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Innovative Approach for Maximizing CO_2 Storage and Enhancing Oil Recovery by Co-Optimization and Latestage Optimization

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ABSTRACT: The objective of this project is to maximize oil recovery and the total stored CO_2.Continuous CO_2 flooding case was used in this project as a base case reference to evaluate the different approaches in enhancing oil recovery and increasing the stored CO_2. Carbonated water injection (CWI) was suggested in literature to solve the possible lack of available CO_2 sources, however carbonated water requires special transportation material to alleviate the possible corrosion due to the low pH. This would add to the total cost of the project.
It wasshown here that water injection into the top layer and continuous injection of CO_2 into the bottom layer of the reservoir increases the stored CO_2 as well as oil production. Several co-optimization scenarios were addressed.
Increasing water injection rate and injection interval increases the total storedCO_2. This perhaps is due to reduction of gas-oil mobility ratio. However, in this case the ultimate oil recovery may be reduced.
The optimum approach for optimizing CO_2 storage and EOR was by intermittent water injection into the top reservoir layers and continuous CO_2 injection from the bottom layers, achieved 4.46% OOIP increase in oil recovery and 8% more CO_2 stored. Reduction of CO_2utilization factor (UF) from 5.22 tCO_2/Sm^3 oil to 4.15 tCO_2/Sm^3 oil demonstrated that intermittent water injection of 500 m^3/day for 3 months and then injecting water at 750 m^3/day for 6 months (IW500-3-750-6) provided the best economical and practical approach in this project.

KEYWORDS: CO_2trapping; EOR; utilization factor; enhancing interfacial area CO_2 / water

I. INTRODUCTION

The increase of averageglobal temperature is a concern of world leaders and scientists. Paris agreement in December 2015 (FCCC, 2015)wasto hold the global average temperature well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels.Intergovernmental Panel on Climate Change(IPCC's 5th Assessment Report in 2014 Working Group III, 2014), shows that in the year 2100 the CO_2 concentration in the atmosphere needs to be lower than 430 ppm in order to reach the to 1.5 °C target. Currently in April 2016 at Mauna Loa Observatory (Tans, 2016) the current CO_2 concentration is 407.57 ppm.

From the presentation of IEA's energy outlook (Sieminski, 2016) showed that until 2040 liquid fuels consumption will maintain its position as the main source of energy in the world. It means that the world demands for petroleum energy supply will continues.Therefore,the world needs to decrease CO_2 concentration in the atmosphereas well asto increase oil production. As such, an EOR approachto maximize oil recovery,yetincreasethe stored CO_2could help to fulfil the required world demands for energy supply and CO_2 emission reduction. Oil reservoirs are attractive sites because theirgeology are known, therefore reducing the uncertainties associated with gas/CO_2 migration. CO_2 flooding of these reservoir would enhance oilproduction, hence cover some of theCCS and CO_2 transportation costs.

In CO_2 EOR, the injected CO_2 is partially produced back and the rest is stored in the reservoir. Describedas retention: "The amount of CO_2 remaining in the reservoir at any given time, which equals the amount of CO_2 injected less the amount of CO_2 produced"(Jarrell et al., 2002). For example, in The Oxy's project of CO_2 EOR, on the Denver Unit, for a total of 252 million tCO_2 injected, of 115 million tCO_2 purchased, and 137 million tCO_2 produced and recycled, with 756,000 tCO_2 lost from fugitive and operating emissions(Hill et al. 2013). From the CO_2-EOR project operator point of

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view, CO_2 retention is considered as disadvantageous, as it increases the required purchase of additional CO_2 for injecting the same total CO_2 cumulative injection per well pattern (Dilmore, 2010). However, the increase of CO_2availability may lead to the price decrease. In the report from IEA (IEA, 2014), the projected CO_2 price is expected to trending down depending on the climate change mitigation target. Under the 2° scenario it is projected that CO_2 sequestration to actually add revenue to the field operator is predicted. Thus, reducing the CO_2 produced and increasing the CO_2 injected is one of the aim of this paper.

Carbonated water injection (CWI) was suggested in literature to reduce the large CO_2 needed for EOR/sequestration projects. (Sohrabi et al., 2008)deduced that oil recovery by CWI was due to oil swelling and viscosity reduction by the transfer of CO_2 from the carbonated water (CW) into the oil phase.However, CW lowers the pH and requires pressure for dissolving CO_2 into the injection water. This may necessitate special material for transportation of CW to the injection site. This adds to the total project cost.

CO_2 dissolves into brine as it contacts the aqueous. This trapping mechanism is effective on an intermediate time scale(Juanes & MacMinn, 2010). Injection of CO_2 into aquifer, must be controlled by the optimum slug injection size, i.e. injecting more than the optimum leads to production of the injected CO_2(Ghanbarnezhaz & Lake, 2011).

This paper investigated several injection approaches: Continuous gas injection, WAG, and water injection on top of the CO_2 injection. Water injection on the top layer and CO_2 injection at the bottom layers to enhanceCO_2-EOR, was published by Klins(Klins, 1984). In optimization of CO_2 sequestration in Saline aquifer, water injection on top of CO_2 injectorcould improve CO_2 trapping(Nghiem et al., 2009). Jessen studied the effect of CO_2 injector completion, the oil recovery and CO_2 storage was found to be improved when the injector was completed in the bottom layers instead of the whole layers(Jessen et al., 2003). Vitsarutwork shows that the SWAG technique of simultaneously injecting water and gas from the downdip well was able to increase the oil recovery and CO_2 stored(Vitsarut et al., 2013). Sobers analyzed the advantages of water injection over CO_2 injection in improving oil recovery and CO_2 trapping(Sobers, 2012). However, in this project we introduced the concept of intermittent water injection over CO_2 injector. To our knowledge, this has never been investigated.

II. DESCRIPTION OF SIMULATION MODEL

Investigating co-optimization of CO_2 EOR and storage was done using CMG GEM simulator. The template of “gmthr010.dat” from CMG GEM was used as the base for this study. The injected CO_2-EOR in this study was immiscible. The used oil density in the model was 842.9 kg/m3 (36.2 API).

This model is represented as a quarter pattern, with the first 6 layers as the oil bearing zone and the last 2 layers as the water bearing zone. The first 6 vertical blocks represent the oil bearing zone of So 0.79 and Sw 0.21. The bottom 2 vertical blocks represent water bearing zone of Sw 0.999. One injector in the corner block and one producer in the opposite corner both were perforated in the 1st layer to the 6th layer. In this model Land’s hysteresis was applied using sgr_{max} 0.4. The primary inputs for the grid modelling input are shown in Table 1.

Table 1- Grid modelling primary inputs

Grid Properties	Value
Grid	9, 9, 8
length i	9 x 100m
length j	9 x 100m
length k	6x 5m, 1x50m, 1x100m
Porosity	0.28
Permeability horizontal	200 md
Permeability vertical	2 md
Reservoir Temperature	59^0C

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Table 2shows four injection approaches: CO_2-Only, WAG, CW, and IW. A schematic of the injection approaches is shown in Figure 1.

Table 2- Injection approaches

Injection	Sensitivity
CO_2-Only	-
WAG	WAG ratio
Continuous water injection over continuous CO_2 injection (CW)	Water injection rate
Intermittent water injection over continuous CO_2 injection (IW)	Water injection rate and injection interval

The constraint of the maximum gas production in this simulation is set to be the same as the gas injection rate which is 250M Sm^3/day. The reason is that if the gas production rate becomes same as the gas injection rate, then no point of continuing production since there will be no CO_2 stored at this point. When the producer constraint is reached the producer will be shut-in, while the CO_2 injector will continue injecting CO_2 until it reached the maximum allowable pressure of 20,000 kPa. In this project the focus will be on the period when the producer is active.

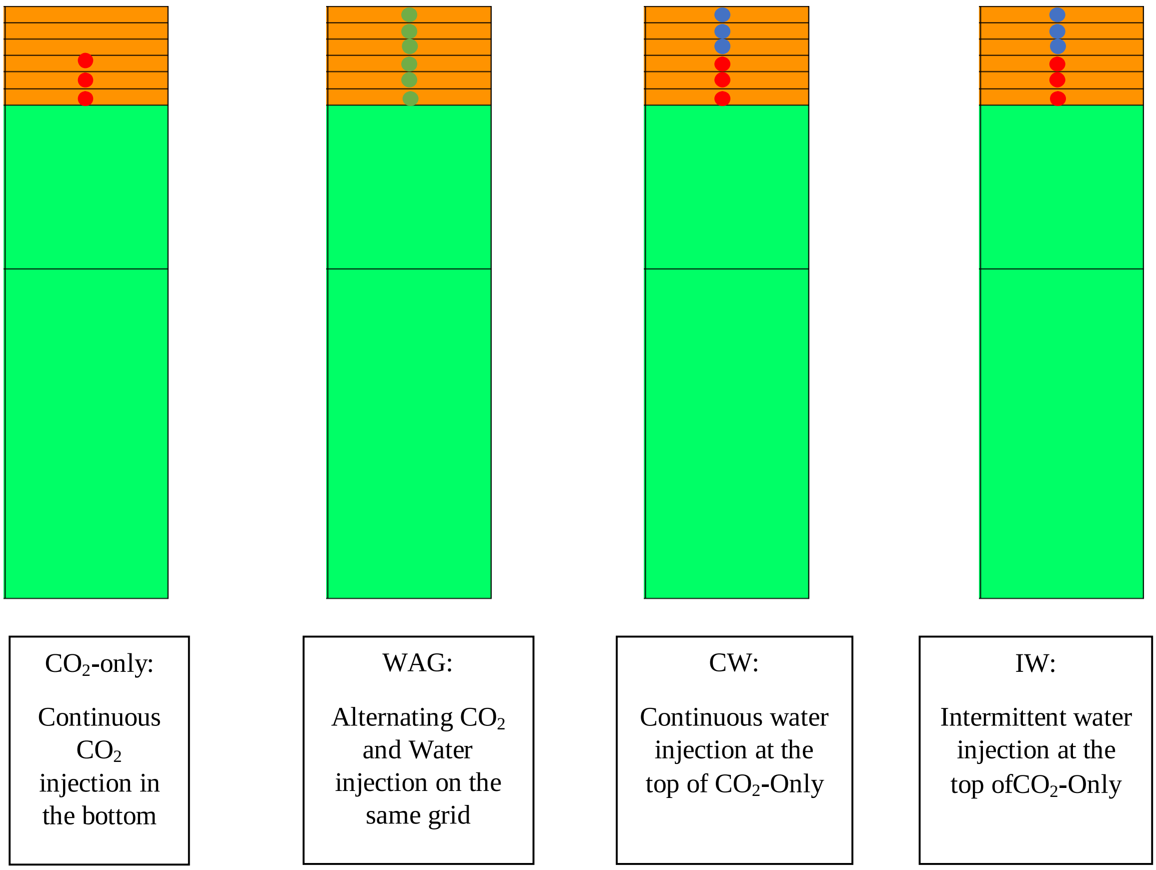

Figure 1- The applied injection schemes. Red is for continuous CO_2 injection, Blue is for water injection, and Green is for alternating of CO_2-water injection

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A. CO_2-EOR STUDY

The simulation of a quarter pattern was done from year 2000 until year 2050. From year 2000 to 2005 is the natural production period, i.e. no injection. From year 2005 until 2015, water injection of 500 Sm^3/day commence for pressure maintenance. From 2015 until 2050, CO_2-EOR started.

1.A Comparison of WAG, intermittent water injection (IW) and continuous water injection (CW) performance

The investigation started with CO_2 injection rate of 250M Sm^3/day and water injection rate of 500 Sm^3/day. Summary of the injection schemes are shown in Table 3.WAG, CW, and IW were shown to prolong the oil production compared to the CO_2-Only case. As shown in Figure 2the oil recovery is ranked as follow: WAG500-12months (≈56.6%), CO_2-Only (≈55.1%), IW500 (≈54.6%), WAG500-1month (≈53.7%), and CW500 (≈49.88%).

Table 3- Injection scheme of WAG, CW, and IW cases

Injection approaches	CO_2 injection rates (Sm^3)	Water injection rates 2015 (Sm^3)	Water injection intervals	CO_2 injection intervals
CO_2-Only	250E+03	0	0	Continuous
WAG	250E+03	500	12 months	12 months
WAG	250E+03	500	1 month	1 month
CW	250E+03	500	Continuous	Continuous
IW	250E+03	500	1 year	Continuous

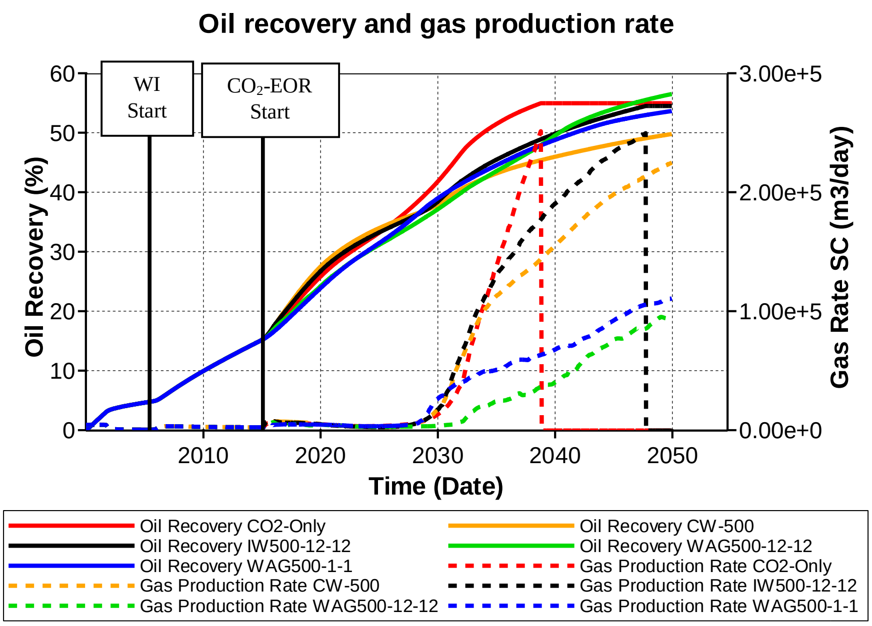

Figure 2 -Oil recovery and gas production rate.WAG, CW, and IW cases produced lower gas production rate than for CO_2-Only case.

Table 4summarizes the total injected amount and the total stored amount of CO_2 before the production shut-in for each individual case (CO_2-only, WAG, CW and IW). The total stored CO_2 is the cumulative produced CO_2 subtracted from the cumulative injected $CO_{2,}$ active CO_2-EOR period (from 2015 until the termination of the production). The total CO_2 injected and total CO_2 stored in Table 4show that the application of IW and CW increased the total stored CO_2. It was shown, in this work, that 18% was the highest increase of the stored CO_2, which was achieved by the CW500 case. The

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WAG cases showed less stored CO_2 due to lower injected amount CO_2 compared to the CO_2-Only case. Therefore, it was decided in this work to continue with the optimization of CO_2-EOR and storage by CW and IW.

Table 4- Amount of CO_2 injected and stored for CO_2-Only, CW, IW, and WAG

Cases	Production shut-in date	Total CO_2 injected before production shut-in (kg)	Total stored CO_2 (kg)	Increased the stored CO_2 compared to the CO_2-Only case (%)
CO_2-Only	11/27/2038	4.07E+09	3.41E+09	-
CW500	Never	5.97E+09	4.01E+09	18%
IW500-12-12	10/21/2047	5.59E+09	3.69E+09	8%
WAG500_12-12	Never	3.07E+09	2.51E+09	-26%
WAG500_1-1	Never	3.01E+09	2.12E+09	-38%

A.2 Effect of injection rates on CW and IW

To better understand the impact of CW and IW approaches in co-optimization of oil recovery and CO_2 storage during CO_2-EOR. Table 5summarizes the simulation cases.

Table 5- Variation of water injection rate and injection length of CW and IW cases

Injectionapproaches	CO_2 injection rates (Sm^3)	Water injection rates after 2015 (Sm^3)	Water injection intervals	CO_2injection intervals
CO_2-Only	250E+03	0	0	Continuous
CW	250E+03	250, 500, and 1000	Continuous	Continuous
IW	250E+03	250, 500, and 1000	1 year	Continuous

Oil recovery and gas production rate in Figure 3show that increasing the water injection rate and water injection length resulted in lower gas production. The case of IW250-12-12 and CW250 resulted in production termination in 2042, where the rate of 250 Sm^3/day was not enough to mitigate the gas production rate. In the case of IW500-12-12, the production was terminated in 2047, but for the case of CW500 the gas production rate was reduced until the end of simulation. One may conclude that water injection rate and water injection length are important parameters to control the gas production rate, hence the total amount of stored CO_2.

Figure 4shows that the decline rate of oil production was very steep in the CO_2-Only case, compared to the IW and CW cases. In both IW and CW cases, it was shown that the higher water injection rate and injection intervals resulted in higher oil production rate in the early EOR stage. This may be explained based on the pressure increase due to the increase of the injected fluid. However, oil production rates from the mid-stage EOR (2020) until the end of simulation were higher for the lower water injection rate and injection intervals. The oil production rate is found to be related to the water-oil mobility ratio which will be explained later.

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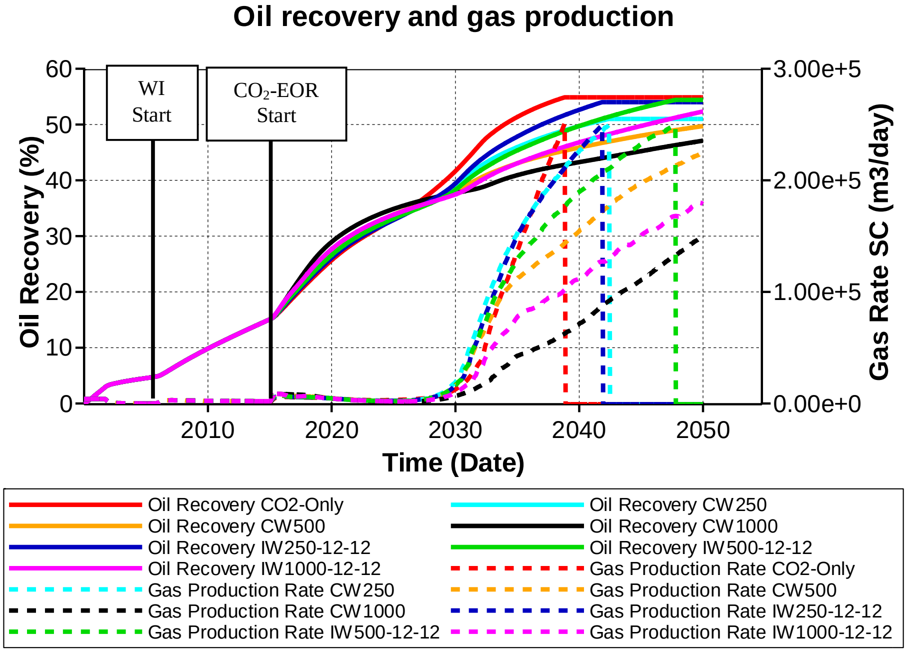

Figure 3 - Oil recovery and gas production rate for various CW and IW cases. CW250, IW250, and IW500-12-12 did not hold the gas production below the constraint until the end of simulation.

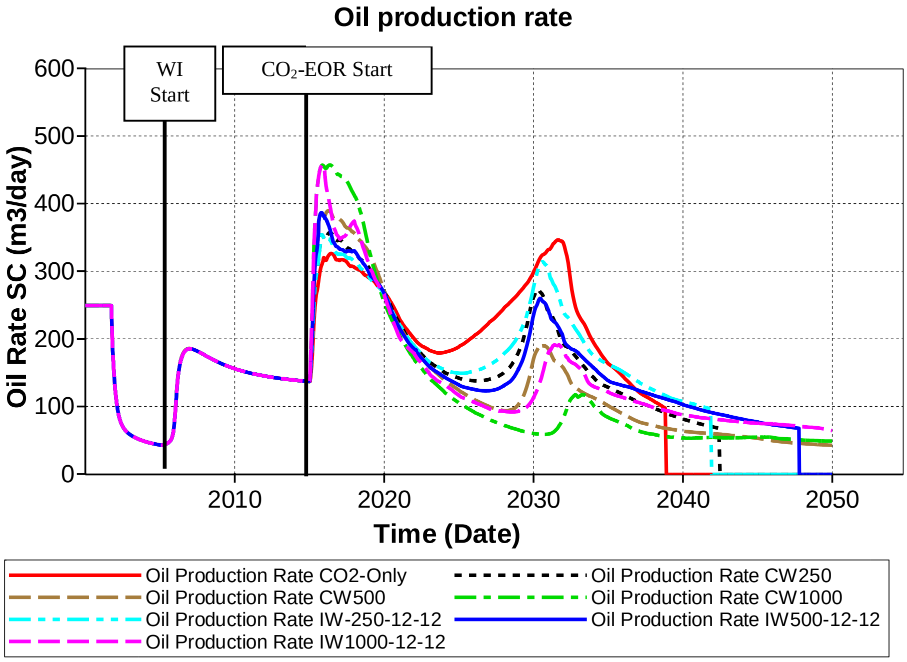

Figure 4-Oil rate of CO_2-Only, CW, and IW cases. CW250, IW250, and IW500-12-12 production shut-in due to gas production constraint. The oil production decline in the CO_2-Only case is very steep compared to the CW and IW cases.

For assessment of the different cases, CO_2 utilization factor (UF) was used. It is defined as the amount of CO_2 stored in the reservoir divided by the amount of incremental oil produced. In other words, when the CO_2 utilization factor increases, the oil recovery decreases as demonstrated in Table 6. CW1000 has the highest UF of about 19.04

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tCO_2/Sm^3oil which reduces the oil recovery by about 7.8 % OOIP, while increasing the CO_2 stored by 46%. On the other hand, IW1000-12-12 having a lower UF of about 8.7 tCO_2/Sm^3oil increased the stored CO_2 to about 34% while the oil recovery was reduced by about 2.25% OOIP. In the case of IW1000-12-12 the performance was much better than CW500 which reduced the oil recovery by 5.17% OOIP while only increasing the stored CO_2 by merely 18%. From the above it seems that the IW to be the best approach for further consideration in this work.

Table 6- Sensitivity study of the stored amount of CO_2, oil recovery, and CO_2 UF by IW and CW

Cases	CO_2stored increase compared to the CO_2-Only case (%)	Oil recovery increase compared to the CO_2-Only Case (% OOIP)	CO_2 Utilization Factor (tCO_2/Sm^3oil)
CO_2-Only	-	-	5.22
CW250	-0.7%	-3.87	7.39
CW500	18%	-5.17	10.20
CW1000	46%	-7.78	19.04
IW250-12-12	0.4%	-0.87	5.61
IW500-12-12	8%	-0.46	5.84
IW1000-12-12	34%	-2.55	8.67

A.1.1.CW and IW mechanisms for oil recovery and reduced gas production

Investigation was done to understand the reason for lower oil recovery by CW cases. Block 8,8,2 was selected because it represents the near producer upper layer that would most likely be affected by the IW and CW approaches.

The reduction of the oil viscosity was similar in all cases. It was reduced from about 2.7 to about 1.9 cp, The gas-oil mobility ratios are displayed in Figure 5. It is shown that the water injection reduces the gas mobility ratios. In the case of CO_2-Only, the high gas-oil mobility ratio led to less efficient oil production as shown in the steep oil production decline as the gas-oil mobility ratios increases. This high gas-oil mobility ratios were lowered in the cases of IW500-12-12 and CW500. Since CW500 has lower gas-oil mobility ratio, the gas production was lower than in the IW500-12-12 case.

Figure 6 shows that the IW case has lower water-oil mobility ratio than in the CW case. The water-oil mobility ratios were around 2.0 and 11.4 at the end for IW500-12-12 and CW500, respectively. In other words, IW is more effective in displacing oil than CW.

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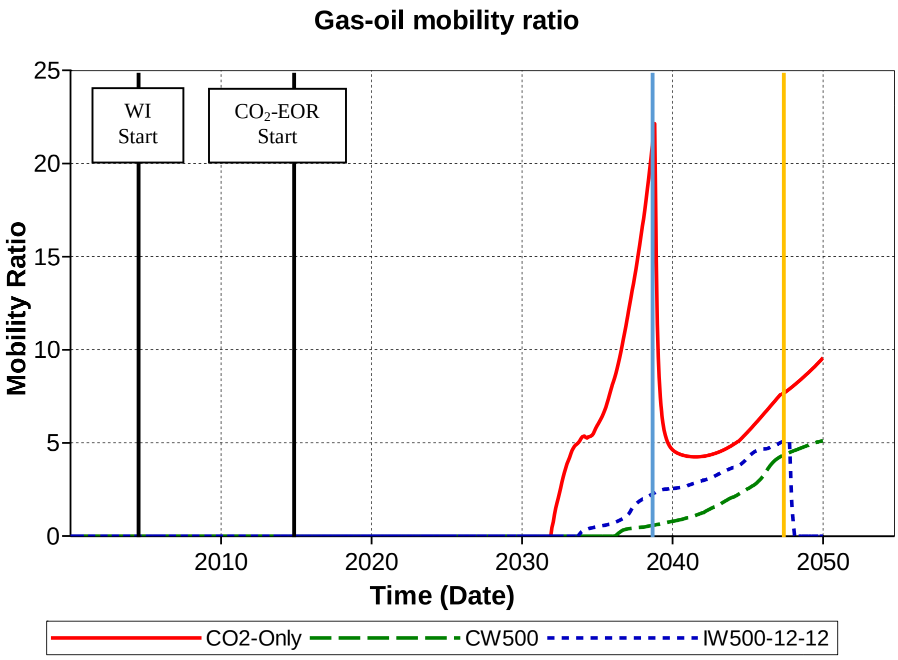

Figure 5- Gas-oil mobility ratio for CO_2-Only, CW500, and IW500-12-12 at near wellbore (8,8,2). The vertical lines represent the production shut-in time: blue for the CO_2-Only case and yellow for the IW500-12-12 case. The gas-oil mobility ratios were reduced in the IW and CW cases.

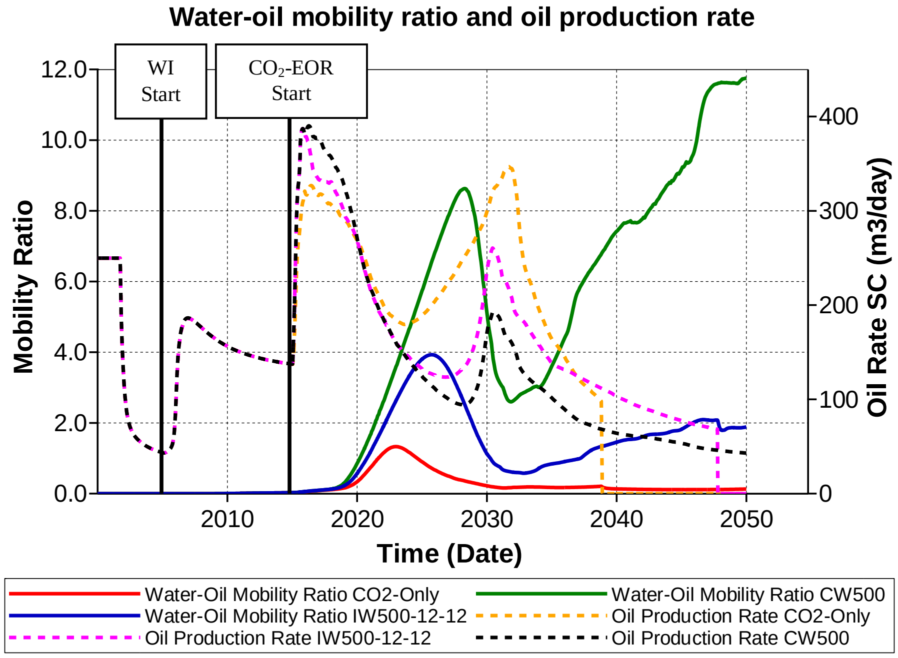

Figure 6- Water-oil Mobility Ratio of CO_2-Only, CW500, and IW500-12-12 at near wellbore (8,8,2). The oil production ranking is the inverse of the water-oil mobility ratio.

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Figure 7 shows that applying the CW500 and IW500-12-12 resulted in better solubility trapping and residual gas trapping than the CO_2-Only case. More solubility trapping was expected due to the additional water injection providing more solution sights for the CO_2 to dissolve. The increase in residual trapping in the IW500 and CW500 cases is perhaps due to the decrease of the gas mobility.

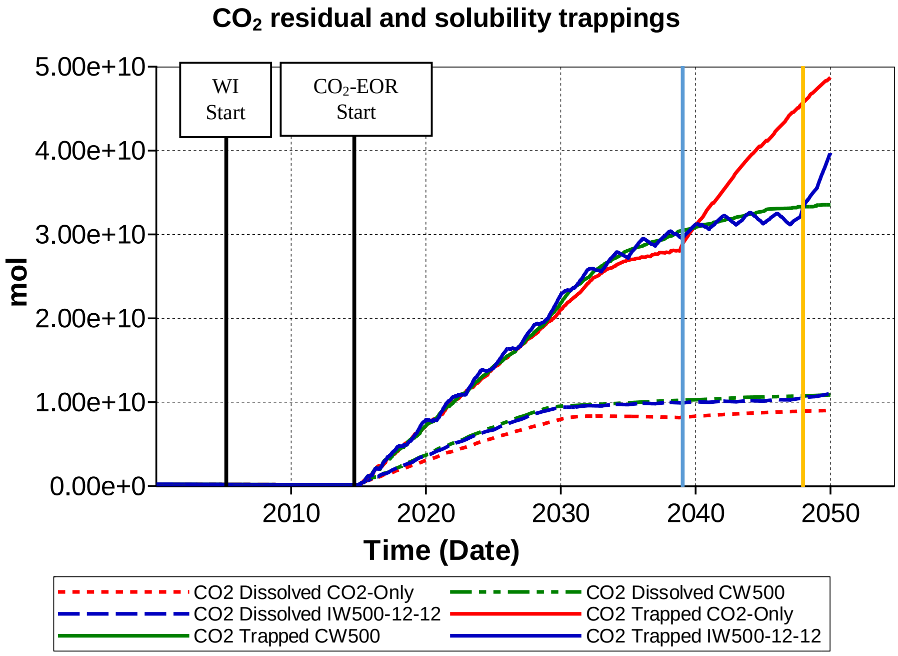

Figure 7-CO_2 Residual and solubility trappings by CO_2-Only, CW500, and IW500-12-12. The vertical lines represent the production shut-in time: blue for the CO_2-Only case and yellow for the IW500-12-12 case. The residual and solubility trapping were improved in the CW and IW cases.

B. CO_2 storage and oil recovery by IW approach

A sensitivity analysis was done with the IW approach by varying the water injection rate and the interval period. The water injection rate of 500 Sm^3/day, 750 Sm^3/day, and 1000 Sm^3/day were selected, since below 500 Sm^3/day was not enough to improve the stored CO_2. The water injection intervals ranged from 3 months, 6 months, 9 months, and 12 months, with shut-in interval of 12 months, were investigated.

All of the IW cases have successfully increased the total amount of the stored CO_2 compared to the CO_2-Only case as shown inTable 7.In the case of IW500-3-12, the lowest increase amount of the stored CO_2 (1%), while IW1000-12-12 showed the largest increase of the stored CO_2 (34%). One may conclude here that for the same water injection rate, the total amount of the stored CO_2 increases with the water injection intervals.

There are 6 cases in which the oil recovery is higher than the CO_2-Only case. The highest oil recovery increase was 2.11% OOIP obtained by IW1000-3-12 case. Also in this case, the total amount of the stored CO_2 increase was 9%. The CO_2 UF was about 4.84 tCO_2/ Sm^3oil, which is lower than the CO_2-Only case (5.22 tCO_2/Sm^3oil). It is interesting to see that there are total of 5 IW cases that have a lower CO_2 UF than the CO_2-Only method. We may conclude here that IW approach could be economically and practically attractive.

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Table 7- Sensitivity study of the stored amount of CO_2, increased oil recovery, and CO_2 UF with application of IW

Cases	**CO_2 stored increase compared to the CO_2-Only case (%)**	**Oil recovery increase compared to the CO_2-Only case (% OOIP)**	**CO_2 Utilization Factor (tCO_2/Sm^3 oil)**
CO_2-only	-	-	5.22
IW500 3:12	1%	0.30	5.10
IW500 6:12	4%	0.35	5.22
IW500 9:12	6%	-0.01	5.47
IW500 12:12	8%	-0.46	5.84
IW750 3:12	3%	0.99	4.97
IW750 6:12	11%	1.69	5.10
IW750 9:12	17%	-0.06	6.09
IW750 12:12	21%	-1.31	6.97
IW1000 3:12	9%	2.11	4.84
IW1000 6:12	20%	0.47	6.01
IW1000 9:12	28%	-1.43	7.45
IW1000 12:12	34%	-2.55	8.59

The gas-oil mobility ratio displayed in Figure 8 shows that the case of IW500-3-12 gave the highest value of around 12, however this value is still way lower than the CO_2-only case which was more than 20. By increasing the rate to 1000 Sm3/day and injection interval to 12 months, a significant reduction of the gas-oil mobility to a value of about 2 was achieved. As such, the decrease in gas production with increasing water injection rate and injection intervals are correlated to the lower gas-oil mobility ratio.

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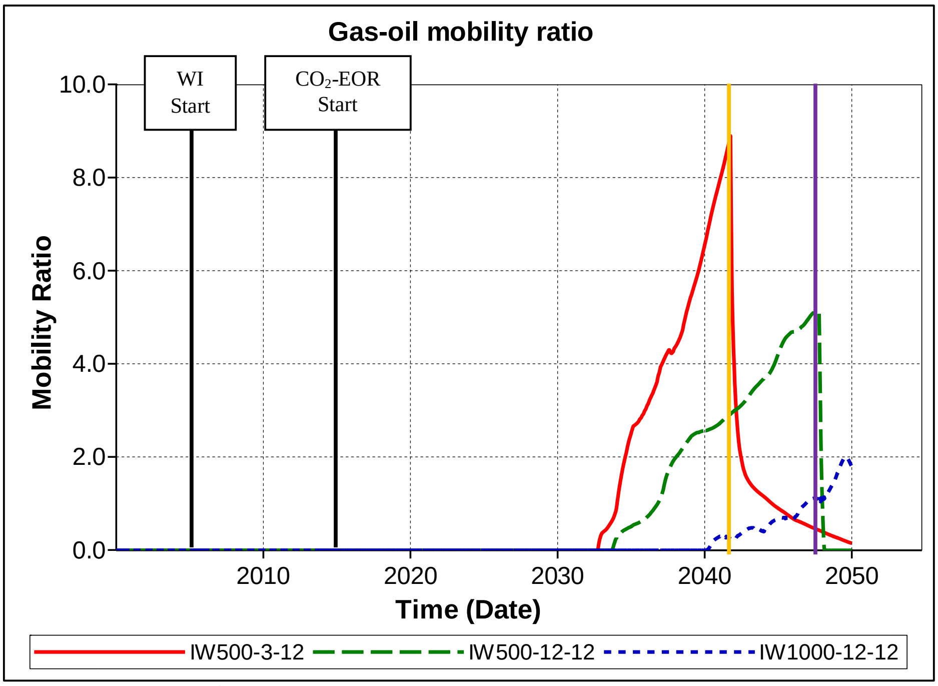

Figure 8- Gas-oil mobility ratio for IW500-12-12, IW500-3-12, and IW1000-12-12 at near wellbore (8,8,2). The vertical lines represent the production shut-in time: yellow is for the IW500-3-12 case and purple is for the IW500-12-12 case. Higher water injection rate and longer water injection interval led to lower gas-oil mobility ratio.

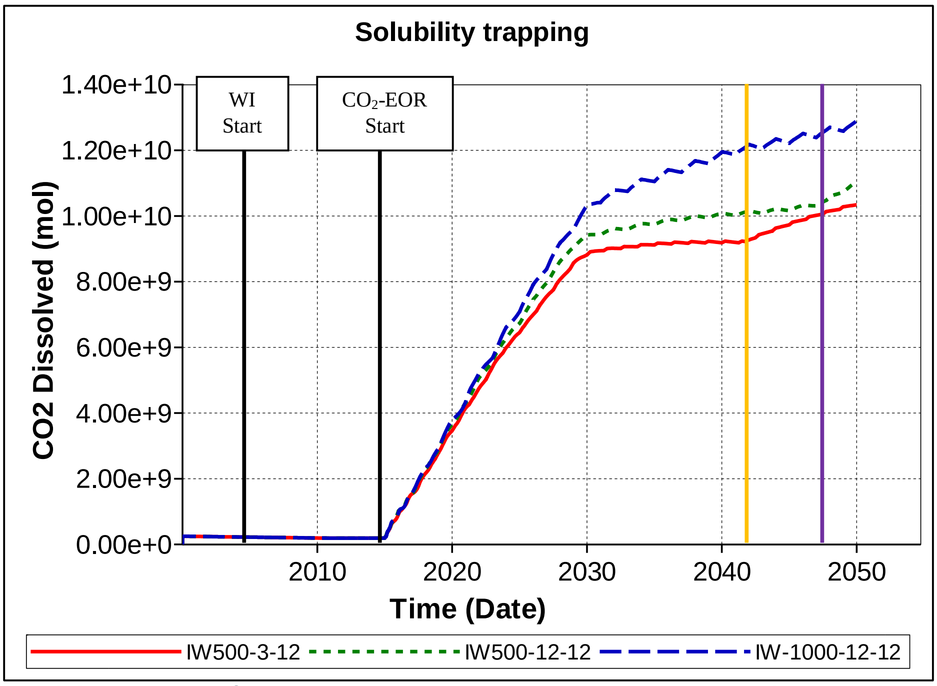

Figure 9-CO_2 solubility trapping of IW500-12-12, IW500-3-12, and IW1000-12-12. The vertical lines represent the production shut-in time: yellow is for IW500-3-12 and purple is for IW500-12-12. Higher and longer water injection intervals increases solubility trapping mechanism of CO_2.

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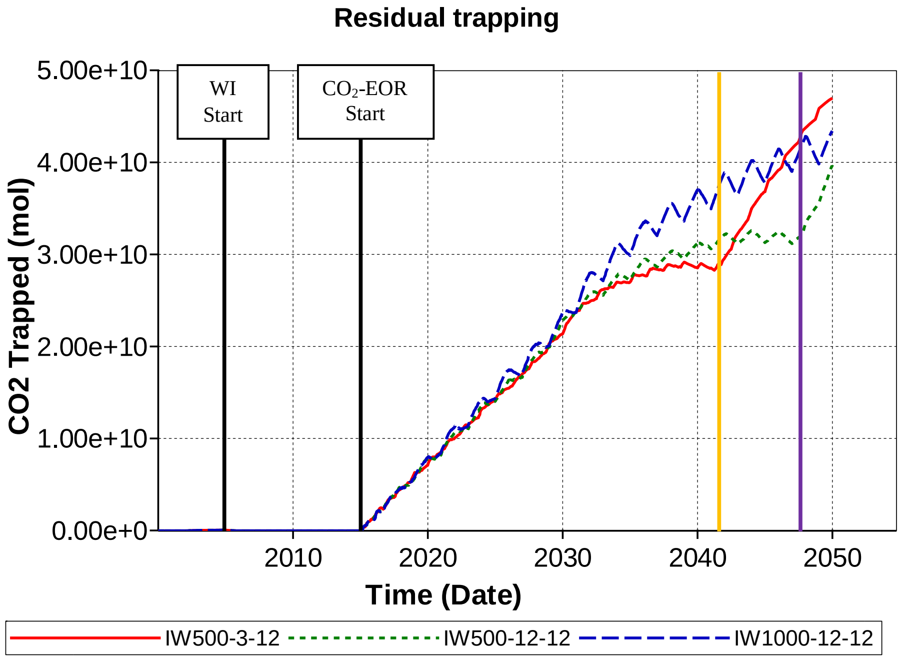

Figure 10- CO_2 residual trapping of IW500-12-12, IW500-3-12, and IW1000-12-12. The vertical lines represent the production shut-in time: yellow is for IW500-3-12 and purple is for IW500-12-12. Higher and longer water injection intervals increases residual trapping mechanism of CO_2

The solubility trapping of IW500-3-12, IW500-12-12 and IW1000-12-12 are shown in Figure 9. From the graph it can be seen that as the water injection rate increases, the solubility trapping increases. Also, as the water injection interval increases, the solubility trapping increases. This agrees with the findings in the solubility trapping in the previous subsection.

A similar behavior for the residual trapping (Figure 10), however for the IW1000-12-12, a more pronounced zig-zag type trend (caused by intermittent water injection) was shown compared to the solubility trapping cases. The ranking in the residual trapping is the same as the ranking in the solubility trapping. The difference in the residual trapping is smaller between the cases. As a summary, in the residual trapping mechanism, the water injection rate and water injection length are important in increasing the residual trapping.

B. 2 Further increase in CO_2storage and oil recovery at late injection stage

The previous subsections demonstrated that the shorter the injection interval the better oil production rate, so the selected cases for further co-optimization are, IW500-3-12, IW750-3-12, and IW1000-3-12 cases. This was done by increasing the water injection rate and/or injection interval, starting from year2031 as indicated in Table 8. Year 2031 was selected because a steep increase in the gas production occurred. So the approach for the optimization was to reduce the gas production.

Figure 11, shows that IW500-3-12 co-optimizations' cases achieved higher oil recovery compared to CO_2-Only and the original IW500-3-12 case (before optimization).In terms of reduction of the produced gas, the largest reduction was achieved by changing the water injection rate to 1000 Sm^3/day with time interval of 12-12. This resulted in a flat gas production rate for about 5 years before it continued to increase again. In other words, the gas production rate was influenced by modifying the IW regime. Oher co-optimization cases showed similar trend in oil recovery increase and gas reduction.

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Table 8- Water injection rate and injection interval length for IW co-optimization

Co-optimization start date	Water injection rates Sm^3/day	Water injection intervals (on:off) Months:Months
4/1/2031	1000	6:12
4/1/2031	1000	12:12
4/1/2031	750	6:12
4/1/2031	750	12:12
4/1/2031	500	12:12

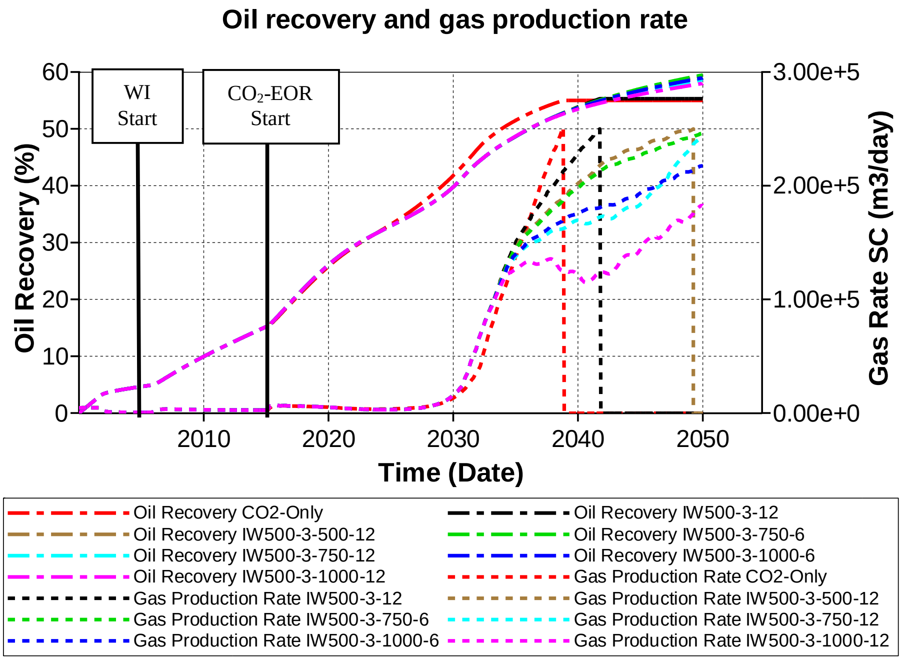

Figure 11- Oil recovery and gas production for CO_2-Only, IW500-3-12, and IW500-3-12's co-optimizations. The co-optimization cases have exceeded the CO_2-Only oil recovery.

Table 9, shows the optimized cases (indicated by two water injection rates), where the total stored CO_2increased compared to the corresponding un-optimized case. As stated previously the total stored CO_2 was dependent on the water injection rate and the injection time interval. The highest total stored CO_2 was by IW1000-3-1000-12 case, which has the highest water injection rate and longest water injection time interval while the least total stored CO_2 was in the IW500-3-500-12 (lowest water injection rate) case.

There are 11 out of the 15 optimization cases that reduced the CO_2 UF below the CO_2-only case (5.22 tCO_2/Sm^3 oil), while storing more CO_2. The lowest CO_2 UF achieved was 4.15 tCO_2/Sm^3 oil from the IW500-3-750-6 case. CO_2 UF is a proportional to the stored CO_2 and the gained incremental oil. CO_2 UF reduction indicates larger increase of oil recovery than the total increase of the stored CO_2. One may conclude that it is possible to economically and practically co-optimize CO_2-EOR and CO_2-storage bythe indicated decrease of the CO_2 UF.

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Table 9- The stored CO_2, oil recovery increase, and CO_2 UF for the co-optimized cases. Blue highlights marked original cases

Cases	CO_2 stored increase compared to the CO_2-Only case (%)	Oil recovery increase compared to the CO_2-Only case (% OOIP)	CO_2 Utilization Factor (tCO_2/Sm^3 oil)
CO_2-only	-	-	5.22
IW500 3:12	1%	0.30	5.10
IW500-3-500-12	6%	3.93	4.22
IW500-3-750-6	8%	4.46	4.15
IW500-3-750-12	16%	3.64	4.68
IW500-3-1000-6	15%	3.97	4.57
IW500-3-1000-12	28%	2.98	5.39
IW750 3:12	3%	0.99	4.97
IW750-3-500-12	8%	2.73	4.61
IW750-3-750-6	9%	3.71	4.39
IW750-3-750-12	18%	2.89	5.00
IW750-3-1000-6	16%	3.32	4.79
IW750-3-1000-12	29%	2.32	5.67
IW1000 3:12	9%	2.11	4.84
IW1000-3-500-12	10%	2.00	4.94
IW1000-3-750-6	11%	2.79	4.74
IW1000-3-750-12	19%	2.23	5.28
IW1000-3-1000-6	18%	2.68	5.05
IW1000-3-1000-12	30%	1.62	5.99

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III. SUMMARY AND CONCLUSIONS

Based on this study, different approaches were assessed using CO_2 continuous injection as a base case reference. The following are summary and conclusions.

1. The approach of injecting water into the top layer and injecting continuous CO_2 into the bottom layerwas successful in reducing the gas production, thus increasing the total CO_2 stored. It was found that the continuous water injectionreduced the oil recovery while the Intermittent water injection increased both CO_2-storage and oil recovery.

2. The best case for CO_2 storage was with the late stage co-optimized of the IW approach. IW-1000-3-1000-12 case, i.e.water injection of 1000 Sm^3/day for 3 month interval, then continued with 1000 Sm3/day for 12 more months. This increased the total stored CO_2 by about 30% while the oil recovery was increased by 1.62% OOIP.

3. The best oil recovery in this project was achieved by the late stage optimization of theIW approach, where the injection rate was about 500 Sm^3/day for 3 months interval then the injection rate was increased to 750 Sm^3/day for 12 months. The oil recovery increased by 4.46% OOIP and total stored CO_2 increased by 8%.

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4. The lowest reduction in the CO_2 utilization factor (ratio of the stored CO_2 to the recovered oil) was obtained by applyingIW water injection of 500 Sm^3/day for 3 months and then injecting water at 750 Sm3/day for 6 months (IW500-3-750-6). In this case the CO_2 UF was reduced from 5.22 tCO_2/Sm^3 oil to 4.15 tCO_2/Sm^3 oil.This indicates economically and practically sound case.

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