Post-Combustion Carbon Capture from Flue Gas

June 4 2015

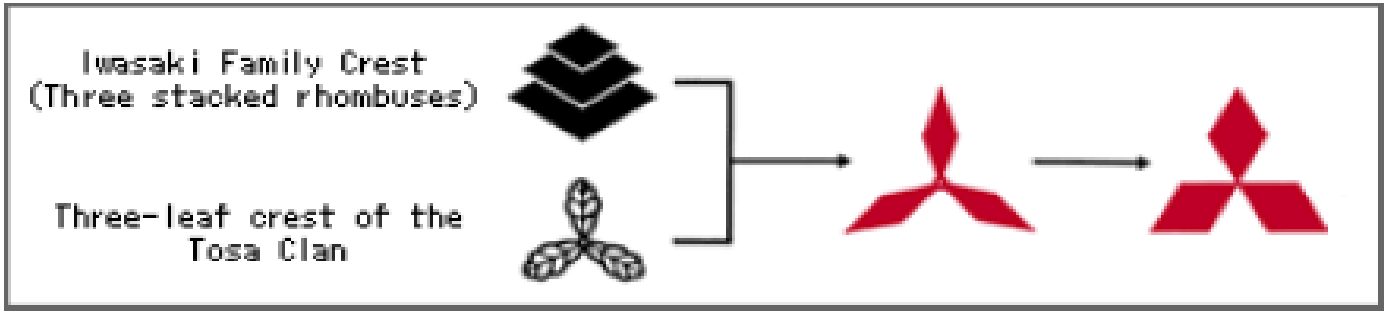
MITSUBISHI HEAVY INDUSTRIES AMERICA, INC.

1. MHI Overview
2. Carbon Capture's Role in Reducing Carbon Emissions
3. MHI’s Carbon Capture Technologies

1.MHI Overview

MITSUBISHI Group

- **"Mitsubishi"** means **"Three Diamonds"**



- **Mitsubishi Group** is the largest Japanese conglomerate, which shares the Mitsubishi brand, trademark and legacy since 1870.
- **Companies of Mitsubishi Group:**

Mitsubishi Heavy Industries (MHI)
Mitsubishi Corporation
The Bank of Mitsubishi-Tokyo UFJ
Tokyo Marin & Nichido Fire Insurance
Mitsubishi Motors (MMC)
Mitsubishi Electric (MELCO)
Nikon
Kirin Brewery, etc.
Total 29 core companies and those group companies

MHI Products

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Energy & Environment

GTCC Power Plant

J-series Gas Turbine

Flue gas CO_2 Recovery

Commercial aviation & Transportation systems

Transportation system

Passenger Ship

Air Craft

Machinery, Equipment & Infrastructure

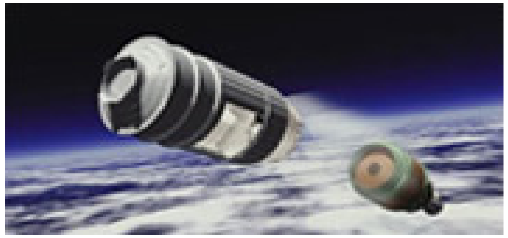
Compressor

Forklift Truck

Machine Tool

Integrated Defense & Space systems

H-II Rocket

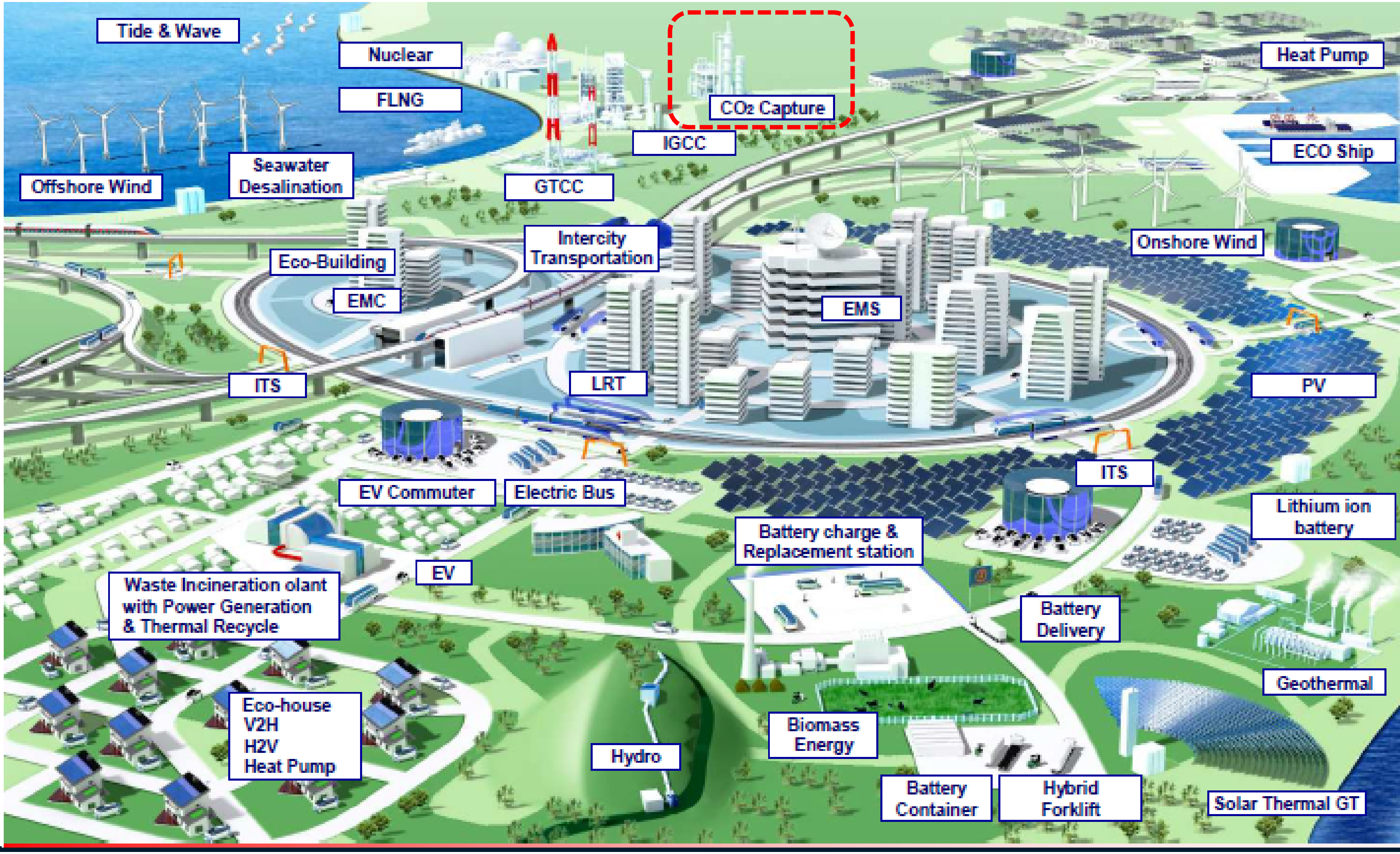


Space Station

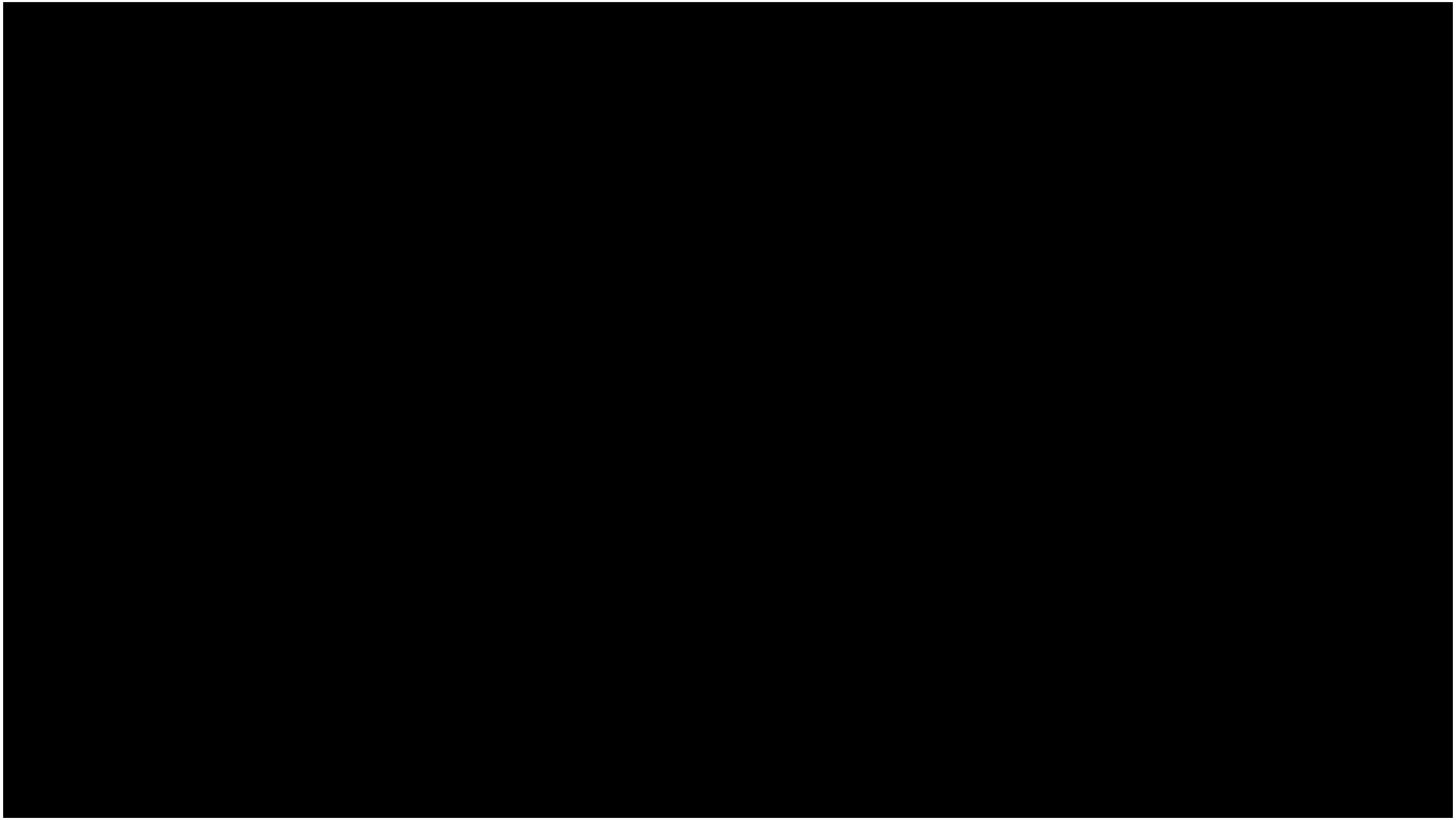
Special Vehicle

Delivering Comprehensive Solutions - Smart Community

- Contribution to realize a Low-Carbon Society with the Integrated solutions of technologies.



“With these hands, we build”



https://www.youtube.com/watch?feature=player_detailpage&v=UZ-5qX1Ia00

2. Carbon Capture's Role in Reducing Carbon Emissions

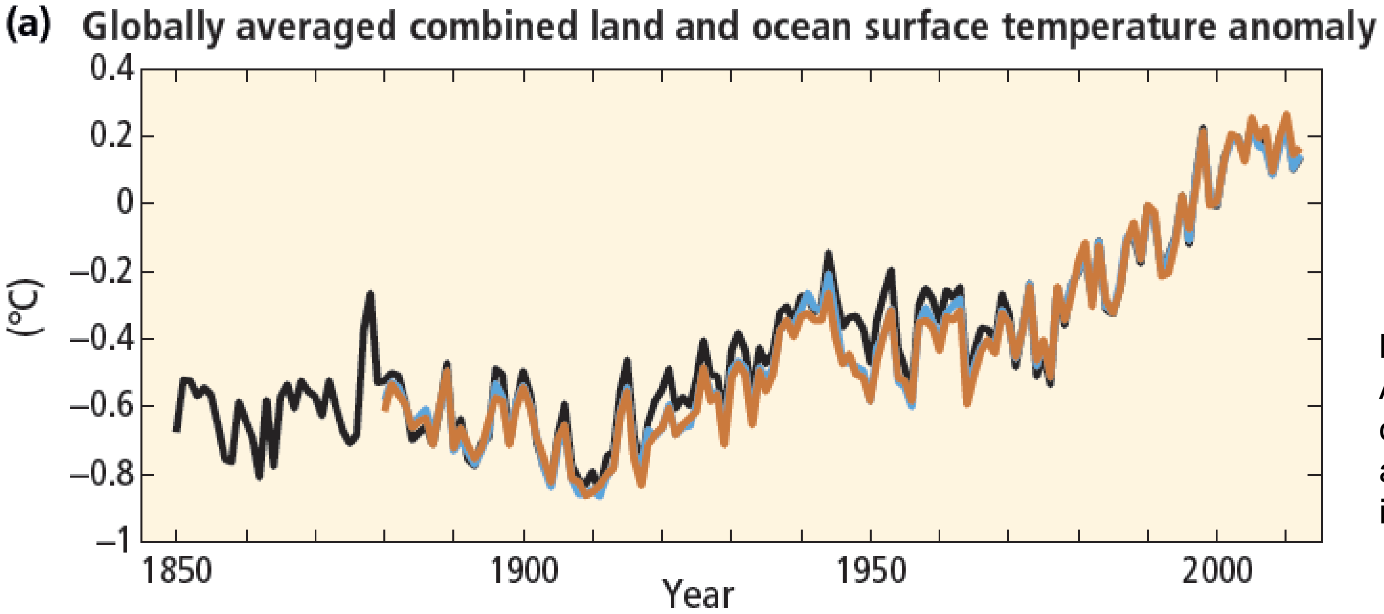


Figure SPM.1 (a)
Annually and globally averaged combined land and ocean surface temperature anomalies relative to the average over the period 1986 to 2005. Colours indicate different data sets.

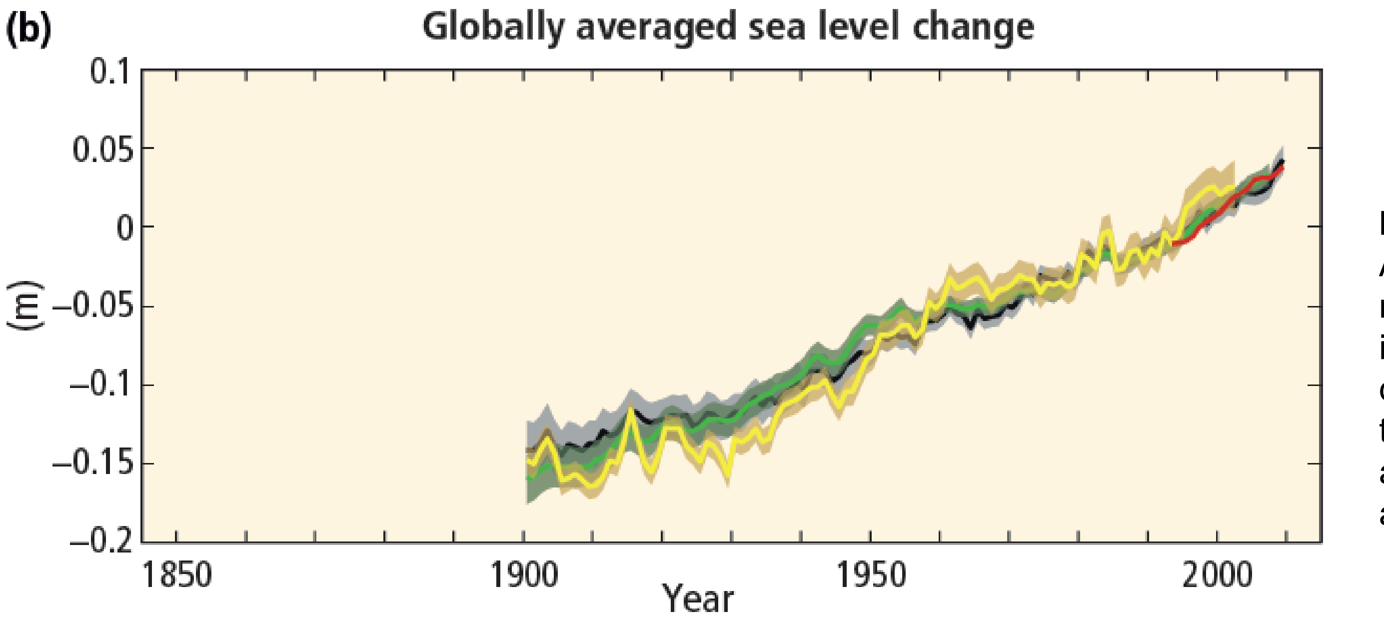
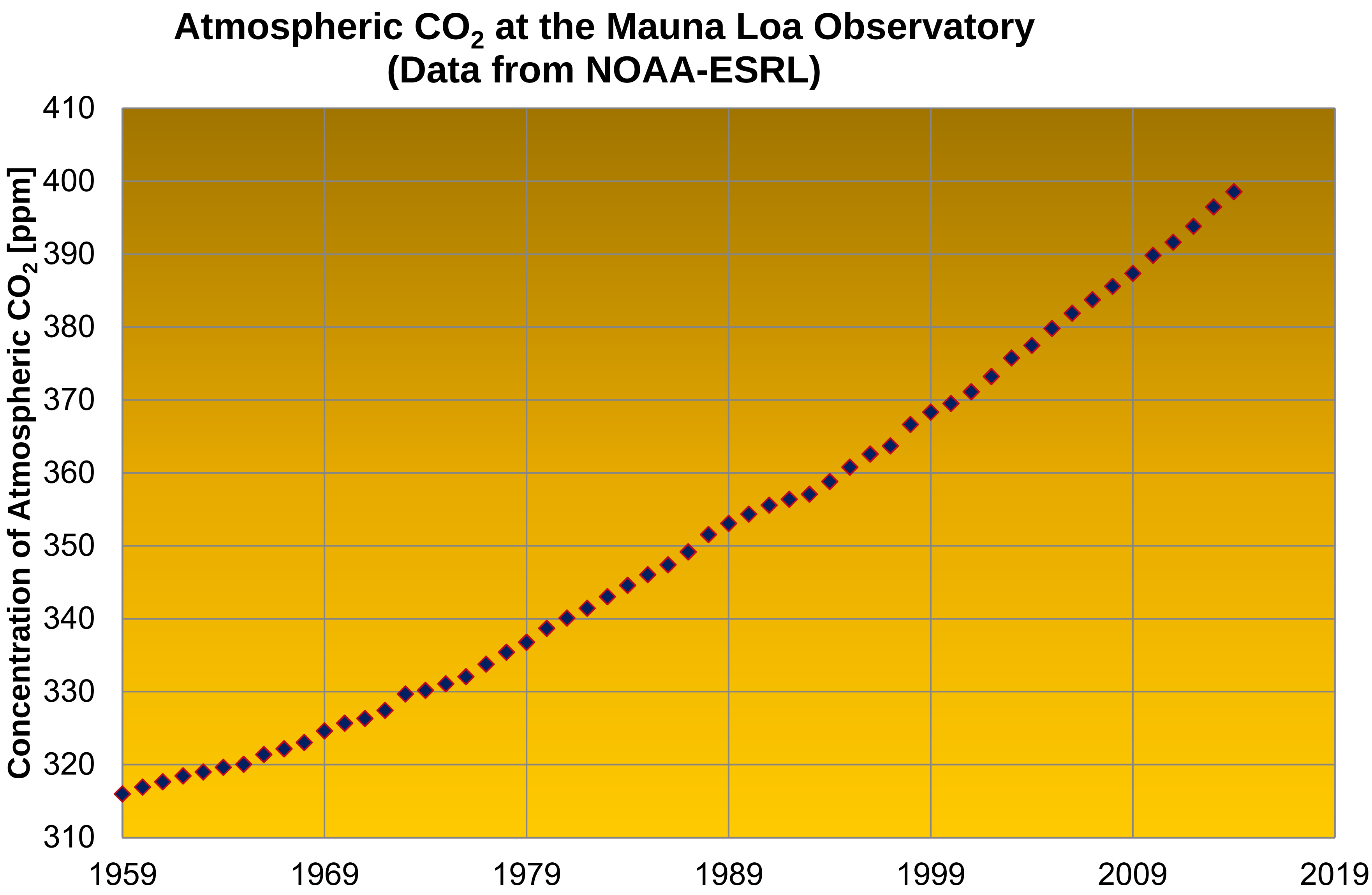


Figure SPM.1 (b)
Annually and globally averaged sea level change relative to the average over the period 1986 to 2005 in the longest running dataset. Colours indicate different data sets. All datasets are aligned to have the same value in 1993, the first year of satellite altimetry data (red). Where assessed, uncertainties are indicated by coloured shading.

IPCC, 2014: Climate Change 2014: Synthesis Report

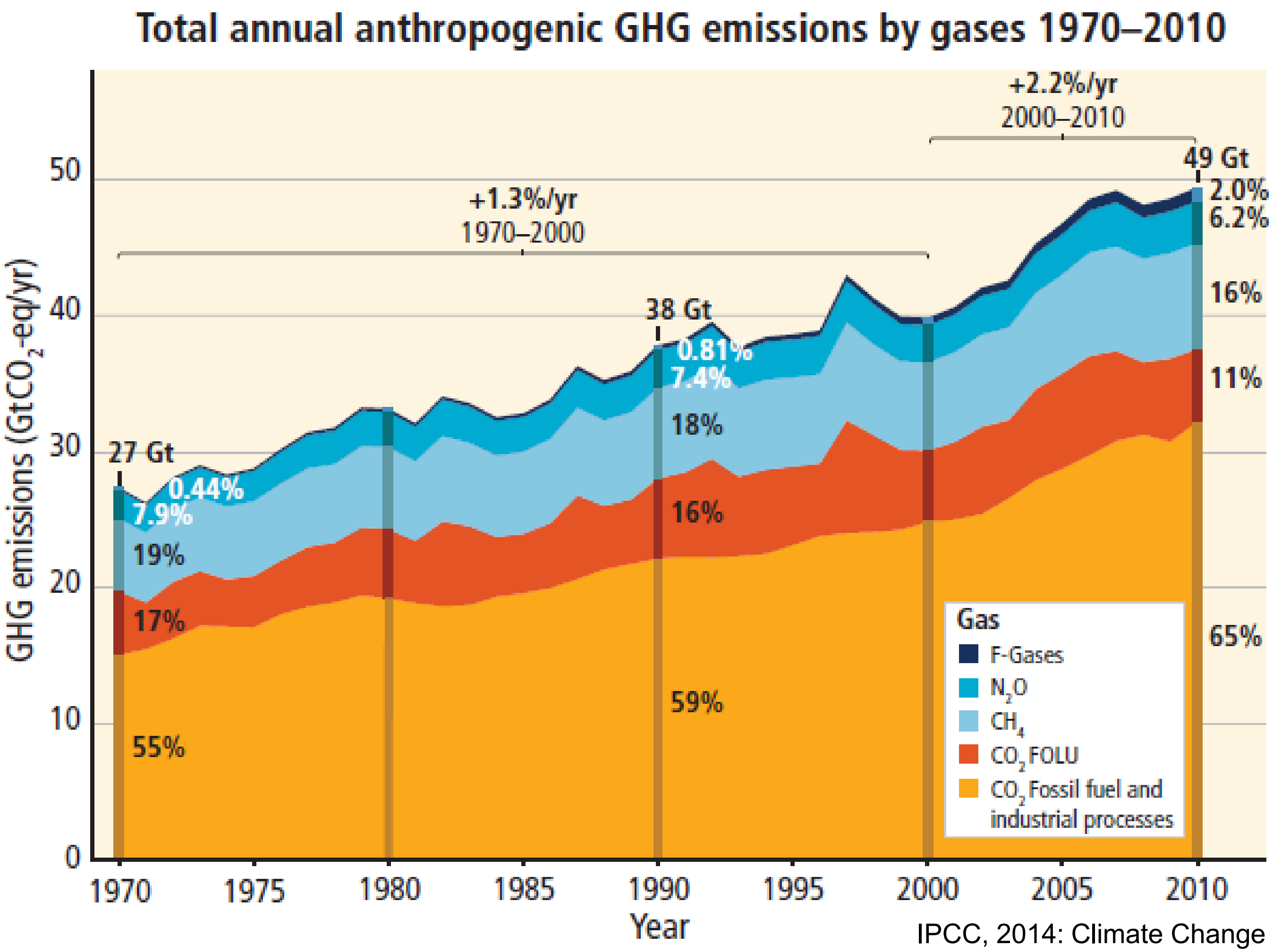
CO_2 rising in the Earth's atmosphere



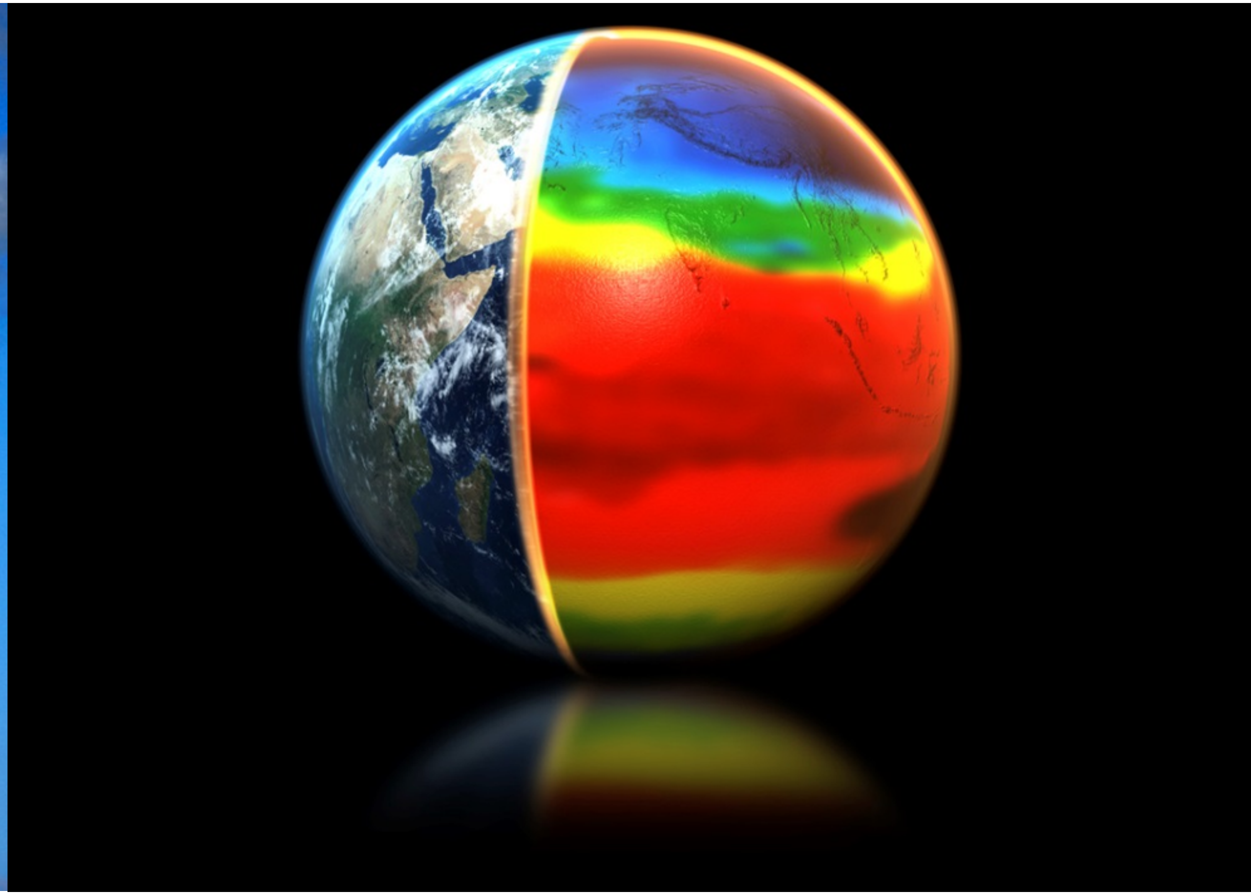
NOAA Mauna Loa CO_2 Data, http://co2now.org/Current-CO2/CO2-Now/noaa-mauna-loa-co2-data.html

Total Annual Anthropogenic GHG Emissions

Anthropogenic GHG emissions have continued to increases over 1970 to 2010, and CO_2 emission from fossil fuel combustion and industrial processes contribute about 78% of total emissions.



IPCC, 2014: Climate Change 2014: Synthesis Report

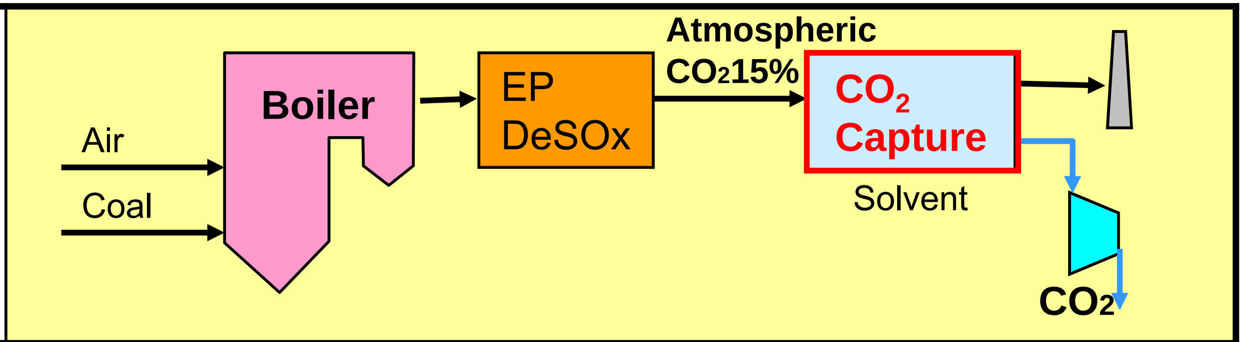



Carbon Capture from Industrial sources is very important to mitigate Global warming!!

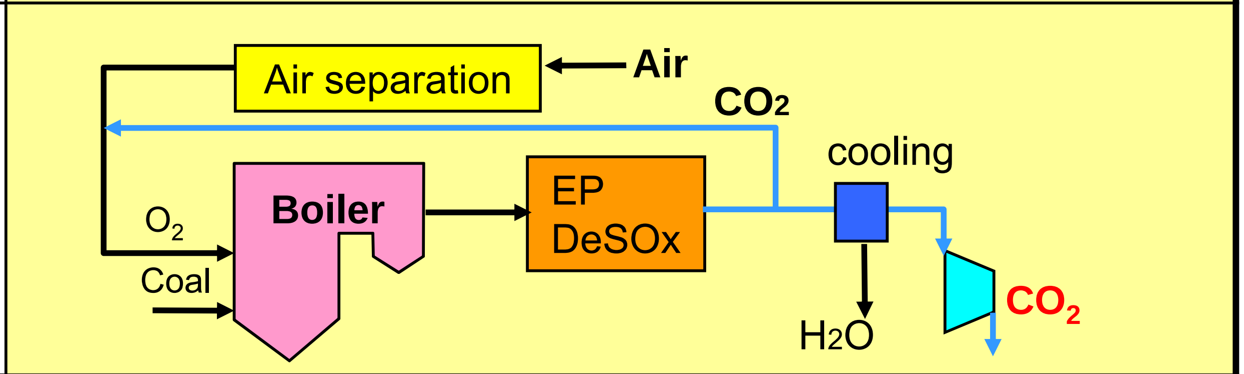
Post-Combustion Carbon Capture (PCC)

Carbon Capture system

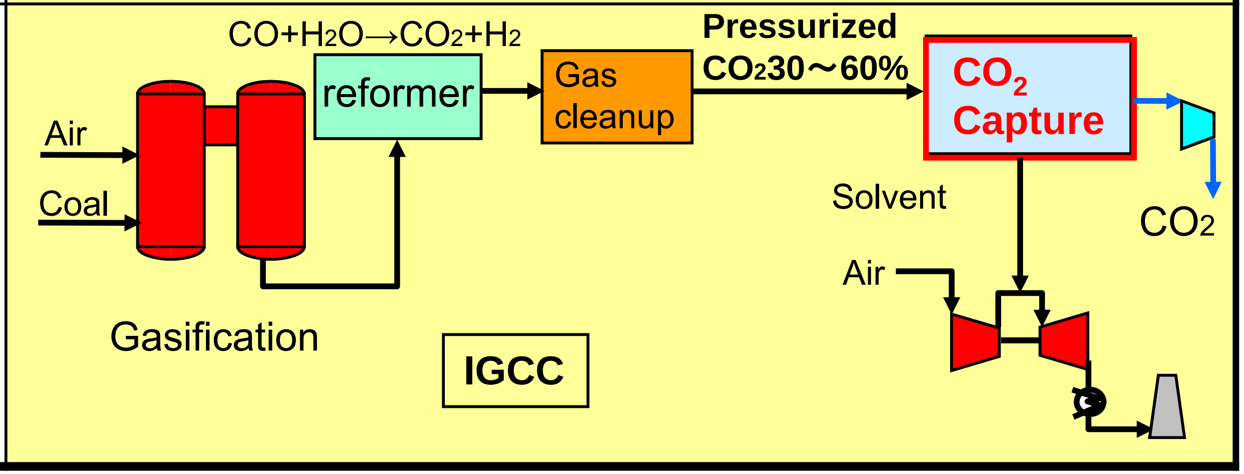
Post Combustion



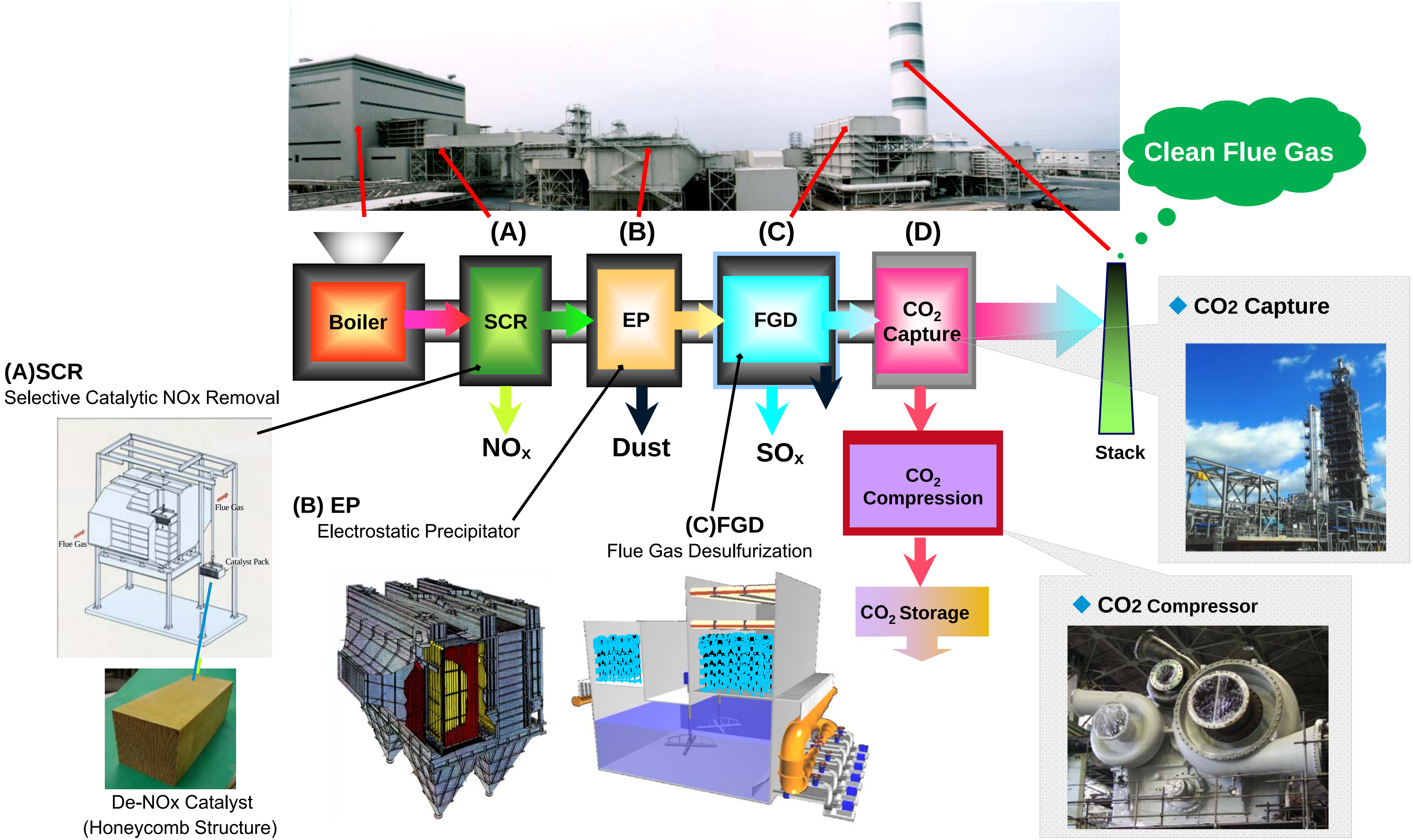
Oxy-Fuel Combustion



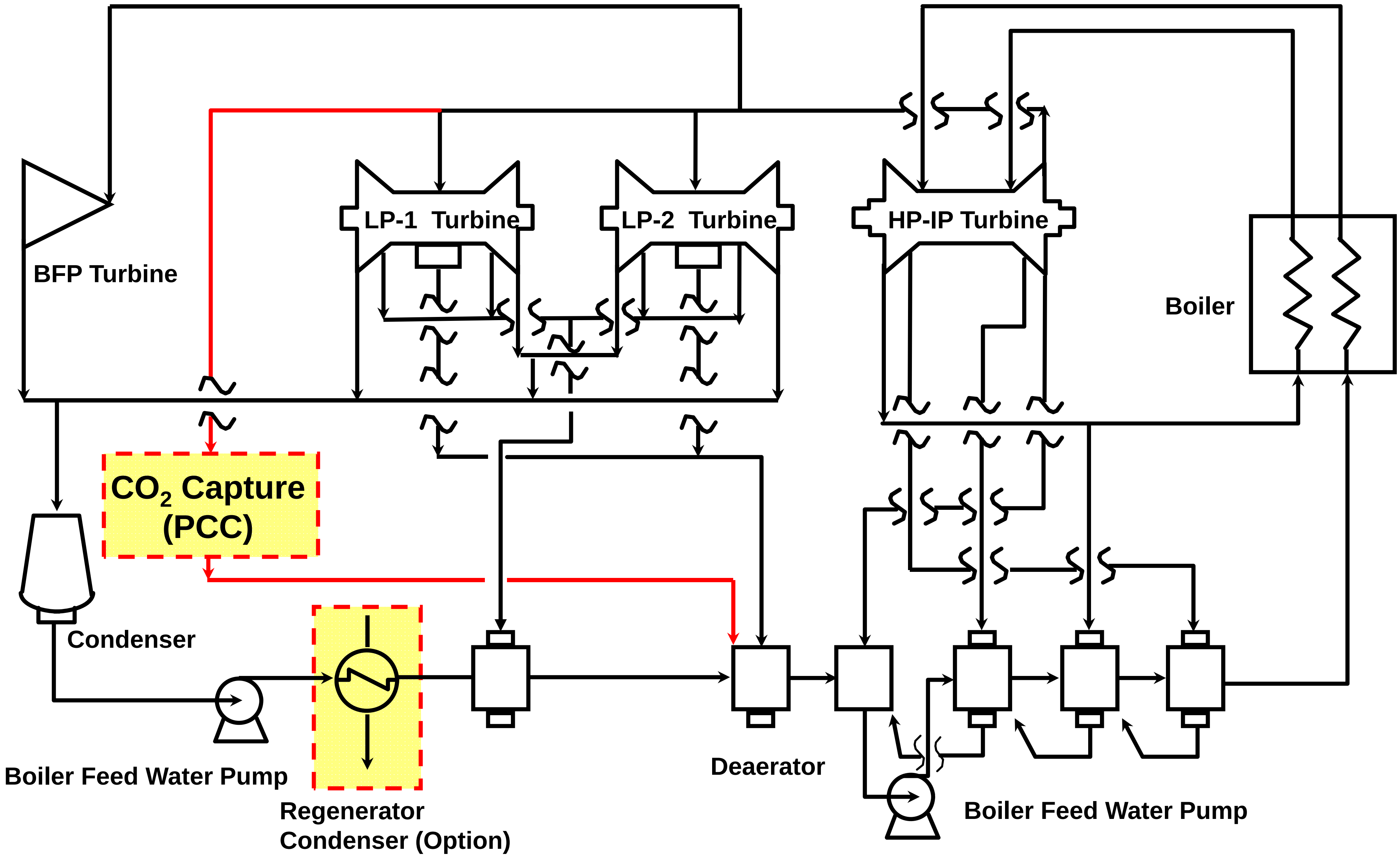
Pre Combustion



Post-combustion Capture from Coal-fired Boiler



Case-1 : LP steam extraction case



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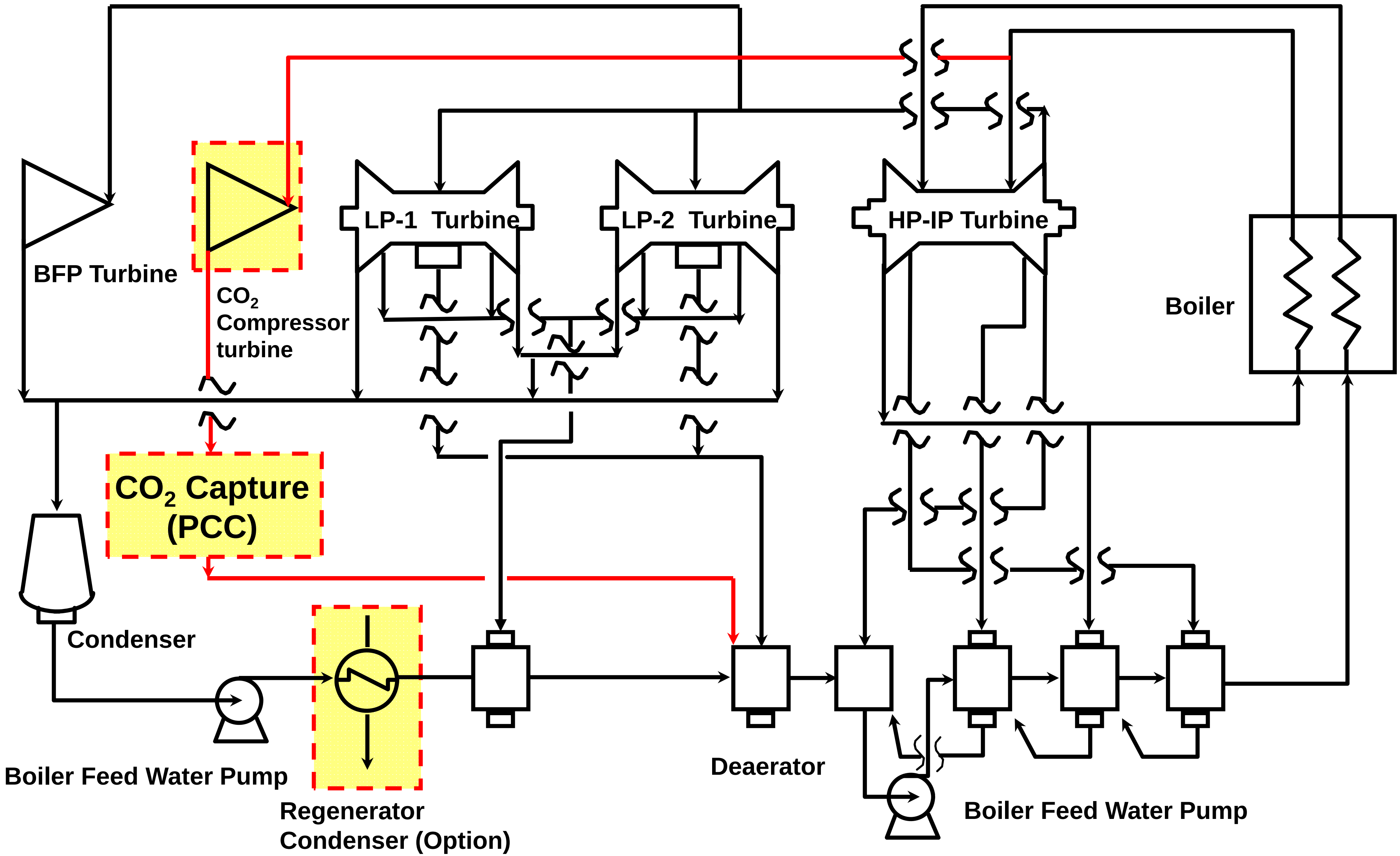
Case-2 : MP steam extraction case



Steam System for Power Plant and CO_2 Capture (3/3)

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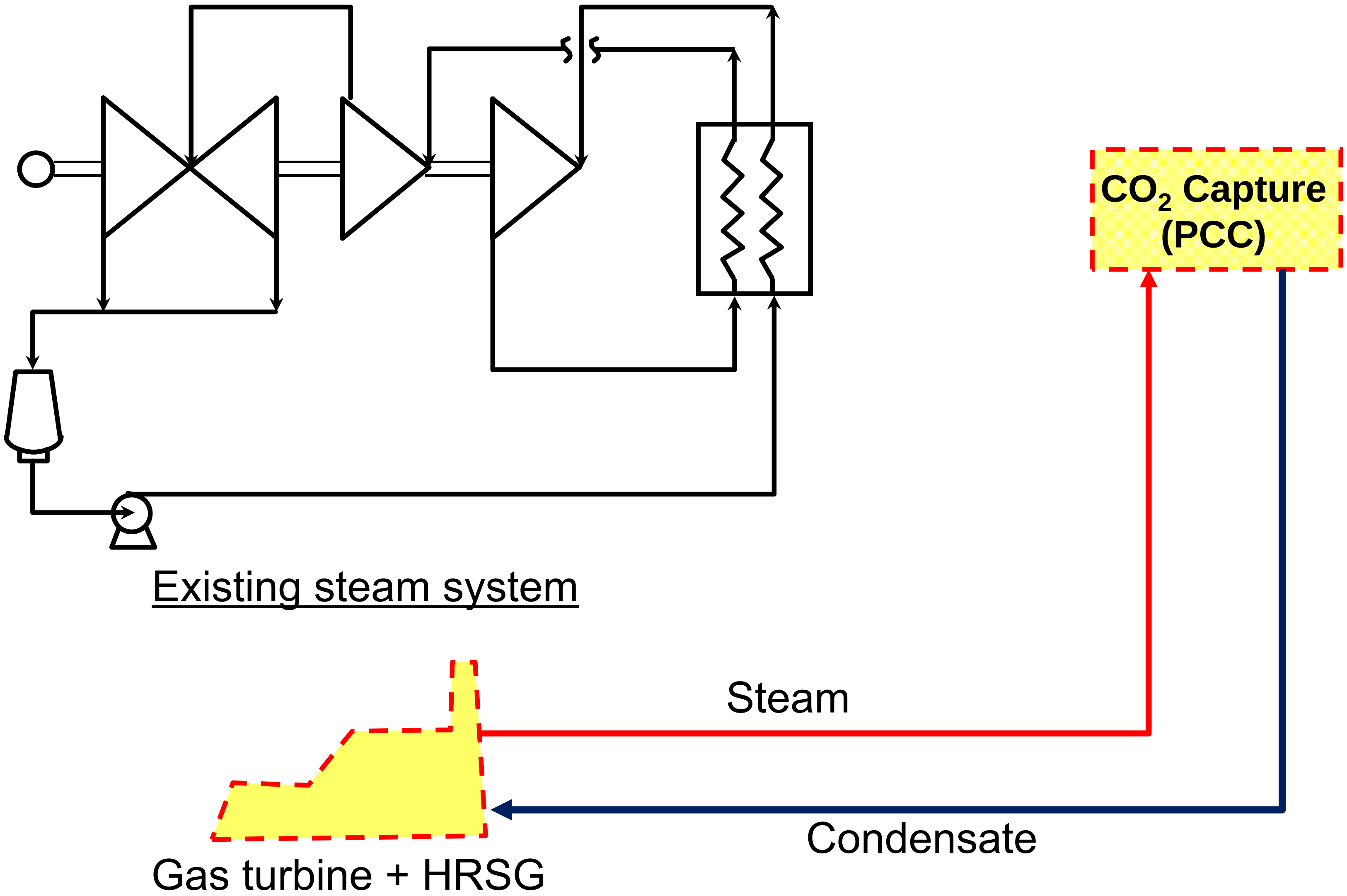
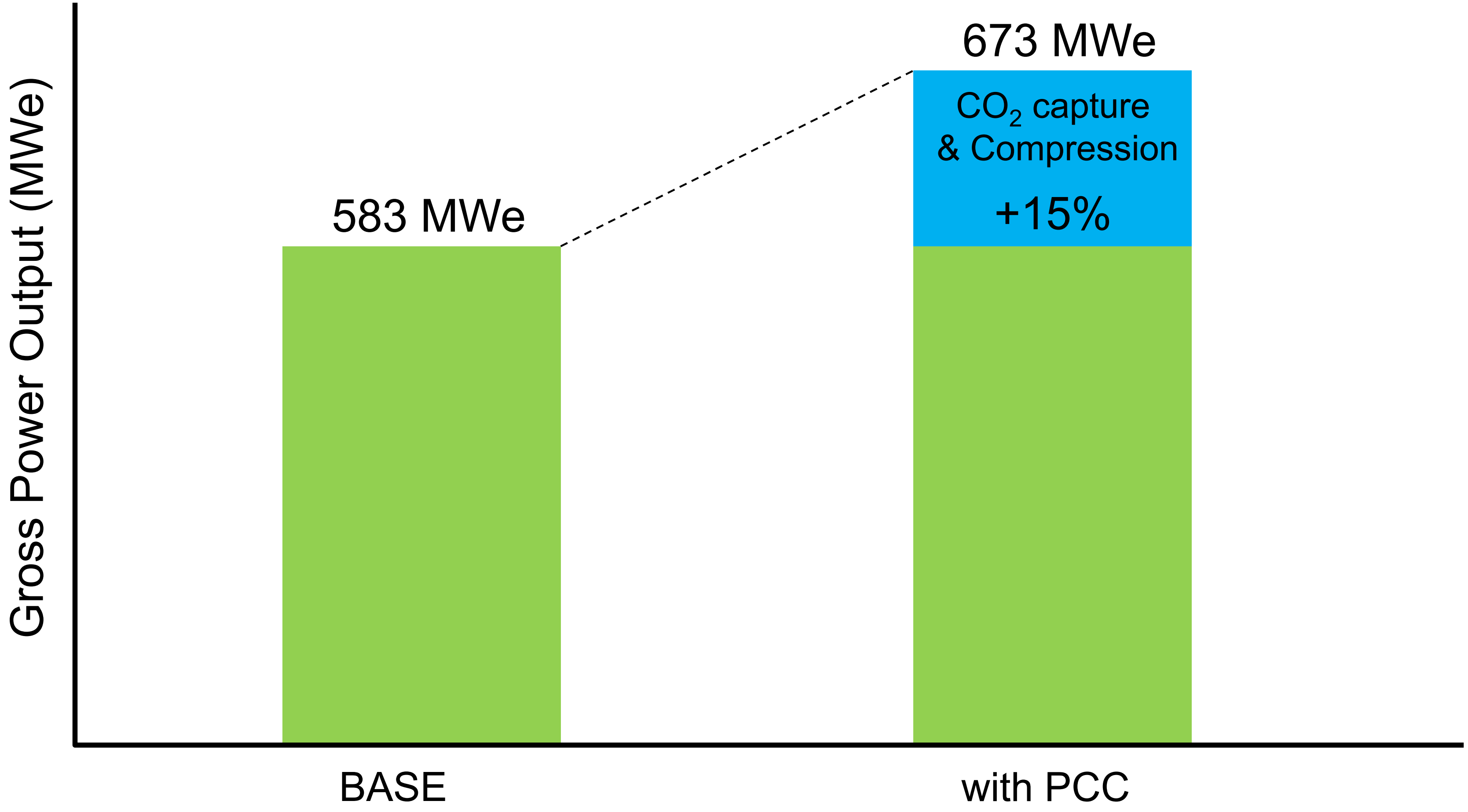
Case-3 : New Natural Gas Turbine



Energy Performance (Typical)

Calculation basis

- **Subcritical Pulverized Coal Boiler**
- **CO_2 recovery 90% (LP steam extraction case without heat integration)**



NETL, Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity, 2013, 1 – 5p

What is CO_2-EOR?

CO_2 Enhanced Oil Recovery (EOR) (1/2)

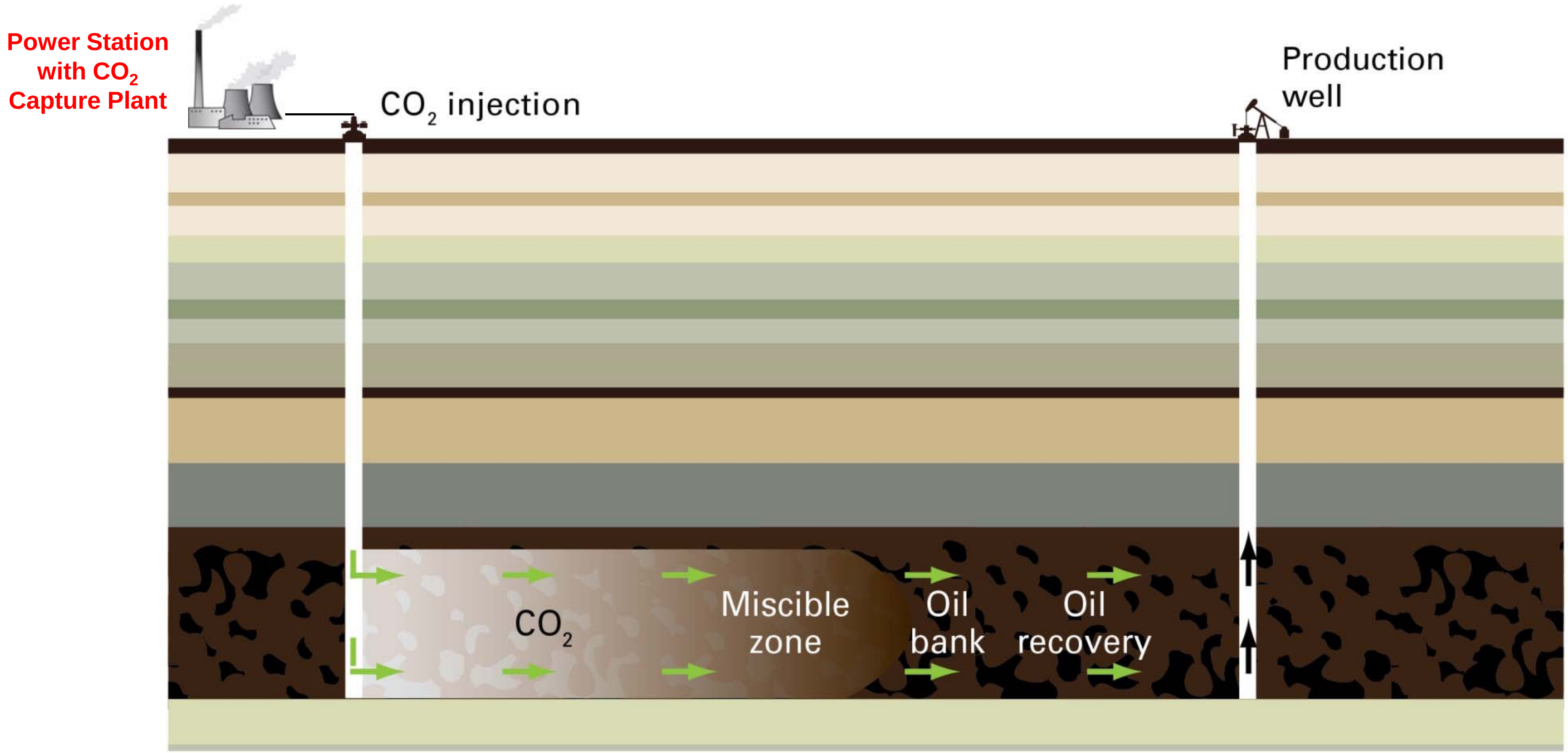


Image: ICO_2N

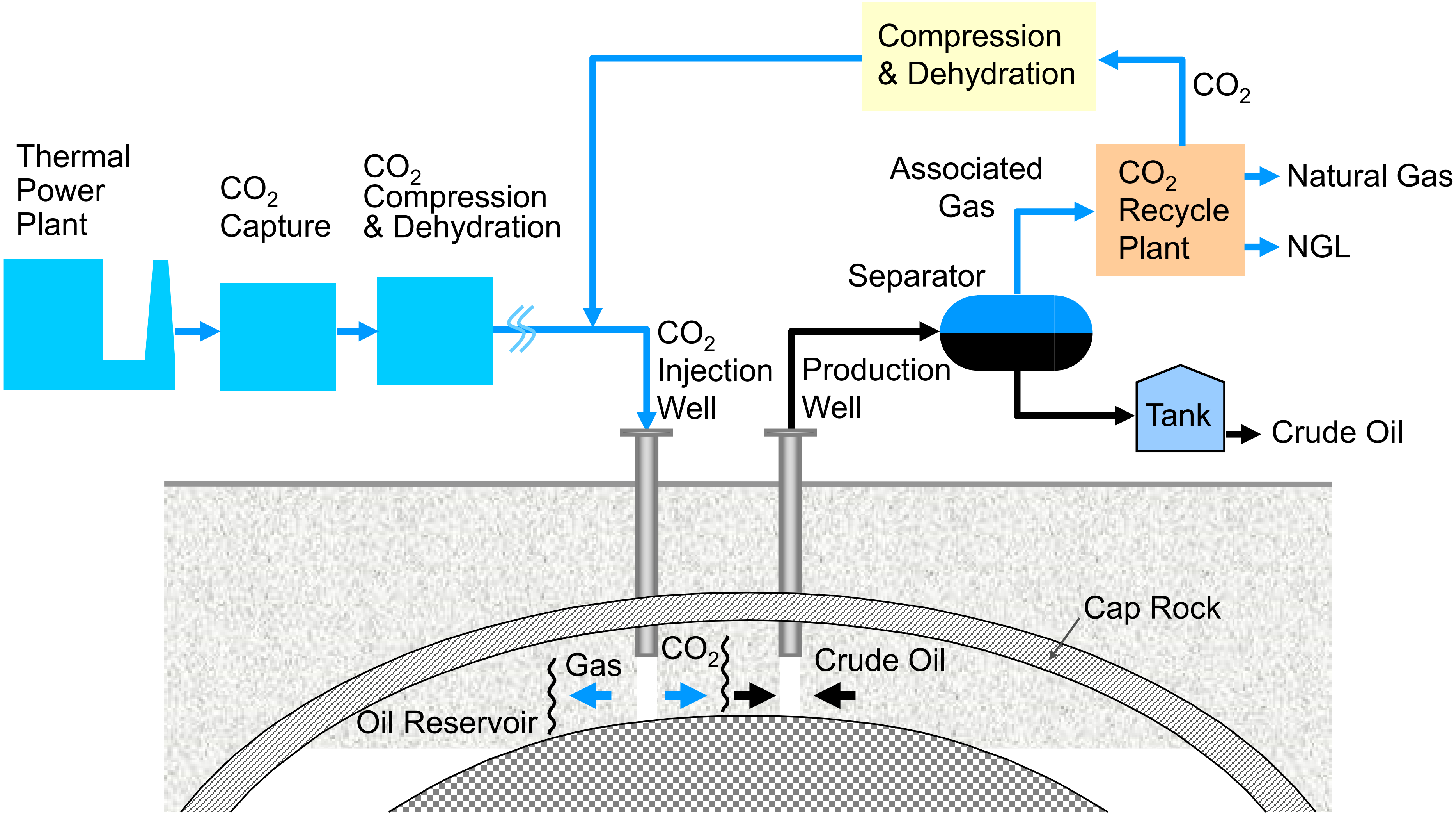
Facts about CO_2 EOR

Supercritical (fluid state) CO_2 is easily dissolved in crude oil under reservoir conditions

This state increases flow-ability of crude oil to the production wells and enhances production

Crude oil recovery ratio can be increased significantly by means of CO_2-EOR

CO_2 Injection and Recycling System in EOR



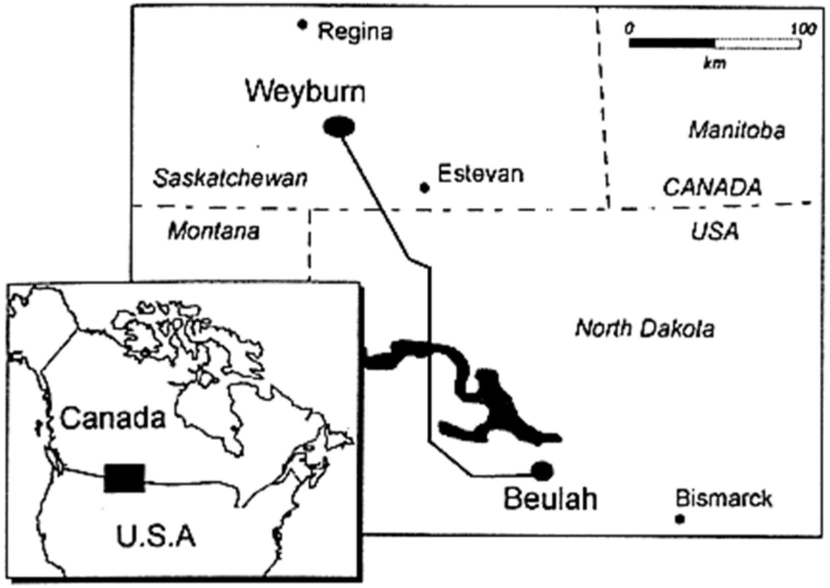
Canada – Weyburn CO_2 EOR Project

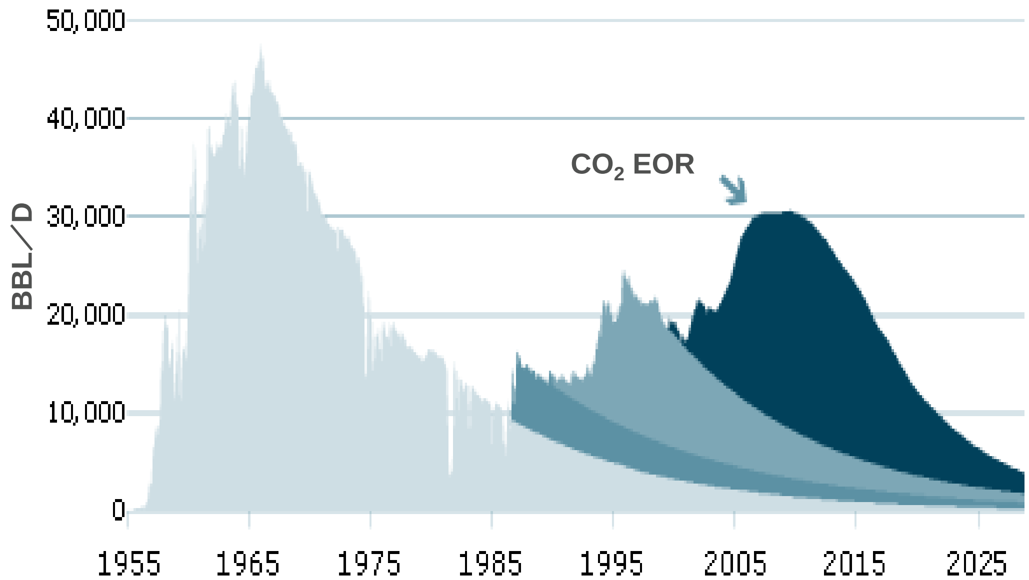
CO_2 Source: North Dakota Coal Gasification Plant

CO_2 Injection: 5000 T/D from Autumn 2001

EOR Start: 5,400 BBL/D incremental increase to crude oil recovery since 2002

In 2006, incremental crude oil recovery exceeded 10,000 BBL/D

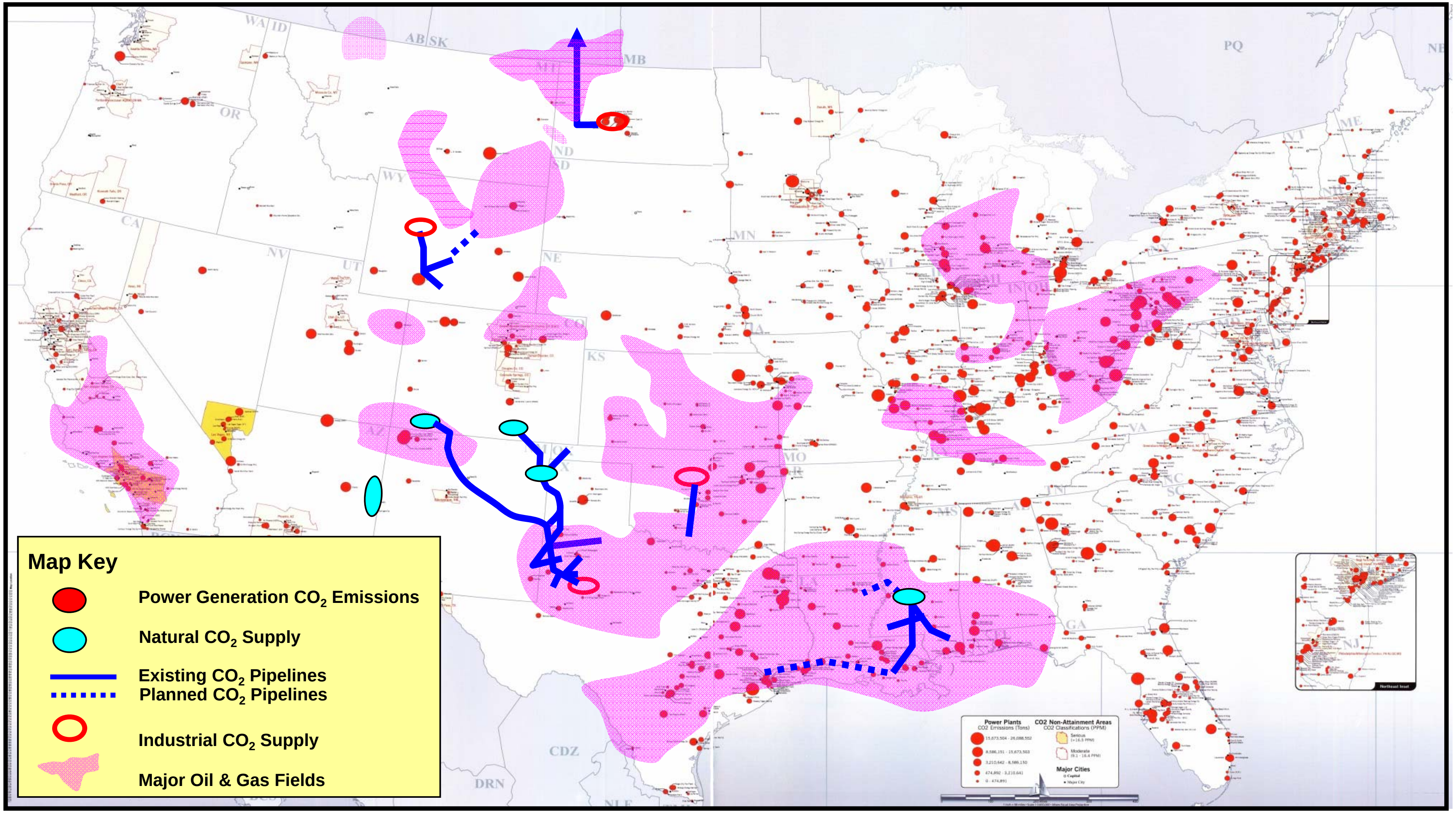




Source: Encana

CO_2 source and Oil & Gas field in the U.S.

CO_2 EOR the USA (Most CO_2 Sources are from Natural CO_2 Gas Reservoirs)



~3,000 Miles of CO_2 Pipe in U.S. Today…350,000 for Natural Gas.

3. MHI's Carbon Capture Technologies

Outline

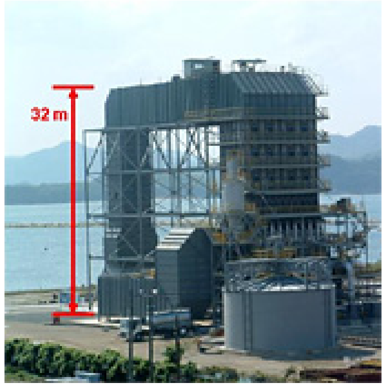
1. History of R&D activity
2. Commercial experience
3. Carbon capture for coal-fired boiler

1. History of R&D activity

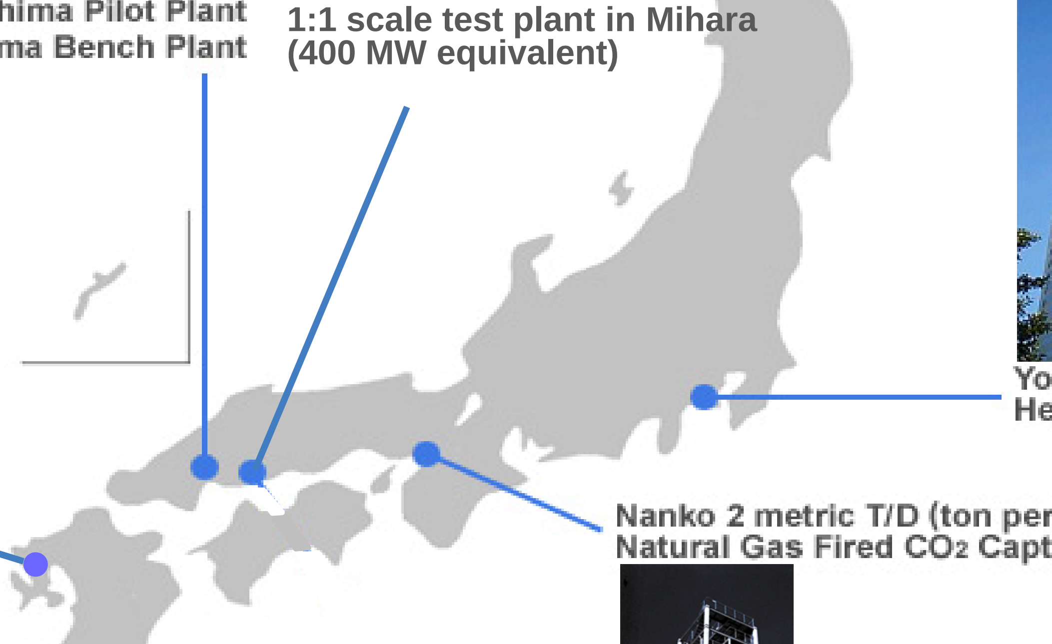
- Development of Proprietary amine
- High energy efficient process
- Patents

R&D, Pilot Plant and Engineering Head Quarters in Japan

MHI CO_2 Capture & FGD R&D Center
Hiroshima Pilot Plant
Hiroshima Bench Plant



1:1 scale test plant in Mihara
(400 MW equivalent)



Yokohama Engineering
Head Quarters

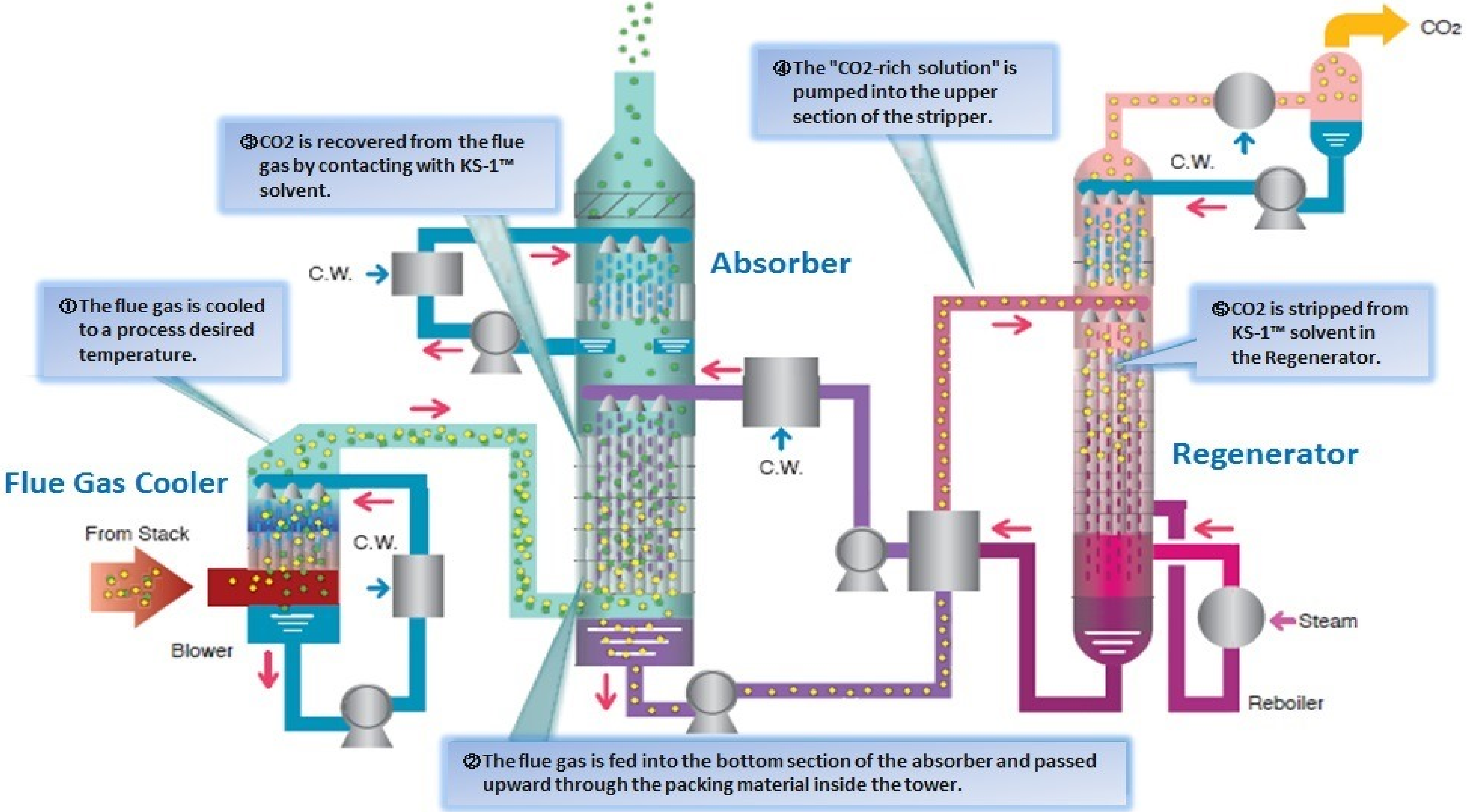
10 tpd Matsushima pilot
for testing coal fired flue
gas (2006 ~ 2008)

Nanko 2 metric T/D (ton per day)
Natural Gas Fired CO_2 Capture Pilot Plant

History of Development of MHI's Carbon Capture Technology

1990	Started R&D activities with Kansai Electric Power Company (KEPCO)
1991	Started a 2 ton per day pilot plant at KEPCO's Nanko Power station
1994	Development of proprietary hindered amine solvent "KS-1®" and "KM CDR Process®" with KEPCO
1999	First commercial plant in Malaysia (200 ton per day, to enhance urea synthesis from the CO_2 recovered from a reformer flue gas)
2002	Started a pilot test for coal-fired power plant at MHI's Hiroshima R&D center
2003	**High energy efficiency -** Development of proprietary energy efficient process "Improved KM CDR Process"
2008	First commercial plant in Middle east (400 ton per day) which "Improved KM CDR Process" applied
2011	**World's first -** Started 500 ton per day fully integrated CCS demonstration plant with Southern Company for a coal-fired power plant at Alabama Power's James M. Barry Electric Generating Plant
2014	**World's Largest -** Received an order for a PCC plant of 4,776 ton per day for EOR mainly promoted by NRG Energy Inc. and JX Nippon Oil & Gas Exploration Corporation

Advanced CO_2 Capture Process – MHI's Own Technology



Solvent Comparison KS-1® V MEA

Amine Reaction Mechanism

Main Reaction

● Mono-ethanol Amine (MEA)

$$2\,R\text{-}NH_2 + CO_2 \rightleftarrows R\text{-}NH_3^+ + R\text{-}NH\text{-}COO^-$$

$$R\text{-}NH_2 + CO_2 + H_2O \rightleftarrows R\text{-}NH_3^+ + HCO_3^-$$

● Sterically Hindered Amine (KS-1)

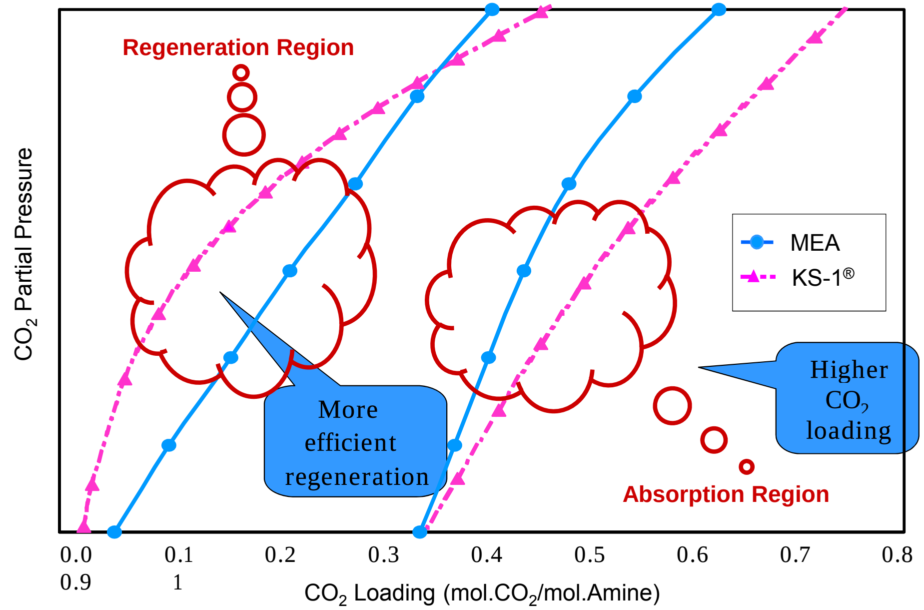
$$2\,R\text{-}NH_2 + CO_2 \rightleftarrows R\text{-}NH_3^+ + R\text{-}NH\text{-}COO^-$$

$$R\text{-}NH_2 + CO_2 + H_2O \rightleftarrows R\text{-}NH_3^+ + HCO_3^-$$

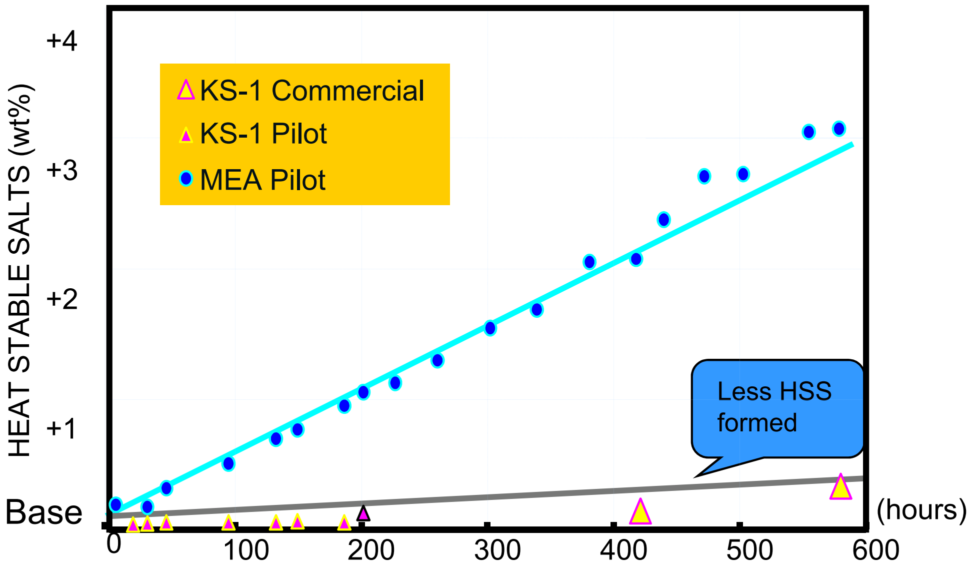
Less Solvent use

Key feature is main KS-1 reaction mechanism requires only 1 mole of KS-1 to react with 1 mole of CO_2 and H_2O

Solubility of CO_2 in KS-1 and MEA Solution



Deterioration of Product



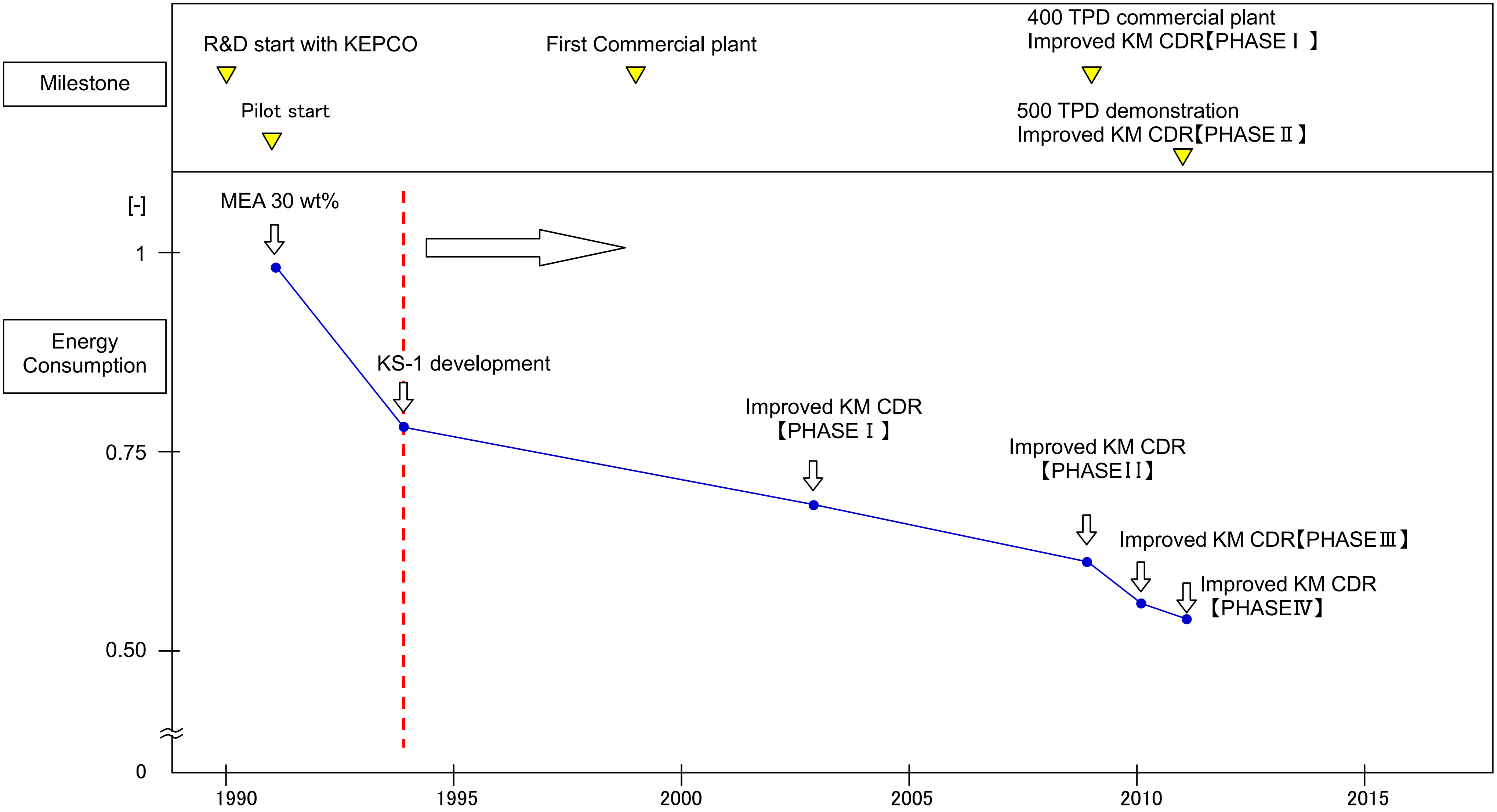
Corrosion Test Result

(Unit : mils per year)	Test 1	Test 2
MEA	93.0	76.4
MEA + inhibitor	9.5	8.3
KS-1	3.1	3.6

Less corrosion

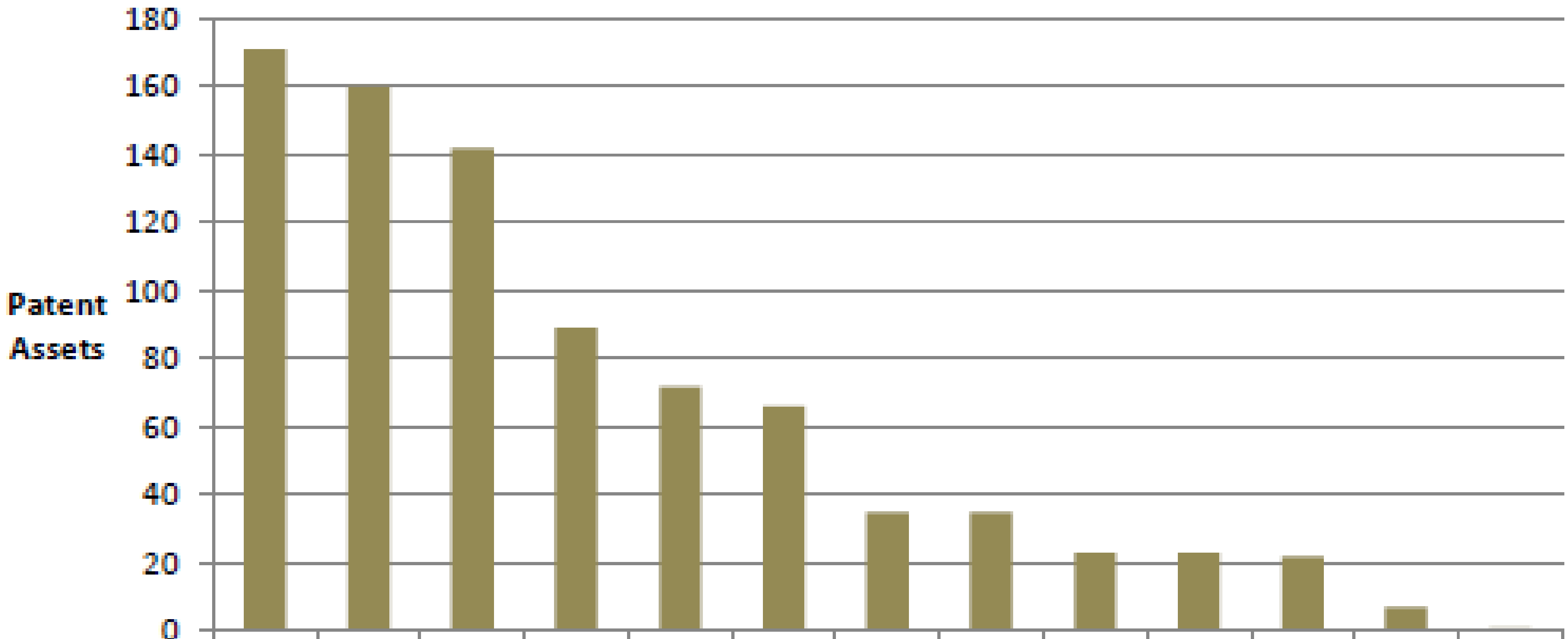
Test condition : 130 ° C, in the presence of O_2

Nanko Test Result



MHI's worldwide granted and pending patents

In the US : 82 granted, 78 pending (as of Nov. 2014)



	EP	US	JP	CA	DE	AU	NO	RU	CN	WO	DK	KR	ID
Jurisdiction	171	160	142	89	72	66	35	35	23	23	22	7	1

2. MHI's Commercial Experience

- General Use
- Chemical Use
- EOR / CCS

Reuse and Application of CO_2

1. General Use

Beverages, Dry ice, Supercritical food application , Welding and etc.

2. Chemical usage of CO_2

■ Urea Synthesis

Natural gas		Urea	Extra H2
$CH_4 + H_2O + N_2$	$\longrightarrow$	$CO(NH_2)_2$	$+\ H_2$
$3H_2 + N_2 + CO_2$	$\longrightarrow$	$CO(NH_2)_2$	$+\ H_2O$

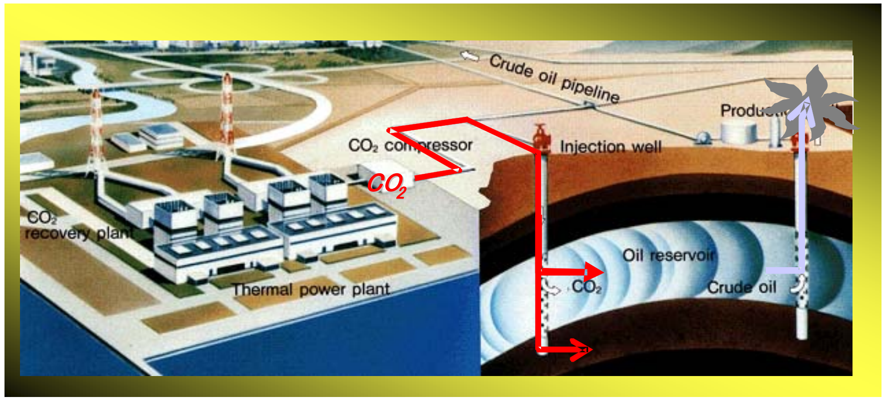
■ Methanol Synthesis

Natural gas		Methanol	Extra H2
$CH_4 + H_2O$	$\longrightarrow$	CH_3OH	$+\ H_2$
$3H_2 + CO_2$	$\longrightarrow$	CH_3OH	$+\ H_2O$

Urea

3. CO_2 EOR（CCS）

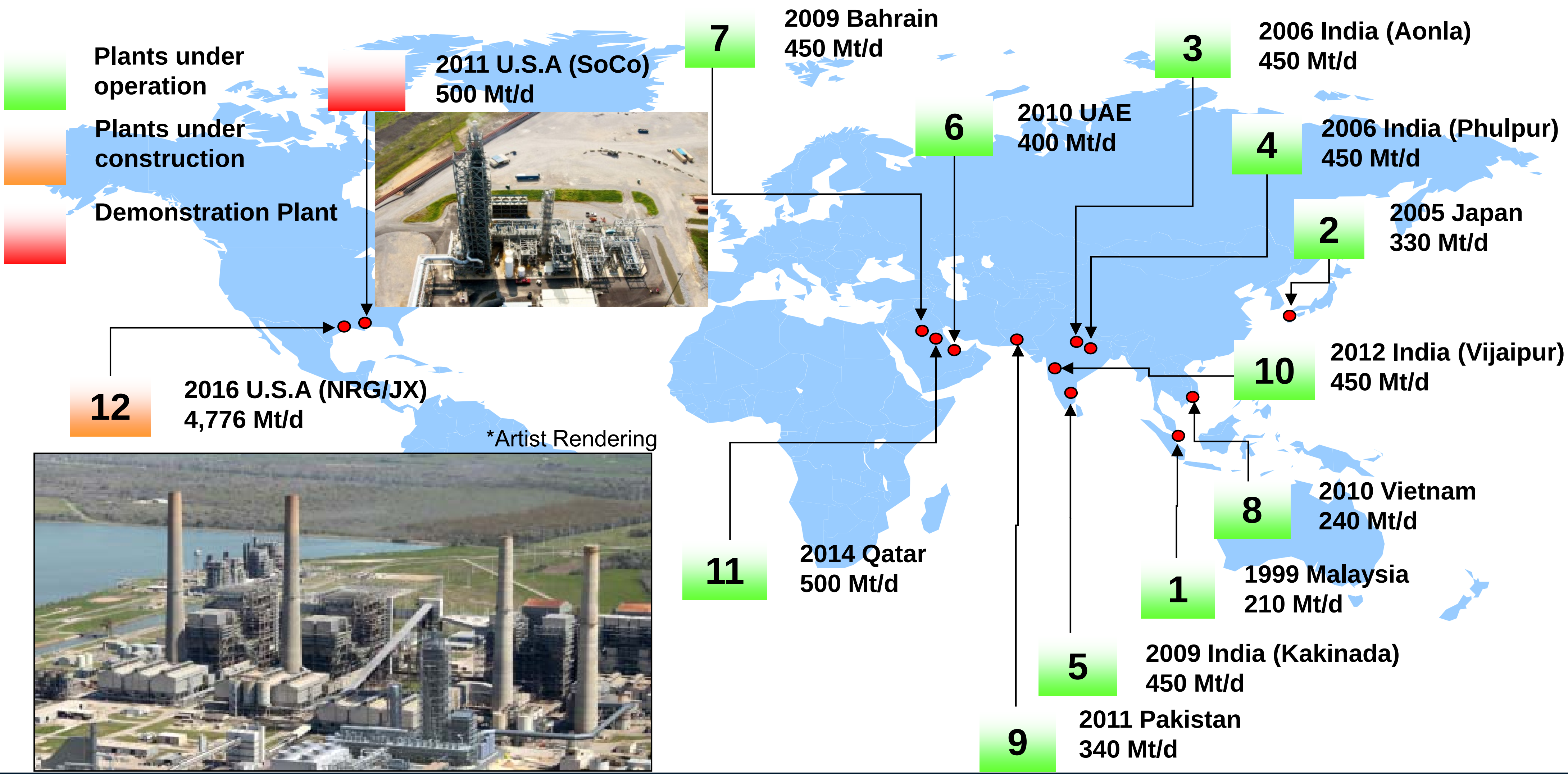
- **SupercriticalCO_2 is easily dissolved in crude oil under reservoir conditions**
- **This state increases flow-ability of crude oil to the production wells and enhances production**



MHI's Worldwide Commercial Experience

MHI is a world leading LARGE-SCALE post combustion CO_2 capture technology licensor, with 11 commercial plants in operation

Total operation hours = 620,000 hrs (As of April 2015)



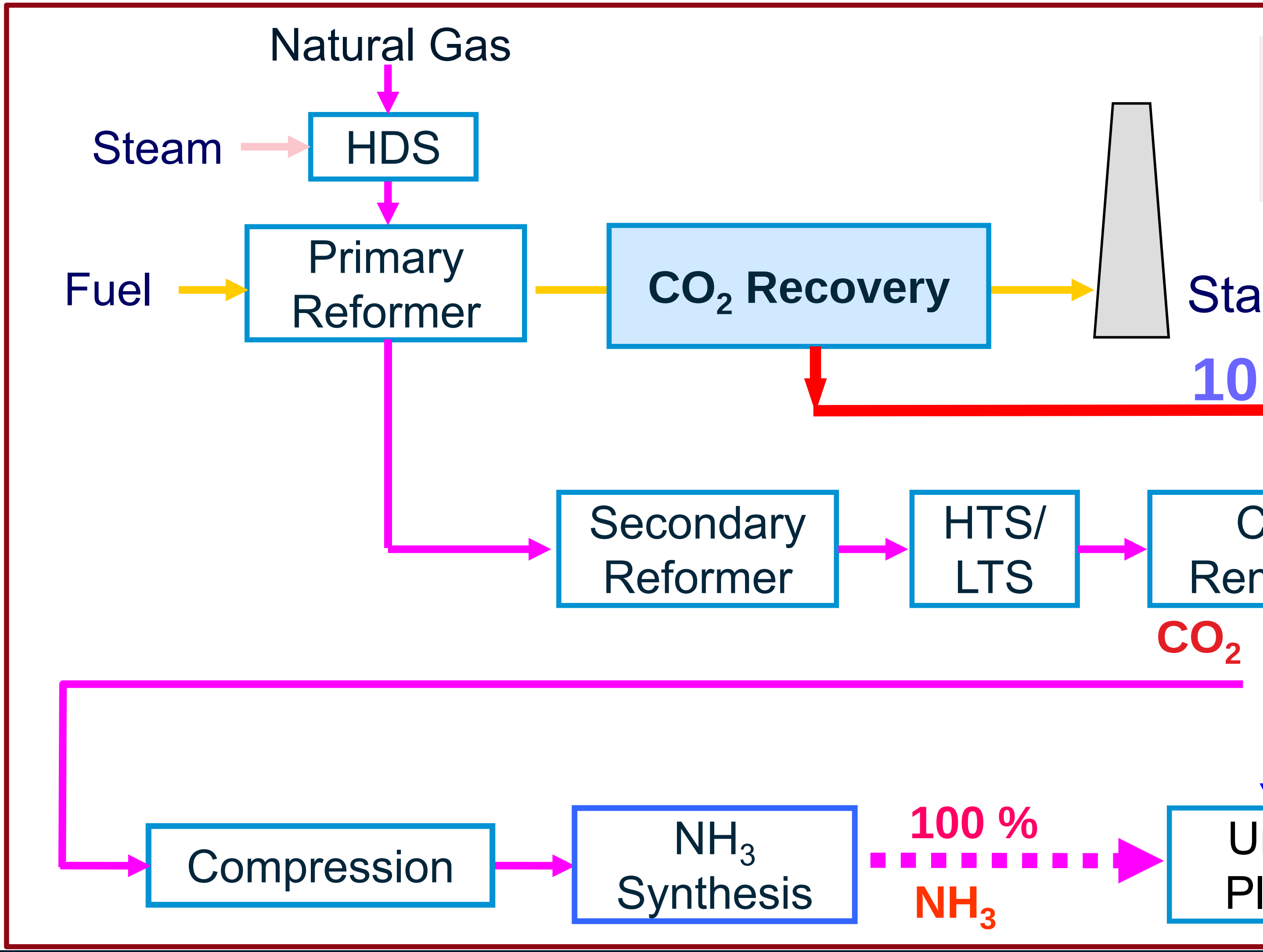
MHI Commercial Experience for General Use

Client	: “A” Chemical Company
Location	: Kurosaki, Japan
Capacity	: 283 T/D (Max 330 T/D)
Feed Gas	: Fuel Oil / LNG fired Boiler
Process	: KM CDR Process®
Solvent	: KS-1® Solvent
Use of CO_2	: General Use
Start Up	: October, 2005
MHI Scope	: EPC & License Package

Increase of Urea Production

To install the flue gas CO_2 recovery unit can realize to maximize urea synthesis by balancing ammonia and CO_2

- Maximize Urea Production
- Minimum Reconstruction
- Reduced CO_2 Emissions



MHI Commercial Experience for Urea Production

1999
210 t/d Malaysia

2006
450 t/d India

2006
450 t/d India

2009
450 t/d India

2009
450 t/d Bahrain

2010
400 t/d UAE

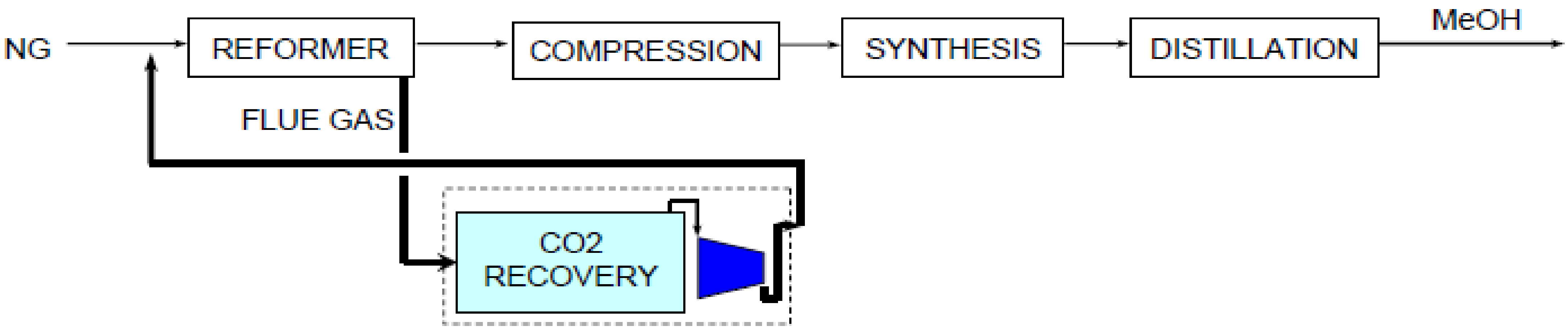
2010
240 t/d Vietnam

2011
340 t/d Pakistan

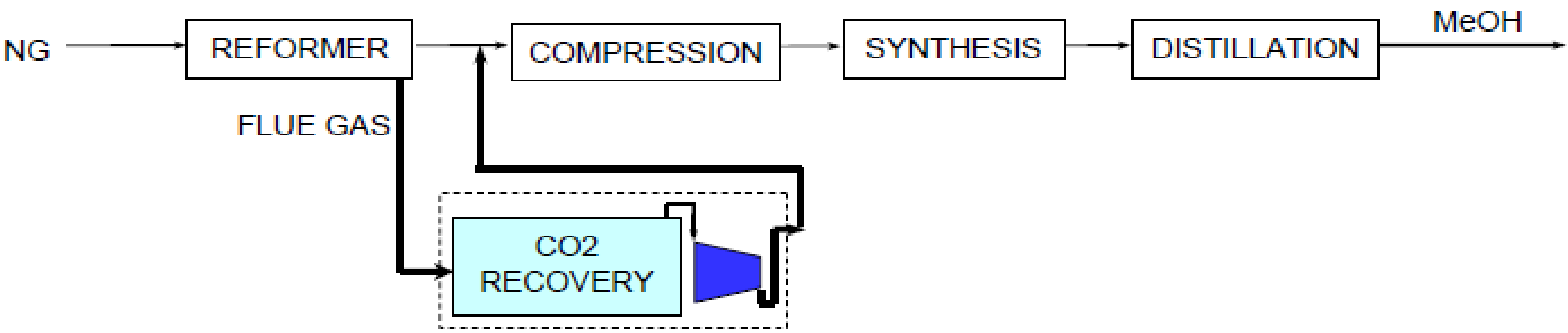
2012
450 t/d India

Increase of Methanol Production

Case-1: CO2 Recovery - CO2 Injection at Reformer Inlet



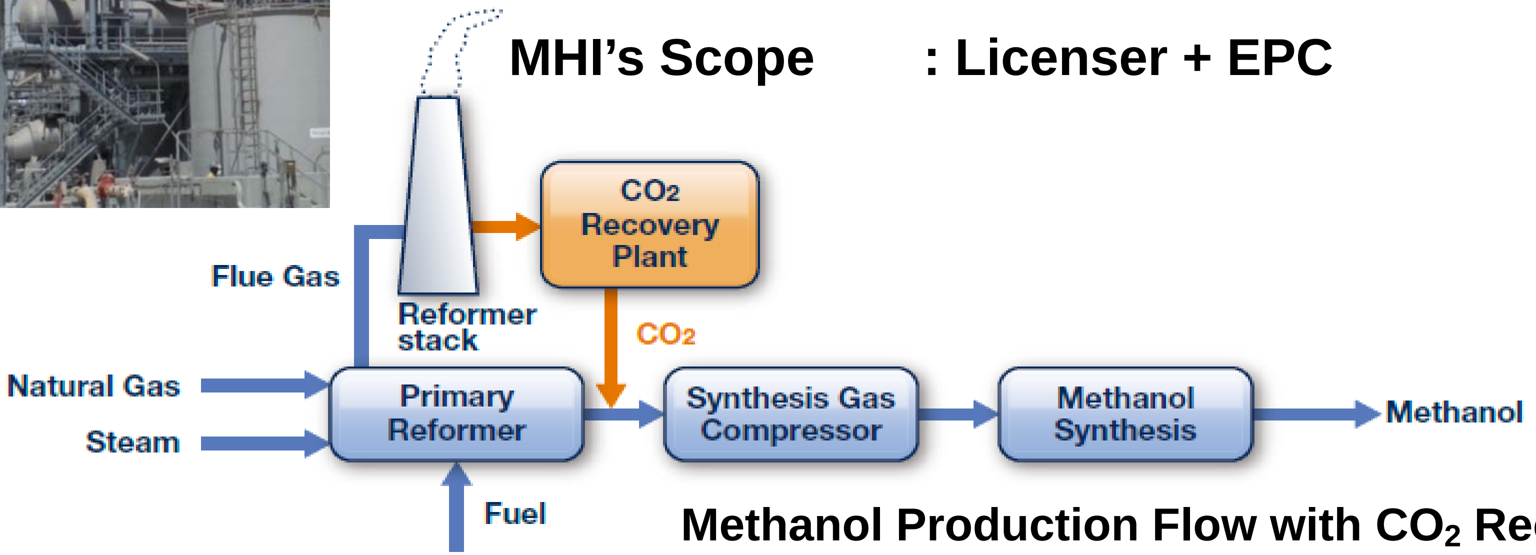
Case-2 : CO2 Recovery – CO2 Injection at Reformer Outlet before Compression



MHI Commercial Experience for Methanol Production

- **World's largest plant for Methanol application**
- Captured CO_2 is utilized to boost Methanol production

Client	**: Qatar Fuel Additives Co. Ltd. (QAFAC)**
Location	**: Mesaieed, Qatar**
Capacity	**: 500 T/D**
Feed Gas	**: Methanol Plant Reformer**
Start Up	**: July, 2014**
MHI's Scope	**: Licenser + EPC**



Methanol Production Flow with CO_2 Recovery Plant

3. MHI's Carbon Capture for Coal-fired Boiler

- 500 tpd Demonstration Plant
- 4776 tpd Commercial Plant for EOR

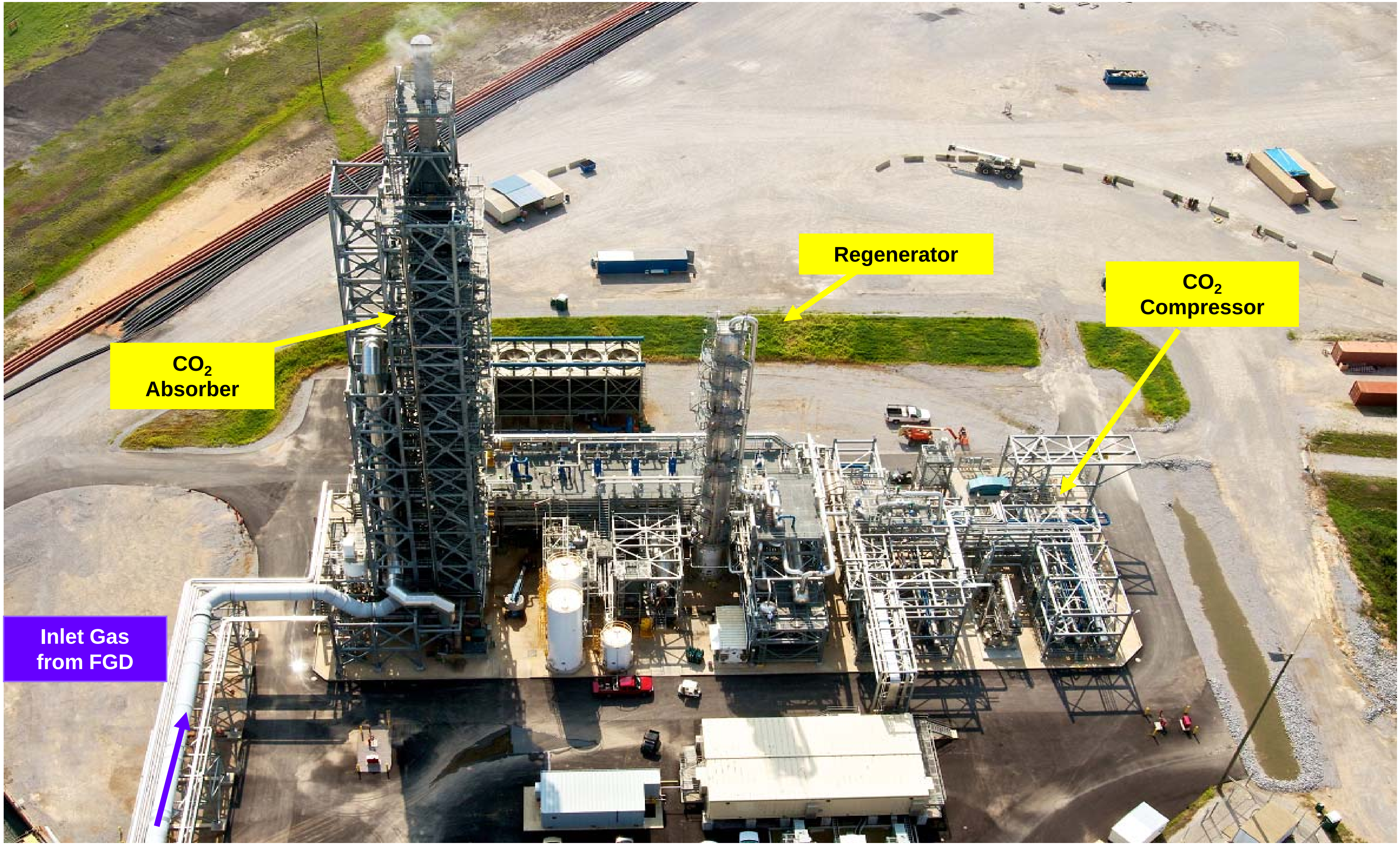
500 tpd Demonstration Plant

Coal Fired CO_2 Capture Demonstration Project (500MTPD)

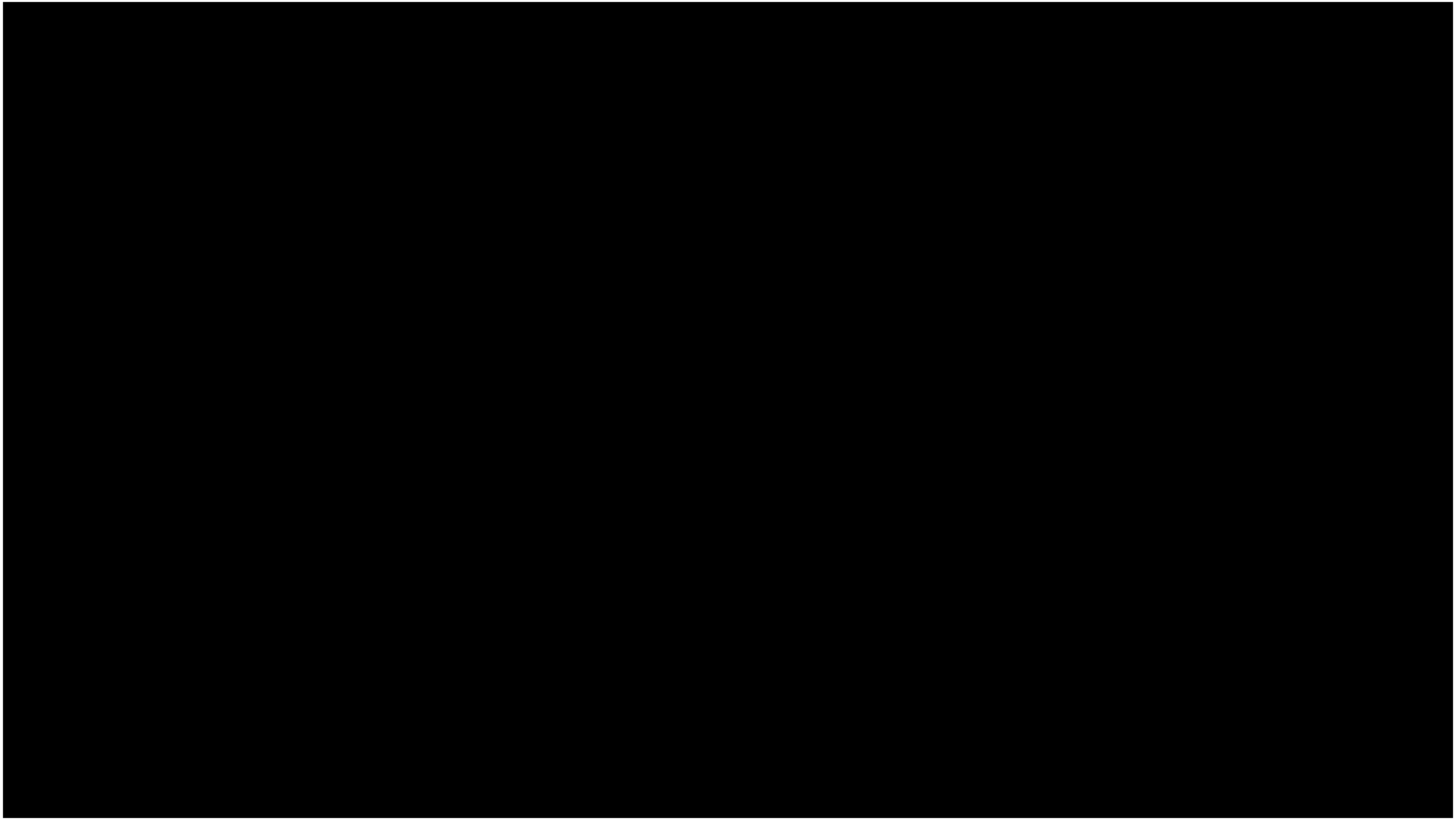
FULLY INTEGRATED carbon capture & storage project with CO_2 storage, by SECARB and Owner, in a saline formation at a nearby oil field

- Location: Alabama Power, James M. Barry Electric Generating Plant
- Partners: Southern Company, MHI & EPRI
- Flue Gas Source: Pulverized Coal Fired Boiler
- CO_2 Capacity: 500 Metric Ton / Day
- Process: KM-CDR Improved Process
- Solvent: KS-1® solvent
- Start Up: June 3, 2011
- Status: 100% load since June 22, 2011
  CO_2 injection started on August 20, 2012

Demonstration Plant Overview



Southern Company Idea Power: Carbon Capture 101



https://youtu.be/SoxtVJQwtzw

Construction Progress Photos

Construction Progress Photos

Construction Progress Photos

49

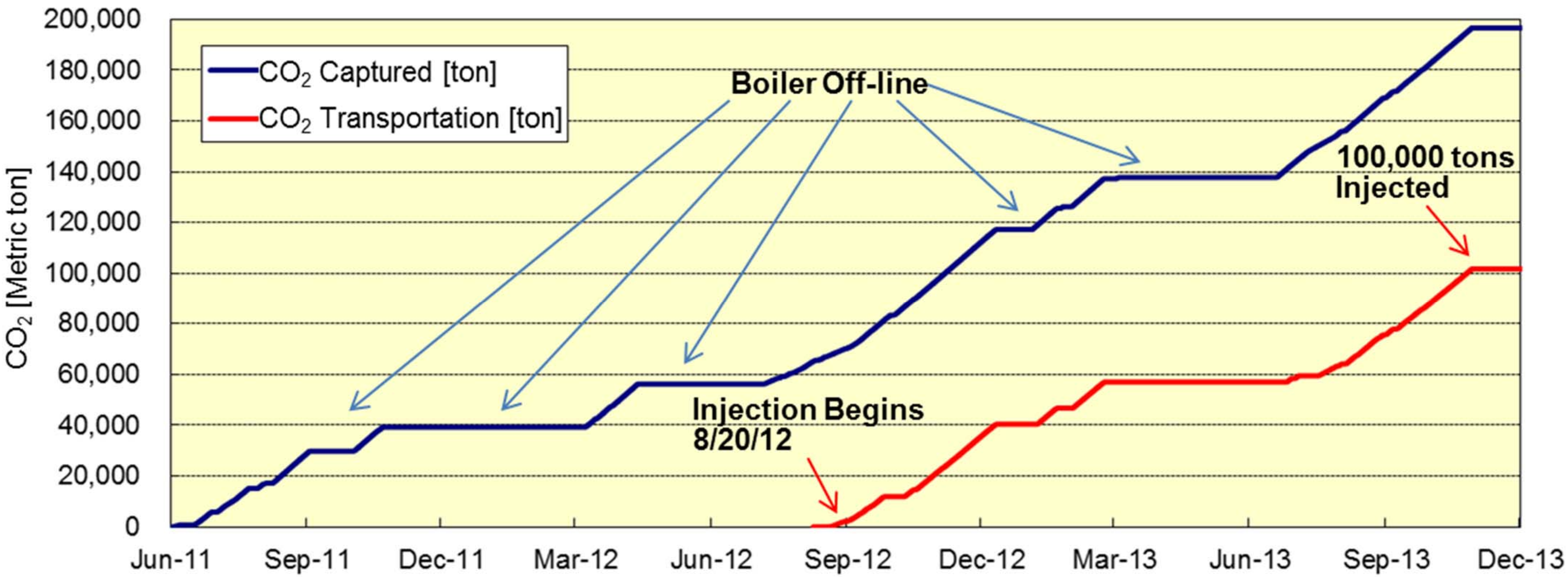
Summary of Test Results

1. Long term operation test
2. Automatic operation control system
3. Amine emission reduction system
4. Online amine analyzer

1. Operation Status

Items	Conditions
Total Operation Time	12,400 hrs *
Total Amount of Captured CO_2	230,100 metric tons *
Total Amount of Stored CO_2	115,500 metric tons *

(* As of August 31, 2014)



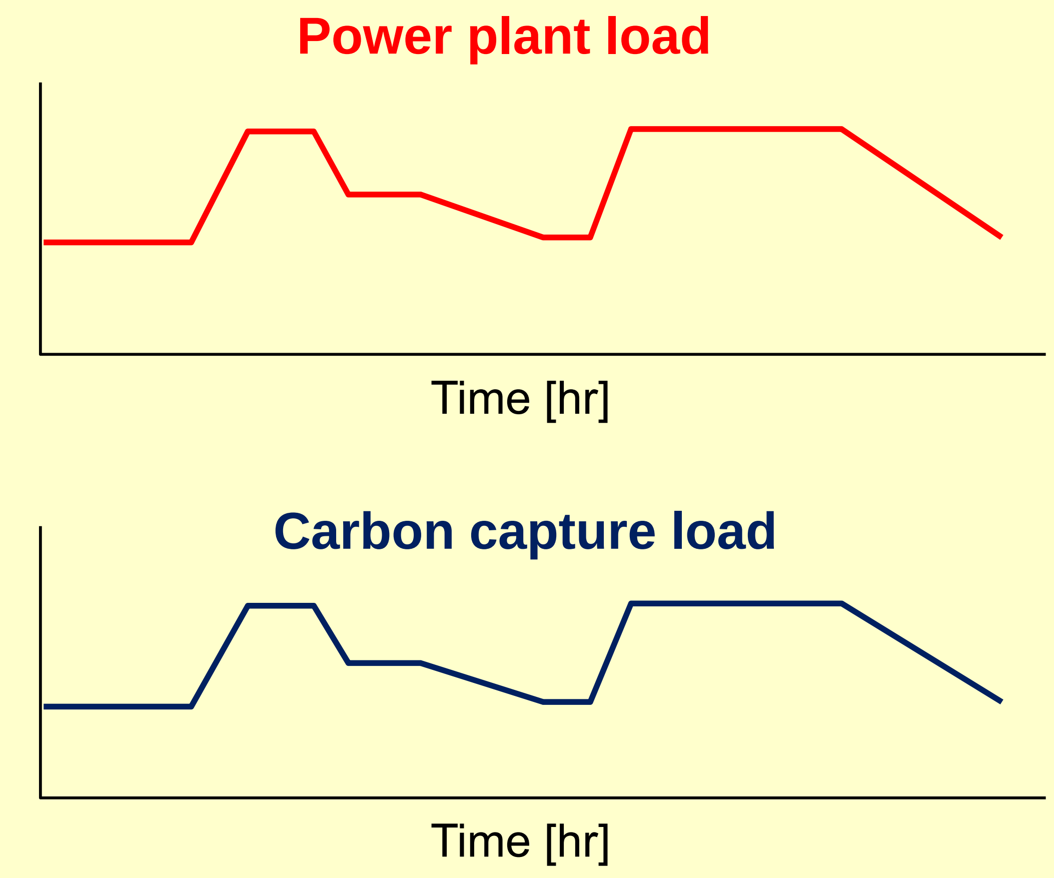
1. CO_2 Quality

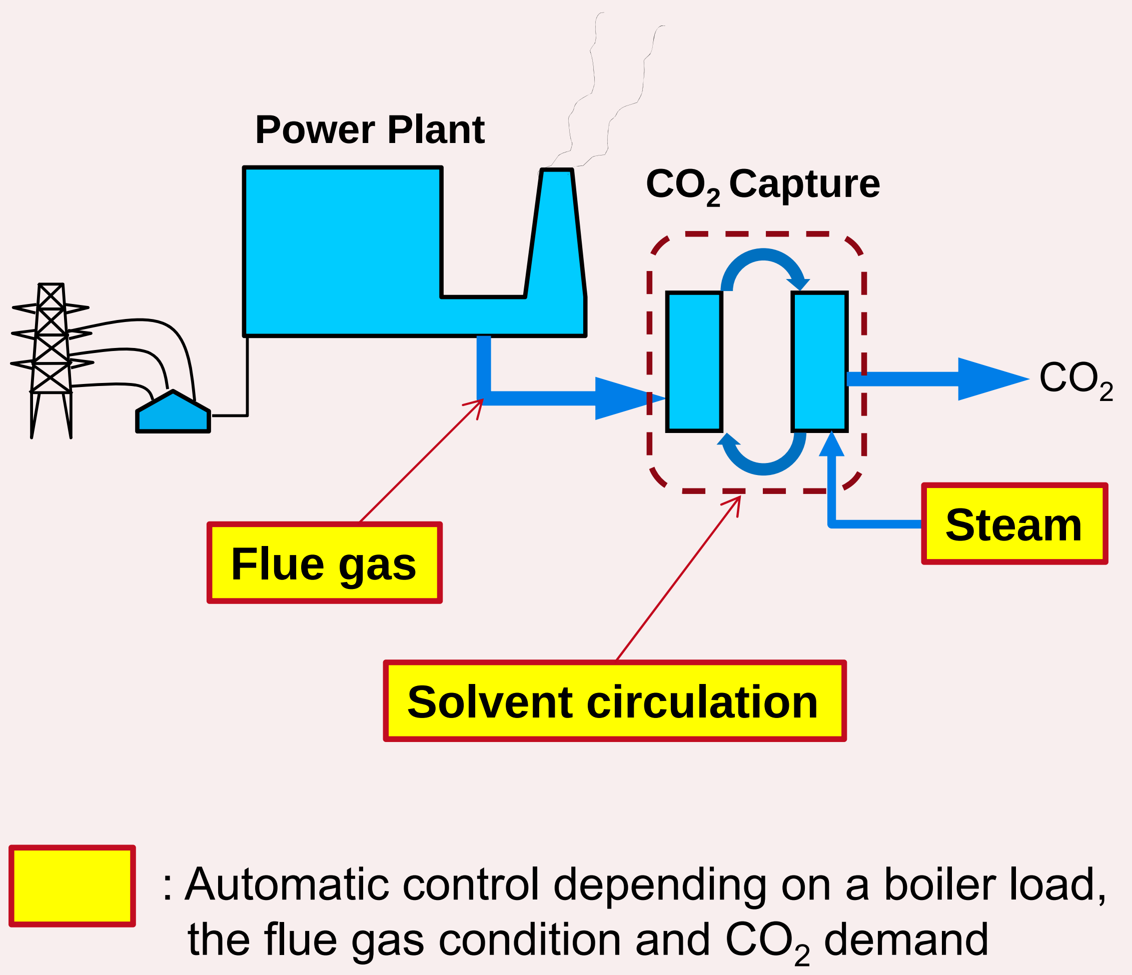
- CO_2 purity is more than 99.9% and impurities concentrations are low.
- Moisture concentration in CO_2 was 200~400 ppm.
- CO_2 quality was satisfied with the criteria of CO_2 pipeline and injection site.

Carbon Dioxide (CO_2) Analysis Performed by Denbury	Results
CO_2 Purity [vol%]	99.9+
Hydrogen (H_2) [ppm vol]	<50
Oxygen (O_2) + Argon (Ar) [ppm vol]	38
Nitrogen (N_2) [ppm vol]	210
Carbon Monoxide (CO) [ppm vol]	<2
Ammonia (NH_3) [ppm vol]	<0.5
Nitrogen Oxides (NO_x) [ppm vol]	<0.5
Phosphine (PH_3) [ppm vol]	<0.25
Total Hydrocarbons [ppm vol as CH_4]	8.1
Methane (CH_4) [ppm vol]	0.3
Total Non-Methane Hydrocarbons [ppm vol as CH_4]	7.7
Acetaldehyde [ppm vol]	7.9
Aromatic Hydrocarbons [ppb vol]	<2
Total Sulfur Compounds [ppm vol]	<2

2. Automatic operation control system

- Power plant load and the flue gas condition changes frequently.
- **The automatic operation control system is to maximize the efficiency of Carbon capture.**

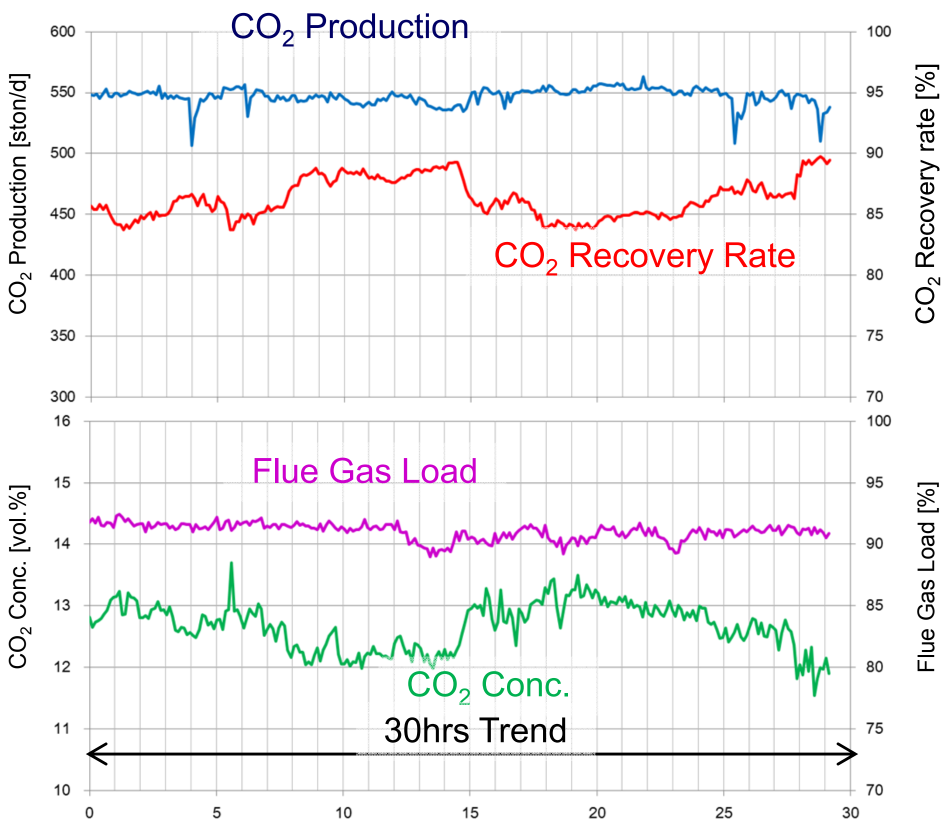




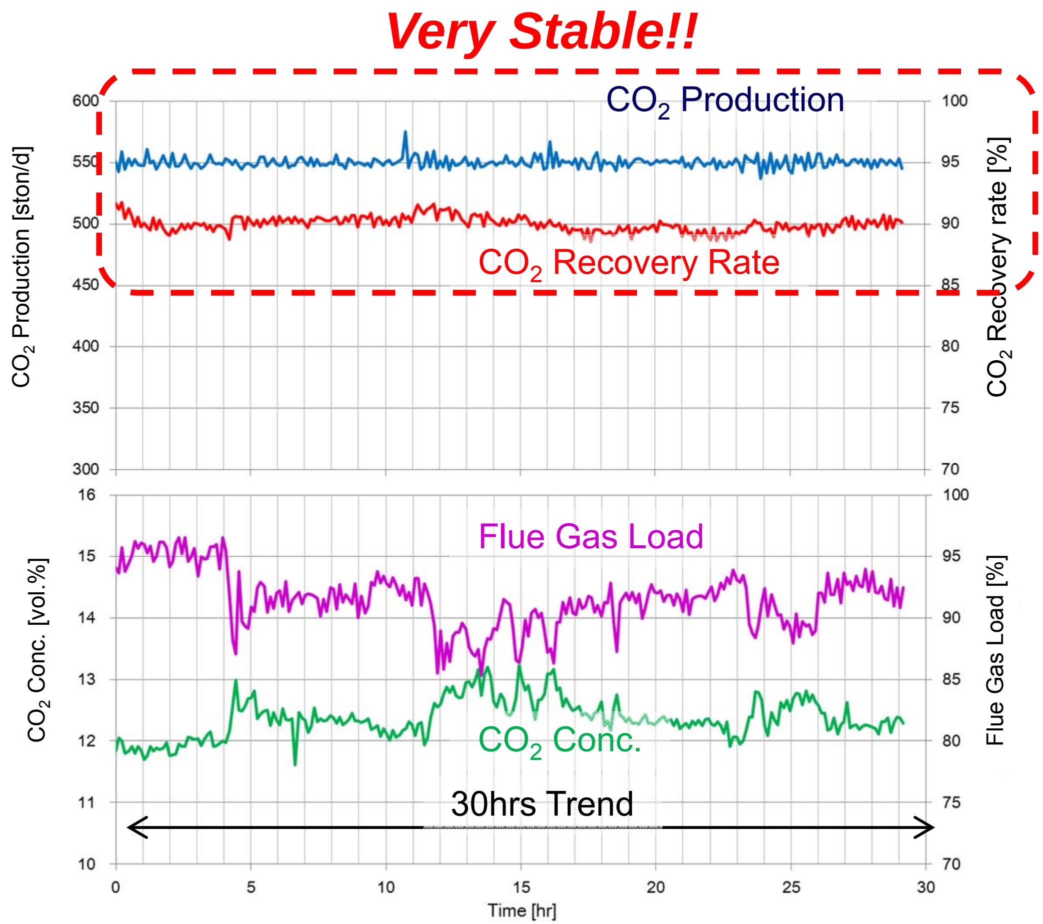
2. Test result of automatic operation

Confirmed

- Load change at 5% per minute without any adverse effect
- Automatically and continuously optimization



Manual operation



Automatic operation control system

■ *Amine Emission*

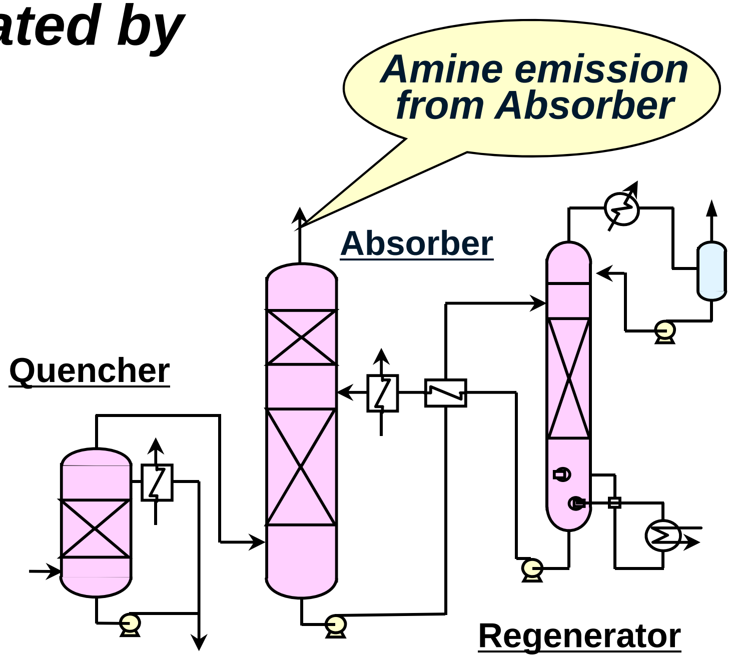
✓ **Amine vapor**

- Evaporated amine from the CO_2 absorption section

✓ **Amine mist**

- Entrained mists/droplets or Aerosols generated by amine and CO_2 reaction, etc

- High sensitivity to SO_3 in flue gas



3. Pilot test Result - SO_3 influence on Amine emission

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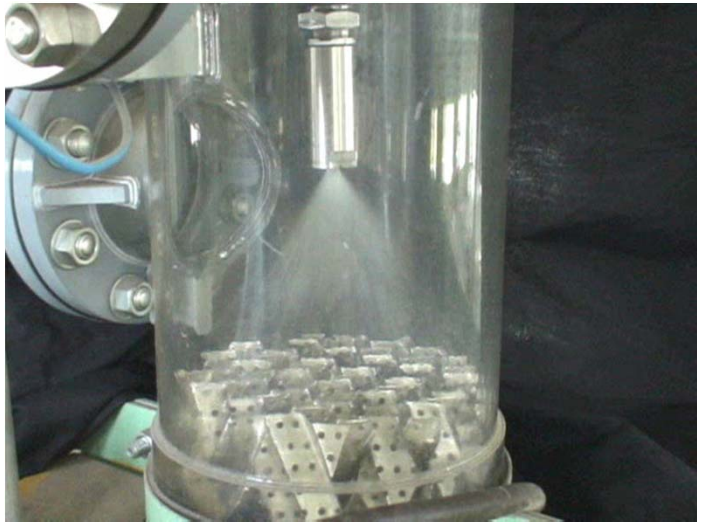
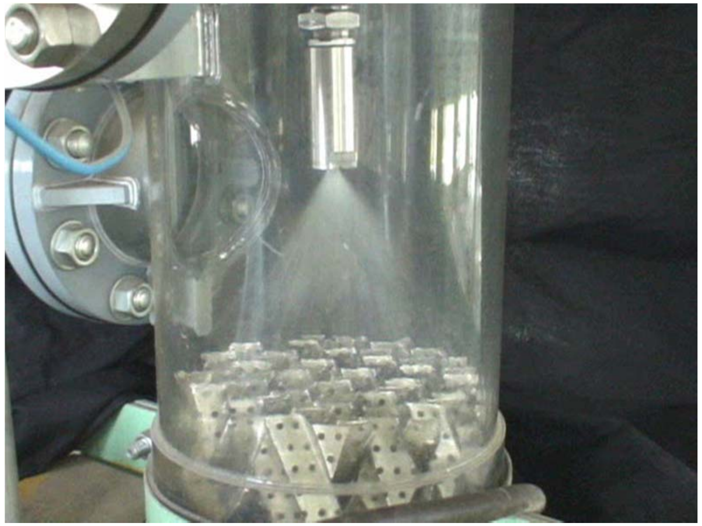
- CO_2 recovery testing from simulated flue gas at Hiroshima R&D center, MEA solvent
- Down stream of CO_2 absorber, white smoke was raised by SO_3 contained in the gas

SO_3	0ppm	3ppm
Quencher Outlet		
Absorber Washing Section Outlet		

3. Amine Emission Evaluation

- Amine emissions increased significantly with a small amount of SO_3.
  → It will cause the solvent consumption significantly.
- MHI's amine emission reduction system decreases amine emission down to less than 1/10 of the emissions of the conventional system.
- The system is effective to maintain the low solvent consumption.

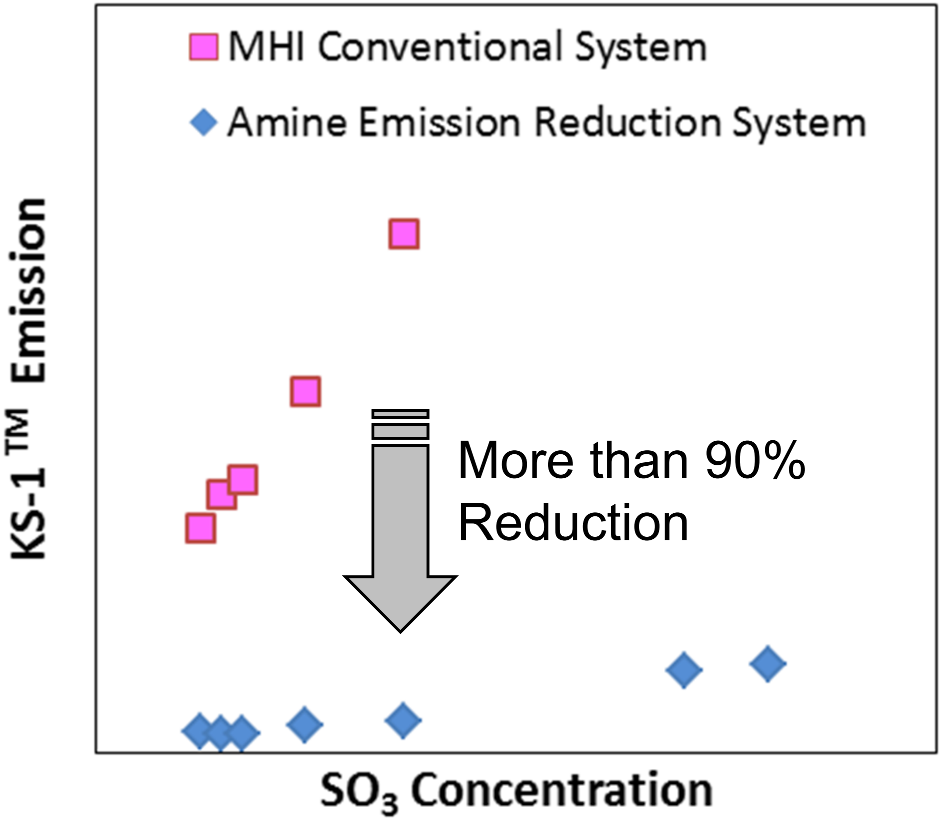


Fig. Relationship between SO_3 conc. and solvent emission

Fig. Absorber top

- MHI developed a proprietary online analyzer to monitor the process conditions and amine emissions.
- The online analyzer improved plant operability and controllability.

Fig. Online Amine Analyzer

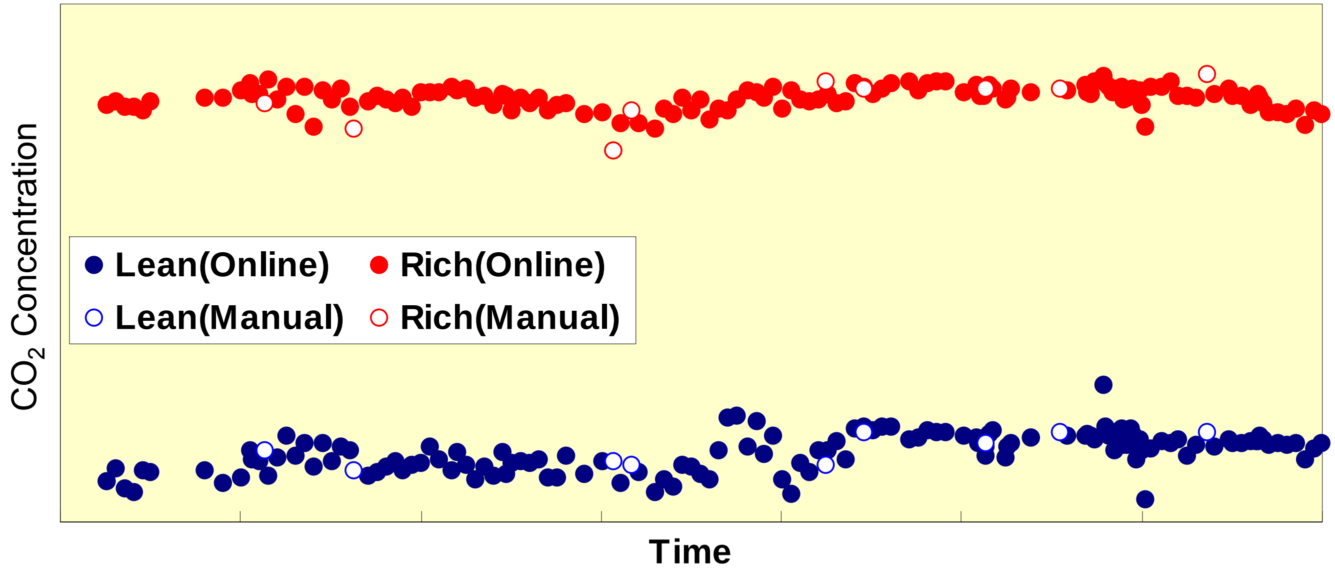


Fig. Periodic Results of CO_2 Concentration Trends in KS-1® Solvent

4,776 tpd Commercial Plant for EOR

MHI's Scale up for Coal-fired CO_2 Capture

MITSUBISHI HEAVY INDUSTRIES AMERICA, INC.

From pilot to full scale

Pilot
1 TPD
Scale

Small Scale
Demonstration
10 TPD Scale

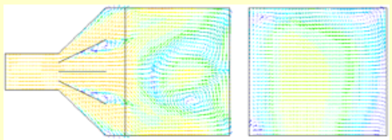
Large Scale
Demonstration
500 TPD

Full Scale

5,000 TPD

Know-how and Lesson learned from 11 commercial plants

Simulator (CFD etc.)



Large Scale experience for FGD

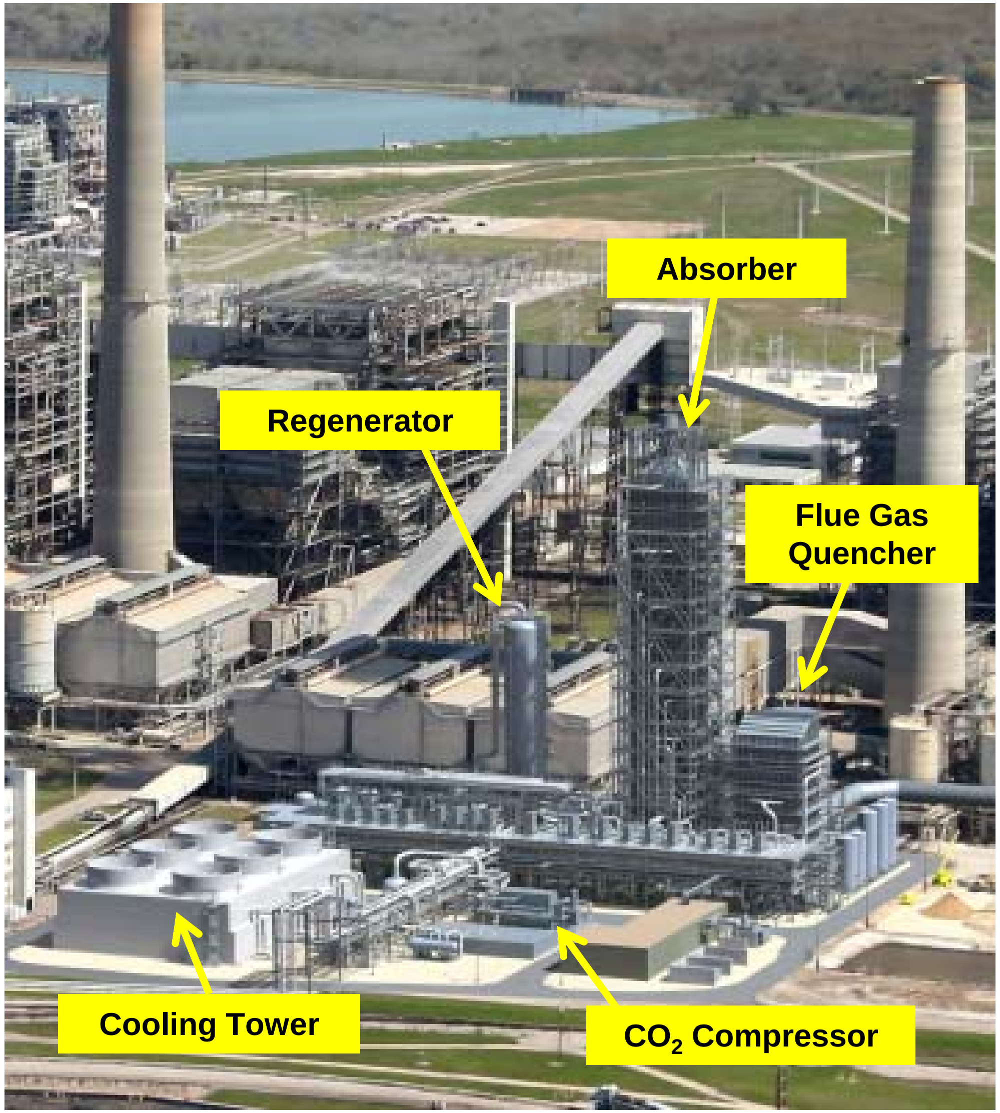
- Large amount of flue gas
- More than 200 commercial plants

World's largest CO_2 capture plant in Texas

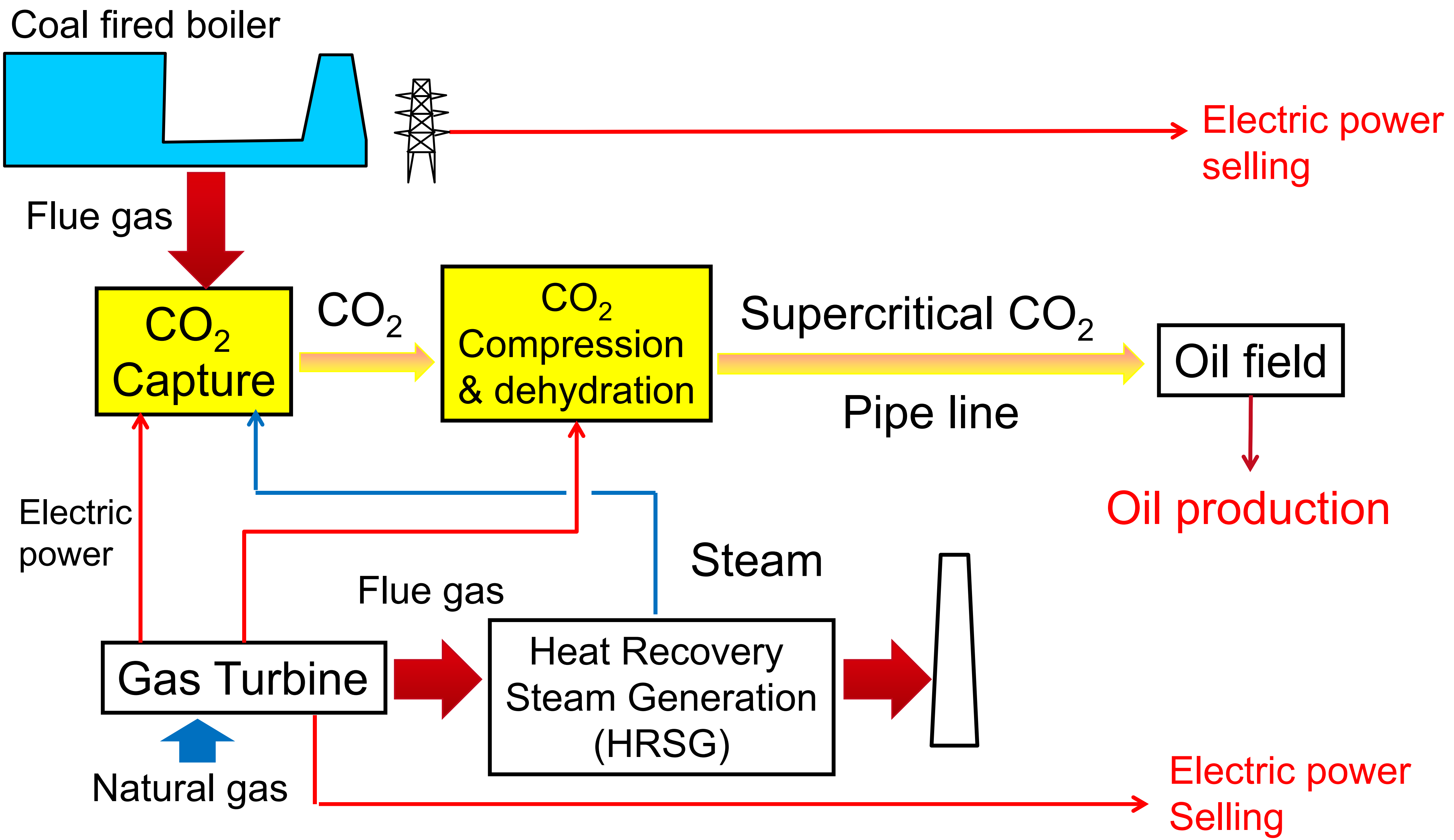
World's largest CO_2 capture plant from an existing coal-fired power plant

- Project Owner: NRG Energy Inc. and JX Nippon Oil & Gas Exploration Corporation
- Location: NRG WA Parish Power Plant near Houston, TX.
- Flue gas source: 240MW slipstream from existing 650MW coal-fired boiler
- Plant Capacity: 4,776 metric ton/day
- CO_2 recovery ratio: 90%
- CO_2 Use: Enhanced Oil Recovery (EOR)
- Injection Site: West Ranch oilfield in Jackson County, TX
- Operation Start: 4th Quarter, 2016

*Artist Rendering

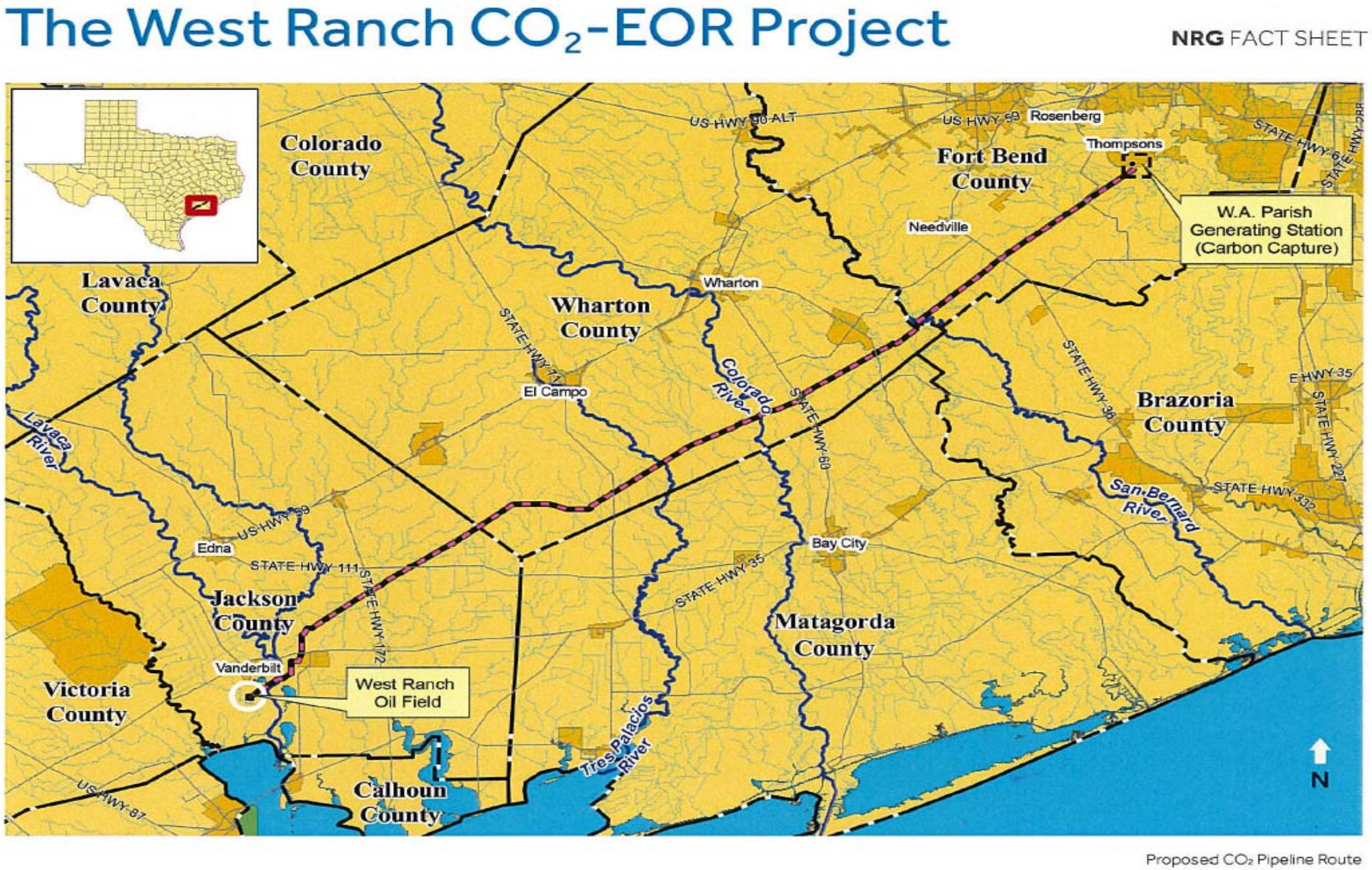


WA Parish CO_2 EOR Overall System



The West Ranch CO_2-EOR Project

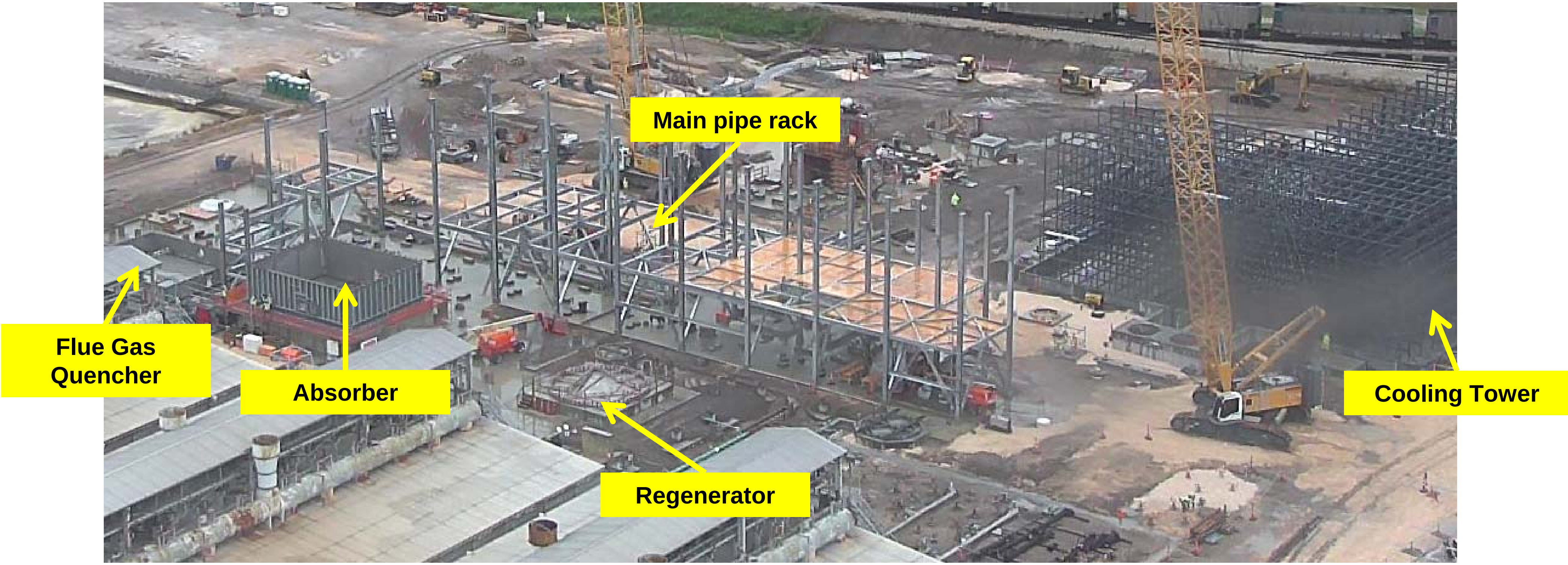
- Captured and compressed CO_2 from W.A. Parish Power Plant will be delivered by 80 mile CO_2 pipeline to the West Ranch oil field.
- 1.4 million metric tons of greenhouse gas will be annually injected into the West Ranch formation.
- It is expected that oil production will be enhanced from 500 barrels/day to approx. 15,000 barrels/day.



Project Progress

Key Progress

- Signed EPC contract, Issued LNTP: Mar 2014
- Issued Final Notice to Proceed (FNTP): Jul 2014
- Construction start : Sep 2014
- Foundation work almost completed
- Structure work on going
- Operation Start：4th Quarter, 2016



Site Photo (2015/5/12)

MHI's Technology for Future

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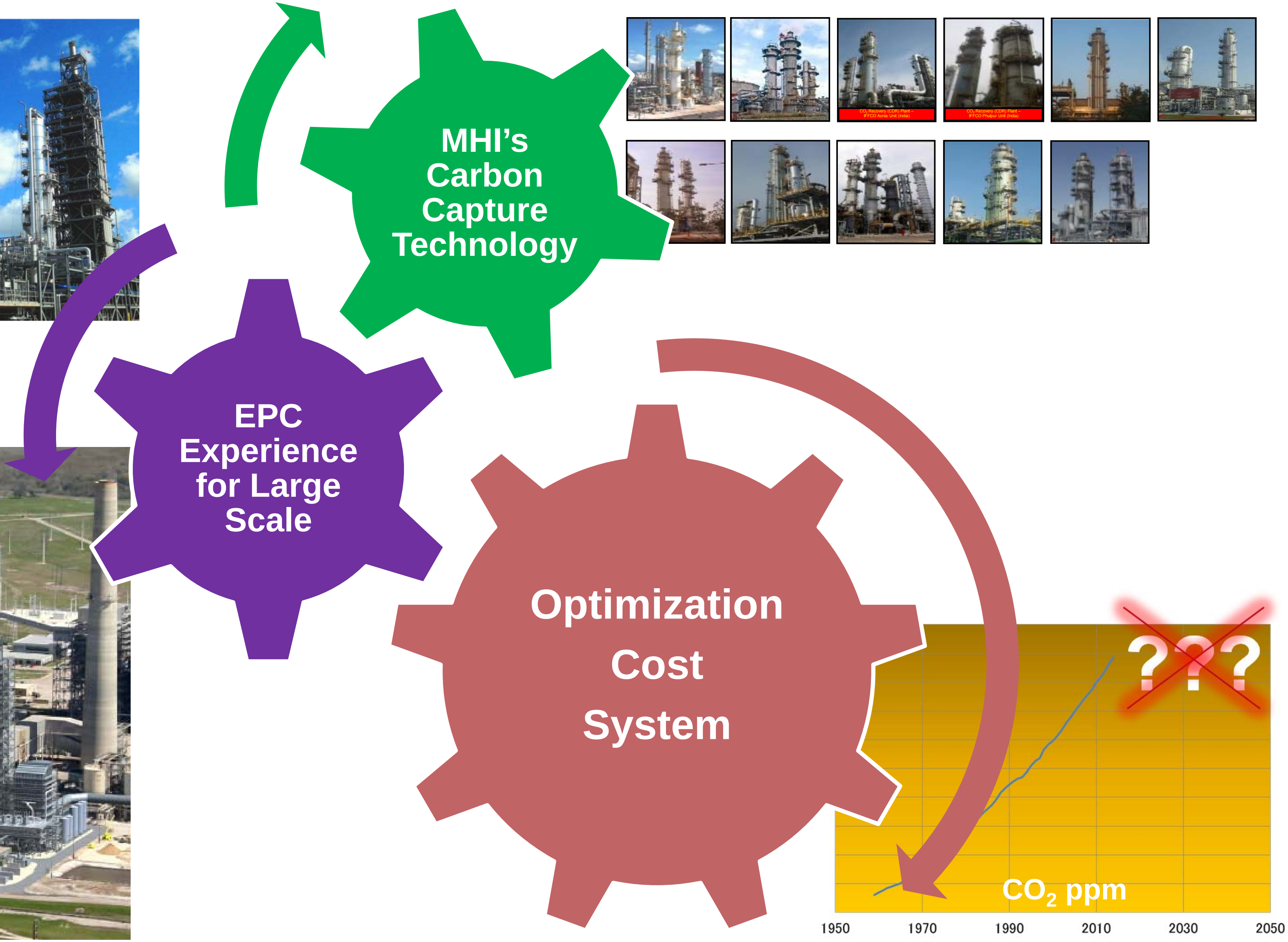

Thank you.