Journal of Cleaner Production xxx (2017) 1–13

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Comparison of carbon balance measuring tools in an enhanced oil recovery project based on the carbon dioxide from the ammonia production process streams

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ARTICLE INFO

Article history:
Received 16 May 2016
Received in revised form
17 December 2016
Accepted 21 December 2016
Available online xxx

Keywords:
Ammonia production
Crave to grave model
Carbon balance
Global warming impact

ABSTRACT

A number of studies addressing the environmental impact of deploying carbon capture utilization and storage are focused on sources of CO_2 in the power sector. However, there is a lack of environmental studies on the use of CO_2 from process stream within the oil and gas industries. The carbon balance of an enhanced oil recovery project for the specific case of using CO_2 process stream of ammonia production from emission factors and regional databases in the Mexican oil and gas sector was assessed. Two independent tools to assess life cycle assessment according to guidelines ISO 14040/14044 were utilized: (i) use of Umberto software to quantify the environmental impact with ReCiPe model midpoint; and, (ii) The American Petroleum Institute method through the use of emissions factor for each source and emission gas of the activity/facility in a spread sheet. The results of the tools were compared and the dissimilarities analysed. The emissions profiles from all direct and indirect activities associated with the enhanced oil recovery system were compared with a "cradle-to-grave" model. The functional unit is one barrel of crude oil extracted and consumed. Global warming as the environmental indicator of both tools was used. Additionally, the energy balance of the project was estimated. The global warming impact of the enhanced oil recovery system was 0.51 tCO_{2e}/barrel (bbl) using the American Petroleum Institute tool, whilst the emissions using Umberto software were 0.54 tCO_{2e}/bbl. Also, for each MJ of energy produced a value of 72 tCO_{2e}/MJ oil and of 66 tCO_{2e}/MJ oil, were obtained. This study demonstrates that both tools delivered an accurate estimation of the greenhouse gas emissions in the enhanced oil recovery system for the oil and gas industries. However, American Petroleum Institute has the advantage that the calculations can be performed 'manually' in a spread sheet using emissions factor adjusted to the facilities and Country. Regarding the results of both tools, this work shows that American Petroleum Institute results have proven to be an efficient tool for practitioners and researchers that intend to analyse the greenhouse gas emission of carbon capture utilization and storage systems to estimate, with accuracy, the global warming impact.

1. Introduction

The number of studies addressing the environmental impact of deploying carbon capture and utilization (CCU) and/or carbon capture and storage (CCS) is rather limited and focuses on sources of CO_2 from the power sector (Corsten et al., 2013). Moreover, CCS

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http://dx.doi.org/10.1016/j.jclepro.2016.12.114
0959-6526/

from industrial applications has so far received little attention, despite International Energy Agency-United Nations Industrial Development Organization, IEA-UNIDO (2011) highlighting that CO_2 emissions should be reduced up to 4.0 gigatonnes (Gt) annually by 2050. The CCS studies suggest that the global warming (GW) resulting from power plants needs to be reduced (Leung et al., 2014).

Many studies marginally discuss different aspects (Cuellar-Franca and Azapagic, 2015) when assessing the environmental performance of power plants with CCS and CCU, despite the difficulty in directly comparing the relative importance of upstream (e.g. coal mining, coal transport, monoethanolamine production), as mentioned by Corsten et al. (2013), and downstream emissions (e.g. CO_2 capture). This emphasises the need for optimal designs in all the value chains. Nevertheless, as the available recent literature aiming to address the life cycle assessment (LCA) of CCS focuses on different technologies, as well as system boundaries; database sources, transparency in the data reported and specific assumptions are not clearly evident in the studies. This makes it even more difficult to draw robust conclusions on the potential environmental impact of CCS and CCU. Marx et al. (2011) gave a synthesis report about LCA-CCS evaluations, in which some shortcomings in the studies' underlying assumptions and methodologies were found. Petrakopoulou and Tsatsaronis (2014) established that the principal aim of CCUS technology is how their environmental impact can be reduced and energy efficiency maximized. Consequently, a valuable way to assess the LCA of enhanced oil recovery operations is to review the carbon emissions profile for the whole operation, and compare this with projects of CO_2 storage profile.

This subject is important since frequently the LCA practitioner will not find one obvious choice among a number of different databases or calculation methods, and the question, therefore naturally arises: “Does my choice of method or database have any influence on the conclusions?”. Based on simulation results and process configuration of the CCS system, the LCA method has been applied to evaluate the environmental impact of the system taking into account the complete life cycle from raw material to CO_2 injection or refinery product combustion from commercial software (Von der Assen et al., 2014). In addition, the life cycle inventory (LCI) calculations could involve either the whole system boundary or not, and include different raw materials (coal and natural gas) or only main stages of the LCA, i.e. a gross inventory, without going into the details of each stage from extraction of raw material to use. Therefore, system boundary or expanded system boundaries and their stages are neither clearly specified nor detailed, generating different results of net emission per barrel of oil in the enhanced oil recovery (EOR) system (Cuellar-Franca and Azapagic, 2015). Specific to the oil and gas industries, there is a lack of direct measurements, or offshore/onshore monitoring of emission gases is rare, and so for most sources only the activity data, such as fuel consumption or the rate of a process activity are available. When direct measurement systems are not in place, the calculation of emissions can be made from an activity factor (Stewart and Haszeldine, 2014).

The most commonly practiced CCS approach, in terms of CO_2 sequestered, is CO_2-enhanced oil recovery (CO_2-EOR). The CO_2 injection from natural sources for EOR has been applied commercially since the early 1970s in the United States for oil recovery, typically in no longer productive mature fields. However, today EOR operations are carried out with the aim of maximizing oil output with the minimum CO_2 injection (International Energy Agency, EIA, 2015).

According to Leach et al. (2011), approximately 30–40% of the CO_2 injected during a single injection usually remains trapped in the reservoir. This value is similar to that reported in the first CO_2-EOR case study in Mexico performed at the Artesa reservoir in the Chiapas and Tabasco states, where 40% of CO_2 injected was stored (Leon-Garcia et al., 2015).

As with any secondary recovery methods, additional energy is consumed in the CO_2 capture, resulting in a higher environmental impact per MWh than without CO_2 capture (Petrakopoulou and Tsatsaronis, 2014). The production of additional oil will be CO_2-EOR that, when combusted will generate additional CO_2 emissions (Jaramillo et al., 2009). Along with this, there is a discussion as to whether these technologies can provide products that sequester the CO_2 for a long or short period (Electric Power Research Institute, EPRI, 2013), how much CO_2 is really sequestrated by each technology, and if CCS should be considered as a mitigation technology (Armstrong and Styring, 2015). Thus, climate change mitigation and long-term CO_2 storage goals are not principal drivers for EOR projects (IEA, 2015). EOR also sequesters CO_2 in the process with potential climate benefits. An important portion of the injected CO_2 remains in place, a technology that has been proved in USA (Dai et al., 2014a) and Canada with the world's first commercial scale post-combustion coal fired carbon capture and storage in the Saskatchewan Project (Stéphenne, 2014). All studies show a substantial reduction of greenhouse gas (GHG) emissions from power production, in the order of 40–97% (Corsten et al., 2013). According to Cuellar-Franca and Azapagic (2015), the reduction in the global warming potential (GWP) is sensitive to CO_2 capture and allocation methods as well as the assumptions for heat recovery from the system.

IEA-UNIDO (2011) published a Technology Roadmap CCS in industrial applications providing an outlook of industrial CCS up to 2050, where high-purity CO_2 sources like ethylene oxide and ammonia production were included in this roadmap.

The 2014 global status of CSS projects states that four projects are in operation from CO_2 fertilizer plants: three for EOR and one as geological storage, with a contribution of 4.5–5.1 $MtCO_2$/year (Global CCS Institute, 2015). These values represent a marginal fraction of the total anthropogenic emission (32,000 Mt CO_2/y) by this sector (Armstrong and Styring, 2015). In 2014, the start up operation of the commercial North Burbank Unit (NBU), in Kansas-Oklahoma USA, CCU and the CCS (EOR) from a fertilizer-urea plant (National Energy Technology Laboratory, NTEL, 2015) were included.

The United Stated Environmental Protection Agency (USEPA) lists 22 ammonia manufacturers in the United States. Eighteen of these are capturing CO_2 as a by-product and selling it as an industrial product to the market (USEPA, 2015). NTEL (2013) published a report on alternative sources of CO_2, documenting a cradle-to-gate footprint per unit of CO_2 produced from ammonia production. This study has not found cradle-to-grave life cycle results published on EOR production from CO_2 by ammonia plants. There are not many references in the literature describing the use of LCA-CCS studies in petrochemical processes or the oil refinery (Nagashima et al., 2011).

Consequently, this work was motivated by the need within the oil and gas sectors, to analyse and compare the results of other methodological models, to identify environmental “hot spots” in the LCI calculations of the CCUS-LCA studies. This study might therefore suggest potential improvement actions to enable a reduction in the environmental impact of the upstream and downstream processes of the oil and gas industries, as well as to assist LCA practitioners to compare the results when they use the CCUS system using regional or local databases.

1.1. Overview of CCUS in Mexico

The Mexican Government recently published the CCUS Technology Roadmap recognizing the need for CCS to aid in reaching the CO2 reduction goal in view of the fast growth in electricity demand

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in the country (Energy Secretariat, SENER , 2014). According to this study, it is estimated that Mexico has a theoretical capacity for storing 100 Gt of CO_2. If it were considered that the CO_2 annual emissions in Mexico in 2012 represented an equivalent of 0.74 Gt, then the maximum storage capacity in the country would be reached in 135 years.

A recent update of the 2013 GHG inventory showed that emissions from the oil and gas sectors in Mexico accounted for 12% of total GHG emissions at the national level, i.e. 80,455 Gt CO2e/y (Secretariat of Environment and Natural Resources-National Institute of Ecology and Climate Change, 2014; SEMARNAT-INECC, 2016). Of this, 20% is generated in the states of Veracruz and Tabasco, where mature fields are located and would require large amounts of CO2 for EOR. For instance, it is estimated that the bigger Mexican oil fields candidates for EOR would need up to 50 million metric tons of CO_2 per year in the Gulf of Mexico (Lacy et al., 2012). Petróleos Mexicanos (PEMEX) Sustainability Report (2014), affirms that 14.7 million metric tons CO_2/year were emitted from fuel combustions, 1.4 million metric tons CO_2/year were produced by venting gas from three ammonia plants' processes, and 0.9 million metric tons CO_2/year from one hydrogen plant in the Southeast of Mexico (Southeast of the states of Veracruz and Tabasco) (Fig. 1).

Specifically, the Cinco Presidentes Oil asset (CPOA) with a 0.085 million barrel (bbl) a day production of domestic oil (20–35°API) (PEMEX, 2015) has been classified as an inclusion zone (D) for the geologic storage of CO_2 (Dávila et al., 2010). In the case of employing CO_2 for EOR, the ammonia plant from Cosoleacaque Petrochemical Complex (CPC) has the advantage of being located only 50–70 km from the CPOA. It is the closest CO_2 source for implementing the technology of EOR in Mexico, with a total 2P volume (Proven and probable reserves) of 249.9 billion barrels of oil reserves, with 565 wells in operation (National Hydrocarbons Commission, CNH, 2016).

The Brillante oil field is a young field, having been in operation for three years, located within the CPOA (Table 1) with a production of less than 3000 bbl/d of 35°API (Arteaga-Cardona et al., 2015).

1.2. CO_2 source: ammonia process from CPC

Ammonia production depends on natural gas (NG) both as a feedstock and as a fuel. Haas and van Dijk (2010) estimated the average energy consumption for ammonia (NH_3) production in Europe to be around 34.7 GJ/t with 1.5 tons of CO_2/t of ammonia emitted to the atmosphere during production. Williams and Al-Ansari (2007) determined a global average energy consumption of 36.9×10^3 MJ/t. Makhlouf et al. (2015) estimated a Cumulative Energy Requirement (CER) of 51.945×10^3 MJ/t of ammonia and 1.44 t CO_{2eq}/t of ammonia for an ammonia plant taking into account the CO_2 in the flue gas in Algeria.

In Mexico, the NG comes from an offshore platform located in the Southeast of the Gulf of Mexico at 500 km distance from the CPC. For synthetic ammonia production there are six principal process steps from NG feedstock (Fig. 2). The primary reforming step converts methane (CH_4) to CO_2, carbon monoxide (CO), and hydrogen (H_2) in the presence of a catalyst. Only 30 to 40 per cent of the CH_4 feedstock to the primary reformer is converted to CO and CO_2 in this step of the process. The secondary reforming step converts the remaining CH_4 feedstock to CO and CO_2. The CO from the secondary reforming step (representing approximately 15 per cent of the process gas) is converted to CO_2 in the presence of a catalyst, water, and air in the shift conversion step. CO_2 is removed from the process gas by the shift conversion process; the hydrogen is combined with the nitrogen (N_2) gas in the process gas during the ammonia synthesis step to produce ammonia. The CO_2 is incorporated to a waste gas stream with other process impurities and absorbed by a scrubber solution (Overcash et al., 2007).

The CO_2 emissions from four ammonia plants (AP) of the CPC, producing 480,000 tNH_3/y and 497,000 tCO_2/y as by-product with

Table 1
Capacity of key facilities in Brillante oil field.

Item	No	Nominal Bbl/d	Nominal MMSCF/d
Operation well	12		
Horizontal separator	1	55,000	16
Slag catcher	1	3.5	20
Storage tank	8	500	
Gas compressor	1		2
Pump	1	10,000	
Flare	1	–	
Tanks	8	4000 bbl	

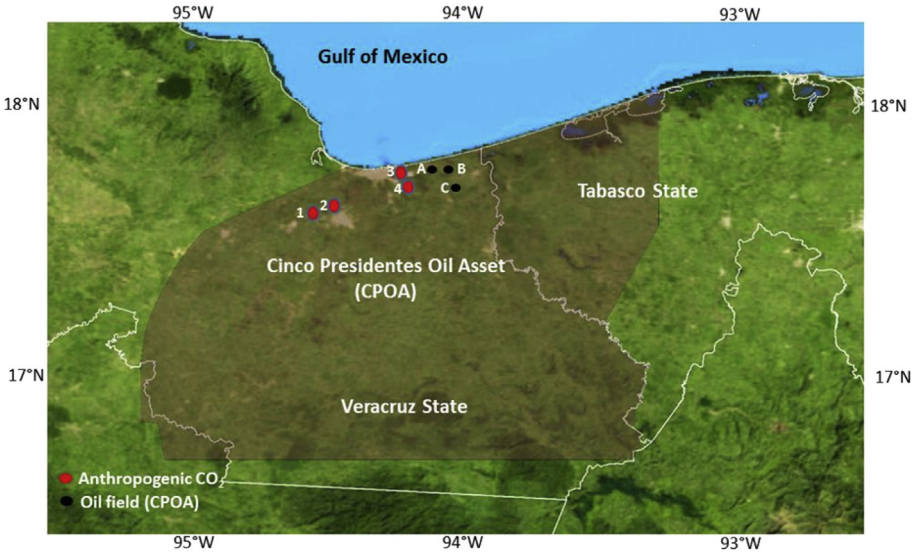

Fig. 1. Sources of anthropogenic CO_2 (1: Cosoleacaque Petrochemical Complex (CPC); 2: Minatitlán Refinery; 3: Morelos PQC and Cangrejera PQC) and oil fields (A: Brillante; B: Rabasa and C: Los Soldados).

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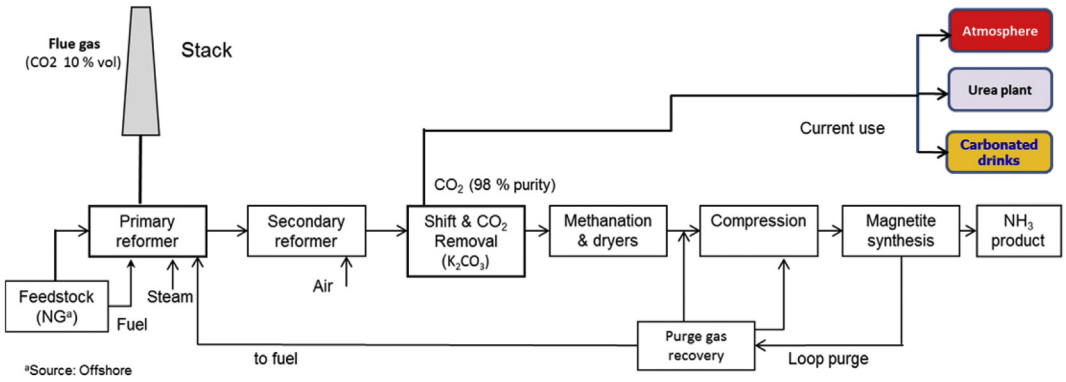

Fig. 2. General process flow of typical synthesis ammonia, sources of CO_2 emissions and uses in the case of the CPC.

98% purity, were considered as supply for the EOR project in this study. Currently, the CO_2 produced is employed to produce urea and for the beverage industry. Of the remainder currently emitted into the atmosphere (Fig. 2), PEMEX plans to use 834 t/d of this CO_2 for EOR in the Brillante field (Arteaga-Cardona et al., 2015).

A considerably lower energy is required to separate and capture the CO_2 from ammonia production. For instance, AP from CPC is 1.35 MJ/kgCO_2, which is lower than in the power sector (2.8–4.2 MJ/kgCO_2) CO_2 capture technologies (Luis, 2015). The CO_2 is removed in a tower with several beds through absorption (pre-combustion) employing 30% solutions of potassium carbonate (K_2CO_3), using heat integration in their facilities. The AP from CPC has an emission factor of 1.4 metric tons CO_2/metric ton NH_3. Therefore, the use of CO_2 that is currently vent into the atmosphere by the ammonia plant and close to mature oil fields as the CPOA, could substantially improve the environmental profile of the plant and energy of the EOR project.

2. Materials and methods

The CCUS technology was considered here as an end-of-life process, so that it can be integrated to any industrial plant that is an anthropogenic source of CO_2. Therefore, the product category was defined either as a system of technologies that integrate the CO_2-EOR project's three stages: carbon dioxide (CO_2) capture (pre-combustion), transport (CO_2) and storage (oil and gas reservoirs) or as utilization (EOR) services (Strazza et al., 2013), using process streams from the AP as a source of CO_2.

2.1. Objective and scope of study

The objective of this study was to assess the impact of GHG emissions and energy balance of the Brillante CO_2-EOR project, located in the CPOA in the southeast of Mexico, using CO_2 process streams from ammonia production, and to compare the single environmental impact: resulting global warming (GW) contrast. Two independent tools to assess life cycle analysis (LCA) according to ISO 14040/14044 guidelines were compared: Umberto software (US) versus American Petroleum Institute (API) calculations through a spreadsheet, with EF adjusted to Mexico. Additionally, to identify environmental hotspots and to suggest potential improvement actions that would reduce the environmental impact of the CCUS system.

The study considered the stages from the extraction of natural gas as feedstock for producing ammonia, to the combustion of the refined petroleum. The studied system operates at six subsystems involving different industrial sites, separated by nearly 500 km which requires the transport of gas and oil by pipeline (Fig. 3).

2.1.1. System boundary

To facilitate the identification of impact sources, the system was divided into six subsystems: (i) gas extraction, (ii) gas processing (iii) ammonia production, (iv) EOR operation, (v) refining process and (vi) refinery product's combustion (Table 2). Fig. 4 shows the system boundary for the whole Brillante CO_2-EOR system. The GHG emissions associated with the life cycle of the project include the emissions from the offshore based oil producing platform (Cantarell), located in the southeast marine region in the Gulf of Mexico, to the Refinery product's combustion (e.g. gasoline) i.e. “cradle-to-grave” model (Fig. 4). Material and energy flow network of process system is shown in Supporting Information (SI) Figure SI-1.

Expanded system boundary and displacement was used to sum the GHG emissions for both methodologies according to Table 2 and Fig. 4, and also for the ammonia product and CO_2 as by-product generated in accordance with ISO standards 14040–14044 (ISO, 2006 a, b).

The boundaries excluded transport of refined petroleum products from the refinery to the consumer, since emissions from transporting these products represent less than 1% of the lifecycle emissions, Wang et al. (2008). In addition, this study also omits the associated emissions for the infrastructure necessary for the construction of the CO_2-EOR because Brillante field already exists.

2.1.2. Functional unit (FU)

Considering that the purpose of the Brillante CO_2-EOR project is to capture CO_2 and employ it in the oil recovery process, for both methodologies, the FU was defined as one barrel of crude oil extracted and consumed.

2.2. Life cycle inventory (LCI)

In order to build and compare the LCIs with both tools, this study was conducted in accordance with ISO standards for LCA ISO 14040 and ISO 14044 (ISO, 2006 a,b).

The LCI includes direct (combustion) and indirect emissions, fugitive emissions (leaks in facilities and pipeline, oil and gas fields) and venting processes; i.e. the direct activities related to exploration, production, gas processing, transportation, distribution and refining by the oil and gas industries (Table 2).

The inventory data were collected from the PEMEX (2015) database to obtain the GHG emissions from assets over which PEMEX has 100% operational control. The characterization of GHG emissions of each stage/activity was made with an up-bottom approach. The uncertainty of the data from upstream and downstream operations to build LCI was evaluated. The data have a confidence interval of 95%. The stage of the direct emissions (combustion and indirect) corresponds to the estimated for the

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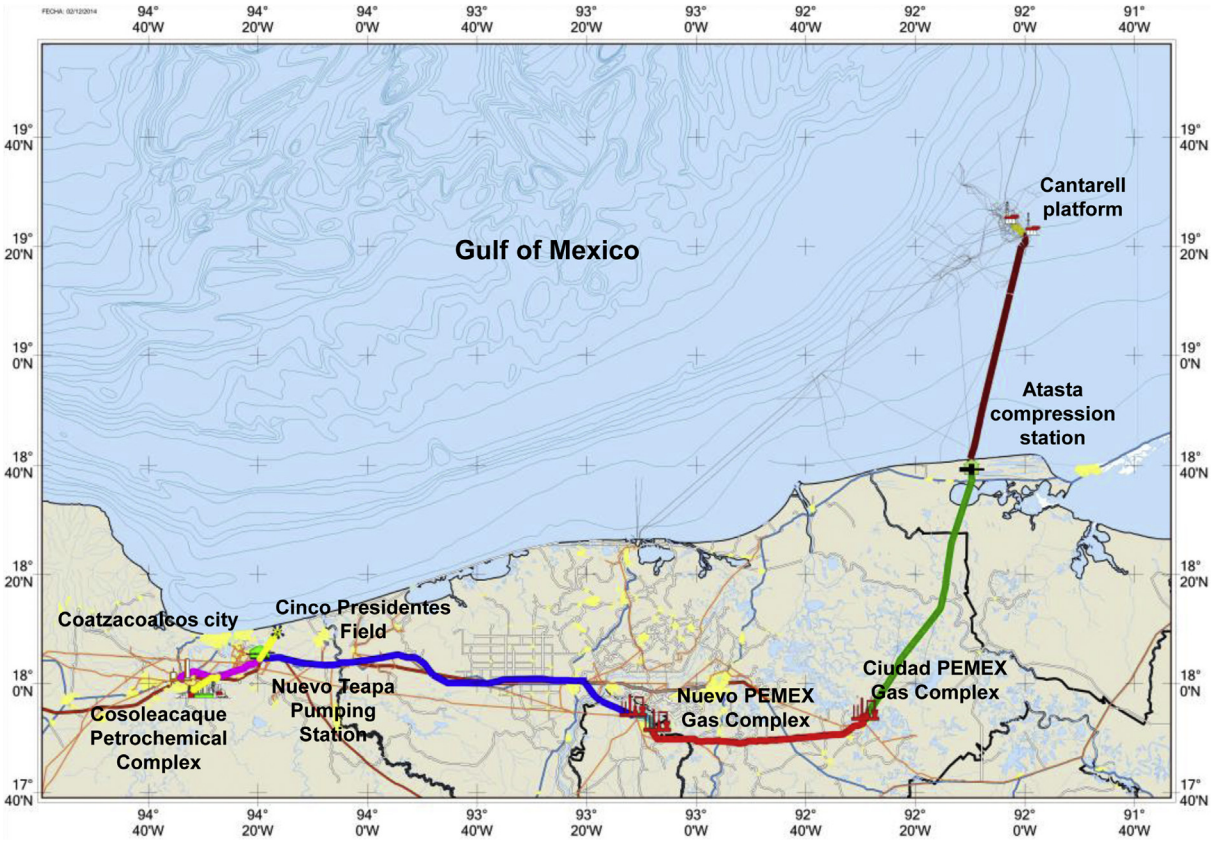

Fig. 3. Study area, trajectory and distance (500 km) from pipeline.

Table 2
Description of the CO_2-EOR subsystems (Adapted from Makhlouf et al., 2015).

Subsystems		Operation units studied	Facility	Functions performed
I	Extraction NG	Extraction and pumping of associated natural gas to Atasta station boosting center (SBC) and then to Nuevo PEMEX Gas Processing Complex (NPGPC). Include separation of natural gas; gas compression; gas NG transport; recompression.	Offshore platform oil and gas and SBC	Natural gas extraction
II	NG processing	Cooling dehydration; separation of gas and liquid hydrocarbons; fractionation; recompression	NPGPC	Liquefaction-compressions
III	Ammonia production	Desulphurization; Primary reformer; Secondary reformer; Shift conversion; CO2 removal; Methanation; Compression; Ammonia synthesis	CPC	Ammonia production
IV	CO_2-EOR	Extraction and pumping of oil recovery to Minatitlan Refinery	Mature oil well	Oil recovery
V	Refining oil	Light, middle and heavy distillates	Minatitlan Refinery	Gasoline, diesel production
VI	Refinery product combustion	Gasoline combustion	Car	GHG emissions

manufacturing processes from PEMEX data. The non-combustion emissions (gas transmission pipeline and CO_2 transport, pipeline leaks, process vents) were estimated according to the EF established by American Petroleum Institute, API (2009), as well as the API SPEC 5L: Specification for Line Pipe, for the emission factor of the CO_2 transport (API, 2011). It was considered necessary to remove 1355 Nm^3/day of natural gas for each ton of NH_3 in the CPC, which is equivalent to 0.0077% of the total NG production at Cantarell, to establish the amount of natural gas to be subtracted from the offshore platform Cantarell for the CP CO_2-EOR project. Finally, it was necessary to do the correction for the actual composition of methane in the handled gas, and therefore CO_2 emissions were calculated by the ratio of methane (CH_4) to CO_2 in the gas produced. Table 3 shows the key input parameters utilized in the model of the CO_2-EOR project.

2.2.1. Establishment and guide calculation

2.2.1.1. API. The LCI emissions were calculated according to Tables SI–1 (Supporting Information) and reported in CO_2-equivalent (CO_{2e}) units. Section 3-technical considerations of the Compendium of GHG methodologies for the oil and natural gas industry (Americam PI, 2009) were used to obtain the results of the GW. The calculation of emissions where direct monitoring results are not available involves the use of an activity factor, such as fuel consumption or flow to flare/vent, and an emission factor for each source (s) and emission gas (i). By multiplying the activity factor (AF) by the emission factor (EF), the masses of emission gas can be calculated. Equation (1) results from applying Tables SI–1 to obtain

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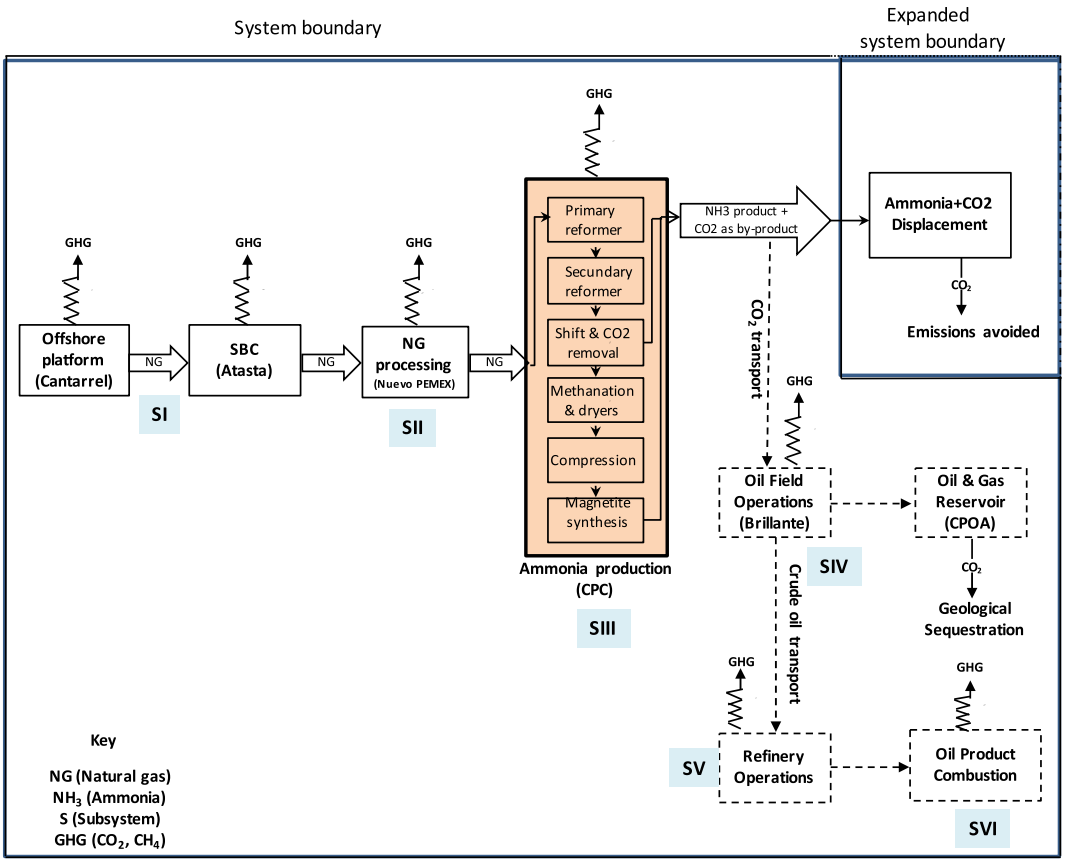

Fig. 4. System boundary for Brillante CO_2-EOR project using CO_2 derived from ammonia process for EOR.

Table 3
Sum up of key input parameters utilized in model of CO_2-EOR project model (adapted from Hussain et al., 2013).

Input parameter/project emissions	Parameter value	Reference
Oil production ratio/EOR process efficiency (Barrels oil extracted per net metric ton CO_2 injected)	7.07 bbl/tCO_2	Arteaga-Cardona et al. (2015)
Geological sequestration of CO_2 during EOR	0.20 tCO_2/bbl	Hussain et al. (2013)
Refined oil product combustion emissions	0.44 t/bbl	INECC (2014)
CO_2 capture efficiency	97.5%	Ammonia plant in CPC
CO_2 leakage rate	0.01%/year	Van der zwaan and Smekens (2010)
Electricity use emissions (PEMEX)	460 kg CO_{2e}/MWh	Own estimate
Refinery operations (tCO_2/bbl oil refinery)	0.03	ARI and Melzer Consulting, 2010
CCS capture efficiency (Brillante field)	50% or 0.263 tCO_2/bbl	Arteaga-Cardona et al. (2015)
CO_2 transport	2.9602E−5	API, 2011
Gg CO_2/km of pipeline per year		
Crude oil transport (gCO_{2eq}/bbl)	6.49E−5	Own estimate
EOR field operations (CO_{2e}/bbl)	0.06	Hussain et al. (2013)
Ammonia plant	0.260	Own estimate
Feedstock gas/combustion (tCO_{2e}/bbl)		

the GHG inventory of the six subsystems, i.e. the sum of all the emissions for a particular facility used:

$$M(is) = EF(is) \cdot AF(s) \quad (1)$$

where:

M (is) = is the emitted mass of a particular emission gas (i) for a given source (s); EF (is) = is the emission factor for the emission gas (i) relevant to the emission source (s); AF (s) is the source (s) activity factor.

To calculate CO_{2e}, equation (2) was used and incorporated in Table SP-1.

$$CO_{2e}\text{tonnes} = \sum_{i=1}^{\#\ \text{GreenhauseGas Species}} (\text{tonnes}_i \cdot GWP_i) \quad (2)$$

where:

CO_{2e} = carbon dioxide equivalent emissions (ton); tonnes_i = GHG emissions of pollutant *i* (tonnes); and GWP_i = global warming potential of pollutant i. (i.e.CO_2, (1), CH_4 (25), N_2O (298)) (tonnes CO_{2e} per ton i).

An emission factor (default and calculated from tables of API or

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another source) represents an average emission rate for a given source, and is generally expressed as a mass or volume of emissions per source type or measure of activity related to the source.

As shown in Tables SI–1, step 1 consists of making a list of number of facilities and type of activity GHG emissions (columns a and b), step 2 add the EF (column c) for type of activity and step 3 multiply and add up to the total emissions as CO_{2e} (column i).

2.2.1.2. Umberto software (US). In the construction of LCI for US, the next step was to adjust the input/output material and then process the six subsystems in Umberto according to the EF of Table 3, as well as the composition and amount of natural gas, to estimate GHG emissions as CO_{2e} for the CO_2-EOR project.

2.2.2. Displacement and allocation of coproduct management

Systems operations produce ammonia and CO_2, in addition to petroleum as by-products. Thus system boundary expansions and displacements were used to allocate lifecycle GHG emissions between petroleum and ammonia (ISO, 2006b).

Given the process characteristics, in which the NG functions as feedstock and fuel, the proportion of mass for each activity was used as a method of assignment, with the aim of reflecting the value of the ammonia product and the CO_2 as subproduct. Since the production of 1 ton of ammonia requires 1355 NM^3 of NG consumption (Feedstock + fuel), generating CO_2 as a by-product (Table 4), the amount of feedstock consumed in the process was calculated (749 NM^3/tNH_3). This value was used to determine the total amount of ammonia displaced by the system, representing the emissions credits (Fig. 4).

Therefore, an allocation factor of 55.2% was subtracted or considered as emissions avoided and used for displacement.

Negative emissions (credits) associated with geological sequestration of CO_2 during EOR were calculated based on storage factor reported by Hussain et al. (2013) and corresponding to about 0.20 tCO_{2e}/bbl.

2.3. Impact assessment of API and US

The life cycle of GHG emissions was quantified using "global warming" (GW), expressed in emissions of CO_2 equivalent (CO_{2e}) as the environmental indicator. The life cycle is considered as the established FU for both API and US.

The mandatory and optional elements of the LCA according to ISO 14040 were used in both methodologies. The time horizon resulting from the use of primary and secondary energy from fossil fuels: (1) time horizon characterization (for calculating GWPs) and (2) time period of assessment (the period over which GHG emissions and removals from a product system) was considered (Levasseur, 2015). The main impact category analysed in this study was GW expressed in emissions of equivalent CO_2 (CO_{2e}) and referred to the established FU: one barrel of crude oil extracted and consumed for both tools.

API. Analytically, with the application of equations (1) and (2) in Tables SI–1, the CO_2 and methane (CH_4) emissions were calculated and reported as CO_{2e} (see first column to the right) using 100-year GWP (Intergovernmental Panel Climate Change, IPCC, 2007) as well as for that established by API (2009) and the Project's nine year lifetime (CCS phase) (Arteaga-Cardona et al., 2015). This time period was adopted for both tools given that CO_2 is the main contributing pollutant. It is important to manage the risk of CO_2 migration through monitoring, verifying and reporting (Bandza and Vajjhala, 2014), given the CO_2 stored by the CO_2-EOR operation. Lastly, the aim is to confirm that combining CO_2-EOR with storage integrity is a promising strategy for GHG reduction.

US. The environmental impacts were quantified by LCA applying Umberto Universal 5.3 software based on the ReCiPe methodology (Goedkoop et al., 2009) and Ecoinvent 2.2 database of material in Umberto. The model of ReCiPe used for this CO_2-EOR system included the application of life-cycle of fossil fuel GHG emissions, involving six subsystems. In this sense, LCA studies have already been employed for the assessment of the CCS technology, which have used ReCiPe Method with Umberto software (Xiao et al., 2014), and Volkart et al. (2013) with SimaPro v7.3.3 software.

Finally, lifecycle GHG emissions and inputs/outputs for CO_2-EOR as metric tons of CO_2 equivalent emissions per barrel of crude oil extracted (tCO_{2e}/bbl) for both tools in each process step, as well as net GHG emissions, are presented to ensure net emission reduction and allow the addressees to evaluate directly a set of relevant inventory data for capture and storage (EOR/CCS) activities, together with a measure of the performance of the whole process.

3. Results and discussion

3.1. Life cycle GHG CO_2-EOR project

Table 5 shows the results of the net GHG emissions for each of the six subsystems and the sixteen steps, along with assessment of results between both tools in CO_2-EOR. For each process step, the values are reported as metric tons of CO_{2e} per barrel of oil extracted (tCO_{2e}/bbl). The total emissions represent the carbon footprint (i.e. GW) for the whole chain.

The GW impact estimated by the API together with the life cycle analysed was 0.88 tCO_{2e}/bbl, only 2.0% higher than US (0.85 tCO_{2e}/bbl). These results do not consider displacement and allocation of emissions. No significant differences between both tools by subsystems or stages were found.

In subsystem III, representing the production of ammonia and transport of CO_2 to the Brillante CO_2-EOR project, the average estimation of GW was of 0.266 tCO_{2e}/bbl, with a contribution of 30.8% of the total emissions (Table 5). These emissions would be generated by ammonia production, compression (electricity), transport and fugitive emission of the total GHG emissions. Subsystems II and V, the operation units, provided the lower emissions. The upstream emissions from the NG extraction on the offshore platform in Cantarell to NG processing were 4.4%. This value is 126.7 times higher than that of upstream emissions reported for Natural gas NGCC CO_2-EOR, but with values almost similar to the Coal SNG plant CO_2-EOR values of 0.02 tCO_{2e}/bbl (Hussain et al., 2013). Lacy et al. (2015) found a GWP impact for this stage of 0.139 tCO_{2e}/bbl, which included construction, operation and dismantling of pipelines and oil wells activities.

Fig. 5 shows the GHG emissions by principal activities. Both LCA-US and API identify that both refinery combustion products and transformation processes represent 50.7% and 30.8% of the total

Table 4
Method of allocation on the basis of the natural gas use as raw material.

Function	Inputs	Used	Unit	Quantity	Allocation factor (%)	Output
Ammonia plant	NG	Process gas (NH_3+CO_2)	NM^3	749	55.2	NH_3+CO_2
	Gas dryers	Fuel	NM^3	606	44.7	Flue gas

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Table 5
Comparisons of the estimating GHG emissions by subsystem and stages with US and API methods (tCO_{2e}/bbl).

Subsystem	Stage	Process	Tools GW (tCO_{2e}/bbl)					
			US			API		
			Emission	%	Emissions for subsystem	Emission	%	Emissions for subsystem
I	1	Oil and gas Marine NE (APC) Cantarell	0.019	2.2	0.03	0.034	3.8	0.04
	2	Gas compression (APC)	0.006	0.7		0.002	0.2	
	3	Pipeline gas transport (APC to Atasta)	0.002	0.2		0.001	0.1	
	4	Gas compression (Atasta)	0.005	0.5		0.003	0.3	
	5	Pipeline gas transport (Atasta to Nuevo PEMEX)	0.004	0.4		0.002	0.2	
II	6	NG sweetening plant (Nuevo PEMEX)	0.015	1.7	0.02	0.035	4.0	0.04
	7	NG (Dry) compression	0.005	0.5		0.003	0.3	
	8	Pipeline NG transport (Nuevo PEMEX to CPC)	0.004	0.5		0.002	0.3	
III	9	Ammonia plant (CPC)	0.259	30.5	0.26	0.270	30.7	0.27
	10	CO2 compression (CPC to CP EOR Project)	0.001	0.2		0.001	0.2	
	11	Pipeline CO2 transport (CPC to CP field)	3E−05	0.0		3E−05	0.0	
IV	12	Operation CO2-EOR (Brillante field)	0.060	7.1	0.06	0.060	6.8	0.06
	13	Oil recovery pumping (CP field to Minatitlan Refinery)	2E−05	0.0		2E−05	0.0	
	14	Oil recovery transport to Minatitlan Refinery	6E−05	0.0		6E−05	0.0	
V	15	Refining oil (Minatitlán Refinery)	0.032	3.8	0.03	0.030	3.4	0.03
VI	16	Refinery product combustion	0.44	51.6	0.44	0.44	49.7	0.44
Total emissions			**0.85**	100.0	**0.85**	**0.88**	100.0	**0.88**

GHG emission, representing 81.5% of the net direct emissions, with similar values in both methodologies. This result was comparable to the GHG emissions of a CO_2-EOR case in the power sector, since the majority of the emissions are from combustion of refined petroleum products (Venkatesh et al., 2011). Additionally, some studies assume that EOR crude from fossil CO_2 is less CO_2 intensive than EOR crude from natural dome CO_2, albeit with the same efficiency of production regardless of CO_2 source (Cooney et al., 2015).

The remainder (18.5%) corresponds to other activities. In the upstream emissions, this study found more contrasting results for each of the methodologies used than LCA-CCS studies calculating CO_2 resulting from power generation.

The contributions by transport and compression were 2% of the net emissions, with CO_2 representing 72% and methane 28%. These values agree with those reported by Zapp et al. (2012). The length of the pipeline has the smallest effect. Spath and Mann (2004) estimated a share of transport on total GW increasing from 0.1% for 300 km to 1% for 1800 km pipeline length.

Table 6 shows that for each MJ used to produce energy from the CO_2-EOR project, 66 tCO_{2e}/MJ oil are emitted in US, whilst the API predicts that, on average the emissions were 72 tCO_{2e}/MJ oil. If it were considered that on average Mexican oils have 6382 MJ/bbl, in this project, only 1% of the total energy generated would be required to produce one barrel. On the other hand, this result is 36.2% higher when compared to that obtained by Lacy et al. (2015) from a hypothetical CCUS case in a natural gas combined cycle power plant (NGCC). They reported values of 44.0 tCO_{2e}/MJ.

It is important to point out that 1350 MJ/tCO_2 are needed to capture one ton of CO_2 as by-product at the ammonia plant, 58% lower than that reported from thermal generation processes of electricity with CO_2 capture (Rochelle et al., 2011). As 4632 tCO_2/d could be sent into the atmosphere in the four ammonia plants from the CPC, then primary energy is being wasted to the equivalent of 6,253,2 GJ/d, a loss of primary energy that could generate 980 bbl/d.

Table 6
Comparison of energy uses with each barrel recovered (tCO_{2e}/MJ).

Subsystem	US	API
I	5.60	6.66
II	3.73	6.44
III	42.14	43.93
IV	9.71	9.71
V	5.16	4.85
Average[a]	66	72

[a] Is not considered the Subsystem VI.

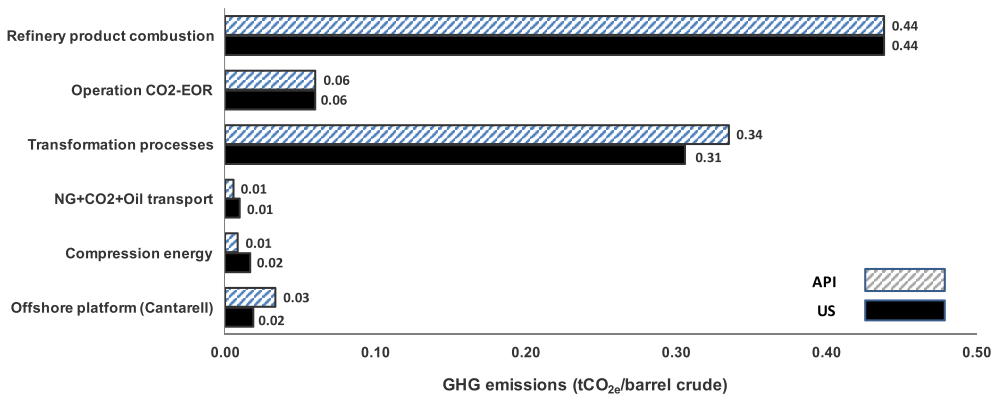

Fig. 5. Contribution lice cycle GHG emissions of main activities.

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Table 7 provides the input/output results expressed in metric tons of CO_{2e} emissions per barrel of crude oil extracted (t/bbl) for each process step and for both tools. With the API method, the result was 0.54 tCO_{2e}/bbl, higher than that predicted by the US with 0.51 tCO_{2e}/bbl. This value is similar if compared to the natural-source and Coal SNG plant CO_2-EOR, and to the average domestic U.S. oil (Hussain et al., 2013) lifecycle emissions factor of 0.50 ± 0.02 t/bbl (Fig. 6). However, it is lower than the result of the life cycle EF of Mexican crude oil of 0.55 tCO_{2e}/bbl reported by Mangmeechai (2009), which includes extraction, transportation, and refining emissions. The slight differences between tools are in the upstream emissions. These minor differences between API and US are due to the relationships between the assumptions and boundary issues that have an impact on the magnitude of the calculated life-cycle emissions. In this regard, the same study can give differing results in likelihood because a different boundary system exists in the process, as well as the material inventory in Umberto at upstream emissions with respect to API. This comparison helps to demonstrate that the choice of boundary, assumptions or accounting methods can have an impact on the end results of the LCA studies.

3.2. Other environmental impacts from the Brillante CO_2-EOR project

Table 8 shows the resulting life cycle assessment impact (LCIA) obtained with US for the whole project.

Fossil depletion registers a value of 4109 kg of oil in the six subsystems. This value represents an equivalent to 0.172 TJ used energy and 5.18 m^3 for water depletion along the value chain. Next to the climate change category, human toxicity is the most important environmental impact category with a value of 44.5 kg 1,4-DCB.

3.3. Assessment of the energy balance

To analyse the storage factor of the Brillante CO_2-EOR project, Arteaga-Cardona et al. (2015) study results were used. Their estimations were based on CO_2 miscible flood predictive models. CO_2 injection is expected to further decrease the sharp decline in pressure of the Brillante field, and increase oil production up to 5900 bpd by injecting 15×10^6cubit feed per day (834 tCO_2/d), for a total of 22×10^9 standard cubic feet (Bscf) throughout the nine-year duration of the project. A cumulative oil production of 5.2 million bbl is expected, with the added benefit of sequestering approximately 50% or 1.3 Mt of the CO_2 injected to the field. This storage factor does not take into account direct and indirect emissions by the EOR operation, so this must be recalculated adjusting the retention rates, which tend to be lower than 50%. Additionally, this result is 10–20% higher to that reported by Leach et al. (2011), who gave a value of approximately 30–40% of the CO_2 injected during a single injection, which typically remains trapped in the reservoir. It is important to point out that retention rates within a CO_2-EOR operation vary depending on the reservoir properties, injection strategy and oil gravity along with other factors. Therefore, according Arteaga-Cardona et al. (2015), considering GHG emissions in the EOR operation, CO_2-EOR Brillante project has storage factors of 203.9 $kgCO_2$/barrel of oil produced, this being within the range of that reported in other cases of EOR operations of 170–300 kg CO_2/barrel of oil (Stewart and Haszeldine, 2014). CO_2 recovered from the reservoir will be re-injected and not vented, meaning that 7.07 barrels oil extracted per net metric ton CO_2 are injected. This value is of interest and is in contrast to that reported by McCoy and Rubin (2008) and Hussain et al. (2013), with values of 4.6 bbl/tCO_2 or compared to the average US figure of 3.8 bbl/tCO_2 (Stewart and Haszeldine, 2014). NTEL also (2010) reported 4.35 bbl/tCO_2 for tertiary injection EOR best practices based on a water alternating gas (WAG). Therefore, an increment in the crude recovery ratio reduces the amount of CO_2 required and the corresponding CO_2 storage (Cooney et al., 2015). As it has been indicated by Dai et al. (2014b), these different results suggest that CO_2 injection/storage and oil/gas recovery rates are the major intrinsic reservoir parameters. For instance, in the case of the Artesa CO_2-EOR project in Mexico, Leon-Garcia et al. (2015) found a value of 2.2 bbl/tCO_2. These recovery rates are different to those of the Brillante project, despite the Artesa project being located in the same region in Tabasco State, but with different geology.

With respect to the effectiveness of CO_2-EOR projects to store net CO_2, if the reasoning of Faltison and Gunter (2011) regarding world oil production being controlled by demand is considered, implementing CO_2-EOR projects will not result in incremental aggregate oil consumption emissions. Thus, this approach is made under the assumption that if oil were not produced by CO_2-EOR, then another source would have to be developed to fill the gap. The study states that only relevant fugitive emissions that are directly associated with the CO_2-EOR project should be included in the life

Table 7
Lifecycle GHG emissions and inputs/outputs for EOR (metric tons of CO_{2e} per barrel of oil extracted) (adapted from Hussain et al., 2013).

Process inputs/outputs	Ammonia plant–CO_2–EOR (US)	Ammonia plant–CO_2–EOR (API)
Feedstock used NG (t)	406	406
Ammonia product (t)	1	1
CO_2 generated as byproduct (t)	1.4	1.4
Upstream emissions (Offshore)	0.019	0.034
Feedstock gas/combustion (Ammonia)	0.260	0.270
NG compression	0.015	0.007
Pipeline NG transport	0.009	0.005
NG Sweetening plant	0.015	0.035
CO_2 compression	0.001	0.001
Pipeline CO_2 transport	0.00003	0.00003
Oil field operations	0.060	0.060
Geological sequestration	−0.20	−0.20
CO_2 leakage (100 years)	0.002	0.002
Crude oil transportation	0.0001	0.0001
Refinery operations	0.032	0.032
Oil product combustion	0.44	0.44
Ammonia/CH_4 Displacement	−0.14	−0.14
Total (tCO_{2e}/bbl)	**0.51**	**0.54**
Energy to produce 1 bbl (MJ)	**66**	**72**

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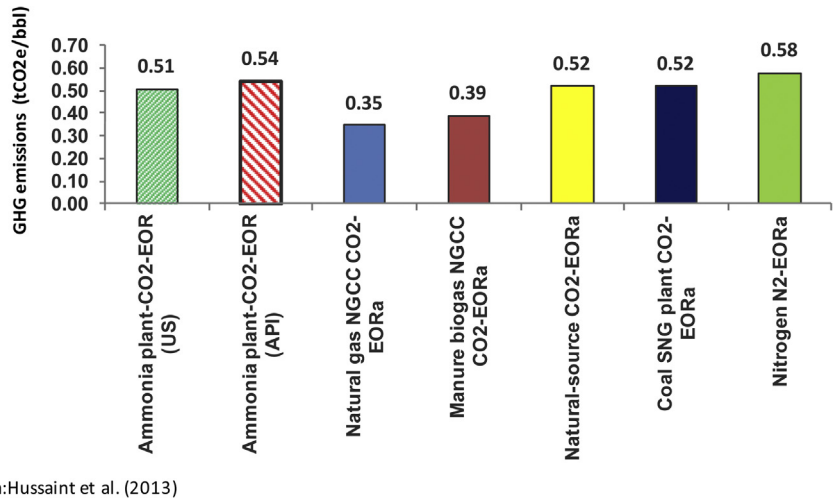

Fig. 6. Comparison results amongst this study versus lifecycle GHG emissions per barrel of oil extracted using different EOR methods.

Table 8
LCIA results of ReCiPe for the production of 1 barrel of CO_2-EOR project.

Midpoint impact category	Unit	Result/FU
Agricultural land occupation	m^2a	0.05
Climate change	t CO_{2e}	8.53E−01
Fossil depletion	t oil	4.11E+00
Freshwater ecotoxicity	t 1,4-DCB	4.60E−04
Freshwater eutrophication	P	1.46E−06
Human toxicity	t 1,4-DCB	4.45E−02
Ionising radiation	U235	4.41E−03
Marine ecotoxicity	t 1,4-DCB	1.19E−03
Marine eutrophication	t N	8.60E−04
Metal depletion	t Fe	1.80E−04
Natural land transformation	m^2	1.76E−04
Ozone depletion	t CFC-11	1.19E−07
Particulate matter formation	t PM10	7.70E−04
Photochemical oxidant formation	t NMVOC	7.16E−03
Terrestrial acidification	t SO2	1.56E−03
Terrestrial ecotoxicity	t 1,4-DCB	1.10E−04
Urban land occupation	m^2a	0.04
Water depletion	m^3	5.18

cycle assessment of the project. Consequently, product refining and combustion in the system boundary of the analysis should be discounted.

From this point of view, if only subsystems III (Ammonia plant) and IV (EOR operation in CPOA) are considered, for every barrel of petroleum recovered, subtracting the geological sequestration and the displacement for ammonia production as avoided burden would, on average, produce a value of 0.03 tCO_{2e}/bbl.

The Brillante CO_2-EOR project case comes with additional useful energy (Faltison and Gunter, 2011) due to the 'additional oil', not being used. Table 9 shows that with the energy provided by the 834 tCO_2/d from the ammonia plant, equivalent to 3699 TJ, the Brillante CO_2-EOR project would provide primary energy additional to 33,189 TJ during EOR operation. This means that with only 11.1% of energy (i.e. 834 tCO_2/d), the net energy generated would be 28,488 TJ, along with economic profits. Without the project, there would continue to be a loss of energy by continual venting of CO_2 into the atmosphere, equivalent to 16,751 TJ, without taking economic profits into account. Hence, when compared with the average US figure of 3.8 bbl/tCO_2 of energy generated, which is the equivalent of 0.024 TJ/tCO_2, the Brillante CO_2-EOR project would provide 53.3% of additional energy.

Table 10 shows the main key indicators of the Brillante CO_2-EOR project, which included the upstream and downstream emissions.

Due to the fact that the current storage factor is very low because of their immiscibility characteristics and given that the results were obtained based on a CO_2 miscible predictive model and not by Huff & Puff tests (pilot tests in the field), verification of the operational parameters and CO_2 storage factor with an immiscible model would be worthwhile. It would be important to consider incorporating a separation and re-injection system for the CO_2 (CO_2 recycle plant), which is mixed with the oil in order to make a "closed loop" system. This approach CO_2-EOR + CCS would allow the CO_2 storage factor ratio to be increased whilst decreasing crude recovery (Cooney et al., 2015).

4. Sensitivity analysis

A sensitivity analysis (SA) was undertaken on three important assumptions used in the study. The scenarios were as follows:

SA1: Use of specific emissions values for the Brillante EOR field operations.
SA2: Changing values of geological sequestration with the change of emissions in EOR field operations.
SA3: Potential CO_2 capture flue gas from primary reformer of ammonia plant, using an old CO_2 capture unit (MEA solutions) from ammonia plant I.

The emissions from EOR field operation are important as they have a significant impact on the GW impact results in the study. Given the facilities (Table 2) and production at the Brillante field (Arteaga-Cardona et al., 2015), this study estimated, using equations (1) and (2), an emission of 0.015 tCO_{2e}/bbl for EOR field operations. This sensitivity recognizes the variations in the emissions of EOR field operations from 0.060 (see Table 3) up to 0.015 tCO_{2e}/bbl. The sensitivity is based on an emitted value that is 75% lower than the Hussain et al. (2013) study. However, it is important to comment that this study does not take into account GHG emissions from the operation of the CO_2 recycling plant; therefore, the value used for EOR operations in Brillante must exceed 0.015 tCO_{2e}/bbl.

When post-combustion CO_2 capture through process simulations (PS) was done assuming a new emissions value for the EOR operation, the geological sequestration changed from −0.203 tCO_{2e}/bbl (base case) to −0.248 tCO_{2e}/bbl or 18.1% more of CO_2 storage.

Table 9
Comparison effects amongst without and with Brillante CO_2-EOR project.

		Unit	Without project	With project
CO_2 vented in the Ammonia plant (Four)	a	t/d	4632	
CO_2 injected Brillante field	b	t/d	0	834[a]
Duration of EOR operation	c	y		9[a]
Total CO_2 injected during EOR operation	d = b·365·c	t	0	2,739,690
CO_2 storage	e	t/d	0	417[a]
Annual CO_2 storage	f = e·365	t/y	0	152,205
Total CO_2 storage during EOR operation	g = f·c	t	0	1,369,845
Additional oil recovered by EOR	h	bbl/d	0	5,900[a]
Oil production ratio/EOR process efficiency	i = h/b	bbl/tCO_2	0	7.07
Net increase in oil production as a result of EOR operation	j[a]	bbl	0	5,200,000
Storage factor CO_2	k = g/j	tCO_2/bbl	0	0.263
Emissions of oil field operations	l	tCO_{2e}/bbl	0	0.060
Net storage factor	m = k−l	$kgCO_{2e}$/bbl	0	203.4
Price one barrel	n	USD/bbl	0	25
Economic benefits by selling additional oil	o = j·n	MUSD	0	130
Energy of one barrel oil	p	MJ/bbl	0	6382
Produce primary energy by EOR	p = j·p	TJ	0	33,186
Energy needed to capture one ton of CO_2	r	MJ/tCO_2	1350	–
Total loss energy by vented CO_2 from ammonia plant	s = a−b·r·365·c	TJ	16751	–
Successful use of energy of CO_2 from ammonia plan during EOR operation	t = b·r·365·c	TJ	0	3699
Net energy generated by the EOR project	u = p-t	TJ	0	29,488
Energy generated/EOR process efficiency	v = i·p	TJ/tCO_2	0	0.045

[a] Arteaga-Cardona et al. (2015).

Table 10
Key findings.

CO_2-EOR performance	Unit	Value
Gross sequestration benefit	tCO_2/bbl oil produced	0.203
Energy consumption	MJ per MJ oil produced	0.010
Energy for CO_2 capture from ammonia plant	MJ/$kgCO_2$	1.35
Incremental oil produced	Mbbl	5.2
Energy generated/EOR process efficiency	TJ/tCO_2 injected	0.045

Results show that 372,426 tons/year of CO_2 may be captured from flue gas of the primary reformer of an ammonia plant of 480,000 tons/y of capacity (Morales-Mora et al., 2016). The emissions of the ammonia plant are 0.26 tCO_{2e}/bbl. This study carried out an LCA for this new scenario in the ammonia plant; the result of CO_2 capture shows a new value of 0.105 tCO_{2e}/bbl, i.e. a CO_2 emissions reduction of 40%. The results of these scenarios were incorporated (Table 7) to visualise the variation of new GHG emission results per barrel extracted.

Fig. 7 shows the change in the GW results depending on the assumptions made for the oil field operation, geological sequestration and CO_2 capture from flue gas from the ammonia plant, and their comparison with the base case (US) and NGCC CO_2-EOR.

For scenario one (S1), the results show that the GW impacts have 7% lower emissions per barrel of oil extracted with a new value of oil field operation with respect to the base case (Ammonia plant−CO_2−EOR, see value US of Table 5). However, the emissions are still 34% higher with respect to the NGCC CO_2-EOR case (Hussain et al., 2013). The results of the sensitivity analysis for S2 show an appropriate response to the induced modifications of geological sequestration which showed the same behaviour, with a reduction of the total emissions per barrel extracted from the 17.6% for base case, but still superior at 20% to the NGCC CO_2-EOR case. The sensitivity analysis for S3 shows a positive impact as a consequence of the potential capture of 1000 t/d of CO_2 gases from combustion of the primary reformer of the ammonia plant. This variable results from implementing post-combustion CO_2 capture from the ammonia plant. It can be observed that with a combination of the three scenarios, the CO_{2e} per barrel produces a reduction in the total CO_2 emissions on the EOR system of the order of 49% in comparison with the base case and 25.7% with respect to NGCC CO_2-EOR case. Consequently, post-combustion CO_2 capture in the ammonia plant may represent a relevant factor to consider for reducing CO_{2e} emissions and increase the energy efficiency of a CCUS system.

5. Conclusions and recommendations

Both LCA and API tools produced accurate estimations of the GHG emission in the EOR system for the oil and gas industries. The differences between both tools were in the upstream emissions (subsystem I and II), with a ratio of 0.42−3.5, which are not relevant since these subsystems contribute only eight per cent of the total emissions. At the downstream emissions (Subsystem III to VI), no differences were found in the results for both methodologies with a ratio close to 1. This lack of difference between the US and API is owed to the adjustment to the conditions of the EF of the oil and gas sectors for Mexico Ecoinvent in Umberto materials and processes.

Both tools appear to be clear, fast and comprehensive for the purpose of LCA-CCS studies, which can be used within the particularities of the oil and gas industries in Mexico. The API used to estimate the GHG emission in the oil and gas sector projects was validated and can be applied through calculations performed 'manually' in a spreadsheet by practitioners and researchers intending to analyse the GHG emission of CCS. This comparison allows the estimation and acknowledgement of GHG emissions in the whole chain of value of the project; as well as the energy demand to produce one barrel of oil through EOR. The results of the comparison between both tools prove that API made an accurate calculation of the life cycle emissions to the EOR system when US with standard databases are not available. Overall, the use of CO_2 process stream in the petrochemical sector for the EOR system in Mexico registered a lower environmental footprint, but slightly higher in comparison with alternative CO_2 sources for CO_2-EOR, to coal or NG combustion (Pulverized coal-fired PP, Integrated gasification CC, NGCC). The use of different boundary systems, databases, allocation of by-products, functional units (1 MWh or kWh of Electricity) and technologies for CO_2 capture in the LCA-CCS study, make it difficult to make comparisons when assessing the environmental performance from power plants versus process stream of the oil and gas sectors.

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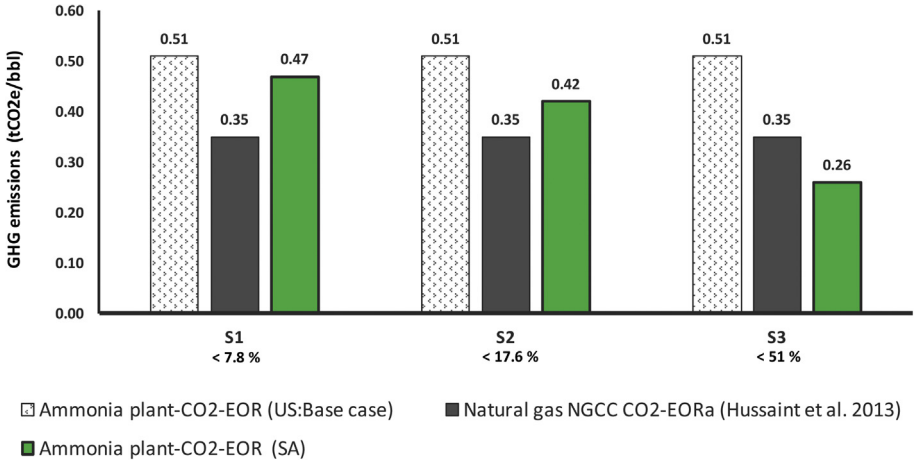

Fig. 7. Effects of GHG emissions results for oil field operation (S1), geological sequestration (S2) and CO_2 capture from flue gas ammonia plant (S3) using different perspectives.

The energy balance is positive because, with CO_2-EOR, LCA from the oil and gas industries has so far received little attention, in spite of being an important tool to address and compare different technological options. From the standpoint of energy efficiency, the Brillante CO_2-EOR project provides 46% of additional primary energy, than average, of CO_2-EOR in the U.S. (3.8 bbl/tCO_2). The total CO_2 storage during the EOR operation could achieve 1.3 million tons. In spite of the limited availability of LCA literature on process streams from petrochemical or refining processes to CCS or EOR, these technologies will generate the lowest relative increase in the environmental impact categories.

Based on the results of this study, the use of manual calculations for studies on LCA-CCUS is recommended, where quick adjustments or updates at the EF regional or local level can be made at any time in the worksheets, in accordance with operative guidelines determined by the oil and gas companies in contrast to the Ecoinvent database.

Acknowledgments

The authors would like to thank the Gregory Conney and Timothy J. Skone of National Energy Technology Laboratory-LCA U.S. Department of Energy for their comments, which helped to clarify and improve the presentation of the results of this work and to Maria del C. Avalos Islas for her invaluable support and contributions to this study. Moreover, the authors would like to acknowledge Mr. Emiliano Leiva and Dr. Anya Leiva for the final writing of the text.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2016.12.114.

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