NET GREENHOUSE GAS IMPACT OF STORING CO_2 THROUGH ENHANCED OIL RECOVERY (EOR)

An analysis of on-site and downstream GHG emissions from CO_2-EOR crude oil production in Western Canada

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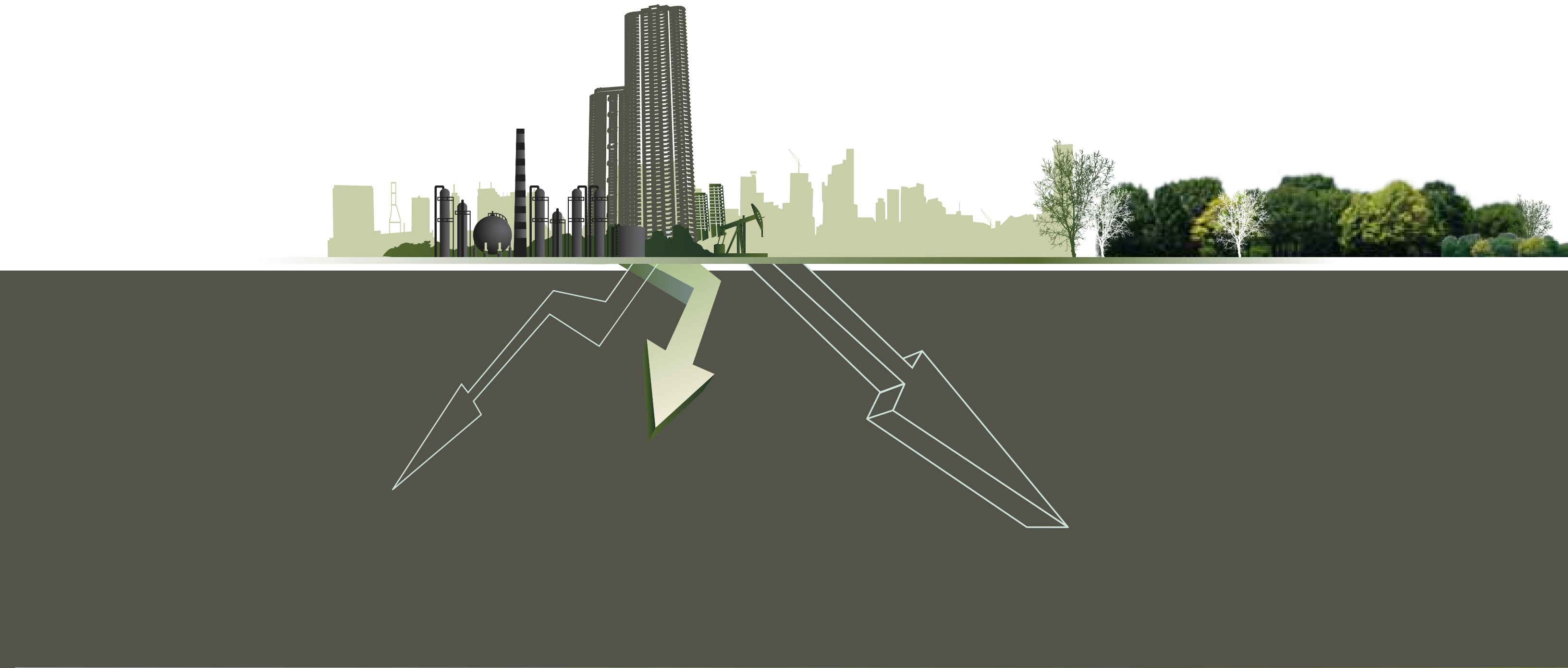

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1. INTRODUCTION

1.1 CONTEXT AND OBJECTIVES

Canada's Integrated CO_2 Network (ICO_2N[1]), an organization focused on developing carbon capture and storage (CCS) in Canada, is interested in better understanding the greenhouse gas (GHG) impact of storing CO_2 for the purposes of enhanced oil recovery (EOR).

Stakeholders, such as environmental groups, government agencies and EOR operating companies, have varying viewpoints on how the GHG impact of CO_2-EOR should be viewed. While some simply look at the CO_2 that is stored underground, others may think of it in terms of the stored CO_2 as well as the downstream impacts of the incremental oil produced. This report is not meant to single out any one viewpoint as legitimate, but rather assess the value judgments imbedded in each and attach quantitative, fact-based data to the discussion.

This analysis uses actual operational data from a single EOR site in Western Canada. This site represents a case study that is then varied with sensitivity analysis that includes theoretical design data from a different Western Canadian site to be more representative of the range of an EOR site. EOR sites can vary considerably in both their operational parameters and the reservoir characteristics that are unique to the local subsurface condition. This study is intended to quantify the GHG performance of EOR as viewed through various perspectives. It is the first of its kind in that it presents numbers that can be attributed to each differing viewpoint for contrast and comparison.

The specific objectives of this analysis are:

1. To quantify the GHG emissions associated with CO_2-EOR using actual operational data, considering various perspectives of CO_2-EOR by stakeholders.
2. To support an informed discussion and dialogue around the GHG impact of CO_2-EOR.

As there can be considerable variability between site characteristics of CO_2-EOR operations, the report discusses the impacts on GHG performance based on a range of site characteristics. Multiple site characteristics were considered, but only those showing to have significant impact on the GHG performance are analyzed in greater depth. The ranges of site characteristics are based on both existing operating projects such as the one presented in detail in Section 2 as well as theoretical data for a future project presented in Section 3.3.

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[1] http://www.ico2n.com

1.2 DEFINING ENHANCED OIL RECOVERY

Enhanced Oil Recovery – or CO_2-EOR – is the process of increasing the amount of oil that can be recovered by injecting CO_2 into an existing depleted oil reservoir to increase pressure and reduce the viscosity of the oil. In a suitable reservoir, using CO_2 for EOR can lead to recovery of another 5% to 15% of incremental oil.

Enhanced Oil Recovery

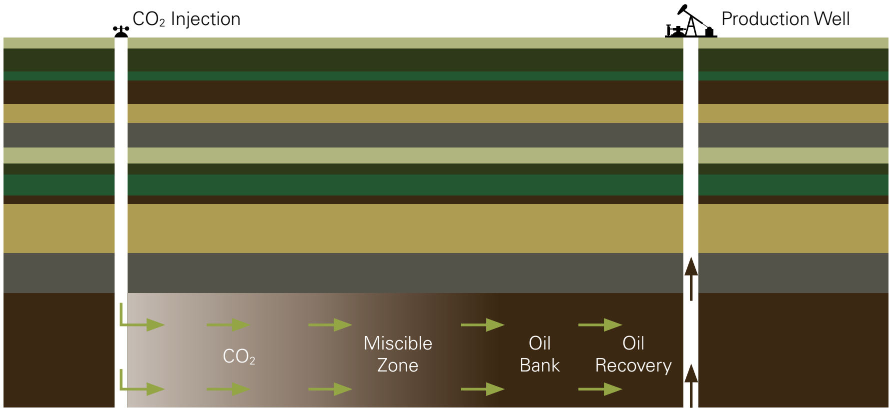

Figure 1. CO2-EOR site diagram

OVERVIEW OF SCENARIOS

This analysis considers the GHG impact of five scenarios that represent the various perspectives stakeholders may hold about how the net GHG impacts of CO_2-EOR are viewed.

It is important to note that the focus of this study is to demonstrate what happens with the CO_2 after it arrives on site and what the potential "downstream" impacts will be, irrespective of the source of CO_2. As such, the "upstream" activities including capture and transport are not included in the analysis. This exclusion was made assuming that the CO_2 is either to be permanently stored (reference or "base" case) or incorporated into an EOR operation, and thus the upstream source of CO_2 would be the same regardless of its source. It is important to note that various analyses have been completed on the GHG impact of capturing emissions that demonstrate variability in the GHG emissions associated with capture depending on process (pre-combustion, post-combustion, oxyfuel combustion) and source of emissions (e.g. coal power plants, fertilizer plants, oilsands upgraders etc.).

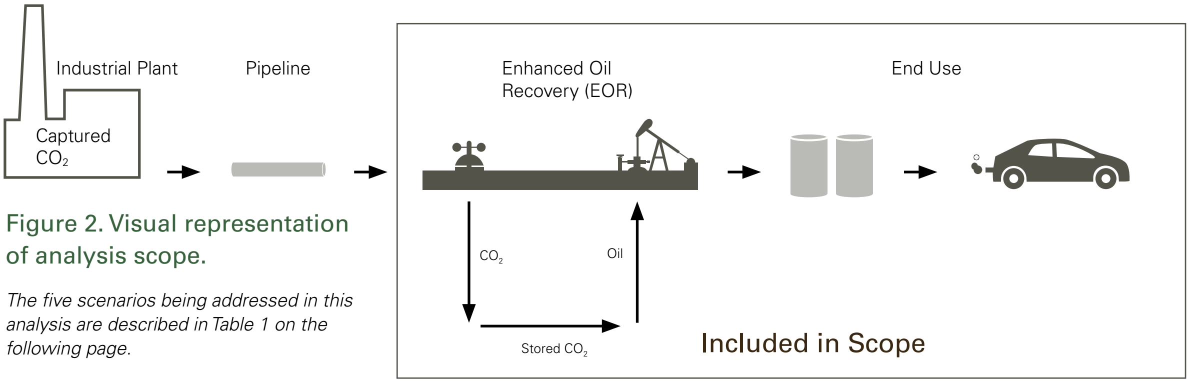

Figure 2. Visual representation of analysis scope.

The five scenarios being addressed in this analysis are described in Table 1 on the following page.

Table 1. Overview of scenario and question being addressed (perspective)

SCENARIO	DESCRIPTION	QUESTION BEING ADDRESSED
S1: Geologic Storage (CCS)	Net[2] CO_2 storage through geologic sequestration: On-site operations[3] of permanent CO_2 injection into a saline aquifer.	How much CO_2 is stored in a scheme where CO_2 is stored in deep geologic formations and not used for any other purpose?
S2: EOR On-Site	Net CO_2 storage through EOR: On-site operations[4] of CO_2 injection into a depleted oil reservoir.	What is the net CO_2 stored in an EOR operation including the impact of recycling CO_2 for EOR and other onsite activities?
S3: EOR system-wide emissions	Net CO_2 emissions associated with EOR on-site activities[5] (S2) as well as downstream emissions (production, transport, refinement, combustion) associated with the barrel of oil produced.	What are GHG emissions of an EOR project including the downstream impacts of the produced barrels of oil?
S4: EOR system-wide emissions with offsetting of barrel of oilsands	Assessing the lifetime emissions of EOR (S3) with the added assumption that oil produced from EOR will offset the production and use of a barrel of oil from the oilsands (50% mineable, 50% in-situ).	What is the net GHG impact of a barrel of oil produced through EOR in the context of global oil supply? Specifically what is the net impact of a barrel of EOR oil replacing a barrel of oilsands in the North American market?
S5: EOR system-wide emissions with offsetting of average barrel	Assessing the lifetime emissions of EOR (S3) with the added assumption that oil produced from EOR will offset the production and use of an average barrel that is processed in the United States.	What is the net GHG impact of a barrel of oil produced through EOR in the context of global oil supply? Specifically, what is the net impact of a barrel of EOR oil replacing another 'average' barrel in the North American market?[6]

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[2] "Net" refers to the total GHG impact to the atmosphere.

[3] On-site operations for geologic sequestration includes the small amount of energy use for monitoring, measurement, and verification (MMV) and fugitives at site.

[4] On-site operations for EOR includes injecting, producing, recycling, and processing the CO_2 and emulsion along with flaring, venting and other onsite emission sources associate with oil production.

[5] "On-site activities" refers to field operations.

[6] "Development of Baseline Data and Analysis of Life Cycle Greenhouse Gas Emissions of Petroleum-Based Fuels", National Energy Technology Laboratory, November 26 2008.

1.3.1 Activities included in scenarios

The following figure provides the basic activities for which GHG emissions are quantified for each scenario. Emissions stored underground are considered permanently removed from the atmosphere and therefore are negative.

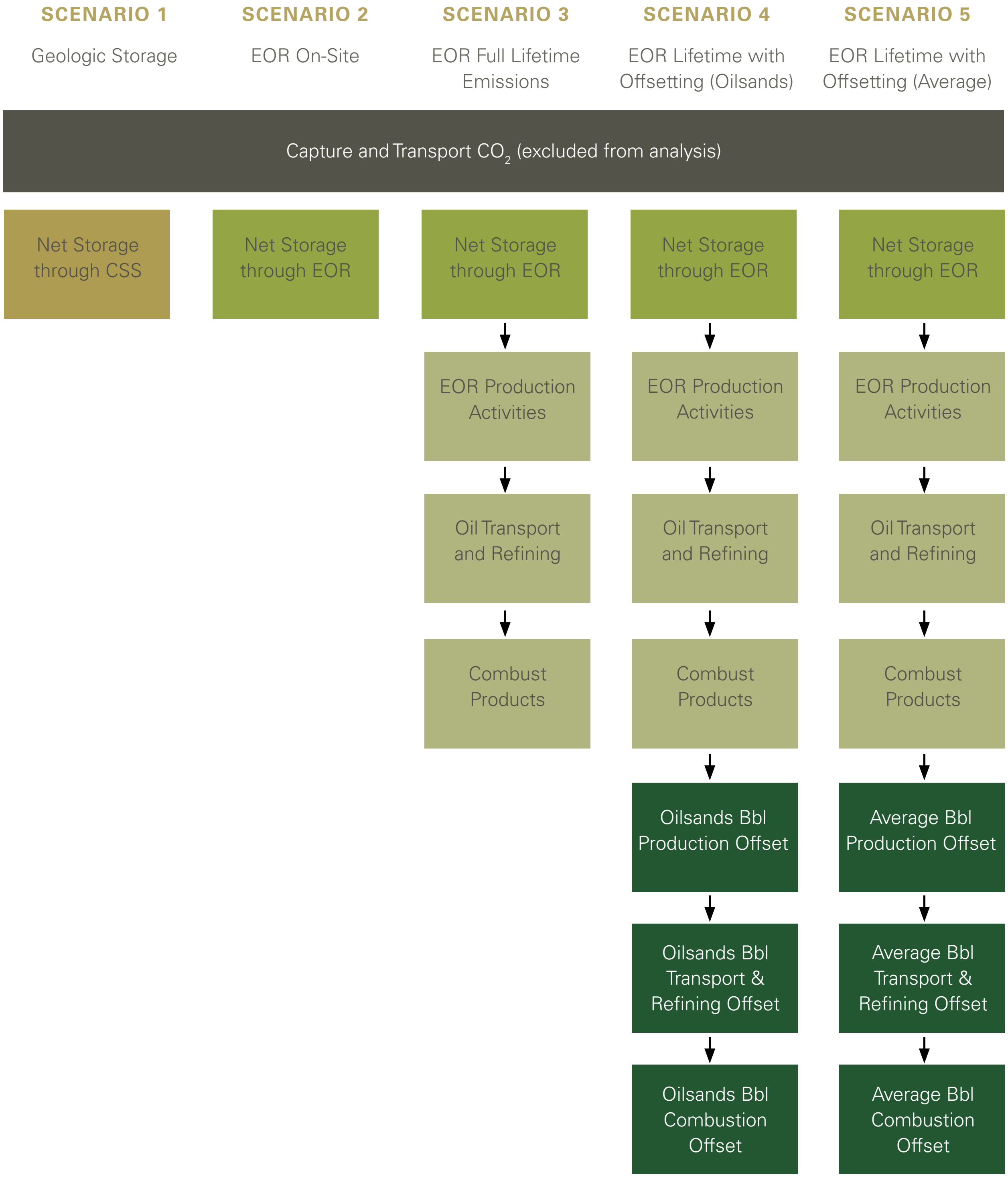

Figure 3. Simplified activity map for GHG scenarios

The scenarios are presented such that they build upon each other:

- As a first step there is straight geological storage. This has been included as a baseline.
- As a second step there is analysis of the stored CO_2 at an EOR site as well as the onsite emissions.
- As a third step the downstream emissions associated with the oil produced through EOR are included
- As a fourth step the oil produced through EOR is assumed to displace other oil in the marketplace and the GHG savings of displacing that oil are included. This analysis was done for both the average barrel in the North American market and a barrel of oilsands crude.

These scenarios can be considered the range of perspectives on how to view the GHG impact of storing CO_2 through the process of EOR. Detailed Activity Maps can be found in the Appendix (Section 5) and also in (Section 1.3).

1.3.2 Limitations of scenarios

All of the scenarios described above and covered in this report have limitations when looked at in isolation or as the absolute viewpoint. Table 2 below describes some of the limitations associated with each of the five viewpoints. This report does not attempt to make a value judgment on one absolute way to view the GHG reduction impact of storing CO_2 through EOR.

Table 2. Limitations of scenario perspectives

SYSTEM PERSPECTIVE	LIMITATIONS OF THIS PERSPECTIVE
S1: Geologic Storage (CCS)	This is included as a reference case to show the alternative storage form to EOR, which is geologic storage in deep saline formations with no oil production.
S2: EOR On-Site	No consideration of GHG implication associated with the incremental oil produced in an EOR scheme.
S3: EOR system-wide emissions	Assumes that oil produced through EOR would have no impact on when future volumes of other types of crude will enter the market (i.e. assumes it will not displace any crude in the future).
S4: EOR system-wide emissions with offsetting of an Oilsands Barrel	These scenarios are likely more relevant in the short-term than long-term as a result of global oil supply and demand market characteristics. Short term: oil demand is relatively inelastic and not affected by small supply variations. With demand remaining constant it is more likely a barrel of EOR oil will displace supply from another region. Long-term: oil demand is more elastic and it is more likely that a barrel of EOR oil will simply add to overall consumption and not fully displace (1:1) another barrel of crude in the market. Overall, if a barrel is offset, it is difficult to conclude which barrel it will be, and thus what associated life cycle GHG savings would be.
S5: EOR system-wide emissions with offsetting of Average Barrel	

2. EXISTING ALBERTA EOR SITE ANALYSIS

2.1 OVERALL METHODOLOGY

The analysis for this report was undertaken in three steps in order to properly evaluate the net GHG impact of CO_2-EOR from various viewpoints. The scenarios that were evaluated are fully described in Section 1.3 but it is important to also explain how each piece of analysis was undertaken and is presented. Table 3 below summarizes the three analytical steps:

Table 3. Summary of Analysis

	I. NET CO_2 STORAGE (Section 2.2 below)	**II. PER BARREL EMISSIONS** (Section 2.3)	**III. GHG IMPACT OF ALL SCENARIOS** (Section 2.4)
Scenarios evaluated	S1 and S2	No scenarios are evaluated; this is an interim step in analysis.	S1, S2, S3, S4, S5.
Analysis description	Compares the emissions associated with operating a CO_2-EOR project to those of a pure geologic storage (CCS) operation.	Compares the emissions of one barrel of each of three types of crude oil. The per barrel emissions are used to quantify the impact of displacement in the last step of analysis.	This is the cumulative analysis that presents the various viewpoints one may take when evaluating CO_2 storage through EOR. All numbers are presented in terms of the downstream impacts of one tonne of CO_2 being brought to an EOR site.
Units	Net impact (TCO_2e) per TCO_2 delivered to a storage site.	Net impact (TCO_2e) per barrel of oil produced, processed and consumed.	Net impact (TCO_2e) per tonne of CO_2 brought to a CO_2-EOR site.

Note that while high-level methodology is described for each step of analysis in the following sections, all data and sources can be found in Appendix 5.2.

Certain metrics are typically collected to evaluate the performance and operational characteristics. The site characteristics that are often most relevant to GHG performance are the "Performance Ratio" and "Recycle Ratio", which are defined below:

Table 4. Site characteristics definitions

PERFORMANCE RATIO (units: barrels of oil produced/Tonnes CO_2 injected)	The ratio of produced oil to the total volume of CO_2 injected over a given timeframe. The total volume of CO_2 required to produce oil can change based on the reservoir characteristics, injection pressures and several other factors. This is also the total volume of CO_2 injected that can change in composition between recycled and new CO_2 as described below.
RECYCLE RATIO (units: Tonnes recycled CO_2 injected/ Total volume of CO_2 injected)	The ratio between the volume of new CO_2 brought to site and the volume of CO_2 that is recycled at any given time in the operational lifespan. The recycle ratio tends to change over the life of a project as initially the total injected volume of CO_2 is new CO_2 delivered from the capture facility, yet as greater volume of CO_2 begins to come back up the production wells with the oil and then recycled, the recycled CO_2 begins to displace the new CO_2 and the ratio increases.

These metrics can range based on a number of factors such as field operating pressure, reservoir characteristics and the maturity of a project. The data in Section 2 is specific to one mature CO_2-EOR field in Alberta and is likely not representative of all CO_2-EOR projects at any given time, but benefits from being actual operation data. The analysis in Section 3 incorporates sensitivities for key parameters, including design data from other Western Canadian CO_2-EOR project. Both sites are described further in table 5 below.

Table 5. EOR site descriptions

OPERATIONAL ALBERTA CO_2-EOR PROJECT	THEORETICAL ALBERTA CO_2-EOR PROJECT
Mature field operating as a CO_2 EOR project since 1984.	Proposed CO_2-EOR project.
Actual operational data from all site emission sources was considered for the analysis.	Theoretical data based on expected performance was used to represent potential emission levels at the site.
Operated at varying efficiencies for a number of years in order to maintain oil production.	Expected to operate field at lower pressure differential to decrease compression power requirements.

2.2 NET CO_2 STORAGE: GEOLOGIC STORAGE (S1) VS. EOR (S2)

OBJECTIVE OF ANALYSIS

By comparing the emissions associated with operating a CO_2-EOR project to those of a pure geologic storage (CCS) operation we can see the specific on-site difference in CO_2 stored and released at site.

METHODOLOGY & ASSUMPTIONS

This analysis excludes any upstream or downstream emissions that result from either scenario. These values were derived from actual operational data from a Western Canadian EOR and geologic storage project. The comparison is presented in terms of an equivalent volume of CO_2 brought to site.

The site operations for geologic sequestration (S1) include all GHG emissions associated with the small amount of energy use for monitoring, measurement, and verification (MMV) and fugitives at site.

The site operations for EOR (S2) include all GHG emissions (represented as dark green in Figure 4 below) associated with injecting, producing, recycling, and processing the CO_2 and emulsion along with flaring, venting and other onsite emission sources related to oil production.

RESULTS

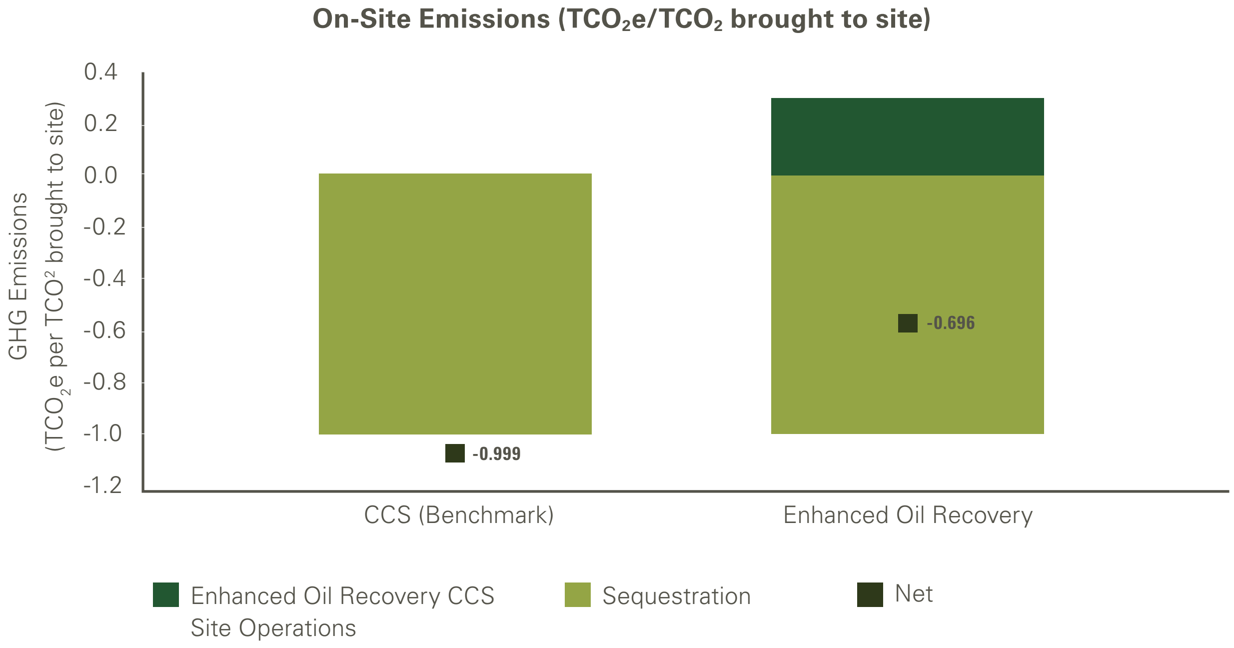

Figure 4. Geological storage vs. CO_2-EOR

In the geologic storage scenario, 0.999 tonne (T) CO_2e of every 1 TCO_2e brought to site is stored in the reservoir. The CO_2-EOR scenario has a net (i.e. due to on-site GHG emissions) on-site storage of 0.696 TCO_2e per 1 TCO_2e brought to site.

2.3 PER BARREL GHG EMISSIONS OF VARIOUS CRUDE SOURCES

OBJECTIVE OF ANALYSIS

By comparing the GHG emissions associated with producing, processing, refining and end use of a barrel of crude oil produced from the CO_2- EOR operation alongside a barrel produced from oilsands and an average conventionally produced barrel it is possible to see their relative GHG intensity outside of any CO_2 storage activities.

METHODOLOGY AND ASSUMPTIONS

CO_2-EOR operational data was used to calculate the onsite energy intensity of producing a barrel of CO_2-EOR crude. The volume of barrels produced is based on the actual production performance of the EOR site used in this analysis (1.1 bbl. of crude oil per T CO_2 injected).

Publicly available data was used to determine the GHG intensity of the other two types of crude production – oilsands[7] crude[8] and average crude[9].

Assumptions for refining and end use are that all crudes will be transported and refined at PADD II (US Midwest) where they will then be sent to market. End use is assumed to be the same for all sources of crude.

The storage of CO_2 is *not* applied to the EOR barrel of oil in Figure 5 to inform those interested in just the comparison of GHG/energy intensity performance of the competing sources. The number represented below is a gross number (i.e. not the net GHG emissions when considering CO_2 stored during the production of the oil). The net impact is provided in Figure 6 on page 12.

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[7] GHG intensities were computed assuming 50% mining and 50% in situ as reflected in: ST98: Alberta's Energy Reserves and Supply/Demand Outlook — Crude Bitumen, Energy Resources Conservation Board, available at http://www.ercb.ca/docs/products/STs/st98-2012_CrudeBitumen.xls

[8] Greenhouse gas intensity was calculated based on data presented in: Adam Brandt, Upstream greenhouse gas (GHG) emissions from Canadian oilsands as a feedstock for European refineries, Executive summary (Stanford, CA: Department of Energy Resources, Stanford University, 2011), 42, https://circabc.europa.eu/d/d/workspace/SpacesStore/06a92b8d-08ca-43a6-bd22-9fb61317826f/Brandt_Oil_Sands_Post_Peer_Review_Final.pdf

[9] This report presents data from several life-cycle studies including three from which the data were selected for calculations:

a) (S&T)2. GHGenius, model version 3.18. Technical report, (S&T) 2 consultants, for Natural Resources Canada, 2010.

b) Rosenfeld, J.; Pont, J.; Law, K.; Hirshfeld, D.; Kolb, J. Comparison of North American and imported crude oil life cycle GHG emissions. Technical report, TIAX LLC. and MathPro Inc. for Alberta Energy Research Institute, 2009.

c) Keesom, W.; Unnasch, S.; Moretta, J. Life cycle assessment comparison of North American and imported crudes. Technical report, Jacobs Consultancy and Life Cycle Associates for Alberta EnergyResources Institute, 2009.

RESULTS

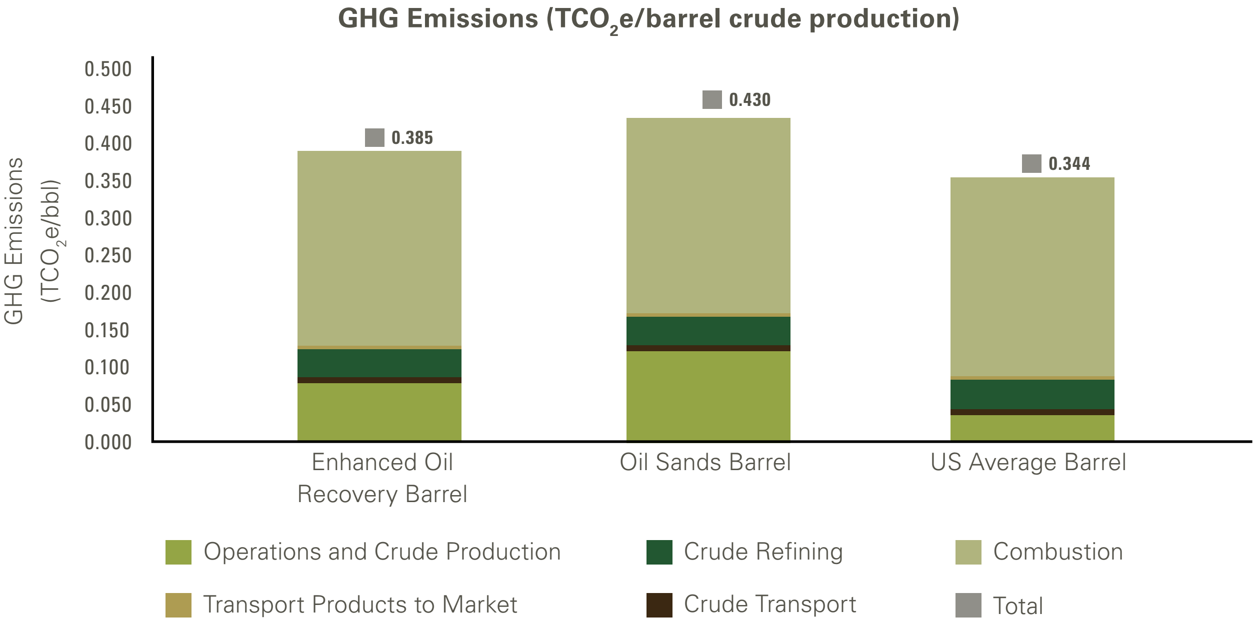

Figure 5. GHG Emissions per Crude Oil Source

The per-barrel emission intensity for crude produced from this CO_2-EOR site falls between those from the oilsands and the average barrel. The main difference between the various crude oils is a result of the differences in energy intensity of extraction methods which is represented by the operations and crude production category shown in Figure 5.

2.4 ASSESSING GHG IMPACT OF CO_2 STORAGE THROUGH EOR FROM VARIOUS VIEWPOINTS

OBJECTIVE OF ANALYSIS

By bringing together the range of different viewpoints represented by the scenarios we are able to assess the GHG impacts of CO_2-EOR through various perspectives.

METHODOLOGY AND ASSUMPTIONS

Scenario 1 and 2 use the data from the analysis of net CO_2 storage and represent the viewpoint that does not consider any of the downstream impacts of CO_2-EOR.

Scenario 3 looks at the GHG impact of one tonne of CO_2 being brought to a CO_2-EOR site. The tonne is stored and in turn 1.1 barrels of oil are produced (operational data). The GHG intensity of a barrel of oil is then used to derive the net impact[10].

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[10] It is important to note that the productivity of an EOR field, i.e. the amount of barrels produced per CO_2 input, is based on the amount of CO_2 *injected* and not the CO_2 *brought to site.* The amount of CO_2 "brought to site" is new CO_2 delivered to the EOR site from the capture facility. This arrives at injection pressure and is delivered into the reservoir through the injection wells. The amount of CO_2 "injected" is the total volume of CO_2 that is injected into the reservoir at a given time. This volume of CO_2 injected is a combination of new CO_2 (CO_2 brought to site) and recycled CO_2. Recycle CO_2 is the volume of CO_2 that returns to surface with the oil-water emulsion from the production well. The CO_2 is separated from the oil and water and then re-compressed to injection pressure where it is then re-injected to produce additional oil. The amount of injected CO_2 can be multiple times more than the is then re-injected to produce additional oil. The amount of injected CO_2 can be multiple times more than the amount of CO_2 brought to site.

RESULTS

Scenarios 4 and 5 assume that the CO_2-EOR oil produced using the single tonne of CO_2 will fully displace an equivalent volume of either oilsands crude or average crude. In reality, any level of displacement entirely depends on market dynamics at the time of production. Results are presented in this manner as an extreme case that helps bound the comparative results.

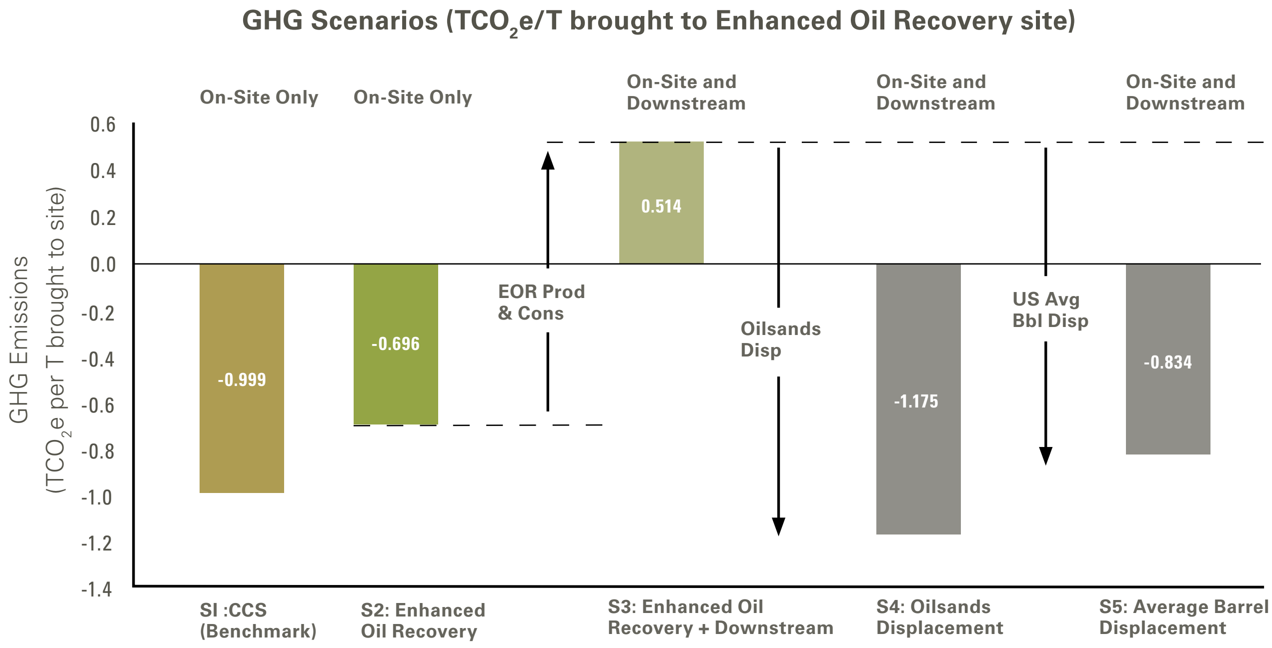

Figure 6. GHG scenarios (T CO_2e emitted per T CO_2 brought to site)

On a per tonne of CO_2 brought to site basis, it can be seen that a net (i.e. including storage) 0.5 T CO_2e is generated from the EOR case when downstream production is taken into account.

Should a barrel of EOR fully displace an average barrel from the oilsands or an average barrel from the U.S. Midwest, there would be a reduction of 1.2 and 0.8 T CO_2e per T CO_2 brought to (EOR) site, respectively. This is the same as saying the difference between the EOR scenario and the oilsands or average barrel is 1.2 and 0.8 T CO_2e per T CO_2 brought to the EOR site when including the stored CO_2.

3. POTENTIAL GHG PERFORMANCE RANGES

3.1 OVERVIEW OF POTENTIAL PERFORMANCE RANGES

Sensitivities are used to analyze the potential variance of the results by changing one or more parameters or assumptions. Changes to several variables or assumptions may be required in order to demonstrate how these results might translate to different CO_2-EOR operations, refining locations, or product end uses.

Table 6 outlines several potential variables, including performance and recycle ratios as described above, that can impact the GHG performance ranges of a CO_2-EOR operation. These variables are often inter-related and thus are difficult to analyze on their own. For example, the on-site electricity demand is directly correlated to the volume of CO_2 that is being recycled and the suction and discharge pressure at which the field is operated. This has distinct impacts on the on-site energy intensity of each operation and the overall net storage at the site.

The data ranges are based on extensive research of operational and design data for planned CO_2-EOR operations around North America. In addition to the various metrics from researched sites, a separate set of design data for a potential Western-Canadian project was obtained to provide a complete picture of a site operationally distinct (i.e. largely based on performance and recycle ratios) compared to the case presented in Section 2. The variables considered as part of a sensitivity analysis and there general impacts are described below.

RESULTS

The results from the sensitivity analysis show that there are several factors that can have a range of influence the GHG performance of a CO_2-EOR operation, with the most important of these being the Performance Ratio. The potential differences between sites can be seen in the range of data considered for this analysis.

Table 6. Sensitivities considered

VARIABLE CONSIDERED	DATA RANGE	IMPACT ON RESULTS	RATIONAL AND JUSTIFICATION
Performance ratio	Considered cases ranging from the operational case presented in Section 2 at 1.1 bbls produced per TCO_2 injected to 5bbls /TCO_2inj which is representative of several EOR sites in North America.	A reduction in on-site GHG emissions on a per barrel basis as the ratio increases. The net emissions, accounting for storage but not including displacement, increase by about 50% on a per barrel basis between the 1.1 and 5bbl cases.	See Section 3.2.
Recycle ratio	The recycle ratio can vary between projects but also can vary at different times in the project life span. Typical ranges span between less than 1 at the initial stages of a project to over 7 near the end of a project.	This variable is interrelated to many key components of the EOR operational process and cannot be analyzed independently of the others. As changes to the recycle ratio are indicative of the temporal aspects of the project as well it is not useful to analyze this at a specific point in time.	As the recycle ratio increases to include a greater volume of CO_2 being recycled and less new CO_2 brought to site, less overall net CO_2 is stored. Maintaining a low recycle ratio enables the project to actively store additional new CO_2.
Crude transportation	Distance required to transport crude from production site to refinery. For Alberta the distance from the EOR site to the Hardisty hub ranges from 150 km (Lloydminster to Hardisty) to 1100 km (Zama to Hardisty).	Transportation of the crude accounts for 1.2% of the overall emissions associated with producing oil from CO_2 EOR. The range of possible EOR sites impacts the results by less than 2%.	As the impact on the results is relatively negligible, the transportation distance of crude was not analyzed further.
On-site electricity demand	Electricity is the major on-site energy demand and is determined by the recycle compression requirements. Range of data considered is between ~35kWh/TCO_2 recycled and 120 kWh/TCO_2 recycled. This range is informed by the EOR site presented in Section 2 and the theoretical project presented in Section 3.3.	As the electricity demand is directly influenced by the volume and pressure of recycle CO_2 compressed it is difficult to consider independently of other variables. The impact on the results between the two ranges results in a 20% net GHG reduction in on-site emissions.	The potential variability in this parameter is directly indicative of the variability between unique EOR operations. The actual operational case (Section 2) has an electricity demand on the higher range of variables considered and the Theoretical Design Case (Section 3.3) operates at the lower range. These two data sets represent the potential variability of site characteristics.

3.2 CO_2-EOR PERFORMANCE RATIO SITE SENSITIVITY

Presented here is the performance ratio sensitivity looking at the result of producing a greater volume of crude oil for each tonne of CO_2 injected at the CO_2-EOR site, which is a variable that is shown to produce the greatest range of impacts on the results. Many CO_2-EOR operations will differ from the site used in this analysis in terms of crude oil production volumes per volume of CO_2 injected, including differing over time at a given site. The data used for this analysis (1.1 bbl produced per T CO_2 injected) came from a single site and is well below the metrics industry typically applies. In order to see how other CO_2-EOR sites might compare to the emissions from the oilsands and the average barrel scenario, the ratio of crude produced per tonne of CO_2 *injected*[11] was modified. In the analysis below, only the performance ratio was modified. All other parameters remain consistent with the operational data presented in Section 2.

The sensitivity below shows both the original site data used in this analysis, and cases where the CO_2–EOR operation produced 3 and 5 bbls/TCO_2 injected respectively. The results in Figure 7 below are presented on a *per barrel* basis as per Figure 5 above to make a direct comparison of the GHG impact of different sources of crude (i.e. outside of CO_2 sequestration).

The modeled cases represent theoretical CO_2-EOR sites with better reservoir characteristics or different site operations to facilitate the increased performance ratio. This assumes that the operational energy requirements to inject the volume of CO_2 remain the same.

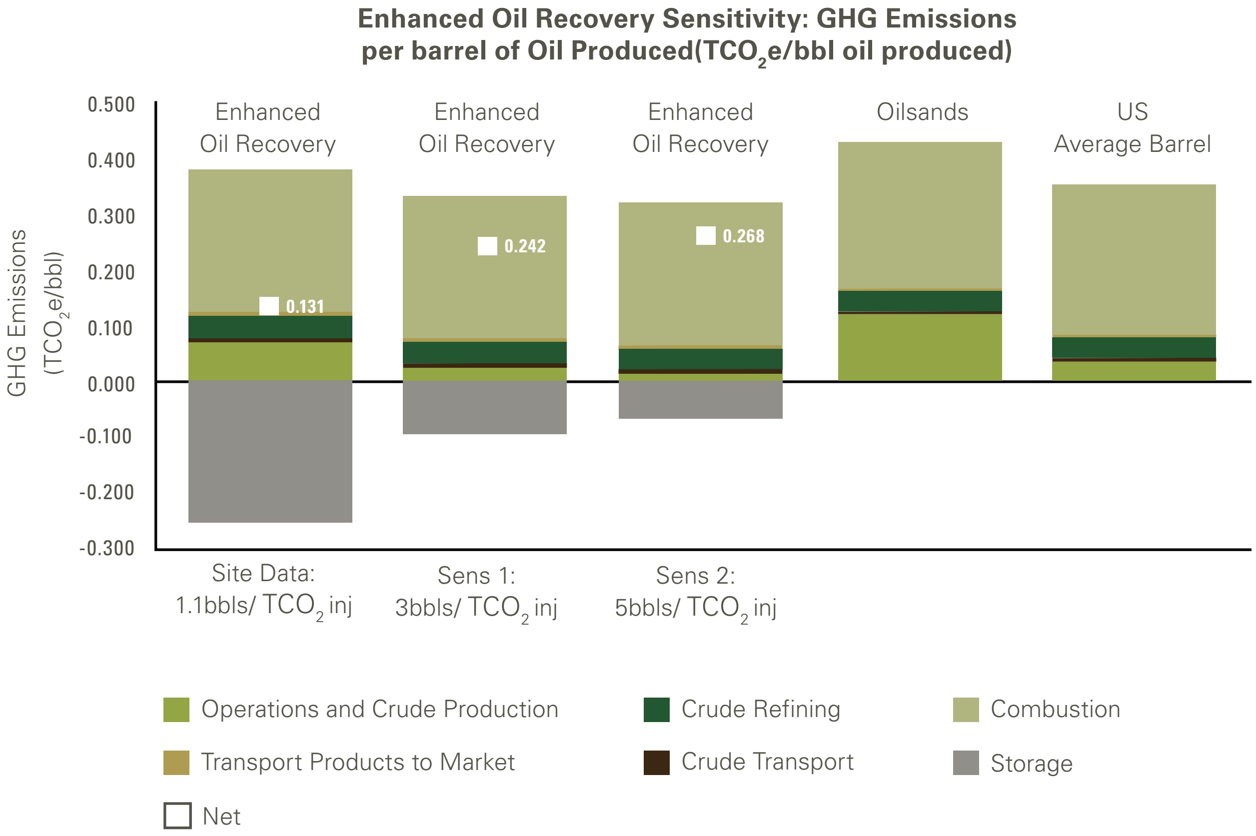

Figure 7. Sensitivity analysis: effect on GHG/Bbl of changing EOR field performance ratio

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[11] See Footnote 10.

From this graph, one can see a reduction in GHG emissions on-site (light green - Operations and Crude Production) on a per barrel basis in the EOR cases. However, if one were to also include the stored CO_2 in this calculation, there is less CO_2 stored on a per barrel basis as EOR field oil productivity improves. The net emissions associated with oil produced through EOR would increase on a per barrel basis. As there is no storage for the oil sands and average scenarios, their GHG emission intensity remain the same. As such, the life-cycle GHG performance of a CO_2-EOR system decreases with more barrels produced using the same amount of stored CO_2.

When considering the various perspectives around viewing the impact of CO_2 storage through EOR (the five scenarios), the effect of running the same sensitivity can be seen below in Figure 8. This figure provides the results of how the different scenarios illustrated in Figure 6 would be impacted. Here you'll note that S1 and S2 remain unchanged, as the sensitivity affects the number of barrels produced and as such impacts downstream activities only.

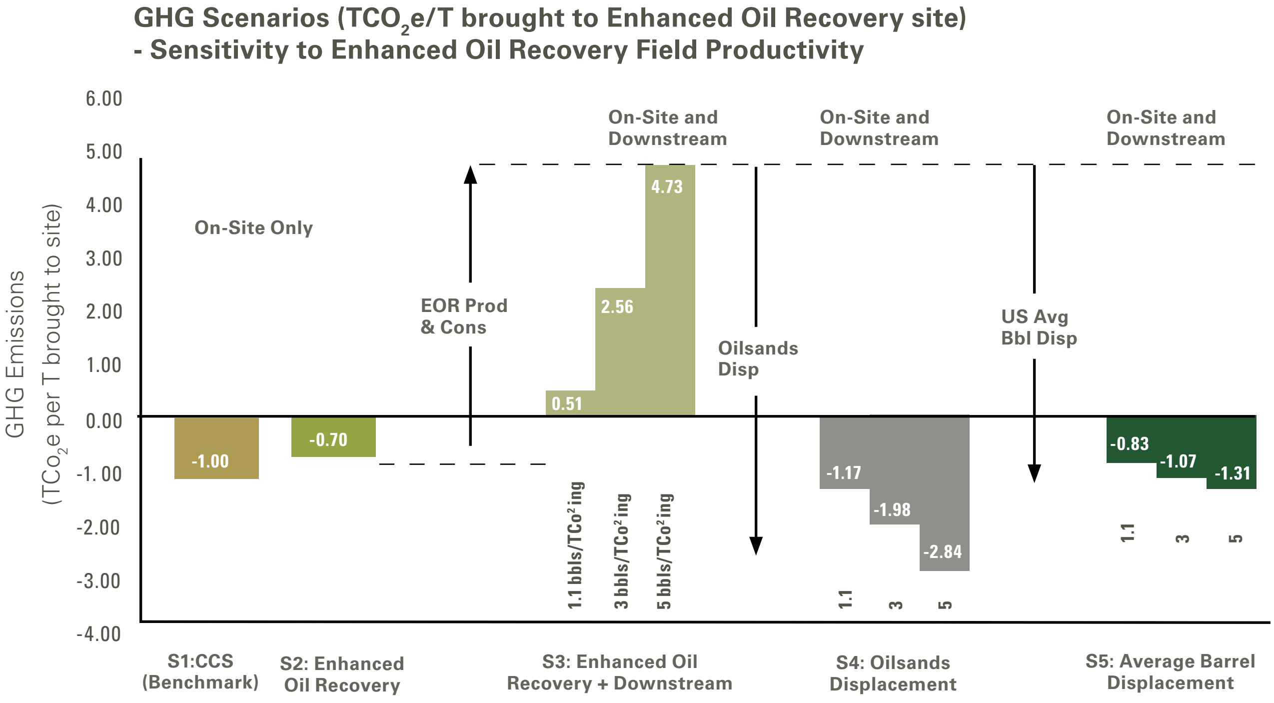

Figure 8. Sensitivity analysis: effect on GHG/T brought to EOR site of changing EOR field

It can be seen that the GHG intensity, unsurprisingly, is compounded by the increase in oil production per T CO_2 injected. While the GHG emissions increase from 5 to approximately 10 times in the EOR + downstream (S3) case, the amount of GHGs offset by displacing a barrel of oilsands (S4) doubles to triples while the GHG emissions displaced by the average barrel (S5) increases by 25% to 50%.

3.3 THEORETICAL DESIGN CASE

Data from a design case for a different Western Canadian project was also considered in this report to provide a comparison to a potentially new project that will employ the latest in CO_2-EOR technology and operational experience. The theoretical design case represents a project that will operate with different on-site operations and reservoir parameters from the project that was used in Section 2 of this report. Operating conditions for this site are expected to result in a recycle ratio of 3.45 compared with a recycle ratio of 1.1 for the site described in Section 2, and an oil production ratio of 0.451bbls/total TCO_2 injected. As a result, this theoretical case may provide insight into how a future CO_2-EOR project might be optimized to provide the greatest net GHG benefit.

Unlike Section 3.2, which analyzed the sensitivity to changing only the performance ratio, this case analyzes a site that has different characteristics for all aspects of the operation. Therefore, this is not a sensitivity on the actual operational data used, rather a picture of an entirely different (potential) EOR operation.

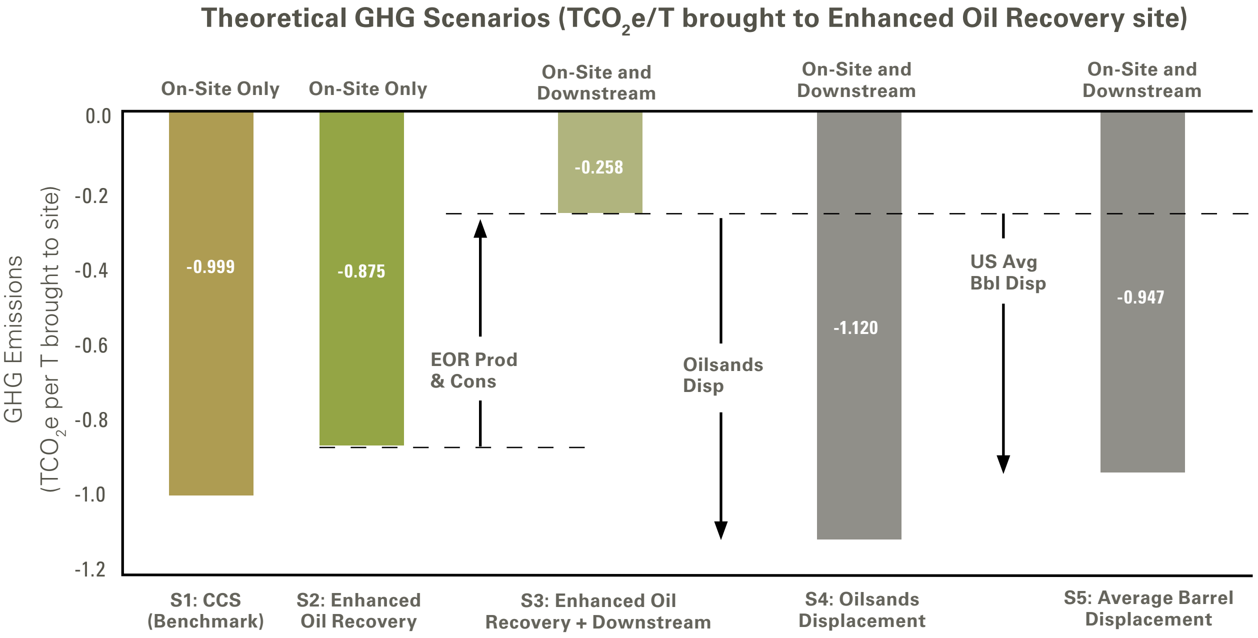

Figure 9. Theoretical Alberta based EOR project showing variability in net GHG performance with displacement scenarios.

As the figure above demonstrates, on-site operational variability can greatly affect the overall story of a CO_2-EOR operation. The modeled data for the site above represents a site with a much smaller on-site emission intensity (per bbl produced basis) as compared to the actual operation case described in Section 2 of this report. On a per tonne of CO_2 brought to site basis, it can be seen that a net (i.e. including storage) -0.258 T CO_2e is sequestered from the EOR case when downstream production is taken into account. The major differences contributing to the lower intensity can be attributed to a lower performance ratio (less oil per tonne of CO_2 injected and thus less oil-derived products combusted downstream) and less electricity needed for recycling CO_2 as the operating pressure of the field is increased[12]. This type of variability can make it difficult to illustrate what a typical CO_2-EOR operation would look like and demonstrates that this type of analysis is needed on a per-project basis in order to fully understand what the net GHG story is for each new project.

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[12] The operating pressure of the field can be modified based on predicted reservoir response. If the field is maintained with a smaller pressure difference between injection and production pressures, the recycle compression requirements decrease and correspond directly to decreased electricity demand.

4. SUMMARY

This analysis helps to provide fact-based quantification to different viewpoints on the relative GHG impact of using CO_2 for EOR purposes. Site-specific factors, such as the recycle ratio, suction and discharge pressure, and the performance ratio, makes it very difficult to generalize all EOR projects. This analysis was specifically undergone to avoid assigning value judgments and instead focuses on adding real data into the discussion around the impact of EOR. There are a few high level conclusions that can be drawn.

Geologic storage has more significant GHG reductions. On all accounts, whether the downstream impacts are counted or not, straight geologic storage of CO_2 has a more significant GHG benefit. Total on-site net CO_2e emissions from an EOR operation, including GHG emissions on-site, are slightly more than when considering CCS alone. That is, less GHG savings are generated given the energy required to produce crude oil from the EOR reservoir.

Oil produced from EOR falls in between comparative crudes on a GHG intensity basis. When comparing the on-site emissions of an EOR facility (producing 1.1 bbl/TCO_2 injected) including the emissions associated with downstream activities, outside of any CO_2 stored, the EOR life-cycle performance is 11.5% better than an equivalent amount of oil sourced from an oilsands operation and 10.8% higher than an average barrel of oil.

The ratio of CO_2 injected to barrels of oil produced has a large impact on the overall GHG benefit of CO_2-EOR. When considering improved EOR site performance in terms of barrels produced per tonne of CO_2 injected (performance ratio), an increase in EOR production translates to less intensive per barrel on-site energy requirements. In essence, an improved EOR performance ratio results in increased site level efficiency and more oil being brought to market. When the CO_2-stored through EOR is viewed through the lens of scenario 3 (including downstream consumption, but not offsetting of oil) then net GHG emissions increase significantly as the production rate of a site improves. However, if the CO_2-stored through EOR is viewed through the lens of scenarios 4 or 5 (including downstream consumption and the offsetting of oil) then the net GHG reduction impact increases significantly as the production rate of a site improves.

When assuming full displacement of competing sources of crude oil, EOR has a GHG benefit. If you consider market dynamics and that oil produced through EOR would mean that a barrel of oil from another source would not be required, the GHG benefits of EOR are significant; 1.175 TCO_2e reduced for an oilsands barrel and 0.834 TCO_2e for an average barrel. It is important to note that market dynamics are extremely complex and it is difficult to determine when sources displace others. It is highly unlikely that a full barrel of an alternate crude would be displaced but there is likely some market offsetting that would occur, particularly in the short term.

Understanding the net GHG impact of EOR is complicated and varies depending on site-specific factors. The variability between different CO_2-EOR projects can drastically change the net GHG impact. Understanding and quantifying the operational factors that influence the net GHG impact is essential in order to present the complete GHG impact of each project.

The impact of storing CO_2 through EOR varies greatly depending on perspective. The impact of storing CO_2 through EOR is highly dependent on the viewpoint that one takes. The variability between different CO_2-EOR projects can drastically change the net GHG impact. Value judgments on whether or not different factors should be included when assessing the CO_2 storage potential of EOR will lead to greatly diverging conclusions. This analysis will help to put numbers to the various perspectives on viewing CO_2 storage through EOR and further dialogue amongst stakeholders.

5. APPENDIX – SUPPORTING DETAIL

5.1 SCOPE AND METHODOLOGICAL CONSIDERATIONS

5.1.1 System functions for comparing oil production

Table 7 below summarizes the system functions for comparing oil produced through EOR, oilsands and an average barrel. Downstream activities have been considered in this analysis.

Table 7. System functions per oil production type

OIL PRODUCTION METHOD	CO_2 STORAGE	CRUDE PRODUCTION
EOR Barrel	Yes	Yes
Oilsands Barrel	No	Yes
Average Barrel	No	Yes

5.1.2 Temporal and geographical boundaries

The EOR study system is representative of a current Canadian EOR operation. The data used to model the on-site EOR operations (i.e. injection, production, recycle battery and vehicles) is taken from an operating Canadian site that has been in operation for the past fifteen years, although data is only for eight of these years. These eight years of operational data (crude production, CO_2 injection, on-site fuel use) have been averaged into a single operating year.[13] Produced crude oil from both the CO_2-EOR barrel and average barrel is assumed to be transported to the Hardisty terminal and then to Patoka for refining. Synthetic crude produced from oilsands is assumed to be upgraded at Heartland, and then transported to Hardisty and then Patoka.

5.1.3 Critical review and advisory committee

The study team engaged an advisory committee of academic and industry experts to comment on project methodology and results.

The advisory committee was engaged at several stages throughout the project and advisors included Paulina Jaramillo (Carnegie Mellon University), Joule Bergerson (University of Calgary), Jeremy Moorhouse (Simon Fraser University), and Andrew Higgins (CNRL).

The advisory committee was convened at several project milestones in a teleconference format to review project scope and background, data sources/ assumptions and results. They also commented on the final draft version of the report.

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[13] Note that the relative amount of CO_2 stored per barrel produced can change over the lifespan of a EOR project which could be up to 50 years. Our data did not provide the resolution effectively address the level of variability over time, however the possibility exists of this influencing the results over the full life of an EOR project.

5.1.4 Outside of project scope

The following activities are excluded from the study:

- CO_2 capture and transport activities (to injection site) are excluded, as these are common amongst all scenarios and will cancel out in scenario comparisons.
- CO_2 is assumed to remain sequestered without any long-term leakage. In reality, CO_2 leakage will depend on site-specific conditions (i.e. depth, fault lines, groundwater pathways etc).
- Well drilling activities prior to EOR operations are excluded.
- Infrastructure manufacturing and construction (facilities, pipelines, vehicles) are not included.

Economic modeling was not performed for this analysis. This study assumes that the market is inelastic and that EOR crude will displace other sources of crude production (i.e. oilsands synthetic crude oil). As well, residual CO_2 entrained in produced crude was assumed negligible.

5.1.5 Carbon storage as an equivalent "service"

When quantifying the life-cycle of any system, a fundamental requirement (as encoded in ISO 14040) is that each system being compared provide the same quantity (and quality) of services or functions. One can see from the activity maps provided in Section 5.3 that each scenario includes provision of the same three following services or functions:

- An equivalent amount of "X" product/service (used as an example source of CO_2, such as a coal-fired power plant or fertilizer plant)
- An equivalent volume of oil produced
- An equivalent volume of CO_2 stored

As this analysis is driven by an EOR site as a source of oil that also stores CO_2, the source of the CO_2 is considered independent of the analysis. Indeed, should the analysis consider the same source of CO_2 in each scenario, the emissions associated with this source would cancel out, as it is the same in all scenarios.

However, it is important to recognize that the EOR system provides the service – something valued by society, typically implied by a market value/cost – of storing CO_2. This is analogous to any waste management service. As such, when considering competing methods of oil production, it must be ensured that each method provides the same service (or "sub system") of storing CO_2 (regardless of location). However, this particular analysis does not include the "service" of storing CO_2 during the production of the U.S. average barrel of oil or during oilsands production.

Given the current market value of CO_2 for jurisdiction across Canada, the only market incentive to store CO_2 underground (in certain jurisdictions) is via an EOR operation. In other words, pure CCS is not viable from a market perspective (i.e. independent of subsidies) and as a result not currently happening in Canada on an unsubsidized basis.

Should market dynamics associated with CO_2 change in the future, and CO_2 storage be included as a sub-system in all oil production methods (the same amount as is stored through EOR), the difference in net life-cycle GHG emissions of the oil would be the same relative amounts as presented in Figure 5.

5.2 DATA AND LIMITATIONS

5.2.1 Study limitation

A core limitation for this analysis was assuming that EOR performance such as crude produced per TCO_2 injected, CO_2 recovery and on-site energy requirements, is fixed in time. In reality it will change over time (i.e. crude production per TCO_2 injected will be different in the first 5 years of production compared with the last 5 years). Ideally the study team could have obtained operational data for the entire project lifespan; however, this data is limited. The study team assumed that the data that was obtained from a short project timeframe is representative of average operations. Additionally, the operational data used in this study was from a single site and therefore may not be representative of EOR more broadly.

5.2.2 Data sources

The activity data and emission factors used in this study are listed below in Table 8 and Table 9.

Table 8. Activity data for all scenarios

UNIT PROCESS	S1: ON-SITE CCS	S2: ON-SITE EOR	S3: EOR + DOWNSTREAM	S4: OILSANDS + DOWNSTREAM	S5: AVG BBL + DOWNSTREAM
On-site Electricity Use (MWh)	~0	2430	2430	NETL	GHGenius[14]
On-site FF Use (GJ)	~0	10,511	10,511	NETL	GHGenius
Venting, Flaring, Blowdowns (TCO_2e)	9	70	70	n/a	n/a
Transport Crude to Refinery Distance (km pipeline)	n/a	n/a	2414	2714	2414
Refine Crude	n/a	PADD2	PADD2	PADD2	PADD2
Transport Petroleum Products to Market Distance (km)	n/a	200	200	200	200
% of Refined Products Combusted	n/a	90%	90%	90%	90%
Crude Production Rate (000s bbls)	n/a	171	171	171	171

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[14] See www.ghgenius.ca

Table 9. Emission factors

EMISSION FACTORS	DATA	UNITS	SOURCE
On-site electricity Use	960	g/kWh	Environment Canada[14]
On-site natural gas combustion	1919	$gCO_2e/m3$	Environment Canada
On-site propane combustion	1544	gCO_2e/L	Environment Canada
On-site diesel combustion	2730	gCO_2e/L	Environment Canada
On-site gasoline combustion	2474	gCO_2e/L	Environment Canada
Transport crude (by pipeline)	181	J/kg-km	Jaramillo[16]
Refine crude composite	41	Kg CO_2e/bbl	TIAX 2009[17]
Transport petroleum products (tanker truck)	80	gCO_2e/T-km	NREL LCI[18]
Combust products	90%	Carbon	Calculated
Oilsands crude production – mining	96	Kg CO_2e/bbl	GHGenius
Oilsands crude production – in situ	146	Kg CO_2e/bbl	GHGenius
Oilsands crude production – average	121	Kg CO_2e/bbl	GHGenius
Average barrel crude production	35	Kg CO_2e/bbl	National Energy Technology Laboratory[19]

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[15] Environment Canada. 2011. National Inventory Report 1990-2008. Greenhouse Gas Sources and Sinks in Canada. Annex 8.

[16] "Life Cycle Inventory of CO_2 in an Enhanced Oil Recovery System", Jaramillo et al, Environment, Science, and Technology, 2009, 42, 8027-8023.

[17] See Footnote 8b.

[18] See Footnote 5

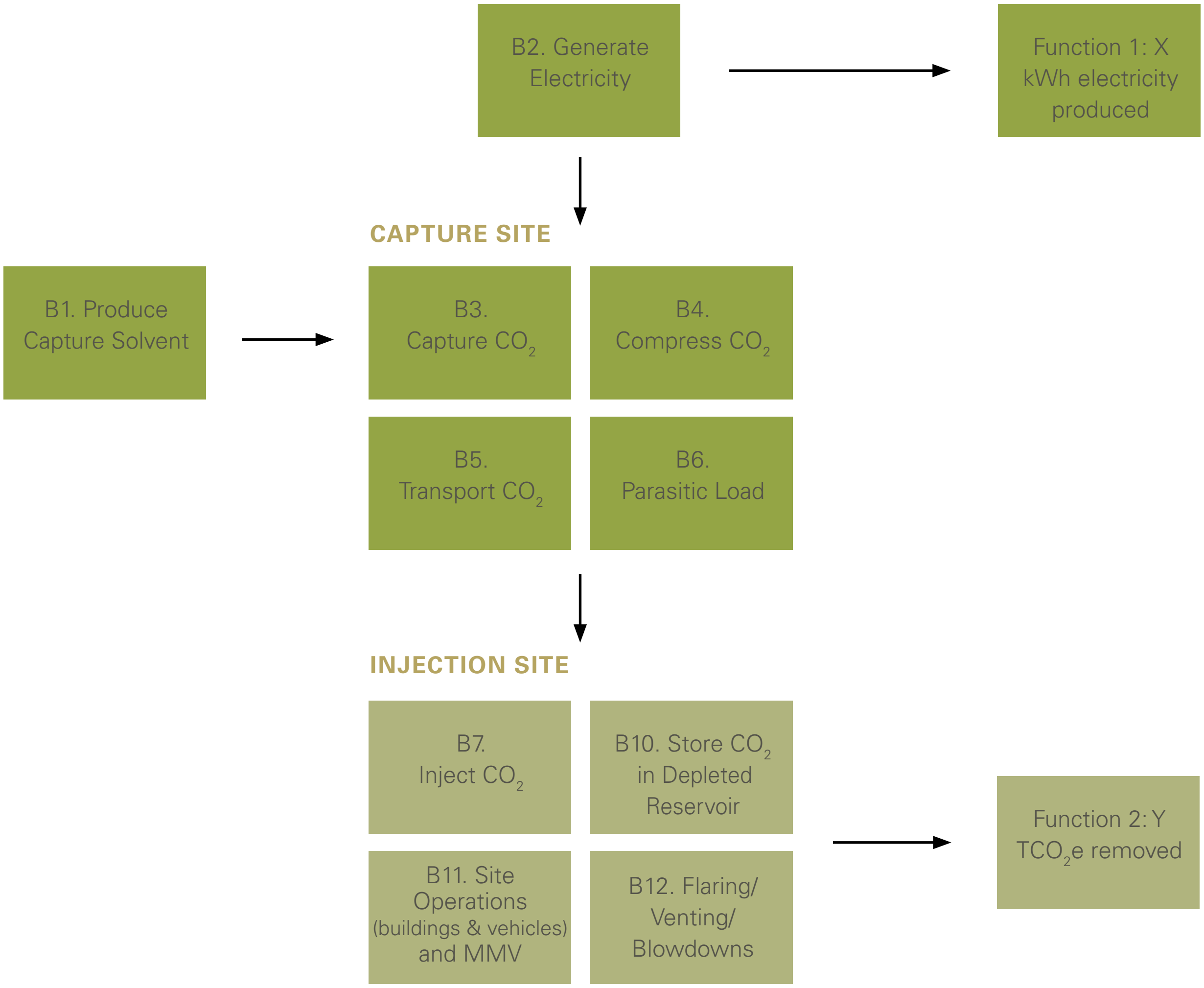
[19] See Footnote 5

5.3 ACTIVITY MAPS

S1 ACTIVITY MAP - CCS

The following activity maps provide an overview of the key activities or processes involved in the different scenarios. Boxes that are green are not included in the analysis.

Figure 10. Activity Maps - Scenario 1



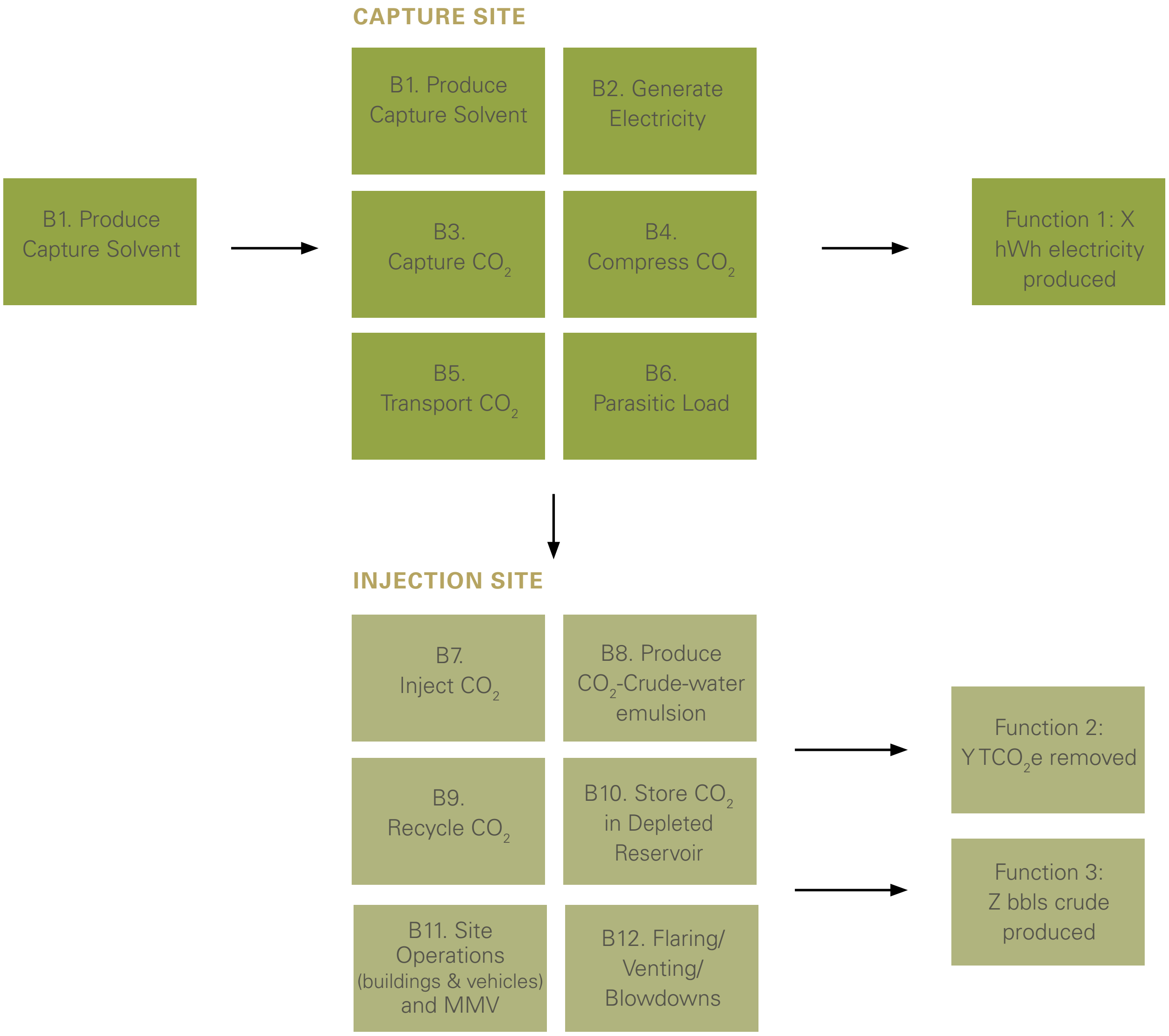
LEGEND

▨ Activity - included

🟩 Activity - not included

S2 ACTIVITY MAP - EOR SITE OPERATIONS

Figure 11. Activity Maps - Scenario 2

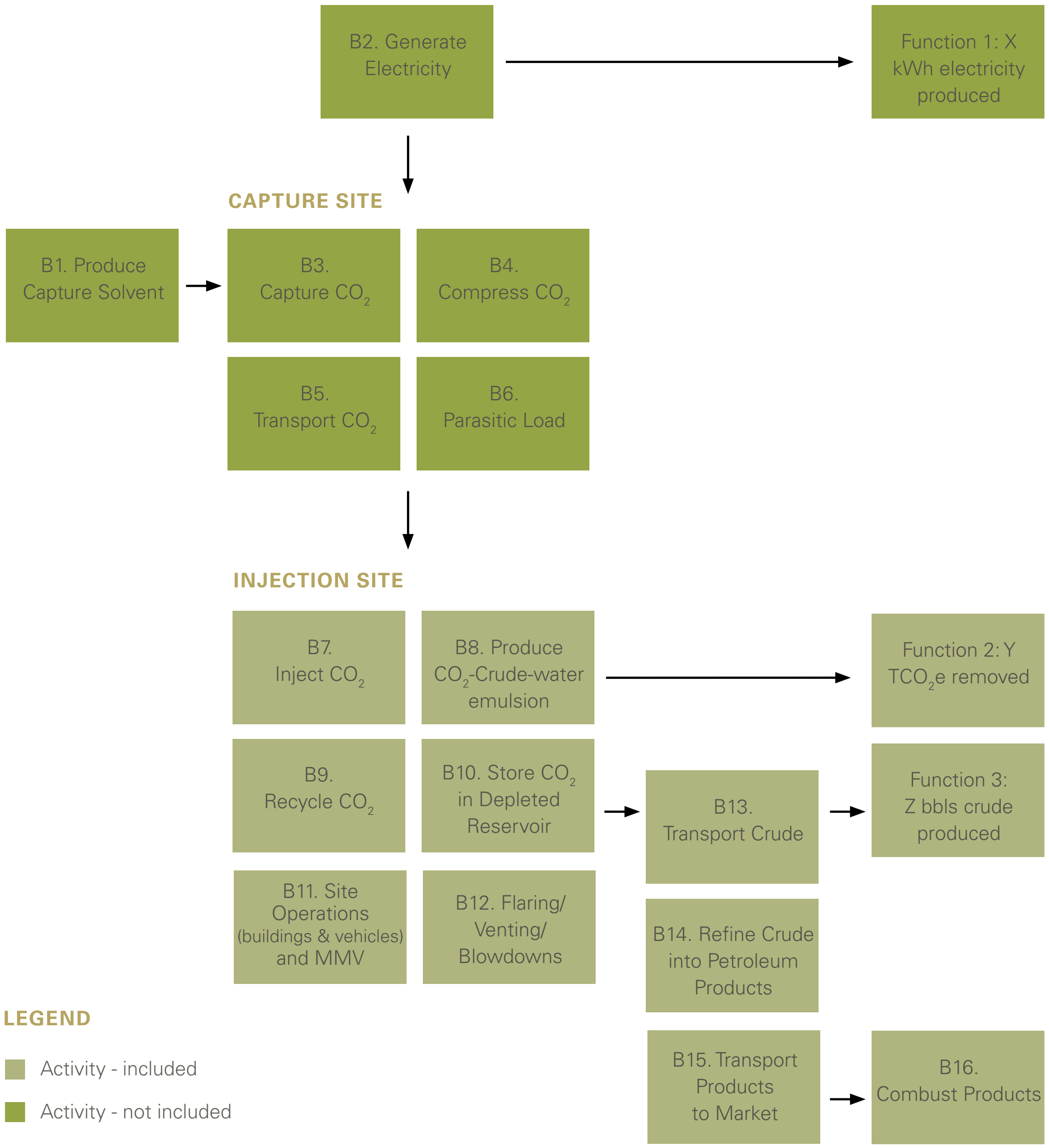


LEGEND

- 🟩 Activity - included
- 🟩 Activity - not included

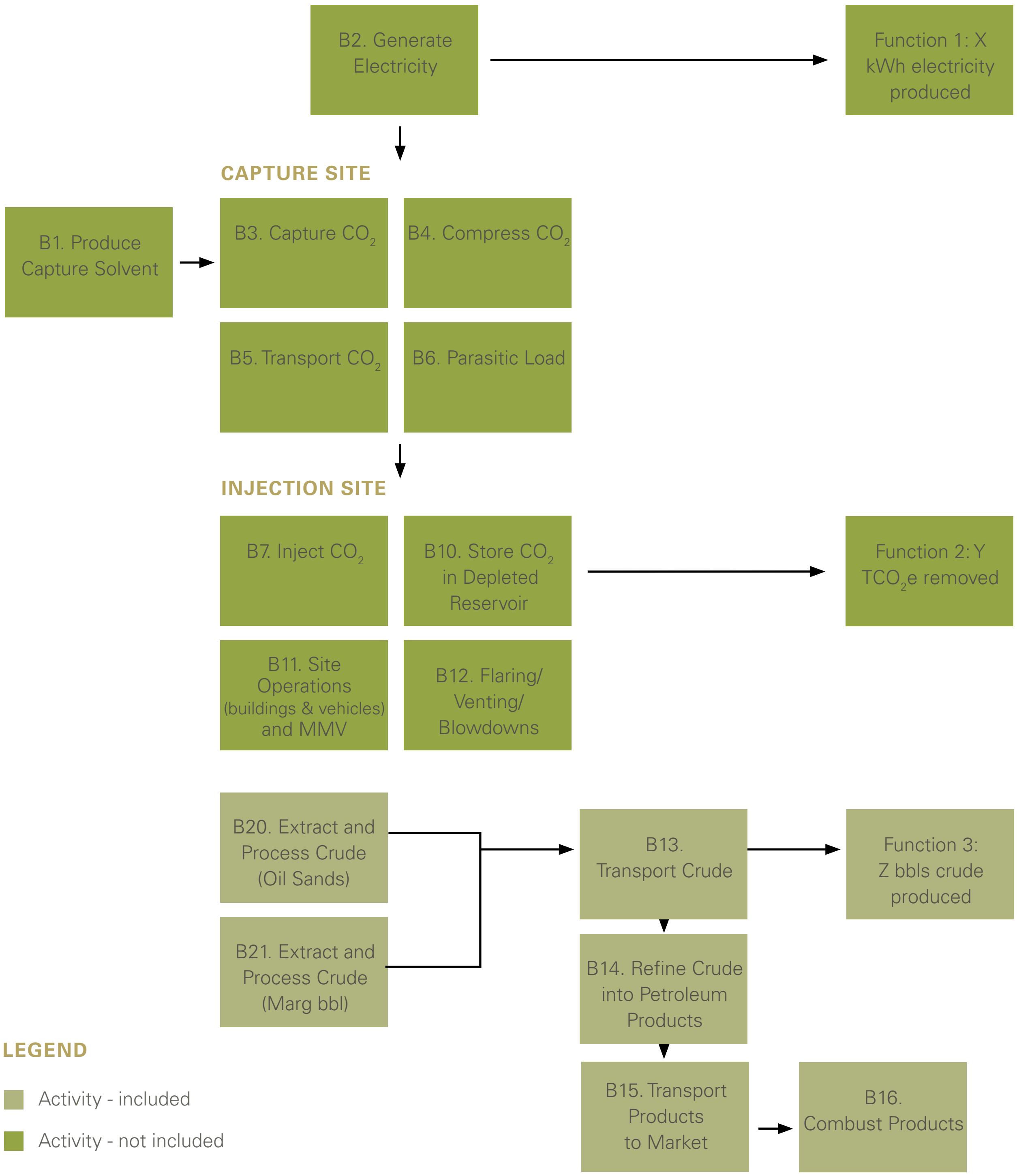
S3 ACTIVITY MAP - EOR W/REFINING AND COMBUSTION

Figure 12. Activity Maps - Scenario 3



S4 & S5 ACTIVITY MAP - ALTERNATE CRUDE PRODUCTION

Figure 13. Activity Maps - Scenario 4 and 5



5.4 ADVISOR COMMENTS

CO_2 credits, while important to consider in many instances, have not been included in this analysis. The application of credits changes by jurisdiction and can complicate the way CO_2 impact is viewed. When comparing EOR oil to other crudes, the stored CO_2 has been left out to show the comparative GHG intensities of the various production methods. While an intermediary step in the overall analysis, one advisor feels that this is a limitation as by excluding upstream processes there is an implicit assumption that credits associated with CO_2 storage in the EOR field are allocated to oil production as opposed to the CO_2 capture company.

Barrel of oil GHG intensities were not the main subject of this analysis and therefore the assumptions in these numbers are pulled from literature and not specific to this study. One of the advisors feels there is more information required around consumption assumptions and this is something that could be addressed in a future analysis.

Prepared
for ICON2