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# OPEN Life-cycle assessment of oil recovery using dimethyl ether produced from green hydrogen and captured CO<sub>2</sub>

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Hydrocarbon fuels are widely recognized as significant contributors to climate change and the rising levels of CO<sub>2</sub> in the atmosphere. As a result, it is crucial to reduce the net carbon intensity of energy derived from these fuels. This study explores the feasibility of using dimethyl ether (DME), produced through the hydrogenation of CO<sub>2</sub>, as a low-carbon method for generating electricity from hydrocarbon fuels. The proposed approach involves capturing the emitted CO<sub>2</sub> during combustion and utilizing it to produce the necessary DME in a closed cycle. It is shown that for a mature reservoir in the Middle East, this method can mitigate approximately 75% of the CO<sub>2</sub> emissions released from burning the produced oil. By incorporating zero-carbon electricity throughout the process, the total abatement of CO<sub>2</sub> can reach 85%. Furthermore, the study highlights the importance of improving the DME utilization factor (bbl-oil/tDME). By optimizing this factor, high abatement rates can be achieved. However, it is important to note that implementing this method comes with a high exergetic cost. During a certain period in the field's lifetime, the invested energy exceeds the energy produced. The stages with the highest exergy consumption are CO<sub>2</sub> capture and hydrogen production.

Hydrocarbon fuels currently dominate the global energy supply and remain the primary choice for transportation. In the absence of major technological advancements, hydrocarbon fuels are expected to continue meeting a significant portion of the growing energy demand in the near future. However, the combustion of hydrocarbons to release their chemical energy leads to the release of substantial quantities of carbon dioxide (CO<sub>2</sub>) into the atmosphere, which is the primary driver of climate change and global warming. Additionally, the extraction of hydrocarbons from subsurface reservoirs necessitates energy, and the energy requirements escalate as the producing fields age. Consequently, the resulting CO<sub>2</sub> emissions from these operations contribute to over 20% of the total emissions in prominent oil-producing countries such as Russia, Norway, and Canada<sup>1,2</sup>.

Considering the urgent need to limit global temperature rise to below 2 °C above pre-industrial levels, the reduction of CO<sub>2</sub> emissions has become a matter of utmost importance. To achieve this, it is crucial to develop innovative production schemes that can effectively decrease the CO<sub>2</sub> intensity of energy (defined as the mass of CO<sub>2</sub> emitted to atmosphere per unit energy, or gr-CO<sub>2</sub>/MJ) derived from hydrocarbons. These efforts are essential until alternative low-carbon energy sources can be scaled up and widely adopted. To accomplish this objective, it is necessary to integrate low-carbon energy sources into existing hydrocarbon production systems. Additionally, the utilization of materials or processes with minimal environmental impact can contribute to reducing CO<sub>2</sub> emissions from hydrocarbon-based energy production<sup>3</sup>.

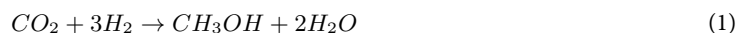
Enhanced oil recovery (EOR) methods, typically employed during the later stages of hydrocarbon reservoir life, offer the potential to produce oil with lower carbon intensity (measured in g-CO<sub>2</sub>/bbl oil) by optimizing the utilization factor of injectants, defined as the mass or volume of injected fluids required to produce a unit volume of oil<sup>4,5</sup>. These methods involve the injection of various substances such as chemicals (e.g., surfactants and polymers), gases (CO<sub>2</sub>, CH<sub>4</sub>, steam), and solvents<sup>6</sup>.

EOR techniques utilizing anthropogenic CO<sub>2</sub> captured from concentrated sources like power plants or directly from the air appear particularly attractive. This approach has the potential to reduce both the net CO<sub>2</sub> intensity of oil production and the costs associated with subsurface CO<sub>2</sub> storage<sup>7</sup>. However, the efficiency of CO<sub>2</sub> EOR, from an oil extraction perspective, relies on the development of miscibility between the injected CO<sub>2</sub> and the oil within the porous reservoir media. Achieving miscibility typically requires high pressures, making

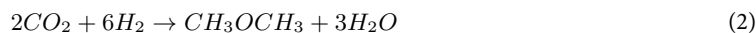
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CO<sub>2</sub> injection into shallower reservoirs less economically viable. Moreover, the efficiency of CO<sub>2</sub> in extracting oil diminishes with increasing reservoir heterogeneity, characterized by variations in permeability, leading to premature breakthrough of the injected CO<sub>2</sub> in production wells<sup>8</sup>. To overcome these limitations, the injection of solvents in combination with gas or water has been explored<sup>9</sup>. However, it is crucial to ensure that the selected solvent does not contribute to the overall CO<sub>2</sub> footprint of hydrocarbon fuels.

A recent advancement in EOR techniques involves the utilization of dimethyl ether (DME) as an EOR agent. DME exhibits high solubility in water and demonstrates first contact miscibility with hydrocarbons<sup>10,11</sup>. The chemical properties of DME are summarized in Table A.1. in the appendix. DME is dissolved in water and injected into the oil-bearing reservoir and therefore the process is referred to as DME-enhanced waterflooding (DEW). Within the reservoir pores, DME exhibits a strong affinity for oil, leading to its partitioning into the trapped oil phase. This process effectively reduces the viscosity of the oil and increases the volume of the oleic phase<sup>12,13</sup>. These combined effects ultimately result in an enhanced oil recovery and a reduction in the remaining oil saturation<sup>10,14</sup>. The economic viability of this process is heavily dependent on the volume of injected DME that can be recycled<sup>15,16</sup>. Despite the potential benefits, the large-scale application of DME-EOR has not yet been realized, primarily due to the high cost associated with DME. Nevertheless, studies have advanced the understanding of the phase behavior of Dimethyl Ether (DME) in contact with oil and water<sup>17</sup>, its impact on relative permeability<sup>18</sup>, and the development of efficient simulation methods<sup>12,13,19</sup>. Moreover, DME has been proposed as an efficient additive to steam to enhance production of heavy oils under gravity drainage<sup>20–22</sup>. Conventional methods for manufacturing DME typically rely on natural gas or coal as feedstock to produce syngas, which is then used to produce DME. However, the generation of syngas is both energy-intensive and costly. To simplify the process and reduce costs, this step should be eliminated<sup>23</sup>. An innovative alternative is the hydrogenation of CO<sub>2</sub>, which allows to produce methanol using either a homogeneous or heterogeneous catalyst<sup>24</sup>. The necessary hydrogen can be obtained through water electrolysis using renewable energy sources, while the required CO<sub>2</sub> can be captured from industrial plant emissions (such as cement plants or power plants) or directly from the air. Methanol production follows the Eq. (1):



The methanol produced is subsequently dehydrated to obtain DME through a process known as indirect DME synthesis. This method of methanol production has already been implemented in several countries, including Japan, where commercial plants have been established<sup>23,24</sup>. Additionally, DME can also be produced through direct catalytic CO<sub>2</sub> hydrogenation<sup>25,26</sup>.



The method works by using hybrid catalysts consisting of a methanol synthesis catalyst and a dehydration catalyst<sup>25</sup>.

The purpose of this study is to assess the feasibility of using CO<sub>2</sub> hydrogenation-derived DME injection as a carbon-neutral method for oil recovery. This paper differs from previous studies related to DME-enhanced waterflooding in two ways. Firstly, the focus of this paper is to investigate the use of renewable DME in the process with the aim to abate CO<sub>2</sub> released from produced oil. Secondly, this paper presents an integrated view of the surface and subsurface components of the process and aims to identify the key parameters that contribute to the sustainability of the process. To achieve this, a comprehensive life cycle assessment of the DEW injection process is conducted, considering the principles of the second law of thermodynamics. Additionally, the concept of exergy-return on exergy-investment (ERoEI) is employed to determine the exergetic efficiency and CO<sub>2</sub> intensity of the oil produced through the DEW process.

## Methodology

To conduct a life cycle exergy analysis, it is essential to identify the primary work and material streams involved<sup>3,27</sup>. Work streams refer to the components that consume exergy and are therefore the primary sources of CO<sub>2</sub> emissions in the process. Typically, the analysis focuses on the main contributors to simplify the assessment. On the other hand, material streams are the components that generate exergy. This exergy can be in the form of electricity (in power plants), chemical exergy (in fuels), or heat. In the case of the DME-EOR process, two indicators are utilized to evaluate the exergy efficiency. The exergy-return on exergy-investment (ERoEI), and the exergy recovery factor,  $ex_{RF}$ , defined as

$$ERoEI = \frac{ex_{return}}{ex_{invested}} \quad (3)$$

$$ex_{RF} = \frac{ex_{return} - ex_{invested}}{ex_{fuel}} \quad (4)$$

In hydrocarbon recovery techniques, the chemical exergy of the produced hydrocarbons (oil and gas) serves as the exergy of the fuel. The volumes of these hydrocarbons are determined through numerical or analytical models. Subsequently, the chemical exergy of the produced hydrocarbons is converted into electricity or heat considering the conversion efficiency of hydrocarbon-fueled power plants or boilers. Calculating the invested exergy involves determining the amounts of exergy and material consumed during the production of hydrocarbons. The volumes of injected fluids (such as water, solvents, and gas) and the materials (e.g., chemicals or solvents) are obtained from simulations. The invested exergy can be in the form of electricity or material. For instance, the injection of fluids requires electric-driven equipment like pumps or compressors. The CO<sub>2</sub>

emissions associated with this equipment depend on the power source and the conversion efficiency of the power generator. When chemicals such as polymers or surfactants are used to enhance oil production, the conversion of exergy to CO<sub>2</sub> emissions is more complex. These chemicals often possess a significant embodied chemical exergy. However, since they are not oxidized and are typically retained in the reservoir, their primary contribution to the CO<sub>2</sub> footprint of the oil recovery process arises from their manufacturing and transportation stages.

### DME-based enhanced oil recovery

The proposed DME-based Enhanced Oil Recovery (EOR) system, aimed at producing low-carbon oil, is illustrated in Fig. 1. The system begins by capturing CO<sub>2</sub> emissions from oil-fueled power plants but can also be applied to CO<sub>2</sub> from other sources. To facilitate the hydrogenation reaction (Eq. 2), the required hydrogen is obtained through water electrolysis, powered by renewable or low-carbon electricity sources, such as solar electricity in this case. A portion of the produced DME is utilized to generate more oil, albeit with reduced CO<sub>2</sub> intensity. The excess or recycled DME can be reinjected into nearby fields or used for various purposes, including electricity generation, methanol production, or the production of light olefins like propylene or ethylene. Alternatively, it can be used as a replacement fuel for diesel. In this analysis, any additional DME is converted to electricity using fuel cells. The produced oil is transported to an oil-fueled power plant, where it is utilized to generate electricity.

#### Material stream

The material stream associated with the DME-EOR process consists of the produced oil and gas, as well as DME. In this study we assume that the main exergy source is produced oil. The chemical exergy of the crude oil is dependent on its composition. In the case of a light oil with a composition as reported in Farajzadeh et al., 2020, the estimated chemical exergy is 45.63 MJ/kg-oil. The chemical exergy values for natural gas (CH<sub>4</sub>) and DME are considered to be 52 MJ/kg-CH<sub>4</sub> and 30.57 MJ/kg-DME, respectively<sup>28</sup>.

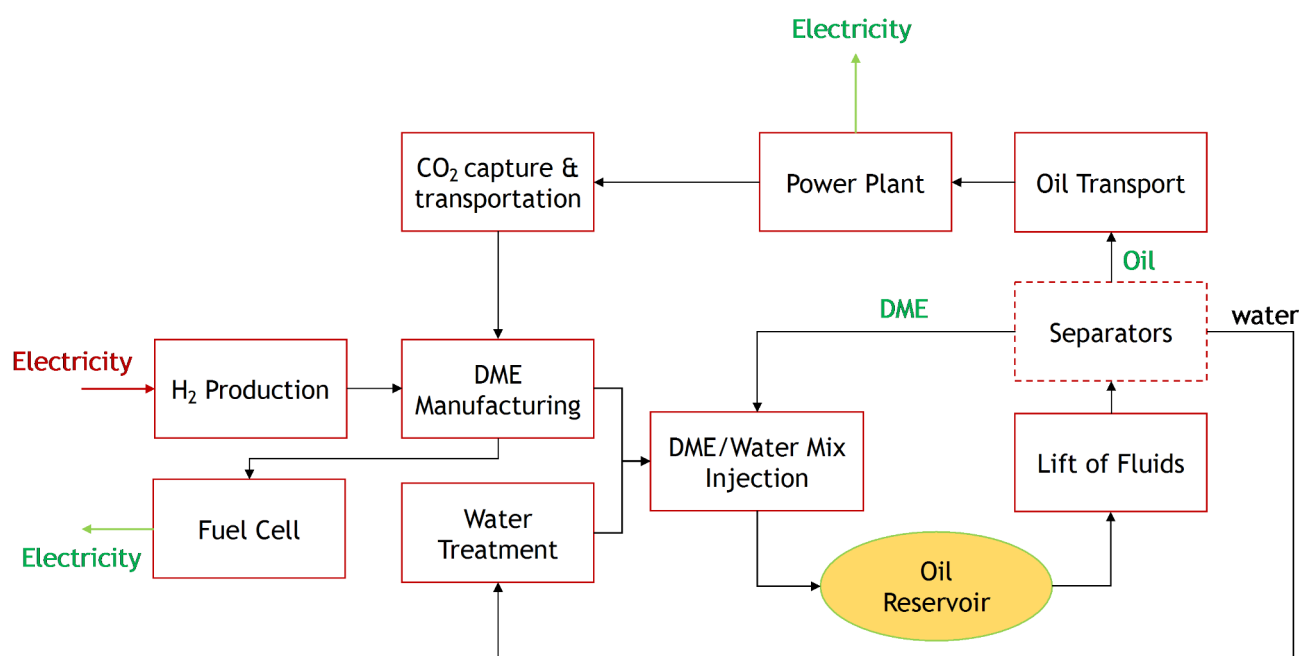
#### Work stream

Based on Fig. 1, the DME-EOR process involves several key work streams. These include hydrogen production, CO<sub>2</sub> capture and transportation, DME synthesis, injection of DME/water mixture, lifting of produced fluids, transportation of produced oil to the power plant, and the work required for electricity generation.

**Hydrogen production:** The exergy of hydrogen production through water electrolysis has been reported to range from 180 to 220 MJ/kg-H<sub>2</sub>, with a CO<sub>2</sub> intensity of 0.7–2.0 kg-CO<sub>2</sub>/kg-H<sub>2</sub><sup>29,30</sup>. In this study, the exergy of DME synthesis includes the exergy of hydrogen production.

**DME synthesis:** The exergy of DME manufacturing via CO<sub>2</sub> hydrogenation is estimated to be 74 MJ/kg-DME<sup>31,32</sup>. This value does not account for the exergy of CO<sub>2</sub> capture and transportation. It is assumed that DME is produced near the field site, thus neglecting the transportation exergy of DME.

**CO<sub>2</sub> capture and transport:** Power plants with high CO<sub>2</sub> concentrations typically use monoethanolamine (MEA) as a solvent to absorb CO<sub>2</sub> from flue gas. This process requires 3.5–6 MJ/kg-CO<sub>2</sub>, with a capturing efficiency of 80–95%<sup>33,34</sup>. It is assumed that the capturing energy is supplied by the power plant fueled by the oil



**Fig. 1.** Schematic of the considered system for the DME-enhanced waterflooding or DME EOR process. The exergy consumed is calculated for each process. All the red squares are CO<sub>2</sub> emitters.

produced from the DME-EOR process. The overall process efficiency of the oil-fueled power plants is assumed to be 40%<sup>35</sup>.  
*Renewable electricity:* When specified, low-carbon electricity is assumed to be sourced from solar power plants with a specific CO<sub>2</sub> emission of 12.5 gr-CO<sub>2</sub>/MJe<sup>36</sup>.

*Other processes:* It is assumed that an additional 10% exergy investment is required for processes such as fluid separation, well stimulation, gas processing, and pigging of pipelines, which are not considered in this study<sup>37,38</sup>.

*Efficiency of DME fuel cells:* Fuel cells directly convert the chemical exergy of fuels like H<sub>2</sub> and DME into electricity. The conversion efficiency of DME fuel cells is like that of hydrogen fuel cells, ranging from 40 to 85%<sup>39</sup>, with an average practical conversion efficiency of 70%.

In summary, for the DME-EOR system depicted in Fig. 1, the terms in Eqs. (3) and (4) are defined as follows:

$$ex_{return} = ex_{oil}^{ch} \eta_1 + ex_{DME}^{ch} \eta_2 \tag{5}$$

$$ex_{invested} = ex_{DME}^{manu} + ex_{inj} + ex_{treat} + ex_{lift} + ex_{trans} + ex_{CO_2}^{capture} + ex_{other} \tag{6}$$

$$ex_{fuel} = ex_{oil}^{ch} \tag{7}$$

where  $ex_{oil}^{ch}$  is the chemical exergy of the oil,  $ex_{DME}^{ch}$  is the chemical exergy of DME,  $ex_{DME}^{manu}$  is the exergy of DME manufacturing,  $ex_{inj}$  is the exergy of injection pumps,  $ex_{treat}$  is the exergy of water treatment,  $ex_{lift}$  is the exergy of lift pumps,  $ex_{trans}$  is the exergy of oil transportation to the refinery,  $ex_{CO_2}^{capture}$  is the exergy of CO<sub>2</sub> capture from the oil-fueled power plant, and  $ex_{other}$  is the exergy of the other processes (assumed to be 10% of the total exergy invested).  $\eta_1$  and  $\eta_2$  are the conversion efficiency of oil and DME to electricity, i.e., the conversion efficiency of the power plant and the DME fuel cell, respectively. Specific chemical exergy values of oil, methane, and DME are assumed to 45.63, 52.0, and 30.75 MJ/kg, respectively.

The work stream and the main assumptions of the calculations are summarized in Table 1, respectively.

Injection and production data

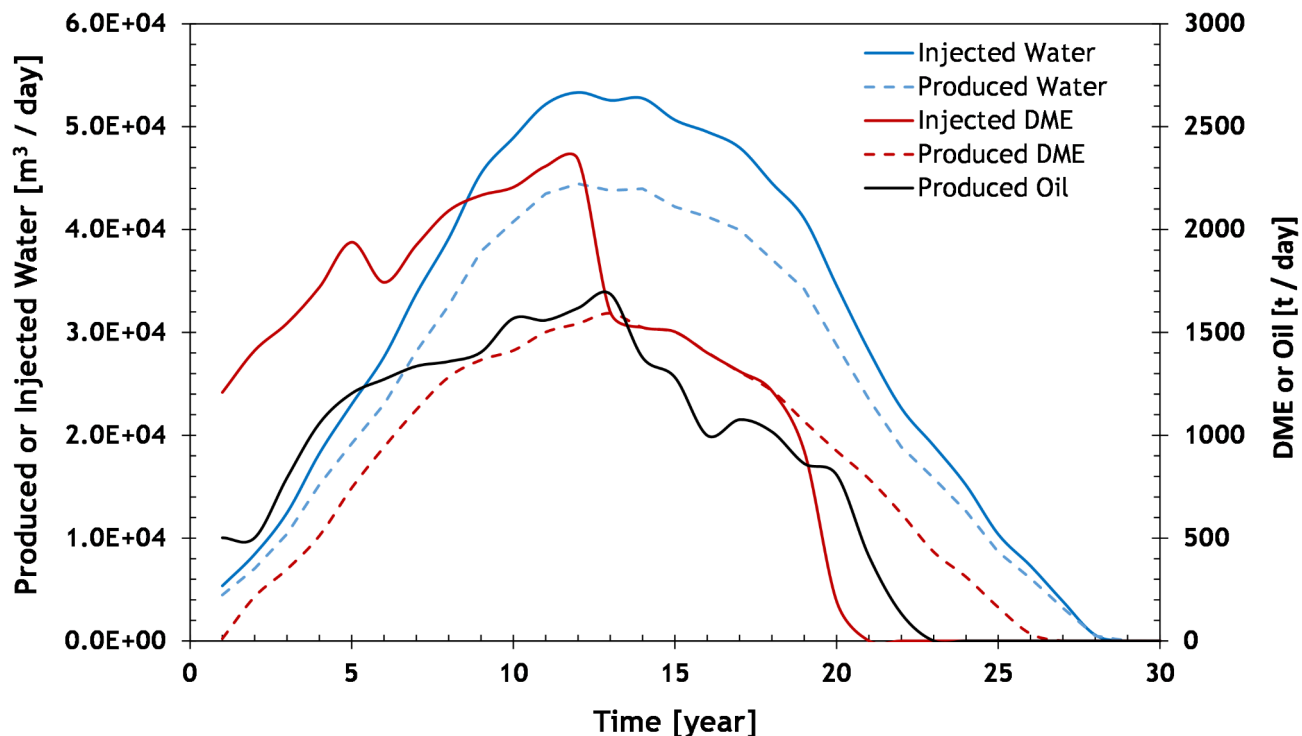
The work and material stream calculations are derived from the injection and production histories of the DME EOR process in a field located in the Middle East. These histories are obtained through numerical simulations with parameters calibrated to experimental data. Further details can be found in refs<sup>10,15,16</sup>. Figure 2 illustrates the total volumes of injected and produced fluids.

Results and discussion  
Producible DME volume

In the DME EOR process, it is common to inject significant volumes of solvents into subsurface formations to displace and recover oil. Figure 2 presents the oil production data, which is utilized to assess whether the

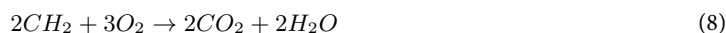
Work stream	
DME synthesis	Exergy: 74 MJe/kg-DME
CO <sub>2</sub> capture and transport	MEA-solvent: 4.0 MJ/kg-CO <sub>2</sub> with capture efficiency of 90%
Conversion efficiency of gas power plant	40%
Conversion efficiency of DME fuel cell	70%
Water treatment	Exergy: 18 (5 kWh/m <sup>3</sup> )
Injection pumps	Exergy rate: $\dot{Q} \Delta P / \eta$
Lift pumps	$\left[ \dot{Q} (f_w \rho_w + (1 - f_w) \rho_o) g h \right] / \eta$
Average overall pump efficiency, $\eta$	0.36
Transportation of oil	188 Je/kg/km
Distance to power plant	500 km
Specific CO <sub>2</sub> emission for gas	0.055 kg-CO <sub>2</sub> /MJ
Specific CO <sub>2</sub> emission for oil	0.073 kg-CO <sub>2</sub> /MJ
Specific CO <sub>2</sub> emission for solar electricity	0.0125 kg-CO <sub>2</sub> /MJe
Water density	1000 kg/m <sup>3</sup>
Oil density	885 kg/m <sup>3</sup>
DME density	668 kg/m <sup>3</sup> (@ 25 °C)
Injection pressure	Reservoir pressure + 50 bar

**Table 1.** Main assumptions and inputs of the calculations. References to numbers can be found in <sup>40,41</sup>.  $\dot{Q}$  (m<sup>3</sup>/s): flow rate,  $\Delta P$  (Pa): pressure,  $\eta$  (-): pump efficiency,  $\rho$  (kg/m<sup>3</sup>): density,  $g$  (m/s<sup>2</sup>): acceleration due to gravity,  $h$  (m): reservoir depth.



**Fig. 2.** The simulated history of the injection and production fluids of the DME EOR for a reservoir in the Middle East.

produced oil from the field, along with the resulting  $\text{CO}_2$  emissions from the power plant, can generate the necessary volume of DME required for the field operations. To determine the amount of  $\text{CO}_2$  generated by burning oil, a stoichiometric balance is employed. Oil is assumed to be  $\text{CH}_2$  with the combustion reaction:



According to Eq. (8), burning 1 kg of  $\text{CH}_2$  releases 3.14 kg of  $\text{CO}_2$ . With a  $\text{CO}_2$  capturing efficiency of 90%, 10% of the produced  $\text{CO}_2$  in the power plant will be emitted to the atmosphere. According to Eq. (2), 1.91 kg of  $\text{CO}_2$  is needed to produce 1 kg of DME, therefore, the minimum amount of the manufactured DME per barrel of oil can be calculated as

$$1 \text{ bbl} - \text{oil} \times 0.159 \frac{\text{m}^3 - \text{oil}}{\text{bbl} - \text{oil}} \times 885 \frac{\text{kg} - \text{oil}}{\text{m}^3 - \text{oil}} \times 3.14 \frac{\text{kg} - \text{CO}_2}{\text{kg} - \text{oil}} \times 0.90 \times \frac{1}{1.91} \frac{\text{kg} - \text{DME}}{\text{kg} - \text{CO}_2} = 208.2 \text{ kg} - \text{DME} \quad (9)$$

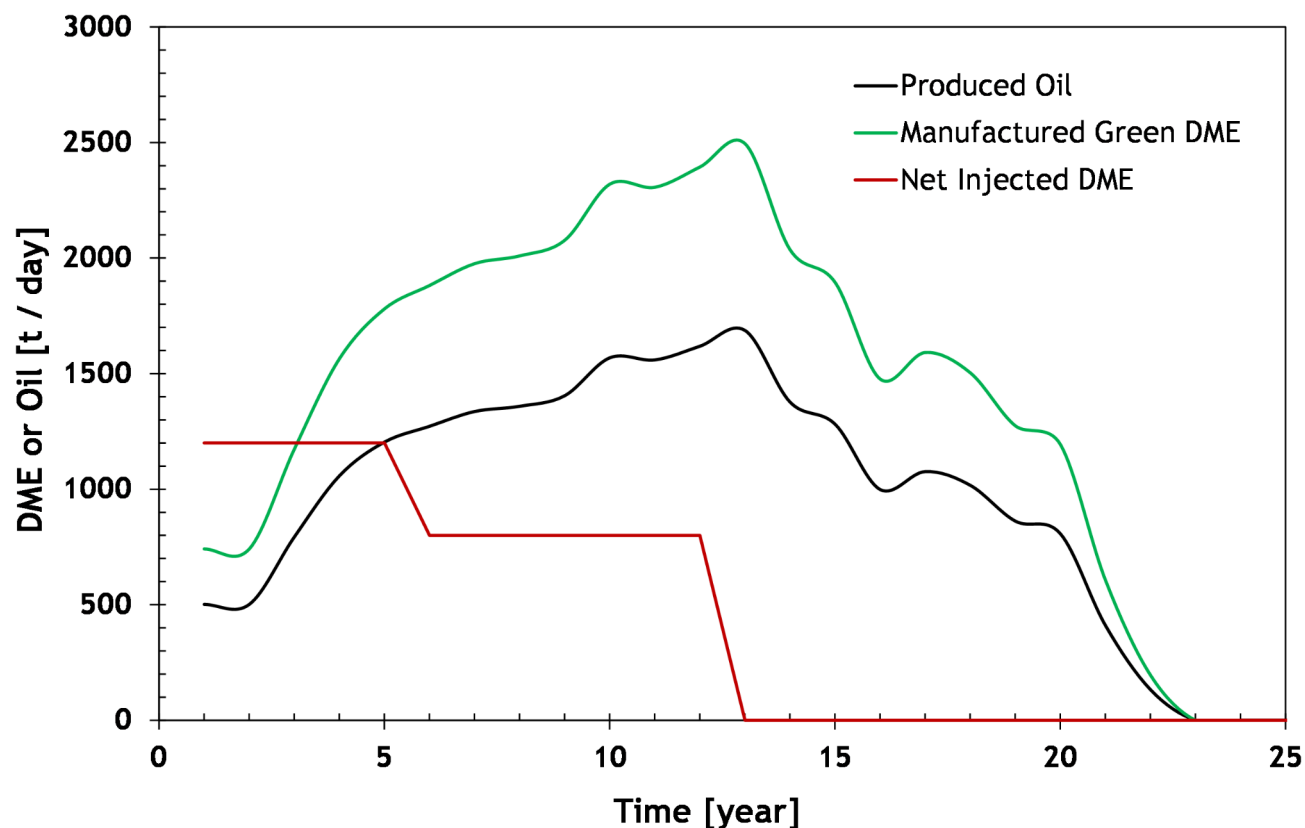
Based on the analysis, it is observed that approximately 0.21 tons of DME (equivalent to 1.48 kg-DME/kg-oil) can be produced from every barrel of oil burned in the power plants. Figure 3 illustrates the total producible DME using the hydrogenation method, considering the oil production data presented in Fig. 2. Except for the first two years, the DME production is sufficient to meet the field's requirements. The surplus DME can be utilized in other fields or for various purposes, such as electricity generation, methanol production, or transportation.

#### Power requirement to manufacture DME

The estimated maximum installed capacity needed to supply the power required for producing approximately 3000 tons per day of DME (as shown in Fig. 3) is around 2.5 GW, based on an energy requirement of 74 MJ/kg-DME. In recent years, solar and wind power have accounted for over 60% of the installed capacity from renewable energy sources, which amounts to around 3300 GW globally<sup>42</sup>. This growth has been primarily driven by significant investments in solar power. In the Middle East and North Africa region, where there is abundant sunlight, there has been a notable increase in solar PV investments. As of 2022, approximately 16 GW of power is produced using solar PV in the Middle East, and this number is expected to rise rapidly to over 35 GW by 2026<sup>42</sup>.

However, a challenge lies in obtaining the required capacity from a single solar farm. Currently, the largest solar farm in the UAE has an installed capacity of around 1.0 GW, which is projected to increase to 5 GW by 2030. While the capacity in the region is expected to grow, meeting the energy requirements of the DME EOR project would likely necessitate sourcing from multiple solar farms. Furthermore, it is important to note that the





**Fig. 3.** Oil Production, manufactured DME, and net DME Injection (injected–back produced) rates as a function of time using the field data shown in Fig. 2. In the calculation it has been assumed that 0.21 tDME/ bbl-oil can be produced (see Eq. 9).

estimated installed capacity of 2.5 GW assumes that all the captured  $\text{CO}_2$  is used for DME production, which exceeds the requirements of the field. Depending on availability, a lower installed capacity may be sufficient to meet the field's needs. For instance, to produce the net DME requirement of 1200 tons per day (as shown in Fig. 3), an installed capacity of 1 GW would be necessary. Alternatively, dividing the DME EOR project into several smaller projects could be considered to reduce the size of the initial investments.

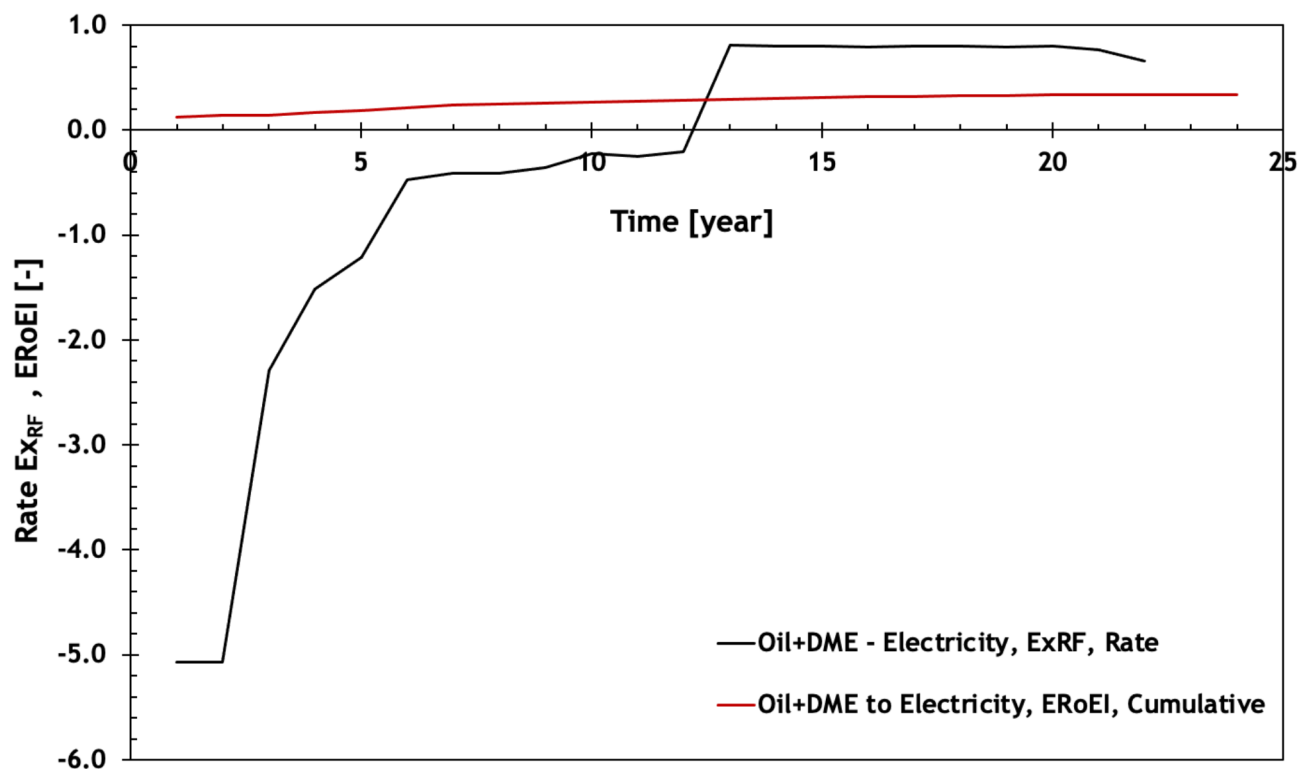
### Exergy balance

This section presents the findings of the exergy analysis conducted on the DME-EOR process with the system depicted in Fig. 1 and input parameter in Table 1. Figure 4 depicts the history of the exergy-recovery-factor ( $Ex_{RF}$ ) for the scenario where the produced oil and excess DME are converted into electricity. The injection of DME leads to additional oil production until year 13; however, this necessitates the manufacturing of large volumes of DME. Due to the significant exergy involved in DME synthesis, the amount of invested exergy is considerably greater than the recovered exergy. Consequently, the overall  $Ex_{RF}$  for the process is negative.

Nevertheless, after year 13, the  $Ex_{RF}$  starts to increase and becomes positive as the volume of back-produced DME is sufficient to meet the injection requirements. By the end of year 20, there is no DME injection or oil production, resulting in no exergy being used for DME synthesis. The injected DME is fully recovered even after oil production ceases. The cumulative Energy Return on Energy Invested (EROEI) for the entire process reaches 0.34 at the project's conclusion, indicating an overall exergetic efficiency of 34%, as depicted in Fig. 4.

Figure 5 illustrates the distribution of the invested exergy among different components of the system depicted in Fig. 1. As shown in Fig. 5, during the initial phase of the project, the exergy required for DME synthesis accounts for approximately 80% of the total invested exergy until year 13 when the net injected DME reaches zero. During this period,  $\text{CO}_2$  capture consumes less than 20% of the total invested exergy. However, once the back-produced DME from the reservoir is sufficient to sustain oil recovery, the exergy investment in  $\text{CO}_2$  capture and transport becomes the largest. This trend continues until year 20 when oil production ceases, resulting in no  $\text{CO}_2$  emissions and, consequently, no exergy required for  $\text{CO}_2$  capture.

After this point, the lift and injection pumps become the primary exergy consumers, accounting for approximately 50% and 30% of the total exergy investment, respectively. It is important to note that after oil production stops, water is injected to recover the retained DME in the reservoir. The contribution of oil transportation to the overall exergy invested is minimal and does not have a significant impact. Figure 5 also reveals a general increase in the exergy investment associated with oil and water. This is attributed to the increasing oil production over time. Additionally, the exergy investment related to lift and injection pumps and



**Fig. 4.** Rate exergy recovery factor (defined in Eq. 3) and cumulative EROEI as functions of time for the case where the produced oil and the excess DME are converted to electricity. The resulting CO<sub>2</sub> assumed to be captured.

water treatment increases due to the larger volume of injected water required for back-producing the injected DME. However, the magnitude of this increase is not comparable to the exergy invested in DME synthesis and CO<sub>2</sub> capture from the power plant. The corresponding Sankey diagram of the process is plotted in Fig. 6 for year 5 of the injection.

Figure 6 further illustrates the CO<sub>2</sub> intensity of the DME-EOR process over time, particularly in terms of specific emission reduction performance, measured in kg-CO<sub>2</sub>/bbl-oil. This includes CO<sub>2</sub> emissions from DME synthesis, injection, and production operations, as well as the oil-fueled power plant. The reservoir oil has a calculated CO<sub>2</sub> intensity of approximately 442 kg-CO<sub>2</sub>/bbl-oil. With a 90% CO<sub>2</sub> capturing efficiency, the dashed red line in Fig. 6 represents the emission of 44.2 kg of CO<sub>2</sub> for every barrel of oil consumed in the power plant. Most the total CO<sub>2</sub> emissions is attributed to the manufacturing of the required DME, particularly in the early stages of the project. To reduce this emission, efforts can be made to lower the carbon footprint of the exergy needed for CO<sub>2</sub> capture and H<sub>2</sub> production. In this study, it is assumed that solar energy with a specific CO<sub>2</sub> emission of 12.5 gr-CO<sub>2</sub>/MJe is used to supply the exergy for DME synthesis. The field equipment operates on electricity generated from gas turbines.

In summary, Fig. 7 presents the cumulative CO<sub>2</sub> intensity of the process and the fraction of abated CO<sub>2</sub>. Over time, the cumulative CO<sub>2</sub> intensity decreases, and by the end of the project, with the assumptions made in this paper, it is reduced to less than 50 kg-CO<sub>2</sub>/bbl-oil. This means that approximately 74% of the CO<sub>2</sub> resulting from burning the produced oil is prevented from entering the atmosphere. If zero-carbon electricity is used throughout the entire process, the total abated CO<sub>2</sub> can reach 85%.

Figure 8 presents a comparison of the CO<sub>2</sub> intensity between the electricity generated in the system of Fig. 1 and the oil produced through water injection, with CO<sub>2</sub> capture considered in both cases. Following refs.<sup>40,41</sup>, the CO<sub>2</sub> emissions of the water-injection project is

$$e_{CO_2,WF} = \frac{a}{1 - f_w} \quad (10)$$

Here,  $f_w$  represents the overall water cut of the reservoir, and the factor  $a$  (kg-CO<sub>2</sub>/m<sup>3</sup>-water) represents the CO<sub>2</sub> emission associated with handling the injected water. For water cuts of 95% and 98%, CO<sub>2</sub> intensities of 25 and 64 kg-CO<sub>2</sub>/bbl oil are calculated, respectively. Assuming a 90% CO<sub>2</sub> capture efficiency and a 40% power plant efficiency, the CO<sub>2</sub> intensity of the electricity is calculated to be 30 and 47 g-CO<sub>2</sub>/MJe, respectively. It is worth noting that the emitted CO<sub>2</sub> for the low-carbon DME EOR is lower (approximately 33% for  $f_w = 0.95$  and 65% for  $f_w = 0.98$ ) compared to the water flooding case. This difference is more pronounced in the initial stages of the project, as less energy is required for DME manufacturing due to lower oil production. The exergetic efficiency of the DME-EOR process starts off relatively low but reaches about 80% by the end of the project.



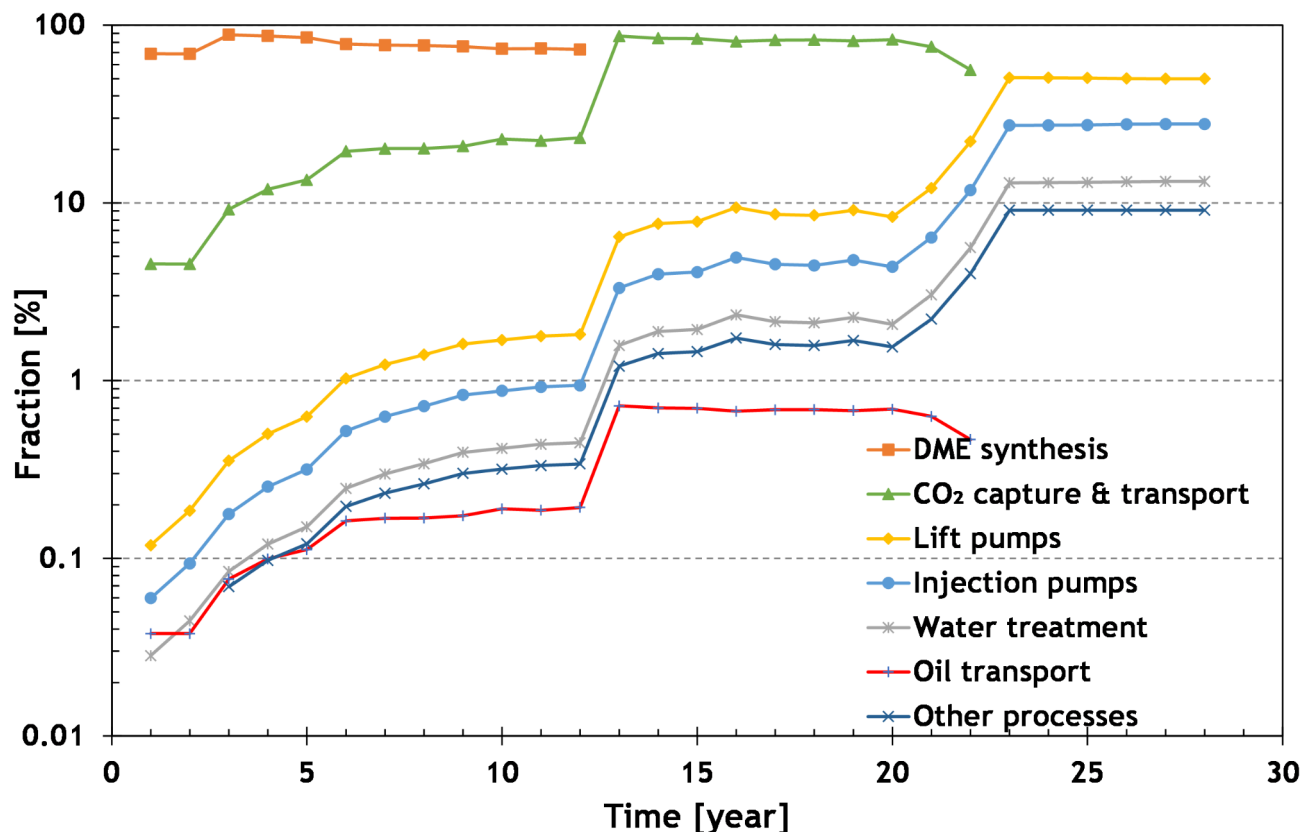


Fig. 5. Fractions of the invested exergy in different Components of the considered system in Fig. 1.

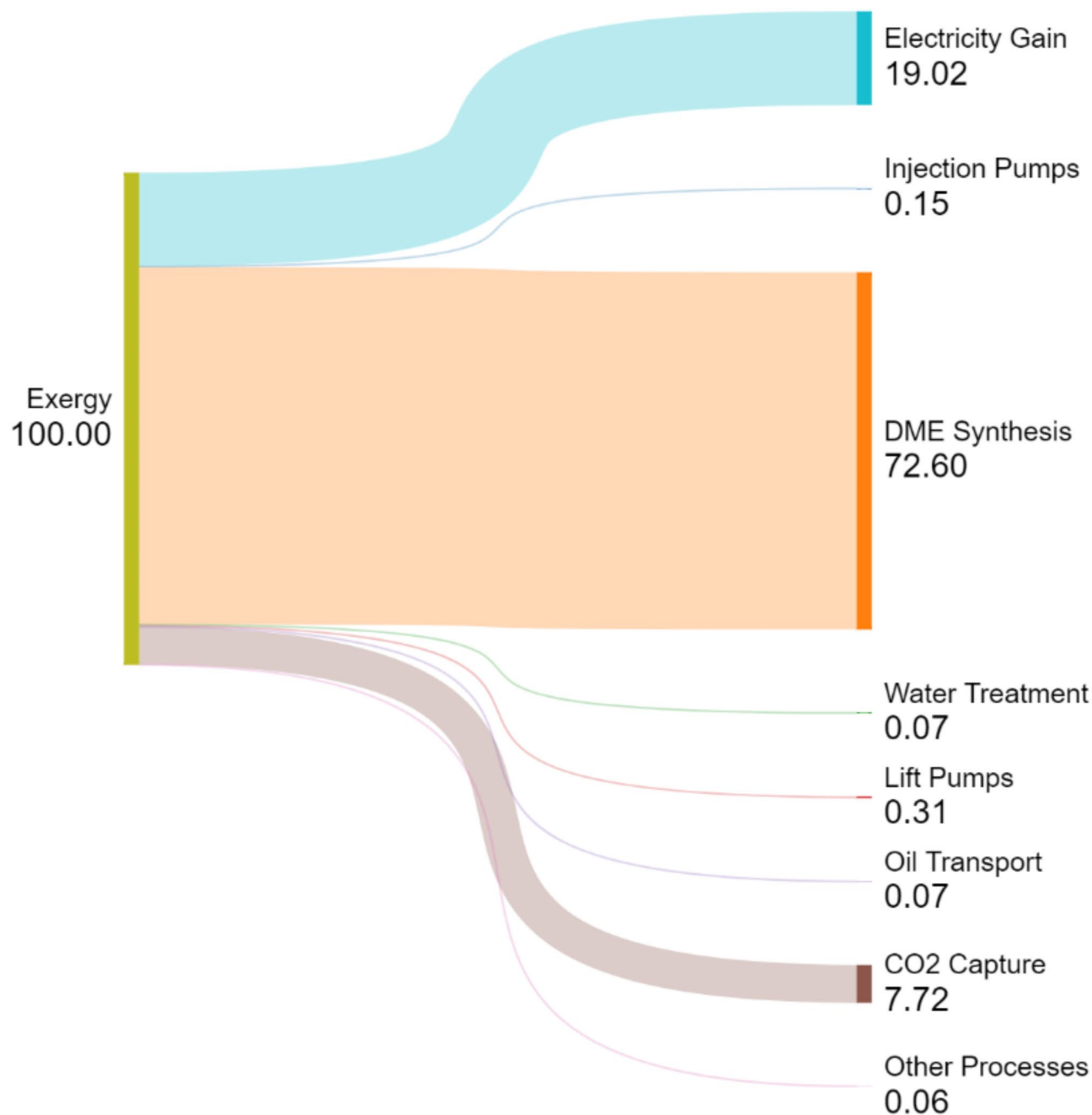
Figure 9 illustrates the relationship between the DME utilization factor (bbl-oil / tDME) and the total emitted  $\text{CO}_2$  per barrel of oil in the DME-EOR process. DME utilization factor is defined as the volume of oil produced per mass of DME injected. Utilization factor in ( $\text{CO}_2$  and chemical) enhanced oil recovery is a good indicator of the efficiency of injectants in extracting oil. The utilization factor usually.

The DME utilization factor is quantitatively defined as the volume of oil produced per unit mass of DME injected into the reservoir. The utilization factor is commonly used to evaluate efficiency of injectants in ( $\text{CO}_2$  and chemical) EOR projects and is influenced by the physicochemical properties of the reservoir, degree of reservoir heterogeneity, thermodynamic conditions (pressure, temperature, salinity), the type of injectant, the characteristics of the crude oil, the interaction between the injectant and the reservoir rock, and the operational parameters of the injection process.

The  $\text{CO}_2$  emissions considered in Fig. 10 include the 10% of  $\text{CO}_2$  released from burning oil (with 90% of the released  $\text{CO}_2$  captured) as well as the  $\text{CO}_2$  emissions from DME synthesis and injection. As shown in this figure, the DME utilization factor significantly impacts the life-cycle analysis of the DME-EOR process, like the  $\text{CO}_2$  EOR process (Farajzadeh et al., 2020). Improving the DME utilization factor can be achieved by enhancing the mobility control between the injected DME solution and the in-situ oil. One approach to achieve this is by adding polymers into the DME solution<sup>9</sup>. Under favorable conditions, such as a DME utilization factor of 20 bbl/tDME, the total  $\text{CO}_2$  intensity of oil decreases to less than 30 kg- $\text{CO}_2$ /bbl oil. This indicates that more than 93% of the resulting  $\text{CO}_2$  from burning oil can be abated. This is a significant reduction compared to other EOR methods. In particular, with typical utilization factors of 2–4 bbl-oil/t $\text{CO}_2$ ,  $\text{CO}_2$  EOR reduces  $\text{CO}_2$  intensity of oil by 75–80%<sup>7</sup>.

## Conclusions

Indirect  $\text{CO}_2$  Enhanced Oil Recovery (EOR) is a promising approach that offers multiple benefits for oil production and carbon mitigation. It enables the utilization of  $\text{CO}_2$  that would otherwise be emitted into the atmosphere, thereby reducing greenhouse gas emissions. This paper evaluates the use of dimethyl-ether (DME), produced from anthropogenic  $\text{CO}_2$  and renewable or green hydrogen, as an EOR agent in a closed system. Our analysis demonstrates several advantages of the proposed indirect  $\text{CO}_2$  EOR method, including  $\text{CO}_2$  capture and utilization, increased energy extraction, utilization of existing infrastructure, and reduced  $\text{CO}_2$  intensity. In the case studied, DME synthesis accounts for the largest fraction of the total exergy investment followed by  $\text{CO}_2$  capture, specially at the initial stages of the project. Furthermore, our findings indicate that the proposed indirect EOR method emits less  $\text{CO}_2$  compared to the water flooding process, with a difference of approximately 33% for a water cut of  $f_w=0.95$  and 65% for  $f_w=0.98$ . This difference is more pronounced in the initial stages of the project due to lower energy requirements for DME manufacturing resulting from lower oil production. The



**Fig. 6.** Sankey diagram of the DME EOR process at time = 5 years.

CO<sub>2</sub> intensity of the system is strongly influenced by the DME utilization factor, which can be improved by incorporating a mobility-control agent into the DME-water solution.

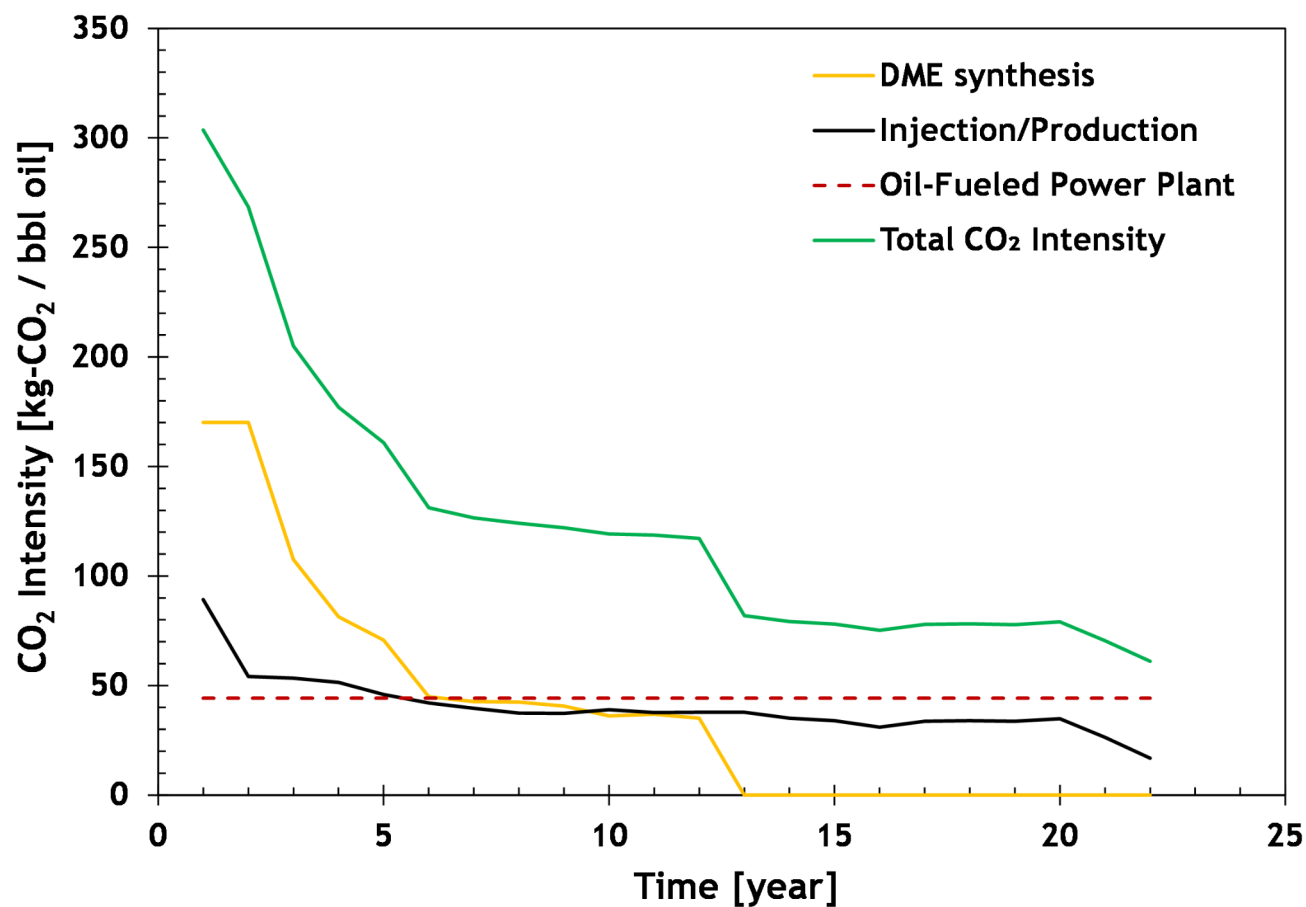
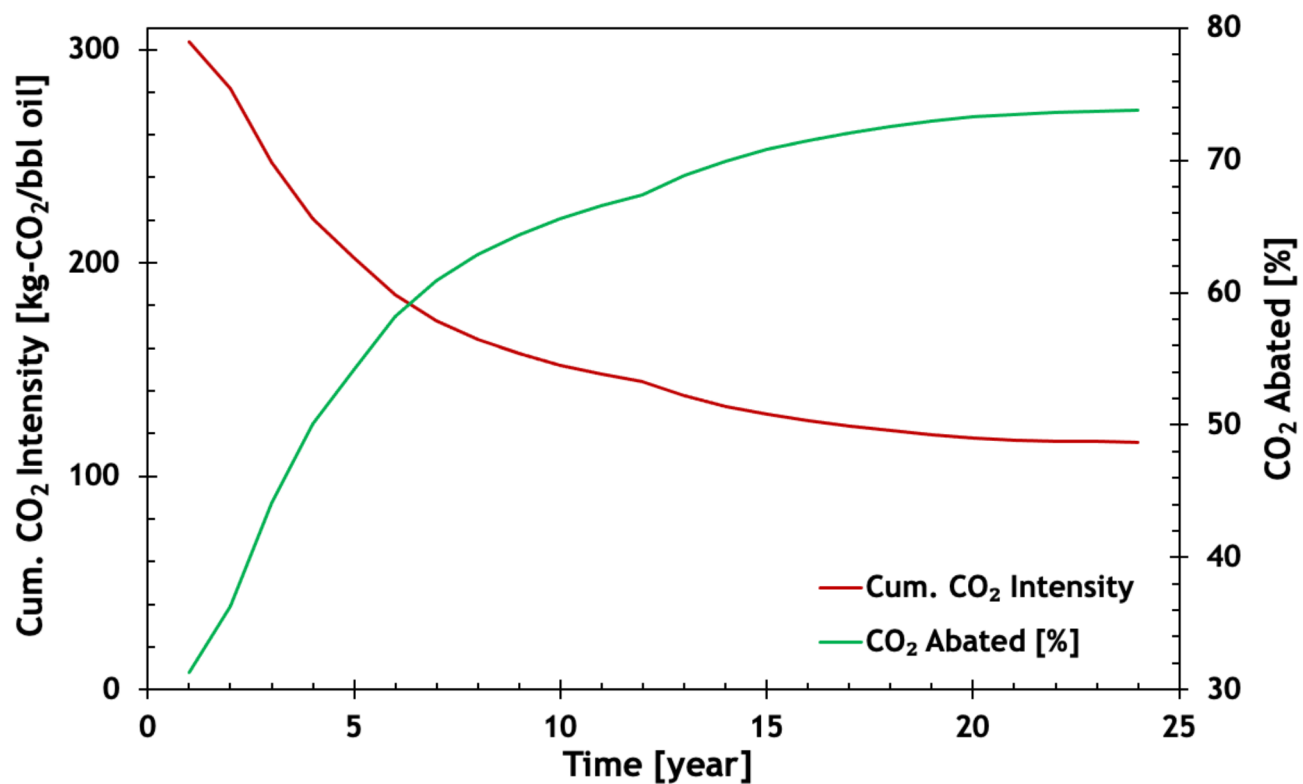
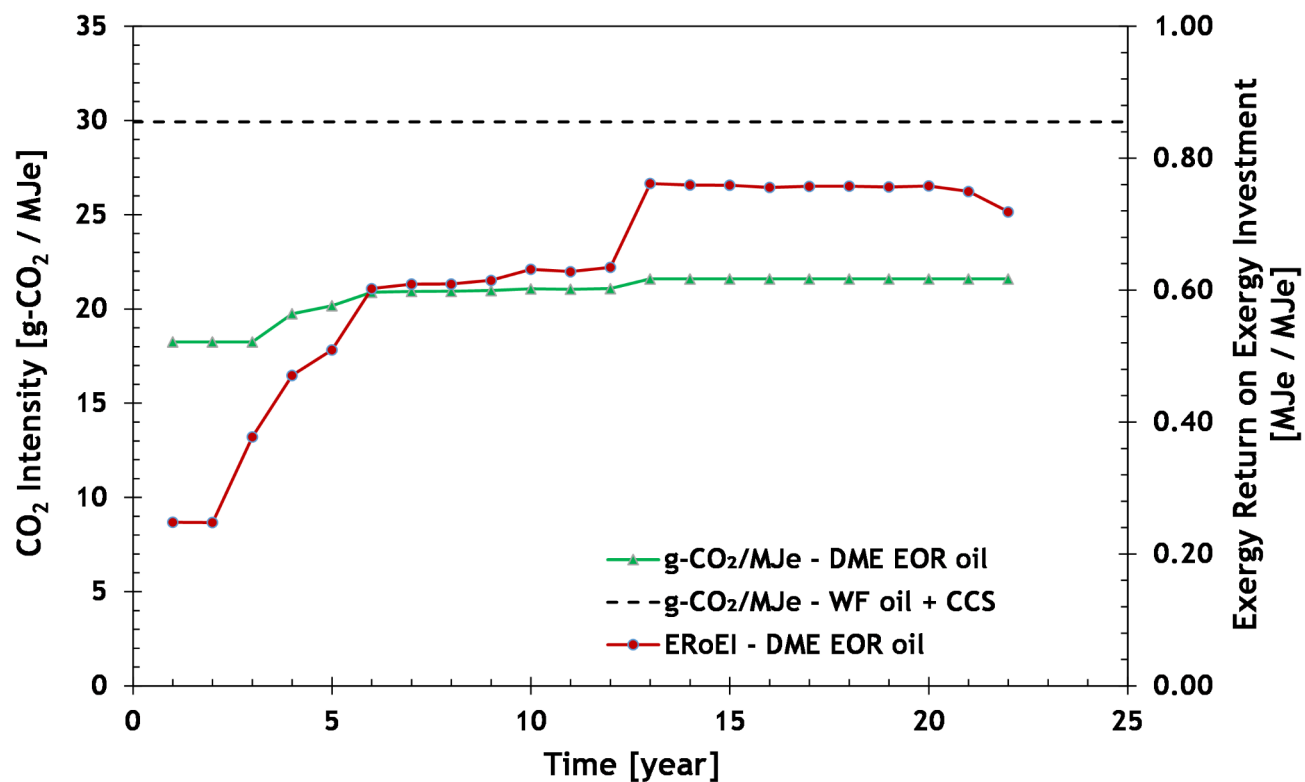


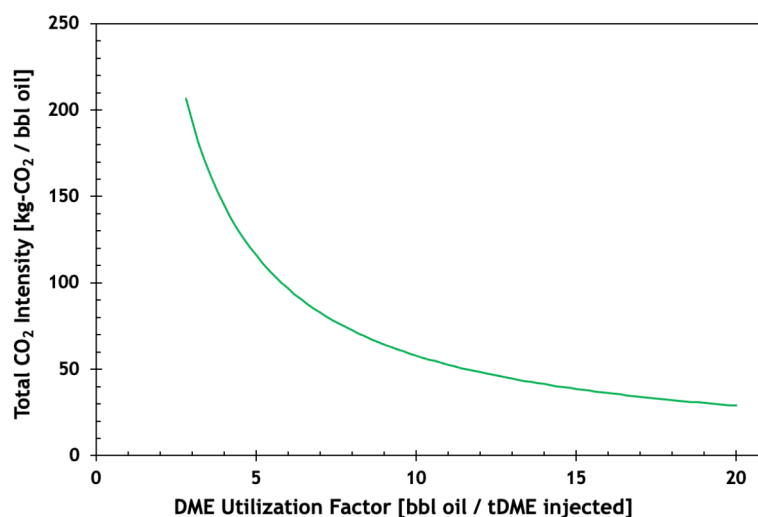
Fig. 7. CO<sub>2</sub> intensity of the low-carbon DME-EOR process (Fig. 1) as a function of time.



**Fig. 8.** Cumulative CO<sub>2</sub> intensity of the low-carbon DME-EOR process and the percentage of the abated CO<sub>2</sub>. The CO<sub>2</sub> intensity of burning oil is 442 kg-CO<sub>2</sub>/bbl oil.



**Fig. 9.** CO<sub>2</sub> intensity of the electricity generated from the system considered in Fig. 1. The black dashed line is the CO<sub>2</sub> intensity of the oil production from waterflood project with 95% water cut. Both cases consider Carbon Capture and Storage (CCS) option. The red is the exergetic efficiency of the low-carbon DME EOR process.



**Fig. 10.** Total CO<sub>2</sub> intensity of a barrel of oil produced as a function of DME utilization factor. The numbers include CO<sub>2</sub> emissions from burning oil and CO<sub>2</sub> released from synthesis of DME.

### Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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## Author contributions

R.F. developed the idea, performed the analysis, prepared figures, and wrote the initial draft of the paper. N.K. performed part of the analysis and reviewed the paper. D.S. performed the initial exergy analysis. S.M. and J.B. helped with interpretation of the results and reviewed the final version of the paper.

## Competing interests

The authors declare no competing interests.

## Additional information

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