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ESTADOS UNIDOS MEXICANOS

CCUS Technology Roadmap in Mexico

Produced by

Secretaría de Energía - SENER -

Participants:

Secretaría de Medio Ambiente y Recursos Naturales - SEMARNAT -
Petróleos Mexicanos - PEMEX -
Comisión Federal de Electricidad - CFE -
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INTRODUCTION

Since 2008, Mexico has taken a number of measures to implement Carbon, Capture, Use and Storage technologies (CCUS). Nevertheless, collective efforts are needed to optimize the process and obtain results in the short term.

The General Law on Climate Change has established several national measures to mitigate the effects of climate change:

- To guarantee health & environmental rights.
- To define concurrent measures on climate change at the three levels of government.
- To reduce the vulnerability of natural systems due to climate change.
- To regulate adaptation and mitigation measures.
- To promote research, development and technology transfer within the field.
- To facilitate the transition to a low carbon economy while promoting environmental, social and economic benefits.

For this reason, the Ministry of Energy of Mexico (SENER) has initiated an orderly process, through a CCUS Technology Roadmap. To achieve this goal, SENER has formed a working group headed by SENER and SEMARNAT. Other participants include PEMEX, CFE, UNAM, IPN and Mario Molina Center.

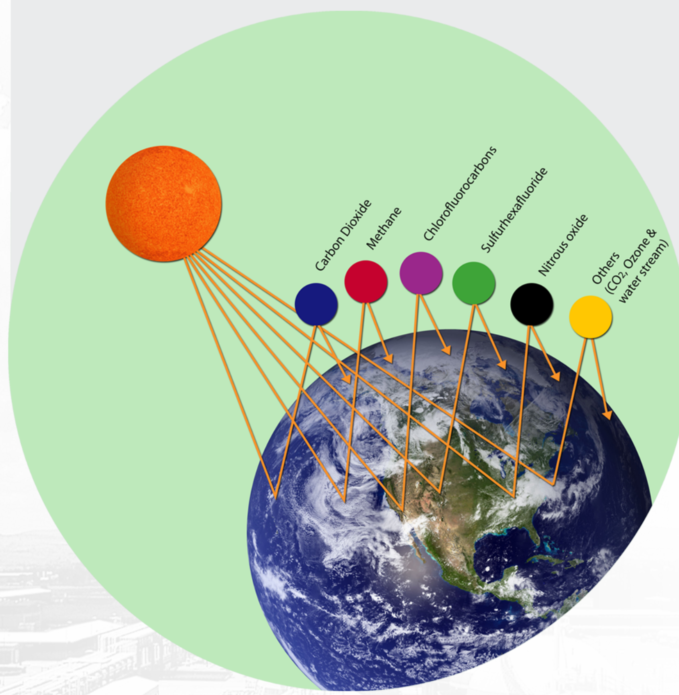
CLIMATE CHANGE

Climate change is the variation in climate caused by natural processes or human activities - altering the atmosphere composition and natural climate variability over comparable time periods.

The greenhouse effect is a major element of climate change caused by gas concentration in the atmosphere; it is a natural phenomenon essential to keep the heat in the Earth and prevent freezing. However, high concentrations of these gases are mainly attributed to human activities.

The main greenhouse gases are carbon dioxide, methane, ozone, nitrogen oxides, chlorofluorocarbons and lesser water stream and carbon monoxide.

Source: SEMARNAT. Ley General de Cambio Climático. Junio 2012. México



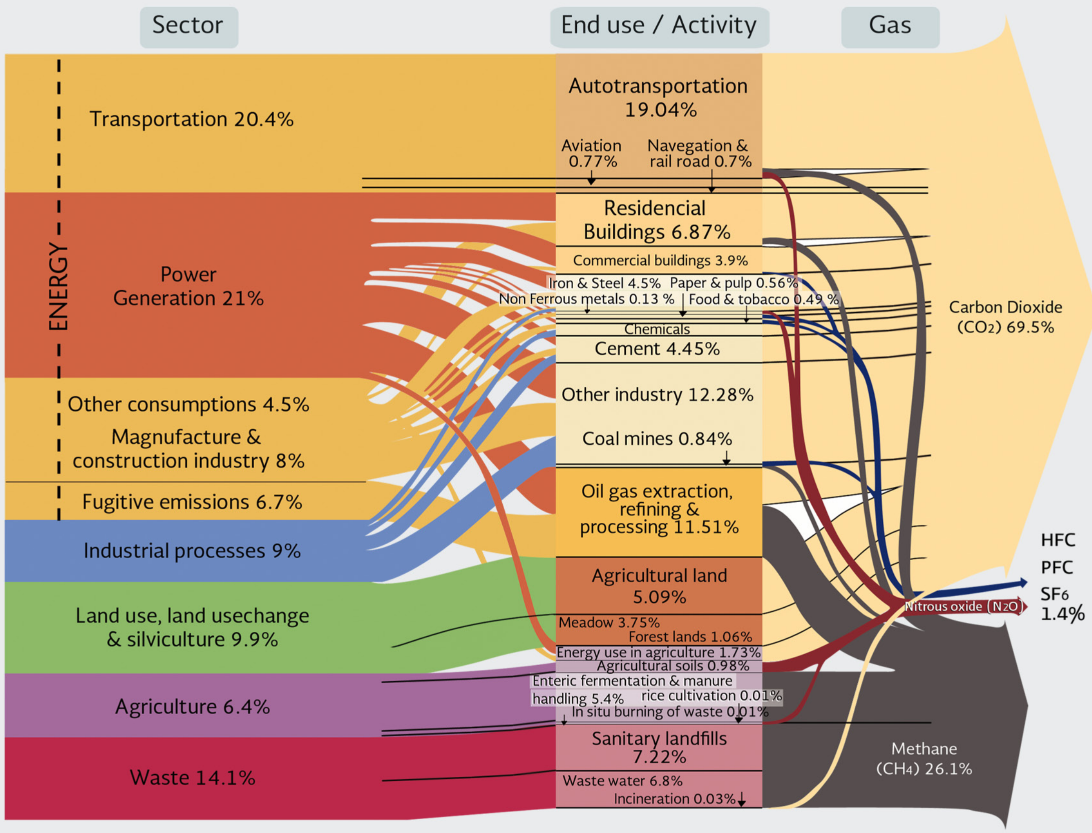
Source: Blasing et. al. 2013

GHG IN MEXICO, MAIN SECTORS

The largest greenhouse gases emissions come from activities based on fossil fuel consumption as well as power generation and transport.

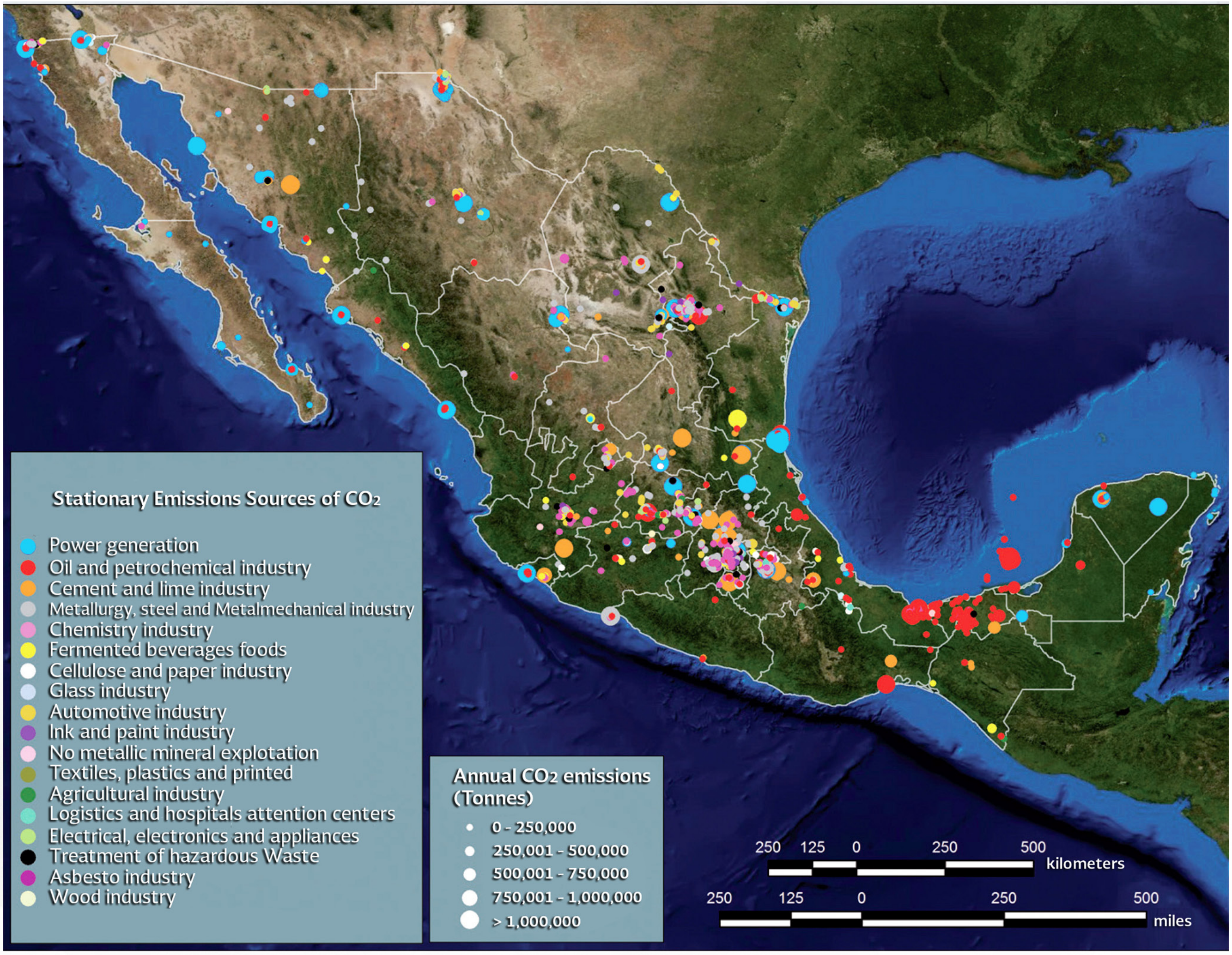
The main stationary emission source, in Mexico and in the world, is the energy sector.

The following picture summarizes the emission contribution by category in Mexico:



Source: INE, 2006

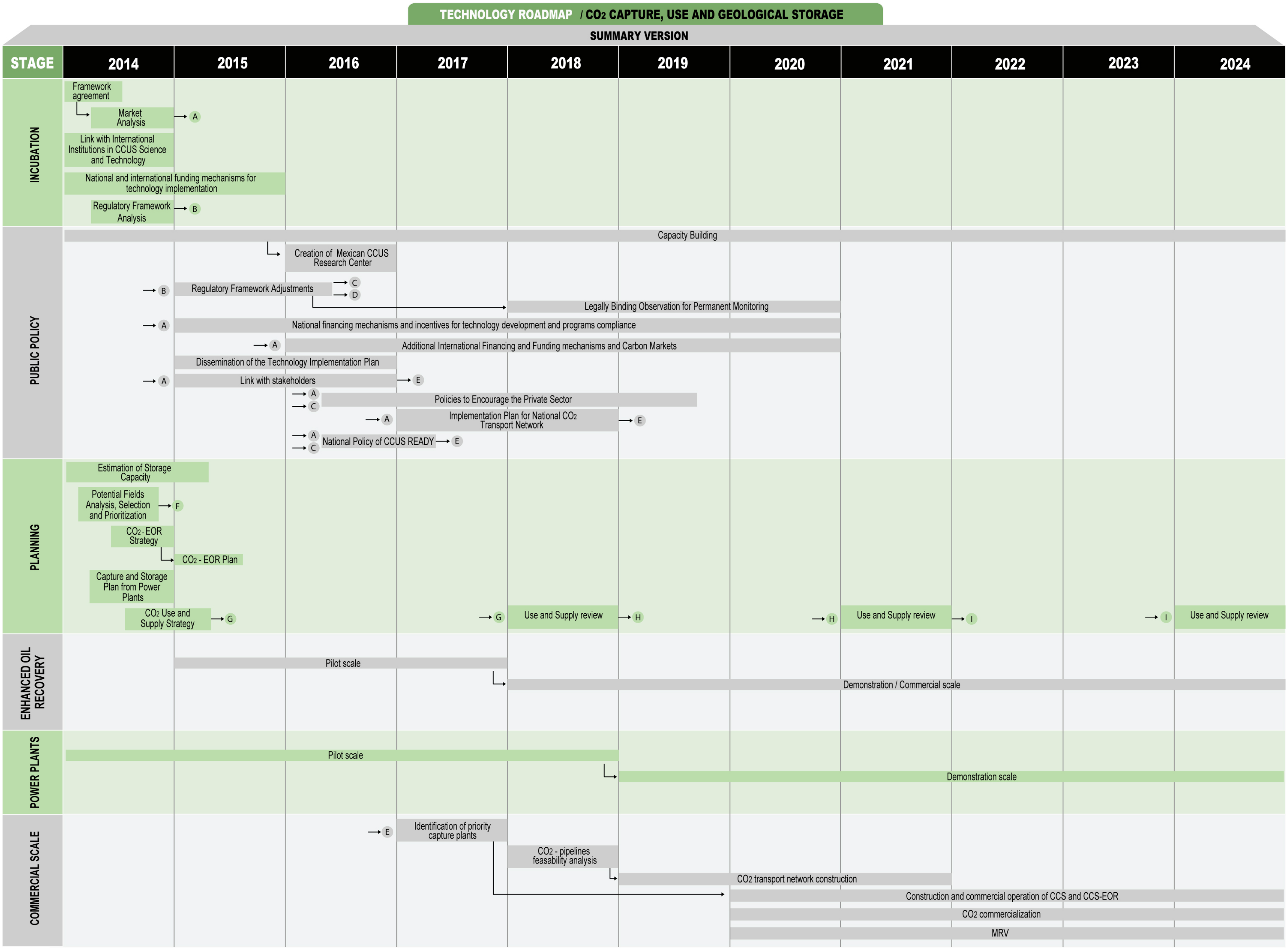
MAJOR STATIONARY SOURCES EMITTING GHG IN MEXICO



Source: SENER / CFE, 2012

OBJECTIVES

- To design the official roadmap for CCUS, from incubation to commercial scale.
- To establish a systemic and orderly basis for CCUS resources management and assimiliation of technological knowledge.
- To promote economic and regulatory incentives for technology implementation.
- To promote emissions and carbon markets in which Mexico can participate, as well as facilitate international support.
- To coordinate research activities on CO_2 regulation, capture, transport, use and storage.



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Construction and commercial operation of CCS and CCS-EOR
CO_2 commercialization
MRV

TECHNOLOGY ROADMAP STAGES

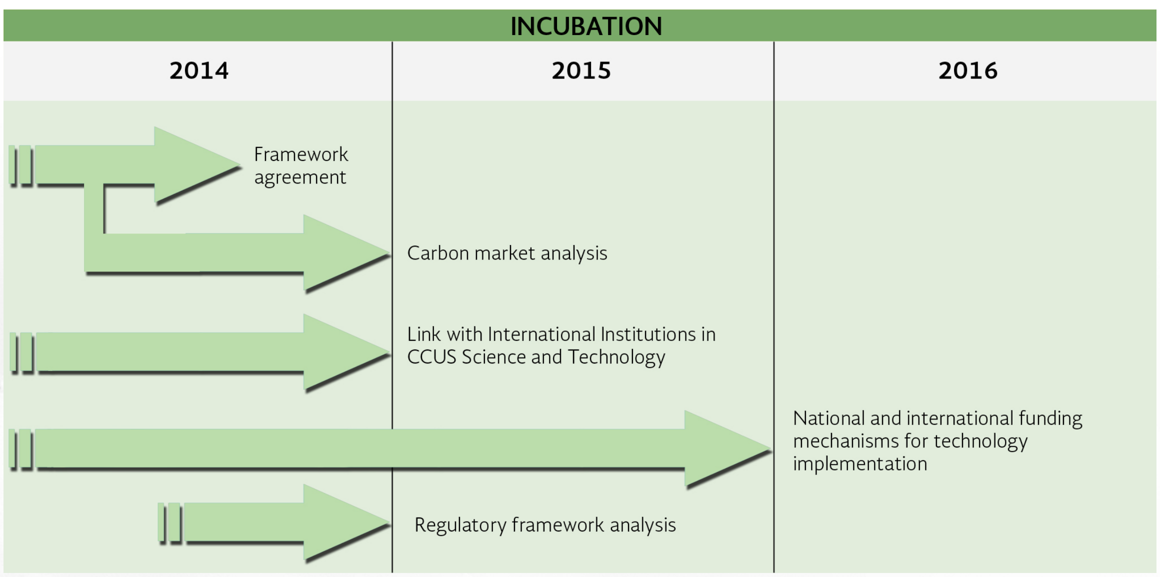
The development of the CCUS technology roadmap includes six stages. These are described below in a chronological order according to chart in the previous page.

I.- Incubation.

This stage represents the set of strategic measures to be undertaken prior to developing a public policy. Chart below shows the key phases of the incubation stage.

TECHNOLOGY ROADMAP

USE, CAPTURE AND GEOLOGICAL STORAGE OF CO_2

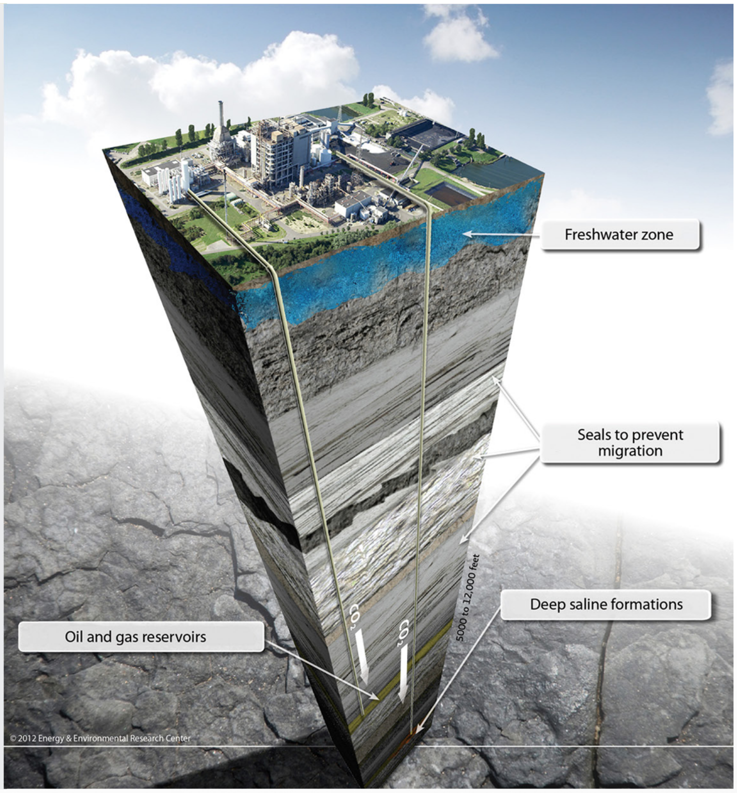


CCUS TECHNOLOGY

The CCS Technology (Carbon, Capture and Storage) is a set of applications to reduce carbon emissions in the atmosphere - capturing CO_2 and storing it underground. The suitable sites in the subsoil for carbon storage are exhausted oil fields, deep saline aquifers or unmineable coal seams.

It is known that CO_2 is one of the most abundant greenhouse gases in the atmosphere, in particular due to fossil fuel combustion. Alternative energy is still not widely available to substitute hydrocarbons, although they are developing, with strong prospects.

The CCUS technology will be an important solution to the need for fossil fuels. This technology has had good results in various countries. In Mexico, it could have important impacts, as fossil fuels are the basis of the country development in industry and economy.



Source: Peck et. al. 2012

Framework agreement. Due to lack of a public policy, a new regulatory framework will be agreed upon between SENER and SEMARNAT, the main regulatory institutions for the energy and environment sectors. PEMEX and CFE as the primary energy companies will also take part. One of the main objectives will be to set commitments for CFE and PEMEX to develop an integrated CCUS project, using CO_2 from a power plant for enhanced oil recovery (EOR).

Analysis of carbon markets. It is of utmost interest to analyze and to understand current carbon markets, including: the price of CO_2 emission reductions as well as the penalties for emissions to the atmosphere. It is important to consider that carbon capture and storage technology is not profitable when there are no financial mechanisms in place to promote its implementation. Therefore, an analysis of these scenarios should be done to design or adopt monitoring, report and verification mechanisms (MRV). According to international standards for funding mechanisms and carbon markets, it is necessary to ensure the permanent storage of CO_2 in the reservoirs.

CCUS STAGES

Carbon Capture and Storage Technology (CCS) follows a process sequence to ensure the storage of CO_2 from stationary emission sources and injected in deep geological formations. Below these processes are illustrated.

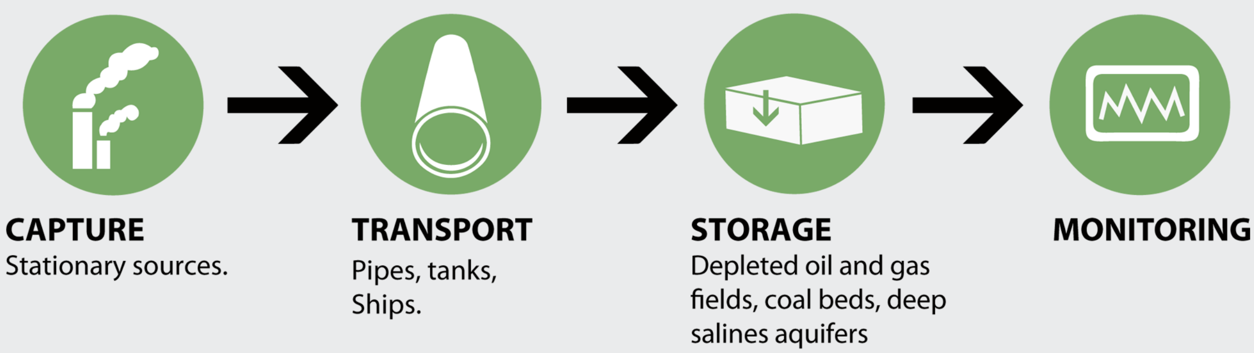
The greenhouse gases emitted by stationary sources are captured, and CO_2 is separated from the others. It is then compressed for efficient transport.

The CO_2 could be transported onshore by pipes, tanks or train, and offshore by ship.Optimal CO_2 pressure and temperature conditions are required for handling, transport and injection.

For storage process, sites are located underground where there are rocks with sufficient voids to storage large amounts of CO_2. These voids must be interconnected to let the flow and storage of CO_2 move according to the injection rhythm. And to ensure the right conditions to prevent leakages to surface or fresh water aquifers.

The geological CO_2 storage projects also require monitoring stages before and during operation even after closure. Risk analysis and development of mitigation strategies have to be implemented if a leak occurs.

The effective implementation of monitoring technologies provide reliability to the projects, ensuring safety around the potential health and environment impacts.



Source: Mota-Nieto, 2013

Connect with International Institutions in CCUS Science and Technology. Among the main barriers for CCUS development in Mexico is due to the lack of capacity builing, both for technology infrastructure and availability of human resources. Thus, the importance of international networking for knowledge and technology transfer for Mexico to develop its own capabilities within the medium term.

National and international funding mechanisms for technology implementation. CCUS technology requires significant capital investment resources, therefore the participation of the Ministry of Finance (SHCP) should be also considered. Moreover, collaboration among Government, private sector and research institutions should be encouraged and strengthen. There are international mechanisms responsible to support the climate change mitigation technologies as CCUS, where Mexico takes part; however, more international support will be required.

Analysis of the Regulatory Framework. The permanent storage of CO_2 has considerable concerns and responsibilities that should be analyzed in more detail. Although leading countries have uncertainties about CCUS full implementation, some regulatory framework for CO_2 management, sequestration methods and monitoring responsabilities have been developed. Mexico should make a diagnosis of all regulations to ensure the right use of the technology and define responsibilities between the stakeholders.

II.- Public policy.

Once the Incubation Stage has begun, policies regarding CO_2 use and sequestration must be made public.

Under the terms of the voluntary targets, it will be necessary to implement policies to assess GHG emissions in Mexico.

The relevant phases of Public Policy-making are:

Capacity Building. Although there have been efforts to spread knowledge around CCUS, it is necessary to accelerate the diffusion. One mechanism is via capacity building in undergraduate and graduate programs. Internships and courses guided by international experts will be promoted; and subsequently more elsewhere in the country.

Regulatory Framework Adjustments. Once the regulatory framework analysis is completed, adequacy of regulations will be required. At this stage to those regulations which need to tackle pilot programs should be given and be followed by those for demonstration and commercial scale.

Legally Binding Observation for Permanent Monitoring. The responsibility of those who stored CO_2 is a key policy. It is important to wind public confidence around storage security. This policy should be ready when the first pilot projects begin operations. The most important policy implementation will be at commercial-scale projects.

Dissemination of the Technology Implementation Plan. The public should be aware of CCUS implementation plans in the country. It is necessary to promote and disclose the technology to local governments, public organizations and those institutions targeting to sustainability. This phase has taken several years in other countries. This is a key stage to consider.

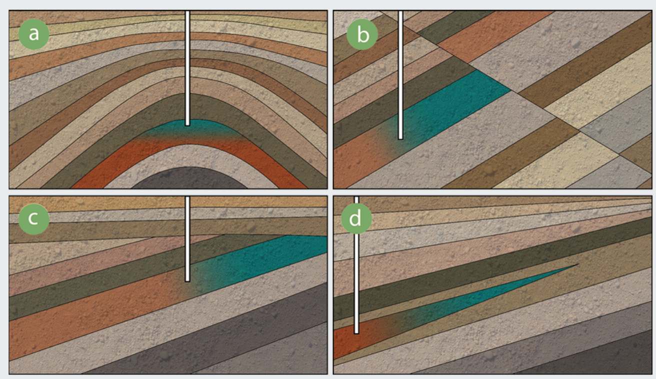
STORAGE MODELS

Once CO_2 is injected in a geological unit, it should due to various physical/chemical trapping mechanisms, such as:

Physical trapping: in this mechanism the CO_2 remains in rocks due to crustal strain, and there is an impermeable rock over the host rock to prevent upward movement of the gas. These traps are known as structural traps.

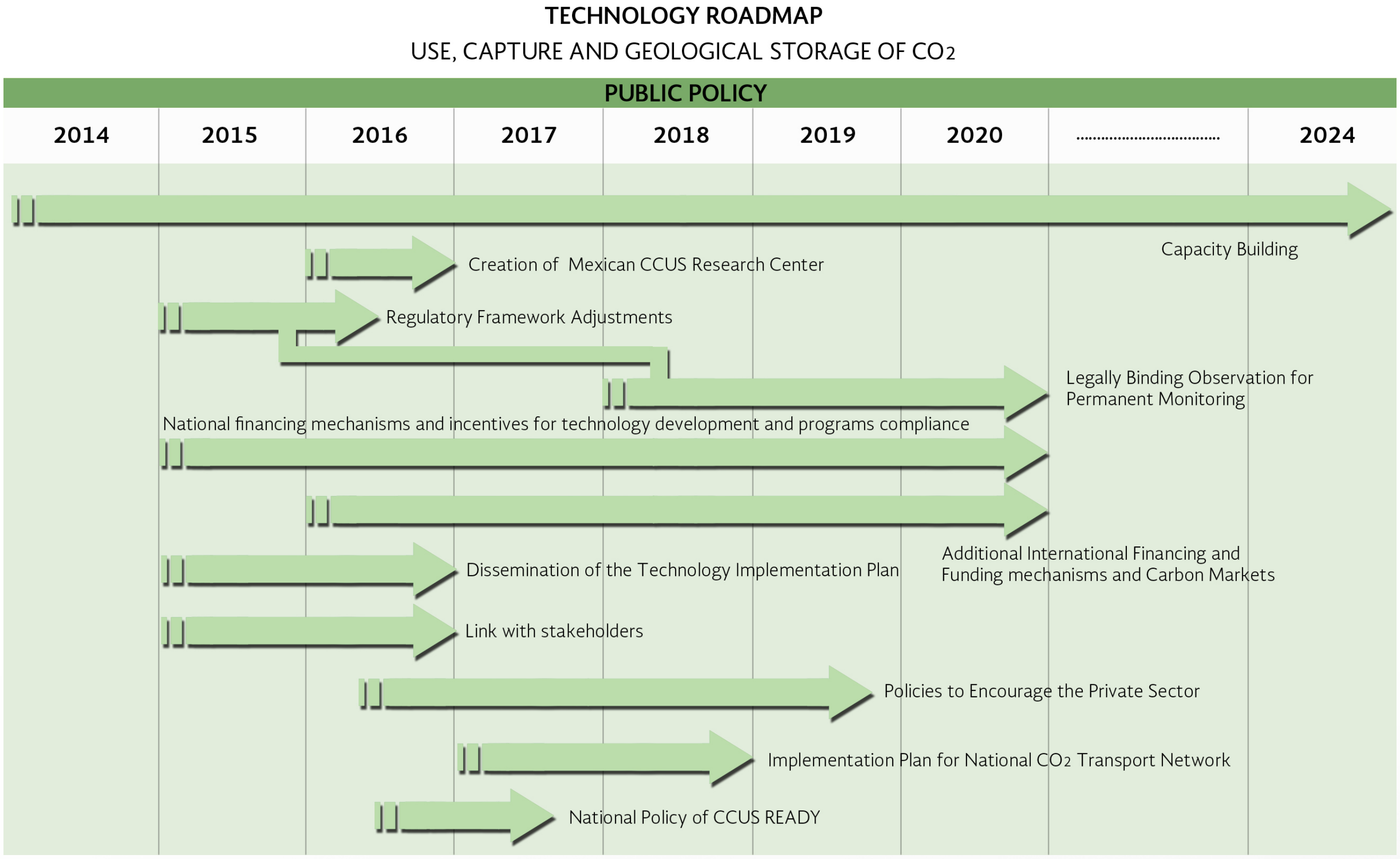
Naturally, there are some changes and variations in the characteristics of the rocks due to different processes involved during the deposition of rock-forming elements, it is known as facies change, which provides another kind of trap when permeable rocks are in contact with permeable ones. This mechanism is called as stratigraphic trap.

Below these two mechanisms are shown:



Chemical trapping: the empty spaces in the rocks decrease in depth because they are occupied by fluids, generally water. The CO_2 could be dissolved with reservoir fluids in the geological formation, and over the time, will produce a solubility trapping. Another mechanism is when dissolved CO_2 reacts with reservoir rock so carbonate minerals can precipitate, this trapping mechanisms is known as mineralization that provides the most stable storage form, however the timeline for this trapping is over thousands of years

Source: Daniel et. al. 2008



Link with stakeholders. In the CCUS technology development many industries should be involved: cement, steel, chemicals, oil and power generation industries, as well as academia and research institutions. This is a major challenge for a functional and timely public policy.

Policies to Encourage the Private Sector. CCUS technology requires significant financial resources. It is profitable in some specific cases, so it is necessary to create some mechanisms to make this technology more attractive as part of a public policy.

Implementation Plan for National CO_2 Transport Network. CO_2 should be provided in sufficient amount to be considered as a reliable product. This could be possible if a pipeline network is built to transport it from distant sites in Mexico to other places or foreign countries (mainly the US). Otherwise, individual emission sites will not be attractive. A policy on this topic should be designed based on rigorous carbon market analysis.

CCS Ready National Policy. Currently the CO_2 emitting industries are not still ready for a capture scheme. Therefore, a timely public policy is required to regulate the new facilities. This concept is called CCS Ready that involves a significant investment over production costs. It is made to get lower costs in CCS projects than those ones that are no planned from the beginning.

National Funding Mechanisms and Incentives for Technology Development and Compliance Programs. Infrastructure investments must be done by national funding to achieve established goals. A key objective is to show the importance to tax authorities and government for funding.

International funding mechanisms and carbon market. There are already numerous international funding mechanisms that are focused on CCUS technology implementation. It is necessary to develop public policy around GHG emissions mitigation to promote activities to merit such funding.

Creation of Mexican CCUS Research Center. CCUS technology should be a strong feature in the country. It is necessary to establish an innovation center which ensures technological independence to improve the design, building and infrastructure costs of CCUS.

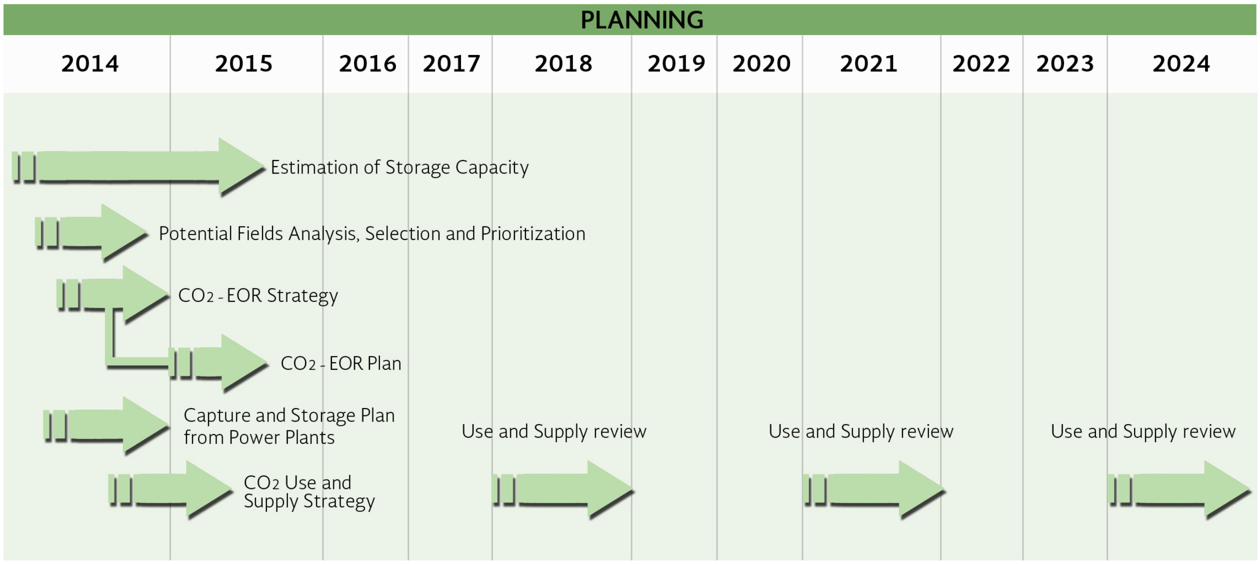
III.- Plannning.

Power generation is the main source of CO_2 emissions, and the enhanced oil recovery industry can be a customer of this CO_2.

There are some planning activities that must be developed jointly by the two major CO_2 emitting industries (oil and power generation). This process should be developed based on optimizing the emissions-capture-storage cycle that could change, according to technological advances and carbon price.

TECHNOLOGY ROADMAP

USE, CAPTURE AND GEOLOGICAL STORAGE OF CO_2



Carbon Capture and Storage from Power Plants. The power generation industry should take the first steps to adopt sequestration technology. This effort should first be associated with a profitable use such as enhanced oil recovery; in addition we must locate deep saline aquifers as an option to storage the unmarketable CO_2.

Capacity Storage Estimation in Deep Saline Aquifers. We should continue reviewing the deep subsurface geology to find the best sites for safe storage. We should aim to have a subsurface geological census so that CO_2 emitting industries can identify their proximity to underground reservoirs. These kind of reservoirs, even when they do not produce an economic valuable product may be considered as the most common means of long-term storage.

CCUS operation of CO_2-EOR considers a planning stage before trigger a pilot project. It consists of the following activities:

Analysis of Potential Fields. Fields and reservoirs of potential storage regions in Mexico will be assessed. Select geological information will be obtained during exploration and field development activities by PEMEX (along with CFE geothermal fields) to identify deep saline aquifers.

Field Selection and Prioritization. Those fields that meet the criteria established for technical feasibility processes of CO_2-EOR, as well as deep saline aquifers will be prioritized.

STORAGE CAPACITY ESTIMATION

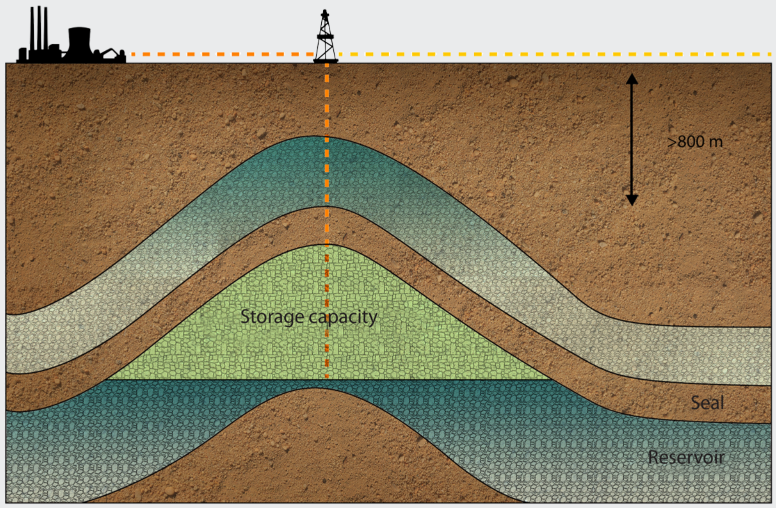
For storing CO_2 we require a porous and permeable rock covered by an impermeable rock that prevents gas leakage.

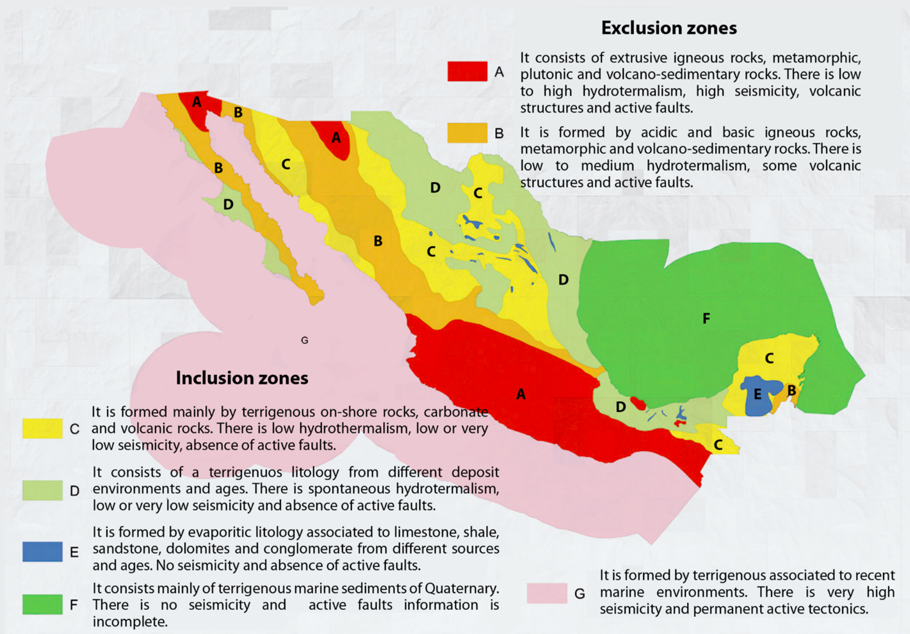
In 2011, a country-level study identified suitable conditions for CO_2 storage through an inclusion and exclusion storing areas map.

Regional sections were analyzed and 11 geologic provinces were identified, with a total estimated theoretical capacity of 100 Gt of CO_2 storage in Mexico.

In the next stage - ongoing - information from deep wells and geological structures in the subsurface are being analyzed to estimate the effective storage capacity.

Geological trap dimensions are measured according to the sedimentary environment of the rock, an efficiency factor is selected. The volume of the geological horizon is multiplied by that efficiency factor. Currently the Sabinas and Burgos basins are being evaluated at the regional level to estimate the effective storage capacity.

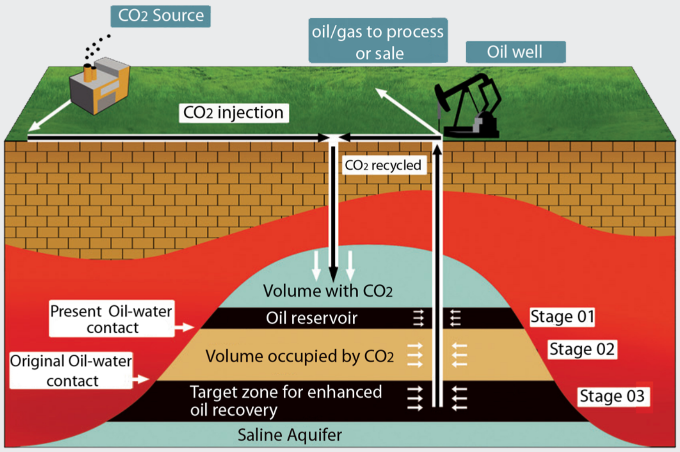




Source: Dávila et. al. 2010

EOR

Enhanced Oil Recovery (EOR) is a set of methods used to increase the hydrocarbon recovery behind the conventional primary and secondary recovery processes.



Source: SENER / CFE. 2012.

CO_2 injection in hydrocarbon fields provides additional pressure, and also reacts with oil, decreasing its viscosity and swelling it through the geological media to a producing well. However, the oil recovered will have some CO_2 that must be separated and reinjected into the field.

EOR is among the best economic options for CO_2 capture and storage because of the oil production increase and the improvement in capture, transport and injection costs for CCS.

The reservoirs where the EOR is applied have the reliability for CO_2 storage because of the hydrocarbon accumulations over millions of years; also petroleum infrastructure could be used for CO_2 transport and injection.

CO_2-EOR Strategy. The CO_2-EOR strategy will be defined based on the National CCUS Policy. It will include a CCUS program for PEMEX and CFE facilities.

CO_2-EOR Plan. The implementation plan for EOR projects will be established to ensure the supply of CO_2 coming from PEMEX and CFE facilities, both at the pilot and demonstration scale.

CO_2 Use and Supply Strategy. This strategy applies to CO_2-EOR and capture strategies for considering the measures and resources required at medium and large scale. It is critical to ensure the CO_2 supply for EOR projects over the long-term.

This strategy should be reviewed every three years.

IV. Pilot and demonstration scale projects.

Once the CCUS Incubation, Public Policy and Planning phases have been initiated, it is time to start the pilot stage, followed by demonstration and commercial ones. It is not necessary to complete one stage to begin the next, but the foundation must ensure that the proper development can be carried out uninterrupted.

Below are described the pilot, demonstrative and commercial stages, for both the oil and power generation industries.

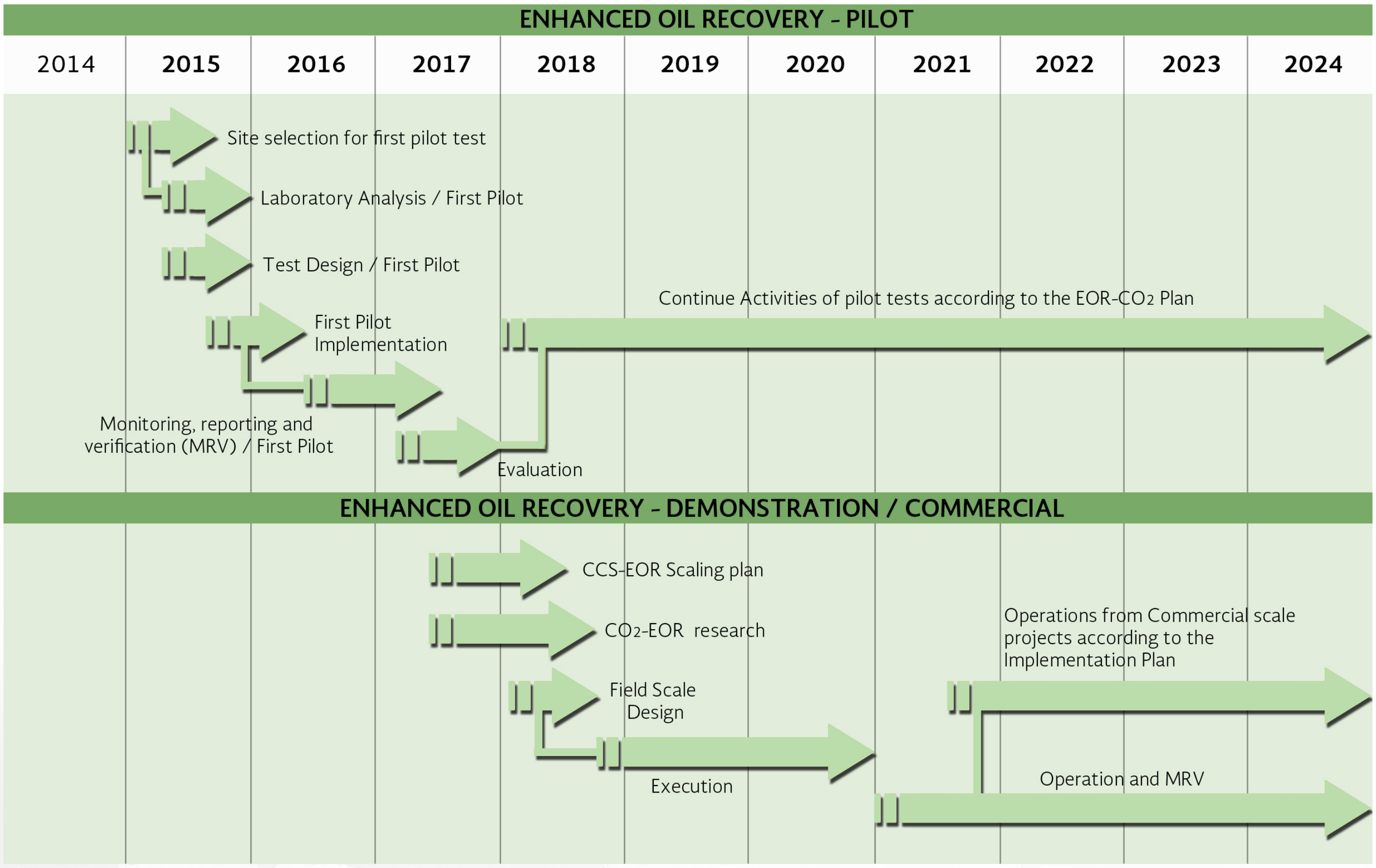
IVa. Pilot project in oil industry.

In EOR, this stage represents a set of measures to verify the feasibility of CO_2 injection. At first it is conducted in laboratory and then in the field. Based on the established CO_2-EOR Plan, an enhanced recovery pilot test with CO_2 will be defined. Detailed and specific works will be made in fields with the best features for successful implementation of a CCUS-EOR project. The CO_2-EOR and capture pilot projects will be designed together to ensure the CO_2 supply and the transport to the test site. The CO_2-EOR pilot stage takes at least three years to achieve a full-scale application. The implementation to analogous fields could reduce the time at commercial scale. The beginning of the commercial stage will be defined with the first CCS-EOR pilot project, and initial works to be applied on field-scale.

Below are the main phases:

TECHNOLOGY ROADMAP

USE, CAPTURE AND GEOLOGICAL STORAGE OF CO_2



Selection of test sites. It is necessary to select a sector that contains specific features representative of the reservoir. All test activities will define the feasibility of CO_2-EOR application at commercial-scale. Mechanical condition of the wells and surface infrastructure are considered, facilitating potential adjustments required in project operations and monitoring.

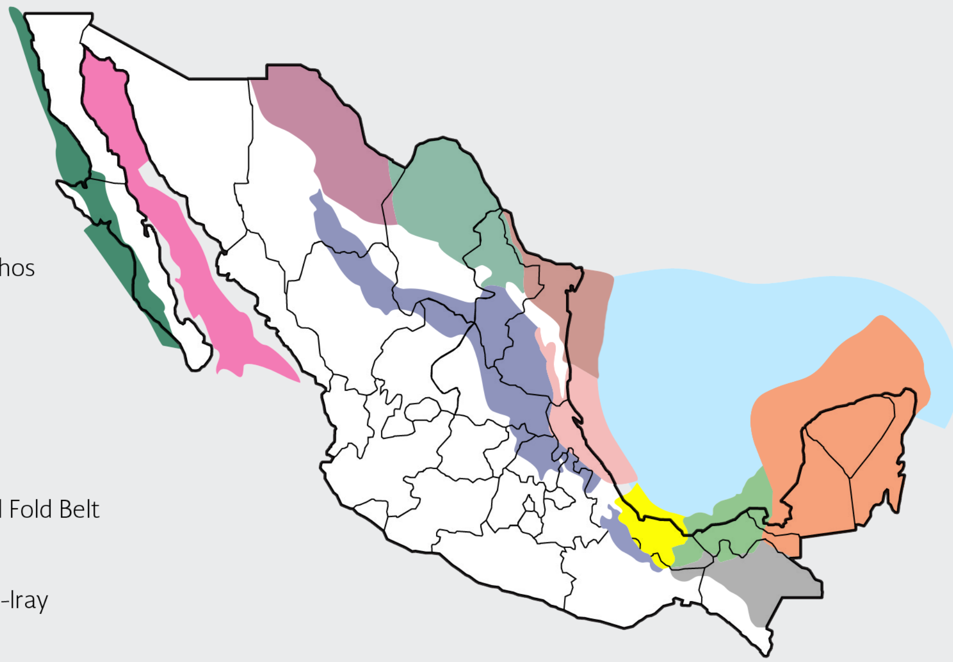
Laboratory studies. This phase includes the characterization of CO_2 and reservoir fluids mixtures. The most common features to study are: the minimum miscibility pressure of the CO_2, oil swelling and viscosity reduction once the CO_2 is dissolved. The oil displaced by CO_2 or alternating water and CO_2 (WAG: water alternating gas) and the reservoir pressure and temperature conditions are also considered to characterize the performance of laboratory-scale process.

OIL PROVINCES IN MEXICO

Oil Provinces: Areas where commercial quantities of oil have been identified and favorable conditions for hydrocarbon accumulation occur.

Producing provinces:

- 01.- Sabinas-Burros-Picachos
- 02.- Burgos
- 03.- Tampico-Misantla
- 04.- Veracruz
- 05.- Southeast
- 06.- Deep Gulf of Mexico
- 07.- Yucatan Platform
- 08.- Chiapas Fold Belt
- 09.- Sierra Madre Oriental Fold Belt
- 10.- Chihuahua
- 11.- Gulf of California
- 12.- Vizcaíno- La Purísima-Iray



Source: PEMEX, 2013

Pilot test design. The design is based on the construction and use of a numerical model to describe the process of CO_2 injection in the selected area. The model is a mathematical representation of the fluid in the reservoir and hydraulic flow in wells. This information provides the data to estimate the additional oil recovery after CO_2 injection and is used for the technical and economic viability assessment.

The CO_2 injection rates, pressure and compression requirements are considered. The rates of oil production in wells, monitoring parameters and the frequency of data acquisition are also defined, as well as the duration of the test.

Execution. This phase involves the execution of works, adaptations of wells and surface facilities, and the purchase of special equipment and services to support the operation of the pilot test.

Operation, monitoring and assessment. This phase involves the implementation of the injected and produced fluids in wells. This is done according to the design, monitoring, injection, production and composition data of fluids obtained during the test. The emergence of CO_2 in wells and the evolution of its concentration in the flow produced are crucial. The assessment of benefits should be based on pre-established criteria. The numerical model may be updated to estimate the benefits of CO_2 injection and help analyze the additional oil recovery. It will be necessary to calculate the amount of CO_2 remaining in the reservoir and to predict the concentration changes in the production. This information is required in all CCS-EOR programs to define the separation and recycling of hydrocarbon gas management in the reservoir.

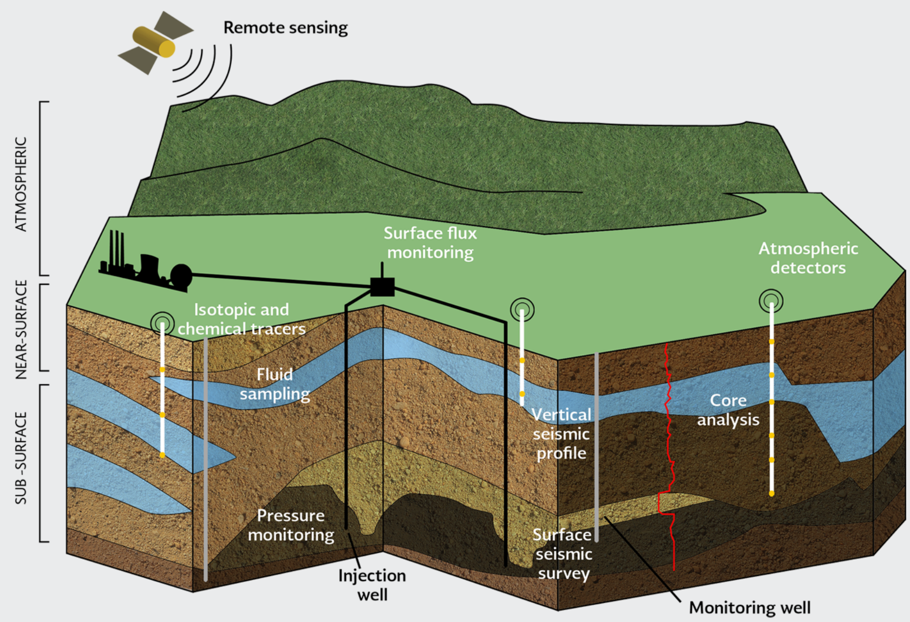
WHY MONITOR RESERVOIRS?

Monitoring is one of the most important stages of CCUS technology to provide confidence to the public about CO_2 storage reliability. A site selected for storage must ensure the minimal risk of leakage.

The monitoring methods are applied before, during and after injection to obtain the base parameters, and to observe the performance during injection and to guarantee permanent storage of CO_2 underground. Each project needs a monitoring program for deep and shallow areas as well as an atmospheric analysis.

Monitoring in deep areas is focused on the injection geological horizon; in shallow areas, away from the injection, 3D and 4D seismic surveys are necessary to observe the CO_2 movement in the sub-surface. Chemical samplings are taken in shallow aquifers to identify any fresh water contamination. The surface monitoring analyzes the air composition and surface deformation.

The monitoring time after closure has not yet specified for these projects.



Source: http://www.slb.com/services/additional/carbon/monitoring.aspx

IVb.- Pilot project in power Generation.

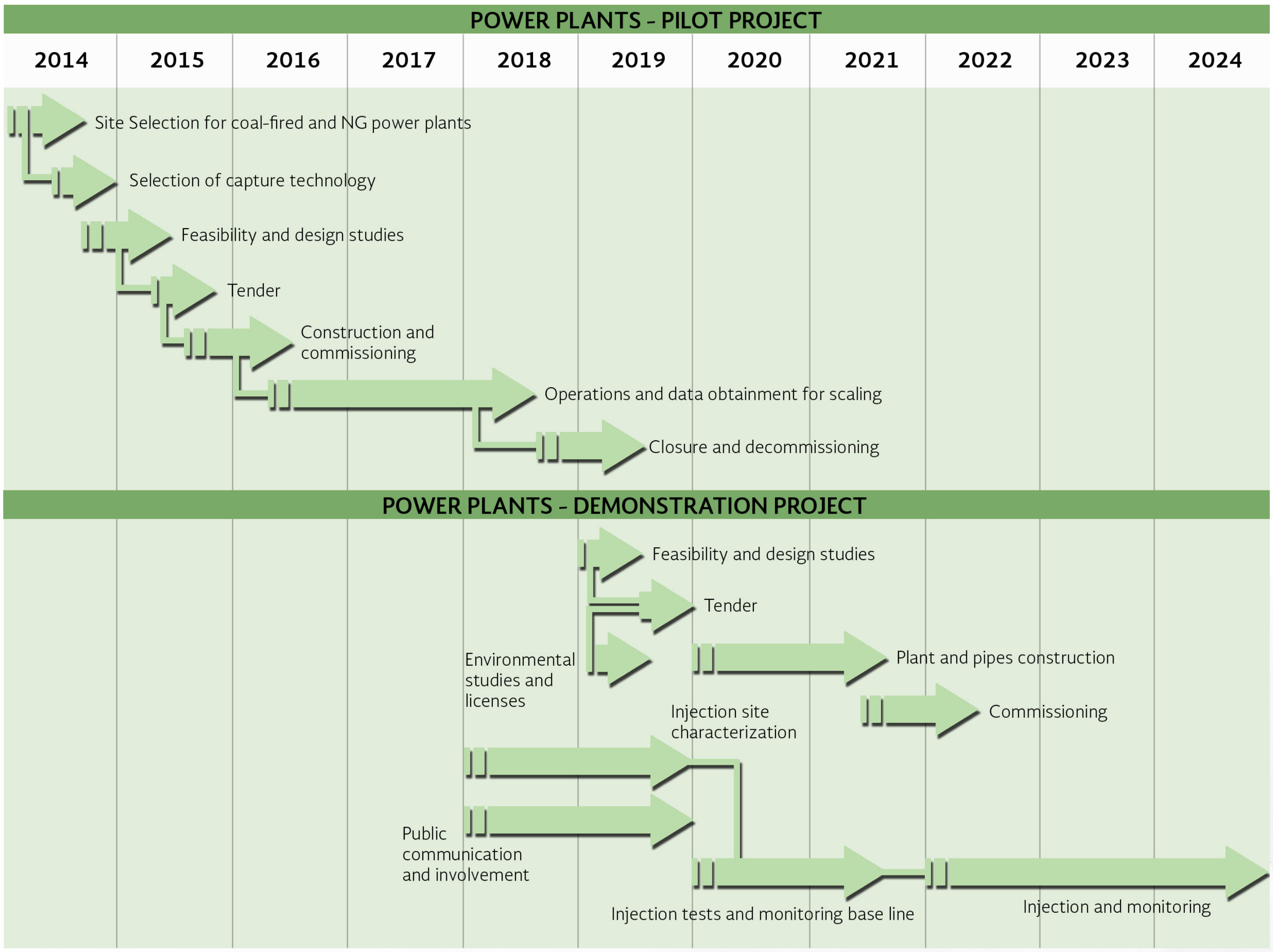
The pilot project for power plants considers the CO_2 capture from a power plant to evaluate the technical and economic feasibility. The critical parameters for the demonstration scale should be obtained.

According to current infrastructure conditions, the capture plant could be implemented using post-combustion technology by amine of 2 MW power plant with a maximum CO_2 flow rate of 10 tonne/day.

The main phases are:

TECHNOLOGY ROADMAP

USE, CAPTURE AND GEOLOGICAL STORAGE OF CO_2



Selection of a natural gas or coal-fired plant. The activities of the pilot test begin with identifying power plants to install a capture-separation plant of CO_2. The most appropriate facility is selected to implement a capture test. It is important to look for future projects between CFE-PEMEX in this area.

Capture technology selection. Different capture technologies are considered to select the best one for existing power facilities in Mexico. Moreover, a cost-benefit analysis is made to decide the most appropriate technology to apply in the design of a new power plant.

Feasibility studies and design. Feasibility studies/ design methodologies are necessary to obtain information to establish technical specifications, building cost and commissioning of pilot plant. This information will determine the basis for the tender.

Tender. The construction project of the pilot plant will be tendered.

Construction and commissioning. To confirm that the construction of the pilot plant is by design and to show it operates adequately.

Operation and data acquisition for scaling. Once the pilot plant is built, it will be operated by CFE personnel. Frequent evaluations are necessary to determine the capture efficiency based on monitoring. Information about energy penalty and costs of pilot-scale development will be considered.

Closure and decommissioning. Once the test stage is completed, the capture plant will be closed and decommissioned

IVc.- Demonstration project.

Once the pilot project is running, the demonstration project should be developed (possibly with an equivalent flow from a 20 MW power plant). Several prior steps are required such as: field and technology selection, laboratory tests, design and implementation of a pilot plant.

CCS PROJECTS IN THE WORLD

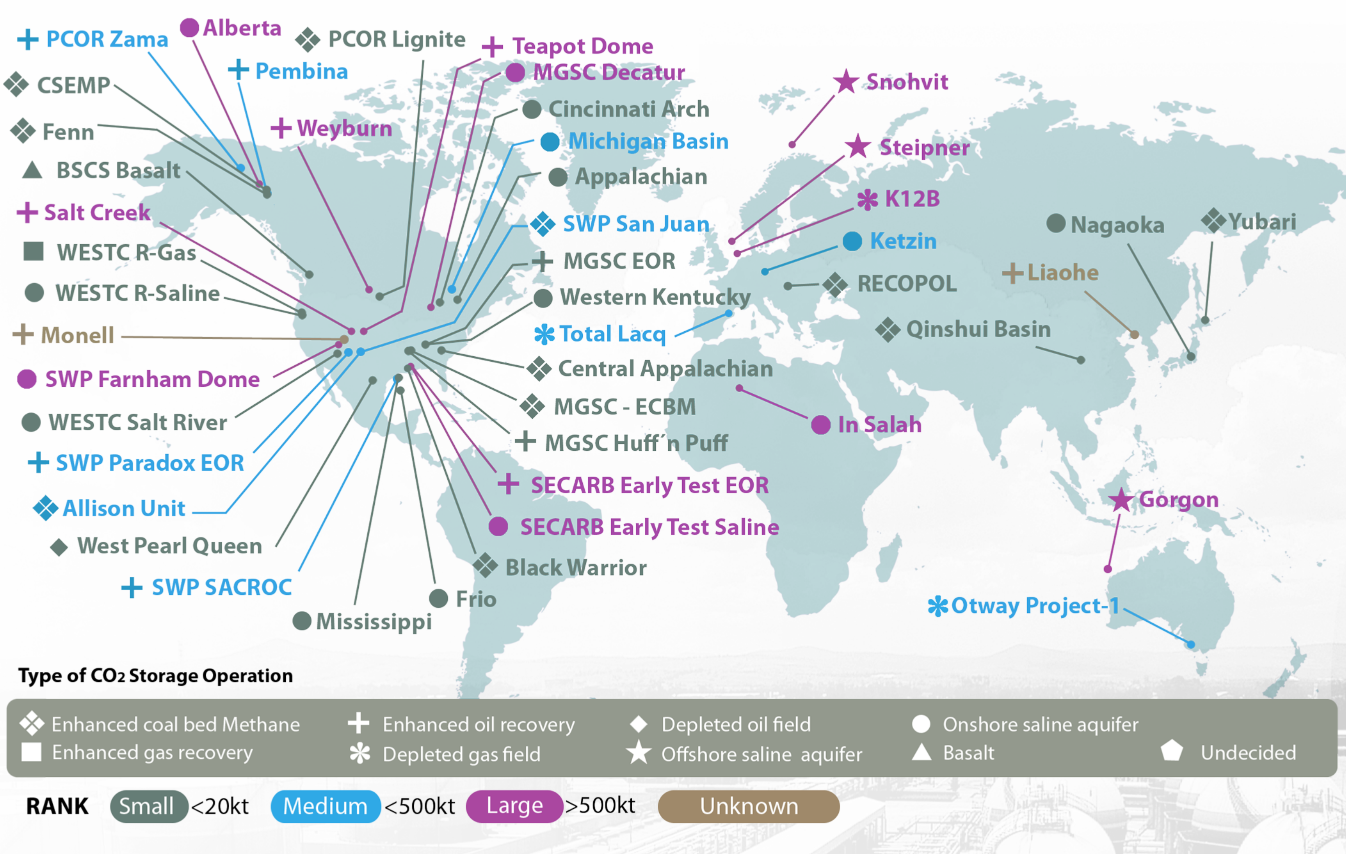
CCS projects are defined according to their development scale as:

PILOT (<20 kt of CO_2 per year). CCS technology is applied at small-scale. The aim is to obtain data and information to guide future planning and investment.
DEMONSTRATION (<500 kt of CO_2 per year). This is a medium-scale to validate the efficiency, security, and range of the technology.
COMMERCIAL (>500 kt of CO_2 per year). This scale is implemented once the technology is proven, with fully analyzed social and economic benefits.

These projects can be classified according to their operating profile as:

- Enhanced oil recovery
- Oil and gas depleted fields
- Deep saline aquifers
- Other

These projects have been implemented all over the world, primarily in North America and Europe. That said, more countries are joining the commitment to reduce emissions of greenhouse gases using CCS systems.



Source: Global CCS Institute, 2011

The following are the main phases:

Injection site characterization. A detailed injection model is built to determine the saline reservoir conditions for injectivity and caprock security. The mechanical condition of wells, and surface infrastructure should be carefully considered to prevent leakages and optimize the procedures. This characterization is different from the potential use of CO_2 for EOR. To locate a storage site, it is necessary to ensure the CO_2 sequestration, even if there are no EOR activities.

Feasibility study and design. The results of the pilot plant are analyzed and scaled by laboratory studies. The acquisition of additional data reduces the uncertainty of the application in larger-scale. The economic and technical specifications are obtained to be included in the bidding of demonstration project.

Tender. The proposed construction of the demonstration plant will be tendered for construction.

Environmental studies and licenses. Once carried out the scaling design of the capture plant , environmental studies and permits for construction should be made.

Social communication and public involvement. All greenfield projects should be communicated to public. It is necessary to establish an outreach area and professional communication for communities located near the plant.

Scaling plant (Construction) and pipelines. A construction license should be obtained for the plant and pipelines. To proceed to scaling, it must be authorized by the environmental authority, receive the land use licenses, and right of ways for pipelines.

Injection tests and monitoring base line. Knowledge of the sub-surface is necessary to model the behavior of the CO_2 plume during injection. At least two monitoring wells should be drilled and a seismic cube must be acquired over the relevant region.

Commissioning. This phase could start once operating licenses are obtained including the capture, transport and injection processes at demonstration and commercial-scales

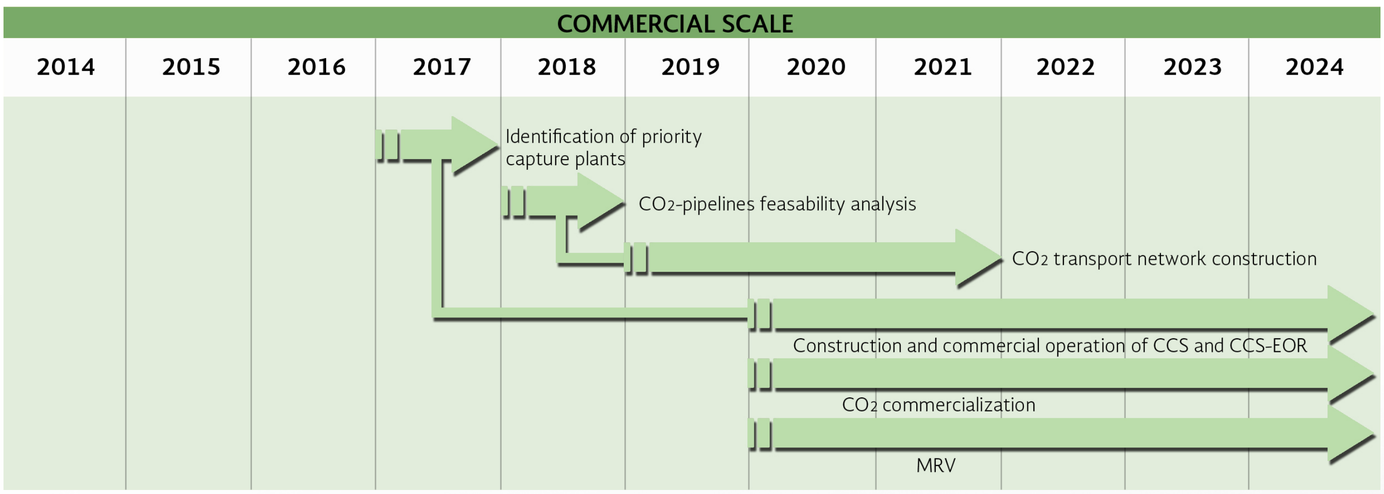
Injection and monitoring. Once the injection is started, a monitoring program will run and be adapted according to operational results.

V.- Commercial scale.

Once the pilot and demonstration projects have been implemented, it is possible to bring the CCUS technology to commercial-scale, thus expanding to other CO_2 emitting industries. For that stage, implementation costs and incentives must be resolved. At this point, capture and storage technology should be handling significant volumes of emissions. The "commercial" concept enables widespread availability, with key technical risks and economic issues already mitigated via the pilot and demonstration-scale project:

TECHNOLOGY ROADMAP

USE, CAPTURE AND GEOLOGICAL STORAGE OF CO_2



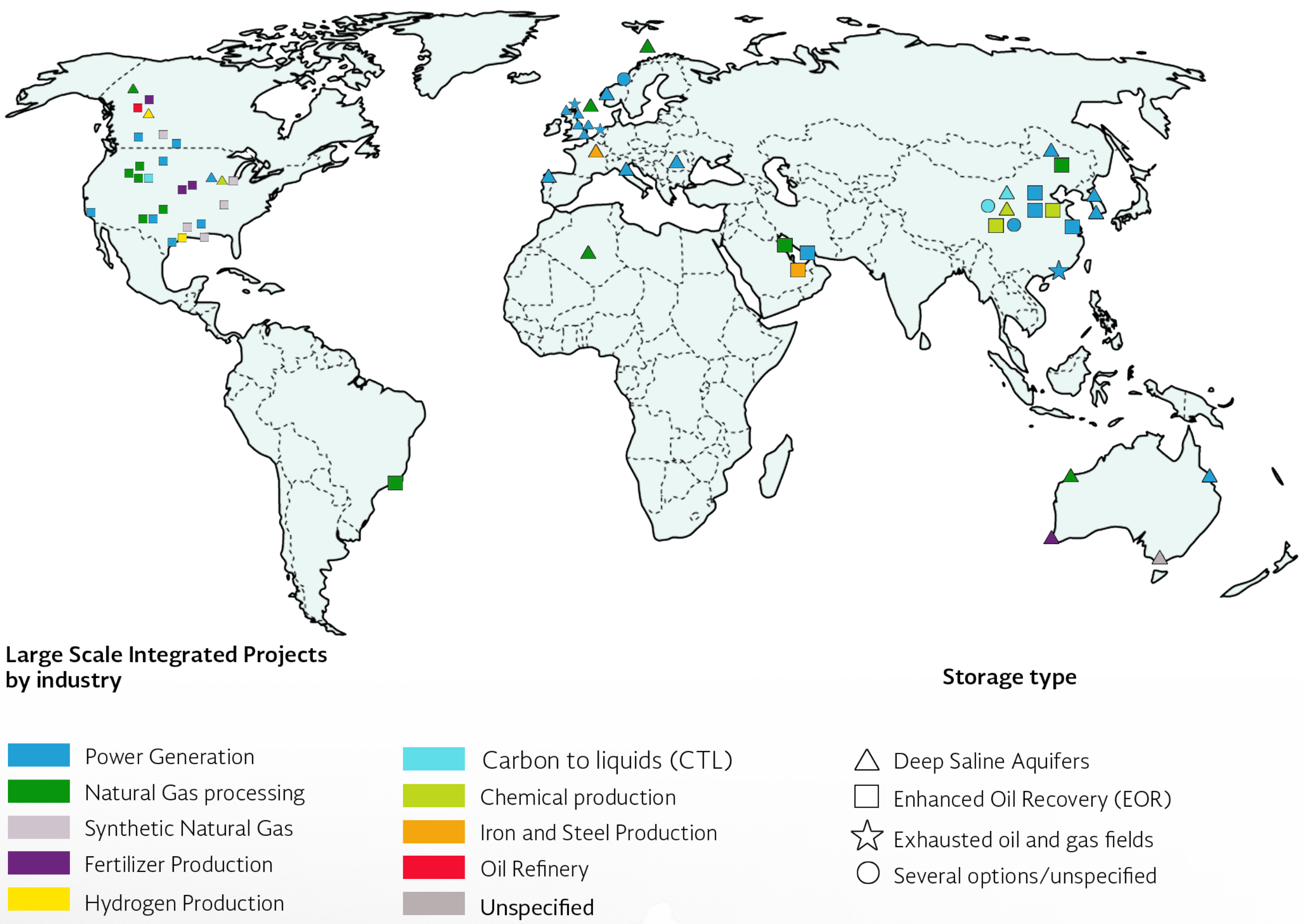
LARGE SCALE INTEGRATED PROJECTS (LSIP)

Through 2013 have developed 65 large scale projects: 20 operating, building or running, with a storage capacity greater than 33 million tones of CO_2 per year.

The following projects are those that have contributed more knowledge. They have demonstrated capture, transport and storage technologies, as well as monitoring and verification:

- Sleipner (Norway) in a deep saline aquifer for carbon geosequestration
- Weyburn-Midale (Canada) applied to enhanced oil recovery /monitoring and verification.
- In Salah (Argelia) in a deep saline aquifer for carbon geosequestration
- Snohvit (Norway) in a deep saline aquifer for carbon geosequestration

The storage scale is defined based on the typical minimum volumes emitted by power plants and other industrial sectors. These have been established as: at least 800,000 tonnes of CO_2 per year from power generation plants and at least 400,000 tonnes of CO_2 per year for emissions coming from other industries associated with CCUS technology.



Source: Global CCS Institute, 2013

CCS-EOR

Once the CO2-EOR benefits are validated by pilot tests, projects will be developed for enhanced oil recovery initiatives at commercial-scale. It is possible to reduce the uncertainty due of heterogeneities in the reservoir through laboratory research. Furthermore well and production facilities analyses are required for the project design and implementation. The CO_2-EOR commercial-scale design must ensure the supply the CO_2 volumes required, as well as the transport to the injection site. The field-scale design, execution and assessment will be given by the first commercial CCS-EOR project.

The following are the main phases:

Scaling Plan. Consists of those activities to extend the application of CCS-EOR to field-scale and verify the technical, environmental, public and economic viability. All information is used to support the scaling plan.

Complementary studies. Laboratory studies are used to reduce the uncertainty at the field-scale. Injectivity tests and well logs to determine oil saturation are required. The numerical model should be updating with current information from field to predict the CO_2 injection effects. This procedure is made by a sector model calibration from pilot results to know what kind of tools are required at the commercial-scale design.

Design of field-scale applications. This phase is focused on designing the best conditions for CO_2-EOR implementation. It is based on a numerical model adapted from injection process data. The number and location of wells, the injection rate and oil production should also be determined, as well as the injection pressure and compression in well. Monitoring data will be used to establish the main parameters and optimize the operation. The remaining CO_2 must be separated from hydrocarbon to be recycled. The CO_2 trapped in the reservoir could then be determined.

Execution. This phase is about the execution of various initiatives around the adjustment of wells and surface facilities. It is likely to require special equipment and services to support the operation and monitoring for CCS- EOR projects at commercial scale.

Operation of CCS-EOR projects. Consists of the implementation of a CO_2 capture program, injection, and production. Monitoring is necessary to observe the CO_2 concentration in relation to the hydrocarbon produced. System behavior verification is important to identify potential leakages and guarantee security practices. The CO_2 monitoring and storage verification in the field should be calibrated with the established standards.

Other activities at commercial-scale are:

Priority Capture Plants Identification. A national strategy must identify all CO_2 emission sources. They will be classified according to the volume generated, the proximity to an injection site, and by profitability of carbon dioxide use in a process. These industries should be the first involved with the CCUS scheme. Later on, additional industries can be incorporated to the national capture system.

Feasibility Study for CO_2 Pipelines. As mentioned in the Public Policy , the volume of CO_2 from one emitting plant alone is not profitable. A CO_2 pipeline network is required to transport the CO_2 profitably. In this stage it is necessary to conduct a technical-economic analysis to develop an efficient and cost effective construction of the pipeline network.

Construction of CO_2 Transport Network. The previous stage allows the timely construction of the CO_2 transport network for capture.

CCUS and CCS-EOR Commercial Construction and Operation. Mature CO_2 storage in geological industry will be a reality closer to 2050. Otherwise it means that either humanity has found how to replace fossil fuels, or the greenhouse gas reduction goals have not been met. If the CCUS industry reaches maturity, each country will require a scheme of CO_2 emitting industries and storage sites. The storage sites could be associated to enhanced oil recovery (CCS-EOR) or only carbon storage (CCS). This procedure must be done at the final stage of TRM once many CO_2 emitting industries are part CCS processes. The industries can deliver their CO_2 emissions through the CO_2 pipeline and receive incentives or avoid taxes.

CO_2 Marketing. It is expected that as time goes on, the CO_2 price will increase. This aspect is a reason to believe that in the final phase of the TRM process is relative to participate in a national and international emissions market.

Monitoring, Reporting and Verification. Once the CCUS technology is implemented in the country, adherence to regulations will be necessary to ensure the permanent storage of CO_2 in geological media. International certified monitoring procedures must be implemented and verified. There should be reports to let the public understand the evolution of each reservoir and know if there is any measure to apply for better reservoir operations.

CO_2 PIPELINES

CO_2 must be transported from the capture locations to the storage site.

Currently, pipelines are a mature market technology and are the most common way for CO_2 transport.

CO_2 is dried and compressed to a pressure greater than 8MPa to make the transport easier and cheaper.

The first long-distance CO_2 pipeline triggered early 1970s. In the United States, 40 Mt of CO_2 are transported by more than 2,500 km of pipelines from natural and anthropogenic sources to storage sites, mainly in Texas where CO_2 is used for enhanced oil recovery.

In most of these pipelines, the flow is driven by compressors from leading end and, in some cases, intermediate compressor stations.

Many of the countries where CCUS technology is implemented have installed a pipeline network to transport CO_2 from stationary emission sources to use and storage sites; these networks let handle volumes for profitable processes, for example in enhanced oil recovery fields.

Photo: BP p.l.c.

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