NATIONAL ENERGY TECHNOLOGY LABORATORY

"Coal-Fired Power Plants, CCS, and a Use for the CO_2"

Charles E. Taylor, Director, Chemistry and Surface Science Division

National Energy Technology Laboratory

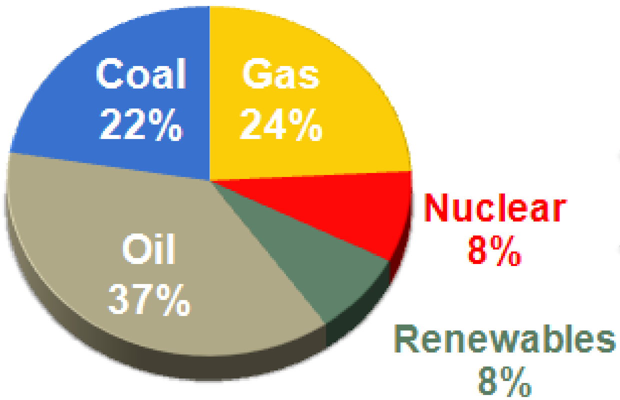
- **Only DOE national lab dedicated to fossil energy**
  - Fossil fuels provide 85% of U.S. energy supply
- **One lab, one management structure, five locations**
  - Full-service DOE Federal laboratory
  - 3 R&D locations
- **>1,200 Federal and support-contractor employees**
- **Research spans fundamental science to technology demonstrations**

Energy Demand 2008

Energy Demand 2035

United States

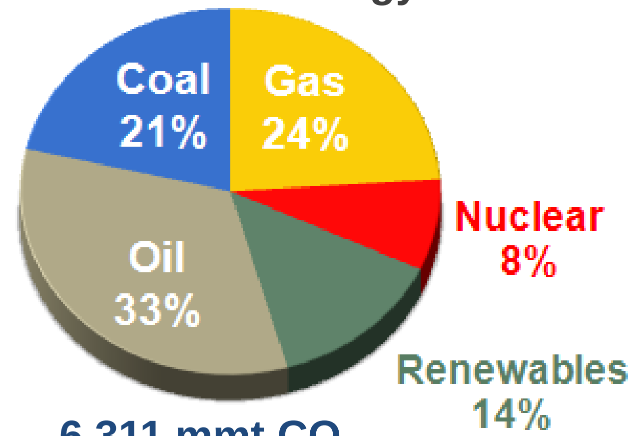
2008: 100 QBtu / Year
84% Fossil Energy



5,838 mmt CO_2

+ 14%
United States

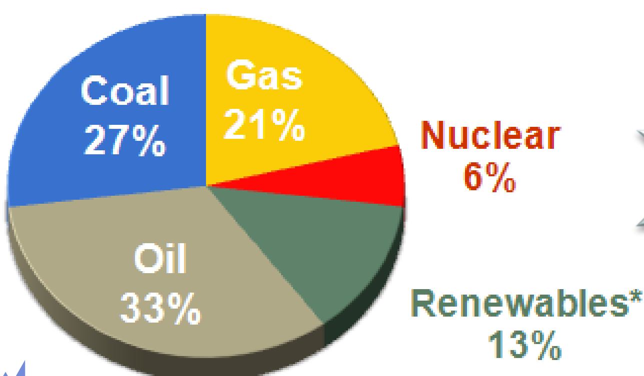
2035: 114 QBtu / Year
78% Fossil Energy



6,311 mmt CO_2

World

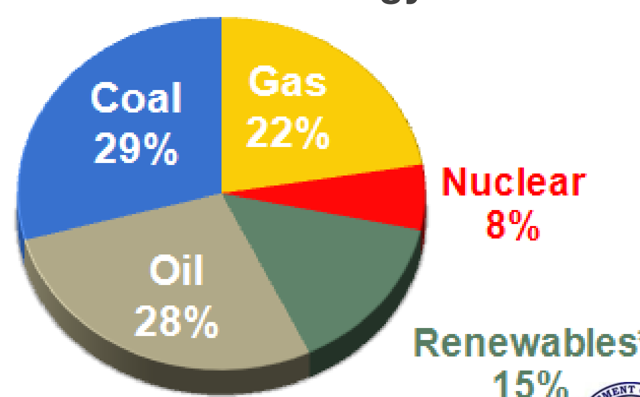
2008: 487 QBtu / Year
81% Fossil Energy



29,259 mmt CO_2

+ 47%
World

2035: 716 QBtu / Year
79% Fossil Energy



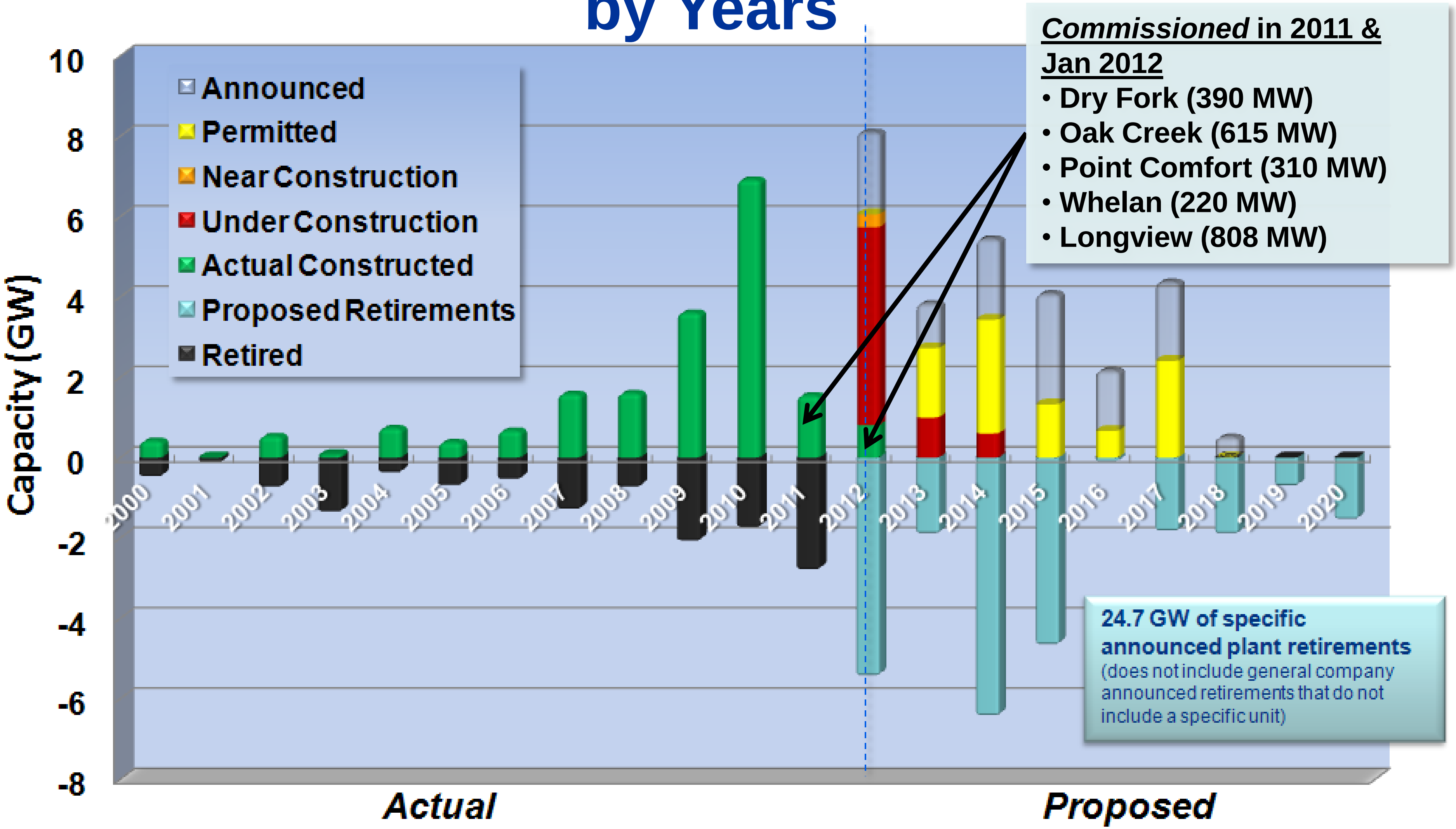
42,589 mmt CO_2

Office of Fossil Energy

U.S. data from EIA, Annual Energy Outlook 2011; World data from IEA, World Energy Outlook 2010, Current Policies Scenario

* Primarily traditional biomass, wood, and waste.

Current Coal Capacity Additions/Retirements by Years

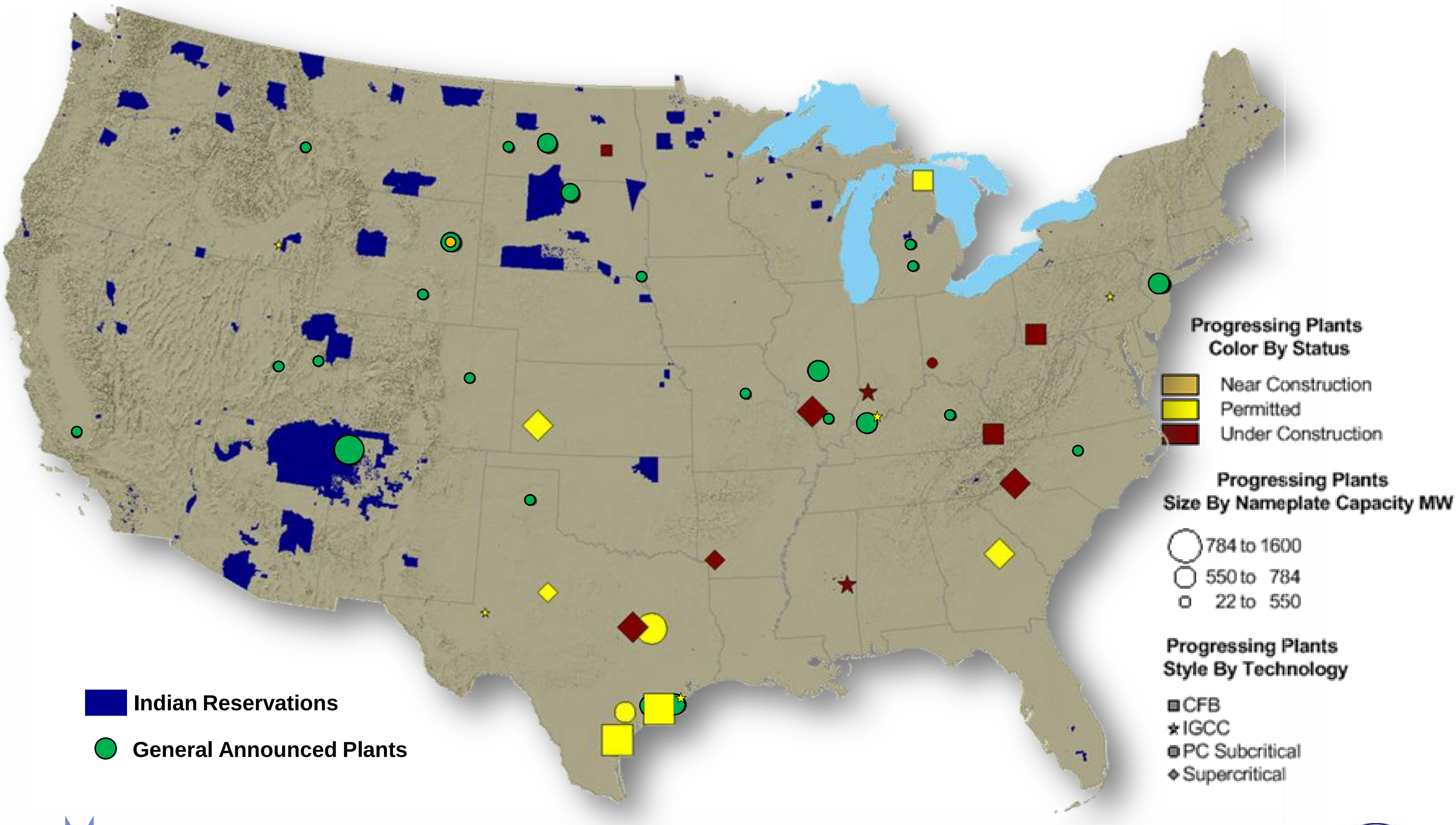


Operational Dates (above) / Retirement Dates (below)

Office of Fossil Energy

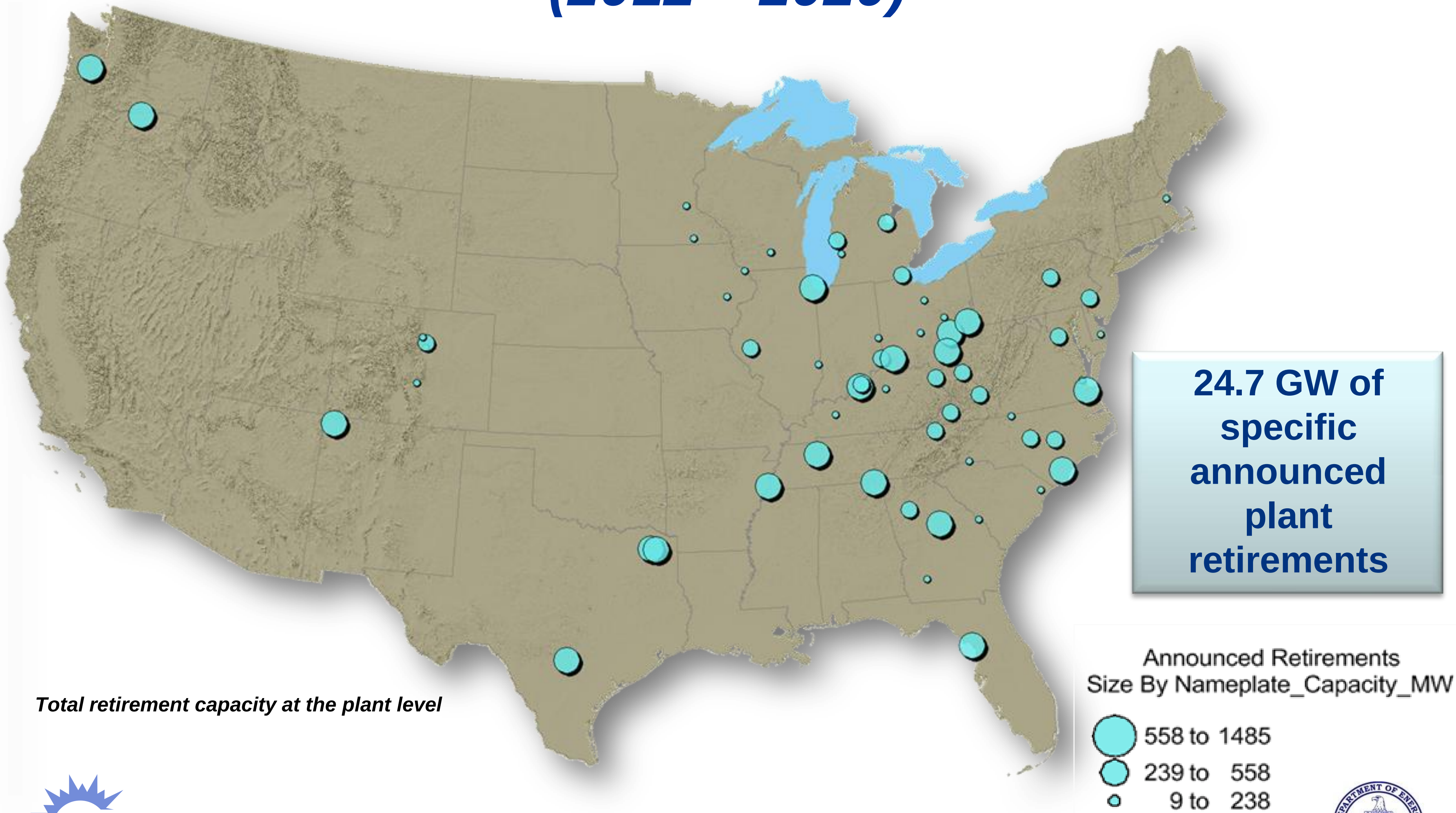
Ventyx – Velocity Suite (1/13/2012)

Progressing and Announced New Coal Units



Office of Fossil Energy

Announced Coal-Fired Retirements
(2012 – 2020)



Total retirement capacity at the plant level

U.S. Coal-Fired Power Plant Summary – 2011

12/13/2010 – 1/13/2012

- **Five new coal-plants totaling 2,343 MW were *Commissioned* in 2011**
- ***Progressing/Commissioned* projects by January 2012 have had a net increase of 3 plants; a net change in capacity of 1,388 MW (+10%) over *Progressing* projects**
- **1,599 MW of new capacity has been *Announced* and 2,890 MW have been canceled**
  - Of 2,890 MW canceled plants, 54% were *Announced* phase and 46% were *Progressing*
- **Compared to previous years, fewer projects are being *Announced* to offset recent *Commissioning***

Pathways To CO_2 Emission Reduction

- **Energy efficiency (14 $GtCO_2e/yr$)[1]**
  - Vehicles, Buildings, industrial equipment
- **Low-carbon energy supply (12 $GtCO_2e/yr$)**
  - Wind, Nuclear, Solar Energy
  - Biofuels for transportation
  - Fossil fuels with Carbon Capture and Storage
- **Terrestrial carbon (12 $GtCO_2e/yr$)**
  - Reforesting, halting deforestation
  - CO_2 storage in soils through changing agricultural practices
- **Behavioral change (~4 $GtCO_2e/yr$)**

1. CO_2 Reduction opportunities by 2030 from Pathways to a Low-Carbon Economy, McKinsey & Company, 2009.

DOE/NETL CO_2 Capture RD&D

R&D Programs

Carbon Capture
- Post-Combustion (PC)
- Pre-Combustion

Carbon Storage

Advanced Energy Systems
- Advanced Combustion
- Gasification
- Hydrogen Turbines
- Fuel Cells
- Hydrogen and Syngas

Advanced Research

↔ NETL's Carbon Capture R&D ↔

Demonstration Programs

Clean Coal Power Initiative

FutureGen 2.0

Industrial Carbon Capture

Deployment Barriers For CO_2 Capture On New And Existing Coal Plants Today

1. **Energy Penalty**
   - 20% to 30% less power output
2. **Cost**
   - Increase Cost of Electricity by 80%
   - Adds Capital Cost by $1,500 - $2,000/K
3. **Scale-up**
   - Current Post Combustion capture ~200 TPD
   - 550 MWe power plant produces 13,000 TPD
4. **Regulatory framework**
   - Transport — pipeline network
   - Storage
5. **Economies of Scale**
   – Land, power, water use, transportation, process components, …

High Efficiency Low Emission (HELE) Coal-Fired Power Plants

- Coal is an inexpensive and abundant energy source
- World coal usage is projected to more than double by 2050 in base-line scenarios
- U.S. coal usage is projected to increase by ~10%
- Non-OECD countries will be the main coal consumers
- CCS and efficiency improvements are critical for future use of coal in power generation

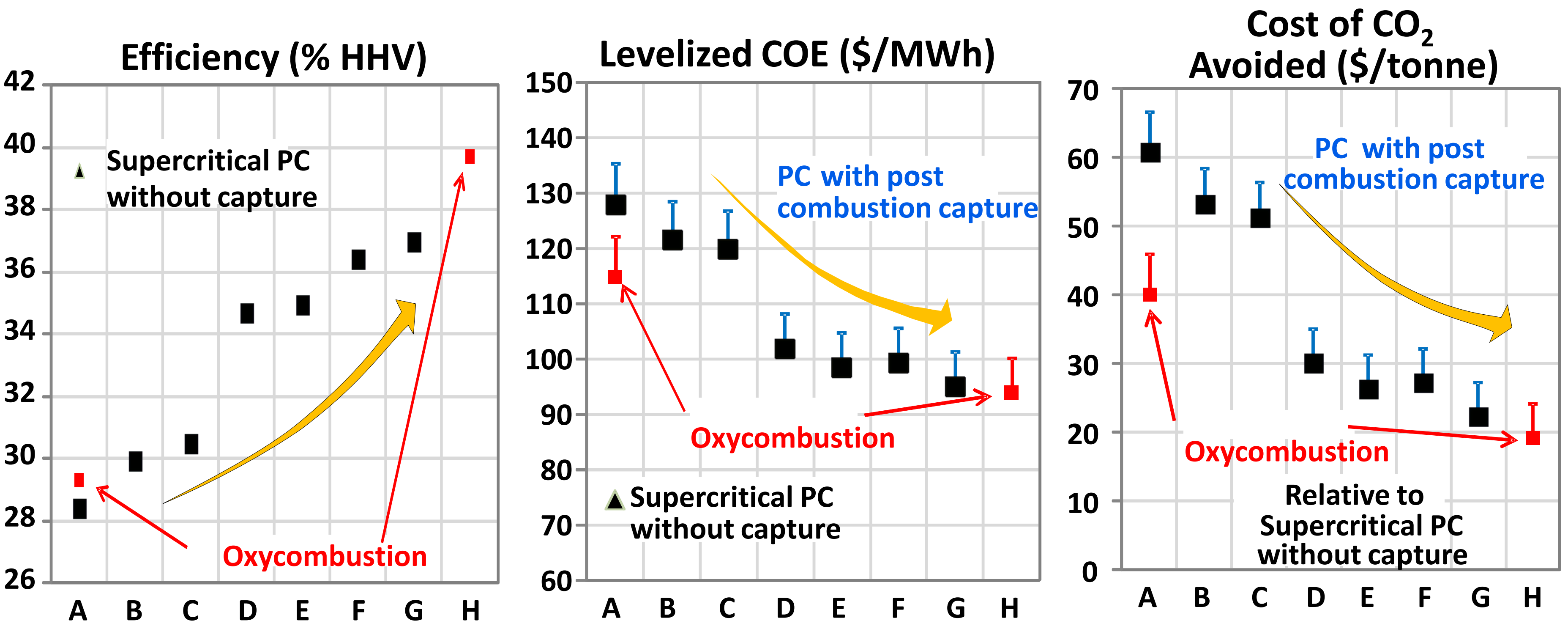
Technologies For Improving The Efficiency Of Existing Power Plants

- **Renovation and Modernization Technologies for Existing Power Stations**
  - **~40% of U.S. CO_2 from electricity generation [1]**
  - **Average age of >250 MW plants in U.S. is 34 years [1]**
- **Waste Heat Recovery from Power Plants**
- **Higher-Efficiency New Power Plant Technologies**
  - **Supercritical and Ultra-Supercritical Technologies**
  - **Integrated Coal Gasification Combined Cycle (IGCC)**
  - **Advanced Ultra-Supercritical Technology**
- **Development and Deployment of Other Innovative High-Efficiency Cycles**
  - **More Efficient CO_2 Capture Technologies**

[1] http://www.netl.doe.gov/publications/proceedings/11/co2capture/presentations/1-Monday/22Aug11-Hutson-EPA%20Rulemaking%20for%20GHG.pdf

http://www.majoreconomiesforum.org/images/stories/documents/mef%20helec%20tap%2014dec2009.pdf

Advanced Combustion Systems



A – Supercritical PC, Current Amine

B – Ultrasupercritical PC, Current Amine

C – Supercritical PC, Amine + Adv. Comp.

D – Supercritical PC, Adv. CO_2 Sorbent

E – Supercritical PC, Adv. CO_2 Membrane

F – USC PC, Adv. Sorbent + Adv. Comp.

G – USC PC, Adv. Membrane + Adv. Comp.

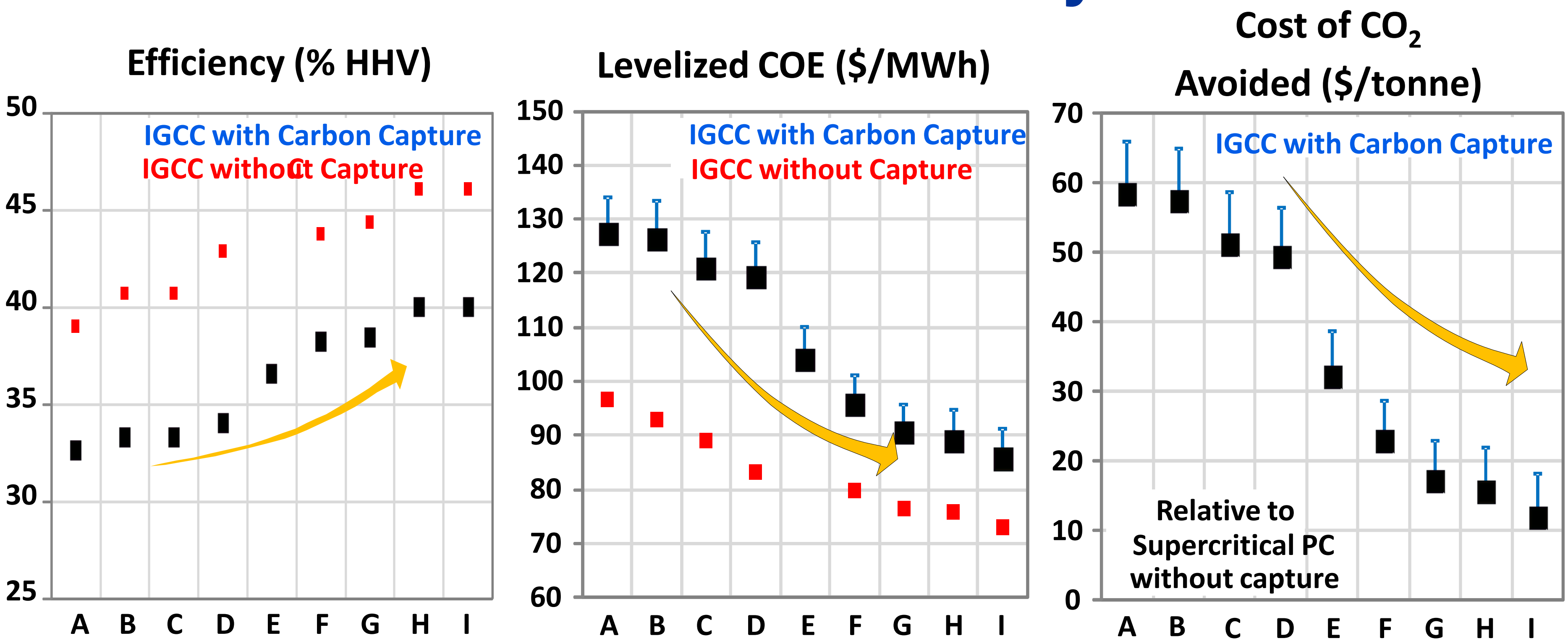
H – Advanced Oxycombustion

Office of Fossil Energy

*USC = Ultra-supercritical PC (4,000 psig/1,350ºF/1,400ºF)

CO_2 transport, storage and monitoring cost

Advanced Gasification Systems



A – Current State of the Art IGCC

B – Advanced Coal Pump

C – Advanced Gasifier Materials

D – Warm Gas Cleanup

E – Hydrogen Membrane

F – Advanced Hydrogen Turbine (2,550ºF)

G – Ion Transport O2 Membrane

H – Advanced Hydrogen Turbine (2,650ºF)

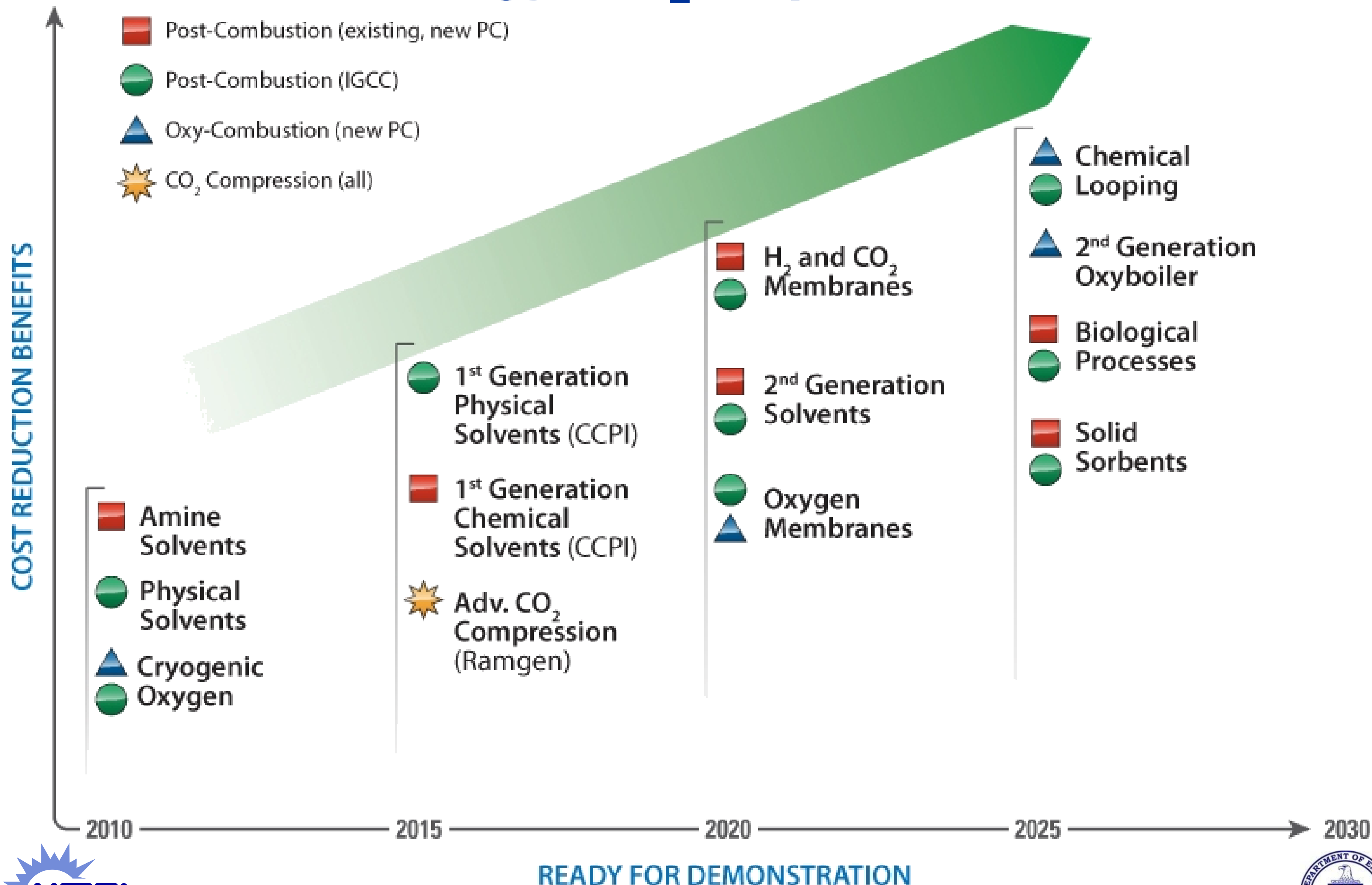
I – Advanced Controls

CO_2 transport, storage and monitoring cost

Office of Fossil Energy

*USC = Ultra-supercritical PC (4,000 psig/1,350ºF/1,400ºF)

Fossil Energy CO_2 Capture Solutions



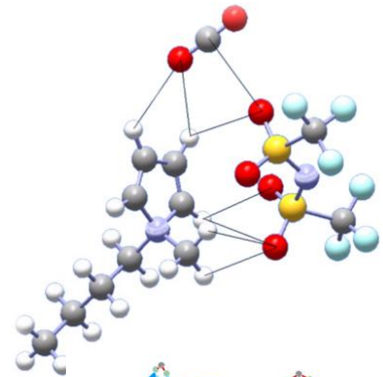
NETL

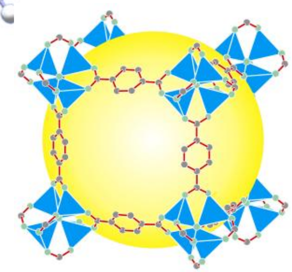
Office of Fossil Energy

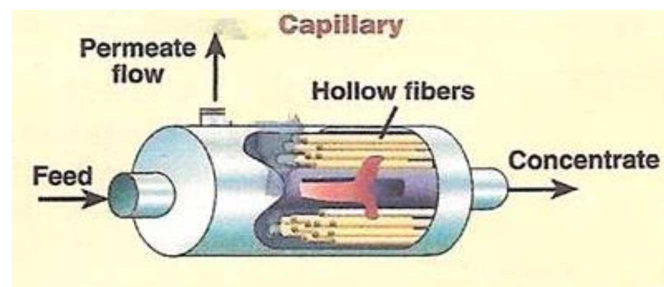
http://www.netl.doe.gov/technologies/coalpower/ewr/index.html

CO_2 Capture Technologies

1) **Solvents**
2) **Sorbents**
3) **Membranes**
4) **Oxy-combustion**
5) **Chemical looping**
6) **CO_2 Compression**

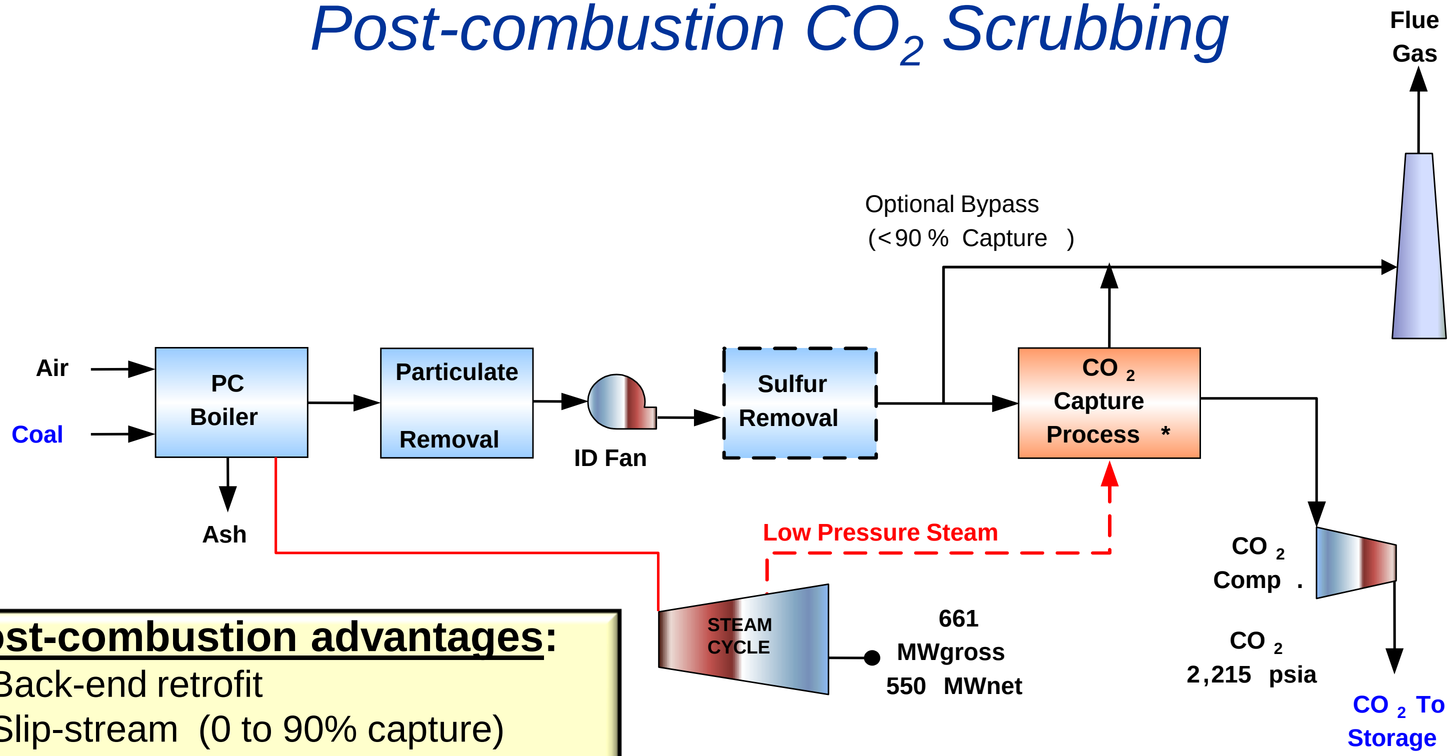






Pulverized Coal Power Plant System

Post-combustion CO_2 Scrubbing



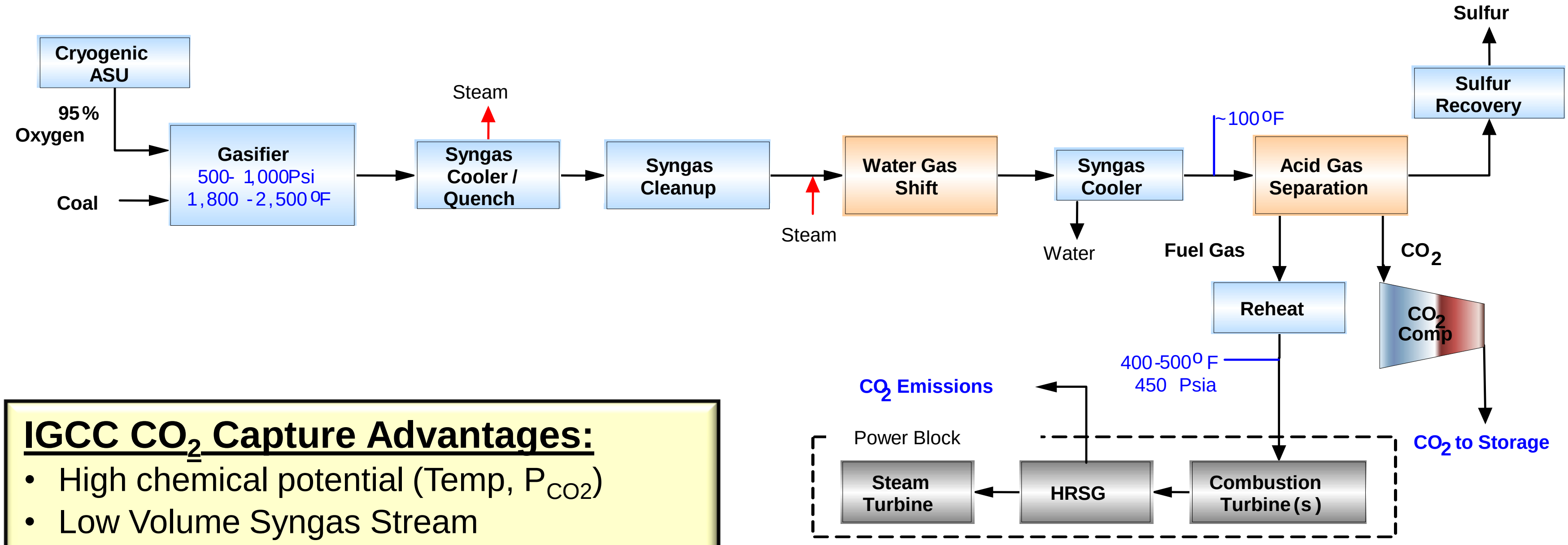
Post-combustion advantages:
- Back-end retrofit
- Slip-stream (0 to 90% capture)

Amine scrubbing Advantages:
- Proven Technology (Petroleum refining, NG purification)
- Chemical solvent → High loadings at low CO_2 partial pressure
- Relatively cheap chemical ($2-3/lb)

Key Challenges:
- Dilute flue gas (12-15 volume %)
- 2-3 MM acfm for a 500-600 MWe plant
- ~50% currently scrubbed for SOx/NOx
- Increased cooling requirements

IGCC Power Plant System

Pre-combustion CO_2 Scrubbing



IGCC CO_2 Capture Advantages:

- High chemical potential (Temp, P_{CO2})
- Low Volume Syngas Stream

Selexol™ CO_2 Capture Advantages:

- 30+ years of commercial operation (55 worldwide plants)
- Physical Liquid Sorbent
- Highly selective for H_2S and CO_2
- CO_2 is produced at "some" pressure

Key Challenges:

- Complex, integrated power process
- Additional process (WGS) to get high capture rates
- Current technology (Selexol) requires cooling and reheating

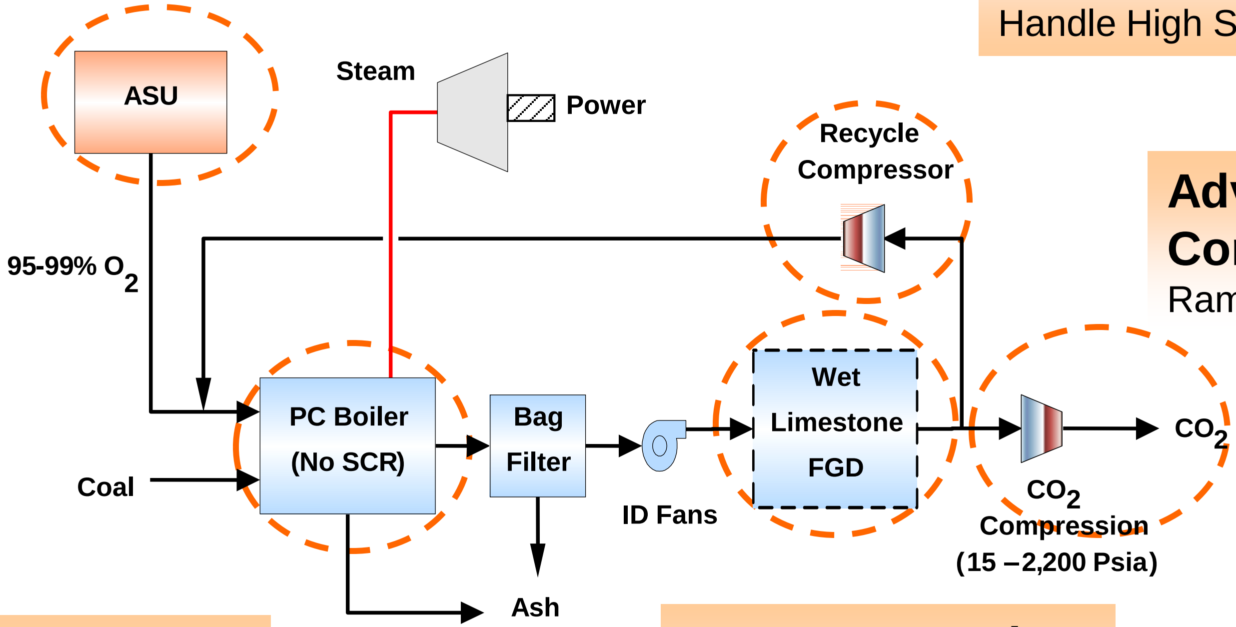
Pulverized Coal Oxyfuel Combustion

Technology Opportunities

Cheap Oxygen
Oxygen Membra

Coal + O_2 → CO_2 + H_2O

Advanced MOC*
Reduce CO_2 Recycle
Handle High Sulfur Conc.



Advanced Compression
Ramgen, SwRI

Oxyfuel Boilers
Compact Boiler Designs
Adv. Materials (USC)
Advanced Burners

Co-Sequestration
Multi-pollutant capture

Advanced CO_2 Solvents

R&D Focus

- High CO_2 working capacity, optimal ΔHrxn, low heat capacity, non-volatile
- Fast kinetics (enzymes)
- Thermally and chemically stable
- Non-corrosive, environmentally safe
- Low cost solvent and process MOC*
- Improved mass transfer systems
- Advanced Process Design/Integration

Solvent Technologies

- Novel high capacity oligomers
- Phase change solvents
- Ionic liquids
- Amino Acids
- Carbonates
- Enzymes
- Advanced Processes

Partners:

1. *GE Research Corporation (Polymers)*
2. *3H (Phase change)*
3. *Ion Engineering (IL/Amine mixtures)*
4. *University of Notre Dame (IL)*
5. *Georgia Tech. (IL)*
6. *Akermin (Enzymes)*
7. *Illinois St. Geological Survey (Carbonate)*
8. *University of Illinois (Carbonate)*
9. *URS Group (Piperazine)*
10. *Southwest Research Institute (Carbonate)**
11. *LBNL (Bicarbonate, Membrane ILs)*
12. *Babcock and Wilcox (Amine-based)*
13. *Novozymes (Enzymes)*
14. *Carbon Capture Scientific (Process)*
15. *Battelle (CO2BOLs)*
16. *NETL ORD (Amino Acid)*
17. *Linde (amine, process)*
18. *Southern Company (HX Process)*
19. *University of Kentucky (amine, process)*
20. *Siemens Energy (Amino Acids)*
21. *Neumann Systems Group (Process)*

Pilot (items 17–21)

*Pre-combustion Applications

Advanced CO_2 Sorbents

R&D Focus

- Optimal CO_2 working capacity, low heat capacity, fast kinetics (enzymes)
- Matching systems to sorbents
- Durability: thermally, chemically and physically
- Non-corrosive, environmentally safe
- Low cost sorbent and process MOC
- Hybrid (Shift + Capture) for IGCC

Project Types

- Metal organic frameworks
- Supported amines
- Metal organic framework (MOF)
- Carbon-based
- Alumina
- Water-gas shift (IGCC)
- Sorbent systems development

Partners:

1. *ADA-ES (amine, process)*
2. *University of Akron (amine)*
3. *SRI International (carbon)*
4. *TDA (Carbon, alumina)**
5. *URS Group (IGCC WGS sorbent)**
6. *NETL ORD (Supported amines)*
7. *NETL/LBNL (Membrane/MOFs)*
8. *Innosepra (Zeolite, process)*
9. *W.R. Grace (Zeolite, process)*
10. *RTI International (Amines)*
11. *Univ. of North Dakota*
12. *Georgia Tech.*

2011: Bench scale → 1 MWe slipstream design (ADA-ES)

2016: 10 – 25 MWe Pilot Scale

2020: 50 MWe – ***ready for demonstration***

*Pre-combustion Applications

Advanced Membranes

Membrane Advantages

- **Simple operation; no chemical reactions, no moving parts**
- **Tolerance to acid gases & O_2**
- **Compact, modular→ small footprint**
- **Builds on existing technology at similar scale (NG purification)**

Membrane Approaches

- Spiral wound & hollow fiber
- Cryogenic membrane separation
- Membrane/solvent hybrid
- Fuel Cell Hybrid
- Integrated water-gas shift*
- H_2 Selective zeolite*
- High Temperature Polymer*
- Nanoporous*
- PSA/Membrane Hybrid*
- Palladium Alloy*

Partners:

1. *Membrane Technology Research (MTR)*
2. *RTI International*
3. *Air Liquide*
4. *Gas Technology Institute*
5. *GE Research*
6. *Ohio State University*
7. *Rice University*
8. *Fuel Cell Energy*
9. *Univ. of Minnesota**
10. *Pall Corporation**
11. *Arizona State University**
12. *Gas Tech. Institute**
13. *Membrane Technology**
14. *New Jersey Institute of Technology**
15. *LANL/SRI**

Bench scale → 1 MWe slipstream design

*Pre-combustion Applications

Pulverized Coal Oxy-combustion

Challenges

- Cryogenic ASUs are capital and energy intensive
- Existing boiler air infiltration
- Corrosion and process control
- Excess O_2 and inerts (N_2, Ar) ↑ CO_2 purification cost

Project Types

- "2nd Gen" oxyboiler designs
  - Adv. Materials and burners
- Existing boiler retrofits
  - Air leakage, heat transfer, corrosion, process control
- Low cost O_2 (membrane)
- CO_2 purification
- Co-sequestration

Partners:

1. *Praxair (O_2 Membrane, CO_2 Purification)*
2. *Air Products (CO_2 Purification)*
3. *Jupiter Oxygen (Burners)*
4. *Alstom (Pilot plant)*
5. *B&W (Cyclone pilot test)*
6. *Foster Wheeler (Corrosion)*
7. *Reaction Engineering Int. (Retrofit)*
8. *Southern Research Institute (Retrofit)*
9. *NETL ORD (Modeling, CO_2 Purification)*

Development Timeline

Today: 10 MWe wall-fired test (B&W)
5 MWe T-fired pilot (Alstom)
5 MWe burner pilot (Jupiter)

by 2015: 1st Gen (Cryogenic) demo.

2020: 2nd Gen demonstration*

Chemical Looping Combustion

Oxy-combustion <u>without</u> an O_2 plant

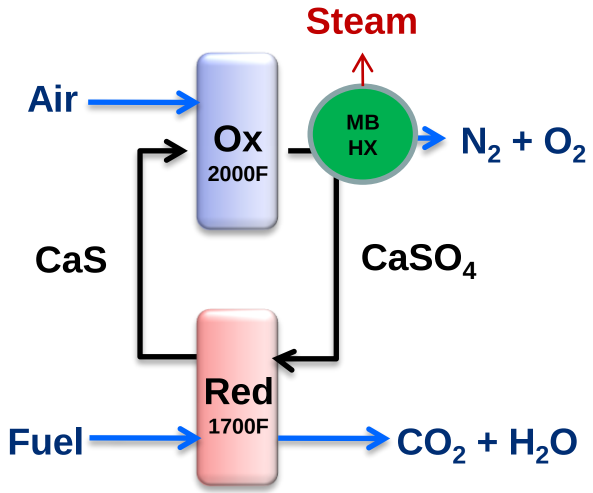
- ***Potential* lowest cost option for near-zero emission coal power plant**
- **New <u>and</u> existing PC power plant designs**

Key Challenges

- **Solids transport**
- **Heat Integration**

Air Reactor (Oxidizer)

$CaS + 2O_2 \rightarrow CaSO_4 + Heat$



Fuel Reactor (Reducer)

$CaSO_4 + 2C + Heat \rightarrow 2CO_2 + CaS$

$CaSO_4 + 4H_2 + Heat \rightarrow 4H_2O + CaS$

Oxy-Firing without Oxygen Plant

- **Solid Oxygen Carrier** circulates between **Oxidizer** and **Reducer**
- **Oxygen Carrier:** Carries Oxygen, Heat and Fuel Energy
- **Carrier picks up O_2** in the Oxidizer, leaves N2 behind
- **Carrier Burns** the **Fuel** in the Reducer
- **Heat** produces **Steam for Power**

2011 Alstom Pilot test (1 MWe)

✓ **1000 lb/hr coal flow**

✓ **1st Integrated operation**

✓ **1st Autothermal Operation**

Office of Fossil Energy

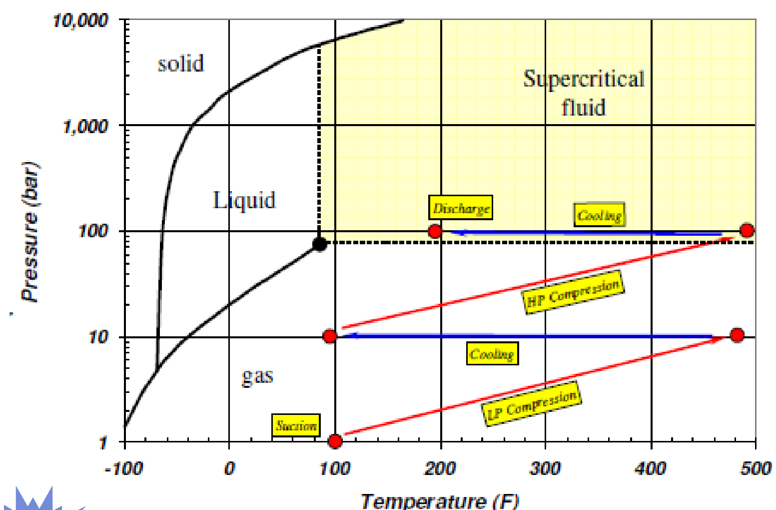
Key Partners (2 projects): ***Alstom Power (Limestone Based), Ohio State (Metal Oxide)***

Advanced CO_2 Compression

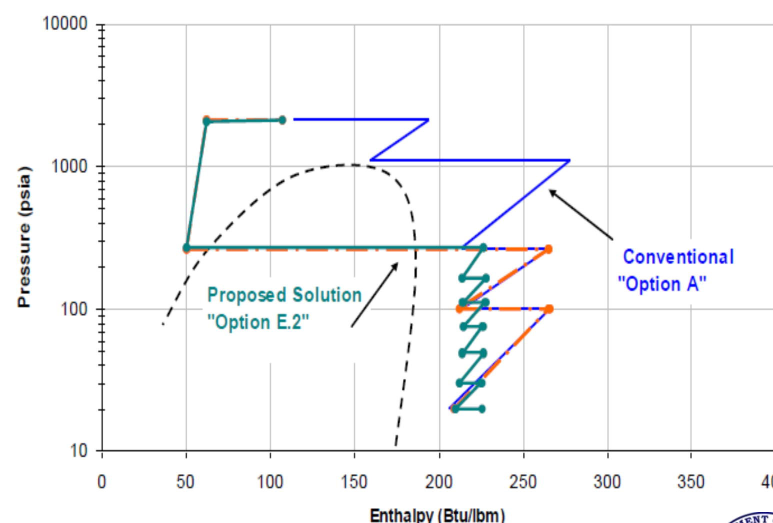
Challenges
- Scale-up (550 MWe plant = 15,000 TPD)
- Parasitic load
- Contaminants (O_2, SOx, NOx, …)
- Cost

R&D Objectives
- Increase compression efficiency
- Reduce footprint and capital cost
- Power plant integration/heat recovery

Approach 1: High PR 2-Stage Inter-stage Heat Recovery



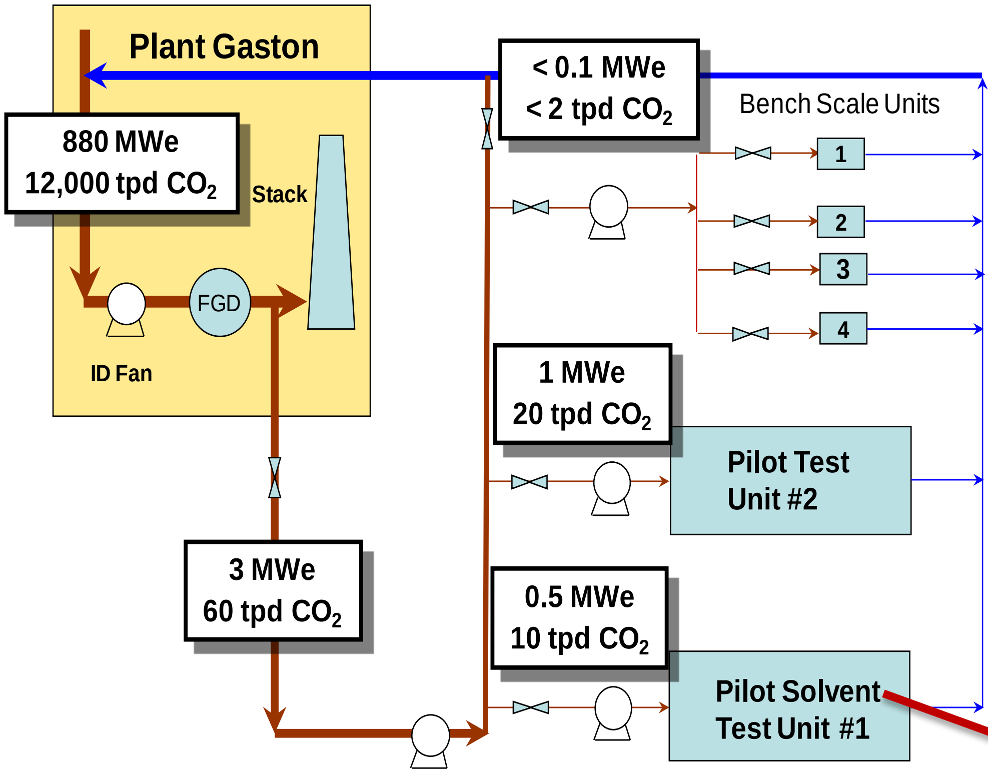
Approach 2: Compression → Cool → Pump



Office of Fossil Energy

DOE National Carbon Capture Center

Post-combustion Carbon Capture



- 6 MWe Transport Gasifier
- 3 MWe Post-Combustion Slipstream

Pilot Solvent Test Unit
Wilsonville, AL

Pilot Solvent Test Unit:

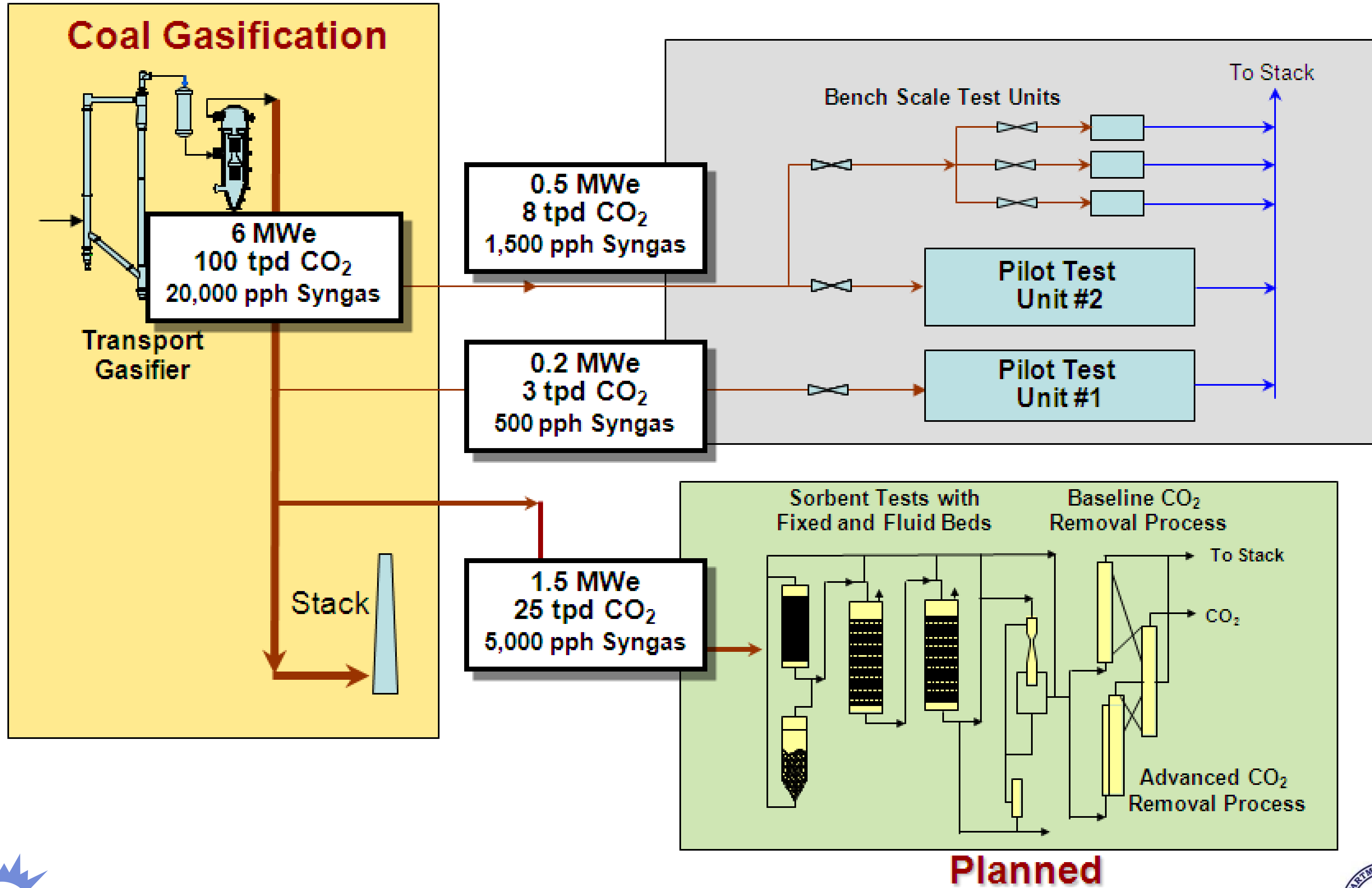
*Amine baseline

*B&W Advanced CO_2 Capture Solvent

Office of Fossil Energy

DOE National Carbon Capture Center

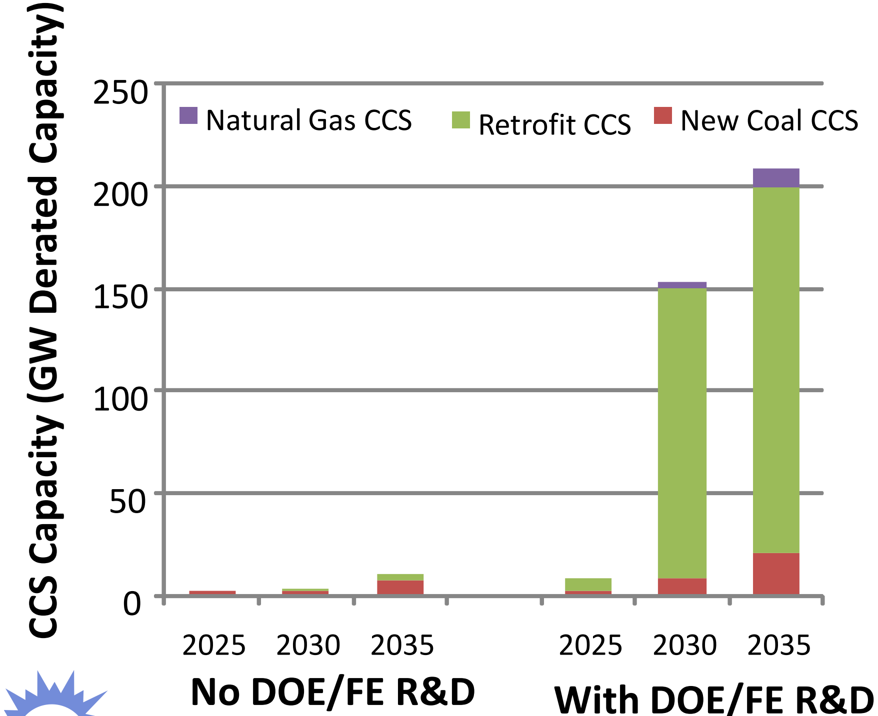
Pre-combustion Carbon Capture



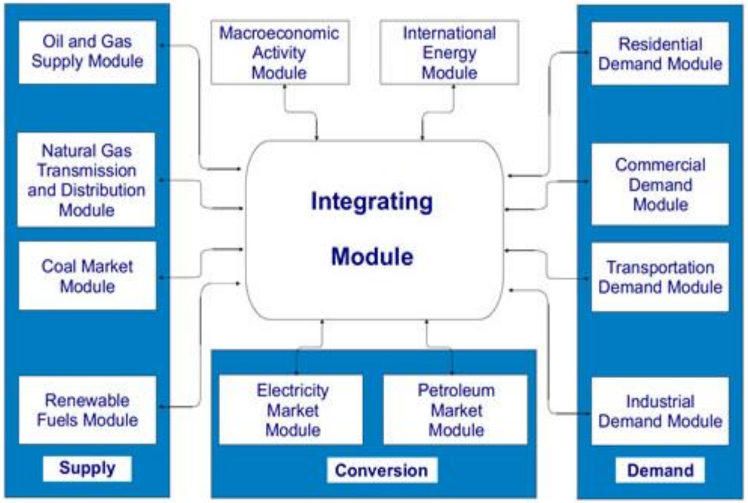
Office of Fossil Energy

Would Advanced CCS Technologies Dispatch?

- **EIA uses the National Energy Modeling System (NEMS) to project energy-economic-environmental impacts of policy through 2035**



NEMS schematic (EIA)



..........Yes!

Enhanced Oil Recovery (EOR) As A Catalyst For CCS

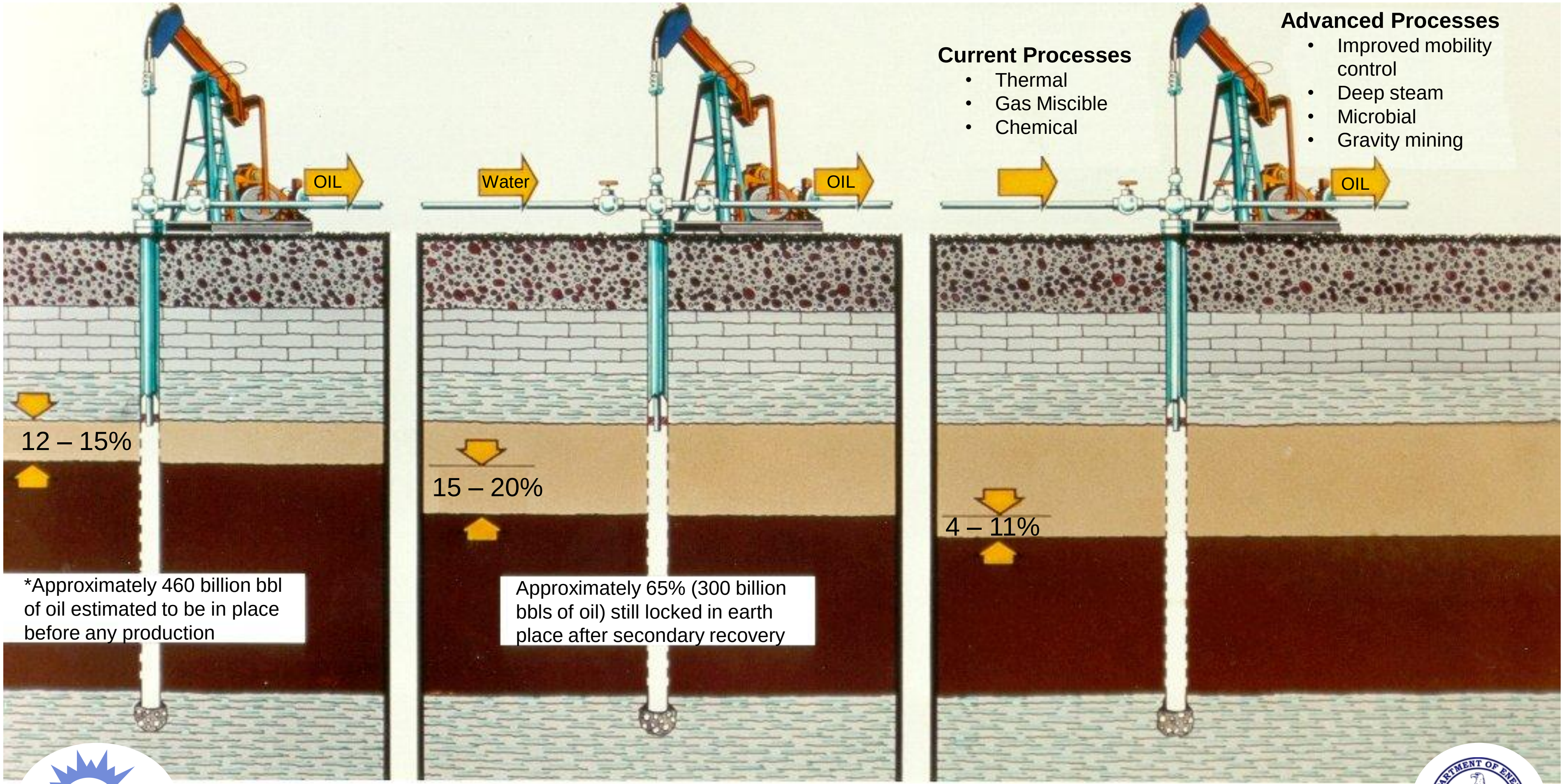
- **Current Status**
  - 50 years of experience
  - 50MMT added to system every year
  - 1^{st} Gen capture technologies economic at today's oil prices
- **Advantages**
  - Existing infrastructure and knowledge base
- **Challenges**
  - Is it storage? 1:0.8 BAU and 1:1.2 at best
  - Second generation recovery approaches need to be demonstrated
  - Distributing Value of CO_2 to incentivize capture

Methods of Oil Production

Primary Recovery
Produces 12 – 15% of oil in place*

Secondary Recovery
Another 15 – 20% of the original oil in place* may be produced by water flooding

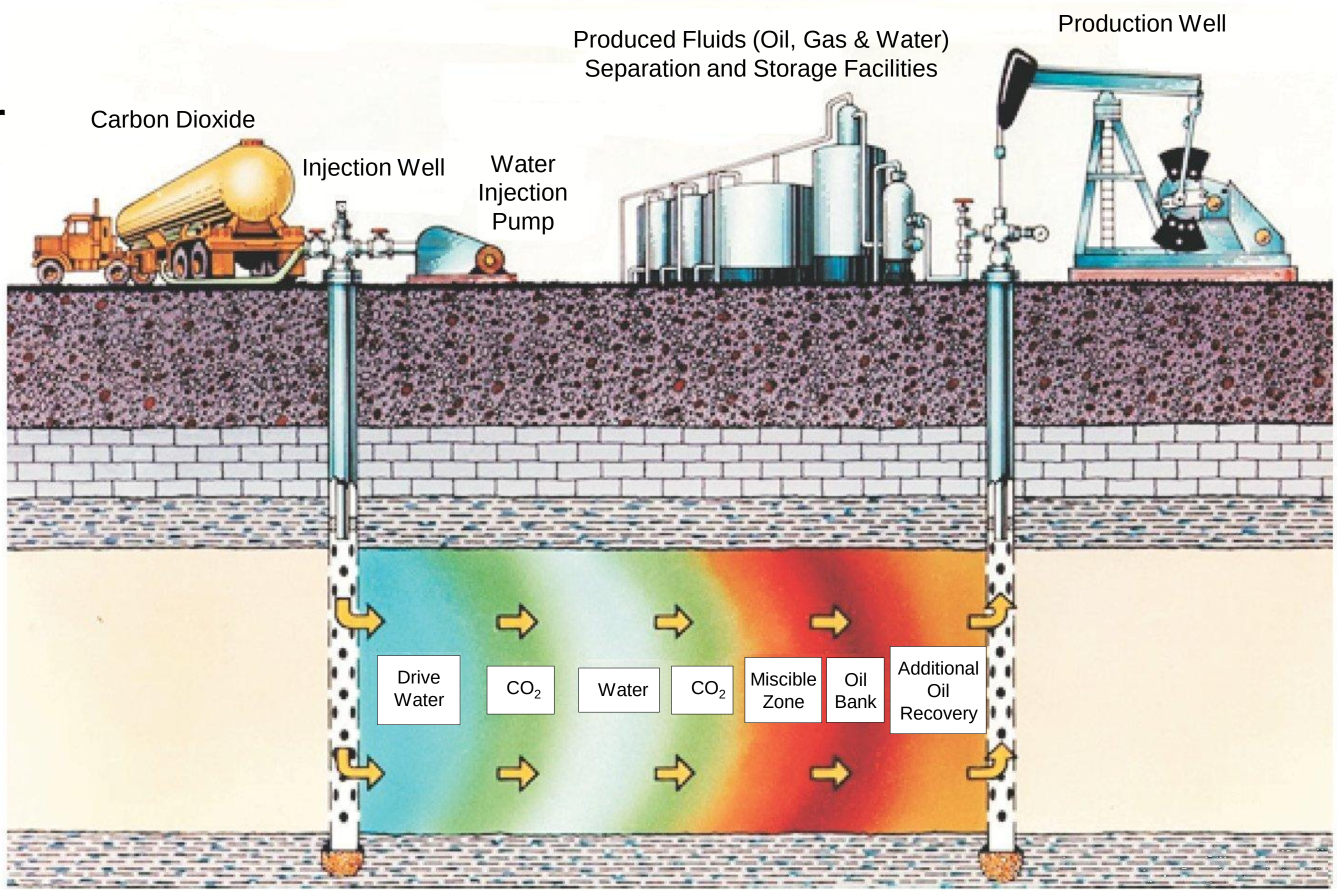
Enhanced Oil Recovery (EOR)
Another 4 – 11% of the original oil in place* may be produced using current and advanced technology



CO_2 Enhanced Oil Recovery

- Currently, over 48 million metric tons (tonnes) per year of CO_2 are used for EOR. Of this total, about 25% is anthropogenic in origin.

- Worldwide, potential for CO_2 EOR is 130 billion tonnes.



Viscosity of oil is reduced providing more efficient miscible displacement

Office of Fossil Energy

Examples of DOE- Sponsored CO_2 Sequestration Projects in the U.S. Involving EOR

EOR Field	CO_2 Source	Geological Stratum	Injection Start Date	Cumulative CO_2 Injection	Description
Zama Field, Alberta, Canada	Natural Gas Processing Plant	Pinnacle Reef, Middle Devonian Keg River	December 2006	230,000 tons	The Zama oil field validation test being conducted in Alberta, Canada, is evaluating the potential for geologic sequestration of CO_2 in an acid gas stream that also includes high concentrations of hydrogen sulfide (H_2S) for the concurrent purposes of CO_2 sequestration, H_2S disposal, and EOR. The acid gas is generated as a by-product during the processing of raw natural gas being extracted from the field.
Williston Basin	Pulverized Coal Power Plant	Devonian Duperow or Mississippian Madison Group	2011	500,000 tons/year	The Williston Basin demonstration test will evaluate the potential for geological sequestration of CO_2 in a deep carbonate reservoir for the dual purpose of CO_2 sequestration and EOR. Characterization studies indicate that the oil fields of the Williston Basin may have over 1 billion tons of CO_2 storage capacity. Additionally, the volume of incremental oil that could be produced from Williston Basin oil fields has been estimated to be approximately 1 billion barrels.
Louden Field, Illinois	Refinery or Ethanol Plant	Mississippian Weiler Sandstone	March 2007	43 tons	The Louden field test, an enhanced oil recovery “huff-n-puff” project, is designed to inject (huff) CO_2 into a producing well for 3-5 days, allow the gas to soak for approximately one week, then place the well back on production and measure the amount of petroleum fluids produced (puff).
Louden Field, Illinois	Refinery or Ethanol Plant	Mississippian Weiler Sandstone	February 2008	2,500 tons	The well conversion EOR field test does not require the drilling of any new wells because available well(s) will be converted to handle CO_2 injection and the pattern and spacing of existing wells is adequate to test EOR processes in the reservoir. Well conversion represents a potential near-term, low-cost opportunity to implement EOR.
Snyder, Permian Basin, Texas	McElmo Dome	Strawn- and Canyon-age carbonate reefs	Second Quarter 2008	700,000 tons	This test will include a post-audit modeling analysis of injected CO_2 for EOR over the last 30 years at the SACROC Unit in the Permian Basin of Texas, in addition to intense monitoring analyses of ongoing CO_2 injection at SACROC.
Aneth Oil Field, Bluff, Utah	McElmo Dome	Paradox Formation, Pennsylvanian Desert Creek	Second Quarter 2007	300,000 tons	The primary research objective of this EOR-sequestration test is to evaluate and maximize the efficacy of CO_2 subsurface monitoring technologies, and to improve the ability to track the fate of injected CO_2 and to calculate ultimate storage capacity.
Weyburn, Saskatchewan	Dakota Gasification Plant	The Midale Beds of the Mississippian Charles Formation,	September 2000	33 million tons	The Weyburn program is organized around five technical themes: geological integrity, wellbore integrity, storage monitoring methods, risk assessment and storage mechanisms, and data validation and management. The technical objectives are to determine the long-term storage risks and monitoring requirements to mitigate [illegible] risks.

Summary of CO_2 EOR

CO_2 EOR is a promising technology to safely store CO_2 underground so that it cannot contribute to climate change. While this technology has been implemented by the oil industry since 1972, further research is needed to ensure that the stored CO_2 remains isolated from the atmosphere and the biosphere on the order of thousands of years and that the storage process remains as safe and economically viable as possible.

DOE's Carbon Sequestration Program is currently addressing the following challenges:

- **Improving understanding of oil reservoir characteristics relative to CO_2 fate and transport**
- **Reducing the costs of capturing, processing, and transporting anthropogenic CO_2, particularly from power generation facilities**
- **Further developing technologies to monitor and verify CO_2 storage, and**
- **Developing CO_2 emissions trading protocols.**

For Additional Information

Office of Fossil Energy
www.fe.doe.gov

NETL
www.netl.doe.gov

Charles Taylor
412-386-6058 –or– 304-285-0232
charles.taylor@netl.doe.gov