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Overview of World Bank CCUS Program Activities in Mexico

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Abstract

This paper describes Phase I of the World Bank Group's (WBG) technical assistance project for the development of carbon capture, utilization and storage (CCUS) in Mexico. Phase I was concluded in early 2016 and saw the completion of three studies:

1. A pre-feasibility study of a proposed post-combustion capture (PCC) pilot plant at a natural gas-fired combined-cycle (NGCC) power plant in Mexico. This study, carried out by NEXANT Inc. under a consultant's assignment from the WBG, included a comparative techno-economic evaluation of six advanced amine-based PCC technologies and a generic amine-based conceptual pilot plant design.
2. A review of state-of-the-art practices related to combining carbon dioxide-enhanced oil recovery (CO_2-EOR) with geological storage of CO_2 in Mexico. Specifically, this review, conducted by the Battelle Memorial Institute under a consultant's assignment from the WBG, assessed the requirements a CO_2-EOR project must satisfy in order to qualify as a permanent storage project and earn carbon credits.
3. A study of the development of a CCUS regulatory framework for Mexico. This study, prepared by Milieu Ltd. under a consultant's assignment from the WBG, undertook a comprehensive and in-depth assessment of the current regulatory framework in Mexico as it pertains to CCUS, identified critical gaps and barriers that are expected to impede the development and implementation of CCUS, and made a series of recommendations for overcoming these and barriers.

These three studies, funded by the WBG administered Trust Fund for Carbon Capture and Storage Capacity Building in Developing Countries (WB CCS TF), form the foundation for further work and will benefit the implementation of the planned

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pilot projects. The subject studies were also important for building capacity, increasing the awareness of CCUS among the various stakeholders in CCUS and building up their capacity, in line with the objectives of the WB CCS TF.

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Keywords: World Bank Group; Mexico; CCS; CCUS; developing country; CO_2 capture; CO_2 storage; CO_2 utilization; CO_2-EOR; pilot projects.

1. Introduction and Background

1.1. The World Bank Group (WBG)

The WBG has been engaged in providing assistance to its partner developing countries in carbon capture and storage (CCS) capacity building since the establishment of the WB CCS TF in December 2009. The donors of the WB CCS TF include the Governments of the United Kingdom and Norway, and the Global Carbon Capture and Storage Institute (Australia). The objectives of the fund are to support strengthening capacity and knowledge sharing, create opportunities for WBG partner developing countries to explore their CCS potential and facilitate the inclusion of CCS options into low-carbon growth strategies and policies being developed by national governments and institutions.

In 2013, the WB CCS TF and the Government of Mexico (GoM), represented by the Department of Energy (SENER, for its Spanish acronym), agreed to fund the first phase of a technical assistance project to strengthen the capacity of domestic energy sector institutions in Mexico in the area of the design, development and implementation of CCUS policies, programs and projects as part of a set of climate change mitigation measures aimed at supporting the country's low-carbon development goals (note that in Mexico CCS typically includes CO_2 utilization, hence the term CCUS is usually used). This technical assistance project was jointly administered by SENER and the WBG's CCS team. The main deliverables of this first phase were the three study reports presented in this paper. The full reports can be downloaded from www.gob.mx/sener/en/documentos.

1.2. CCUS in Mexico

Although Mexico is committed to reduce its greenhouse gas (GHG) emissions, fossil fuels are expected to remain the country's main primary energy source until the end of the century, implying that the rising trajectory of CO_2 emissions – 456 Mt/y CO_2 in 2014 or 1.3% of global CO_2 emissions – will far exceed the 30% and 50% reduction goals (as compared to 2000 levels) established for 2030 and 2050, respectively, by the country's National Strategy for Climate Change. This situation has led Mexico to explore the potential of CCUS as part of its GHG emissions mitigation strategy. In 2014, the GoM established an 11-year CCUS Roadmap (also available from the above-noted website), which comprises five partially overlapping phases (incubation, public policy development, planning, pilot- and demonstration-scale projects, and commercialization).

The most important activities in this Roadmap, at least for the next three to five years, are (1) the construction and operation of a PCC pilot plant at the NGCC Poza Rica power plant in the State of Veracruz, and (2) the implementation and operation of a CO_2-EOR storage pilot project in the Cinco Presidentes oilfield (also located in the State of Veracruz). The studies reported in this paper form the foundation for these two pilot projects.

2. Pre-Feasibility Study for Establishing a Carbon Capture Pilot Plant in Mexico

2.1. Project background and study objectives

The design, construction and operation of a PCC pilot plant to demonstrate the feasibility of capturing CO_2 from NGCC power plants in Mexico is an integral part of the Roadmap. This endeavor will create a knowledge and experience base for the various stakeholders and allow them to further advance the application of CCUS in Mexico.

A consultant (Nexant, Inc., USA) was tasked to carry out a pre-feasibility study to: 1) assess and recommend the most appropriate, commercially-available PCC technology for NGCC power plants in Mexico, and 2) develop a conceptual design for a PCC pilot plant to be located at the 250-MW Poza Rica NGCC power station in the State of Veracruz. The pilot plant conceptual design was to be developed with sufficient process detail in order to enable the preparation of a front-end engineering design (FEED) package as part of a future Phase II project activity. The FEED preparation was not part of the pre-feasibility study.

2.2. Technology selection, evaluation and recommendation of best available PCC technology

2.2.1. Prescreening and selection of PCC technologies

Based on previous work conducted by the U.S. Department of Energy and the Electric Power Research Institute, which had assessed the technology readiness level of different types of PCC technologies, as well as the consultant's own assessment of current state-of-the-art PCC technologies, the recommendation was made to focus only on solvent-based absorption processes that are commercially available and ready for near-term deployment. This recommendation was made in order to meet the WBG and GoM's time line of building and completing the operation of the Poza Rica PCC pilot plant by 2019. Ten advanced solvent-based absorption technologies were identified and selected, and their developers/licensors were asked to participate in the study. Of the ten PCC licensors contacted, six responded positively and were willing to participate, while four declined for various reasons (see Table 1).

Table 1. List of PCC technology licensors participation

Participated	**Did Not Participate**
Alstom (Advanced Amine Process)	Aker Solutions
BASF	CO_2 Solutions
Fluor	Hitachi
HTC	Siemens
MHI	
Shell Cansolv	

Based on the Design Basis developed by Nexant for the Poza Rica PCC pilot plant, a technology survey questionnaire was prepared to collect process information from the six participating PCC technology developers. Their responses, supplemented with Nexant's in-house knowledge, formed the basis for the technology screening, evaluation and comparison described below.

2.2.2. Overall NGCC performance before and after full-scale PCC retrofit

A decision was made at the start of the study that the selection of the most appropriate PCC technology for the pilot plant would be based on a comparison of the performance of the six participating PCC technologies in a full-scale PCC plant at the Poza Rica NGCC power plant,. To this end, a generic 30% monoethanolamine (MEA)-based PCC process design was developed to serve as a benchmark for comparing the six PCC technologies against, assess their claimed efficiency improvements, and fill in any missed data that were needed for a full-scale Poza Rica retrofit analysis. A companion power train model was also developed for the Poza Rica NGCC power plant in order to estimate its performance before and after the full-scale PCC retrofit.

Table 2 summarizes the overall Poza Rica power plant performance and power balance for the generic 30%-MEA design case as well as the six proprietary PCC technologies before and after the full-scale PCC retrofit. As can be seen, all six PCC technologies show a 20-25% lower heat of regeneration compared to the generic 30%-MEA case. However, within the group of six PCC technologies, the differences are rather small, only ± 3%. As a result, all six technologies demonstrate an improvement in overall efficiency over the generic 30%-MEA-base case, reducing the loss of power plant efficiency from 9.9% for the MEA case to a range of 8.4% to 9.3%.

2.2.3. Poza Rica NGCC PCC retrofit economic evaluation results

The six PCC technologies were then compared against the 30%-MEA base case and ranked using the Cost of Electricity (COE) as the figure-of-merit to estimate the potential economic penalty for the Poza Rica power plant with CO_2 capture. COE is a measure of the revenue received per net MWh that provides the stipulated internal rate of return on equity over the entire economic analysis period.

Since Fluor had provided data based on a capture rate of 90%, Nexant prorated Fluor's total CO_2 regeneration duty from 90% to 85%, revising the PCC auxiliary power consumption, CO_2 compression power requirements and cooling duty, and reducing its costs accordingly.

Table 2. Poza Rica NGCC power plant pre-PCC vs post-PCC performance summary for selected technologies

See *Note 1*	**Pre-PCC**	**Generic 30% MEA PCC**	**Alstom**	**BASF/ Linde**	**Fluor**	**HTC Pur-energy**	**MHI**	**Shell Can-Solv**
NGCC CO_2 emissions, t/d (tonnes/day)	2297	345	328	344	229	346	346	342
Recovered CO_2 product, t/d	0	1952	1969	1953	2068	1951	1951	1955
Percent CO_2 capture	0	85%	86%	85%	90%	85%	85%	85%
Power balance, MW								
Generation								
Gas turbine gross output	166.6	166.6	166.6	166.6	166.6	166.6	166.6	166.6
Steam turbine gross output	82.5	39.6	49.6	49.4	46.0	46.7	49.2	49.4
Back pressure turbine	0	21.6	17	17	18	18	17	16.7
Total gross output	249.1	227.8	232.8	232.7	231.0	231.3	232.6	232.7
Auxiliary Consumption								
Existing NGCC parasitic loads	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2
Flue Gas Blower	0	8.8	8.8	8.8	8.8	8.8	8.8	8.8
PCC+CO_2 compression+mods	0	16.1	17.3	14.1	16.6	14.0	15.7	14.2
Total new PCC parasitic load	7.2	32.0	33.3	30.1	32.5	29.9	31.7	30.1
Net power plant export, MW	241.9	195.8	199.5	202.6	198.4	201.4	200.9	202.5
Plant export reduction, MW		-46.1	-42.4	-39.3	-43.4	-40.5	-41.0	-39.3
Plant export reduction, %		-19	-18	-16	-18	-17	-17	-16
Net plant heat rate, MJ/kWh	7	9	8	8	8	8	8	8
Net plant efficiency (LHV), %	51.8	42.0	42.7	43.4	42.5	43.2	43.1	43.4
Plant efficiency reduction, %		-9.9	-9.1	-8.4	-9.3	-8.7	-8.8	-8.4
Incremental water import, L/min	0	1,537	3,058	1,718	1,618	1,328	2,561	1,580

Note 1: Values presented here are Nexant's interpretation of the data provided by the PCC licensors.

Table 3 shows the incremental COE for each of the six PCC technologies retrofitted into the Poza Rica NGCC power plant. For comparative purposes, the various technologies were ranked according to their incremental COEs; the lower the incremental COE, the higher the ranking. After the adjustment of the Fluor data, the estimated COE for Fluor is only marginally lower than that for the other five technologies.

Table 3. Estimated incremental PCC costs and incremental Cost of Electricity for participating technologies

	Incremental Costs for Poza Rica NGCC Power Plant *[Note 1]*						
	Generic 30% MEA PCC Design	**Alstom**	**BASF/ Linde**	**Fluor** *[Note2]*	**HTC Pur-energy**	**MHI**	**Shell Can-Solv**
CAPEX Estimate, US $Million (Gulf Coast)							
PCC Plant + CO_2 Compression	181.4	234.7	187.7	174.0	194.5	178.8	194.9
Flue Gas Blower	14.2	14.2	14.2	14.2	14.2	14.2	14.2
Poza Rica Plant Modifications	32.8	32.4	30.4	31.4	29.1	30.9	30.4
TOTAL	228.4	281.4	232.3	219.7	237.8	223.9	239.5
O&M Estimate, US $Million							
Variable Costs *[Note 3]*	7.6	7.6	7.6	7.5	7.3	7.5	7.5
Fixed Costs	11.0	13.3	11.1	10.9	11.4	10.8	11.6
TOTAL	18.5	21.0	18.7	18.4	18.7	18.3	19.1
Estimated COE, US $/MWh *[Note 4]*	**37.6**	**41.4**	**35.3**	**35.0**	**36.2**	**35.1**	**36.0**
Ranking based on COE	***N/A***	***6***	***3***	***1***	***5***	***2***	***4***

Note 1 – All figures except Nexant's generic 30%-MEA design case are based on licensor-provided proprietary data.
Note 2 – Adjusted for 85% CO_2 capture.
Note 3 – The largest component is the amine replacement cost, which is considered proprietary.
Note 4 – COE shown is incremental to estimated existing Poza Rica NGCC power plant COE of US $40.7/MWh

2.2.4. Technology selection – conclusions and recommendations

Within the level of data accuracy of the study, it was concluded that the top five proprietary PCC technologies all demonstrate similar technical and economic performance and that it cannot be determined with certainty that one is clearly superior to the others. Therefore, since no single "best" technology could be selected at this time, final technology selection for future Poza Rica PCC implementation will most likely need to take into account additional factors, such as process guarantees, technology licensing fee, willingness to actively work with GoM stakeholders, etc.

Since none of the top five proprietary PCC technologies stands out among the rest and all of them are amine-based technologies that operate along the same basic principles as an MEA plant, Nexant recommended, in order to proceed with the conceptual design of the pilot plant, that the pilot plant be designed as a generic MEA plant, albeit with additional design features that will provide it flexibility and allow for the testing and validation of any of the above advanced amine-based technologies. This recommendation was accepted by the WBG and the GoM.

2.3. Conceptual CO_2 capture pilot plant design study

2.3.1. Pilot plant size selection

In order to proceed with the pilot plant design, a decision on a pilot plant size that would be agreeable to all stakeholders was required. In order to facilitate this decision, Nexant performed an analysis of the impact of PCC pilot plant size on the Poza Rica NGCC power plant's performance and its various support facility demands. A key consideration was that the generic PCC pilot plant, designed for MEA, should be able to accommodate the testing of advanced amine technologies with minimal pre-investment modifications to the capture plant design.

After reviewing the integration requirements for pilot plant sizes ranging from treating 1% to up to 25% of the flue gas stream from the Poza Rica NGCC gas turbine (GT), Nexant recommended that the PCC pilot plant be sized to treat no more than 5% of the GT flue gas flow – a decision, which was based on the pilot plant's technical viability, its potential impact on Poza Rica power plant operations and on maximum utilization of existing NGCC support facilities without adding new capacities.

While a relatively large pilot plant would facilitate a better assessment of technology scale-up issues, it was also recognized that both capital and operating expenses could become prohibitive for a larger plant. Hence, with potential funding constraints in mind, a decision was made by the WBG team and its Mexican partners to size the PCC pilot plant to treat 1% of the Poza Rica power plant flue gas. Key specifications are shown in Table 4.

Table 4. Pilot plant – key specifications

MWe Plant Equivalent	2.4 MWe
Flue Gas Throughput	387 t/d
CO_2 in Flue Gas	23 t/d
Recovered CO_2	20 t/d
CO_2 Recovery Rate	85%

2.3.2. PCC pilot plant system design

A conceptual design for a generic, MEA-based PCC pilot plant, integrated into the Poza Rica NGCC power plant, was completed. The design package contains sufficient definition to facilitate FEED preparation in a future Phase II of the WBG's technical assistance project. It includes only the CO_2 capture facility plus support facilities and modifications needed for the existing power plant to support the PCC pilot plant operations. Captured CO_2 will be vented; hence a CO_2 compression facility was not included. The process design package contains the following items:

- Simplified process flow diagram and description
- Major stream flow heat, material and utility balances
- Preliminary plot plan
- Major equipment list and preliminary datasheets
- Specification of effluents
- Description of integration requirements into the Poza Rica NGCC plant, and
- Preliminary capital and operating cost estimates, including all catalysts and chemicals and utility consumption estimates.

Modeling of the following three operating scenarios was carried out:

1. Design Case (DES), used to size almost all of the pilot plant equipment. This case represents an easily achievable MEA operation that results in conservative equipment sizes;
2. Expected Operation Case (EXP) for expected pilot plant performance. This case represents a projected, best achievable MEA operation, based on Nexant's past experiences with commercial amine plants;
3. Absorber Intercooled Operation Case (IC), used to size the absorber intercooling equipment. This case represents a projected, achievable MEA operation, based on a colder absorber bottom temperature resulting from absorber interstage cooling.

2.3.3. Overall NGCC performance before and after PCC pilot plant integration

The overall power balance, cooling water (CW) and cooling tower (CT) loads of the Poza Rica NGCC power plant without and with integrated PCC pilot plant are summarized in Table 5. The existing, pre-PCC performance is shown for comparison purposes. As can be seen from the summary table, due to the small size (1% flue gas slipstream) of the pilot plant, the impact on the overall NGCC power plant operation is minimal.

Table 5. Overall NGCC balance and performance pre-PCC and post-PCC

Overall Poza Rica NGCC Power Plant Performance	**Pre-PCC**	**Post-PCC (Design Operation)**
Flue Gas Feed and CO_2 Recovery Rates		
Flue gas feed rate, t/d	N/A	387
CO_2 in pilot PCC feed gas, t/d	N/A	23
CO_2 in recovered stream, t/d	N/A	20
CO_2 recovery rate, %	0	85
Steam Consumption Rates		
Reboiler steam (4.1bara/151°C), t/d	N/A	40.0
Reboiler steam, tonne/tonne CO_2 recovered	N/A	2.07
Output at Generator Outlet, kW:		
Existing Siemens/Westinghouse gas turbine	166,570	166,570
Existing Siemens steam turbine (total for 3 operating)	82,500	82,272
Total Gross Generation	**249,070**	**248,842**
Parasitic Loads, kW		
Existing HP & IP BFW pumps	1,047	1,047
Existing condensate & hot cond recycle pumps	100	100
Existing raw water & filtered water pumps	159	160
Existing cooling water pumps	3,626	3,626
Existing cooling tower fans	1,350	1,350
Transformer loss allowance	730	729
Misc existing NGCC loss allowance	200	200
PCC pilot plant CO_2 capture loads	0	162
Total NGCC/PCC Electrical Loads	**7,213**	**7,375**
Net Poza Rica Power Export, kW	**241,857**	**241,467**
Reduction Power Export, kW	**--**	**-391**

Poza Rica CW/CT Duty Breakdown: MEA PCC Pilot Plant	**Pre-PCC**	**Post-PCC (Design Operation)**
Existing NGCC CW/CT Duty, GJ/h	666	662
New PCC CW/CT Duty, GJ/h	0	6
Total Poza Rica CW/CT Duty, GJ/h	**666**	**668**

2.3.4. Poza Rica NGCC PCC pilot plant cost estimation

The capital cost of the MEA-based PCC pilot plant was estimated, with a target accuracy of ± 30%, using a major equipment factored estimation approach. Table 6 summarizes the estimated capital cost of the PCC pilot plant. The total capital cost includes cost allowances for the associated NGCC plant modifications and pilot plant support facilities, which include the control and laboratory testing equipment plus trailer costs. Factoring in all of the above-mentioned costs, the estimated total plant cost for the PCC pilot plant is about US $22.1 million.

Table 6. MEA PCC pilot plant estimated capital cost

	Material	**Installation**	**Total**
Major Equipment Costs	**All Costs in US $1,000**		
Columns and internals	1,438	356	1,794
Vessels and tanks	57	22	78
Heat exchangers	221	12	233
Blowers	519	3	522
Pumps and drivers	185	49	234
Others – MEA filter package	66	11	78
Others – soda ash package	6	4	10
Others – ductwork	108	86	194
Freight	125		125
Total Major Equipment Costs			3,268
Bulk Material Costs			5,938
Total Direct Costs			9,206
Construction Indirect Costs			1,818
Total Field Costs			11,025
Startup vendor reps			272
Home office costs			2,288
Plant mod allowance			400
Control, lab and admin trailer allowance			3,000
Total Constructed Cost w/o Contingency			16,985
Contingency (30%)			5,096
Total Plant Cost			**22,081**

The operating and maintenance (O&M) costs of the MEA-based PCC pilot plant are allocated as either fixed or variable operating costs. Fixed O&M costs are essentially independent of the actual capacity factor, number of hours of plant operation or amount of kilowatts produced, and consist mainly of the cost of employee salaries, taxes and insurances. Variable O&M costs are directly proportional to the PCC pilot plant throughputs and include the purchase costs of the pilot plant's process consumables, catalysts and chemicals. Table 7 summarizes the estimated annual O&M costs and provides a percentage breakdown.

The PCC pilot plant's annual O&M cost is US $2.5 million. The fixed O&M costs, at US $2.1 million, make up the bulk of these costs, at 84% of the total O&M costs, whereas the variable O&M costs, at about US $0.41 million, make up the remaining 16%.

Table 7. Estimated O&M costs for MEA PCC pilot plant operation

Annual Operating Cost: MEA PCC Pilot Plant	Post-PCC (Design Operation)	
	US $1,000/year	**%**
Process Consumable Costs (Variable)		
River water import	2.2	0.1
Process waste water disposal	0.1	0.0
CO_2 product export	-	-
Export power losses	156.2	6.1
Total Process Consumables	**158.5**	**6.2**
Catalysts & Chemical Costs (Variable)		
Water treating chemicals	18.7	0.7
PCC amine/additives makeup & disposal	223.1	8.8
PCC carbon/filters/dessicant replace & disposal	7.4	0.3
Total Catalysts & Chemicals	**249.3**	**9.8**
Fixed Costs		
Operating labor	744.0	29.2
Maintenance labor	331.2	13.0
Maintenance material	220.8	8.7
Overhead charges	400.0	15.7
Insurance & property tax	441.6	17.3
Total Fixed Costs	**2,137.6**	**84.0**
Total Operating & Maintenance Cost	**2,545.4**	**100.0**

3. Combining CO_2 enhanced oil recovery with permanent storage in Mexico

3.1. Objectives and methodology

The objectives of this second study, conducted by the Battelle Memorial Institute (USA), were to identify what issues need to be addressed and what requirements must be met to ensure that (1) future CO_2-EOR operations in Mexico can be recognized as permanent storage, and (2) the mass of injected CO_2 is counted towards Mexico's national emission reduction goals and/or is eligible for national or international carbon credit trading mechanisms. These objectives were accomplished through (1) a literature review of state-of-the-art practices related to combining CO_2-EOR with geological storage of CO_2 as well as discussions with relevant subject experts, (2) the identification of key issues for CO_2-EOR storage with relevance to Mexico, supplemented with the consultant's own experience in conducting multiple geological CO_2 utilization and storage projects, and (3) various technology transfer activities involving a broad group of stakeholders in Mexico.

3.2. Key issues for CO_2-EOR storage projects

The information collected during the literature search and expert interviews was compiled and synthesized to highlight key issues for CO_2-EOR storage projects with relevance to Mexico. The following summarizes the issues and challenges for CO_2-EOR storage as well as recommendations to address each of these challenges.

3.2.1. Risk assessment

Risk assessment methods are used to characterize and catalog the safety attributes of CO_2 storage sites. The risk assessment process often includes site screening, selection and characterization to provide guidance in CO_2 storage system design, operation and closure. The potential for wellbore leakage, a major risk factor, is identified during the risk assessment. Wellbore integrity is especially important for transitioning from CO_2-EOR to CO_2 storage, because oil fields typically have many legacy wellbores that penetrate the confining layers. Recommendations include:

- Perform risk screening and leakage pathway analysis to identify major risk factors related to geology, environment, operations, people, natural hazards and other factors at the project location.
- Survey surface environmental features related to CO_2 storage risk.
- Complete survey of wellbore conditions for pilot-scale project.
- Review risk framework options for larger scale CO_2 storage expansion.
- Perform a review of area to characterize well integrity and remediate.
- Monitor casing performance, which can degrade rapidly.

3.2.2. Reservoir Simulation

The performance of CO_2-EOR processes is evaluated and validated at each site from operational indicators as well as reservoir simulation studies. Simplified empirical models as well as detailed numerical simulation models are used to study and/or predict CO_2-EOR performance over time. Recommendations include:

- Integrate reservoir modeling and analysis with CCUS operations and monitoring activities.
- Periodically update models during the course of a project with latest field data for relevant and valid predictions of CO_2-EOR performance.

3.2.3. Monitoring, Reporting and Verification (MRV)

Monitoring requirements can be grouped into different categories based on the operator's objectives: (1) mandatory requirements for credits (includes mass balance, wellbore integrity, conformance monitoring and post-injection monitoring), (2) performance monitoring (not required, but routinely done as part of EOR operations), and (3) environmental monitoring (not required, but may be invaluable).

More formal reporting will generally be required, including the development of an MRV plan, which should contain the following:

- Determination of storage volume.
- Identification of potential leakage pathways.
- Remediation of potential leakage pathways.
- Injection and post-injection monitoring strategy to demonstrate storage of CO_2.
- A plan for monitoring parameters.

Recommendations include:

- Develop a strategy for detecting and quantifying any CO_2 surface leakage and establishing a baseline for comparison.
- Develop an MRV plan to help proactively manage project risks.

3.2.4. Accounting

The quantity of CO_2 that can be stored as a result of EOR operations is determined by many factors. These include both operational factors and geological or reservoir-related factors. The operational stages are especially relevant to the project when transitioning from CO_2-EOR to CO_2 storage. After the start of CO_2-EOR operations, previous operations, including primary depletion, must be included in the analysis of overall storage capacity available. Recommendations include:

- Review CO_2 flow metering equipment and flow circuits to ensure all streams are tracked adequately and reliably.
- Develop a plan for accounting of CO_2 net balance, based on relevant metrics.
- Plan for periodic (e.g., monthly) reports on CO_2 storage volumes.
- Consider CO_2 leakage potential in surface EOR systems (pipelines, oil processing, wellheads).

3.2.5. Post-injection monitoring and site closure

Post-injection monitoring and site closure requirements constitute key differences between CO_2-EOR and CO_2-storage. At the end of an EOR operation, oilfield operations are terminated and wells plugged and abandoned in accordance with applicable oil and gas regulations and applicable industry standards and practices. At the end of the CO_2 injection period, a CO_2 storage project enters a post-injection monitoring phase, followed by site closure. While the well plugging and abandonment procedures may remain the same in CO_2-EOR and CO_2-EOR storage operations, EOR operators need to implement a post-injection monitoring strategy, which will continue to account for the CO_2 that was stored in association with the EOR operations, in order to receive credits. Recommendations include:

- Integrate post-injection monitoring with CO_2-EOR operations activities.
- Use reservoir simulations to validate/establish conformance.
- Develop plugging and abandonment plans for wells once system stabilization has been determined to be acceptable.
- Close out the project once the conditions in the subsurface have stabilized and the wells have been plugged.
- Determine how to ensure permanent CO_2 storage without limiting potential future oil extraction.
- Recognize post-closure site access and other liability concerns related to CO_2 storage integrity.

3.2.6. Economics

As discussed above, the barriers for pursuing co-optimized CO_2 storage with EOR are primarily economic. One reason is the limited availability and high cost of anthropogenic CO_2, while another factor is the cyclic nature of oil prices, which makes capital intensive projects such as CO_2-EOR less attractive. Economic models illustrate that storage-related strategies require substantial incentives to support near-term deployment. Budgetary requirements for monitoring and reporting, as well as optimization strategies, need to be considered. Project plans that cover the entire project life cycle and include one or more surface, near-surface and/or subsurface monitoring techniques need to be developed. The market for CO_2 storage must be aided by environmentally conscious government entities through placing economic (rather than regulatory) incentives on using anthropogenic CO_2 for EOR.

3.2.7. Legal and regulatory issues

Legal and regulatory requirements may affect site characterization, operations, monitoring and site closure for CO_2 storage projects. They also may include subsurface rights, surface property access, liability issues and long-term financial mechanisms for funding site closure. In general, the main regulatory items for CO_2-EOR storage may include environmental permits, monitoring reports and site closure reports. In addition, international standards may require some level of monitoring, accounting and documentation for certification of carbon storage credits. A review of the legal and regulatory requirements for transitioning CO_2-EOR to CO_2 storage was not a primary objective of this project and readers are referred to the companion WBG study on legal and regulatory issues presented below.

3.3. Concluding comments and recommendations

The technology and operational practices for CCUS have been developed over decades of CO_2-EOR experience established in the oil and gas industry. Hence, the key barriers and uncertainties in accounting for associated CO_2 storage during CO_2-EOR operations are not technical, but economic and policy-related. While economic favorability can be improved by investing in improvements to the current CO_2 infrastructure, strong, constructive policy measures and incentives are needed for promoting geological CO_2 storage.

Many of the requirements for storage within EOR will be built on the operator's business as usual, but additional effort will be required to confirm storage integrity. Secure, permanent geological storage of CO_2 must be documented by operators through showing how sites have been characterized and existing wells evaluated to ensure containment. EOR projects may require operational or reporting modifications to qualify for regulatory and other credit-related requirements. Additional monitoring or reporting, for instance, may be needed to track and demonstrate CO_2 storage beyond typical EOR operations. Likewise, modeling efforts may need to be modified to optimize storage and for use as a tool to show storage integrity in the reservoir of interest.

The MRV plan to track CO_2 storage within the EOR project boundaries and developed in consultation with pertinent regulatory and credit granting agencies is a major consideration that helps the operator proactively manage project risks. Because the monitoring program is generally derived from risk assessments, the recommendations for the MRV program presented in the report form a tiered approach based on the risks identified. Primary requirements would be reservoir zone monitoring to adequately track the pressure, temperature and CO_2. Should leakage signals be detected, the second tier of monitoring for leakage detection and management would be implemented by monitoring above-zone, and, as the third tier, near-surface and surface monitoring would be implemented.

While the same monitoring and modeling technologies are applicable to CO_2-EOR and geological storage projects, CO_2-EOR project operators may need to make additional investments in monitoring, measurement and reporting to characterize, manage and ensure long-term integrity of CO_2 storage as well as optimize EOR operations. The CO_2 quantification and reporting requirements as well as the post-closure obligations are crucial to provide a pathway to the credit standards that constitute best practices for responsible geological storage operations.

CO_2-EOR projects demonstrating storage of anthropogenic CO_2 in Mexico may be eligible to provide carbon credits. The minimum requirements to gain storage credits according to protocols stated in the United Nations Framework Convention on Climate Change Clean Development Mechanism (CDM), California Cap-and-Trade Regulation Instructional Guidance, American Carbon Registry, and U.S. Environmental Protection Agency regulatory guidance were compared and contrasted. The protocols typically outline requirements as performance measures without prescribing technologies to meet these requirements. Accordingly, there is significant flexibility for the project proponent to submit for approval plans that describe how requirements will be met.

While CO_2-EOR projects demonstrating storage of anthropogenic CO_2 may be eligible to earn carbon credits, this study did not identify any CO_2-EOR projects with associated storage, or transitioning to storage without EOR, as having applied for or received credits. The lack of experience with applying CDM and European Union protocols to CCS projects in general and to CO_2-EOR projects in particular could prove a hindrance, as could the absence of any provisions in these protocols that are specifically tailored to oil field operations.

Under the European Union Emission Trading System Directive, an offset project involving the incidental storage of anthropogenic CO_2 in association with an EOR project in Mexico could be creditworthy if it meets the requirements of the CDM CCS methodology. However, because no such projects have been considered and credited to date, uncertainty surrounds the qualification process. Practical implementation without untenable economic costs will be indispensable for qualification. Although the ongoing process for developing International Standards Organization standards for CO_2 capture, transportation and storage - including incidental storage in association with EOR - promises to provide a better pathway to credits, final standards are still several years away.

An offset project in Mexico has the potential to qualify for credit for the California Cap-and-Trade Program; however, significant steps must be accomplished before the availability of credit could be a reality. First, the California Air Resources Board (ARB) needs to approve a Compliance Offset Protocol for CO_2 geological sequestration associated with EOR. In addition, that approved protocol must include Mexico within the approved project area. Before that process is completed, it would also be useful to have California ARB approval of an early action quantification methodology for geological storage associated with CO_2-EOR. This approval could be based on the American Carbon Registry protocol, but that protocol would need to be expanded to include Mexico in addition to the U.S. and Canada.

Despite the challenges imposed by the evolving regulatory and credit mechanisms, it is widely agreed that the CO_2-EOR projects provide a viable and economically attractive pathway for GHG emission reduction and a potential bridge to storage in saline formations. That said, there is a need to build more project experience and test the various credit mechanisms under realistic conditions. For Mexico, any planned CO_2-EOR field tests, even if these are small-scale huff-n-puff or continuous injection pilots, offer an early opportunity to build the practical knowledge and lay the foundation for successful credit accruals for future full-scale projects. Therefore, it is recommended that the risk management, modeling, monitoring and accounting activities identified in the study be implemented and evaluated as a prototype in any future pilot tests.

4. Development of a regulatory framework for carbon capture, utilization and storage in Mexico

4.1. Study objective

The objective of this third study, conducted by Milieu Ltd - Law & Policy Consulting (Belgium), was to provide an in-depth assessment of the regulatory framework in Mexico and to identify necessary modifications in order to allow the implementation of the pilot and demonstration projects set out in Mexico's CCUS Roadmap, especially in view of the recent changes in the overall framework for energy policy in Mexico. The assessment of detailed regulatory issues in this report provides a sound basis for the GoM in developing and adapting its regulatory framework for each of the key issues of a CCUS project.

A regulatory framework for CCUS activities should cover a wide range of aspects. The CCUS chain covers several very different, though closely connected, activities which require an integral approach. Nonetheless, some aspects of CCUS activities are very similar to other existing activities and could be covered to a large extent by existing legal provisions. Other aspects of CCUS are likely to be unaddressed in existing laws and regulations and will require development. This is, for instance, the case for the monitoring and liability requirements when transitioning from CO_2-EOR to permanent storage. It is important to capture the entire CCUS chain in a regulatory framework for several reasons, from limiting gaps in the legal framework, in particular for issues such as ownership and liabilities, to enabling the effective and environmentally sound implementation of CCUS projects.

A sound regulatory framework for CCUS activities must enable the deployment of the CCUS projects envisaged in Mexico in both the short and longer term, while providing the necessary guarantees from a perspective of public health and environmental protection as well as for investors in such activities.

4.2. Scope of the analysis and methodological approach

A systematic approach was followed for the review of international best practices and the Mexican regulatory framework for CCUS activities, with the objective to identify possible gaps and barriers and, ultimately, to develop recommendations. At the outset of the project, tables were developed with a similar structure to ensure a coherent approach to the analysis. A list of key issues (see Table 8) to be covered in the review was prepared, with the intention of ensuring the comprehensiveness of the analysis. The list was first developed on the basis of the key issues in the International Energy Agency's (IEA) CCS Model Regulatory Framework and then completed with additional issues that the consultant considered useful to include. Special attention was paid during the analysis of the regulatory approaches taken for specific issues in each country as well as of their regulatory context.

The list groups the key issues in the lifecycle of a CCUS project into five main categories. The first category covers general overarching issues, which could be applicable to several phases of the CCUS project. The second category deals specifically with CO_2 capture, the third with CO_2 transport, and the fourth with CO_2 storage and usage. A fifth category covers environmental and health and safety requirements applicable to all stages in a CCUS project.

Potential gaps and barriers in the Mexican regulatory framework for CCUS activities were assessed against international best regulatory practices and international regulatory models, and subsequently prioritized on the basis of a set of agreed criteria. The list of international best regulatory practices and models was developed jointly by the consultant and the WBG team. It covers the regulation of CCUS activities in a number of countries that have already developed comprehensive regulatory frameworks for CCS activities. These countries were selected on the basis of, for example, proximity, similarity in the legal frameworks or activities in the countries, or because they are considered as leading best practices in regulating such activities. The countries selected for an in-depth review on this basis were Australia, Canada, the United States and the European Union. Domestic circumstances were considered as they provide important contextual information on the approach taken towards regulating each of the key issues. This allowed for distilling similarities and differences when identifying good regulatory practices for the regulatory framework for CCUS in Mexico.

Table 8. List of key issues for the development of a regulatory framework for CCUS

General issues	
1.	Classification of CO_2 and its legal implications
2.	Property rights
3.	Competition with other users and preferential rights
4.	Composition of the CO_2 stream
5.	Engaging the public in decision making
6.	Scope of framework and prohibitions
7.	Definition of ´CCS ready´
8.	Incentives for CCUS as part of climate mitigation strategies
CO_2 **capture**	
9.	Authorization for capture
10.	Monitoring, reporting and verification requirements
11.	Inspection
CO_2 **transport**	
12.	Authorization of transportation infrastructure (pipeline regulations, etc.)
13.	Third-party access to transportation infrastructure
14.	Transboundary movement of CO_2
CO_2 **storage and usage**	
15.	Definitions and terminology applicable to CO_2 storage
16.	Third-party access to storage site
17.	Authorization of storage site exploration activities
18.	Regulating site selection and characterization activities
19.	Authorization of storage activities
20.	International laws for the protection of the marine environment.
21.	Project inspections
22.	Monitoring, reporting and verification requirements
23.	Corrective measures and remediation measures
24.	Liability during the project period
25.	Liability during the post-closure period
26.	Financial contributions to post-closure stewardship
27.	Using CCUS for biomass-based sources
28.	Enhanced hydrocarbon recovery with CCUS
Environmental and health and safety requirements applicable to all stages	
29.	Planning requirements (e.g. Strategic environmental assessment)
30.	Environmental impact assessment
31.	Pollution prevention requirements (air, water)
32.	Nature legislation requirements (consideration of protected habitats and species)
33.	Waste legislation requirements
34.	Coastal and marine protection requirements
35.	Coverage by GHG trading schemes
36.	Protecting human health
37.	Protecting workers´ safety
38.	Sharing knowledge and experience through the demonstration phase

The in-depth assessment of best regulatory practices also included international model policies for CCUS activities. These are regulatory models or detailed checklists developed by international organizations, such as the

IEA or research institutes. These models were considered as comprehensive checklists for all aspects of the CCS chain that should be covered by regulatory frameworks.

4.3. The existing regulatory framework for CCUS in Mexico

The Mexican legal system is a civil law system, with the Constitution, laws issued by the Congress of the Union and international treaties being the main sources of law. Case law is secondary and subordinated to statutory law. The various levels of the Mexican executive branch are entitled to issue regulations to specify and develop the provisions established by the Constitutional and Secondary Laws. Mexican Official Standards regulate specific aspects, such as technical standards, security standards, measurement processes and environmental prohibitions, among others, in a legally binding manner.

Within the Mexican legal system, very few legal requirements explicitly apply to CCUS activities in Mexico. This can be explained by the early stages of development of such activities in the country. However, as a result of the 2013 constitutional amendment and the secondary legislation adopted in 2014, for the first time general regulatory requirements for some CCUS activities were introduced in the Mexican legal framework for energy, together with other legal requirements for clean energy.

The recently revised Hydrocarbons Law includes the possibility of CO_2-EOR implementation. Additionally, the Energy Reform established a National Agency for Industrial Security and Environmental Protection of the Hydrocarbons Sector (ASEA) as the authority entitled to inspect and control activities in the hydrocarbons sector, including CO_2-EOR projects. On the basis of the ASEA Law, ASEA is expected to issue new guidelines and rules on CO_2-EOR in the coming months.

Relevant environmental requirements for aspects of a CCUS project can also be found in the existing framework for infrastructure and energy projects, as stated in the General Law on Ecological Equilibrium and Environmental Protection (LGEEPA). The General Law on Climate Change establishes the legal framework for climate change mitigation in Mexico, including, among others, the establishment of the Mexican National Emissions Inventory of GHG and associated reporting obligations, which although not specifically referring to CCUS activities, will be mostly relevant. Finally, the Law on Electricity Industry introduces the use of clean energy certificates for the production of clean energy, in which the issuance of certificates for CO_2 capture is considered.

There are some other aspects of CCUS projects that are protected under present regulations. For instance, environmental permits, such as the Environmental Impact Authorization and the Sole Environmental License, would be required for CCUS activities. Preferential rights regarding superficial occupation and right of way of the hydrocarbons sector are also provided for in the Hydrocarbons Law, and should be considered important tools for CCUS projects, where the projects are related with energy generation or with the oil sector. Other preferential rights are included in several other areas of law.

4.4. Recommendations for a Mexican regulatory framework for CCUS

The gap and barrier analysis and associated issue prioritization showed there is an important distinction to be made in the Mexican regulatory framework between those CCUS activities that will take place in or are related to the hydrocarbons sector and activities outside this sector. The distinction is particularly relevant for Mexico as CCUS activities in the hydrocarbons sector would be regulated differently from those in other areas such as aquifers or depleted coal mines.

As mentioned above, there is currently no regulatory framework for CCUS specifically in Mexico. However, the revised Hydrocarbons Law provides ASEA with the authority to regulate the generation, capture, transportation and storage of CO_2 within the hydrocarbons sector. No such legal basis currently exists for other CCUS activities outside this sector. It was also noted that certain other aspects of CCUS activities, such as those related to the capture of CO_2, could be covered by existing regulation. Finally, consideration could be given to modifying existing legislation with a view to explicitly include CCUS activities within their scope.

The development of recommendations was structured around the main categories of key issues used throughout the report. Recommendations, therefore, distinguish between the regulatory aspects of capture activities, transport and storage, and several overarching regulatory issues relevant to all of the activities that are part of the CCUS chain.
CO_2 capture

Most aspects related to the capture side of CCUS activities seem adequately covered by the existing regulatory framework comprising LGEEPA. There is currently no explicit authorization procedure for CO_2 capture activities in Mexico. Nevertheless, a sole environmental license is required under LGEEPA for all stationary industrial facilities. Such license would cover CO_2 capture aspects as part of the general permitting requirements for such installations (e.g. electricity plants).

However, not all installations subject to a sole environmental license are required to monitor and report on their emissions. The monitoring and reporting requirements ultimately depend on whether an installation is considered a CO_2 source under federal or local jurisdiction and currently only cover installations generating more than 25,000 t/y of CO_2. The recommendation is, therefore, to amend the monitoring requirements of the General Law on Climate Change and extend its scope to installations emitting less than 25,000 t/d of CO_2. This would ensure a coherent approach to the monitoring requirements for all industrial installations proceeding with the capture of CO_2.

Furthermore, the Energy Reform has modified the regulatory authorities for activities in the hydrocarbons sector. In relation to capture this means that capture activities in industrial plants in the hydrocarbons sector, such as refineries or petrochemical installations, will be covered by means of new regulations to be issued by ASEA.

4.4.1. CO_2 transportation

In relation to CO_2 transportation, legislative changes may be needed to enable the transport of CO_2, either through the expansion of existing legal requirements or the development of a new legal basis. There are currently no specific regulations for CO_2 transport either via pipeline, road, railroad or sea transport. However, existing regulations for the transport of natural gas via pipelines, or for the transport of materials, hazardous materials and hazardous waste via other means of transport, could be amended or serve as an example for a broad regulatory framework for CO_2 transport. Specific operational conditions for the transport of CO_2 could be adopted by means of implementing regulations as has been done in other jurisdictions. The regulation of CO_2 transport within the hydrocarbons sector would, similarly to capture, fall under the jurisdiction of ASEA.

4.4.2. CO_2 storage activities in the hydrocarbon sector

The regulation of CO_2 storage in the hydrocarbon sector is particularly relevant for the pilot projects currently envisaged in Mexico, including the CO_2-EOR storage projects to be managed by Mexico's state oil & gas company (PEMEX) at its Cinco Presidentes site, as well as future storage activities in the hydrocarbons sector.

The issue of long-term storage of CO_2 could be dealt with by declaring CO_2 a hazardous waste, similarly to the classification used for such activities in Canada. Such treatment would have several distinct advantages, but during a stakeholder workshop to discuss regulatory options concerns about this approach were raised by some stakeholders, in particular in anticipation of possible negative reactions by the general public and non-government organizations as well as of the administrative burden imposed by existing waste legislation, which project developers would have to comply with.

If a decision is made not to consider CO_2 as a hazardous waste, an alternative option could possibly consist of ASEA including the permanent storage of CO_2 in its CO_2-EOR or hydrocarbon sector regulations. Alternatively, the Mexican Department of Environment and Natural Resources (SEMARNAT) could be granted with the entitlement to permit the long-term use of the Mexican subsurface for permanent CO_2 storage through an amendment of LGEEPA, including a new chapter on CCUS activities, long-term CO_2 storage and corresponding regulations.

4.4.3. CO_2 storage activities outside the hydrocarbon sector

As for longer-term demonstration and commercial-scale projects, which are not located in or related to the hydrocarbons sector and hence not subject to ASEA CCUS Regulations (when issued), the option of storing CO_2 as hazardous waste could be considered, similarly to the situation described above for activities in the hydrocarbons sector. Existing legal provisions that regulate such activities would not require amendments or the adoption of new legislation.

In case the storage of CO_2 as a hazardous waste is not considered a viable option, LGEEPA, which operates as the general framework on environmental matters, could be amended to regulate CCUS activities. More precisely, inclusion of an additional chapter regulating permanent storage aspects, including temporary and permanent storage, liability aspects and other issues not covered by existing legislation, would be required. Likewise, the long-term use of the subsurface of the land where the CO_2 is being permanently stored needs to be regulated. As the issue is essentially one of environmental protection or GHG reduction, SEMARNAT could be granted with the entitlement to permit the long-term use of the Mexican subsurface for permanent CO_2 storage through an amendment of LGEEPA, including a new chapter on CCUS activities, long-term storage and corresponding regulations.

4.4.4. Long-term liability for CCUS activities

The manner in which liability (in particular long-term liability) has been treated in most of the reviewed legislative frameworks is similar. In most cases, subject to certain conditions, the liability is transferred to the appointed state authority after a certain period of time. However, in the current Mexican regulatory framework environmental liability has a statute of limitations of 12 years as of the beginning of the environmental damage or its effects, and there is certainly no transfer of liability. Under the Energy Reform, PEMEX remains permanently liable, which places a heavy burden on this and similar operators. Following best practices from other jurisdictions, it is recommended to amend LGEEPA (in what would be the CCUS chapter) and modify the liability period stated in the Federal Environmental Responsibility Law, exclusively for CCUS activities, and stating the time period and conditions under which the liability transfer is made to SEMARNAT.

4.4.5. Environmental protection and climate change mitigation

Finally, the report recommends that additional regulatory changes of an overarching or supporting nature be made in Mexico for the deployment of CCUS activities. An extension of LGEEPA that aims to apply the requirements for environmental impact assessments would enhance environmental protection and prior identification of potential environmental risks associated with a specific project as well as ensure the engagement of the public in decision-making on the projects. It is also recommended that the Mexican regulatory framework for climate change mitigation be enhanced to provide incentives for CCUS activities as part of climate mitigation strategies. While still insufficient or not operational, several initiatives are currently underway to provide concrete incentives for the deployment of CCUS activities. The further operationalization of the Mexican carbon market coupled with emission performance standards or emission limitations could provide such incentives.

5. Next steps

The three studies presented in this paper have been instrumental in laying the groundwork for further CCUS development in Mexico and contributed greatly to building general awareness of and engagement in CCUS among a wide range of government agencies, research institutions and universities. The next major steps, as set out in Mexico's CCUS Roadmap, will be the construction and operation of the proposed PCC pilot plant at Poza Rica and the CO_2-EOR storage pilot projects at the Cinco Presidentes oil field. Discussions between the WBG and the GoM are underway to move these pilots, as well as several supporting projects including a continuation of the regulatory work, forward under a future WBG Phase II project.

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