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DOI
10.1016/j.jclepro.2019.07.034

Publication date
2019

Document Version
Final published version

Published in
Journal of Cleaner Production

Journal of Cleaner Production 235 (2019) 812–821

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Life-cycle assessment of water injection into hydrocarbon reservoirs using exergy concept

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ARTICLE INFO

Article history:
Received 3 May 2019
Received in revised form
20 June 2019
Accepted 4 July 2019

Handling Editor: Sandro Nizetic

ABSTRACT

Water injection into hydrocarbon reservoirs has been studied in great detail both from the subsurface and from surface perspectives, usually aiming at maximizing the production of low-cost oil. Here, the exergy concept is used to examine the potential life-cycle impact of injecting water into hydrocarbon reservoirs by considering the energy requirements of the process. It is found that the exergy recovery factor, being the ratio between the produced exergy corrected for material and process exergy requirements for its extraction and the gross exergy of the source decreases with time. Usually the process exergy requirements to produce the exergy increases with time. In the case of water injection the main contributors to the process exergy are due to treatment of water and the pumping of reservoir fluids. The method presented in this paper can also quantify the amount of CO_2 per unit volume of the produced oil. It is contended that the volume of water required to produce the oil is an important indicator of the efficiency of water drive recovery of oil. Moreover, the amount of carbon dioxide produced for the extraction of one barrel of oil depends strongly on the water cut f_w in the producers. Below $f_w = 80\%$ little CO_2 is produced; however, when $f_w > 90\%$ a small increase in the water cut leads to a large increase of carbon dioxide production. This emphasizes the importance of water management in water drive recovery of oil.

1. Introduction

A large part of the global energy demand is supplied by fuels extracted from subsurface hydrocarbon reservoirs (International Energy Agency, 2015). Initially, these reservoirs contain pressurized fluids and no external energy is required to push the in-situ fluids towards the production wells. However, only a minor fraction of the oil in place can be produced by the natural energy of the reservoir and eventually in the secondary stage of the production external energy should be supplied (Dake, 1978; Farajzadeh et al., 2019).

Water injection has been the most common secondary method to maintain the reservoir pressure (usually above the bubble point pressure) and displace movable oil (Graig et al., 1955; Bedrikovetsky, 1993). The injected water moves through the formation and sweeps the oil from the pore space towards the production well. Water injection is relatively simple and inexpensive to implement and operate at large scales. Moreover, water is available almost everywhere or can be made available at relatively low costs. When conditions are favorable and depending on the reservoir and fluid characteristics, water injection can recover a significant fraction (sometimes as high as 60–70%) of the oil initially in place (OIP) (Dake, 2001; Lake et al., 2014).

In water-injection projects, the injected water is initially supplied from an external water source (surface water sources such as seawater, lakes, rivers; and/or shallow or deep aquifers). However, during the production phase not only oil but also water is produced from the reservoir. Produced water (PW) is by far the largest waste product of the upstream petroleum industry (Allen, 2008; Fakhru'l-Razi et al., 2009). Worldwide, oil companies, on average, produce three barrels of water per barrel of oil (Al-Abduwani et al., 2005; Benoie, 2014). The produced water is sometimes injected back into the reservoir to meet environmental regulations and/or the limitations in the withdrawal of fresh water from aquifers or other water sources. However, the injected water must be treated before it can be reinjected or disposed (van den Hoek, 2004; Bedrikovetsky, 2008). The treatments include removal of (large) suspended solid particles, chemical contaminant, bacteria, oil droplets and sometimes reductions in the total ionic composition

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https://doi.org/10.1016/j.jclepro.2019.07.034
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(Noirot et al., 2003; Abdallah, 2014).

Furthermore, depending on the water quality, costs of water treatment and other economic considerations, water can be injected in two different ways, viz., "matrix injection" and injection under fracturing conditions (Van den Hoek et al., 1996, 2000). *Matrix injection* is done at small well pressures. In this case no fractures are induced and the reservoir is left as is. For this injection strategy, the quality of the injected water must meet stringent requirements; because large suspended particles or oil droplets can significantly damage the well injectivity by plugging the pores near the injection well (Kalantariasl et al., 2015). The reduction in injectivity has an adverse effect on the amount of produced oil. Therefore, to maintain the injectivity it is required to inject water under *fracturing conditions*, i.e., with injection pressures above the fracture or parting pressure of the formation rock. Fractures in a reservoir can be generated either by the application of high hydraulic pressure or by the thermal stresses (Van den Hoek et al., 1996). When the fluid pressure in the well exceeds a critical value, fractures are generated or the existing fractures are propagated. Injection under fracturing conditions increases the reservoir tolerance to lower water quality, and reduces operational costs. Also, higher water-injection rates (and thus oil production rates) are achieved. Nevertheless, the fracture length should be regularly monitored and controlled so that the fracture does not create a short circuit between the injector and producer.

Water injection has been studied in great detail both from subsurface and from surface perspectives, usually aiming at maximizing the production of low-cost oil. Here, a different approach is taken and the potential life-cycle impact of injecting water into hydrocarbon reservoirs is examined by considering the energy requirements of the process. It is asserted that for any oil-production system a similar approach should be followed to determine its (potential) impact on climate change and green-house gases (GHG) emission into the atmosphere. Such analyses can provide information on energy-intensive components of the production scheme and identifies opportunities to optimize the field-development scenario. (Dewulf et al., 2005; Murphy et al., 2011). This eventually leads to designing oil-production systems that could create the balance between the energy-demand and climate-change challenges. In the current study, it is demonstrated that the exergy concept can be used to evaluate the sustainability of a certain oil-production system.

Exergy is the maximum useful work that can be obtained from an energy stream that is brought in equilibrium with the environment or its surroundings called dead state (Szargut, 1987; Eftekhari et al., 2012). Unlike energy, exergy of a system can be dissipated because of irreversibility and generation of entropy (Van Ness and Abbott, 2001). The exergy analysis considers the exergy inputs and exergy "wastes". The proposed approach is similar to the energy return ratio (ERR) or energy return on investment (ERoEI) concept, that has been used to measure the "energetic productivity" of the oil industry (Brandt et al., 2015; Hassan et al., 2019). The ERR is the ratio between the energy provided and the energy consumed (Hassan et al., 2019). The energy efficiency of offshore oil and gas platforms in the North Sea and Brazil has also been analyzed using exergy (Oliveira et al., 1997; Nguyen et al., 2013). It was shown that the most exergy-consuming parts of the considered platforms were the gas-compression and oil-heating and water disposal processes.

The need to keep the global temperature rise below 2 °C has necessitated taking measures to reduce the carbon footprint of the industrial processes. Hydrocarbon fuels are the key driver of the global economy because of their large (volumetric) energy density, abundance, and ease of access and transportation (Farajzadeh, 2019). However, hydrocarbon fuels are the major carbon emitters to the atmosphere and therefore their negative impact on climate change should be mitigated during energy transition period by considering new (sustainability) measures. In this paper, a novel exergy-based workflow has been developed that can be used to determine the energy efficiency and/or CO_2 footprint of the different recovery processes applied to produce oil and gas. As an example, the full-cycle exergy analysis of the waterflooding will be presented, which provides new insights into effect of certain process parameter on CO_2 footprint of the projects. This can eventually help cleaner production of the hydrocarbon reservoirs. A full exergy analysis of an oil production scenario determines the time at which the exergy required to produce oil becomes larger than the exergy gained from the system, i.e., no useful work performed. This time is referred to as *exergy-zero time* and corresponds to an *exergy-zero recovery factor* beyond which the oil production is no longer sustainable and could emit significant amounts of greenhouse gases (GHG) (Farajzadeh, 2019).

The structure of the paper is as follows. First different stages of a water-injection project is explained, based on which the system and its boundary is defined for the assessment. This identifies the material and work streams involved in the process. Next, the details of the exergy calculations and a brief description of the method employed to forecast the amount of the oil produced by water injection for the reservoir of interest is presented. Afterwards the results of the analysis are explained highlighting the effect of different parameters on the exergy recovery factor and the required energy to produce a "waterflood barrel" of oil. The new criteria based on water utilization factor and water fraction of the produced fluids (water cut) are then defined, which can be considered to reduce the CO_2 footprint of the water-injection projects. The paper is ended with concluding remarks.

2. Method

This section describes the methodology used in this paper to assess the life-cycle impact of the water-injection projects.

2.1. System definition

A major difficulty in life-cycle analysis of any system is the choice of the boundary (disregarding labor costs). The selected system in this paper, is shown in Fig. 1 and includes the exergy analysis of the main stages of a water-injection project that aims at increasing the amount of produced oil. The oil field is assumed to be above its bubble-point pressure, i.e., there is no free gas in the reservoir. For the case considered the amount of dissolved gas is oil is small and therefore its effect on our calculations is negligible. Initially water from an external source is transported from the water source to the field site. Water is treated to meet the required quality and then injected into the reservoir. Pumps are used to move the water to the water treatment facilities and to the oil field. Usually this requires energy and thus is denoted by red arrows. Water is injected into the oil field and oil, gas, and water are produced. The produced oil and gas are the exergy sources and therefore are shown by green arrows. The produced water is treated and then re-injected back into the reservoir. Therefore, because of the reinjection of the produced water less fresh water is required from the water source. It is assumed that 20% of the injected water is not back-produced or lost/consumed during the process. The transfer of the produced water to the water treatment facilities requires exergy and thus denoted with red arrows (though it is considered negligible here). The artificial lift by pumps is considered in the producers. The produced oil is heated to a certain temperature and then transferred to a hydrocyclone to remove the water and other dense components (Puprasert et al., 2004). Finally, the oil is pumped to refineries to produce the final product, e.g.,

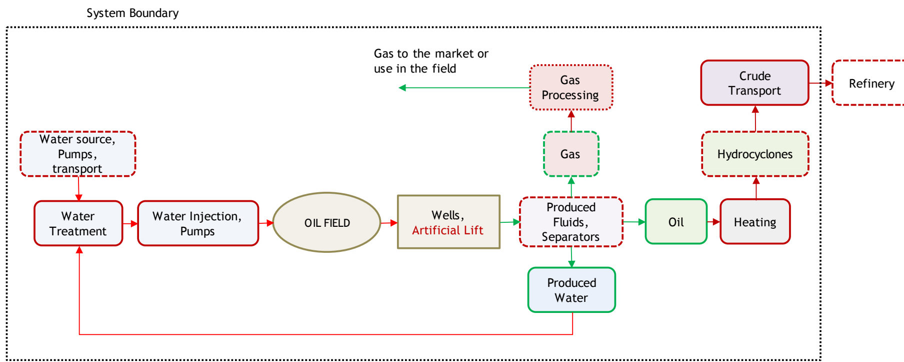

Fig. 1. Schematic of the production cycle system and the selected boundary considered in this work for production of oil by water injection. The boxes bordered by broken lines are either not considered in the calculations or are assumed to have negligible impact on the outcome.

fuel. The distance between the field and the refinery is assumed to be 500 km.

2.2. Exergy streams

The exergy analysis of the system defined in Fig. 1 is performed by considering the material (shown by green arrows) and work (red arrows) streams. The chemical exergy values of the components of the process are taken from Szargut and Morris (1987); Szargut, 1989. The dead state is assumed to be at a temperature and pressure of 298.15°K and 1 atm (101.325 kPa), respectively. Potential and kinetic exergy were assumed to be negligible in comparison with the chemical and physical exergy in this study.

2.2.1. Material stream

The chemical exergy of hydrocarbons is often considered to be their heating value (Finnveden and Ostlund, 1997; Liu and Li, 2015). For example, the chemical exergy of methane, CH_4, is $Ex^{ch}_{CH_4} = 831.65\ kJ/mol$ or $51.98\ MJ/kg$. The chemical exergy of crude oil depends on its composition (light components, sulfur, metals, etc.) and can be calculated from

$$E^{ch}_{ex,oil} = \sum_{i=1}^{n_{sc}} x_i E^{ch}_{ex,\ psc} \tag{1}$$

where x_i and $E^{ch}_{ex,\ psc}$ are the mole fraction and the chemical exergy of the pseudo-component in the crude oil. Usually, the heavier components of the crude oil are lumped into one pseudo-component for which an average molecular weight (M_w) and specific gravity (SG) is expressed (Rivero et al., 1999). To calculate the chemical exergy of these heavy components their lower (excluding the heat of water condensation) heating value (LHV) is used, which is obtained from

$$LHV\left[\frac{MJ}{kg}\right] = 55.5 - 14.4SG \tag{2}$$

For a hydrocarbon with a formula of $C_\alpha H_\beta$ the chemical exergy can be calculated from

$$E^{ch}_{ex} = LHV\left(1.04224 + 0.011925\frac{\beta}{\alpha} - \frac{0.042}{\alpha}\right) \tag{3}$$

To calculate the exergy value of the C_{7+} fraction of the crude oil it was assumed that the average carbon number in the C_{7+} fraction is 19 because of its molecular weight. Using eq. (2) and eq. (3), this gives an exergy value of 12.7 MJ/mol for this fraction. Using eq. (1) the exergy of the crude oil (with the composition defined in Table 1) is calculated to be 10.32 MJ/mol or 45.63 MJ/kg. The chemical exergy of the produced water is assumed to be negligible.

Table 1
Composition of a crude oil sample in mole fraction (Riazi, 1997). $\overline{M}_W = \sum x_i M_i = 226$ g/mol.

Component	Composition mol%	M_w g/mol	Specific gravity	Exergy KJ/mol
C_2	0.19	30.07	0.356	1495.0
C_3	1.88	44.10	0.508	2152.8
C_4	4.54	58.12	0.584	2804.2
C_5	6.57	72.15	0.631	3461.3
C_6	8.59	82.00	0.690	4106.0
C7+	79.23	266.00	0.895	12073

2.2.2. Work streams

Water treatment. Usually, water sources are in the proximity of the field and therefore water transport is neglected in our assessment. However, the water requires further treatment to meet the specifications imposed by the reservoir properties (mainly permeability to avoid pore plugging) and surface facilities and material. A variety of technologies are available for produced water treatment comprising chemical, physical and biological treatment methods. The energy consumption for treatment of the produced water can vary between less than 1 (floatation, filtration, adsorption methods) to more than 100 kWh/m^3 (e.g. multi-stage flash distillation method) depending on the applied technology (van der Bruggen and Vandecasteele, 2002; Miller, 2003). In this study, the membrane technology is chosen as a prototype because of its wide application, ease of operation, high efficiency, and more importantly its low energy consumption. The driving force for the membrane separation is the pressure gradient. By applying a certain pressure gradient the produced water passes through a membrane with an average pore size, which captures the larger particles and other pollutants. For the case with matrix injection, higher water quality and consequently higher energy is required, for which the energy consumption is 5 kWh/m^3 (18 kJ/kg) is assumed (Mallevialle et al., 1996). For the injection under fracturing conditions the water quality can be relaxed and therefore for this case the energy consumption is considered to be 1 kWh/m^3 (3.6 kJ/kg). The energy consumption of the hydrocyclone is minimal (unless when pumps are required to move water to the hydrocyclone) and therefore is neglected here.

Pump. The theoretical pumping exergy rate of the injected water is

$$\dot{Ex}^{th,pump}_{liquid} = \dot{Q}\Delta P \quad (4)$$

where, $\dot{Ex}\left[\frac{J}{s}\right]$ is the exergy rate, $\dot{Q}\left[\frac{m^3}{s}\right]$ is the rate of the injected water and ΔP [Pa] is the pressure difference between the injection and production wells. The practical pumping exergy is calculated by including the mechanical efficiency of the pump (80%), efficiency of the electrical driver (90%), and the efficiency of the power plant (50%), which gives overall efficiency of 36% for the pumps (Eftekhari et al., 2012; Hassan et al., 2019):

$$\dot{Ex}^{pr,pump}_{liquid} = \frac{\dot{Ex}^{th,pump}_{liquid}}{\eta_{pump}\eta_{driver}\eta_{PP}} = \frac{\dot{Q}\Delta P}{\eta_{pump}\eta_{driver}\eta_{pp}} \quad (5)$$

Transport. The exergy requirement for transport of crude oil is assumed to be 260 Btu/ton-mile (~188 J/kg-km) (DOE NETL, 2008; Wang, 2008).

Artificial lift. The rate of exergy to lift the liquids from the well was calculated from the following equation:

$$\dot{Ex}^{th,lift}_{liq} = \dot{Q}(f_w\rho_w + (1-f_w)\rho_o)gh \quad (6)$$

where f_w is water fraction of the produced liquid (or water cut), and h is the depth of the reservoir. The same pump efficiency of 36% was assumed in the calculations.

Heating. The exergy required for heating oil (assumed to be the electrical energy of heating of the oil) was calculated using the following equation:

$$\dot{Ex}^{heating}_{oil} = \dot{m}_{oil}c_p\Delta T \quad (7)$$

where $\dot{m}_{oil}$ [kg/s] is the mass rate of the produced oil, c_p [J/kg-K] is the heat capacity of the oil and T [K] is the temperature. In this work, $c_p = 3$ kJ/kg-K and $\Delta T = 20\,°C$, which results in specific exergy value of 60 kJ/kg for heating the crude oil.

Other processes. It is assumed that an additional 10% of the total invested exergy is required in other processes such as stimulation of the wells for matrix injection, pigging the pipelines, gas processing, etc (Patzek, 2004). For the case of the injection under fracturing conditions the additional required exergy assumed to 5% of the total invested exergy, because in this case less intervention and well stimulation is required. Table 2 summarizes the input values for the exergy analysis performed in this study.

2.2.3. Exergy recovery factor

The exergy recovery factor, Ex_{RF}, is defined as the ratio between the produced exergy corrected for material and process exergy requirements for its extraction and the gross exergy of the source, i.e.,

$$Ex_{RF} = \frac{Ex_{gained} - Ex_{invested}}{Ex_{fuel}} \quad (8)$$

Ex_{gained} is the exergy of the final product (within the selected boundary), $Ex_{invested}$ is the amount of exergy invested to produce hydrocarbons, and Ex_{fuel} is the amount of exergy stored in the hydrocarbon reservoir (Eftekhari et al., 2012; Farajzadeh, 2019). For production of oil by water injection, Eq. (8) can be re-written as

$$Ex_{RF} = \frac{Ex^{ch}_{oil} - \left(Ex^{pr,pump}_{water} + Ex^{pr,lift}_{fluid} + Ex^{pr,trans}_{oil} + Ex^{pr,treatment}_{water} + Ex^{pr,heating}_{oil} + Ex^{pr,other}\right)}{Ex^{ch}_{oil}} \quad (9)$$

2.2.4. Production forecast

The basic fractional-flow data from an oil field in the Middle East (summarized in Table 3) are used in a simplified semi-analytical streamline methodology combined with the modified Buckley-Leverett method to construct the volumetric history of the produced and injected fluids (Van den Hoek et al., 1996). Both water injection under matrix and fracture conditions was considered. For the injection under fracture condition, the bottom-hole pressure (BHP) in all injectors is set to the fracturing pressure of the rock, which is the maximum achievable BHP in all injectors regardless of the (higher) capacity of the pumps. When the pressure is below the fracturing pressure then the injection occurs under matrix conditions. Therefore, the maximum pressure difference between the injector and producer is the difference between fracturing pressure

Table 3
Reservoir and fluid properties for the base case.

S_{wc}	0.18	Water viscosity	0.59 cP
S_{wi}	0.18	Oil viscosity	110 cP
S_{or}	0.10	Average permeability	250 mD
k^e_{rw}	0.3	ΔP (Injector − Producer)	100 bar
k^e_{ro}	0.9	Injector-producer distance	150 m
n_o	1.2	V_{DP}	0.50
n_w	3	Total Suspended Solid (TSS)	0.1 ppm
Porosity	0.30	Fracture length	15m
		Permeability of the filter cake	0.01 mD

Table 2
Summary of the required exergy for material and work streams.

Material Stream	Specific Exergy [MJ/kg]	Work Stream	Specific Exergy [kJ/kg]
Crude oil	45.63	Pump	Eqs. (4) and (5)
Gas (methane)	51.98	Artificial lift	Eq. (6)
Produced water	0.0	Water treatment	3–20
		Heating	60
		Transport to refinery	188 J/kg-km
		Other process	5–10% of the total exergy

and producer BHP. This drawdown pressure drives the fluids towards the producers. In the calculations, a constant BHP was assumed for the producers. Moreover, water and oil were assumed to be incompressible, which implies a voidage replacement ratio of unity. For the case with a favorable mobility (the ratio between the relative phase permeability and its viscosity) ratio between water and oil ($M < 1$), the exact analytical solutions based on conformal mapping were used in the streamline simulations. For $M > 1$ (the case in this study), the 1-D solution from Buckley-Leverett theory was separately applied to each streamline. To account for the reservoir heterogeneity, the streamlines were modified based on the Dijkstra-Parsons coefficient (V_{DP}) of the porous medium. The V_{DP} assumes values between 0 (homogeneous medium) and 1 (extremely heterogeneous medium). Finally, the impact of water contamination is captured via filter-cake built-up, which results in abrupt increase in the pressure drop between the injection and production wells. The magnitude of the pressure increase in the injector depends on the injection rate, water quality (in particular concentration of the total suspended solids, TSS), injection duration, and the filter. For the case of induced fractures, the thickness of the external filter-cake is assumed to follow the fracture-width profile in that it has an elliptical shape declining towards the fracture tip, i.e., the filter-cake thickness at the fracture tip (like the fracture width) is equal to zero. More details of the recovery calculations can be found in Van den Hoek et al. (1996) and Van den Hoek et al. (2000).

3. Results and discussion

Fig. 2 shows the calculated oil recovery factor and its corresponding exergy recovery factor for the base case with the parameters listed in Tables 2 and 3. As time elapses, more oil is recovered from the reservoir, albeit with declining oil production rate. This comes at the expense of more water injection and production into and from the reservoir. Consequently, the exergy recovery factor decreases because more energy is required to treat and inject the water with time. However, it is noticed that because of high exergy of oil, the magnitude of the invested exergy is significantly less than the recovered exergy and consequently large exergy recovery factors are obtained. After 1 PV of water injection, only 3% of the recovered exergy is consumed for water injection requirements. Fig. 3 presents the fraction of the exergy consumed by different sections of the system depicted in Fig. 1. The exergy related to oil (i.e., heating and transport to refinery) decreases with time because of the reduction in oil production. At the early stages of the injection, a large volume of oil is produced; and therefore, a considerable fraction of the total exergy is consumed for heating and transportation of the oil. This adds up to more than 65% of the total exergy in our case; however, shortly after water breakthrough, these exergies decrease due to lower amounts of produced oil. In contrast, water-related exergies (e.g., pumps and treatment facilities) account for a large fraction of the invested exergy and their contribution increases with time. It appears, indeed, that pumps consume the largest fraction of the invested exergy. Water injection and lift pumps consume about 50% of the total invested exergy. Moreover, the exergy required for treating water increases with time, and its magnitude becomes about 30% of the total exergy after 1 PV of water injection.

The ratio between the calculated exergy invested in the individual components of the water-injection process and the amount of the produced oil provides the unit exergy consumed per barrel of oil produced, as shown in Fig. 4. With the assumption that all the invested energy is delivered from an electricity grid network, it is

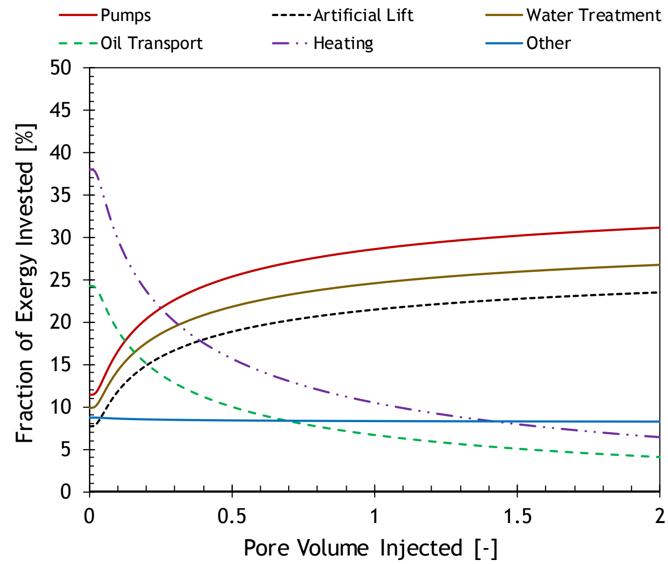

Fig. 3. History of the fractions of the invested exergy in different components of the considered system.

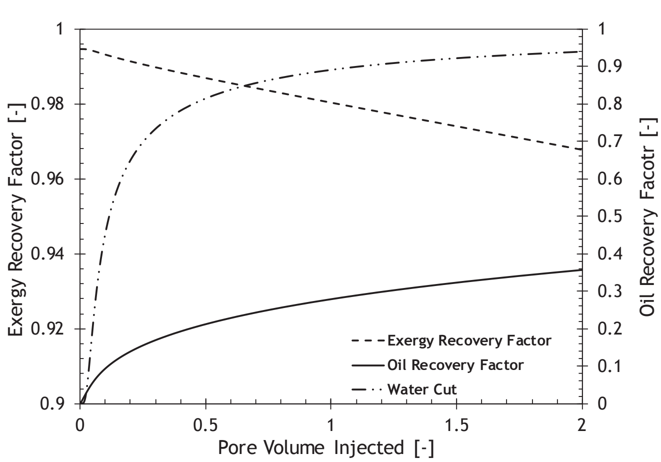

Fig. 2. The oil and exergy recovery factors as a fucntion of pore volume of injected water for the base case.

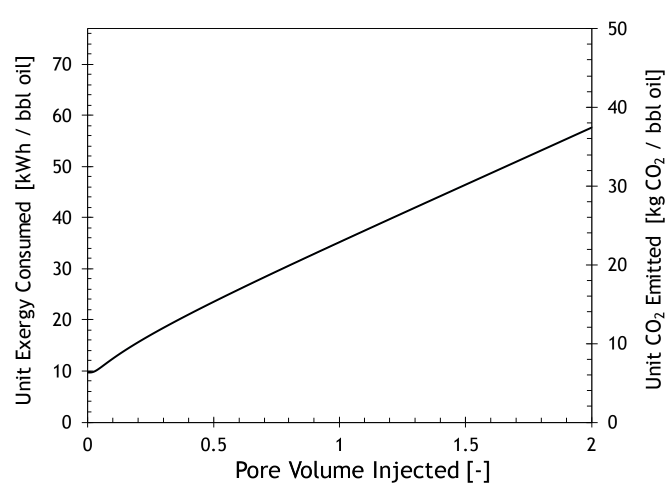

Fig. 4. Unit energy consumed and emitted CO_2 as a function of pore volume of water injected. It is assumed that the required energy come from electricity with the CO_2 footprint of 650 gCO_2/kWh.

possible to calculate the amount of CO_2 per barrel of oil produced. Electricity generation emits certain amount of CO_2 depending on the technology used. The average emission rate in the Middle East region is 650 gCO_2/kWh compared to the average value of 300 gCO_2/kWh in Europe (International Energy Agency, 2015). It appears from Fig. 4 that the amount of CO_2 emitted per unit volume of produced oil (i.e., kg CO_2/bbl oil) increases over time due to increased exergy investment. This suggests that an efficient way to reduce the carbon emission during production of fossil fuels is to use electricity generated from "cleaner" sources.

It is demonstrated that pumps are the most energy-intensive component of the water-injection production scheme. Therefore, the optimization of the process should consider improving the efficiency of the pumps. This will lead to significant improvements in the exergy recovery factor and ultimately lower CO_2 emission levels. Fig. 5 shows the effect of overall pump efficiency (pump efficiency combined with the efficiency of the electrical drive and the power plant) on the exergy consumed to produce a unit volume of oil. The exergy saved by using more efficient pumps can be significant, especially in reservoirs with high degree of heterogeneity.

Fig. 6 compares the exergy recovery factor for reservoirs with different level of heterogeneity characterized by the Dijkstra-Parsons coefficient or V_{DP}. The exergy recovery factor decreases with increasing level of heterogeneity. This is the combined effect of two factors: (1) as the reservoir heterogeneity increases, the amount of produced oil (exergy gained) at a certain time decreases and (2) more water injection (invested exergy) is required to produce the same amount of oil.

The effects of other parameters such as well spacing and the pressure drawdown on the exergy recovery factor of the water injection project were also investigated. In real time increasing the well spacing (injector-producer distance) and keeping the pressure drawdown the same (or decreasing the drawdown pressure and keeping the well spacing the same) delays the oil production and extends the life time of the project. This is because the water injection rate should be reduced to keep the injection pressure below the fracturing pressure. Fig. 7 reveals an interesting feature of the water injection process. Here, the exergy recovery factor of all the cases is plotted as a function of the water utilization factor (WUF), defined as the volume of the injected water to produce one unit volume of oil. Fig. 7 implies that the exergy recovery factor of a reservoir under waterflooding is only function of the water utilization factor. As water utilization factor increases the exergy factor

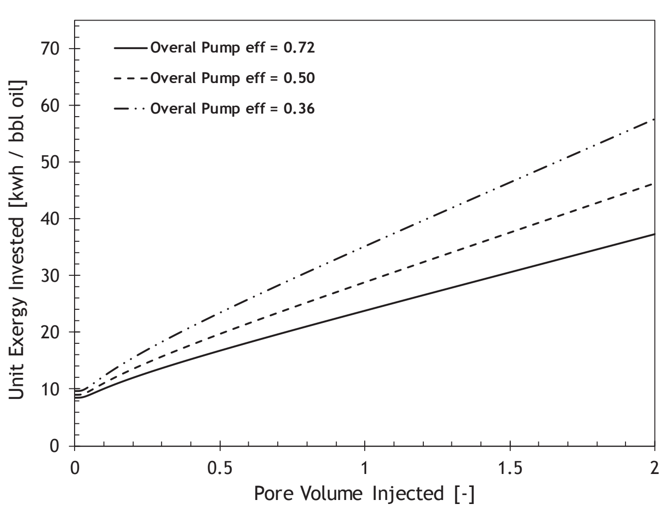

Fig. 5. Effect of overall pump efficiency on the unit exergy invested per barrel of oil produced.

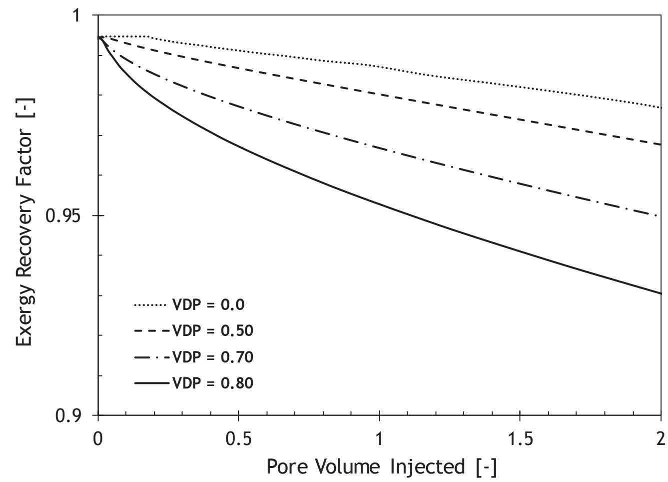

Fig. 6. Effect of reservoir heterogeneity on the exergy recovery factor.

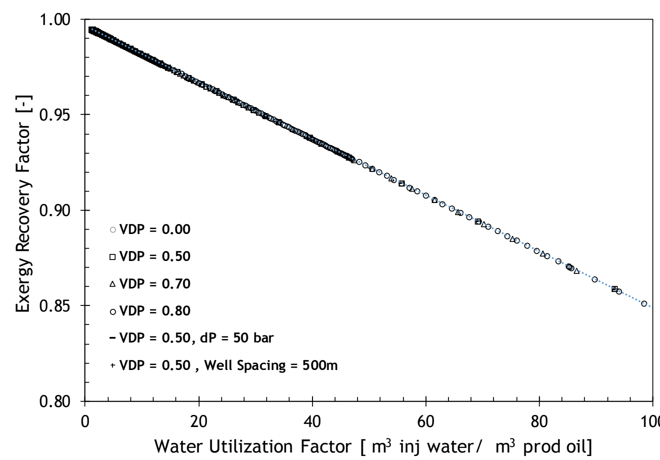

Fig. 7. Exergy recovery factor as a function of water utilization factor (unit volume of oil produced per volume of injected water) for different cases considered.

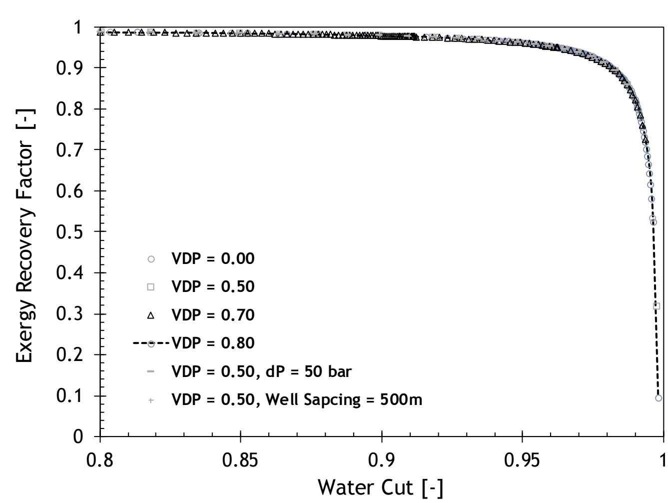

Fig. 8. Exergy recovery factor as a function of water cut for different cases cosnidered.

decreases. Fig. 8 and Fig. 9 plot the exergy recovery factor and the unit emitted CO_2 as a function of water cut (or the water fraction of the produced fluids) in the wells. When the water cut is below 80%,

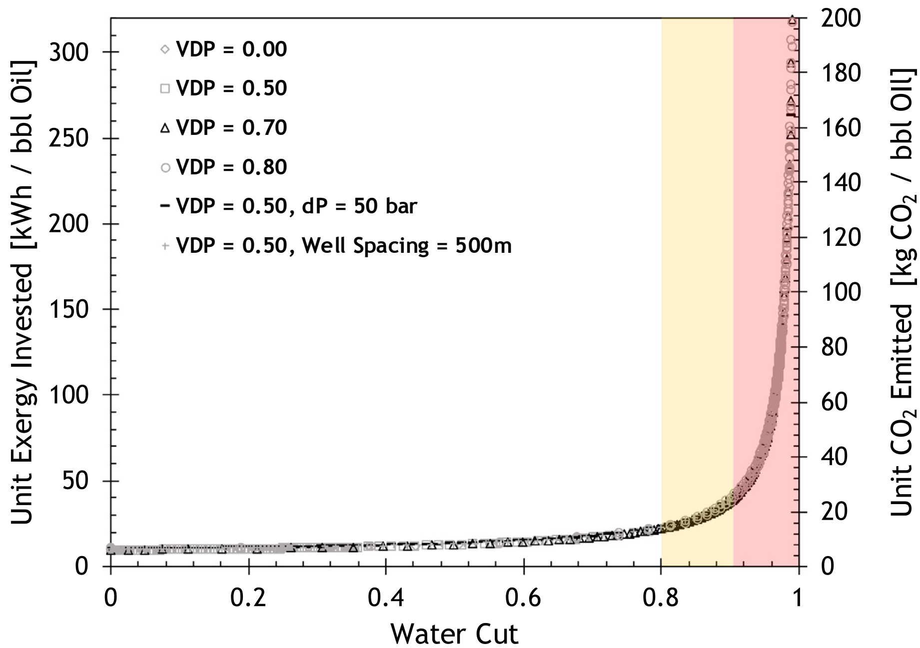

Fig. 9. Exergy recovery factor as a function of water cut for different cases cosnidered. The shaded area is associated with large CO_2 emissions.

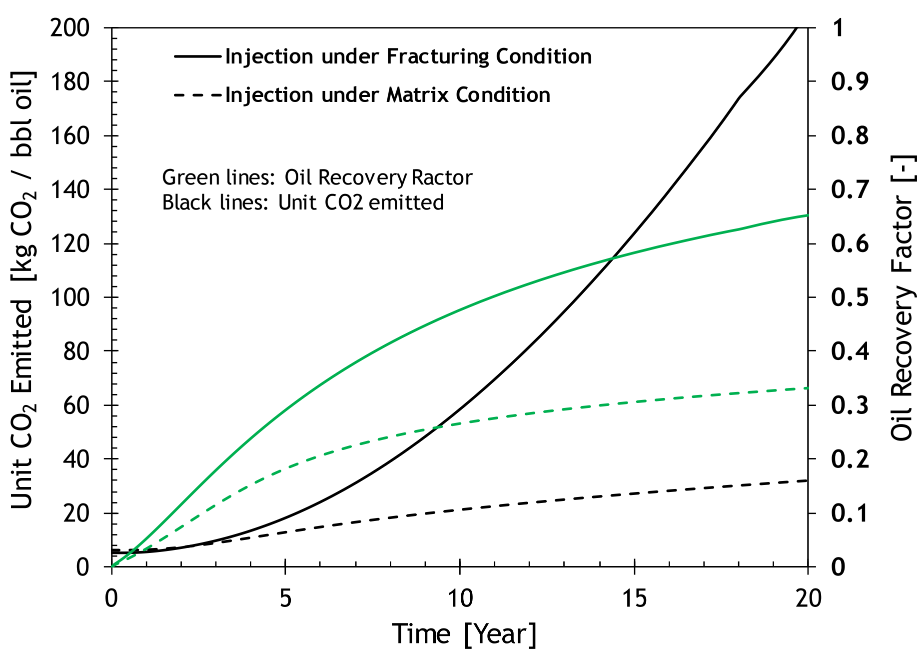

Fig. 10. Exergy consumed to produce one barrel of oil and oil recovery factor for injection under fracturing and matrix condition as functions of time.

relatively low exergy is required to produce oil. However, above water cut of 80% the invested exergy (and consequently the carbon footprint) begins to increase. Above 90% water cut this increase becomes dramatic and every one percent rise in the water cut has a significant impact on the invested exergy or emitted CO_2. Therefore, to reduce the carbon emission from water injection projects and improve the exergy recovery factor, high water cuts (>90%, the area shaded by red color in Fig. 9) should be avoided. This could be achieved by, for example, mechanical shut off, in-depth conformance control or even polymer injection.

Fig. 10 compares the unit exergy invested for water injection under fracturing and matrix conditions as a function of time. It is noticeable that in real time, because of large volumes of the injected water, the injection under fracturing conditions consumes considerably larger amount of exergy to produce one barrel of oil. However, to produce the same amount of oil (or the same recovery factor) injection under fracturing condition appears to emit less CO_2 than injection under matrix conditions, as shown in Fig. 11. The difference is attributed to the lower exergy consumed in water treatment and other process for injection under fracturing condition.

The effect of oil viscosity on the exergy recovery factor and the unit exergy invested is shown in Fig. 12 and Fig. 13, respectively. For low-viscosity oil no heating is required at the facilities. Also, as

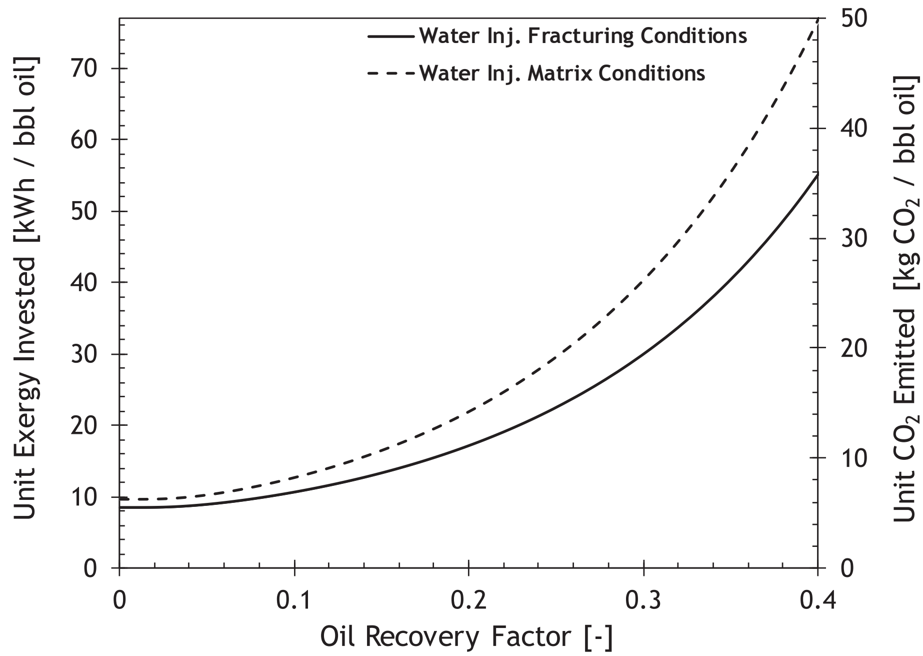

Fig. 11. CO_2 emission as a function of oil recovery factor for water injection under fracturing and matrix conditions.

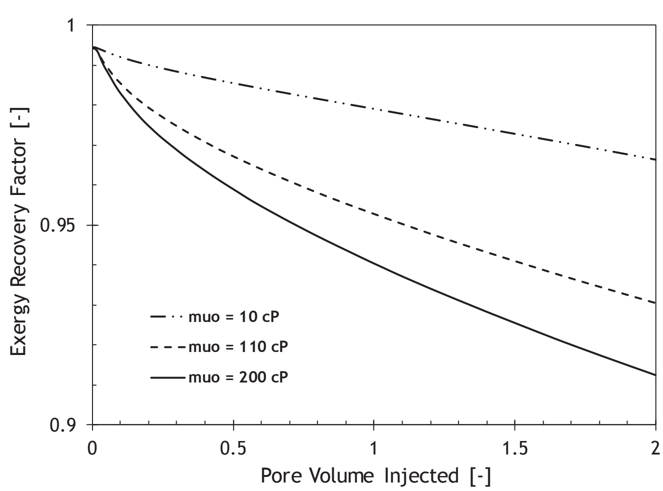

Fig. 12. Effect of oil viscosity on the exergy recovery factor ($V_{DP} = 0.80$).

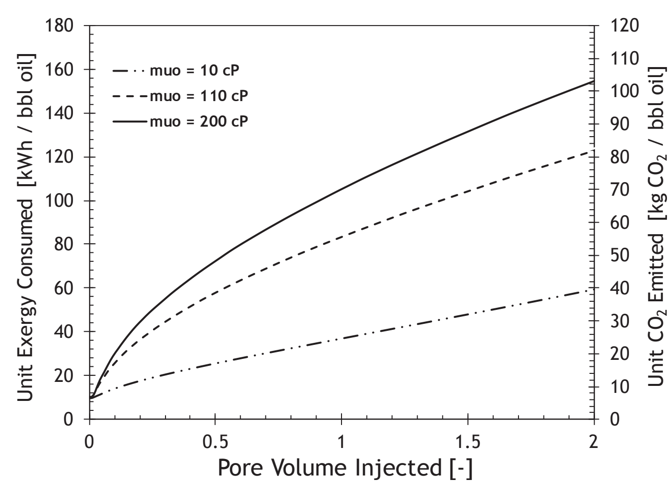

Fig. 13. Effect of oil viscosity on the unit exergy consumed and unit CO_2 emitted ($V_{DP} = 0.80$)..

mentioned earlier the specific exergy of oil depends on its composition, so it is likely that oils with different viscosities will have different exergy values, although the difference will not be significant.. The exergy recovery factor decreases with increasing oil viscosity due to increased volume of water injection. The increase in the oil viscosity, increases the mobility ratio between the injected water and the oil and makes the waterflooding less efficient. In other words, the water utilization factor increases considerably for heavy oil reservoirs and therefore the CO_2 footprint of their production are considerably higher than for the light-oil reservoirs.

4. Conclusions

In this paper, a methodology has been developed that can be used to analyze the life cycle of water injection in oil fields. The method integrates the concept of exergy with the production history of the oil field and provides the energy efficiency and CO_2 footprint of each component of the process. The results of the analysis can be used to optimize the reservoir such that hydrocarbons are produced in a more sustainable and cleaner manner during energy transition time. The following conclusions are drawn from this study:

- The exergy concept is a powerful notion to assess the life-cycle efficiency of water injection projects and shows which components in the considered system are the most important contributors to exergy loss.
- The exergy recovery factor, being the ratio between the produced exergy corrected for material and process exergy requirements for its extraction and the gross exergy of the source decreases with time. This indicates the process exergy requirements to produce the exergy increases with time. For water injection the main contributors to process exergy are

caused by treatment of water and the pumping of reservoir fluids.

- The methodology presented in this paper can also quantify the amount of CO_2 per unit volume of produced oil.
- Pumping is largely responsible for the process exergy requirement, which may add up to more than 50% of the exergy requirements for producing the oil recovered by water drive. It also shows that avoiding unnecessary losses in the pumping system increases the recovery factor and thus reduce the CO_2 emission.
- The amount of carbon dioxide produced for the extraction of one barrel of oil depends strongly on the water cut f_w. Below $f_w = 80\%$ little CO_2 is produced; however when $f_w > 90\%$ a small increase of the water cut leads to a large increase of the carbon dioxide production. This shows the importance of water management in cleaner and more sustainable production of the oilfields under water injection.
- The exergy recovery factor decreases with increases in reservoir heterogeneity or oil viscosity because more water is required to produce a unit volume of oil from heterogeneous and heavy oil reservoir.

Nomenclature

g	Acceleration due to gravity (m/s^2)
Ex	Exergy (J/mol)
Ex_{RF}	Exergy recovery factor (−)
$\dot{Ex}$	Exergy rate (J/s)
$\dot{Q}$	Flowrate (m^3/s)
ΔP	Drawdown pressure (Pa)
x	Molar fraction (mol%)
ΔT	Temperature difference (K)
η	Efficiency coefficient
c_p	Heat capacity (J/kg-K)
f_w	Water cut (−)
ρ	Density (kg/m^3)
μ	Viscosity (Pa.s)
LHV	Lower heating value (MJ/kg)
M_w	Molecular weight (g/mol)
SG	Specific gravity (−)
$_{ch}$	Chemical
$_{th}$	Theoretical
$_{pr}$	Practical
$_w$	Water
$_o$	Oil
$_g$	Gas
S_{wc}	Connate water saturation
S_{wi}	Initial water saturation
S_{or}	Residual oil saturation
k^e_{rw}	End-point water relative permeability
k^e_{ro}	End-point oil relative permeability
n_o	Oil Corey exponent
n_w	Water Corey exponent
V_{DP}	Dykstra-Parsons coefficient
WUF	Water Utilization Factor

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