ID: 906

Sustainability Of CO_2-EOR As Geological Carbon Storage Based On Two Giant Field Applications

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ABSTRACT

CO_2-EOR (enhanced oil recovery) has been proven to be profitable in commercial scale oil production for more than 50 years being mostly applied EOR technology in the last decades. As the CO_2 is injected underground, it is also stated that the CO_2-EOR should be a part of geological carbon storage (GCS) solutions. The benefits of each utilization/storage project must be evaluated by performing a comprehensive lifecycle analysis.

In this paper we aim to highlight and discuss critical parameters affecting the perspectives of using CO_2 EOR as one of the GCS methods based on two "giant" oil field applications. Bati Raman and Weyburn-Midale fields are similar in terms of oil content which can be ranked in the lower range of huge oil reservoirs, both in carbonate formations. However, they show distinct petrophysical and production characteristics. The most attractive aspects of both field operations are the excellent quality and quantity of available data on the executed and on-going works allowing post evaluation opportunities in terms of CO_2-EOR as GCS.

With the data used for the above discussed cases, from a volumetric and therefore optimistic point of view, if CO_2 replaces the same volume of oil produced the stored amount would be 0.4t/Stm^3 in Bati Raman and 0.8 t/Stm^3 in Weyburn-Midale reservoirs. In a very basic level, it can be then assumed that also considering the CO_2 emitted by the EOR process and by the oil produced, maximum of 1t CO_2 per Stm^3 oil produced can be stored in a reservoir, a number strongly depending on the thermodynamic conditions in the reservoir, the depletion rate, the carbon emission intensity of the oil as well as on the optimal use of the depleted reservoir for CO_2 storage afterwards.

EXTENDED ABSTRACT

Introduction

CO_2-EOR (enhanced oil recovery) has proven profitable in commercial oil production for more than 50 years and has been the most widely used EOR technology in recent decades. Since CO_2 is injected underground, CO_2-EOR should also be part of geological carbon storage (GCS) solutions. However, this statement is not always easy to make. Since CO_2 use should not necessarily lead to an overall reduction in emissions, the benefits of each utilization/storage project must be assessed through a comprehensive life-cycle analysis. This requires clear methodological guidelines, which are currently being developed by several expert groups (Ettehadtavakkol et al., 2014; Novak et al., 2021).

CO_2-EOR involves injecting CO_2 into the target oil reservoir to recover a portion of the oil remaining after the primary and secondary recovery production stages. The captured and conditioned CO_2 is transported to the field and injected into the reservoir. The injected CO_2 (C_i) is dissolved in the oil, improving its mobility (immiscible), and/or it is mixed with the oil to achieve better microscopic and macroscopic sweep (miscible). When properly designed and applied, miscible CO_2-EOR is known to be the most effective EOR method. Eventually, some of the injected CO_2 will be permanently stored in the reservoir in the gas (C_{sg}), water (C_{sw}) and oil (C_{so}) phases. The CO_2 sequestration in mineral form can generally be neglected as this is a longer term process compared to the life time of oil production. Two additional factors should be considered in the balance between injected, stored and back produced CO_2. The first factor is the CO_2 emitted as the result of the EOR operation (C_e; conditioning, transport, etc) and the additional global emission created by the recovered oil including gas and water phases as well (C_{eo}). A part of the produced CO_2 (C_p) is usually captured, conditioned and recycled as a part of the injected amount(C_r as part of C_i). The CO_2 that can be stored after the termination of a CO_2-EOR field application, C_s, can therefore be formulated as follows:

$$C_s = C_i - C_p - C_e = C_{sg} + C_{sw} + C_{so}$$

The whole process of CO_2-EOR is schematized in Figure 1. The units of each component can be expressed as mass or mole to determine the total mass of CO_2 stored.

The purpose of this paper is to highlight and discuss critical parameters affecting the prospects for using CO_2-EOR as one of the GCS methods, based on two "giant" oilfield applications. We address the technical aspects of miscible and non-miscible CO_2-EOR methods; we evaluate CO_2 utilization and storage capacity by various mechanisms downstream of EOR operations based on available data. We discuss the additional capital and operating costs of CO_2-EOR as a GCS to estimate emissions as well as financial compensation. We highlight potential enhancement techniques that lead to higher oil recovery and CO_2 storage capacity.

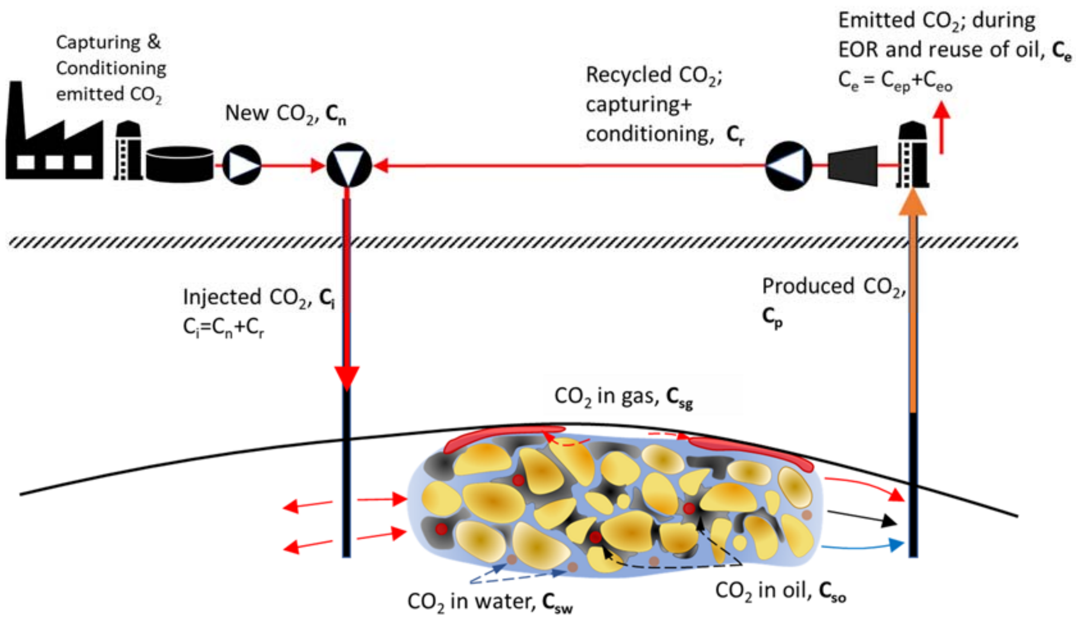

Figure-1: Schematic of the CO2 storage mechanisms and material balance in CO_2-EOR operations.

Bati Raman Field Immiscible CO2-EOR

Bati Raman field in southeastern Turkey discovered in 1961 is producing heavy oil of 9,7-13°API with a viscosity from 450 to 1000 mPa.s under reservoir conditions from a fractured carbonate reservoir. Due to unfavorable recovery conditions (e.g. heavy oil, low initial pressure, fractured structure) the primary recovery remained around 1.5% of OOIP (original oil in place) which is estimated to be 294 M (million) Stm^3. To increase the production various recovery techniques were studied in laboratory works with numerical exercises and it was found that the injection of CO_2 to be produced from the Dodan field situated 85 km away from the field can be an economically viable process. It should be noted that these studies finalized in the early 80's where scientific as well as public awareness on climate change due to anthropogenic emissions was not yet developed. In Dodan field surface facilities consisting of sweeting and dehydration as well as compression systems were designed and built to supply ca. 1.7 $MStm^3$/day (ca. 3150 tons/day) CO_2 to be transported to Bati Raman field via a carbon steel pipeline of 10" diameter in supercritical phase. The project launched first as a pilot under huff'n puff modus, continued as a flooding process starting from 1991 with 33 injector wells partly recompleted for CO_2 injection. As a result of the operation, by the end of 2011, 10.3 $MStm^3$ additional oil was produced which is equal to the 3.5 % of the estimated OOIP. An ultimate recovery factor of 12 % is predicted as the result of the CO_2-EOR application (Özgür, 2019). Because of reservoir and oil characteristics the process is immiscible relying mainly on the swelling effect of the CO_2 dissolved in oil, reducing its viscosity and density; the recovery reduced from this time on, techniques like WAG (water alternate gas), foam and/or gel application are being tried both at laboratory and field scales to improve the efficiency of the process (Alkan et al. 1991; Karaoguz et al. 2007).

The cost of CO_2 production sweeting and compression at Dodan facilities is given around 21.2 USD_{2010}/k (kilo, thousand) Stm^3 of CO_2. A recycling and dehydratation facility with 0.5 $MStm^3$/day capacity was completed and put in operation in mid-1991 in Bati Raman field. Recycling cost of produced CO_2 is in the order of 15.9 $USD_{2010}/kStm^3$ on average. (Sahin, Kalfaoglu, Celebi, 2012). In spite of the capital costs for the facilities as well as OPEX costs also comprising the retrofitting, the process is economical considering the amount of additional oil recovery. The revenue can be estimated around 3.2 B(billion)USD_{2010} with the assumption of 50 USD_{2010}/STB as average without considering the cost/revenue of CO_2 stored. Including todays CO_2 trade conditions for a hypothetical case in which CO_2 is offered from an emitter, with an average pricing of 30 USD/t CO_2, an additional revenue of approximately 500 MUSD could be added to this sum.

However, from an environmental point of view, the project seems to be disastrous, since the natural CO_2 is produced, a small part is used for the process and stored, while the remaining part is released into the atmosphere. It is reported that a total of ca. 17.8 Mt of CO_2 was injected until 2010, the 12,87 Mt was produced back and 4.8 Mt CO_2 was recycled. To our calculations another ca. 9 Mt CO_2 could be injected by the end of the life time of the reservoir making the stored amount around 14 Mt of CO_2 assuming an ultimate recovery factor of 6%. An approximate average value of 1.5 tons/Stm^3 is obtained as CO_2 utilization per unit of oil production, which is consistent with data from various studies (IEA, 2015; Azzolina et al. 2016, Farajzadeh et al. 2020). However, it should be noted that this amount is equal to the total CO_2, including the amount that was produced again. On the other hand, the total amount of CO_2 that can be stored in the reservoir could be much higher considering the underlying aquifer volume, the injection pressure limits as well as the dissolution of the carbonate matrix of the reservoir; a more precise definition of the storage volume is due to the quantification of involved parameters. The sustainability of the life cycle CO_2 footprint needs the assessment of the exergy balance of the whole system considering the energy required for capturing, transporting and conditioning of the CO_2.

Two aspects of this simplified evaluation should be emphasized. First, if the CO_2 were purchased by an industrial activity such as cement factories or power plants (which also exist near the field under study), it could be argued that higher than14 million tons of CO_2 from the industrial activity would be permanently stored. The other issue is the emissions generated by the use of the additional recovered oil. There are various approximations for the amount of CO_2 that the oil emits depending on its type and consumption. Assuming that 1 Stm^3 of oil emits a minimum of 3 tons of CO_2 during its production, transport, refinery and consumption, the oil recovered using CO_2-EOR in the Bati Raman field could emit about 30 Mt of CO_2, which again makes the operation questionable from an environmental/ sustainability point of view.

Weyburn and Midale Fields Miscible CO_2-EOR

The Weyburn and Midale oil fields, located in southeastern Saskatchewan, Canada, were brought into primary production in 1954. Following the primary recovery, production has been maintained in both fields through the use of water flooding coupled with the drilling of additional (infill) wells to reach parts of the reservoir that had not been previously accessed. With its initial temperature of 59°C, API gravity of 29° and oil viscosity of 4.7 mPa.s at reservoir conditions, the reservoir was found to be ideal for CO_2 miscible and near-miscible EOR process in this carbonate reservoir. In this application the CO_2 is a by-product of coal gasification at the Great Plains Synfuels Plant in North Dakota, USA. The compressed CO_2 is delivered to the fields through a 323 km pipeline that crosses the international boundary. In October 2000, the CO_2 injection is reported to begin into the Weyburn field from over 100 injection wells. Currently most of these wells inject CO_2 alternate water, but there are at least 17 CO_2-only injectors (Malik and Islam, 2000).

In Whittaker et al. 2011, it is reported that after one decade of CO_2 injection in Weyburn field more than 16 Mt of CO_2 stored. At Midale, over 2 Mt CO_2 has been stored in a similar reservoir during 5 years of injection (and including pilot and demonstration phases). Thus more than 18 Mt of greenhouse gases were omitted in these two depleting oil fields. The Weyburn and Midale fields combined are expected to produce at least 35 $MStm^3$ of incremental oil through miscible or near-miscible displacement with CO_2 corresponding to an incremental recovery factor of approximately 12% of OOIP. EOR extends the life of the fields by approximately two to three decades. It is also mentioned that the Weyburn-Midale project is surveyed with a unique comprehensive monitoring and verification pilot program undertaken between 2000 and 2012. Overall, it is anticipated that around 40 Mt CO_2 will be permanently sequestered over the project's lifespan – 30 Mt in Weyburn and 10 Mt in Midale. The total CO_2 injection rate is approximately 15000 tons/day from which a half consists of recycled CO_2 (Whittaker et al. 2011).

A similar material balance performed for the Bati Raman field can be repeated for the Weyburn and Midale fields based on the available information. The CO_2 utilization factor for Weyburn is estimated to be between 1.05 and 1.35 t of CO_2 per Stm^3 of incremental oil. This is even lower for Midale case being approximately 0.8 t/Stm^3. The total investment costs of EOR operations in both fields is given as 1.8 $BUSD_{2010}$. With the assumption of 50 USD_{2010}/bbl oil price the revenue of the incremental oil is 10.7 $BUSD_{2010}$. It is clear that the project is highly profitable also considering the CAPEX and OPEX costs including the transport, retrofitting of the fields and monitoring activities. The CO_2 mitigation rewards reaching to 1.2 $BUSD_{2010}$ with the assumption of 30 USD/tCO_2 can also be added to the revenue increasing the hypothetical profitability considerably. However, additional CO_2 generation due to produced oil can be calculated to be ca. 110 Mt also considering the CO_2 generated during the process. According to Jaramillo et al. (2009) the production of 16 $MStm^3$ oil from Weyburn field is estimated to generate approximately 65 Mt of CO_2, a ratio higher than the one assumed for Bati Raman case and much higher than the CO_2 injected in the reservoir during the same period.

Conclusions

Two ongoing CO_2 EOR field operations are discussed in terms of financial viability and CO_2 mitigation. The Bati Raman and Weyburn-Midale fields are very similar in terms of oil content originally in place and can be classified in the lower range of huge oil reservoirs; both in carbonate formations. However they show distinct petrophysical and production characteristics; Bati Raman contains heavy oil whereas Weyburn-Midale fields are light, low viscosity oil reservoirs. These features are reflected in their production behavior being the primary recovery factor of Bati Raman significantly lower than the others. Screening studies suggested the feasibility of CO_2-EOR in both field systems to be applied due to different recovery mechanisms. In the course of time Bati Raman CO_2-EOR application became the greatest immiscible CO_2 injection process worldwide whereas Weyburn and Midale fields show excellent incremental oil recovery results. The most attractive aspects of both field operations in terms of CO_2-EOR as CO_2 mitigation measure are the quality and quantity of available data on the executed and on-going operations. Following conclusions can be cited and discussed:

Both applications support the expertise and previous experiences that CO_2 injection is a powerful EOR method with both immiscible and miscible recovery processes. The performance of the applications are improved by various techniques; WAG in both reservoirs, foam and gel applications in Bati Raman field.

The financial aspects of both CO_2-EOR applications seems to be quite positive due to incremental oil. In both cases the recycling of used CO_2 is planned and ongoing. Such projects can obviously more attractive considering the emission tax/trade benefits. Costs of undertaking CO_2-EOR for storage, is obviously higher than for traditional CO_2-EOR due to additional monitoring, measuring and verification (MMV) and closure activities and could also increase as a result of changes to flood design and operations.

It is estimated that the CO_2 utilization rates during the operations are in the range predicted by various references, in Bati Raman case being slightly higher than Weyburn and Midale cases. However whether these calculations consider the total of CO_2 injected or net usage of CO_2 is not clear from the data provided.

In Suebsiri et al. (2006) the simulation results show that CO_2-EOR projects have the capacity to store approximately one-third of the total CO_2 emissions from the EOR process through the refinery and oil production usage. According to IEA, on a life cycle basis, the net emission reduction per ton of CO_2 utilized for EOR is 0.63 tons (CAFT, 2019). This is obviously valid compared to the conventional oil production. With the data used for the above discussed cases, from a volumetric and therefore optimistic point of view, if CO_2 replaces the same volume of oil produced the stored amount would be 0.4t/Stm^3 in Bati Raman and 0.8 t/Stm^3 in Weyburn-Midale reservoirs. In a basic level, it can then be assumed that also considering the CO_2 emitted by the EOR process and by the oil produced a maximum of 1 t CO_2 /Stm^3 oil produced can be stored in a reservoir, a number strongly depending on the thermodynamic conditions in the reservoir, the depletion rate, the carbon emission intensity of the oil as well as the optimal use of the depleted reservoir for CO_2 storage afterwards.

References

Alkan, H., Goktekin, A., & Satman, A. (1991). A Laboratory Study of CO_2-Foam Process for Bati Raman Field, Turkey . Proceedings of Middle East Oil Show. doi:10.2523/21409-ms

Azzolina, N. A., Peck, W. D., Hamling, J. A., Gorecki, C. D., Ayash, S. C., Doll, T. E., … Melzer, L. S. (2016). How green is my oil? A detailed look at greenhouse gas accounting for CO_2 -enhanced oil recovery (CO_2-EOR) sites. International Journal of Greenhouse Gas Control, 51, 369–379. doi:10.1016/j.ijggc.2016.06.008

CATF (2019) CO_2-EOR Yields a 37% Reduction in CO_2 Emitted Per Barrel of Oil Produced – Clean Air Task Force (catf.us)

Ettehadtavakkol, A., Lake, L. W., & Bryant, S. L. (2014). CO_2-EOR and storage design optimization. International Journal of Greenhouse Gas Control, 25, 79–92. doi:10.1016/j.ijggc.2014.04.006

Farajzadeh, R.; Eftekhari, Ali Akbar; Dafnomilis, G.; Lake, L.W.; Bruining, J. (2020) *On the sustainability of CO_2 storage through CO_2 – Enhanced Oil Recovery*, *Applied Energy*. Elsevier.

IEA (2015) Storing CO_2 through Enhanced Oil Recovery

Jablonowski, C. J., & Singh, A. (2010). A Survey of CO_2-EOR and CO_2 Storage Project Costs. SPE International Conference on CO_2 Capture, Storage, and Utilization. doi:10.2118/139669-ms

Jaramillo, P., Griffin, W. M., & McCoy, S. T. (2009). Life cycle inventory of CO_2 in an enhanced oil recovery system. *Environmental Science & Technology*, *43*(21), 8027–8032. https://doi.org/10.1021/es902006h

Karaoguz, O. K., Topguder, N. N. S., Lane, R. H., Kalfa, U., & Celebioglu, D. (2007). Improved Sweep in Bati Raman Heavy-Oil CO_2 Flood: Bullhead Flowing Gel Treatments Plug Natural Fractures. SPE Reservoir Evaluation & Engineering, 10(02), 164–175. doi:10.2118/89400-pa

Malik, Q. M., & Islam, M. R. (2000). CO_2 Injection in the Weyburn Field of Canada: Optimization of Enhanced Oil Recovery and Greenhouse Gas Storage With Horizontal Wells. SPE/DOE Improved Oil Recovery Symposium. doi:10.2118/59327-ms

Novak Mavar, K., Gaurina-Medimurec, N., Hrncevic´, L. (2021) Significance of Enhanced Oil Recovery in Carbon Dioxide Emission Reduction. Sustainability, 13, 1800. https://doi.org/10.3390/su13041800

Özgür E., (2019) The role of enhanced oil recovery in the upstream petroleum sector, a case study from Turkey, Bull. Min. Res. Exp.158: 291-297

Sahin, S., Kalfa, U., & Celebioglu, D. (2012). Unique CO_2-Injection Experience in the Bati Raman Field May Lead to a Proposal of EOR/Sequestration CO2 Network in the Middle East. SPE Economics & Management, 4(01), 42–50. doi:10.2118/139616-pa

Suebsiri, Jitsopa & Wilson, Malcolm & Tontiwachwuthikul, Paitoon. (2005). Life-Cycle Analysis of CO_2-EOR on EOR and Geological Storage through Economic Optimization and Sensitivity Analysis Using the Weyburn Unit as a Case Study†. Industrial & Engineering Chemistry Research - IND ENG CHEM RES. 45. 10.1021/ie050909w.

Whittaker, S., Rostron, B., Hawkes, C., Gardner, C., White, D., Johnson, J., … Seeburger, D. (2011). A decade of CO_2 injection into depleting oil fields: Monitoring and research activities of the IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project. Energy Procedia, 4, 6069–6076. doi:10.1016/j.egypro.2011.02.612