated recovery. Continuation of polymer injection after 5 years is a decision that can be made. In this case it is best to decide ceasing polymer injection around two years prior to field abandonment; that is the time before the water cut will rise sharply. With field abandonment as a moving target, it is comforting to have the control to continue polymer flooding at the higher OPEX or to cease injection and prepare for abandonment based on the demands at that time. For the 5-year polymer injection period, the differentiator in terms of CO_2 emissions is the fact that in 2029 the field already exceeds the EUR of the waterflood in 2038. This implies 9 years shorter OPEX and CO_2 emissions to land on the same recovery and a lower cost. Similar acceleration was observed in the Captain filed (Poulsen et al., 2018).

Detailed engineering work showed that during waterflood the total CO_2 emission is around 213 kt/annum. The incremental CO_2 emission for CO_2 is 1.3 kt/annum. So, the total CO_2 savings would yield 1917 kt and the additional CO_2 for polymer facilities is 6.5 kt.

There will be incremental costs for the polymer flood implementation. In this case this is estimated to be 50 MMUSD CAPEX and 30 MMUSD OPEX per year. A reduction of overall operating costs for 9 years and reduction of nearly 2000 kt of CO_2 which penalized can be as high as 50 MMUSD, will be easily covering for these costs. The CAPEX and OPEX for waterflood have been calculated to be 2000 MMUSD and 100 MMUSD/year, respectively. The incremental CAPEX and OPEX for polymerflood have been calculated to be 50 MMUSD and 30 MMUSD/year, respectively.

Studies on the upside of polymer flooding will have inherent risks and uncertainties. Since CO_2 intensity is influenced by the incremental oil profile and associated water cut reversal, as described in the previous section, any downside risk or uncertainty will impact the CO_2 intensity forecast. Not meeting the project promise will then have a double hit: both on the incremental oil and on the CO_2 intensity. When CO_2 emissions are penalized, the impact will be a further unit technical cost (UTC) increase. To cover for the risks and uncertainties, predicting the CO_2 intensity should include reporting the uncertainty ranges. Specific risks such as polymer shear degradation, high retention, polymer throughput or thermal degradation can therefore have an impact on both the economic attractivity and the promised CO_2 intensity. The impact of these events is even higher when the polymer project is intended to produce the prospected oil in a shorter period because of the acceleration of oil as described in the previous paragraph. Using the same example, the impacts of (1) a lower throughput of polymer; (2) a later start of the polymer injection; (3) polymer viscosity loss; (4) a combination of events; and (5) an earlier start of the polymer flood are investigated.

3.5. Gas enhanced oil recovery

Fig. 13 depicts the schematic of the main surface and subsurface components of a gas EOR project, which includes facilities and equipment required to supply injection gas, gas transport to the field, compression and injection into the reservoir, separation of the produced fluids and recirculation of gas to reinject it into the reservoir. In case, water-alternating-gas (WAG) injection scheme is adapted the system also includes water injection and treatment facilities. In the case of foam injection, the exergy of surfactant manufacturing and transportation should also be considered.

Typical injection gases are CO_2, natural gas (CH_4) and Nitrogen (N_2). CO_2 can either be produced from a subsurface reservoir (natural source) or captured from fossil-fuel burning power plants or directly from air using energy-intensive processes (2.5–12 MJ/kg-CO_2) (Eftekhari et al., 2012; Chatterjee and Huang, 2020). The cryogenic air separation technique is currently the common technique to produce pure N_2. This process has practical exergy of 1525 kJ/kg-N_2 (Cornelissen and Hirs, 1998).

The theoretical exergy of compression can be estimated from Equation (11):

$$\widehat{Ex}_{comp} = \widehat{W} = \widehat{H}_2 - \widehat{H}_1 = \left(\frac{k}{k-1}\right)\left(\frac{z_1+z_2}{2}\right)RT_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1\right] \tag{11}$$

where, $\widehat{W}$ is the specific work [J/kg], $\widehat{H}_1$ and $\widehat{H}_2$ are specific inlet and outlet enthalpy [kJ/kg], P_1 and P_2 are inlet and outlet pressure [bar], T_1 is the inlet temperature [K], R is the universal gas constant [J/K mol], $k = C_p/C_v$ is the ratio of heat capacities at constant pressure and con-

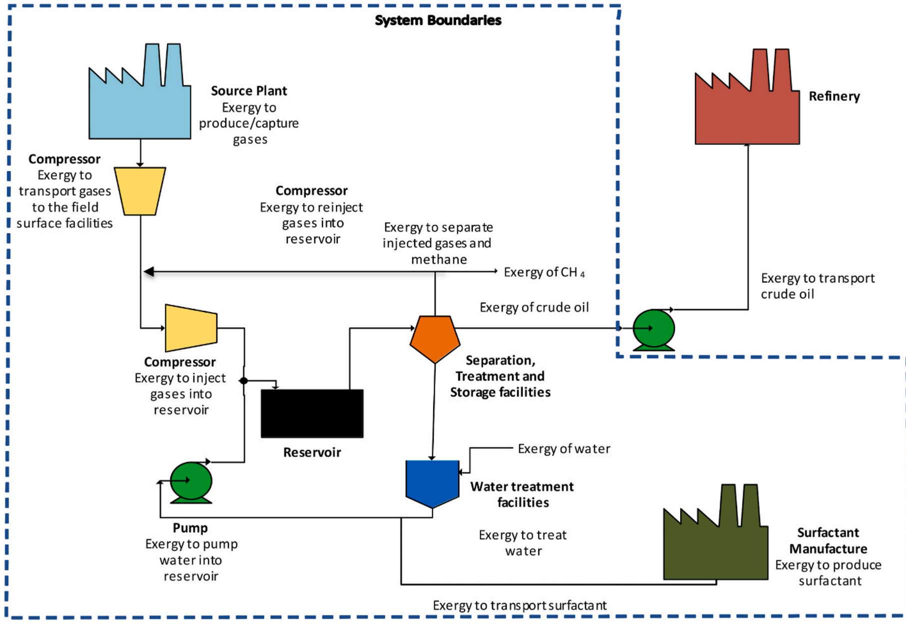

Fig. 13. Schematic of the main component of the oil production by gas or foam injection and the selected boundary for the analysis.

stant volume and z is the compressibility at the inlet and outlet. The practical compression exergy is calculated by considering the efficiency of the power plant (0.4), compressor (0.7) and electrical drives (0.9), with an overall efficiency of 0.25.

In the cases considered here, CO_2 is assumed to be captured from a gas-fired power plant and transported at pressure of 105 bar to the field site. N_2 and methane are delivered at pressure of 20 bar. The flue gas is also transported at 105 bar to the site. To obtain miscibility, for the reservoir of interest CO_2 needs to be compressed to 400 bar. Chemical exergy of methane has been assumed to be 51 MJ/kg. On the production side, all the produced gas is recompressed and re-injected to the reservoir without separation. The summary of the exergy values of the first and the second stages of the compression and their corresponding pressures for different gases is provided in Table 2.

Table 2
Exergy values for second stage of compression. The (practical) compression exergy of N_2 and CH_4 from 1 to 20 bar is 379 and 540 kJ/kg-gas respectively.

	$CO_{2\ (miscible)}$	$CO_{2\ (immisc.)}$	N_2	CH_4	Flue gas
1–105 bar	1173	1173			3435
105–400 bar		271			1065
20–200 bar			980	1545	
Recompression (1–200 bar)	1170	1170	1503	2142	3432
Gas source or capture	4000	4000	1525	51000	0

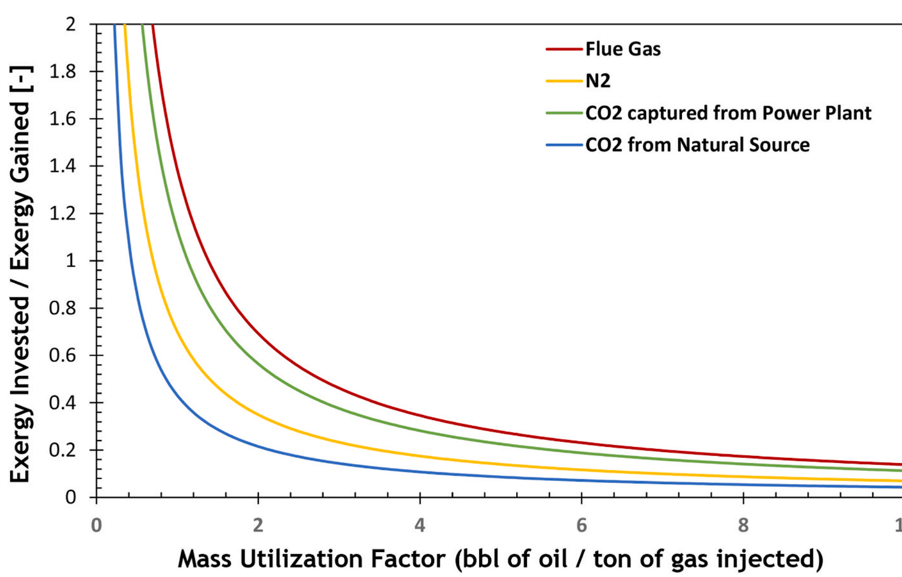

Fig. 14. Fraction of oil exergy (5730 MJ/bbl or 45 MJ/kg) spent on its production as a function of mass utilization factor of different gases.

Fig. 14 shows the fraction of the oil exergy (45 MJ/kg) spent on its production for different gases as a function of mass utilization factor (bbl/ton). Naturally, the microscopic sweep efficiency varies for different gases and depends on whether the reservoir pressure is below or above the minimum miscibility pressure. Among gases CO_2 is more favorable for EOR as it has better solvency properties and can achieve miscibility with oil at relatively lower pressures. Among the gases considered, flue gas has the least efficiency, mainly due to its large compression and transportation exergetic cost. Also, because of high exergetic cost of CO_2 capture from power plants, EOR with this CO_2 source has low exergetic efficiency. The published field data on CO_2 EOR suggests a net mass CO_2 utilization factor of 1.8–4.2 bbl oil/tCO_2, with an average value of ~2 bbl oil/tCO_2. However, it should be noted EOR using CO_2 captured from power plants can store significant amount of CO_2. For example, the total CO_2 intensity of oil (CO_2 emitted from production and combustion of oil in final applications) can be reduced by 80% (Farajzadeh et al., 2020). In other words, if the source of electricity is cheap and low carbon, CO_2 EOR is advantageous as it can reduce CO_2 emissions.

A common drawback in most of the gas EOR projects is the circulation of excessive amounts of gas resulting in poor gas utilization factors. This is a combined result of reservoir heterogeneity and lower viscosity of gas compared to in-situ oil. The low gas utilization factors increase the CO_2 intensity of oil production. Foam can be used to improve the utilization factor of gas in EOR processes. For example, improving the utilization factor from 2 bbl/tCO_2 to 4 bbl/tCO_2 can reduce the CO_2 intensity of the produced oil from 120 kgCO_2/bbl to 80 kgCO_2/bbl (33% reduction) (Rossen et al., 2022).

CO_2 EOR is a mature technology as injection of CO_2 into oil reservoirs has resulted in extraction of significant amounts of oil, owing to its excellent solvency. This indicates that there is plenty of experience in handling CO_2 injection into subsurface formations. This combined with availability of infrastructure (pipelines, compressors, etc) as well as financial gains from selling the produced hydrocarbons make CO_2 EOR an attractive means of sequestration CO_2. In addition to economic incentives and increased oil production, the oil industry can benefit from carbon-tax and other socioeconomic incentives by implementing CCS through EOR (Farajzadeh et al., 2020). However, for CO_2 EOR to be net-positive in storing CO_2, the injected CO_2 should originate from anthropogenic sources. Currently more than 90% of the CO_2 EOR projects utilize CO_2 produced from geological formations (Azzolina et al., 2017).

4. Conclusions

Reducing the CO_2 emission per barrel of oil of an operating field can be achieved either directly, by replacing fossil-fuel-based power sources with renewable electricity, or indirectly by efficient utilization of injectants through I/EOR methods. While it is straightforward to estimate the benefits of the direct method, the indirect methods can be more complicated and require in-depth analysis. By investigating different I/EOR methods applied to a selected number of fields, it is found that.

- Injection of water and/or gas is needed to maintain reservoir pressure and reduce lifting energy; however, such an injection can potentially increase the CO_2 intensity of produced oil, especially when the injected water and/or gas exhibit early break-through limiting the oil production.
- Efficient water and/or gas injection through IOR and EOR schemes prevents such break-through, results in incremental oil production, and under certain conditions, reduces the CO_2 intensity of produced oil. Earlier start of EOR projects is also favorable in terms of CO_2 emissions.
- CO_2 intensity of oil associated with the implementation of chemical EOR process is strongly influenced by water cut at the start of the project, extent of water cut reduction, and chemical utilization factor (see Eq. (10)).
- For the case of a mature medium-heavy oil field it was shown that polymer flood that screens positively with a favorable expected polymer utilization factor has significantly reduced the CO_2 intensity of produced oil compared to conventional water flooding. Only in extreme cases of polymer loss and the late start of polymer injection, the CO_2 intensity would be of the same order as water flooding.
- For high permeable medium-heavy oil reservoir that is under primary depletion it has been shown that polymer flooding can also result in incremental oil production with lower CO_2 intensity. In such a case, water sourcing and treatment are the largest contributors to the CO2 intensity of polymer flooding.
- In addition to incremental oil production with lower CO_2 intensity, the earlier implementation of EOR projects can extend the lifetime of the mature fields if carbon intensity cut-offs are applied to oil production.
- For the gas EOR, the energy intensity of the capture and transport of CO_2 and flue gas, and the circulation of the back-produced gas into the reservoir increase the energy demand of the process.
- In case of CO_2 EOR, the large storage potential for CO_2 can significantly reduce the CO_2 intensity of oil production.
- Using the concept of exergy for evaluating the performance of I/EOR methods from an environmental point of view leads to optimal results that are consistent with the economic analyses.

CRediT authorship contribution statement

R. Farajzadeh: Conceptualization, Investigation, Methodology, Data curation, Formal analysis, Writing – original draft. **G. Glasbergen:** Investigation, Data curation, Writing – review & editing. **V. Karpan:** Investigation, Data curation, Writing – review & editing. **R. Mjeni:** Writing – review & editing, Project administration. **D.M. Boersma:** Writing – review & editing, Project administration. **A.A. Eftekhari:** Investigation, Writing – review & editing. **A. Casquera Garcia:** Software, Investigation, Data curation. **J. Bruining:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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