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Carbon Emissions Accounting in the context of Carbon Capture and Storage (CCS) coupled with Enhanced Oil Recovery (EOR)

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Contents

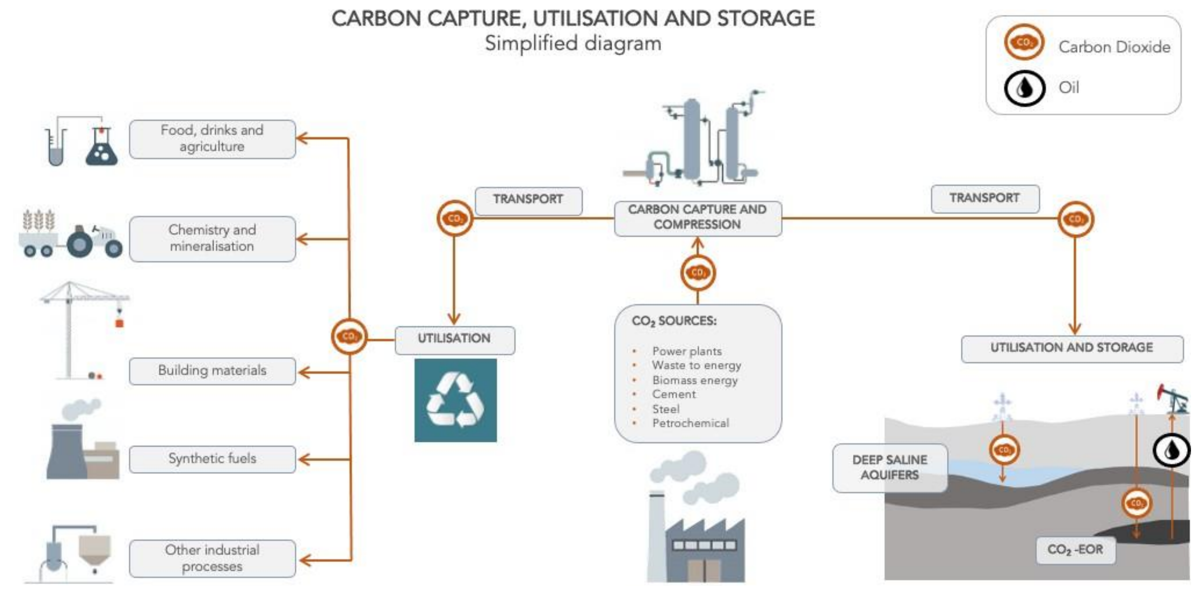
Figures

Tables

Introduction

According to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, industry and energy production are the most significant global contributors to greenhouse gas (GHG) emissions. Reducing industry GHG emissions entails coordinated action throughout value chains to promote all mitigation options, including demand management, energy and materials efficiency, circular material flows, abatement technologies and transformational changes in production processes (IPCC, 2023). To that extent, many industries are developing and implementing decarbonisation strategies to transition to a lower-carbon economy where GHG emissions are minimised or eliminated. Carbon Capture, Utilisation and Storage (CCUS) is one of the technologies for industrial decarbonisation consisting in capturing CO_2 emissions from large-scale industries or directly from the atmosphere, for utilizing the captured CO_2 in industrial or chemical processes or storing it permanently in geological formations (Figure 1).

Figure 1: Simplified schematic diagram of CCUS processes



Note: Including CO_2 capture from industrial sources, transport, and utilisation. Utilisation includes various industrial applications, as shown on the left and utilisation for CO_2-EOR and permanent geological storage in oil reservoirs or deep saline aquifers. Orange arrows and icons indicate CO_2 flow; the black drop icon indicates oil production.
Source: Modified from cowi.com

Besides reducing emissions, CCUS provides opportunities for producing new products such as synthetic fuels, CO_2-based products and materials. CO_2 utilisation has been part of several industrial processes for decades, including natural gas processing, fertiliser production and enhanced oil recovery (CO_2-EOR) (IEA, 2020). EOR has been the most widely adopted use for CO_2 since the 1970s when gas injection was introduced in the Permian Basin in Texas, USA (El-Saleh, 1996; Núñez-López et al., 2008; Hill et al., 2013; Hosseininoosheri et al., 2018). Substitution of natural CO_2 by anthropogenic CO_2 represents the first step for CO_2-EOR to provide environmental benefits by avoiding emissions that improve the recovery factors in oil reservoirs while CO_2 is simultaneously stored in the rock pores. Moreover, selling the additional oil produced enhances the project's economics by providing a stream of revenues for companies.

Evaluating and measuring the impact of CO_2-EOR on overall carbon emissions from such projects is fundamental, and carbon accounting is a powerful tool to achieve that. Different carbon accounting methods and approaches exist and vary depending on the objectives, including measuring and reporting GHG emissions from industries and businesses (WRI, 2014), demonstrating organisations' commitment to environmental sustainability (BSI, 2019), or complying with mandatory and voluntary regulations and certifications. This paper presents a carbon accounting methodology to model the effects of CO_2-EOR and CCUS projects using time-series analysis to evaluate the critical components that affect CO_2 emissions over the project's lifetime. This method contributes to assessing the role of CCUS as a climate change mitigation technology and can be further used to support decision-making.

Section 2 presents the basis of carbon accounting in the context of CCUS and different carbon accounting methods. Section 3 elaborates on the changes in emissions caused by CCUS introduction over time and the proposed methodology for their evaluation, including direct and indirect effects. Section 4 highlights critical considerations related to CO_2 storage coupled with EOR to identify multiple key components for emissions accounting. Section 5 presents a case study where the methodology was applied to a hypothetical CCUS project in Mexico. The paper's conclusions are stated in section 6.

1. Carbon accounting in the context of CCUS

Carbon accounting methods quantify the carbon emissions and contributions to mitigating climate change of a given project or activity (Brander, 2017). The most widely adopted method is life cycle assessment (LCA), introduced by companies in the 1960s and 1970s (Hunt & Franklin, 1996; Jensen et al., 1997) for evaluating the environmental performance of products and services (Pohl et al., 2019). The process is standardised in ISO (2020) and encompasses four phases:

1) Goal and scope definition
2) Life cycle inventory analysis
3) Impact assessment, and
4) Interpretation.

Carbon accounting methods can be divided into attributional and consequential approaches whereby each category has a particular purpose, characteristics, and challenges. For instance, attributional methods use average data to describe the relevant physical flows of emissions of one specific process. They provide a 'snapshot' of the environmental performance of a process within a temporal window (Weidema et al.,2018) and its direct impacts. On the other hand, consequential methods focus on the changes caused by a process or intervention using marginal data. They encompass all possible consequences introduced by the process or intervention, wherever and whenever they occur over time. These approaches are not mutually exclusive and can complement each other (Brander, 2016; Brander et al., 2019). It is noteworthy here that marginal data is less frequent and available than average data, which adds complexity to consequential methods development.

Through the years, both approaches have supported decision-making and the evaluation of project environmental performance. Nevertheless, a consequential method is often recommended to forecast possible systemic consequences (Pedersen Weidema, 1993; Ekvall & Weidema, 2004; Plevin et al., 2014), and is helpful to anticipate the effects that a project or intervention can cause system-wide and avoid unintended outcomes. Project and policy-level accounting (Brander, 2016) and dynamic LCA studies[1] (Levasseur et al., 2010; Collinge et al., 2013; Beloin-Saint-Pierre et al., 2014) are examples of methods that introduce the temporal dimension and help track changes in the emissions along the project's lifetime and beyond.

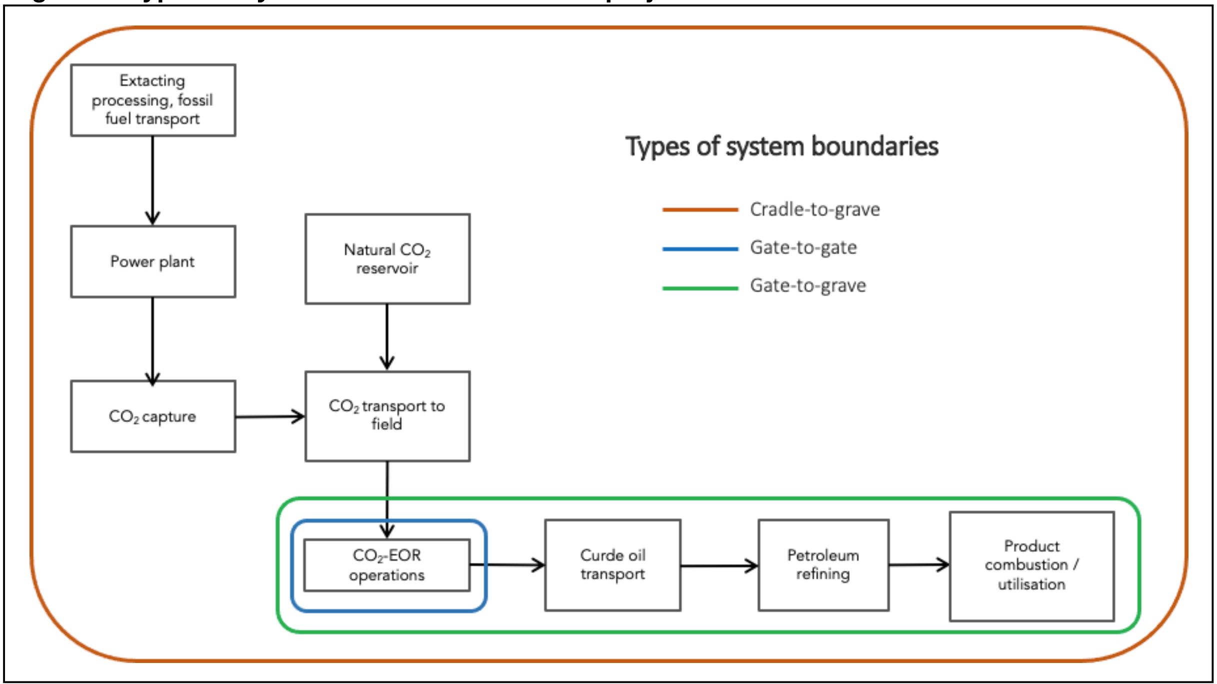
[1] Dynamic LCA is an extension of traditional LCA that considers temporal aspects and dynamic changes that occur along the life cycle of a system. It goes beyond a static snapshot of a system impacts. Dynamic LCA acknowledges that diverse factors influence the environmental performance of a product or system and they can vary over time. It involves time-dependent data, scenario analysis, sensitivity analysis, and an iterative approach.

Since 2007, two years following the publication of the first IPCC report on CCS (IPCC, 2005a), LCA has gained popularity as a tool to evaluate CCUS environmental performance. However, a frequent critique and drawback of LCA studies is that the majority use different system boundaries and functional units, making them hard to compare. Figure 2 shows the three most common system boundaries for reference:

1) Cradle-to-grave, which encompasses all the elements from raw materials production to products utilisation (orange box);
2) Gate-to-gate, which focuses on specific processes or segments of the value chain (blue box); and
3) Gate-to-grave, which covers the system from one particular process to the product's utilisation or disposal (green box).

Furthermore, most existing literature on LCA for CCUS projects is focused on power generation cases and CO_2 utilisation (CCU) (Tobias et al., 2021), perhaps because CCUS was initially identified as a decarbonisation technology in the energy industry and, lately, as a means for CO_2-based commercial activities. Regardless of the case or application, project assessments should be understandable and repeatable (Liu *et al.*, 2020), and reflect the dynamic complexity that CCUS entails.

Figure 2: Types of system boundaries of CCUS projects



Note: The square boxes represent the CCUS processes. The largest orange square represents the cradle-to-grave boundary, the blue square represents gate-to-gate, and the yellow square the gate-to-grave boundary.
Source: Illustrated by the author

Non-attributional carbon accounting methods are seldom present in literature and practice. Tobias et al. (2021) present a comprehensive bibliometric analysis of CCS/CCU LCA publications from 1995 to 2018. The analysis is based on 234 publications which use an attributional approach. Among the authors that have developed non-attributional assessments, of note are Brander & Ascui (2019) '*consequential carbon accounting for CCUS in the iron/steel sector*'; Nuñez-Lopez et al. (2019) '*dynamic LCA for CCUS';* Thonemann & Pizzol (2019) '*consequential LCA for CCU technologies within the chemical industry'* and Briones-Hidrovo et al. (2022) *'dynamic LCA for bio-energy with CCS'*. That said, the attributional-consequential distinction remains limited despite the valuable contributions of consequential methods to decision-making (Brander & Ascui, 2016).

There is an emphasis across LCA publications on the need for methods besides LCA, data collection and identification of hotspots in CCUS (Tobias et al., 2021), for transparent and innovative approaches to understanding the technology impacts and standardised methods that integrate regional contexts (Müller et al., 2020). The interest in comprehensive and informative methods and tools for project evaluation opens the opportunity for improving our understanding of the contributions and goals CCUS provides. CO_2-EOR is a mature application and a leverage element for CCUS implementation that plays a critical role in emissions management. The processes involved have different impacts on CO_2 emissions and, therefore, attention must be paid to project design and implementation.

1.1 CO_2-EOR coupled with permanent CO_2 storage

CO_2-EOR has been an essential catalyst for CCUS. It is a process applied in oil fields to improve their recovery factor, typically in a mature production stage. It is a gas injection technique that injects reactant fluids (e.g. CO_2, nitrogen, methane) into a reservoir and mixes it with oil to decrease its viscosity and make it easier to extract (Santos et al., 2021). A portion of CO_2 is trapped and permanently stored underground, and the remaining CO_2 returns to the surface along with the oil for recycling[2]. CO_2 is a valuable commodity, so the produced CO_2 is recovered and reinjected which typically renders CO_2-EOR a closed-loop process (IEA, 2017).

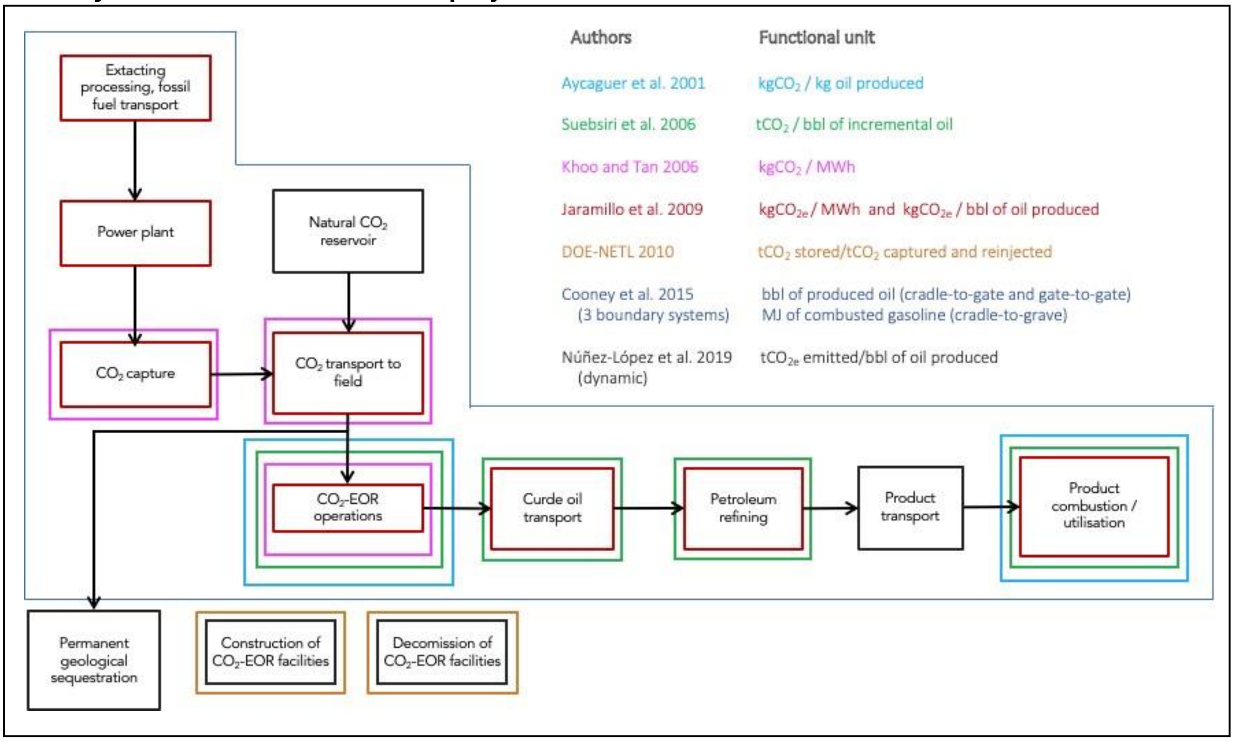
When CO_2-EOR is coupled with permanent CO_2 storage, the carbon footprint of the oil produced might be lower thanks to the balance between the CO_2 emissions embodied in oil production and consumption and the anthropogenic CO_2 permanently stored in the reservoir. However, important considerations determine whether the carbon balance of a CCUS project is negative (a reduction in emissions) or positive (an increase in emissions). In fact, whether CO_2-EOR entails an environmental benefit has motivated discussions and prompted several authors to evaluate the project's environmental performance and emissions accounting. Outstanding publications on this subject include Aycaguer et al. (2001), Azzolina et al. (2016), Cooney et al. (2015), DOE/NETL (2010), Jaramillo et al. (2009), Khoo & Tan (2006), Núñez-López et al. (2019) and Suebsiri et al. (2006) (Figure 3). Apart from these studies, extensive literature addresses this topic; nonetheless, differences in the functional units and system boundaries make them difficult to compare.

Indeed, one advantage of CO_2-EOR analysis is the experience and data accumulated over the years of operations globally. Although site-specific data and simulations are required for the project's deployment, models can be developed to identify critical decision points or improvements in the operations and costs. It is fundamental to note that a CO_2-EOR project qualifies as CCUS only when anthropogenic CO_2 is used, and that the project encompasses additional activities to ensure long-term retention of CO_2, such as a monitoring and verification programme, measurement of fugitive emissions, and field abandonment practices (IEA, 2017; p.387). To better understand the process, a CCUS project is considered carbon neutral if emissions are equal to reductions and carbon negative if removals exceed CO_2 emissions – any other cases are carbon-positive (Müller et al., 2020).

A critical remark is that CCUS projects are not static. The reservoir behaviour evolves with the CO_2 supply, transport, and operation conditions affecting the project emissions balance. It is important to be aware of all the dynamic elements of the system and their performance over time to achieve the desired outcomes or prevent unintended effects. To that extent, Mota-Nieto et al. (2023) introduced a consequential analysis, including a time-series for capturing the dynamism of CCUS projects, which is used in this paper.

[2] The percentage of CO_2 trapped in the reservoir in EOR depends on several factors such as the efficiency of injection and trapping mechanisms defined by the rock and fluids characteristics. On average, approximately 30-50% of the injected CO_2 is permanently stored (Hovorka, 2010; p.7). The rest of the CO_2 volume is recycled and eventually trapped in the reservoir; however, detailed models and validation are necessary to evaluate the storage efficiency.

Figure 3: Graphical representation of the CCUS value chain comparing the system boundaries used by various authors for CCUS projects related to CO_2-EOR.



Note: Coloured boxes are associated with the authors' work. Functional units by authors are also presented for comparison.

Source: Illustrated by the author, Modified from Núñez-López et al. (2019)

Two studies on CCUS LCA were considered relevant for the method presented herein. First, Azzolina et al. (2016) provide a detailed LCA based on previous research and reservoir performance data from 31 CO_2-EOR projects. The study indicates that CO_2-EOR performance varies regionally, emphasising the need for site-specific data collection and modelling. On the other hand, Nuñez-Lopez et al. (2019) propose a dynamic LCA approach to estimate the carbon balance of a CCUS project using data from the Cranfield project, located in southwestern Mississippi, USA. The study compared the most popular CO_2 injection strategies (Continuous Gas Injection (CGI), Water Alternating Gas (WAG), Water Curtain Injection (WCI), and Hybrid WAG+WCI). They determined that the injection strategy selection is critical regarding oil production and carbon storage optimisation. The value of these studies relies on the empirical data used and the introduction of a time dimension. However, each uses different system boundaries and functional units, making it difficult to compare their results.

Carbon accounting of CCUS projects must consider system-wide effects from CO_2 capture and separation, transport of gas and liquids, underground operations, and the related activities that allow CO_2 management and control. Beyond the direct emission sources related to operations and the energy consumed during the CO_2 capture, transport and injection processes, there are other emissions-associated consequences. For example, market-mediated effects and product substitution are an example of indirect changes in emissions caused by CCUS introduction, which can significantly impact the system-wide emissions accounting.

2. Evaluation of CCUS emissions effects over time

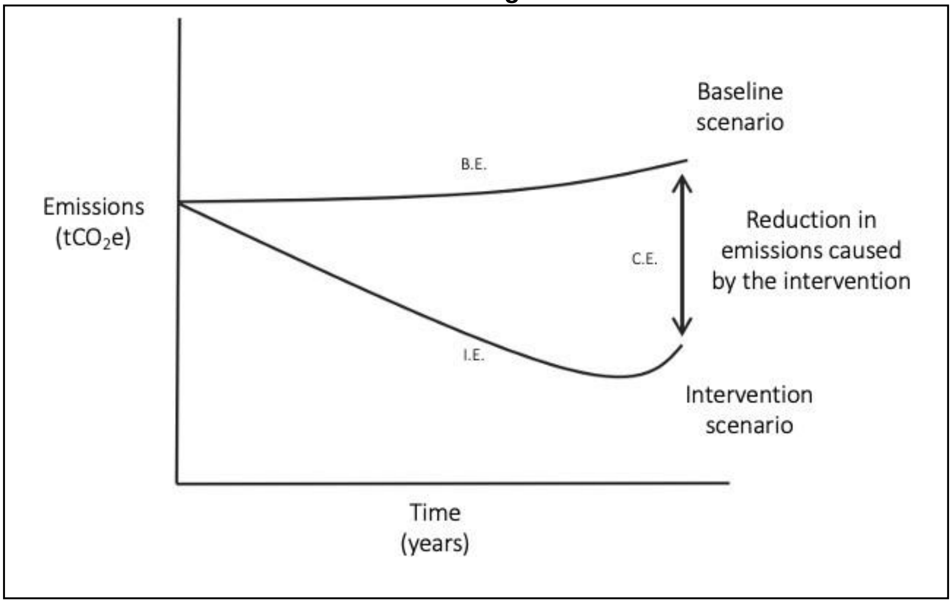
An important reason to evaluate CCUS projects is to determine whether the system is carbon positive or negative, mainly if its implementation aims to contribute to climate change mitigation. Since additional operational and market effects are necessary, estimating and modelling their carbon footprint is fundamental. The following sub-sections present a consequential carbon accounting method as a time-series to identify critical components of CCUS projects and the change in emissions over time. The methodology was developed by Mota-Nieto et al. (2023).

The central methodology uses the GHG Protocol and Action Standard developed by the World Resources Institute (WRI, 2014) to provide a standardised approach for estimating the effects that a given policy or action has on GHG emissions in the future, track expected results, and report the resulting change in emissions. Its primary purpose is to help users assess the GHG effects of their interventions and support decision-makers in developing effective strategies for managing and reducing GHG emissions.

The GHG Protocol method is also referred to as the 'baseline-and-credit' and 'intervention' accounting method. It consists in developing a causal chain map of the project and then defining and modelling a baseline and the intervention scenario(s). Finally, the change in emissions (*C.E.*) is estimated by subtracting the baseline emissions (*B.E.*) from the intervention scenario emissions (*I.E.*), as shown in Equation 1 and Figure 4. Remarks from the proposed methodology highlight that 1) marginal data is required as a consequential accounting method; however, if not available, average data from attributional methods can be used to represent the marginal system; and 2) ideally, the time span should be determined by when the intervention causes a change. If the changes persist beyond the operational lifetime of the project, they should also be included.

C.E. = I.E. - B.E. ***(eq.1)***

Figure 4: Illustration of the intervention accounting method



Source: Modified from Brander (2016)

The time-series in this method for CCUS projects presents a 25-year period of analysis as an average frame in which anthropogenic CO_2 is supplied and injected into the reservoir for EOR. It can be modified, if necessary, based on the assumption regarding when the reservoir reaches maximum CO_2 storage capacity, or the project seizes operations due to economics, low oil demand, regulation, or the socio-political context.

2.1. Determining the baseline and intervention scenarios

Carbon accounting evaluations aim to compare the change in emissions between two or more scenarios. Firstly, it is necessary to model the emissions which would occur without any intervention; then, modelling the possible scenarios derived from a given intervention. For CCUS, the technology application seeks to avoid releasing CO_2 emissions into the atmosphere by capturing and injecting them into a reservoir. Nonetheless, CO_2 management, storage and monitoring imply additional activities which are not exempt from producing GHG emissions.

The baseline scenario is a "hypothetical reference case that best represents the conditions most likely to occur in the absence of a proposed project" (ISO, 2019: p.4). In the context of CCUS projects, it consists of the emissions produced by the industrial source without carbon capture and the emissions from marginal oil production. In contrast, the intervention scenario encompasses all the sources and sinks controlled by, related to, or affected by the project (ISO, 2019). For CCUS projects, they include unavoided emissions from the CO_2 source; embodied emissions from the carbon capture plant construction, operation and decommissioning; embodied emissions from pipelines or other transport options, including construction, monitoring, fugitive emissions, and closure; embodied emissions from the injection site conditioning and closure; emissions from reservoir fluids compression and any other fluids injection and disposal and emissions from CO_2 recycling and reservoir leakage.

2.2. Causal chain mapping

It is necessary to identify all potential effects in a map of the causal chain. They include increases and decreases in emissions (and removals, if applicable) resulting from the project. All relevant inputs and activities described in the previous subsection must be considered. Other intermediate effects related to the project's implementation should be included if they significantly impact emissions (WRI, 2014). This exercise is valuable for identifying the evident and not-so-obvious elements directly and indirectly involved with the project. The mapping process focuses on GHG and non-GHG effects, such as relevant changes in the environmental, social or economic arenas or climate change mitigation, which might be included (WRI, 2014). There are different types of effects that a CCUS project can bring about; for example, the market-mediated effects of marginal oil production. It is estimated that when oil produced through CO_2-EOR hits the global market, 84% of EOR-supplied oil displaces the existing supply (CATF, 2019; p.2). Therefore, CO_2-EOR has an essential impact in replacing other marginal production that is more expensive and, in some cases, more carbon-intensive such as oil sands in Canada.

Literature review, surveys, review of prior assessments, regulations and policies, and expert judgment are some of the approaches and sources of data to identify effects and map the causal chain. For this study, the literature review provided an understanding of the most common methods adopted for CCUS environmental performance evaluation; additionally, prior assessments were consulted for identifying relevant data that could be included for calculations based on theoretical and empirical analysis. Finally, some aspects related to actual practice and experience were elucidated via expert judgment and interviews with operators – in this case with Petroleos Mexicanos (PEMEX) – and complemented with empirical data reported in prior assessments and literature.

2.3. GHG and non-GHG effects

2.3.1. CO_2 emission sources

Power generation and industrial activities represent around 80% of global emissions (Ritchie et al. 2020). CCUS is one of the technology-based options to reduce such emissions. Reducing CO_2 emissions from various sources, including power generation plants, industrial processes, and even directly from the atmosphere, is the main objective of this technology. Therefore, it is necessary to know the amount of emissions from the source and where they are generated.

When emissions are captured from industrial facilities, the process avoids GHG emissions; if the CO_2 is removed from the atmosphere or other sources, such as biomass or bioenergy production or directly from air, we refer to it as a carbon removal process (Climeworks, 2023). This difference is critical for carbon accounting evaluation.

Once the CO_2 source has been identified, we can determine whether emissions can be captured. In such cases, capture can occur using different methods (chemical absorption, membrane or cryogenic separation, among others), which demand the construction of the capture plant and all the capital and operational implications it entails.

2.3.2. Carbon capture plant construction and operation

The carbon capture plant construction and operation has embodied emissions which can be estimated using data from LCA studies, plant design, and emissions factors available in the literature. The plant operation and compression are calculated by multiplying the energy use per ton of CO_2 captured per year (MWh/y) by the electricity emissions factor of the local grid (tCO_2/MWh). Liu et al. (2020) report an emissions factor equivalent to 10 $kgCO_2/tCO_2$ captured for the plant construction.

Local grid emission factors are one of the dynamic components considered in this methodology. They represent the amount of GHG emissions associated with producing a unit of energy in a particular geographic region. They include the type of fuel mix and technologies used to generate electricity, power plant efficiency, and other macroeconomic and demographic variables. This element is relevant because points of energy consumption in the capture plant operation are one of the primary sources of emissions system-wide. Therefore, using local grid emission factors help accurately estimate and assess the environmental impact of energy consumption.

2.3.3. CO_2 pipeline construction and operation

CO_2 transport options depend on source-sink distance, the gas amount to be transported, and the location. Typically, pipeline transport is the most common option (IPCC, 2005b: p.344). Dedicated CO_2 pipelines are necessary for CCUS projects; their construction, monitoring and closure represent another source of embodied emissions.

Pipelines construction requires steel and cement as the primary materials, site preparation and allocation of the infrastructure. Pipelines monitoring may include different techniques of which aerial vehicles are popular. Their closure, once the project concludes, must also be considered. The parameters to estimate the emissions can be calculated using LCA (attributional) methods, ideally using local-based data—the present methodology used parameters from Lacy Tamayo (2014; p.119).

CO_2 transport requires electricity for gas compression and similarly for the capture plant's operation, for which local grid emission factors are used. McCoy (2008) reports 6.5 kWh of electricity consumed per ton of CO_2 transported, which is used to estimate the total emissions from electricity used for CO_2 transport. Additionally, pipelines also present fugitive emissions[3] that must be accounted for. Lamb et al. (2015) provide an average fugitive estimate at 0.282 tCO_2/km-yr that can be multiplied by the pipeline length.

2.3.4. CO2-EOR and storage

Even though CO_2-EOR can be assumed to be a closed-loop process, CO_2 management depends on various considerations and processes. As mentioned earlier, data from traditional LCA studies are difficult to compare due to their different system boundaries and functional units. Furthermore, most studies lack the temporal component depicting the reservoir's complexities and changes over time. As noted by Nuñez-Lopez *et al.* (2019), elements such as the injection strategy, CO_2 recycling and storage are fundamental to avoid underestimating the emissions generated in this segment of a CCUS project.

[3] Fugitive emissions are unintentional or accidental gases released into the atmosphere during operations. They might be caused by leaks, equipment malfunctions, inadequate maintenance, or unexpected events. They can represent a significant source of pollution; therefore, their effective management is crucial for reducing environmental impacts.

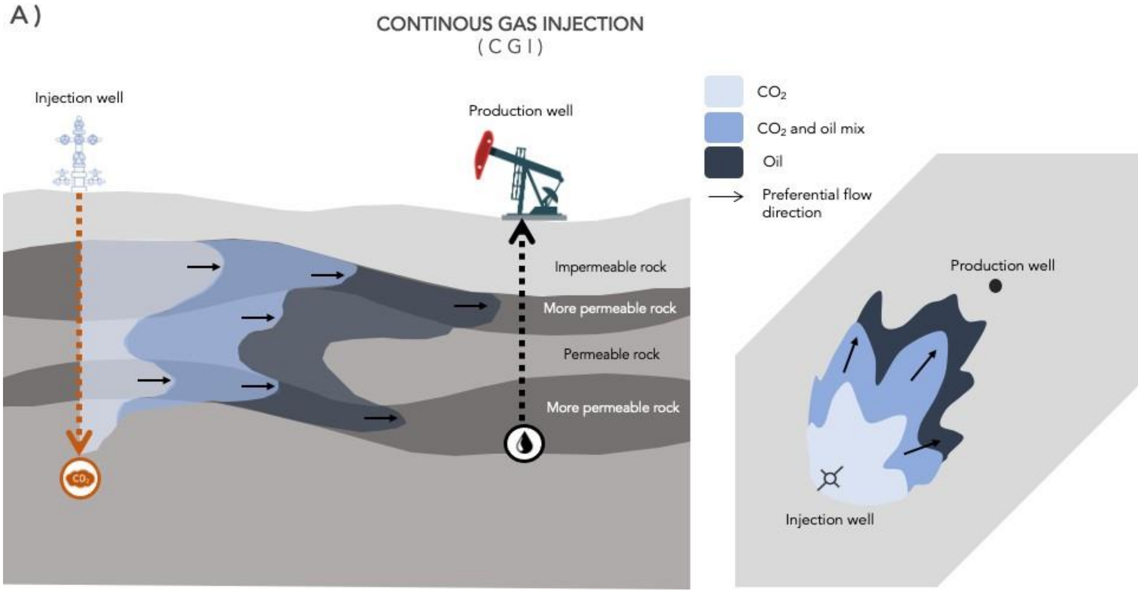
2.3.4.1. Injection strategy[4]

CO_2, as other fluids such as nitrogen and hydrocarbon gases, are injected to improve oil recovery by causing a change in the reservoir fluids' properties when mixing with them. Among these gases, CO_2 has various advantages that allow it to be applied in almost any kind of reservoir (shallow or deep) and for any type of oil (from light to heavy oil). A disadvantage is that CO_2 viscosity is lower than that of the oil, creating a tendency to flow following heterogeneous patterns, also called channels or "fingers", without mixing with all the oil in the reservoir. These effects depend on the geology of the reservoir and the fluids' properties (Heidug et al., 2015). To overcome this challenge, different injection strategies have arisen.

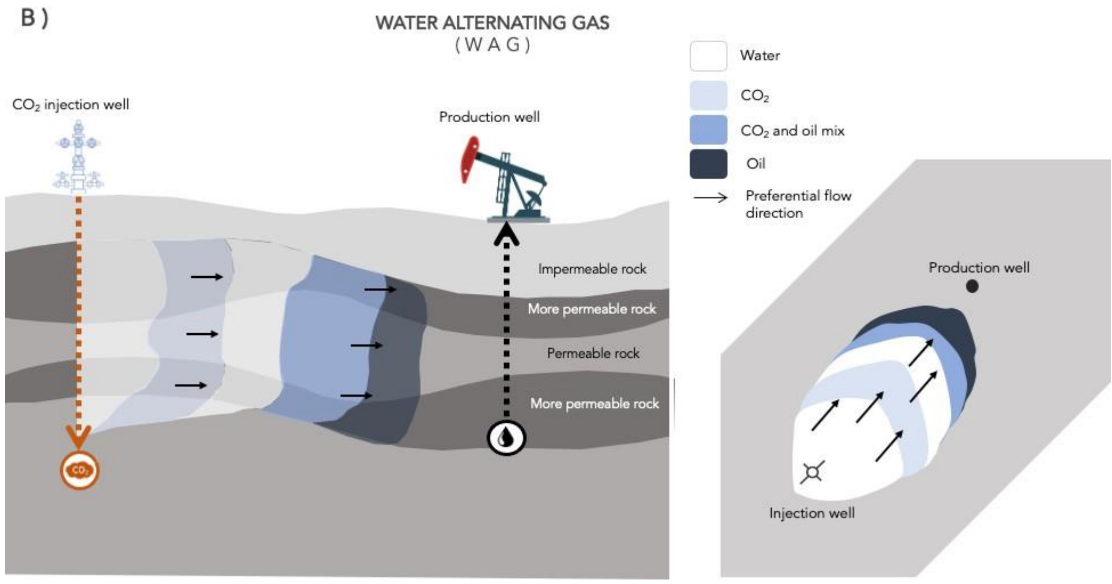
The most common injection strategies combine CO_2 and water injection. Water hinders the CO_2 movement through the reservoir reducing demand for CO_2, which is advantageous for operators since CO_2 purchase is an essential economic factor (Heidug *et al.*, 2015; p.11). Continuous gas injection (CGI), water alternating gas (WAG), and water curtain injection (WCI) are the most common strategies. In CGI, CO_2 is injected continuously (Hosseininoosheri et al., 2018) (Figure 5A); WAG consists of injecting CO_2 and brine alternately (Henson et al., 2002)(Figure 5B), while WCI is a continuous gas injection with a peripheral water injection which creates a barrier that contains the CO_2 within the desired rock volume (Nuñez-Lopez et al., 2019). Each strategy has different operational and resource requirements. According to the empirical data and experience from the Cranfield project in the USA, Nuñez-Lopez *et al.'s* (2019) numerical reservoir simulation indicate that CGI and WAG are the strategies with the highest effectiveness regarding oil production and CO_2 storage.

CO_2 food efficiency varies with each reservoir and injection strategy. One critical concept here is the utilisation rate which refers to the volume of CO_2 that must be injected into the reservoir to produce one barrel of oil (Nuñez-Lopez *et al.*, 2019; p.27). This value evolves significantly over time, which has been considered another dynamic component in this methodology. Furthermore, gross utilisation rates (purchased plus recycled CO_2) were used to estimate the oil produced from CO_2-EOR.

Figure 5: Schematic diagram and map of A) Continuous Gas Injection (CGI) and B) Water Alternating Gas (WAG) injection strategies



4 Gas injection is an important method in EOR industry. Gas injection is used to raise the reservoir pressure and reduce the oil viscosity for improving the sweep efficiency and, therefore, the recovery factor. Different gases (such as CH_4, CO_2 and nitrogen) can be injected. Among them CO_2 has proved to be the more efficient. The injection strategies depend on the injected gas, reservoir geology, and fluids characteristics. The goal of injection strategies is to avoid high residual oil in unswept or poorly swept rock volumes (Nuñez-Lopez et al., 2019).



Note: The cross sections depict rock layers with different permeabilities (reservoir heterogeneity), determining reservoir fluids' preferential flow directions and patterns. The maps on the right present a different perspective of the same fluid's behaviour. In CGI (A), there is a viscous fingering effect from CO_2 flowing through the more permeable layers, which can cause early gas breakthroughs in the oil production well. In WAG (B), water patch injection alternated with CO_2 aid in controlling the viscous fingering effect and improves sweep efficiency; nevertheless, gravity segregation and reservoir heterogeneity may also influence the preferential flow patterns. Source: Illustrated by the author.

2.3.4.2. CO_2 recycling

As the CO_2-EOR project matures, a fraction of the injected gas, oil, and other reservoir fluids return to the surface. The project might include a separation facility that allows for separating CO_2 to be reinjected into the reservoir. Separation technologies (e.g., fractionation, refrigeration, Ryan-Holmes and membrane) are expensive and energy-intensive. Another alternative is to reinject all the produced fluids without separation if the operators determined, based on laboratory tests, that the composition of the gases does not significantly affect the flooding efficiency.

To improve accounting accuracy, the mass of CO_2 injected must be considered as the sum of the purchased (or “fresh”) plus the recycled CO_2, which means the gross utilisation rate. If CO_2 is recycled without separation from other reservoir fluids, gas analysis is required to correct the data for the continuous increase of the impurities concentration in the injection stream (Nuñez-Lopez *et al.*, 2019; p.9). This consideration is also fundamental in the project’s reporting and monitoring programmes.

2.3.4.3. CO_2 storage

The fraction of CO_2 that remains trapped in the reservoir is another component that varies over time and with the injection strategy selected. Using the data provided by Nuñez-Lopez *et al.* (2019) from the Cranfield project, it was possible to estimate the percentage of CO_2 stored and recycled based on the mass of CO_2 injected and the CO_2 produced. It is an alternative to represent the dynamic carbon balance observed empirically and through reservoir simulation. Even though these values may vary from site to site, the methodology intends to highlight that the reservoir behaviour is not static, and this implication plays a critical role in the project’s carbon accounting.

Additionally, CO_2 recycling may present fugitive emissions in the surface facilities accounting for 1% of the mass recycled (Hares, 2020; p. 21). Another recommendation is to consider emissions from venting and flaring during injection operations and maintenance, a value that is also site-specific. Finally, a 0.5% reservoir leakage rate must be included (Cooney et al., 2015) to obtain a more accurate value of the CO_2 stored.

2.3.5. Marginal production effects

Marginal oil production refers to the oil production systems that are less productive or have higher production costs. It requires specialised techniques (e.g. EOR) or comes from unconventional resources (e.g. shale oil, oil sands, arctic). It also represents the incremental increase in production in an existing reservoir by applying new technologies or drilling additional wells. This marginal production is only profitable if oil prices are high enough to absorb the costs associated with the extra oil extraction.

According to the Clean Air Task Force (2019), it is estimated that oil produced from CO_2-EOR can displace 84% of the EOR-supplied crude oil in the global market. The marginal system with the highest operational costs would be the first to be substituted if additional oil is supplied from CO_2-EOR. In practice, Canadian oil sands represent the highest costs of production (Charpentier et al., 2009; BEIS, 2018) and present one of the highest carbon-intensive (130% of relative emissions) compared with conventional oil (100% of relative emissions) and CO_2-EOR (70% of relative emissions) (Suebsiri et al., 2006; p. 2486). The emissions related to the marginal oil production displaced are also accounted for. All the parameters considered for building the baseline and intervention scenarios are shown in Table 1.

Table 1: List of parameters used for the CCUS carbon accounting modelling

CCUS segment	Parameter	Unit	Reference
Carbon capture	Total emissions from CO_2 source	tCO_2/yr	Data from the CO_2 source
	Emissions captured per carbon capture unit	tCO_2/yr	Data from the capture process simulation
	Local electricity emissions factor*	MWh/tCO_2	Data from local databases
	Emissions factor for capture plant construction	$kgCO_2/kgCO_2$captured	Liu et al., 2020
Transport	Emissions factor for pipeline construction	tCO_2	Lacy Tamayo, 2014
	Emissions factor for pipeline closure	tCO_2	Lacy Tamayo, 2014
	Emissions factor for pipeline monitoring	tCO_2/yr	Lacy Tamayo, 2014
	Amount of electricity per ton of CO_2 transported by pipeline	MWh/tCO_2	McCoy, 2008
	Average fugitive emissions from pipeline	tCO_2/km-yr	Lamb et al., 2015
Marginal oil production	Well-to-tank emissions for Canadian tar sands	gCO_2/MJ	Charpentier et al., 2009
	Percentage of oil produced by CO_2 that displaces existing oil supply	%	CATF, 2019
Injection site	Site preparation (land clearance and site access)	tCO_2e	Lacy Tamayo, 2014

	Construction (well construction, compressors, water well, cement, well drilling)	tCO_2e	Lacy Tamayo, 2014
	Decommissioning (cement to seal the wells and cement pump)	tCO_2e	Lacy Tamayo, 2014
	Emissions from monitoring (atmospheric, surface and groundwater)	tCO_2e	Lacy Tamayo, 2014
CO_2 injection and recycling	Utilisation rates*	bbl/tCO_2	Nuñez-Lopez et al., 2019
	Emissions from gas compression*	tCO_2/bbl	Nuñez-Lopez et al., 2019
	Emissions from water injection*	tCO_2/bbl	Nuñez-Lopez et al., 2019
	Emissions from water disposal*	tCO_2/bbl	Nuñez-Lopez et al., 2019
	CO2 stored	%	Nuñez-Lopez et al., 2019
	Fugitive emissions from CO_2 recycling	%	Hares, 2020
	Flaring and venting rate from operations	%	Data from local database
CO_2 storage	CO_2 leakage rate from the reservoir	%	Cooney et al., 2015

Note: Parameters with an asterisk (*) indicate dynamic factors

2.4. Estimation of GHG emissions change

One or multiple intervention scenarios can be developed by "*playing*" with the elements that integrate the system and represent significant emission sources and sinks. These scenarios are modelled and compared with the baseline scenario, so it is possible to estimate the change in emissions caused by them both numerically (using equation 1) and graphically (as shown in Figure 1). The shape of the curves in the graph will vary according to the models.

Developing a simple one-at-a-time sensitivity analysis, including a plus and minus 10% of the central values, is recommended to identify the input parameters most critical to the overall change in emissions. This step in the data analysis helps identify individual activities or a segment of activities that are targets for improvements or require another strategy with a lower emissions impact. Section 4 provides a list of critical considerations for CCUS carbon accounting using the consequential time-series methodology developed by Mota-Nieto et al. (2023), while Section 5 summarises a case study where the methodology was applied to exemplify its application.

3. Key considerations for CCUS carbon accounting

CCUS involves additional operational activities for CO_2 management and disposal, which have their own carbon footprint. These activities include the capture of CO_2 from industrial processes, transportation to utilisation and storage sites, and injection into underground storage formations. Carbon emissions associated with the production and deployment of CCUS equipment and infrastructure and market-mediated consequences impact carbon emissions. Although CCUS could foster the consumption of low-carbon energy and products, it could also increase fossil fuel production in some regions, which could offset the benefits of CO_2 storage.

Industrial processes are significant sources of CO_2. Highly efficient carbon capture systems can be integrated into them for capturing emissions from a specific source or equipment. Therefore, introducing CCUS only partially reduces emissions. Nevertheless, it can still have significant benefits in reducing emissions and providing other benefits, such as enabling the production of low-carbon fuels and chemicals and improving overall environmental performance. While CCUS may not be a complete solution for reducing emissions from industrial processes, it can be a relevant component of a comprehensive strategy to address climate change and promote sustainable industrial practices (Mota-Nieto et al., 2023; Muslemani, 2023).

Carbon accounting is complex and subject to certain assumptions. When CO_2 is captured from industrial sources represents avoided emissions that would otherwise be released into the atmosphere. In contrast, carbon removals (also known as negative emissions) remove CO_2 from the atmosphere either by natural (biomass) or human-assisted processes (direct air capture). Regarding these scenarios in emissions calculations, avoided emissions are not subtracted from the total emissions accounting, while removals are. It is important to carefully identify and reflect the total emissions change associated with avoided emissions or removals in the accounting.

CO_2 represents a cost for field operators. As more CO_2 remains trapped in the reservoir, “fresher” CO_2 is required to maintain the injection rates and conditions for fluids' miscibility. Eventually, a mix of CO_2, other reservoir fluids and oil is produced in the project's lifetime. The mixture can be either subject to a gravity segregation process of separation or integrating a separation technology (e.g., fractionation, refrigeration, Ryan-Holmes or membrane). Here, separation technologies themselves may represent a significant source of CO_2 due to the intensive energy requirements and the local grid electricity (Nuñez-Lopez et al., 2019).

Accounting for recycled CO_2 introduces complexities that may lead to mass account errors or double-counting, so avoiding it is recommended. Moreover, accounting for CO_2 subsurface losses is advisable in line with the International Organization for Standardization (ISO 27916:2019). Field operations seek to reach maximum oil production. However, many challenges – economic, geologic, and resource access, among others – are site-specific and influence the EOR field development, which in turn determines the CO_2 injection strategy selected (Nuñez-Lopez et al., 2019). Other considerations are that CGI requires a secure and continuous supply of CO_2 and is more carbon-intensive regarding separation and recycling. In contrast, WAG requires water injection and disposal and has a lower carbon footprint (Mota-Nieto et al., 2023).

CCUS projects are dynamic systems strongly dependent on the reservoir geological conditions and operational strategies; thus, the carbon balance of the projects changes over time. At the beginning of the project, the carbon balance is negative (i.e., CO_2 is stored). As the reservoir reaches its maximum storage point, the balance between the CO_2 that remains permanently stored in the rocks and the emissions produced during the process becomes similar. Eventually, the projects become carbon positive, with no further environmental benefits generated. Identifying and estimating this transition point is paramount for the project´s design. Different operational strategies can help to extend the period over which the project is carbon negative; for instance, if more than one field is located in close proximity and are amenable to CO_2 injection, the CO_2 produced in the ‘anchor’ or principal field can be reinjected in a ‘tied-in’ or secondary field. Although this strategy requires additional infrastructure for the second field, the project's lifetime, where environmental benefits can be effective, would be extended (Mota-Nieto et al., 2023).

Demonstration of long-term storage requires monitoring activities outside of the target reservoirs and broadening the scope and boundaries of the study. The project's carbon footprint is not limited to CCUS activities but includes other elements, such as market-mediated effects. In this case, the additional oil produced by CO_2-EOR, which enters the market, displaces marginal production from other more expensive and often more carbon-intensive sources. It represents another indirect form of carbon emissions reduction.

The value of CO_2 storage may be supported by carbon credit programmes (e.g., the 45Q in the USA) since CCUS projects enhance oil production and reduce carbon emissions (Nuñez-Lopez et al., 2019).

Storing CO_2 in mature or depleted oil reservoirs also provides an additional source of revenue from selling credits resulting from CO_2 emissions reduction (Suebsiri et al., 2006). Nevertheless, it is crucial to consider the dynamic conditions of the projects and extend the boundary of analysis by adopting consequential carbon accounting methods.

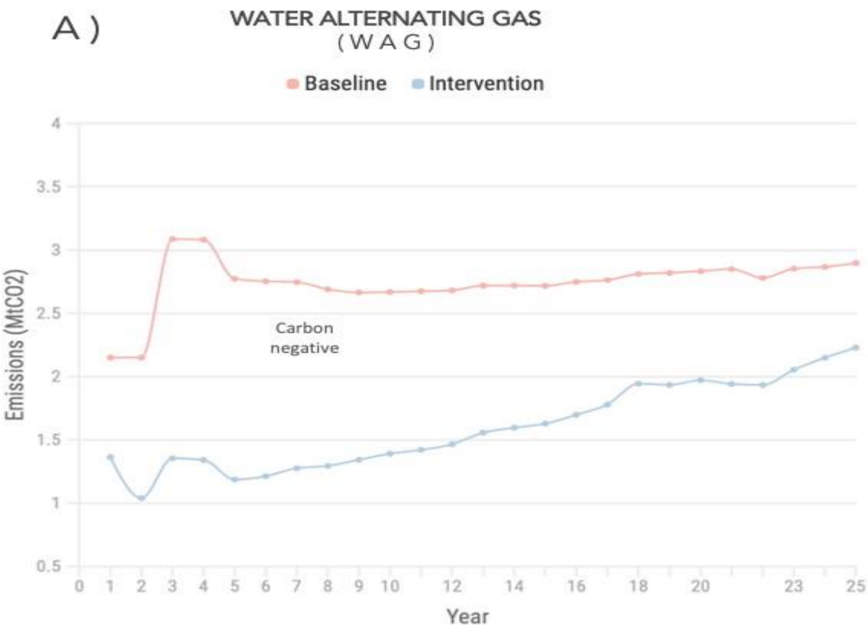
4. Case study: A CCUS project in Mexico

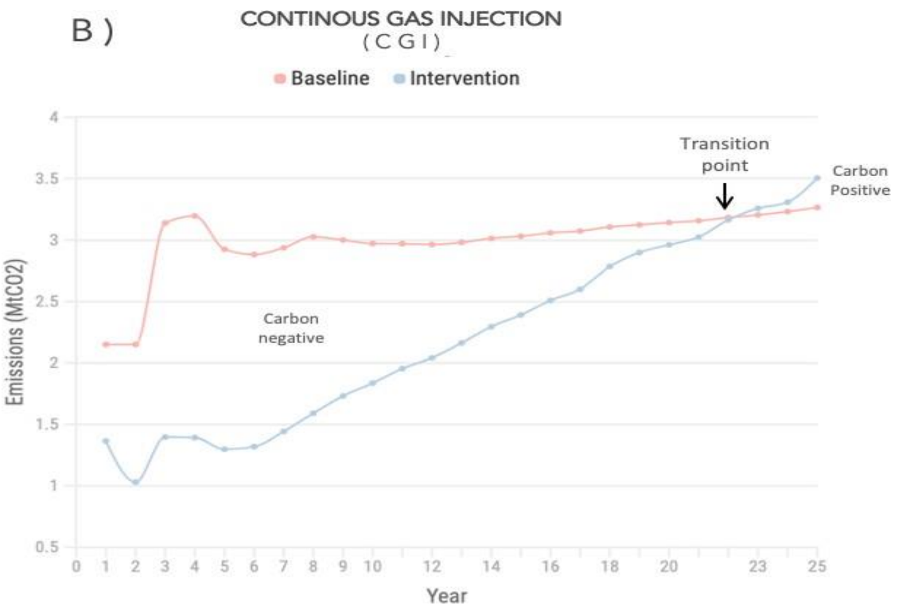
The methodology presented in this paper was applied to a hypothetical case study in the southeast region of Mexico. The assumptions here are that the CO_2 source is a new refinery, and CO_2 is used for EOR in two oil fields. In a post-combustion process, two carbon capture units using monoethanolamine (MEA) were applied to the refinery's two steam methane reformers. CO_2 is transported using a 100km pipeline from the refinery to the 'anchor' field and a second pipeline from the 'anchor' to the 'tied-in' field which is 21km long. Two scenarios were considered for modelling the changes in the energy mix according to the national commitments and projections: one is aligned with the current energy scenario, and the second with a sustainability scenario that meets the country's carbon emissions target by 2047, mainly through incorporating renewables and energy efficiency measures.

On a broad level, the results show that although CCUS introduction represents a reduction in the system-wide emissions, most refinery emissions are uncaptured, suggesting that CCUS should not be used as a long-term or definite option for emissions reduction. Instead, it would be considered a transition technology subject to multiple operational and market-mediated effects. Nevertheless, it is important to note that projects can produce different outcomes depending on the injection strategies adopted and other operational considerations, such as integrating a gas separation process.

More specifically, this case study explores the effects of the CO_2 injection strategies over the project's 25-year lifetime, indicating that, although WAG requires additional water injection and disposal, it is less carbon-intensive than CGI. Another key finding is that CGI reaches the transition point faster than WAG, as shown in Figures 6A and 6B. The findings confirm that the selection of the injection strategy is crucial in determining the project's environmental benefits and that it is not always presumed that CO_2 injection underground is a guarantee of emissions reduction.

Figure 6: WAG injection strategy (A) and CGI injection strategy (B)





Note: Graph A shows the WAG injection strategy, which remains carbon negative along the period modelled. Graph B shows the CGI injection strategy that transitions from carbon negative to carbon positive at year 22. Source: Modified from Mota-Nieto et al. (2023).

The elements or activities that represent the highest source of emissions were the unavoided emissions from the refinery despite considering highly efficient capture systems. Reservoir fluids compression and reinjection are energy intensive and, therefore, are high in emissions. If any fluid separation process is included, it will also represent a significant source of emissions due to the equipment's energy requirements. Although a decarbonised energy mix might sound reasonable to reduce the impact of energy-related emissions, the model indicates a difference of only around 2% between the two scenarios explored. For further analysis of this case study, the reader to refer to the methodology's application in Mota-Nieto et al. (2023)'s *'Carbon accounting methods for the system-wide evaluation of CCUS: A case study in Mexico´s Southeast Region'* study.

Conclusions

Carbon accounting is critical for monitoring and verifying the CCUS project's environmental performance. Moreover, the exercise helps in strategic project planning and decision-making. Nevertheless, selecting an appropriate carbon accounting method is fundamental as each has different objectives and approaches. The methodology introduced by Mota et al. (2023) is based on *consequential* carbon accounting, which uses time series data to expand the analysis of the changes in emissions beyond the actual CCUS value chain. It mainly includes market-mediated effects from marginal oil production, which provides valuable insights for oil and gas companies. The methodology also emphasises the dynamic behaviour of CCUS when coupled with CO_2-EOR since the injection strategy and field development are determinants for the projects to provide environmental benefits. More broadly, it helps identify the elements of the system which are more carbon-intensive and which eventually enhances transparency in the reporting of carbon emissions.

Although CCUS provides a partial solution for emissions reduction, it is also fundamental to consider that CCUS contributes to the Net Zero Emissions Scenario presented by the IEA. Furthermore, the oil industry is critical in achieving climate mitigation goals and making CCUS meet regulatory requirements (Ben Naceur, 2019). As such, considering carbon accounting methods as part of project design and implementation represents an opportunity to contribute to transforming the oil and gas sector and developing sound policies and regulations.

Economically, while CCUS entails additional capital costs, there is an additional value from the CO_2 stored in the form of associated carbon credits sold and revenues generated from oil production and other carbon-based products. Both CO_2 storage and profits from CO_2 utilisation represent an economic incentive for CCUS project development, but they depend on the regulations and market conditions, locally and globally. Regardless of the conditions, it is paramount that transparent carbon accounting analyses – ones which include broader market-mediated effects – are adopted to avoid unintended outcomes.

References

Aycaguer, A. C., Lev-On, M., & Winer, A. M. (2001). Reducing carbon dioxide emissions with enhanced oil recovery projects: A life cycle assessment approach. *Energy and Fuels*, *15*(2), 303–308. https://doi.org/10.1021/ef000258a

Azzolina, N. A., Peck, W. D., Hamling, J. A., Gorecki, C. D., Ayash, S. C., Doll, T. E., Nakles, D. V., & Melzer, L. S. (2016). How green is my oil? A detailed look at greenhouse gas accounting for CO2-enhanced oil recovery (CO2-EOR) sites. *International Journal of Greenhouse Gas Control*, *51*, 369–379. https://doi.org/10.1016/j.ijggc.2016.06.008

BEIS. (2018). *Greenhouse gas reporting: conversion factors 2018*. https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2018

Beloin-Saint-Pierre, D., Heijungs, R., & Blanc, I. (2014). The ESPA (Enhanced Structural Path Analysis) method: A solution to an implementation challenge for dynamic life cycle assessment studies. *International Journal of Life Cycle Assessment*, *19*(4), 861–871. https://doi.org/10.1007/s11367-014-0710-9

Brander, M. (2016). Transposing lessons between different forms of consequential greenhouse gas accounting: Lessons for consequential life cycle assessment, project-level accounting, and policy-level accounting. *Journal of Cleaner Production*, *112*, 4247–4256. https://doi.org/10.1016/j.jclepro.2015.05.101

Brander, M. (2017). Comparative analysis of attributional corporate greenhouse gas accounting, consequential life cycle assessment, and project/policy level accounting: A bioenergy case study. *Journal of Cleaner Production*, *167*, 1401–1414. https://doi.org/10.1016/j.jclepro.2017.02.097

Brander, M., & Ascui, F. (2016). The Attributional-Consequential Distinction and Its Applicability to Corporate Carbon Accounting. In *Corporate Carbon and Climate Accounting* (pp. 99–120). Springer, Cham. https://doi.org/https://doi.org/10.1007/978-3-319-27718-9_5

Brander, M., & Ascui, F. (2019). *Carbon Capture , Utilisation and Storage in China ' s Iron / Steel Sector*. *July*.

Brander, M., Burritt, R. L., & Christ, K. L. (2019). Coupling attributional and consequential life cycle assessment: A matter of social responsibility. *Journal of Cleaner Production*, *215*, 514–521. https://doi.org/10.1016/j.jclepro.2019.01.066

Briones-Hidrovo, A., Copa Rey, J. R., Cláudia Dias, A., Tarelho, L. A. C., & Beauchet, S. (2022). Assessing a bio-energy system with carbon capture and storage (BECCS) through dynamic life cycle assessment and land-water-energy nexus. *Energy Conversion and Management*, *268*(April), 1–4. https://doi.org/10.1016/j.enconman.2022.116014

BSI. (2019). *ISO 14064-3 : 2019 BSI Standards Publication Greenhouse gases*.

CATF. (2019). *CO_2 EOR Yields a 37% Reduction in CO_2 Emitted Per Barrel of Oil Produced* (pp. 1–2).

Charpentier, A. D., Bergerson, J. A., & MacLean, H. L. (2009). Understanding the Canadian oil sands industry's greenhouse gas emissions. *Environmental Research Letters*, *4*(1). https://doi.org/10.1088/1748-9326/4/1/014005

Climeworks. (2023). *In line with climate science, Climeworks calls for a clear distinction between emission reductions and carbon removals* (Issue April).

Collinge, W. O., Landis, A. E., Jones, A. K., Schaefer, L. A., & Bilec, M. M. (2013). Dynamic life cycle assessment: Framework and application to an institutional building. *International Journal of Life Cycle Assessment*, *18*(3), 538–552. https://doi.org/10.1007/s11367-012-0528-2

Cooney, G., Littlefield, J., Marriott, J., & Skone, T. J. (2015). Evaluating the Climate Benefits of CO2-Enhanced Oil Recovery Using Life Cycle Analysis. *Environmental Science and Technology*, *49*(12), 7491–7500. https://doi.org/10.1021/acs.est.5b00700

DOE/NETL. (2010). An Assessment of Gate-to-Gate Environmental Life Cycle Performance of Water-Alternating-Gas CO2-Enhanced Oil Recovery in the Permian Basin. *Doe/Netl-2010/1433*, *64*(1), 61–72. https://doi.org/10.1080/10962247.2013.832713

Ekvall, T., & Weidema, B. P. (2004). System boundaries and input data in consequential life cycle inventory analysis. *International Journal of Life Cycle Assessment*, *9*(3), 161–171. https://doi.org/10.1007/BF02994190

El-Saleh, M. (1996). Analogy procedure for the evaluation of CO2 flooding potential for reservoirs in the Permian and Delaware basins. *Proceedings - SPE Symposium on Improved Oil Recovery*, *1*, 485–500. https://doi.org/10.2118/35391-ms

Hares, R. (2020). *Feasibility of CCUS to CO2-EOR in Alberta*. *21*(1), 1–9. http://hdl.handle.net/1880/112625%0Ahttps://www.golder.com/insights/block-caving-a-viable-alternative/

Heidug, W., Lipponen, J., McCoy, S., & Benoit, P. (2015). *Storing CO2 through enhanced oil recovery*.

Henson, R., Todd, A., & Corbett, P. (2002). Geologically Based Screening Criteria for Improved Oil Recovery Projects. *Proceedings - SPE Symposium on Improved Oil Recovery*, 260–275.

Hill, B., Hovorka, S., & Melzer, S. (2013). Geologic carbon storage through enhanced oil recovery. *Energy Procedia*, *37*, 6808–6830. https://doi.org/10.1016/j.egypro.2013.06.614

Hosseininoosheri, P., Hosseini, S. A., & Lake, L. W. (2018). A Comparative Study of CO 2 -flood Displacement Efficiency for Different CO 2 Injection Strategies : Permian Basin vs . U . S . Gulf Coast. *GHGT-14*, *October*.

Hovorka S., T. S. (2010). *EOR as Sequestration — Geoscience Perspective White Paper for Symposium on Role of EOR in Accelerating Deployment of CCS. Bureau of Economic Geology Jackson School of Geosciences, The University of Texas at Austin* (Vol. 2010).

Hunt, R. G., & Franklin, W. E. (1996). *LCA - How it came about - Personal reflections on the origin and the development of LCA in the USA*. *1*(1), 1–7. https://doi.org/10.1016/S0040-4039(01)81937-7

IEA. (2017). *Energy Technology Perspectives 2017 - Catalysing Energy Technology Transformations*. https://doi.org/10.1787/energy_tech-2017-en

IEA. (2020). Energy Technology Perspectives 2020: Special Report on Carbon Capture Utilisation and Storage_CCUS in clean energy transitions. *Energy Technology Perspectives 2020*, 169. https://doi.org/10.1787/ab43a9a5-en

IPCC. (2005a). *Carbon dioxide capture and storage: special report* (L. M. Bert Metz, Ogunlade Davidson, Heleen de Coninck, Manuela Loos (ed.)).

IPCC. (2005b). Cost and economic potential. In *IPCC Special Report on Carbon Dioxide Capture and Storage.* (pp. 341–362). IPCC. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Cost+and+economic+potential#8

IPCC. (2023). IPCC Synthesis report - Summary for Policymakers. In *AR6 Synthesis Report (SYR)*. https://www.ipcc.ch/report/sixth-assessment-report-cycle/

ISO. (2019). *14064-2: 2019 Greenhouse gases—Part 2: Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements, 2019*.

ISO. (2020). ISO 14044 - Life cycle assessment - Requirements and guidelines. In *ISO 14044:2006*. BSI STANDARDS PUBLICATION.

Jaramillo, P., Griffin, W. M., & Mccoy, S. T. (2009). Life cycle inventory of CO 2 in an enhanced oil recovery system. *Environmental Science and Technology*, *43*(21), 8027–8032. https://doi.org/10.1021/es902006h

Jensen, A. A., Hoffman, L., Moller, B. T., Schmidt, A., Chirstiansen, K., & Ekkington, J. (1997). *A guide to approaches , experiences*. https://www.researchgate.net/publication/299446257%0A

Khoo, H. H., & Tan, R. B. H. (2006). Life cycle investigation of CO2 recovery and sequestration. *Environmental Science and Technology*, *40*(12), 4016–4024. https://doi.org/10.1021/es051882a

Lacy Tamayo, R. (2014). *Análisis de ciclo de vida de la captura, uso y almacenamiento del bióxido de carbono de una Central de Generación Eléctrica para la Recuperación Mejorada de Petróleo*. Universidad Autónoma Metropolitana.

Lamb, B. K., Edburg, S. L., Ferrara, T. W., Howard, T., Harrison, M. R., Kolb, C. E., Townsend-Small, A., Dyck, W., Possolo, A., & Whetstone, J. R. (2015). Direct measurements show decreasing methane emissions from natural gas local distribution systems in the United States. *Environmental Science and Technology*, *49*(8), 5161–5169. https://doi.org/10.1021/es505116p

Levasseur, A., Lesage, P., Margni, M., Deschěnes, L., & Samson, R. (2010). Considering time in LCA: Dynamic LCA and its application to global warming impact assessments. *Environmental Science and Technology*, *44*(8), 3169–3174. https://doi.org/10.1021/es9030003

Liu, C. M., Sandhu, N. K., McCoy, S. T., & Bergerson, J. A. (2020). A life cycle assessment of greenhouse gas emissions from direct air capture and Fischer-Tropsch fuel production. *Sustainable Energy and Fuels*, *4*(6), 3129–3142. https://doi.org/10.1039/c9se00479c

McCoy, S. T. (2008). The Economics of CO2 Transport by Pipeline and Storage in Saline Aquifers and Oil Reservoirs. In *Work*. Carnergie Mellon University.

Mota-Nieto, J., Brander, M., & Díaz-Herrera, P. R. (2023). *Carbon accounting methods for the system-wide evaluation of Carbon Capture, Utilisation and Storage: a case study in Mexico's Southeast Region (working-paper)*.

Müller, L. J., Kätelhön, A., Bachmann, M., Zimmermann, A., Sternberg, A., & Bardow, A. (2020). A Guideline for Life Cycle Assessment of Carbon Capture and Utilization. *Frontiers in Energy Research*, *8*(February), 1–20. https://doi.org/10.3389/fenrg.2020.00015

Muslemani, H. (2023). *Stainless Green: Considerations for making green steel using carbon capture and storage (CCS) and Hydrogen (H2) solutions*. OIES Paper CM03, Oxford Institute for Energy Studies, Oxford, UK. May 2023.

Núñez-López, V., Gil-Egui, R., & Hosseini, S. A. (2019). Environmental and operational performance of CO 2 -EOR as a CCUS technology: A cranfield example with dynamic LCA considerations. *Energies*, *12*(3). https://doi.org/10.3390/en12020448

Nuñez-Lopez, V., Gil-Egui, R., Hosseininoosheri, P., Hovorka, S. D., & Lake, L. W. (2019). *Carbon Life Cycle Analysis of CO_2-EOR for Net Carbon Negative Oil (NCNO) Classification (Final Report)*. *412*. https://www.osti.gov/servlets/purl/1525864%0Ahttp://www.osti.gov/servlets/purl/1525864/

Núñez-López, V., Holtz, M. H., Wood, D. J., Ambrose, W. A., & Hovorka, S. D. (2008). Quick-look assessments to identify optimal CO2 EOR storage sites. *Environmental Geology*, *54*(8), 1695–1706. https://doi.org/10.1007/s00254-007-0944-y

Pedersen Weidema, B. (1993). Market aspects in product life cycle inventory methodology. *Journal of Cleaner Production*, *1*(3–4), 161–166. https://doi.org/10.1016/0959-6526(93)90007-X

Plevin, R. J., Delucchi, M. A., & Creutzig, F. (2014). Using Attributional Life Cycle Assessment to Estimate Climate-Change Mitigation Benefits Misleads Policy Makers. *Journal of Industrial Ecology*, *18*(1), 73–83. https://doi.org/10.1111/jiec.12074

Pohl, J., Hilty, L. M., & Finkbeiner, M. (2019). How LCA contributes to the environmental assessment of higher order effects of ICT application: A review of different approaches. *Journal of Cleaner Production*, *v. 219*, 698–712. https://doi.org/10.1016/j.jclepro.2019.02.018

Ritchie, H., Roser, M., & Rosado, P. (2020). CO_2 and Greenhouse Gas Emissions. Published onlie at OurWorkdInData.org. Retrieved from: https://ourworldindate.org/co2-and-greenhouse-gas-emissions [Online Resource]

Santos, R., Sgouridis, S., & Alhajaj, A. (2021). Potential of CO2-enhanced oil recovery coupled with carbon capture and storage in mitigating greenhouse gas emissions in the UAE. *International Journal of Greenhouse Gas Control*, *111*(August), 103485. https://doi.org/10.1016/j.ijggc.2021.103485

Suebsiri, J., Wilsan, M., & Tontiwachwuthikul, P. (2006). Life-cycle analysis of CO2 EOR on EOR and geological storage through economic optimization and sensitivity analysis using the weyburn unit as a case study. *Industrial and Engineering Chemistry Research*, *45*(8), 2483–2488. https://doi.org/10.1021/ie050909w

Thonemann, N., & Pizzol, M. (2019). Consequential life cycle assessment of carbon capture and utilization technologies within the chemical industry. *Energy and Environmental Science*, *12*(7), 2253–2263. https://doi.org/10.1039/c9ee00914k

Tobias, T., Perrella, J. A., de Toledo, J. M., Vilanova, M. R. N., Oliveira, O. J., & Ávila, I. (2021). Life cycle assessment of carbon capture and storage/utilization: From current state to future research directions and opportunities. *International Journal of Greenhouse Gas Control*, *108*(December 2020). https://doi.org/10.1016/j.ijggc.2021.103309

WRI. (2014). Policy and Action Standard | Greenhouse Gas Protocol. *GHG Protocol*. http://www.ghgprotocol.org/policy-and-action-standard%0Ahttp://ghgprotocol.org/policy-and-action-standard