EOR's Significance in Emission Reduction

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Limiting the increase in CO2 concentrations in the atmosphere, and at the same time, meeting the increased energy demand can be achieved by applying carbon capture, utilization and storage (CCUS) technologies, which hold potential as the bridge for energy and emission-intensive industries to decarbonization goals. At the moment, the only profitable industrial large-scale carbon sequestration projects are large-scale carbon dioxide enhanced oil recovery (CO2-EOR) projects. This paper gives a general overview of the indirect and direct use of captured CO2 in CCUS with a special focus on worldwide large-scale CO2-EOR projects. On the basis of scientific papers and technical reports, data from 23 contemporary large-scale CO2-EOR projects in different project stages were aggregated, pointing out all the specificities of the projects. The specificities of individual projects, along with the lack of standardized methodologies specific for estimating the full lifecycle emissions resulting from CO2-EOR projects, pose a challenge and contribute to uncertainties and wide flexibilities when estimating emissions from CO2-EOR projects, making the cross-referencing of CO2-EOR projects and its comparison to other climate-mitigation strategies rather difficult. Pointing out the mentioned project's differentiations and aggregating data on the basis of an overview of large-scale CO2-EOR projects gives useful information for future work on the topic of a CO2-EOR project's lifecycle emissions.

carbon capture | utilization and storage | large- scale CO2-EOR projects | emissions | lifecycle analysis

1. Introduction

The Paris Agreement came into force in 2016 with the intention of mitigating global warming by keeping the global average temperature increase under 2 °C, and preferably even under 1.5 °C, when compared to pre-industrial levels. The only way to do this is through full harmonization with the energy and climate targets, which are comprised of a significant reduction of greenhouse gas emissions by 2030 (by 45%), as well as total decarbonization by 2050, based on the application of energy efficiency, renewable energy use and carbon capture and storage (CCS), or carbon capture, utilization and storage (CCUS). CCS technology implies avoiding CO_2 emissions to the atmosphere by capturing and storing it in geological formations characterized with long-term containment capability [1][2]. As per the strategies submitted to the United Nations Framework Convention on Climate Change (UNFCCC), CCUS is often recognized as a favorable option to fight climate change due to the turning of unwanted greenhouse gas into valuable products [3]. In order to be reused for various purposes (used for yield boosting or for the production of fuels, chemicals, building materials, etc.) CO_2 is captured from different sources, such as fossil fuel-based power plants, ammonia production plants, biomass fermentation facilities, natural gas processing plants, or it can be captured (removed) directly from the air. The commercial-industrial source of CO_2 should be at least 0.01 to 0.5 Mt CO_2/year [3][4].

At the moment, even though energy efficiency, use of renewable energy sources and fuel switching are often required as the exclusive priority in achieving climate goals, the world's high dependency on fossil fuel is still very much present. Therefore, the fossil fuel production industry (oil, gas and coal industry) has been undertaking different carbon-reduction initiatives in order to retain market competitiveness by providing a constant energy supply with an ecological footprint that is as low as possible [5][6].

Significant experience and existing infrastructure for underground fluid injection represent an essential basis for the development of CO_2 underground deposition technology. Additional oil production by CO_2 injection and CO_2 permanent storage within depleted oil and gas reservoirs or suitable geological formations seem to be sustainable options, which provide multiple benefits [7][8].

Keeping in mind that CO_2 usage for different products should not necessarily result in overall emission reduction, the benefits of each utilization/storage project must be evaluated by performing a comprehensive lifecycle analysis. This requires clear methodological guidelines that are temporarily under development by several expert groups. Furthermore, the retention time for CO_2 differs significantly, being in the range from one year, in the case of fuel generation, up to millions of years, in the case of carbonation [3]. Carbonation refers to a natural reaction of metal oxides, i.e., calcium (Ca) or magnesium (Mg) containing minerals (e.g., serpentine, olivine, wollastonite) with CO_2, which results in the production of calcium or magnesium carbonates ($CaCO_3$ or $MgCO_3$). Such processes can be considered as a CO_2 utilization or storage option. While the utilization refers to the recently developed, accelerated ex situ carbonation, able to produce valuable construction materials, a storage option refers to the last of the trapping mechanisms occurring within a geological formation (underground storage), which enables the permanent retention of CO_2. Since the use of pure CO_2 is not essential for mineralization (impurities simply do not interfere with the reaction), a purification step can be avoided, which results in lower costs [9][10].

Although, as stated before, emission-reduction results differentiate from project to-project, it is obvious that the best results, in terms of both sequestrated CO_2 quantities and sequestration permanency, can be achieved by just performing CCS projects. Other CCUS options, in fact, delay emissions to a greater or lesser extent, but due to economical profitability (they produce valuable products), today, at a time of a relatively low CO_2 market price, such projects are more preferable. However, due to residual oil production, currently, the only form of large-scale industrial carbon sequestration profitable projects are CO_2-EOR projects. Although fossil fuel combustion and waste gas generated during CO_2-EOR operations at an EOR site result in new emissions, substantial quantities of CO_2 remain permanently stored within the depleted reservoirs. Since there are some disagreements over CO_2-EOR emission assessment, a lack of standardized methods for measuring the full lifecycle emissions resulting from CO_2-EOR projects (needed for crediting EOR's carbon reductions) hinders CO_2-EOR application as CCUS technology.

In this paper, captured CO_2 utilization, an overview of the worldwide CO_2-EOR projects and an analysis of CO_2-EOR lifecycle emissions are presented.

2. Discussion

Climate issues related to increasing concentrations of CO_2, mainly released during fossil fuel combustion during power production, put strong initiatives to limit the use of fossil fuels and to increase the employment of alternative power production solutions like renewable energy sources. On the other hand, due to variability in the availability of renewable energy sources, the cost of energy production from it, along with energy storage issues and the constantly increasing global energy demand, especially in developing countries, the world still strongly depends on fossil fuels, and the transition to a carbon-free society will take place over several decades. A possible solution for the transition is seen in CCS and CCUS technologies, which allow the use of fossil fuels while eliminating the adverse climate change impacts associated with greenhouse gas emissions. Both technologies eliminate a facility's direct CO_2 emissions. Although the primary goal of CCS and CCUS technologies is CO_2 sequestration, both technologies result in a certain amount of emissions. Even though CCUS, along with CO_2 sequestration, creates additional benefits (production of new products), sometimes, depending on the type of project, it is a less favorable solution compared to CCS (in cases when CO_2 retention time is relatively short).

CCS comprises various technical and technological solutions depending on the size and type of CO_2 source, capture technology, transportation mean, and the final storage destination (distance from the CO_2 source, depth and characteristics of the geological formation, etc.). Currently, the only type of large-scale CCUS projects are CO_2-EOR projects (see Table 1, Figure 1 and Figure 2), which, along with CO_2 sequestration, also result in residual oil production. According to the KAPSARC database [11], in 2018, 11 of 23 large-scale CO_2-EOR projects were in operation (48%) (see Table 1), grouped, by related industries where applied, into natural gas processing (6 projects, or 55%), fertilizer production (2 projects, or 18%), power generation (1 project, or 9%), synthetic natural gas (1 project, or 9%), and hydrogen production (1 project, or 9%). The rest of the projects were in the execution stage (5 projects, or 22%), definition stage (5 projects, or 22%) or evaluation stage (2 projects, or 9%). With regard to the large-scale CO_2-EOR projects in the execution phases, there is a visible shift towards smaller capacity projects and other industry applications, such as iron and steel production, fertilizer production and oil refining (Figure 2).

Table 1. CO_2-EOR projects, status overview 2018. Modified according to [14].

	Project Name	CO_2 Capture Capacity (Mt/y)	Stage	Location	Industry
1.	Petrobras Lula Oil Field CCS Project	0.7	Operate	Brazil	Natural gas processing
2.	Alberta Carbon Trunk Line ("ACTL") with	0.6	Execute	Canada	Fertilizer

	Project Name	CO_2 Capture Capacity (Mt/y)	Stage	Location	Industry
	Agrium CO_2 Stream				production
3.	Alberta Carbon Trunk Line (“ACTL”) with North West Sturgeon Refinery CO_2 Stream	1.4	Execute		Oil refining
4.	Boundary Dam Carbon Capture and Storage Project	1	Operate		Power generation
5.	Great Plains Synfuel Plant and Weyburn-Midale Project	3	Operate		Synthetic natural gas
6.	PetroChina Jilin Oil Field EOR Project (Phase 2)	0.5	Define	China	Natural gas processing
7.	Sinopec Qilu Petrochemical CCS Project	0.5	Define		Chemical production
8.	Yanchang Integrated Carbon Capture and Storage Demonstration Project	0.4	Define		
9.	Sinopec Shengli Power Plant CCS Project	1	Define		Power generation
10.	Huaneng GreenGen IGCC Project (Phase 3)	2	Evaluate		
11.	Uthmaniyah CO_2-EOR Demonstration Project	0.8	Operate	Saudi Arabia	Natural gas processing
12.	Abu Dhabi CCS Project (Phase 1 being Emirates Steel Industries (ESI) CCS Project)	0.8	Execute	United Arab Emirates	iron and steel production
13.	Texas Clean Energy Project	2.4	Define	United States	Power generation
14.	Kemper County Energy Facility	3	Execute		
15.	Petra Nova Carbon Capture Project	1.4	Execute		
16.	Air Products Steam Methane Reformer EOR Project	1	Operate		Hydrogen production
17.	Coffeyville Gasification Plant	1	Operate		Fertilizer production
18.	Enid Fertilizer CO_2-EOR Project	0.7	Operate		
19.	Lost Cabin Gas Plant	0.9	Operate		Natural gas processing
20.	Shute Creek Gas Processing Facility	7	Operate		

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	Project Name	CO_2 Capture Capacity (Mt/y)	Stage	Location	Industry
21.	Val Verde Natural Gas Plants	1.3	Operate		
22.	Riley Ridge Gas Plant	2.5	Evaluate		
23.	Century Plant	8.4	Operate		

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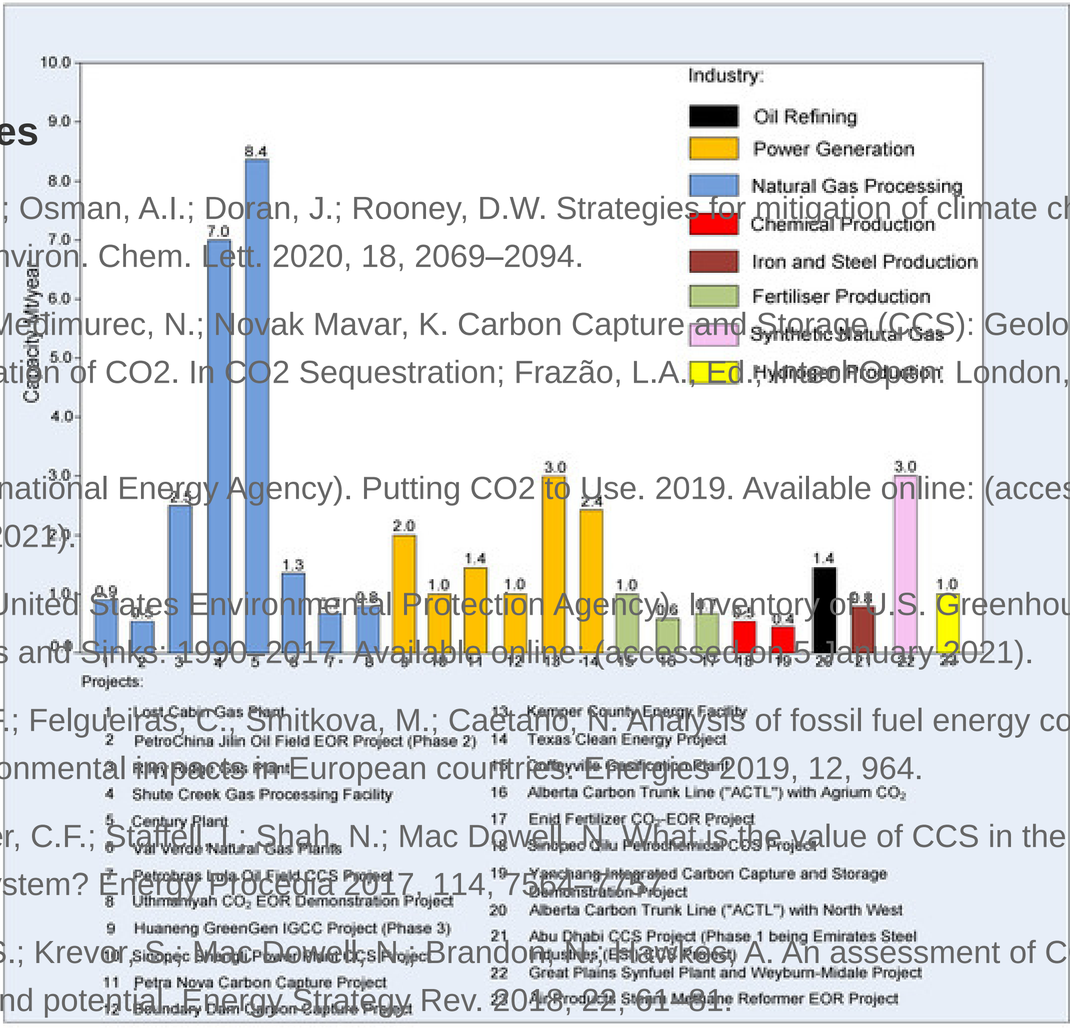

Figure 1. Large CO_2-EOR projects in different project stages by applied industries (according to [14]).

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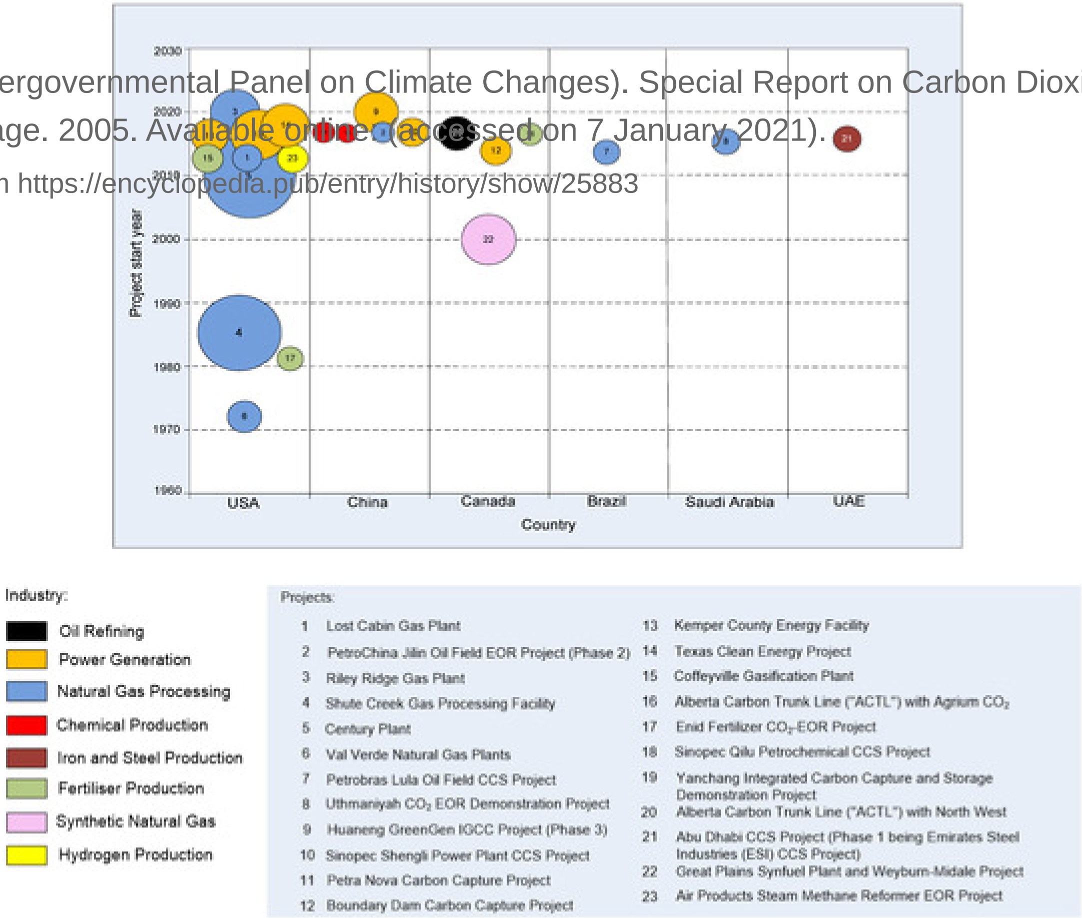

Figure 2. Development timeline of the EOR projects by capacity and country (according to [14]). Figure 1 and Figure 2 are complementary to each other. The circles differ by colors (industry type), sizes (capture capacity) and numbers (ordinal number of the project).

Regarding the capture capacity of these projects, projects related to natural gas processing (52%) have the largest share of capture capacity. This is expected since, as mentioned before, most of the large-scale CO_2-EOR projects are related to natural gas processing, which is not surprising since CO_2 injection technology was developed by the petroleum industry. The capture capacity of large-scale CO_2-EOR projects related to power production is 26%, fertilizer production 5%, synthetic natural gas 7%, oil refining 3%, iron and steel production 2% and hydrogen production 2%.

Most of the projects, at different project stages, are conducted in the USA (48%) and China (22%), followed by Canada (17%), Brazil (4%), Saudi Arabia (4%) and the United Arab Emirates (4%) (Table 1, Figure 3).

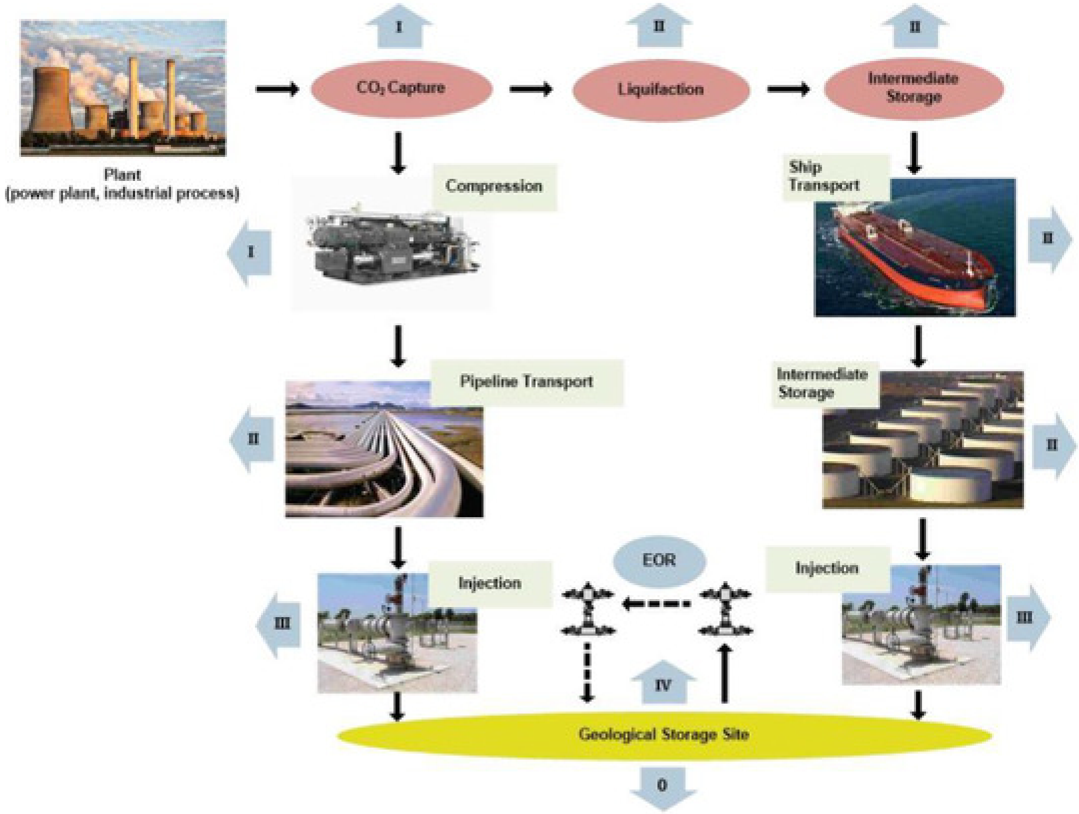

Figure 3. Potential greenhouse gas emissions sources and types of emissions in CCS and/or CO_2-EOR value chain. Modified according to [39].

As can be seen, all of the mentioned projects differ by CO_2 source type and size (and if the same, they differ by fuel type, net output, efficiency, capture technology, capture capacity, captured CO_2 purity, etc.), CO_2 transport (choice of the transportation system and used fuel, distance from the CO_2 capture point to injection/storage point, etc.), injection/storage site characteristics, time horizon, the geographical location of CO_2-EOR value chain elements (thus different environmental impact due to different ecological sensitivity) and different market conditions (cost of CO_2, oil price). All of these differences pose a challenge when estimating emissions from CO_2-EOR projects. The mentioned varieties between CO_2-EOR projects (and generally CCS/CCUS projects), but also the lack of standardized methods for estimating the full lifecycle emissions resulting from CO_2-EOR projects, result in various uncertainties and wide flexibilities on how to estimate emissions from these kinds of projects.

Narrow-analysis of case-specific data could be done, but generally, there is a lack of appropriate lifecycle emission estimation methodologies specific to CO_2-EOR projects (CCS/CCUS projects). In addition, due to the mentioned specifics, in order to estimate the full lifecycle emissions resulting from CO_2-EOR projects, normalization and a set of benchmark information should be done, which will allow the cross-referencing of CO_2-EOR projects and its comparison to other climate-mitigation strategies. Pointing out the mentioned differentiation and giving an overview of large-scale CO_2-EOR projects gives useful information for the future development of standardized methods for estimating the full lifecycle emissions resulting from CO_2-EOR projects.