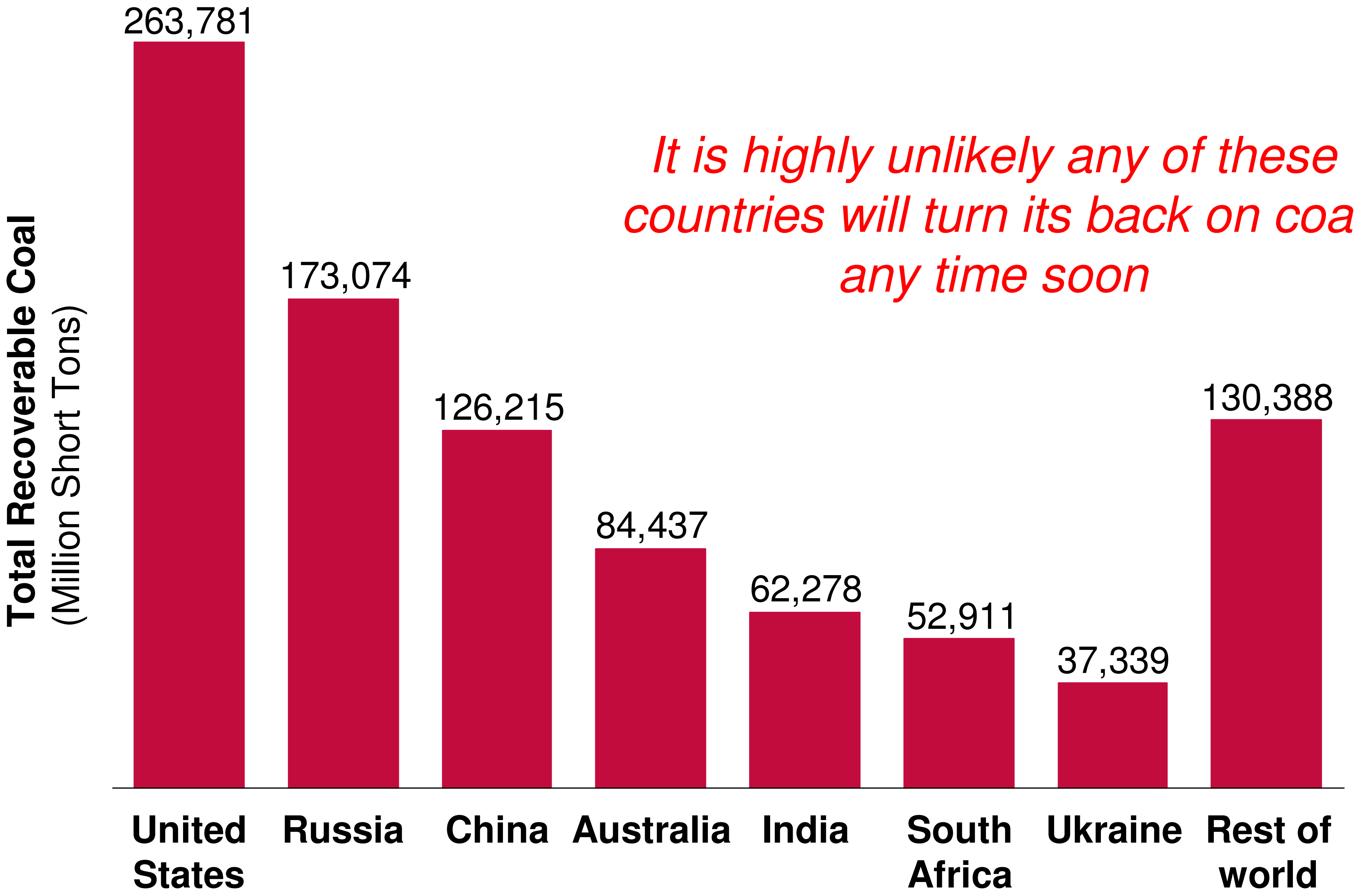
Key Technology Pathways for Carbon Capture and Storage

Carbon Sequestration Leadership Forum
Ministerial Meeting
London
October 13, 2009

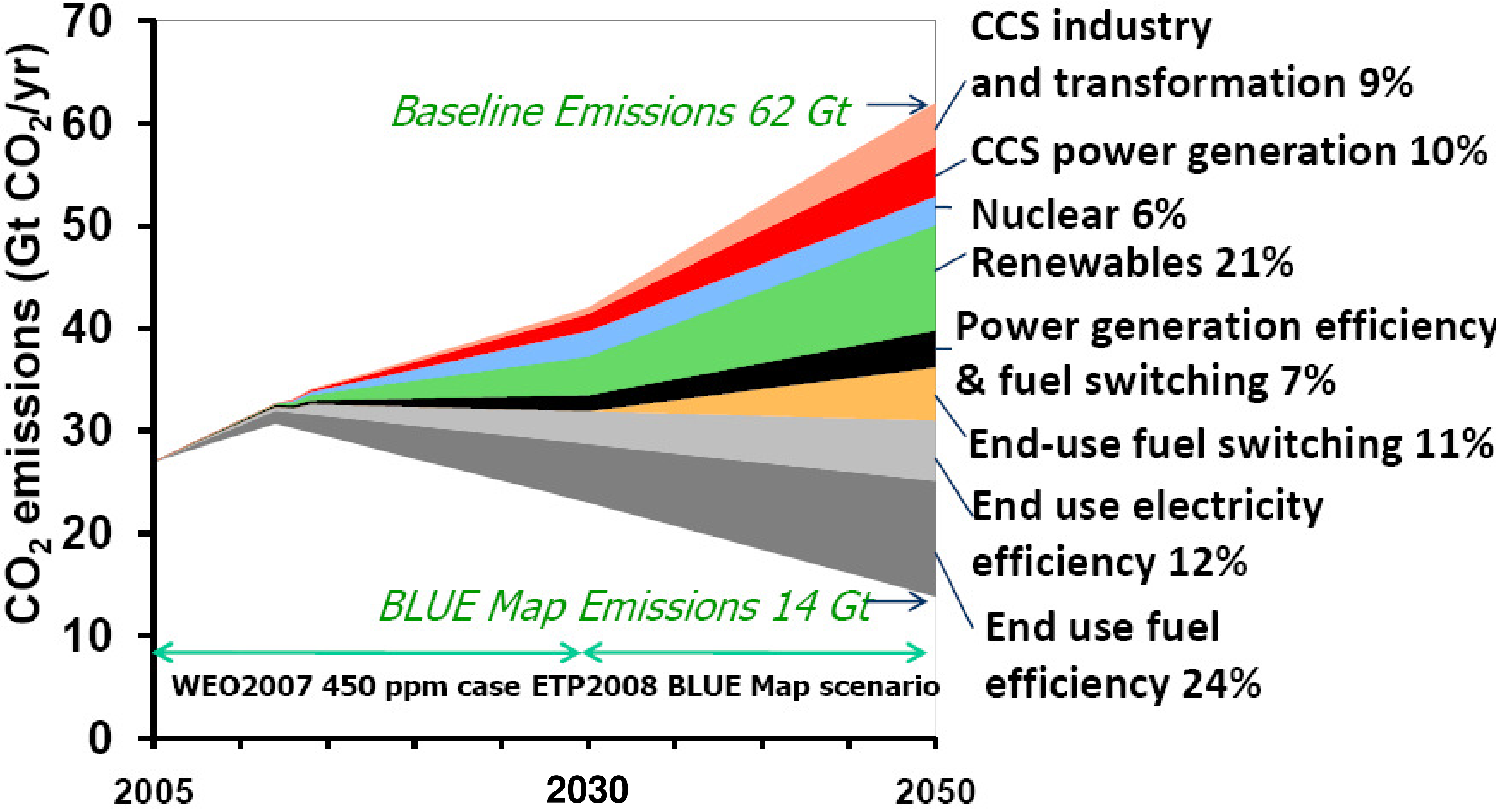
U.S. DEPARTMENT OF
ENERGY

US, China, Russia, Australia, and India have 3/4 of the world's known coal reserves



It is highly unlikely any of these countries will turn its back on coal any time soon

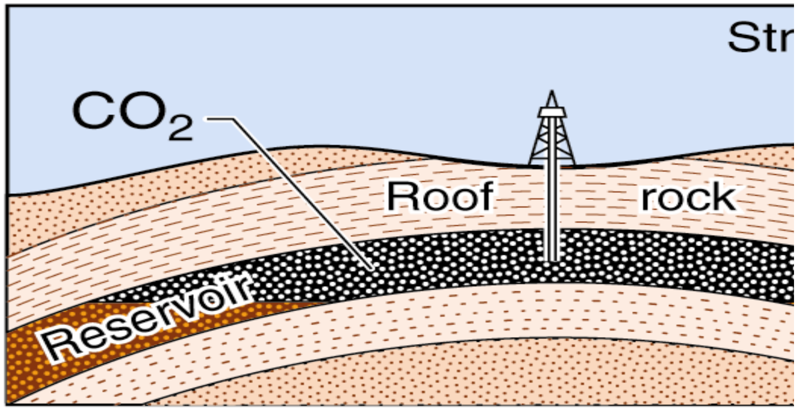
CCS is a part of any realistic CO2 abatement scenario



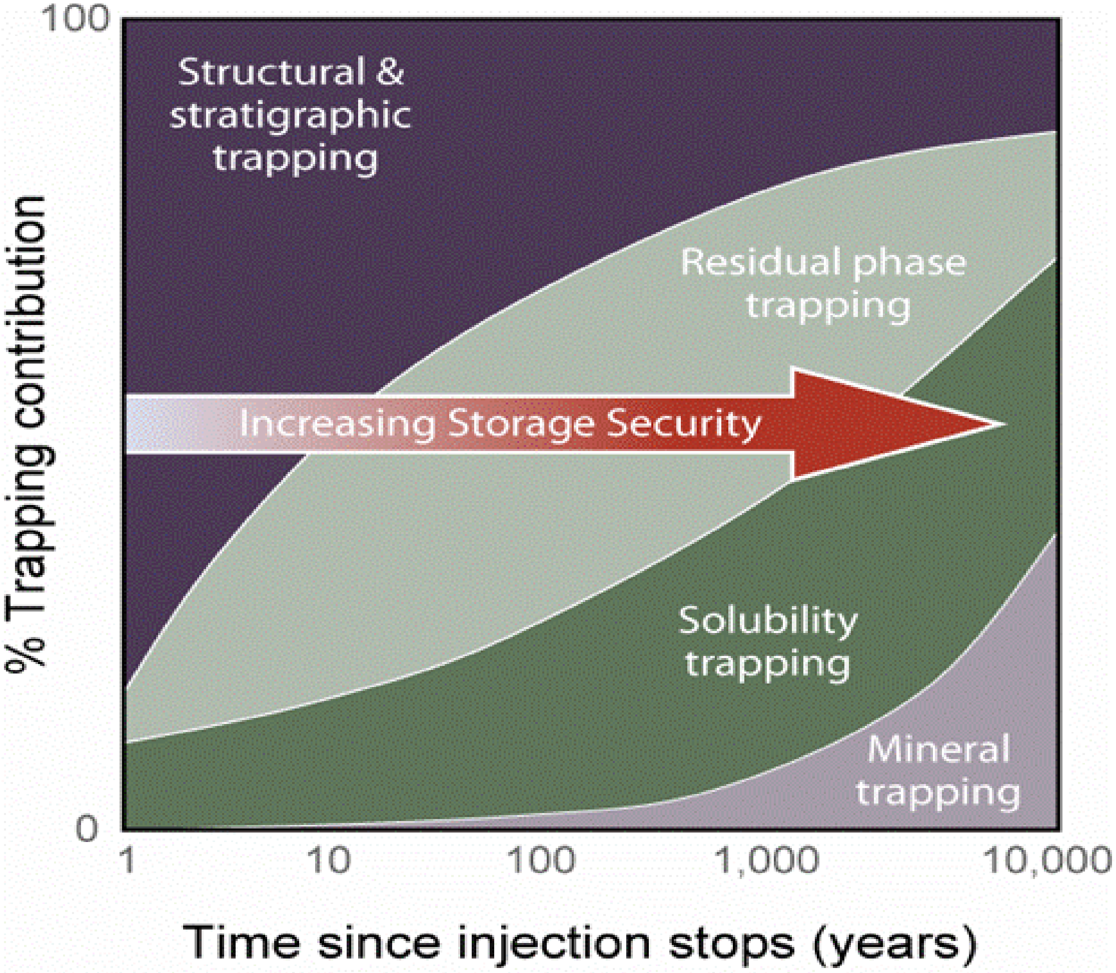
IEA: Energy Technology Perspectives 2008

Geologic Carbon Storage – Mechanisms

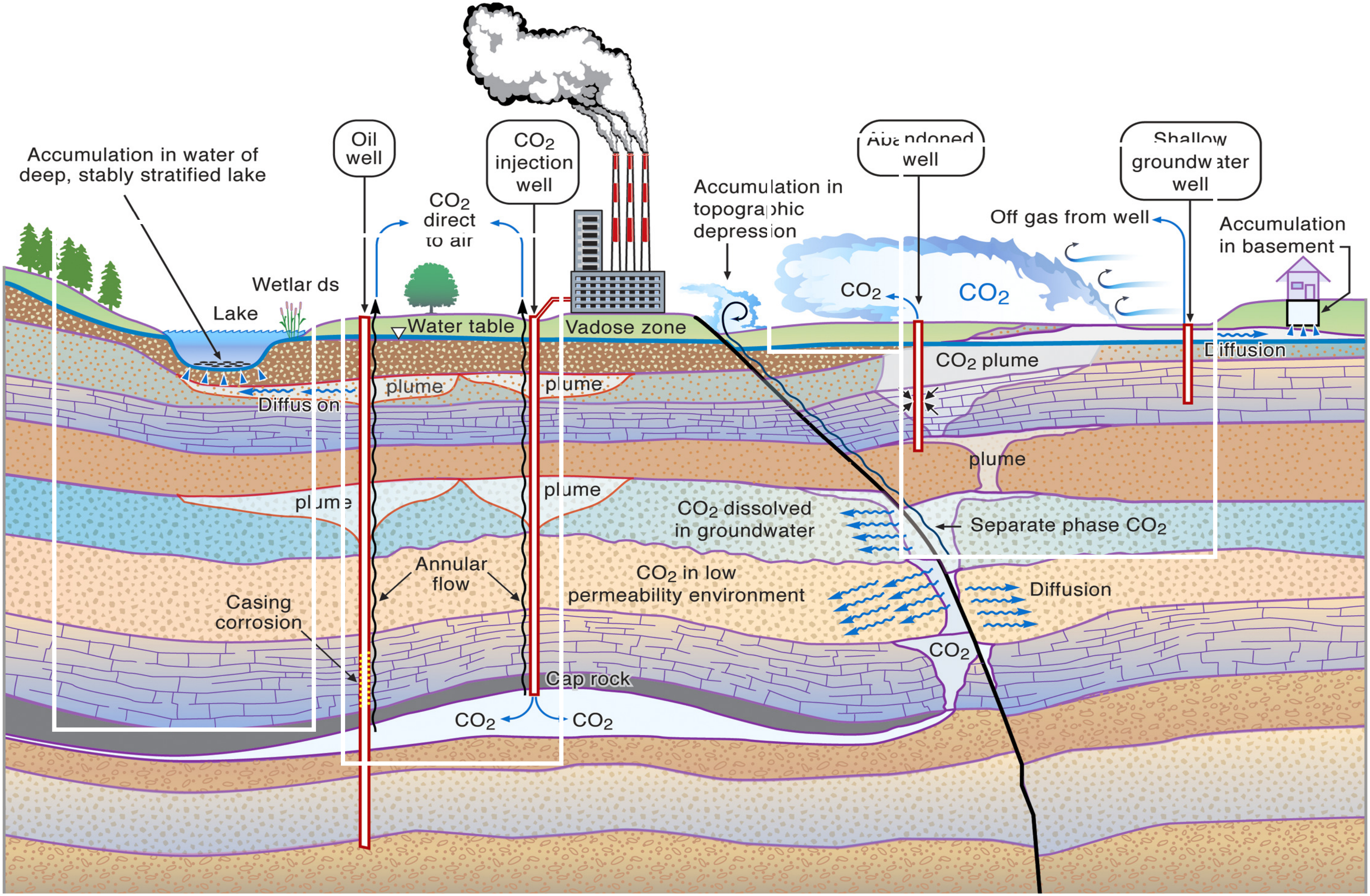
Storage mechanisms vary by target class; generally multiple processes which improve over time



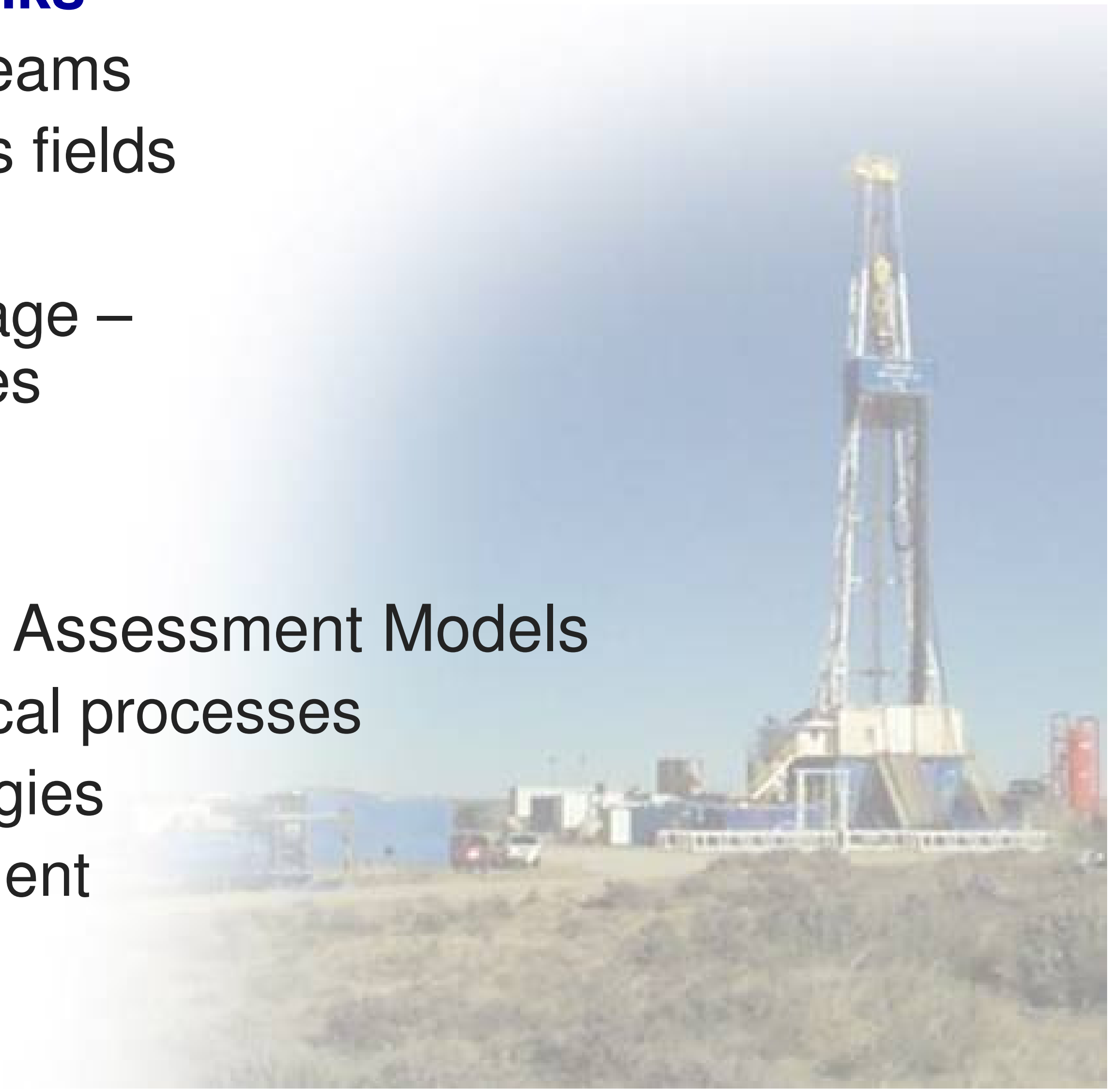
- **Physical trapping**
- **Residual phase trapping**
- **Solution/Mineral Trapping**
- **Gas adsorption**



Long term geological storage in saline aquifers and other potential sites need to be tested.



Geologic Carbon Storage R&D Activities



Geologic Storage Sinks

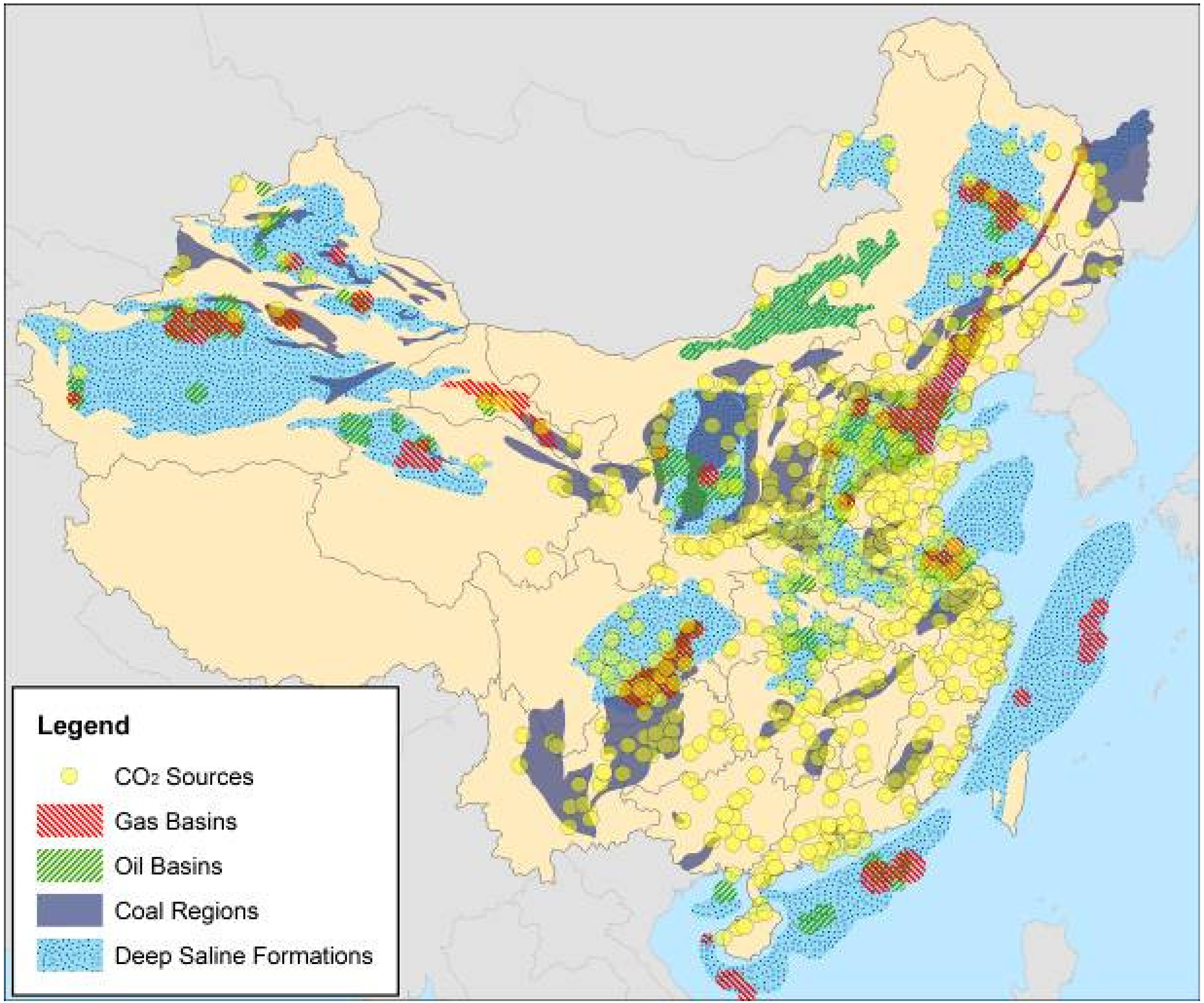
- Un-mineable coal seams
- Depleted oil and gas fields
- Saline formations
- Other potential storage – Basalt and Oil Shales

Research Pathways

- Reservoir and Risk Assessment Models
- Physical and chemical processes
- Monitoring technologies
- Well bore management

China's Large Stationary CO_2 Sources and Candidate Geologic Storage Reservoirs

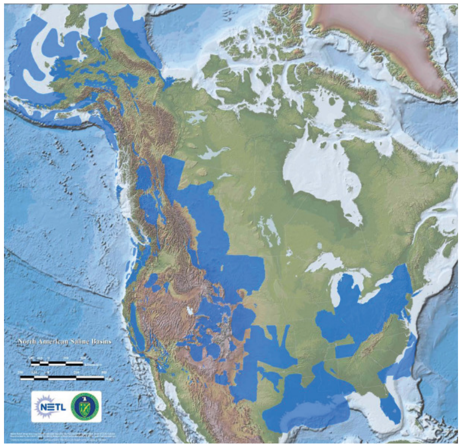
- 1623 large CO_2 point sources with total emissions of more than 3890 $MtCO_2$/yr
- As much as 2300 $GtCO_2$ of onshore storage capacity
    - 2290 $GtCO_2$ in deep saline formations
    - 12 $GtCO_2$ in deep coal seams
    - 4.6 $GtCO_2$ in oil fields
    - 4.3 $GtCO_2$ in gas fields
    - Perhaps 780 $GtCO_2$ more in near offshore basins



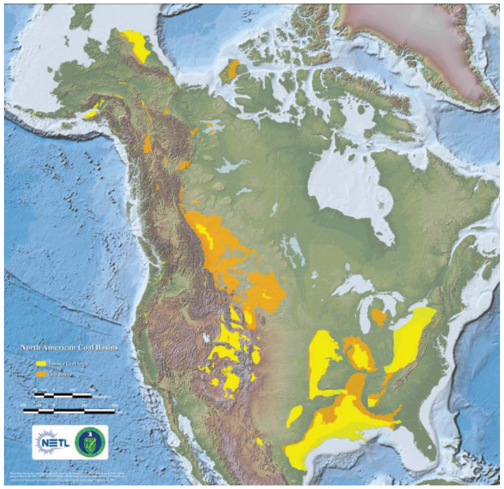
Adequate U.S. Storage Projected

Emissions ~ 3.8 GT CO_2/yr point sources

Oil and Gas Fields



Saline Formations



Unmineable Coal Seams

North American CO_2 Storage Potential (Giga Tons)

Sink Type	Low	High
Saline Formations	**3300**	**12,600**
Unmineable Coal Seams	**160**	**180**
Oil and Gas Fields	**140**	**140**

Conservative Resource Assessment

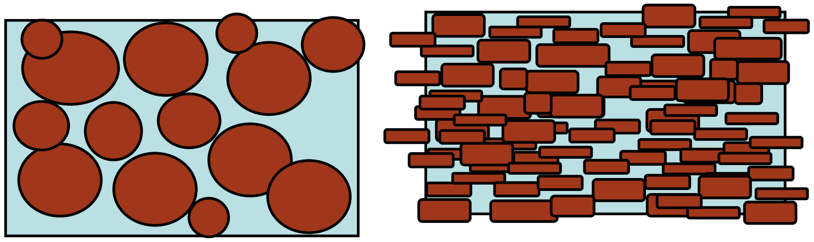
Increases from Atlas I

Hundreds of Years of Storage Potential

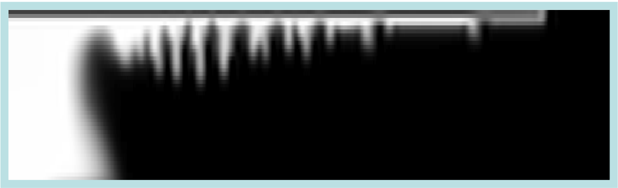
Source: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/atlasII/atlasII.pdf

Storage Security: Trapping Mechanisms

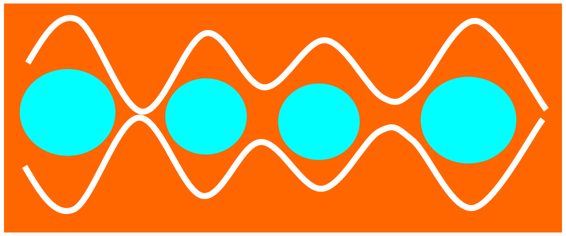
- Structural and stratigraphic trapping
  - Permeability barrier
  - Capillary barrier



- Solubility trapping



- Residual saturation trapping (capillary trapping)

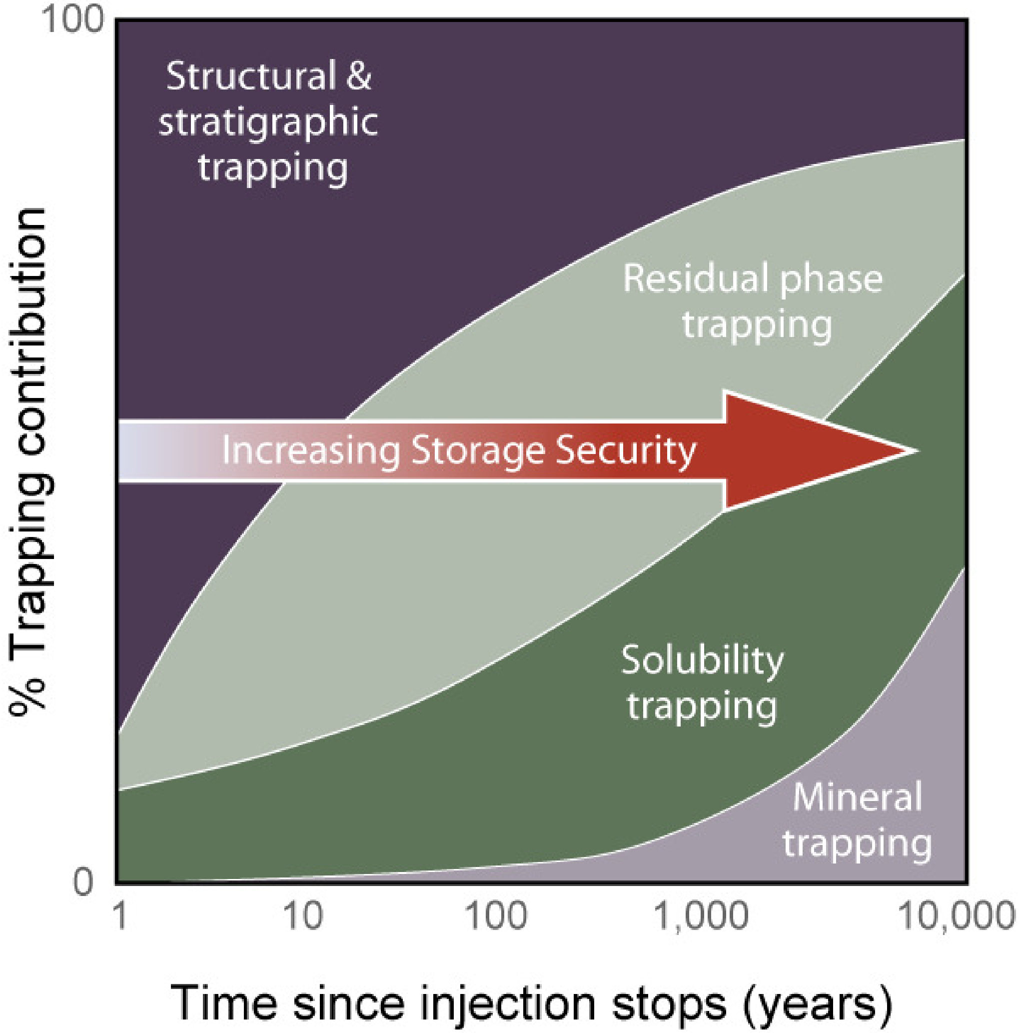


- Mineral trapping

Temporal Evolution of Trapping

6 billion metric tonnes of coal is used each year, producing 18 billion tonnes of CO_2.

At geological storage densities of CO_2, underground sequestration will require a storage volume of 30,000 km^3 per year.



The United States is committed to developing CCS technologies through international collaborations and domestic investments

The Department of Energy is
funding $4 billion in cost share for
CCS projects

Industry is putting up billions more

We can and must begin commercial deployment of CCS in 8 – 10 years

President Obama’s economic Recovery Act included $3.4 billion for CCS

- $800 million for the Clean Coal Power Initiative

- $1.5 billion for a range of industrial carbon capture and energy efficiency improvement projects

- $1.0 billion for fossil energy research and development programs (FutureGen)

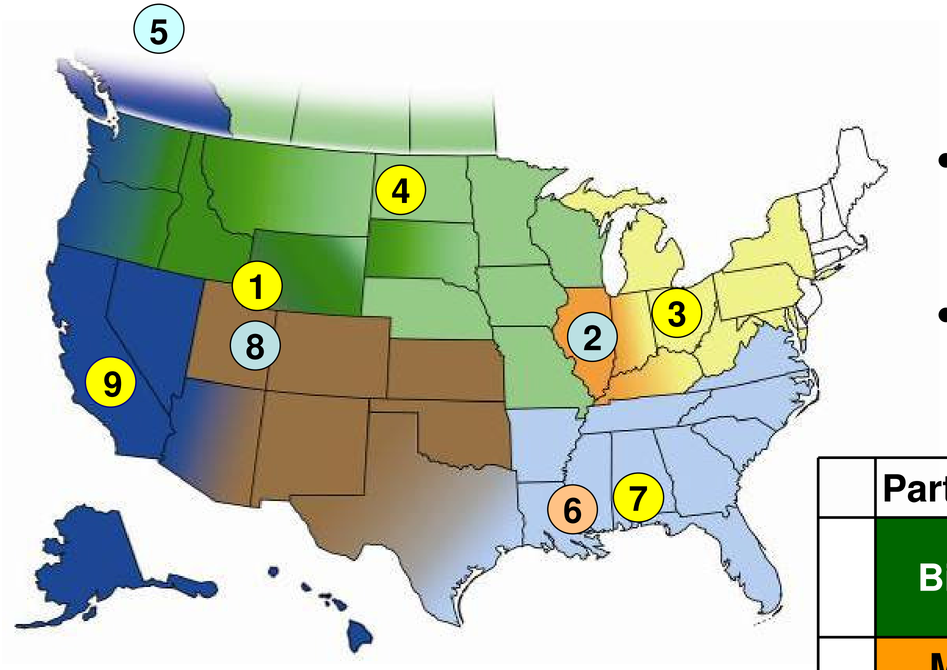
- $50 million for site characterization of geologic formations

- $20 million for geologic CO2 sequestration training and research grants

Additional U.S. investments in CCS R&D

- **In 2010, we are investing over $400 M in CCS-Clean Coal R&D aimed at:**
  - **cost and energy penalty reductions**
  - **to develop the science measurement and verification technology to enable safe, long-term effective geologic storage.**
- **We are investing more than $500M over 10 years in research and modeling of geologic CO2 storage**

U.S. testing storage in 9 geologic formations



- *Nine large-volume tests*
- *Injections initiated 2009 – 2011*

● 2009 Injection Scheduled
● 2010 Injection Scheduled
● 2011 Injection Scheduled

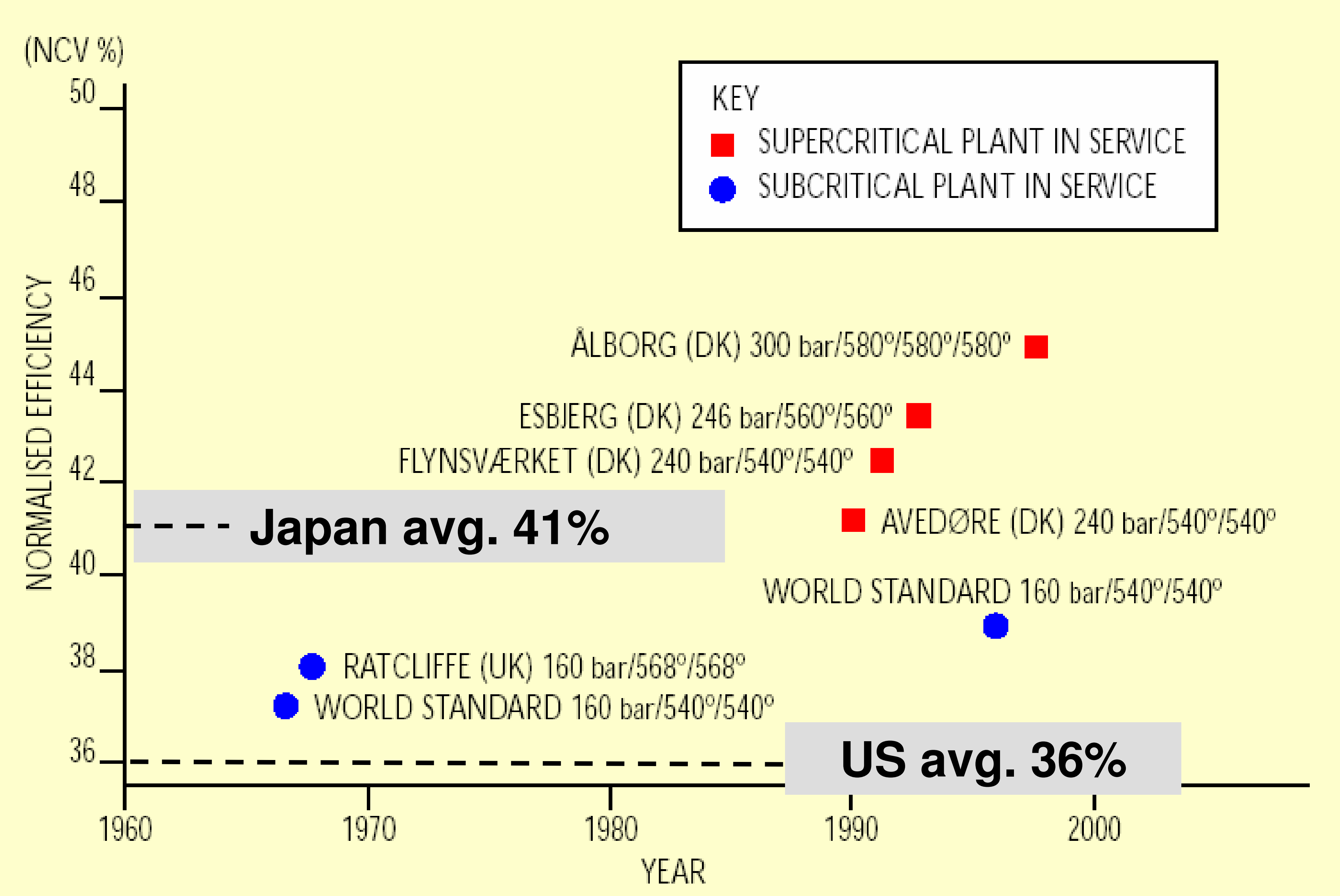
	Partnership	Geologic Province	Type
	Big Sky	Triassic Nugget Sandstone / Moxa Arch	Saline
	MGSC	Deep Mt. Simon Sandstone	Saline
	MRCSP	Shallow Mt. Simon Sandstone	Saline
	PCOR	Williston Basin Carbonates	Oil Bearing
		Devonian Age Carbonate Rock	Saline
	SECARB	Lower Tuscaloosa Formation Massive Sand Unit	Saline
	SWP	Regional Jurassic & Older Formations	Saline
	WESTCARB	Central Valley	Saline

The Efficiency of Coal Burning Plants

- Higher efficiencies may be possible with Supercritical Steam boilers, but new temperature resistant metals are needed for higher steam temperatures.
- Oxygen-burn boilers and at-the-stack retro-fit capable less expensive CO_2 capture.
- IGCC can be 60% efficient

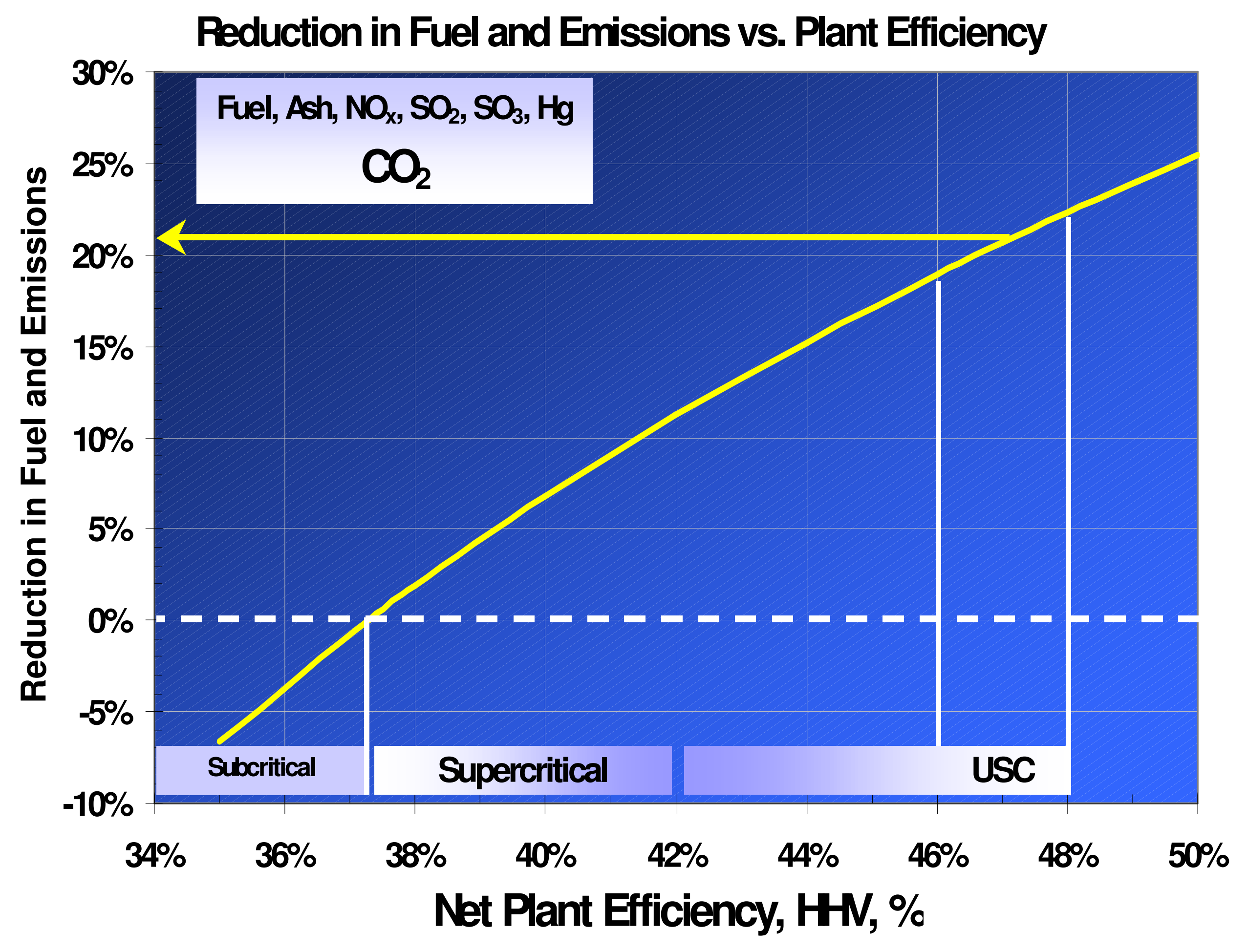
Combined heat and power and other uses of waste heat.

Coal Plant efficiencies



“Advanced” Ultra Supercritical Power Plant

Operating up to 5,000 psi and 1,400 °F



DOE USC plant of 47% efficiency results in 22% reduction in CO_2 compared to subcritical plant of 37% efficiency

Lower capital and O&M cost due to reduced emission control and ash disposal equipment

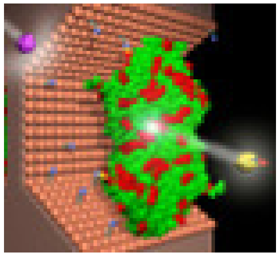
CO_2 capture ready with oxy-firing

Office of Fossil Energy

Post-combustion Carbon Capture

Oxycombustion

Model, develop and optimize coal oxycombustion technologies for new and existing PC power plant applications

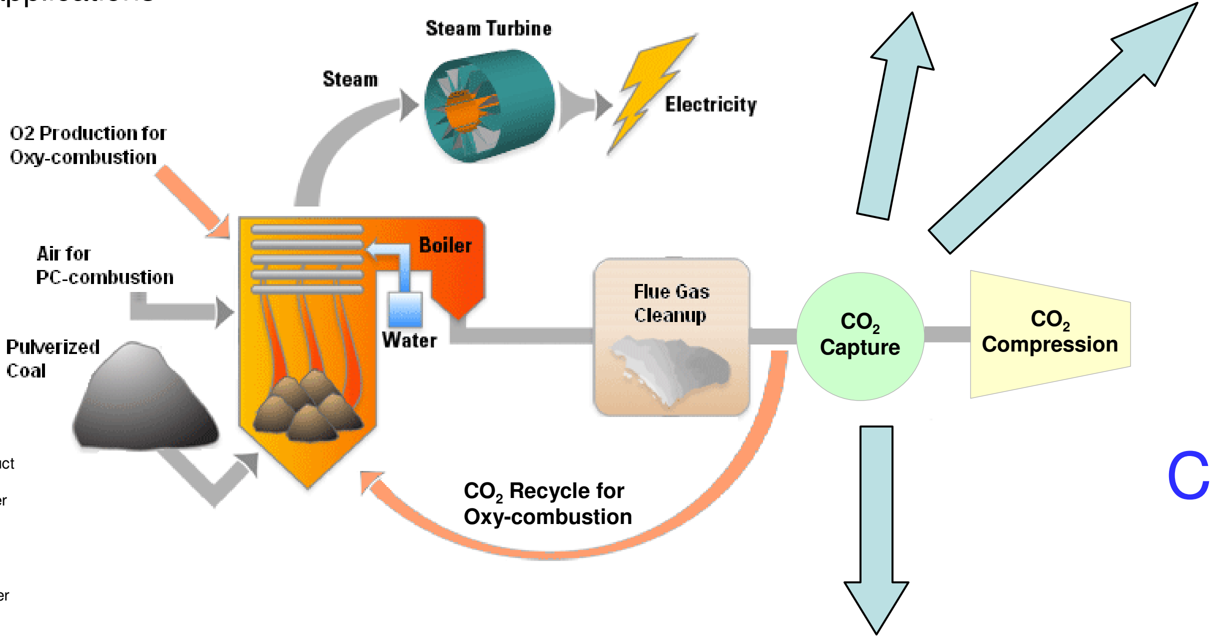


Solvents

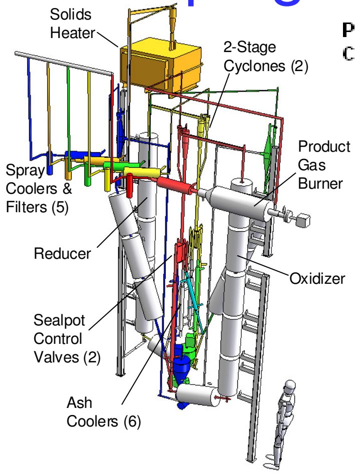
Synthesize and demonstrate physical and chemical CO2 capture solvents for flue gas

Sorbents

Synthesize and bench-test various CO2 capture sorbents for flue gas applications



Chemical Looping

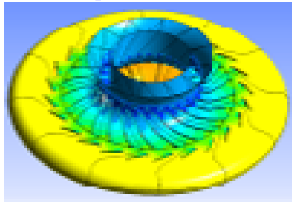


Design, build, test and optimize novel chemical looping processes with inherent CO_2 capture

Membranes

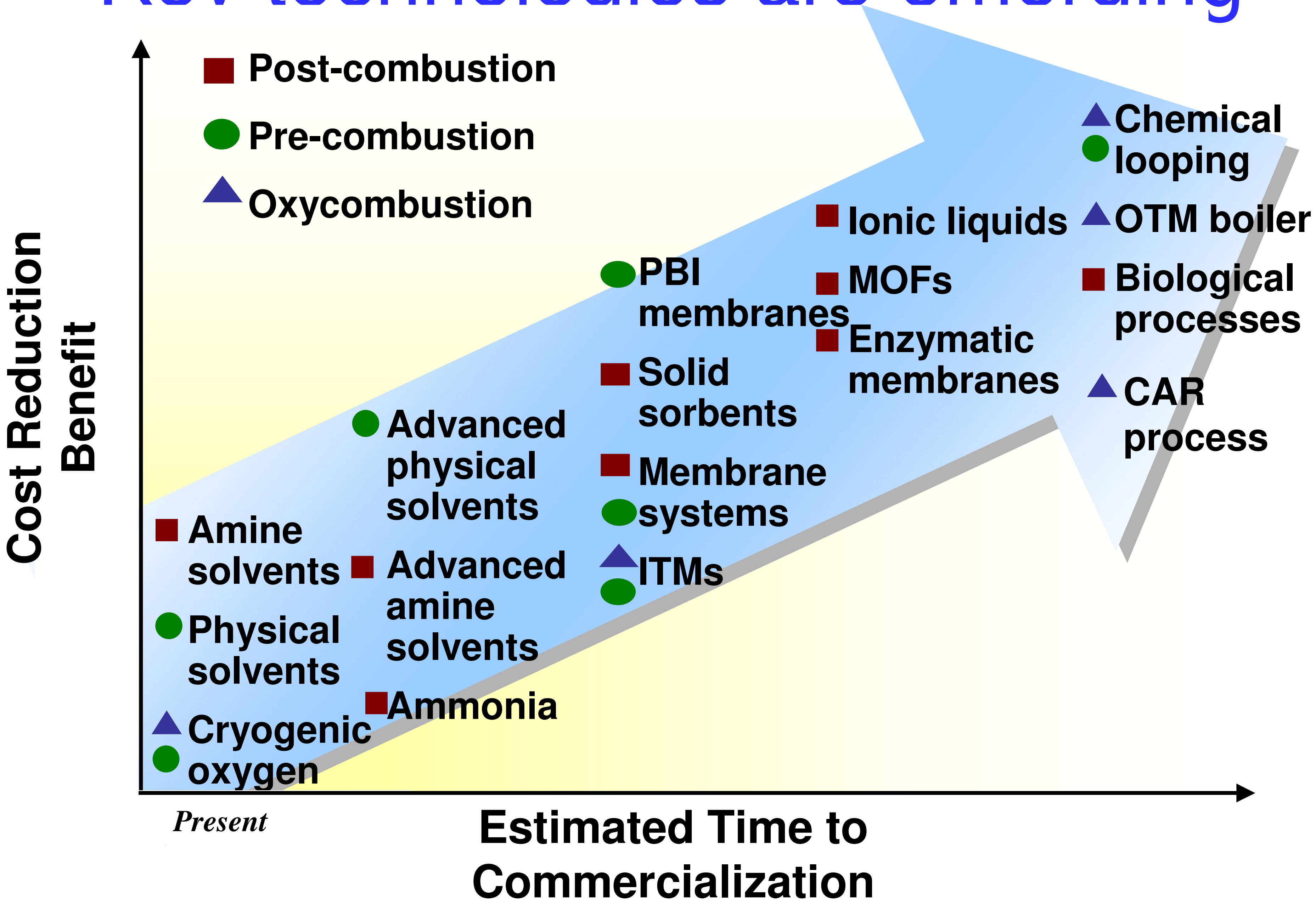
Develop durable, high performing CO2 selective membranes for flue gas applications

Compression



Develop novel systems to significantly reduce the energy needed to compress CO_2

Key technologies are emerging



■ Post-combustion

● Pre-combustion

▲ Oxycombustion

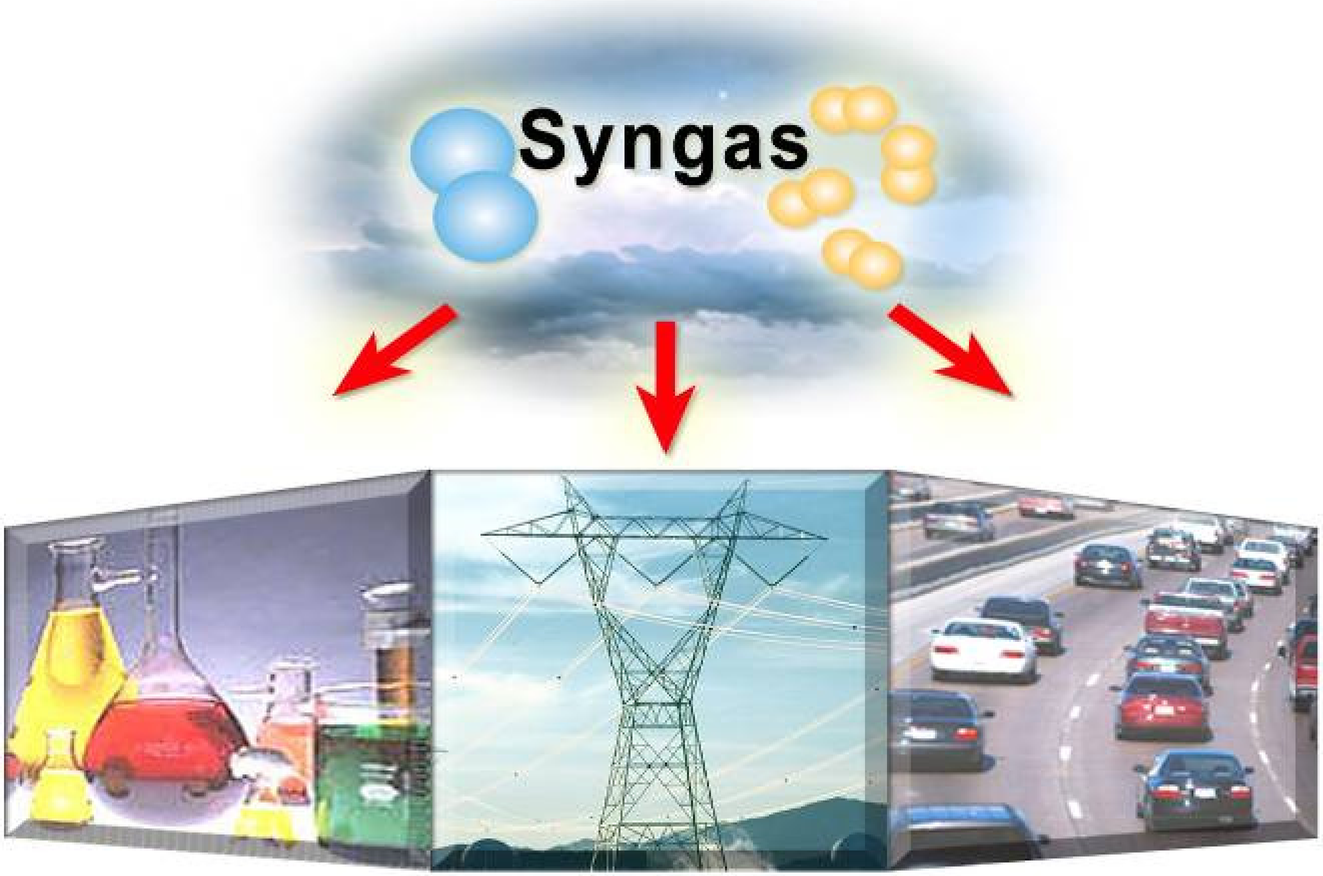
- ■ Amine solvents
- ● Physical solvents
- ▲ ● Cryogenic oxygen
- ● Advanced physical solvents
- ■ Advanced amine solvents
- ■ Ammonia
- ● PBI membranes
- ■ Solid sorbents
- ■ ● Membrane systems
- ▲ ● ITMs
- ■ Ionic liquids
- ■ MOFs
- ■ Enzymatic membranes
- ▲ ● Chemical looping
- ▲ OTM boiler
- ■ Biological processes
- ▲ CAR process

Cost Reduction Benefit

Present

Estimated Time to Commercialization

Polygeneration from CO and H_2



Building Blocks for Chemical Industry

Clean Electricity

Transportation Fuels (Hydrogen)

CO_2 sequestration research is urgently needed

1. We are pursuing both pre and post-combustion CO_2 capture
2. Our goal is to have commercial deployment of CCS begin in 8 – 10 years.
3. We desperately need a commercially viable “after-stack” technology. The human body provides a good proof-of-principle of post combustion CO_2 capture.

Biological Processes
Advanced CO_2 Enzymes

Carbonic anhydrase (CA):

- **Enzyme catalyzes the rapid conversion of CO_2 to bicarbonate**
- **Most efficient, lowest energy catalyst**

  Increases CO_2/HCO_3 reaction rates between 10^4 to 10^6 reactions per second!

  Consumes 30 – 50% less energy than competing chemical scrubbing technology
- **Environmentally safe, chemically stable**
- **Provides H_2O capture and recycle**

$CO_2 + H_2O \rightarrow HCO_3^- + H^+$ (“high” pressure)

Carbonic anhydrase

$CO_2 + H_2O \leftarrow HCO_3^- + H^+$ (“low” pressure)

We are strongly pursuing international collaborations

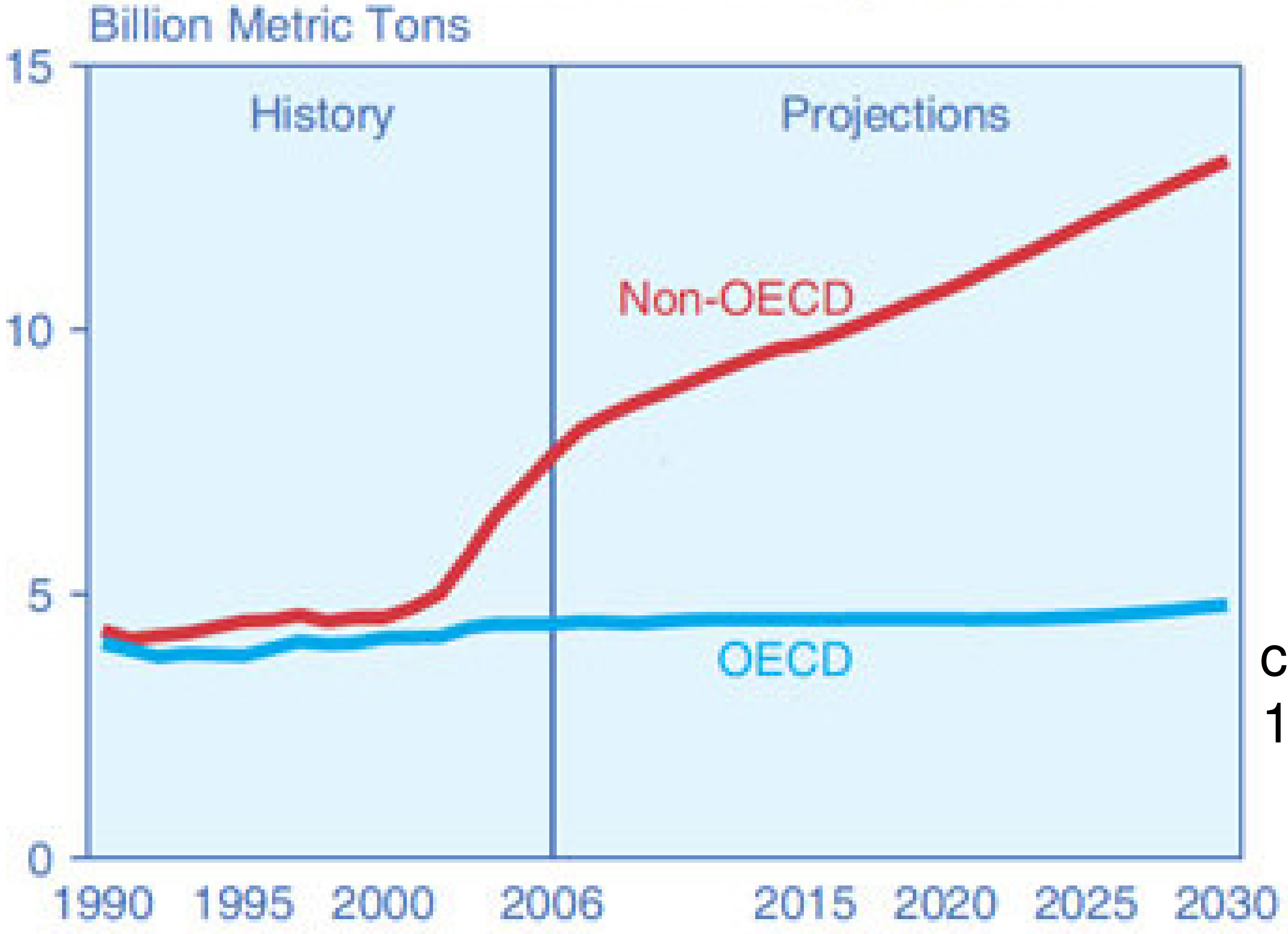
carbon
sequestration leadership forum

G-8 leaders have called for at least 20 CCS projects by 2010

In July, we announced a U.S. – China Clean Energy Research Center

The CSLF is vital for promoting CCS globally

We need to share solutions with developing countries

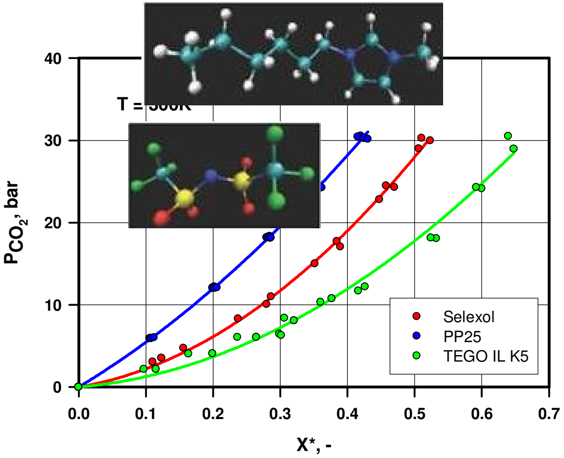


Projected world carbon dioxide emissions from coal combustion, 1990 - 2030

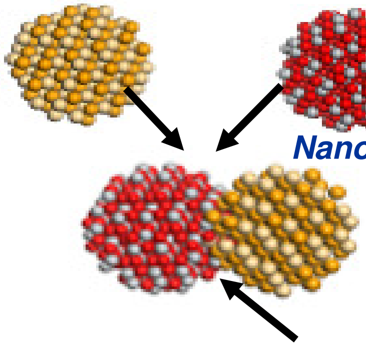
Sources: History: EIA International Energy Annual 2006; Projections:
EIA, World Energy Projections Plus (2009)

Pre-combustion Carbon Capture

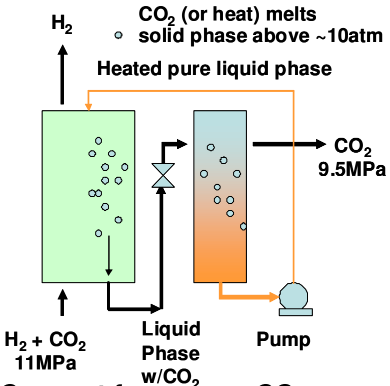
- **Ionic Liquids – tailored CO_2 solvents**
  - Molecular Dynamics Simulation of Transport and Thermodynamic Properties
  - Computationally-guided Screening of CO_2 Sorption Capacity and Kinetic Parameters
  - Development of Membrane Fiber Support
- **Solids CO_2 sorbents for syngas**
  - With water-gas-shift for enhanced H_2 production
  - Reactor configuration/studies in progress
  - New phase-change polymers (solid → liquid)
- **Novel concepts**
  - Re-use opportunities, e.g. photocatalytic reduction



Ionic liquid CO_2 capacity (green) versus other solvents (blue/red)

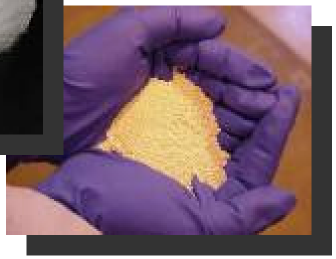


CO_2 photo-reduction occurs here. Demonstrated in NETL labs.



Concept for syngas CO_2 Capture w/phase change polymer

CO_2 membrane disk test and fiber bundle



Syngas CO_2 sorbent and test reactor

CO_2 Membranes

Advantages

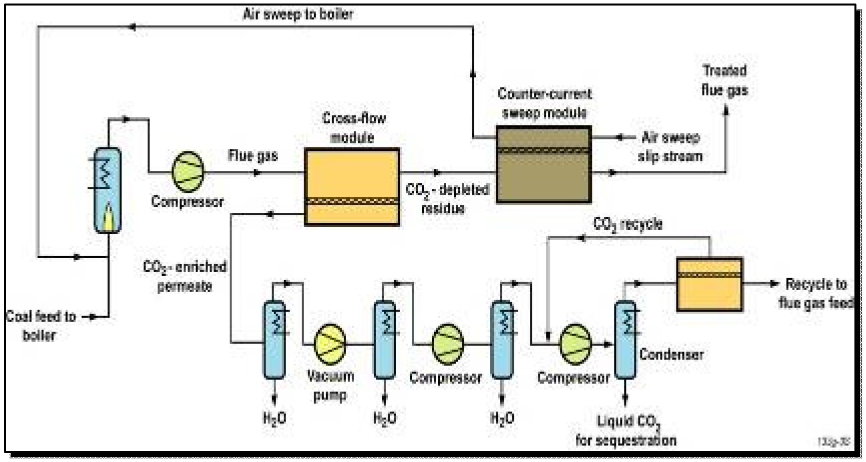
- Simple operation; no chemical reactions, no moving parts
- Tolerance to high levels of wet acid gases
- Compact and modular with small footprint
- Relatively low energy use; no additional water used (recovers water from flue gas)

R&D Focus

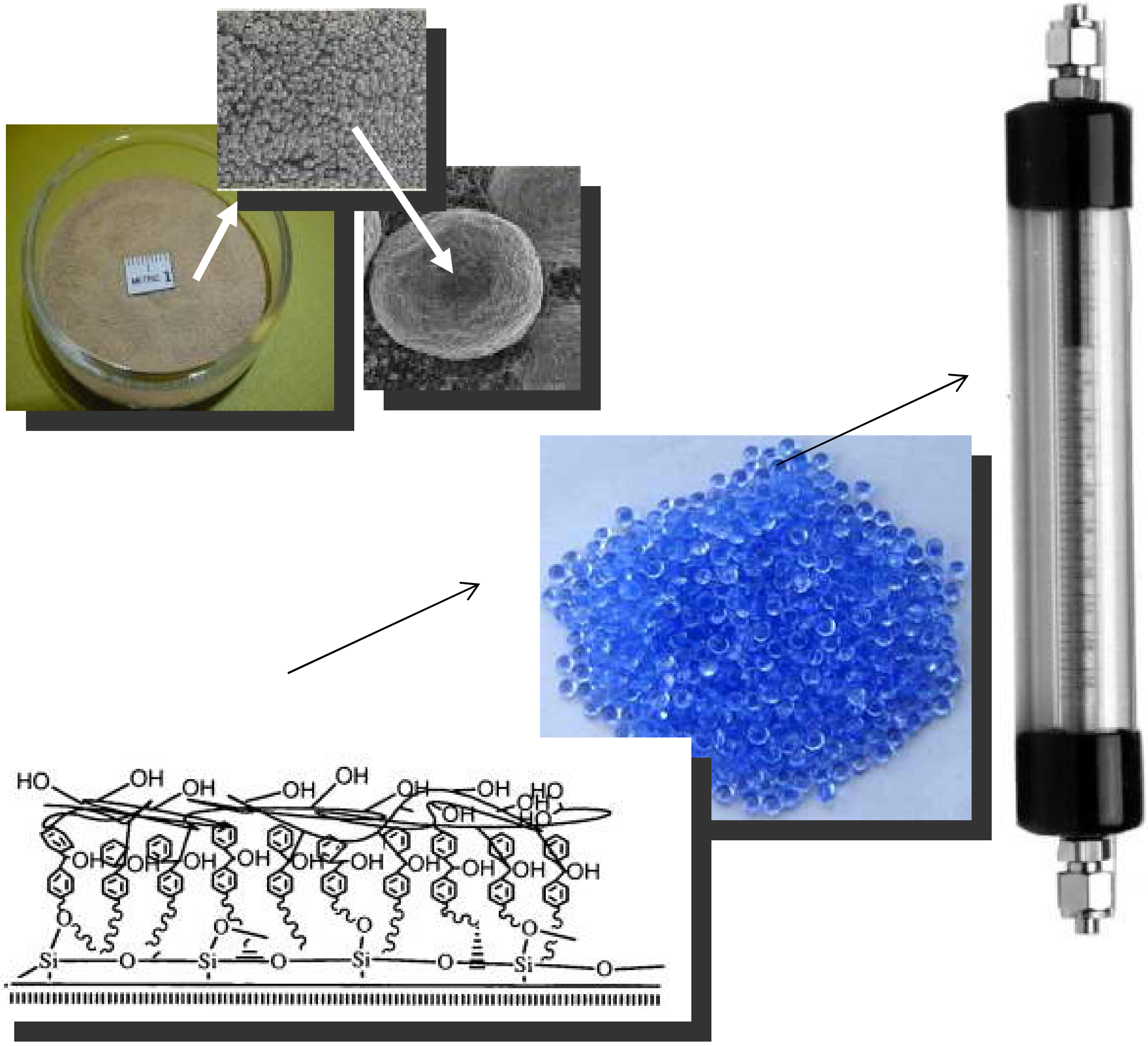
- High CO_2/N_2 selectivity & permeability
- Durability
  - Chemically (SO_2), thermally
  - Physically
- Membrane systems
  - Process design critical
- Low cost
  - Capital and energy penalty

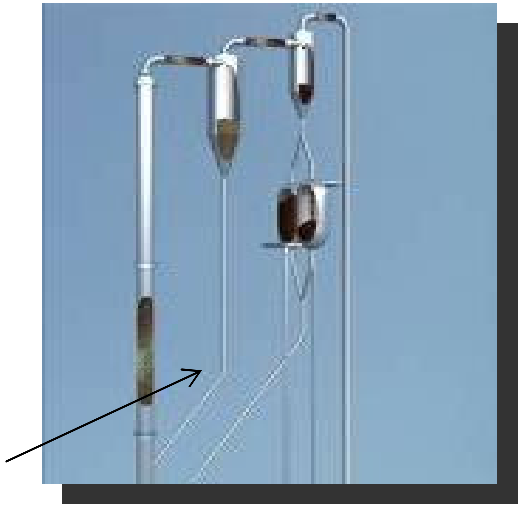
Challenges

- Low flue gas CO_2 partial pressure
- Particulate matter and potential impact on membrane life
- Cost reduction and device scale-up
- Power plant integration (e.g. sweep gas)

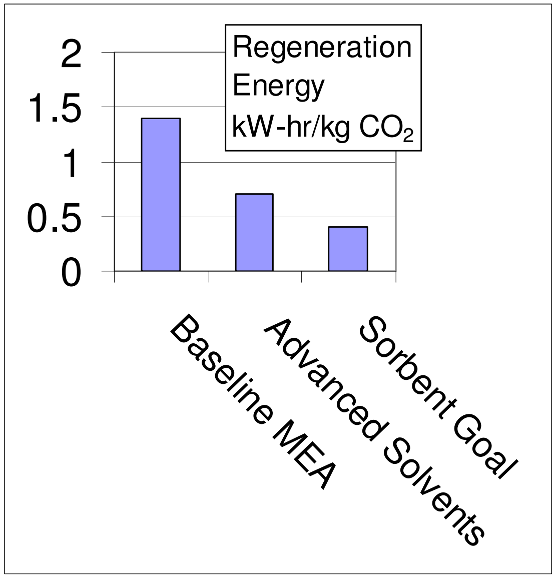


Dry CO_2 Sorbents

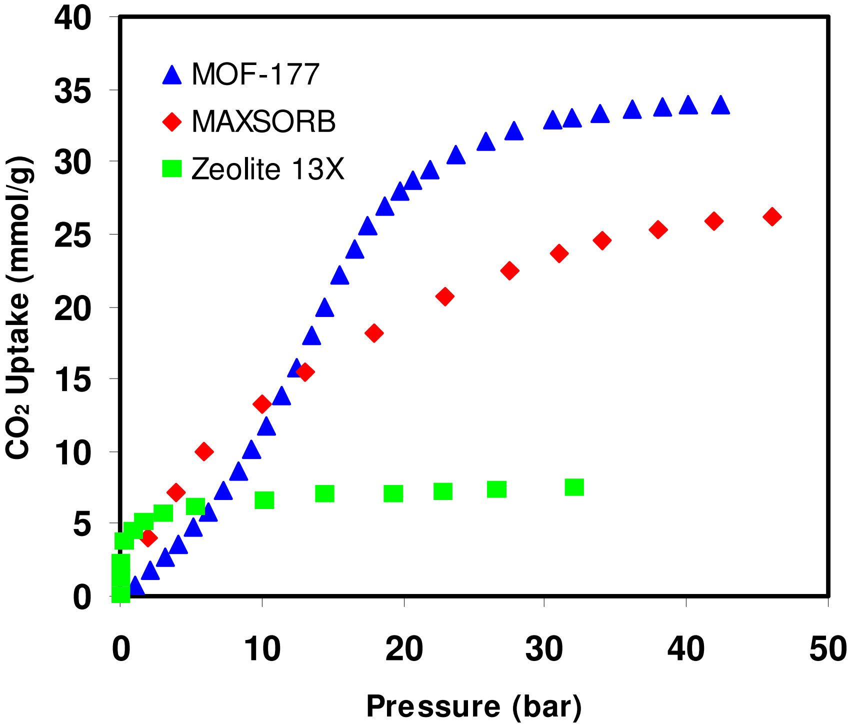




Numeric simulation of reactor concept for solid sorbents



Metal Organic Frameworks for CO_2 Capture

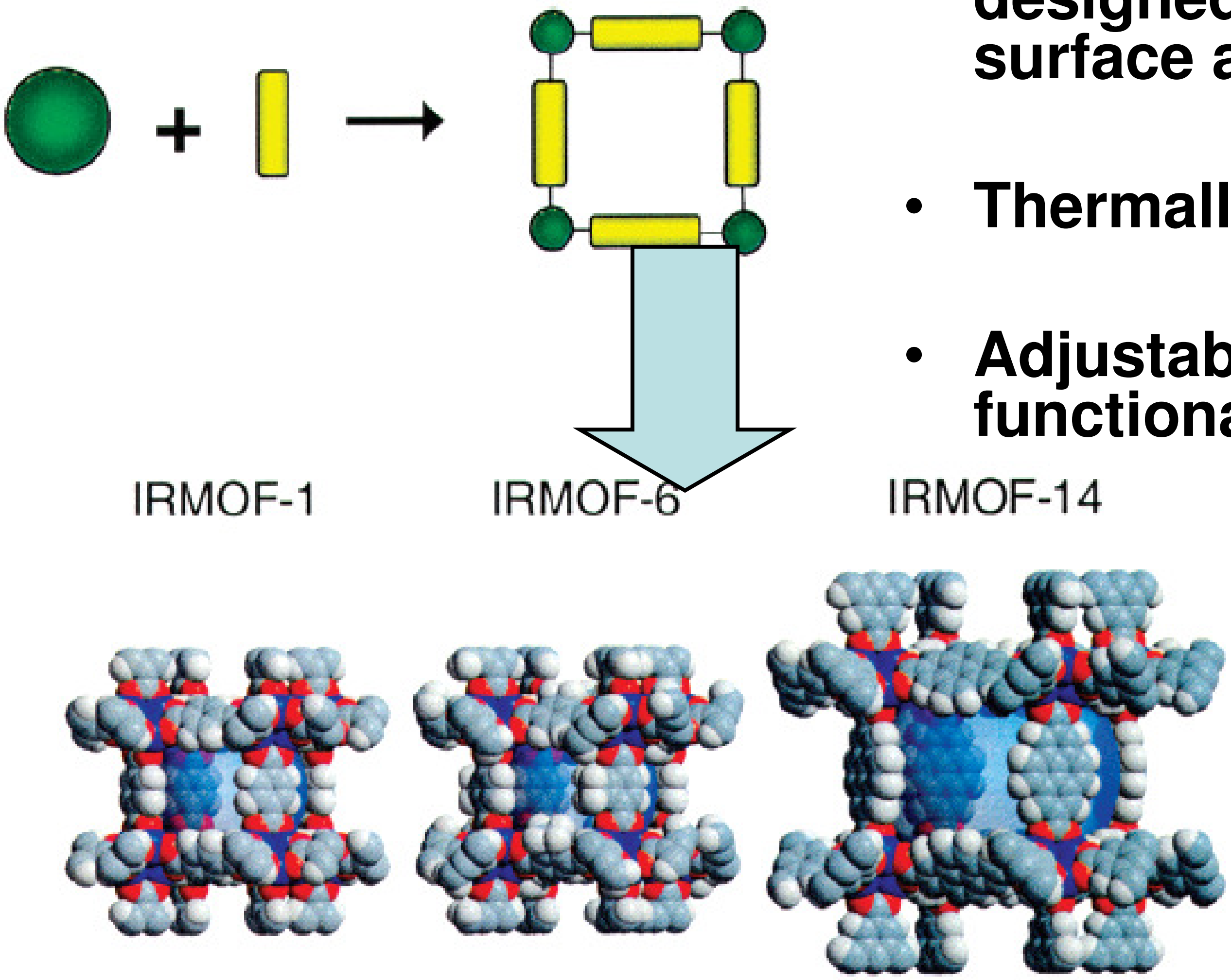


BASF, scaled-up IRMOF-1

- **Current Research Project:**
  - Development of optimum MOFs for flue gas capture
  - Evaluation of contaminant issues

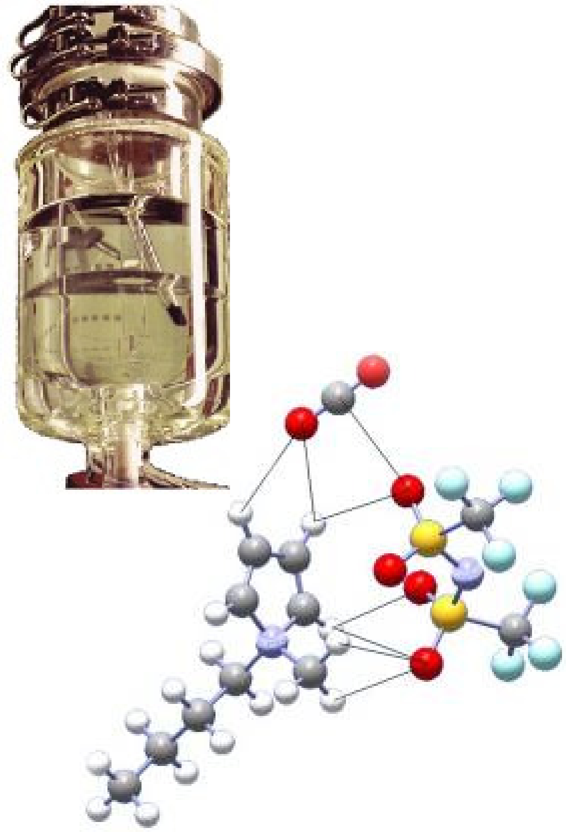
Metal Organic Frameworks for CO_2 Capture

- **Highly porous - structure designed to maximize surface area**
- **Thermally stable**
- **Adjustable chemical functionality**

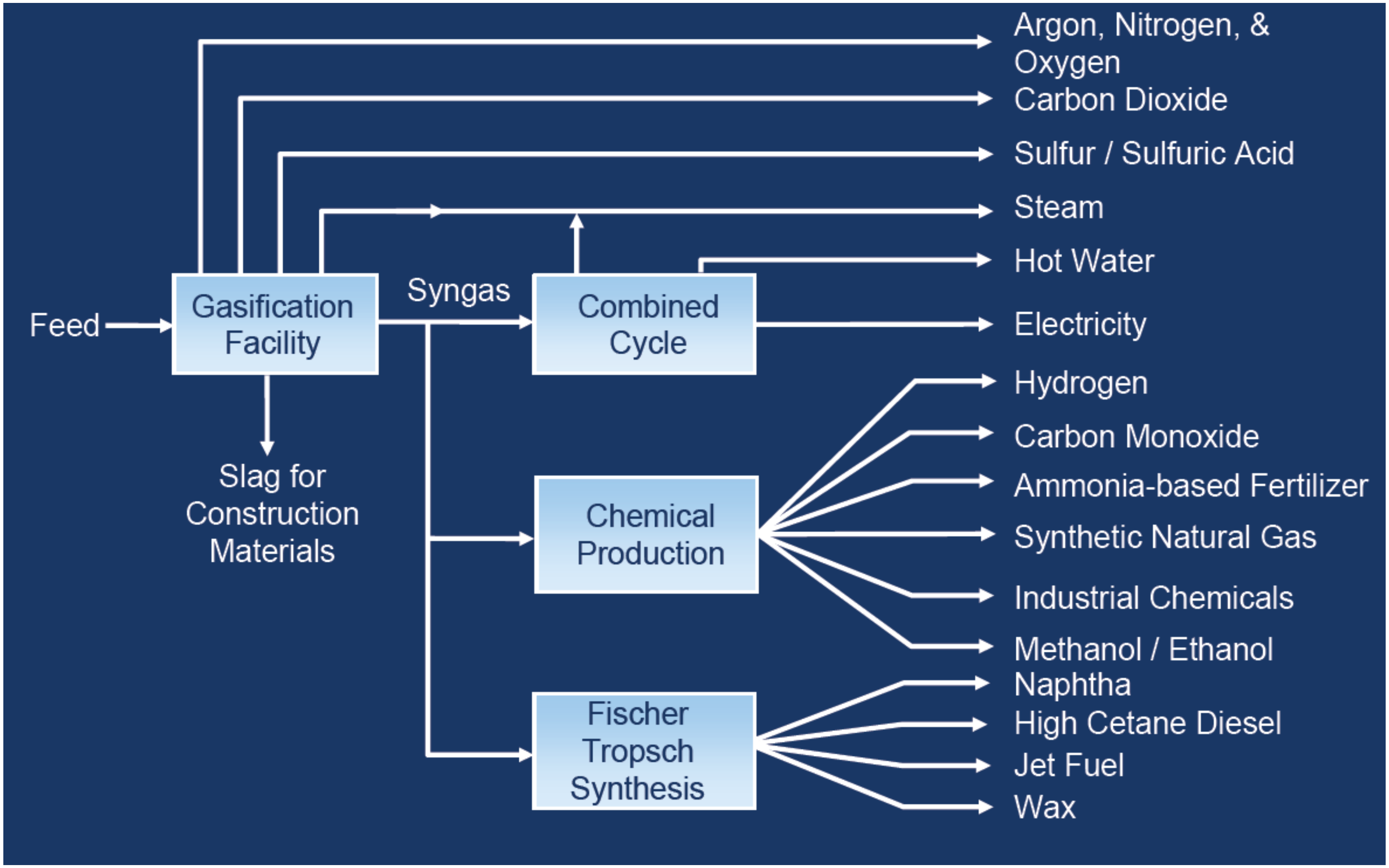


Ionic Liquids as Novel Absorbents

- **Ionic liquids (ILs): salts that are liquid at room temperature**
  - Do not evaporate
  - Can absorb large amounts of CO_2
- **Success at Basic Research Stage**
  - Significant improvement in CO_2 solubility and selectivity
  - May allow for capture of both SO_2 and CO_2
- **Future Work**
  - Selection of optimal ILs and scale-up for testing with actual flue gas compositions
  - Supported liquid membranes



Gasification – Polygeneration Products



Feed

Gasification Facility

Slag for Construction Materials

Syngas

Combined Cycle

Chemical Production

Fischer Tropsch Synthesis

Argon, Nitrogen, & Oxygen

Carbon Dioxide

Sulfur / Sulfuric Acid

Steam

Hot Water

Electricity

Hydrogen

Carbon Monoxide

Ammonia-based Fertilizer

Synthetic Natural Gas

Industrial Chemicals

Methanol / Ethanol

Naphtha

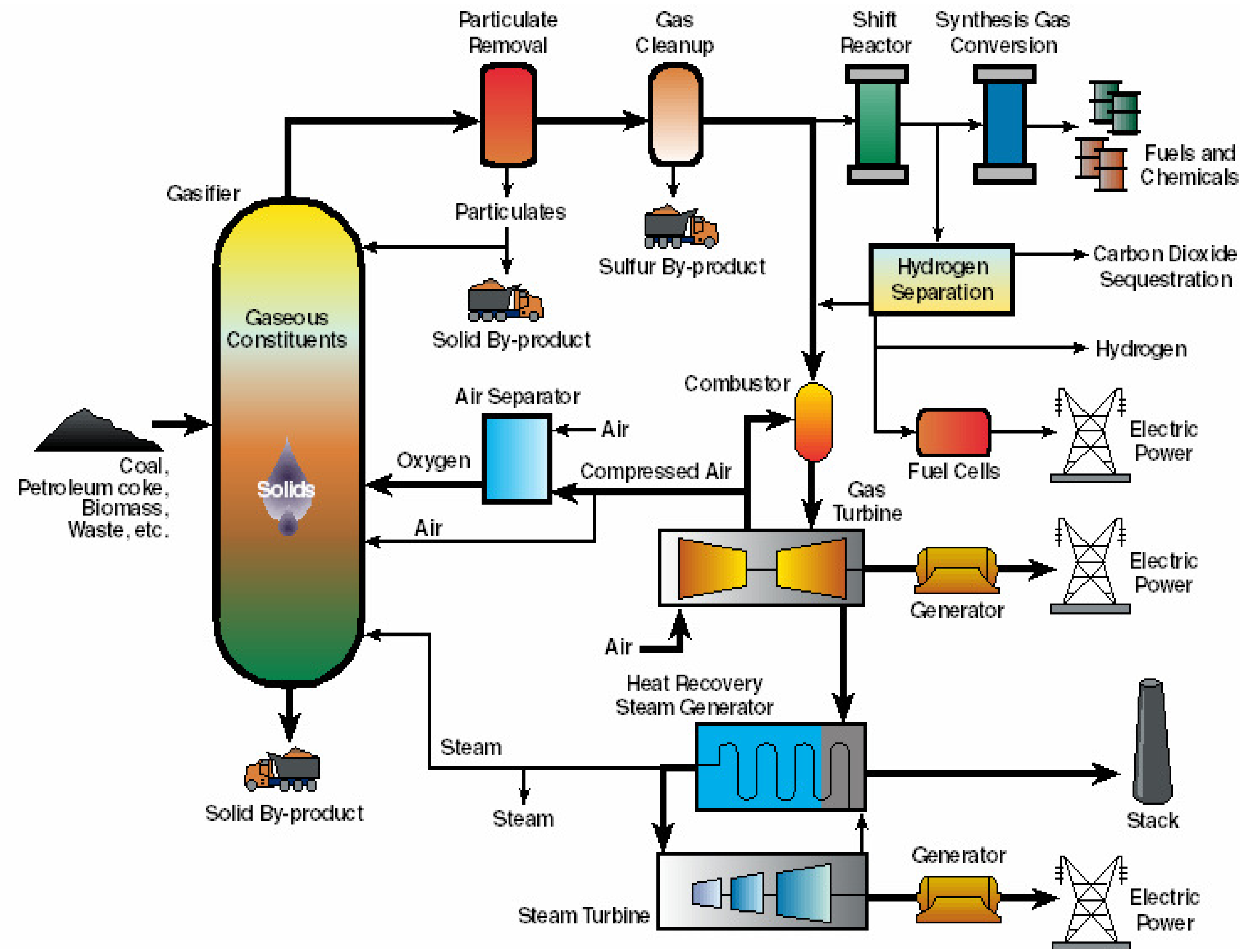
High Cetane Diesel

Jet Fuel

Wax

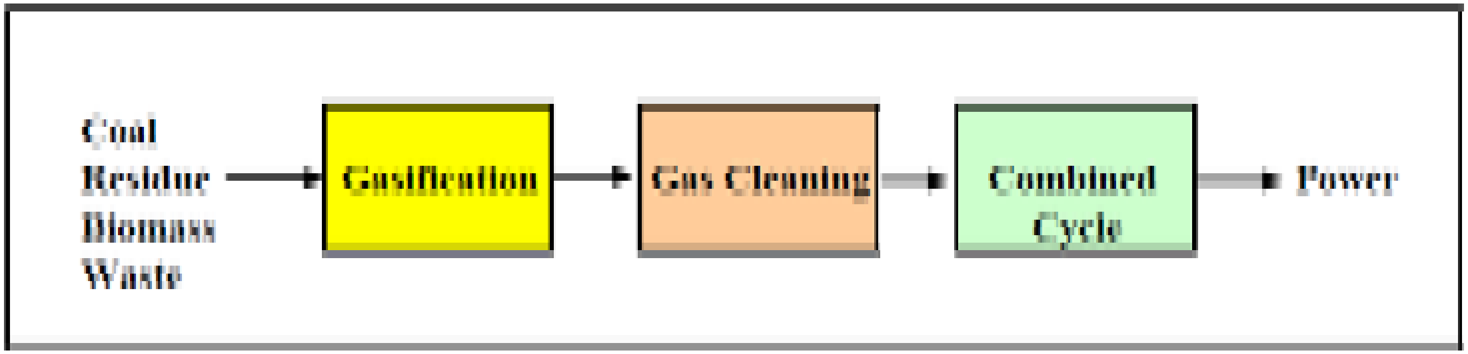
Source: FLUOR®

Gasification: Polygeneration Capability

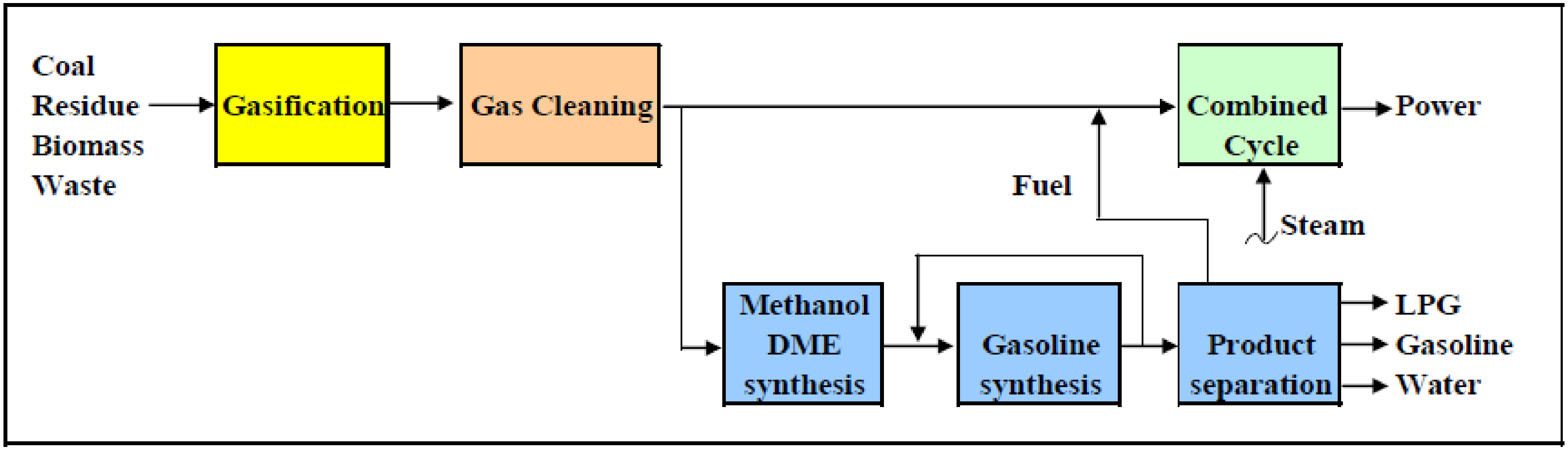


Poly-generation of Power and Chemicals may justify higher IGCC investments

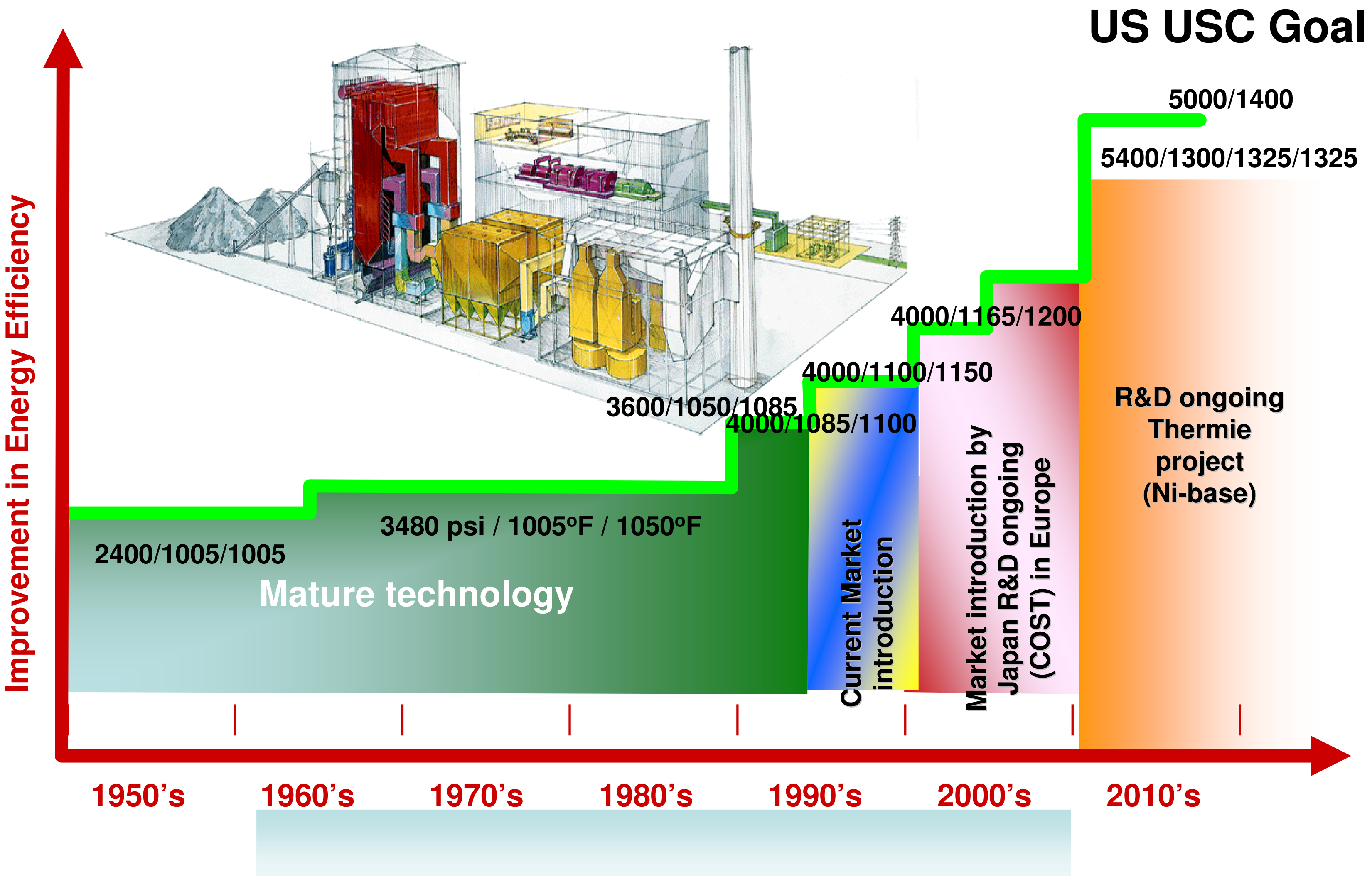
IGCC power plant


Coal
Residue
Biomass
Waste
Gasification
Gas Cleaning
Combined Cycle
Power

Integration of IGCC with chemical synthesis

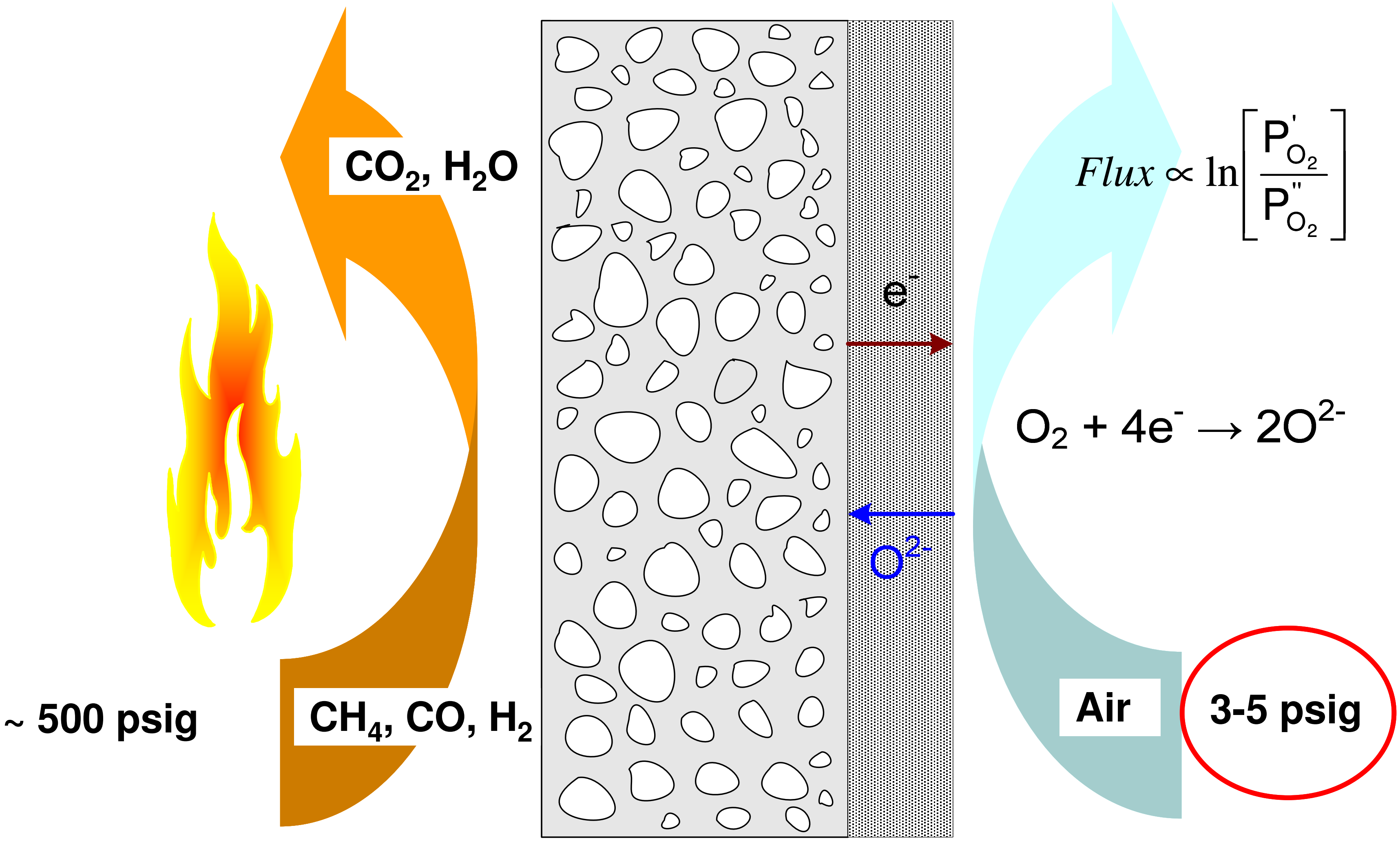

Coal
Residue
Biomass
Waste
Gasification
Gas Cleaning
Combined Cycle
Power
Fuel
Steam
Methanol DME synthesis
Gasoline synthesis
Product separation
LPG
Gasoline
Water

Cost-effective materials are key: Revolutionary progress in materials has made it possible to go to very high temperatures



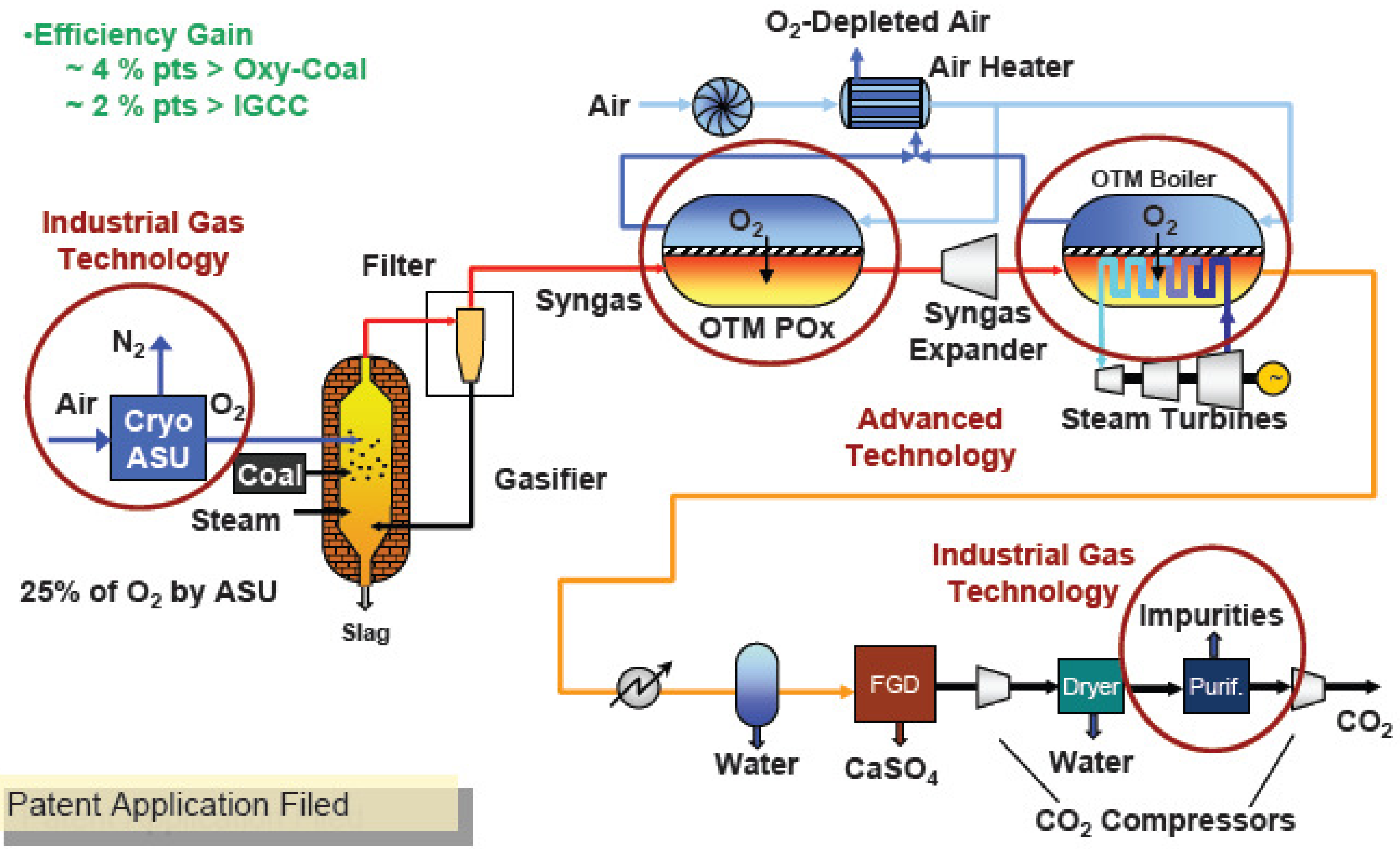
Illustration/data: Alstom

OTM Based Oxy-combustion for CO_2 Capture from Coal Power Plants



OTM Based Oxy-combustion for CO_2 Capture from Coal Power Plants

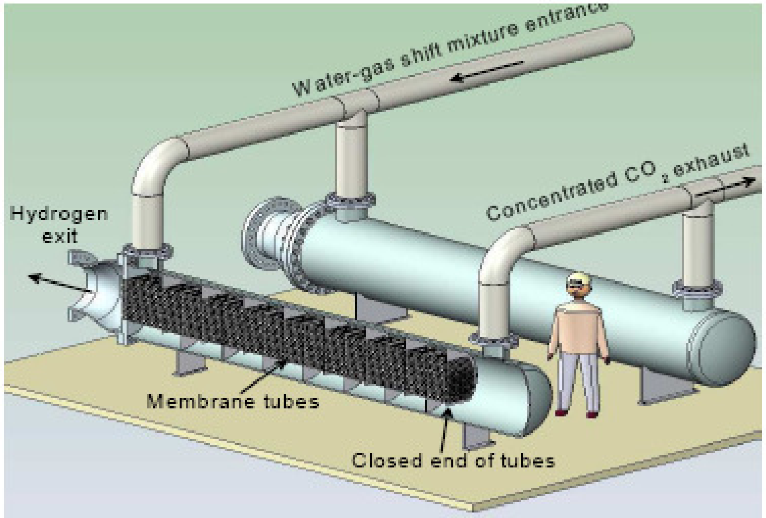
- Efficiency Gain
  - ~ 4 % pts > Oxy-Coal
  - ~ 2 % pts > IGCC



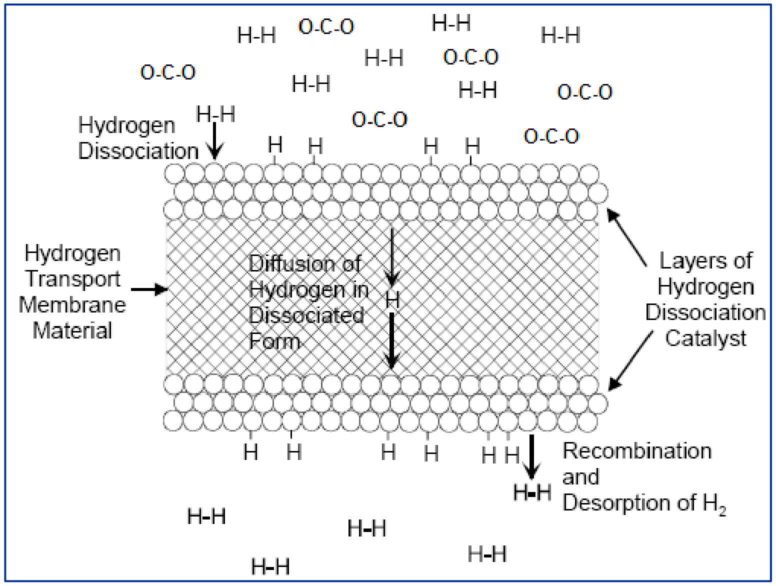
Patent Application Filed

Hydrogen Membranes

- Allows capture of high pressure CO_2
- High hydrogen permeate pressure
- High hydrogen recoveries -– >90%
- Essentially 100% pure hydrogen
- Low cost
- Long membrane life
- Target: 4 tpd module in 2013 / 2014



Conceptual design of a commercial membrane unit capable of separating 25 tons per day of hydrogen.



Status

- Current testingat 1.5 lb/d
- Scale-up to 12 lb/d – 2010
- -Scale-up to 220 lb/day - 2011

Eltron Research & Development Tech Brief http://www.eltronresearch.com/docs/Hydrogen_Membrane_Technology_Summary.pdf

Ion Transport Membrane Air Separation

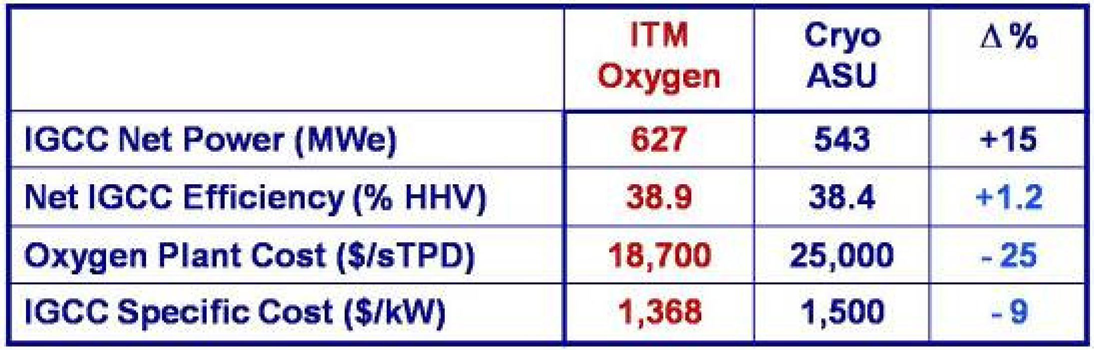
Low cost oxygen: a key technology for CCS

Air Products & Chemicals
Ion Transport Membrane
"ITM Oxygen"

0.5 TPD Modules

5 TPD Subscale Engineering Prototype (SEP) ITM Test unit at APCI's Sparrows Point gas plant

(ITM capacity: 4,550 sTPD oxygen)



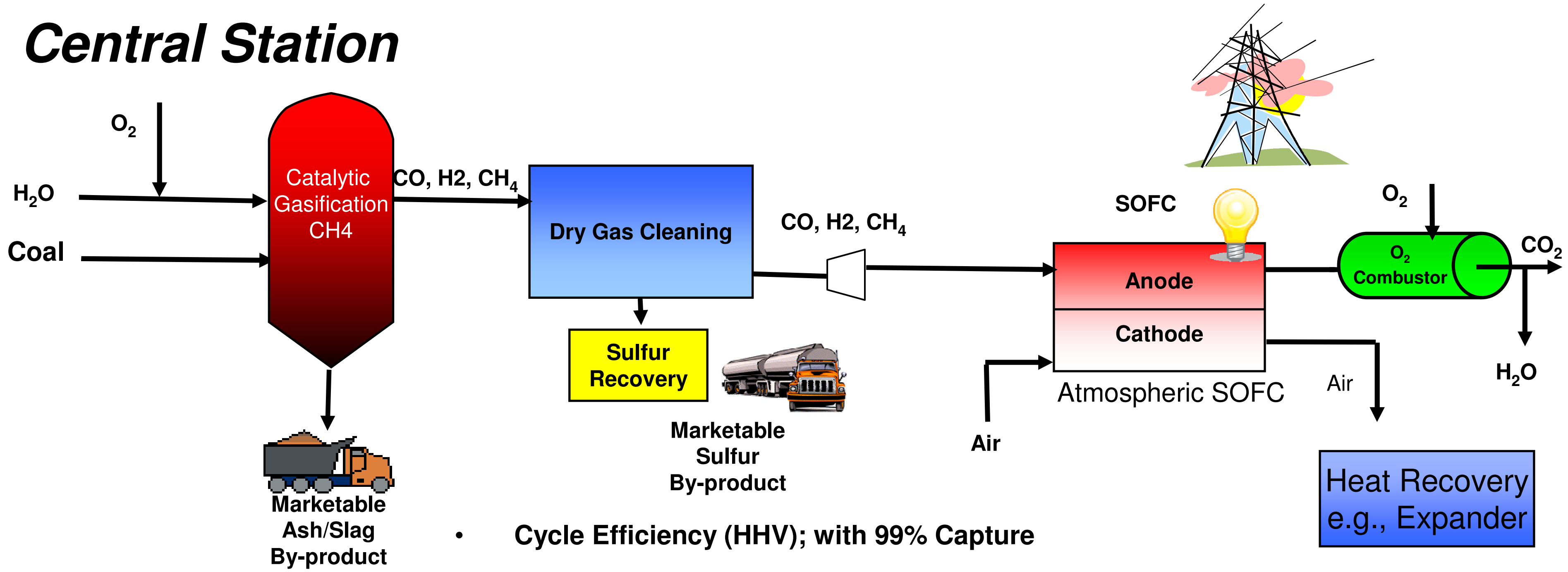
	ITM Oxygen	Cryo ASU	Δ %
IGCC Net Power (MWe)	627	543	+15
Net IGCC Efficiency (% HHV)	38.9	38.4	+1.2
Oxygen Plant Cost ($/sTPD)	18,700	25,000	- 25
IGCC Specific Cost ($/kW)	1,368	1,500	- 9

<u>ITM Benefits</u>: IGCC plant specific capital cost reduced by 9%, plant efficiency increased by 1.2%, with ~25% cost savings in oxygen production

Photos: Air Products and Chemicals, Inc. 2006

Solid Oxide Fuel Cell

Central Station



O_2

H_2O

Coal

Catalytic Gasification CH4

CO, H2, CH_4

Marketable Ash/Slag By-product

Dry Gas Cleaning

Sulfur Recovery

Marketable Sulfur By-product

CO, H2, CH_4

SOFC

Anode

Cathode

Atmospheric SOFC

Air

O_2

O_2 Combustor

CO_2

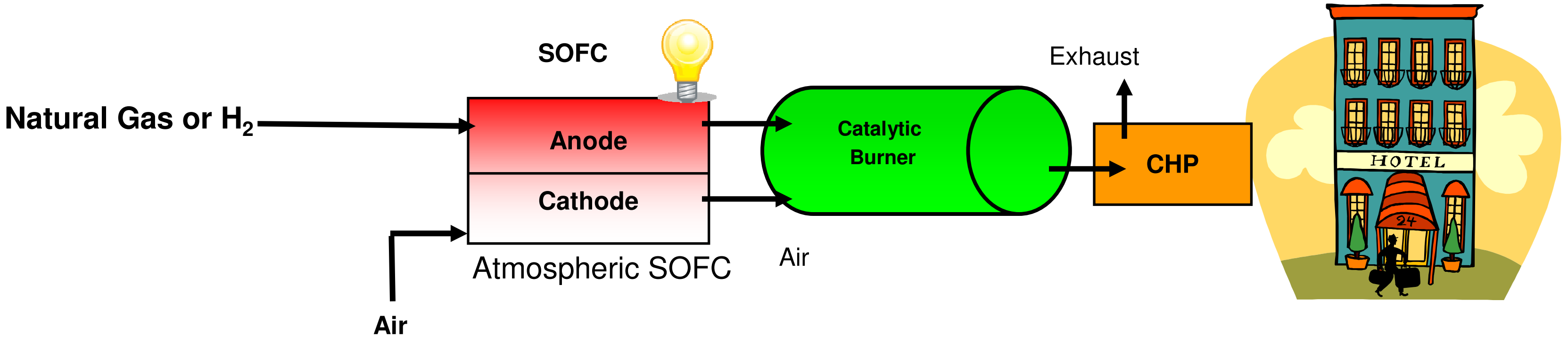
H_2O

Air

Heat Recovery e.g., Expander

- **Cycle Efficiency (HHV); with 99% Capture**
  - ➢ **~50% with CO2 Compression**
  - ➢ **~53% w/out CO2 Compression**

Distributed Generation



Natural Gas or H_2

SOFC

Anode

Cathode

Atmospheric SOFC

Air

Catalytic Burner

Air

Exhaust

CHP

The carbonic anhydrases are a family of enzymes that catalyze the rapid conversion of carbon dioxide to bicarbonate.

$$CO_2 + H_2O \quad \rightarrow \quad HCO_3^- + H^+ \text{ ("high" pressure)}$$

Carbonic
anhydrase

$$CO_2 + H_2O \quad \leftarrow \quad HCO_3^- + H^+ \text{ ("low" pressure)}$$

Catalytic increase in rates range between 10^4 and 10^6 reactions per second.