# CSLF Joint Task Force on the Development of 2nd and 3rd Generation $CO_2$ Capture Technologies

**Update November 2, 2015**

**CSLF Technical Group Meeting**

**Riyadh, Saudi Arabia**

*Lars Ingolf Eide, Norway*

# History

- The following topics of great interest to CSLF that should be moved forward in Task Forces (CSLF Ministerial Meeting in Washington DC in November 2013):
    1. Communications
    2. Global collaboration on large-scale CCS project(s)
    3. Financing for CCS projects
    4. Supporting development of 2nd and 3rd generation CCS technologies
    5. Transitioning from $CO_2$-EOR to CCS.

# Our mission

- The fourth Task:
  - ”Efforts should be taken to better understand the role of 2nd and 3rd generation technologies for CCS deployment, and policies and approaches identified among individual CSLF member countries that can stimulate 2nd and 3rd generation CCS project proposals to improve the outlook for successful Large Scale Integrated Project deployment in the 2020 to 2030 timeframe. Development of these technologies will benefit from the CCS Pilot Scale Testing Network, which is in the process of being stood up. ”

# What to do

- Technical Group
  - Map/Identify 2nd and 3rd generation
    - mature in the 2020 –2030 timeframe,
    - development plans to scale from current readiness
    - major challenges facing technology development.
  - Use existing networks to map potential for testing 2nd and 3rd generation technologies at existing test facilities
- Policy Group
  - Map initiatives and funding mechanisms for 2nd and 3rd generation technologies in CSLF member countries.
  - Prepare a Policy document on how to achieve an accelerated implementation of 2nd and 3rd generation $CO_2$ capture technologies

# Approach Technical Group

- ***Summarise several review papers, NOT an original work (quasi-metastudy).***
  - ***SINTEF (2013), DOE/NETL (2013) and IEAGHG (2015) ZEP (2013), CSLF (2013a) and GCCSI (2014).***
  - ***References to these documents usually not given in the general descriptions, nor to papers and articles used by the mentioned references*.**

## What's new since Regina June 2015?

- Implemented comments and input from Australia, EC, France, Japan, South Africa, South Korea and Canada
- Added information on cost and energy savings potential
- Added overview of test facilities

# Organization of report

- Grouping of technologies
  - E.g. Post-combustion
    - Solvents
    - Sorbents
    - Membranes
    - Other (Cryogenic, hydrates, $CO_2$ enrichment, algae, supersonic pressurized)
- No provider specific technology information
- Test facilities and capabilities
  - Large scale generic
  - Pilot scale generic
  - Non-generic

# Challenges with definitions and classifications

- Funding agencies, reviewers and others differ in definitions of 2nd and 3rd generation technologies
- Reviewers/vendors differs in assessment of maturity
- The boundary between “pilot” and “demonstration” is floating and un-precise, in terms of quantities as well as units.

# Cost and energy reduction potentials are difficult to estimate and compare

- Many factors that contribute to confusion
  - Different baselines
  - Cost of electricy (COE) or levelised cost of electricity (LCOE)
  - Cost per tonne $CO_2$ captured or abated
  - First of a kind (FOAK) or $n^{th}$ of a kind (NOAK)
  - Basically unfamiliar production methods and materials
  - Some may cost the whole process, others just the capture component
  - Reporting in efficiency changes or energy requirements (GJ/tonne $CO_2$)
  - Electricity vs. Work vs. thermal energy
  - Emerging technologies – limited information and testing

# Excluded from this report: Overall process development and integration, materials

- General energy efficiency measures, e.g. for turbines
- Optimized integration a $CO_2$ capture system with the power or processing plant, e.g. heat integration
- Improvement of other environmental control systems ($SO_X$, $NO_X$)
- Part-load operation and daily cycling flexibility
- Impacts of $CO_2$ composition and impurities, for 'new-build' plants as well as for retrofits
- Materials choice and improvements
- Improved process equipment like heat exchangers, pumps fans and other auxiliary equipment.

# Example of technology summary

**Enzymes**

The enzyme carbonic anhydrase (CA) is known to accelerate the hydration of neutral aqueous $CO_2$ molecules to ionic bicarbonate species. CA is amongst the most well-known enzymes, since it operates in most living organisms, including human beings. By adding a soluble enzyme to an energy efficient solvent one may be able to achieve a lower cost process for carbon capture and mimicking nature's own process. Increasing the kinetic rates of the hydration of $CO_2$ and dehydration, as CA does, results in enhanced absorption and desorption of $CO_2$ into and out of a $CO_2$ solvent and/or in various membrane processes with immobilized CA. Novozymes applies ultrasonic energy to increase the overall driving force of the solvent re-generation reaction.

**Maturity**: 3$^{rd}$ generation; TRL 1 - 2 (Bench scale testing with real flue gas)
**Challenges:** Understanding the level of enzyme activation; increasing the chemical and physical stability of the enzymes (mainly thermal stability); advancing the limited cyclic capacity (for carbonates)
**Some players**: $CO_2$ Solutions, Novozymes, Carbozymes, Akermin
**Pathway to technology qualification**: Further basic research to understand the level of enzyme activation and to increase the chemical and physical stability of the enzymes (mainly thermal stability). In addition, the limited cyclic capacity (for carbonates) needs further advancements. Scale-up to lab and small pilot.
**Infrastructure required**: The concept can utilize the existing infrastructure for post-combustion as found at many larger test facilities, such as access to real flue gas, water, electricity and other utilities. Some modifications may be required, depending on the need for recycling enzymes to avoid high temperature exposure.
**Environmental impact**: Potentially low impact. If inorganic carbonates are use as main component and there are no other activators than the enzyme, there should be no emissions.
**Applications**: Power industry, cement industry, steel industry

# Status 2nd and 3rd generation post-combustion capture technologies

| Technology | Generation/ TRL | Potential for energy savings | Potential for cost reduction | Applications |
|---|---|---|---|---|
| Precipitating solvents | 2nd-3rd/4-6 | 10-20% rel. MEA (2.3-3.6 GJ/t $CO_2$) | 5-10% | Power, steel, cement |
| Two-phase liquid system | 2nd-3rd/4-5 | 2.0-2.3 GJ/t $CO_2$ | 5-10% | Power, steel, cement |
| Enzymes | 3rd/1-2(3) | 30-35% rel. MEA (?) | 5-10 | Power, steel, cement |
| Ionic fluids | 2nd-(3rd)/1 – 4 | 15 -20 % rel. MEA | ? | Power, steel, cement |
| Encapsulated solvents | 3rd/1-2 | ? | ? | Power, cement |
| Electrochemical solvents | 3rd/1-2 | Uncertain | Uncertain, may be none | Power, cement, steel, aluminum |
| Calcium looping system | 2nd/5-6 | Coal: Efficiency penalties 5-10%<br>Gas: no benefits | May be significant | Power, cement |
| Other looping systems | 3rd/1-2 | ? | ? | Power, steel, cement |

# Status 2nd and 3rd generation post-combustion capture technologies

| | | | | |
|---|---|---|---|---|
| Vacuum Pressure Swing (VPS) | 3rd/2-3 | Uncertain, could be good | May be not | Power, cement |
| Temperature swing (TS) | 3rd/1-2 | Uncertain, appears limited | ? | Power, cement |
| Polymeric membranes | 2nd/5-6 | Fuel consumption: 50% down rel. MEA? | May be up to 30% | Power, cement, steel |
| Polymeric w/cryogenic | 2nd/2-6 | Better than above | May be up to 30% | Power, cement, steel |
| Molten Carbonate Fuel Cells (electrochemical) | 2nd – 3rd/3-4 | Could result in efficiency higher than base power plant | Inrease electricity$0.02 /kWh | Power, cement, steel |
| Cryogenic (low temp) | 2nd-3rd/3-5 | Competitive MEA | Moderate ? | Power |
| Supersonic | 3rd/1-2 | ? | ? | Power |

# Status 2nd and 3rd generation post-combustion capture technologies

| | | | | |
|---|---|---|---|---|
| **Hydrates** | **3rd/1-3** | **?** | **?** | **Power** |
| Algae | 3rd/1-3 | ? | ? | Power and most other industries |
| $CO_2$-enriched flue gas | 2nd/5-6 | ? | ? | Power |
| Pressurized post-combustion | 2nd-3rd/2-5 | ? | ? | Power |

# Status 2nd and 3rd generation pre-combustion capture technologies

| Technology | Generation/TRL | Potential for energy savings | Potential for cost reduction | Applications |
|---|---|---|---|---|
| Sorption Enhanced Water Gas Shift (SEWGS) | 2nd/4-5 | Efficiency gain 3-4 %-points | May be up to 30% | Power, refinery, $H_2$ production |
| Sorption Enhanced Steam-Methane reforming (SE-SMR) | 3rd/1-2 | Appears limited in NGCC | ? | Power, refinery, $H_2$ production |
| Metal and composite membranes | 2nd-3rd/3-5 | Efficiency gain 3 %-points | May be up to 25-30% (?) | Power, refinery, $H_2$ production |
| Ceramic membranes | 2nd-3rd/2-4 | As above? | May be up to 25% (?) | Power, refinery, $H_2$ production |
| Cryogenic (low temperature) | 3rd/1-3 | Efficiency gain 3-4 %-points; 1 GJ/t $CO_2$ | 30 – 50% (last w/recycle of $CO_2$) | Power, refinery, $H_2$ production |
| Concepts with fuel cells | 2nd-3rd/3-6 | Efficiency gain up to 30 %-points rel. IGCC and gas w/MEA | > 70% | Coal and biomass power, refinery, $H_2$ production |

# Status 2nd and 3rd generation oxy-combustion capture technologies

| Technology | Generation/TRL | Potential for energy savings | Potential for cost reduction | Applications |
|---|---|---|---|---|
| Chemical looping combustion | 3rd/2-3 | Efficiency gain 2-4 %-points (?) | Large | Coal power |
| Oxygen transporting membranes (OTM) power cycle | 3rd/2-3 | Efficiency gain 5 %-points over NCCC w/MEA(?) | ? | Power |
| Pressurized oxy-combustion | 3rd/2-4 | ~35- 40% -efficiency | reduction 22 – 32+%, on power, depending on cycle | Coal and biomass power |

Several technologies that cannot be directly classified as capture technologies but that have potential to reduce costs of $CO_2$ capture:

$O_2$ separation with membranes (ITM)
High pressure oxy-combustion
$CO_2$ processing and clean-up
Advanced cryogenic air separation
Oxy-combustion turbines and boilers

# Preliminary review of test facilities

**ITCN member facilities and capacities**.

| Facility | Owner(s) | Country | Technology approach (post-, pre- or oxy-combustion) that may be tested | Flue gas | Capacity | | Available infrastructure | Comment |
|---|---|---|---|---|---|---|---|---|
| | | | | Type, amount | Carbon dioxide, t $CO_2$/y | Power (real or equivalent) | | |
| National Carbon Capture Center | DOE, operated by Southern Company | USA | Post and pre | Coal power:14 %; Post: Slip stream ~ 17 000 kg/hr. Pre: Syngas 750 kg/hr | | Post: 0.5 – 1.2 MW | Real flue gas, water, electricity | |
| CO2 Test Center Mongstad | Gassnova, Statoil, Shell and Sasol | Norway | Post | Refinery FCC: 12 – 14%, 22 – 50 000 $Sm^3$/hr CHP gas turbines: 3.5-9%; 28 – 56 000 $Sm^3$/hr | FCC : 80 000<br><br>CHP: 25 000 | Coal: 10 - 12 MW<br><br>Gas: ~ 7.5 MW | Real flue gas, water, electricity | |
| Shand | SaskPower | Canada | Post, may evalove into other tyupes after 1 – 2 years | Coal power | 45 000 | 5 – 6 MW | Real flue gas, water, electricity | Presently operated by Mitsubishi, may be open to others from 2017 |
| PACT | UKCCSRC | UK | Post, pre and oxy | | | | Flue gas from stand-alone burner or turbine; water, electricity | |
| Wilhelmshaven | E.ON | Germany | | Coal power: 13%; 16 000 $Nm^3$/hr | 25 000 | ~ 5 MW | Real flue gas, water, electricity | |

# ECCSEL member facilities and capacities

| Facility | Owner(s) | Country | Technology approach (post-, pre- or oxy-combustion) that may be tested | Flue gas | Capacity | | Available infrastructure | Comment |
|---|---|---|---|---|---|---|---|---|
| | | | | Type, amount | Carbon dioxide, t $CO_2$/y | Power (real or equivalent) | | |
| Tiller | Sintef/SOLVit project | Norway | Post<br><br>Separate Chemical Looping Rig | Propane burner, 3 – 20 % $CO_2$, | 4 | 140 kW gas (eq)<br><br>150 kW | absorption tower (20cm inner diameter and 19.5 meter height) stripper column 13.6 meter, electrically heated re-boiler 60 kW, monitoring | |
| THAHRA (TNO's High-Pressure Absorption Hybrid Regeneration Apparatus) | TNO | The Netherlands | | | | | | |
| | University of Stuttgart (USTUTT) | Germany | Post, Calcium Lopping Rig | | | 200 kW | | |
| es.CO2, Cubillos del Sil | CIUDEN | Spain | Oxy | | | Pulverized coal: 20 MWth Circulating Fluidized bed: 30 MWth Biomass: 3 MWth | • Flue Gas Cleaning System.<br>• Recycled Gas Preparation System.<br>• $CO_2$ Compression and Purification Unit (CPU).<br>• $CO_2$ Transport Experimental Facilities.<br>• Fully Equipped Laboratory. | |
| | ETH Z | Switzerland | Post Direct mineralization | Synthetic | Lab scale | | | |
| | CERTH | Greece | | | | | | |

# CSIRO Loy Yang Pilot Plant

- Post-combustion
  - Flue gas from coal fired power plant
  - MEA based solvents
  - Capacity_ 1000 tons $CO_2$/year

# Other small test facilities

US:

USA

- Environmental and Energy Research Center, Univ. of North Dakota, USA: Oxy- well as post-combustion in all three systems) coal or biomass, 0.15 – 0.20 MW
- University of Kentucky, Center for Applied Energy Research
  2 MWth (0.7 MWe) advanced post-combustion CO2 capture pilot plant
  - three novel concepts.
  - a two-stage stripping process for solvent regeneration
  - integrated cooling tower
  - he Mitsubishi Hitachi Power Systems America (MHPSA) H3-1 advanced solvent
  - 

Canada

- CanmetEnergy: 0.3 $MW_{th}$ vertical combustor facility, oxy-combustion, slip streams for pre- and post-combustion possible. 1 $MW_{th}$ under construction.
- Husky Energy Pikes Peak: Post-combustion, flue gas from 14 MW steam generator, capacity 15 tons $CO_2$/day, hope to expand to 150 tons $CO_2$/day. Under construction

*Aerial view of Pikes Peak South heavy oil thermal facility*
*Courtesy: Husky Energy*

# In planning

- UK-China (Guangdong) Carbon Capture, Utilisation and Storage (CCUS) Centre
  - Up to 200 t $CO_2$/day post- combustion facility in planning

- University of Wyoming, plans 1 MW+ postcombustion test facilty for coal based power

- Carbon Management Canada Research Institutes, with NORAM Engineering and BC Research to develop a new Technology Commercialization and Innovation Centre for development, scale-up and pilot testing for CO2 Capture and Conversion technologies, capture facility 1 t $CO_2$/day or 0.1 MW

# CCS Brindisi $CO_2$ Capture Pilot Plant

- Post-combustion capture with amine
- Slip stream form 2640 MW coal fired power station
- Capture rate 8000 t $CO_2$/year
- Large range to change the composition of flue gas
- High flexibility in fact of solvent flow rate; flue gas flow rate, DCS control system, solvent inventory

# Alstom Advanced Amine Process, Le Havre

**Location:** ............................... Le Havre, France
**Customer:** ............................. EDF power plant
**Process / fuel:** ....................... Pulverised coal boiler / bituminous coal
**Capture technology:** ............ Advanced Amine Process
**$CO_2$ capture capacity:** .......... 7,500 metric tons per year
**Commissioning:** .................... July 2013
**Completion of testing:** ......... March 2014

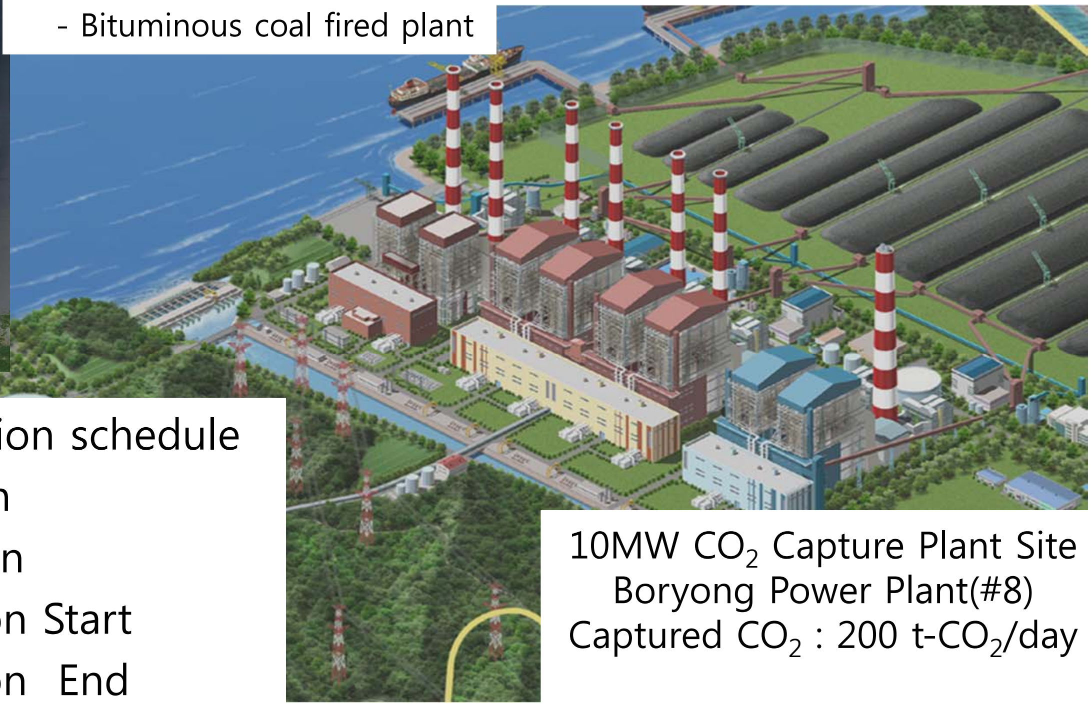
## Tauron in cooperation with Institute of Chemical Processing of Coal (ICPW): The mobile $CO_2$ capture solvents and VPSA

Column diameter: 0.3m
Absorber height: 14.0m
Desorber height: 15.0m

Captures 1,2 t $CO_2$/day from real flue gas
Tested at Lagsza and Jaworzno power

# Korean Electric Power Company RI:
# Boryong 10MW Plant Advanced Amine Absorbent

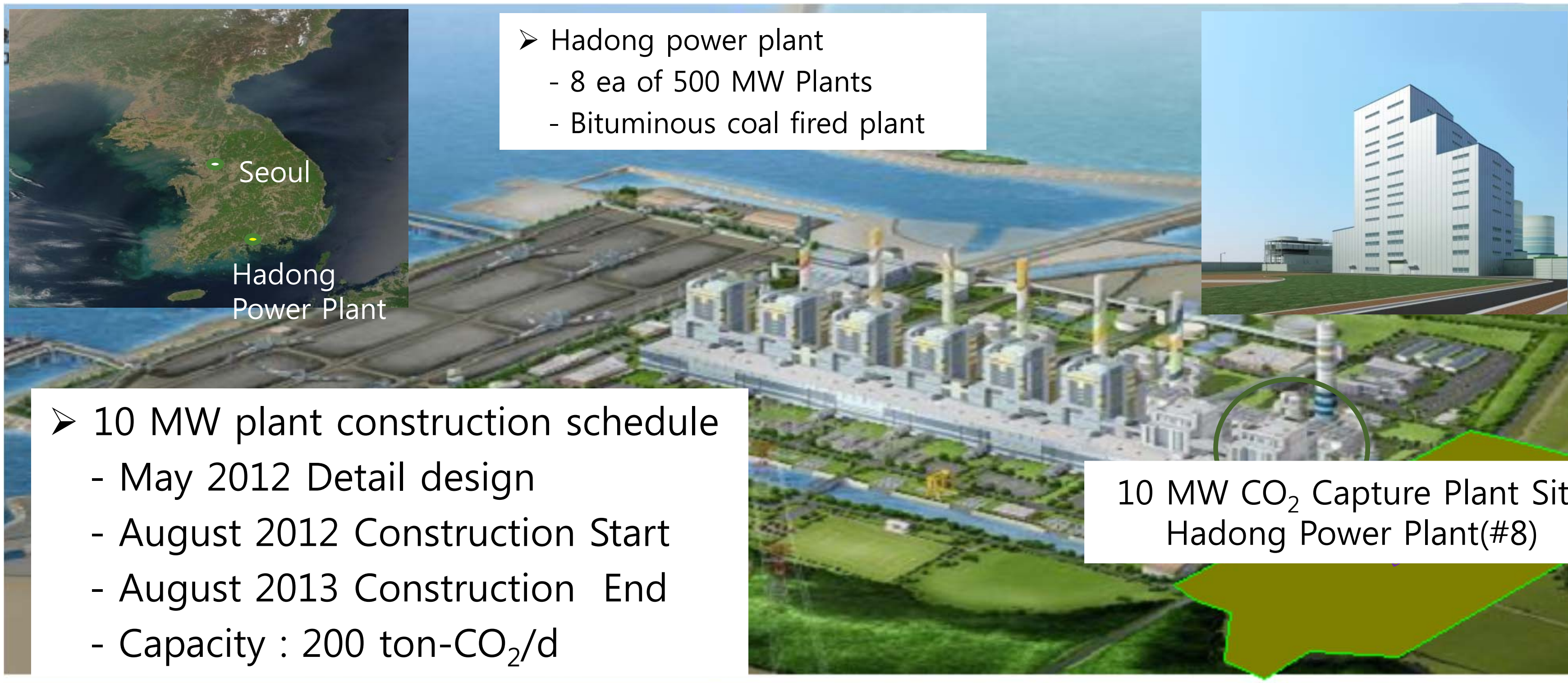
- Boryong power plant
  - 8 ea of 500MW Plants
  - Bituminous coal fired plant

- 10 MW plant construction schedule
  - Sep 2011 Basic design
  - Feb 2012 Detail design
  - May 2012 Construction Start
  - May 2013 Construction End

10MW $CO_2$ Capture Plant Site
Boryong Power Plant(#8)
Captured $CO_2$ : 200 t-$CO_2$/day

# Korean Electric Power Company RI: Hadong 10 MW Plant Solid Sorbent




- Hadong power plant
  - 8 ea of 500 MW Plants
  - Bituminous coal fired plant

- 10 MW plant construction schedule
  - May 2012 Detail design
  - August 2012 Construction Start
  - August 2013 Construction End
  - Capacity : 200 ton-$CO_2$/d

# Some Huaneng test or pilot facilities

3000 tons $CO_2$/year
post-combustion
Capture In Bejing

CCM verification Plant
for coal and natural
gas tons 1000 $CO_2$/year

10000 $CO_2$/year precombustion facility
Palladium membrane $H_2/CO_2$ separation
system

16/11/2015

# Other non-generic test facilities

- Japan
  - Kawasaki Heavy Industries, Ltd.
    - Fixed-bed (10 t $CO_2$/day) and moving-bed (3 t $CO_2$/day) systems with own adsorbent
  - Mitsubishi Heavy Industries
    - Several test, pilot and demonstration scale projects based on own amine technology
  - Tomakomai
    - Feedstock: Hydrogen production unit. Size: 0.1 Mt/yr
    - Capture Technology: Activated amine process
  - Toshiba
    - Amine-based Chemical Absorption (Toshiba's Solvent System), CO2 capacity: 10 ton-$CO_2$ / day. Flue Gas Flow: 2100 Nm3 / hour (from Coal Fired Power Plant).

# Pilot plants –MIT data base

| Pilot CCS Projects- Operating | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Project Name** | **Leader** | **Location** | **Feedstock** | **Size MW** | **Capture Process** | **CO2 Fate** | **Status** |
| Jilin | PetroChina | China | Nat. Gas Processing | 0.2 Mt/yr | Post | EOR | Operational Since 2009 |
| Shidongkou | Huaneng | China | Coal | 0.1 Mt/yr | Post | Commercial use | Operational 2011 |
| Plant Barry | Southern Energy | AL, USA | Coal | 25 | Post | Saline | Operational August 2012 |
| Callide-A Oxy Fuel | CS Energy | Australia | Coal | 30 | Oxy | Saline | Operational December 2012 |
| Jingbian | Yanchang | China | Chemicals | 40 Kt/yr | N/A | EOR | 2013 |
| Polk | Tampa Electric | FL, USA | Coal | 0.3 Mt/yr | Pre | Saline | Operational April 2014 |
| E.W. Brown | Univeristy of Kentucky | KY, USA | Coal | 2 MW | Post | N/A | Under Construction |
| Tomakomai | JCCS | Japan | Hydrogen Production | 0.1 Mt/yr | Post | Saline | Planning |
| Big Bend Station | Siemens | FL, USA | Coal | 1 | Post | Vented | Planning |

# Recommendations for Follow-Up by CSLF

- Implement mechanisms that allow developers of emerging technologies and operators of test facilities to cooperate in mutual beneficial and cost effective ways
- Promote cooperation between facilities with different capabilities, both below and above 2MW or ($10^4$ tons $CO_2$/year, ~ 30 tons $CO_2$/day)
- Encourage and facilitate enhancing the networks to cover additional regions, sectors, and levels of scale
- Enhance opportunities for researchers and developers to participate in extended visits and staff exchanges to other demonstration projects and test centres
- Contribute to derivation of a consistent terminology for new $CO_2$ capture technologies, for maturity as well as for scales
- Contribute to derivation of consistent performance indicators, e.g. common methods for cost and energy consumption.