NETL NATIONAL ENERGY TECHNOLOGY LABORATORY

“CO_2 Capture and Separation: Technology Costs and Progress ”

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

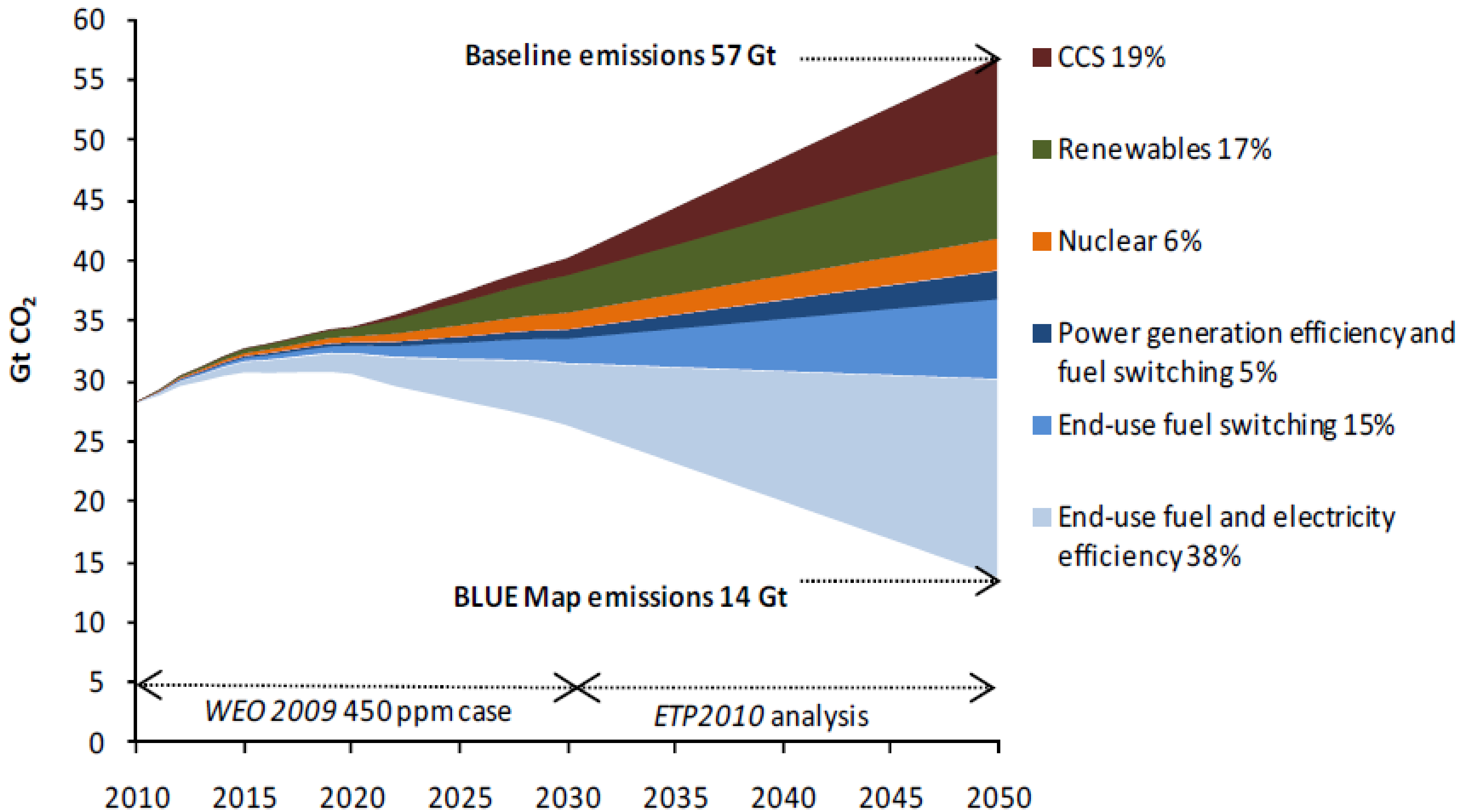
National Energy Technology Laboratory

- **Full-service DOE Federal laboratory**
  - Program Planning
  - Budget Formulation and Execution
  - Procurement
  - Project Management
  - Legal
  - Financial Management and Reporting
  - On-site Research
  - Program Performance and Benefit Analysis

- **Dedicated to energy RD&D, domestic energy resources**
  - Fossil Energy
  - Support OE and EE
- **Fundamental science through technology demonstration**
- **Unique industry, academia, and government collaborations**

Blue Map Scenario

Figure 4. Key technologies for reducing CO_2 emissions under the BLUE Map scenario, 2010



Office of Fossil Energy

www.iea.org/papers/2011/CEM_Progress_Report.pdf

The Challenge:

Meeting the Blue Map Deployment Goals for CCS

The Barriers:

- Storage
- Cost
- Re-Use of Carbon
- Global Action
- Ecological Aspects
- Assurance of Risk
- Public Acceptance
- Uncertain Government Policies

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.

Clean Energy Standard (CES)

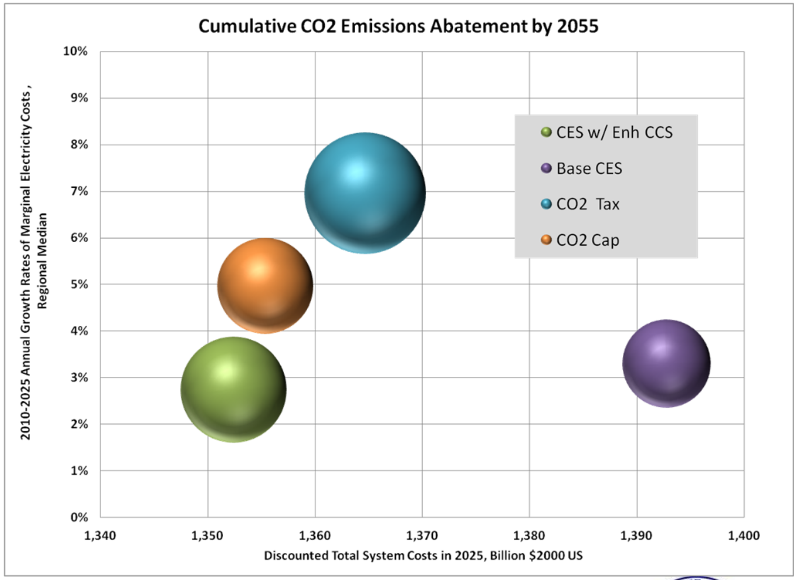
- **In his most recent State of the Union address, President Obama proposed a Clean Energy Standard (CES) to require that 80 percent of the U.S. electricity come from clean energy technologies by 2035.**
- **The model applies the Environmental Protection Agency's Nine Region MARKAL Database (EPAUS9r) that was developed by EPA around the nine U.S. Census divisions.**
- **The model investigated the impacts of a CES mandating 80 percent of electricity must be generated from "clean" energy sources (with carbon capture and storage (CCS) qualifying as 90 percent "clean") by the year 2035.**
- **The analysis looks at the impact of R&D in CCS under a CES and compares tax and cap & trade scenarios**

Clean Energy Standard Scenario Definitions

- **Base case:** resource supply and end-use demands are taken from AEO 2010
- **Base CES:** 80% of electricity from "clean energy" by 2035
  - Renewables worth 1 credit, NG worth 0.5, coal with CCS at 0.9
- **CES with Enhanced CCS: cost and performance of CCS (both coal and NG) meet DOE goals**
- **CO_2 tax:** \$23/t CO_2 emissions tax in 2020, increasing at 5.8 % annually
- **CO_2 cap:** CO_2 reduction level from CES, via CO_2 cap in electricity generation

Clean Energy Standard Model Results

- **The results of the model indicate that while CCS can play a significant role in a CES by minimizing electricity price increases and maintaining baseline electricity generation levels, the cost and performance of CCS must meet the R&D goals of the U.S. Department of Energy in order to meet its full potential.**
- **NETL was first to specifically model CCS in a CES mandate and it is expected that this analysis will establish a benchmark for other analyses as other organizations begin to assess the impacts of a CES.**



http://www.usaee.org/usaee2011/submissions/Presentations/Nichols.pptx

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

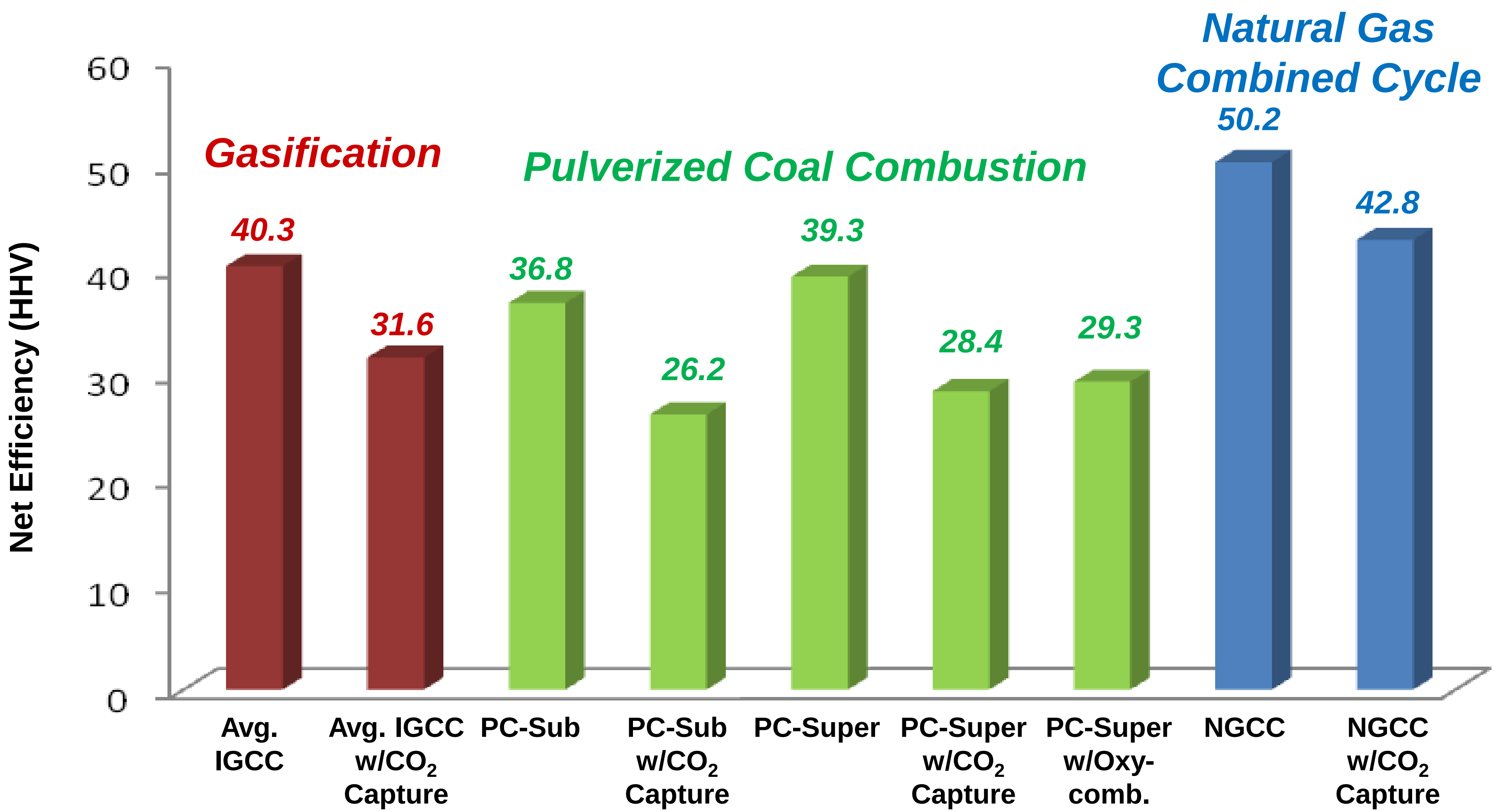
1. **Energy Penalty**
   - 20% to 30% less power output
2. **Cost**
   - Increase Cost of Electricity by 80%
   - Adds Capital Cost by $1,500 - $2,000/K
3. **Scale-up**
   - Current Post Combustion capture ~200 TPD
   - 550 MWe power plant produces 13,000 TPD
4. **Regulatory framework**
   - Transport — 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
- Coal usage is projected to more than double by 2050 in base-line scenarios
- Non-OECD countries and the U.S. will be the main coal consumers
- In Blue Map Scenario, coal usage for power generation is reduced by >75%
- CCS and efficiency improvements are critical for future use of coal in power generation

Net Plant Efficiency

(With and Without CO_2 Capture and Compression)



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

Technologies For Improving The Efficiency Of New Power Plants

- Supercritical and Ultra-Supercritical Combustion
- Integrated Coal Gasification Combined Cycle (IGCC)
- Advanced Ultra-Supercritical Technology
- Fuel Switching
- Co-Firing
- More Efficient CO_2 Capture Technologies

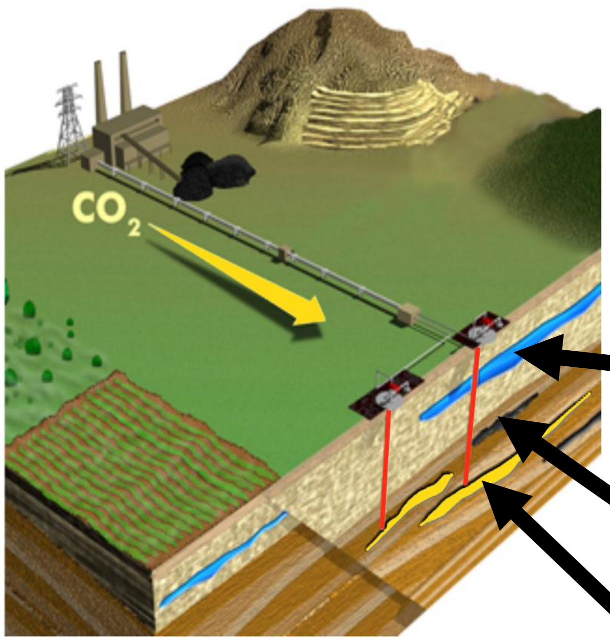
HELE Barriers To Deployment

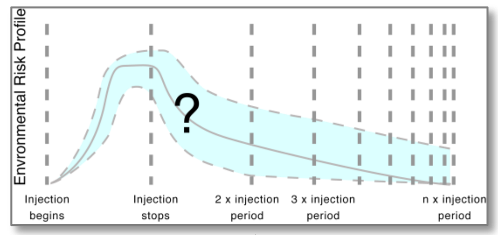
- **Insufficient Information/Sharing of Information**
- **Varying Qualities of Coal**
- **High Upfront Cost of Advanced HELE Coal Technologies**
- **Lack of Appropriate Price, Financial, Legal, and Regulatory Frameworks, (Both in the U.S. and International)**
- **Inadequate Operation and Maintenance Skills**
- **Insufficient Research, Development, and Demonstration**

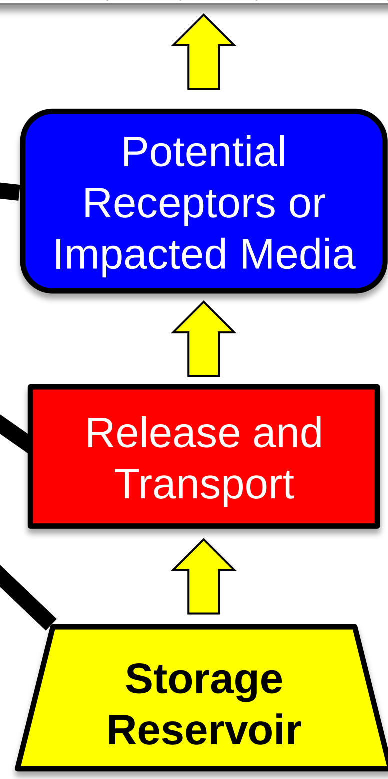
http://www.majoreconomiesforum.org/images/stories/documents/mef%20helec%20tap%2014dec2009.pdf

National Risk Assessment Partnership (NRAP)

Developing a Defensible, Science-Based Methodology for Quantifying Long-Term Liability.







Integrated Assessment Model

- **Storage site described by subsystems**
- **Subsystem behavior can be treated in detail**
- **Uncertainty/heterogeneity handled by stochastic descriptions of subsystems**

NRAP Team

Fossil Energy Lab (fossil energy base)

NETL
- fracture flow models
- geomechanics models
- geospatial databases
- high PT validation

Office of Science Labs (science base)

LBNL
- reactive-flow models
- system models
- field geophysics
- groundwater models

PNNL
- reactive-flow models
- data integration platform
- groundwater models
- high PT validation

NNSA Labs (engineered natural systems)

LLNL
- reactive-flow models
- geomechanics models
- groundwater systems
- high PT validation

LANL
- reactive-flow models
- geomechanics models
- systems models
- geomaterials properties

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

Advanced CO_2 Capture Technologies

Solvent Technologies

- Novel High Capacity Oligomers
- Phase Change Solvents
- Ionic Liquids
- Amino Acids
- Carbonates
- Enzymes
- Advanced Processes

Oxycombustion Technologies

- "2nd Gen" Oxyboiler Designs
- Existing Boiler Retrofits
- Low Cost O_2 (Membrane)
- CO_2 Purification
- Co-Sequestration

Chemical Looping

Advanced CO_2 Compression

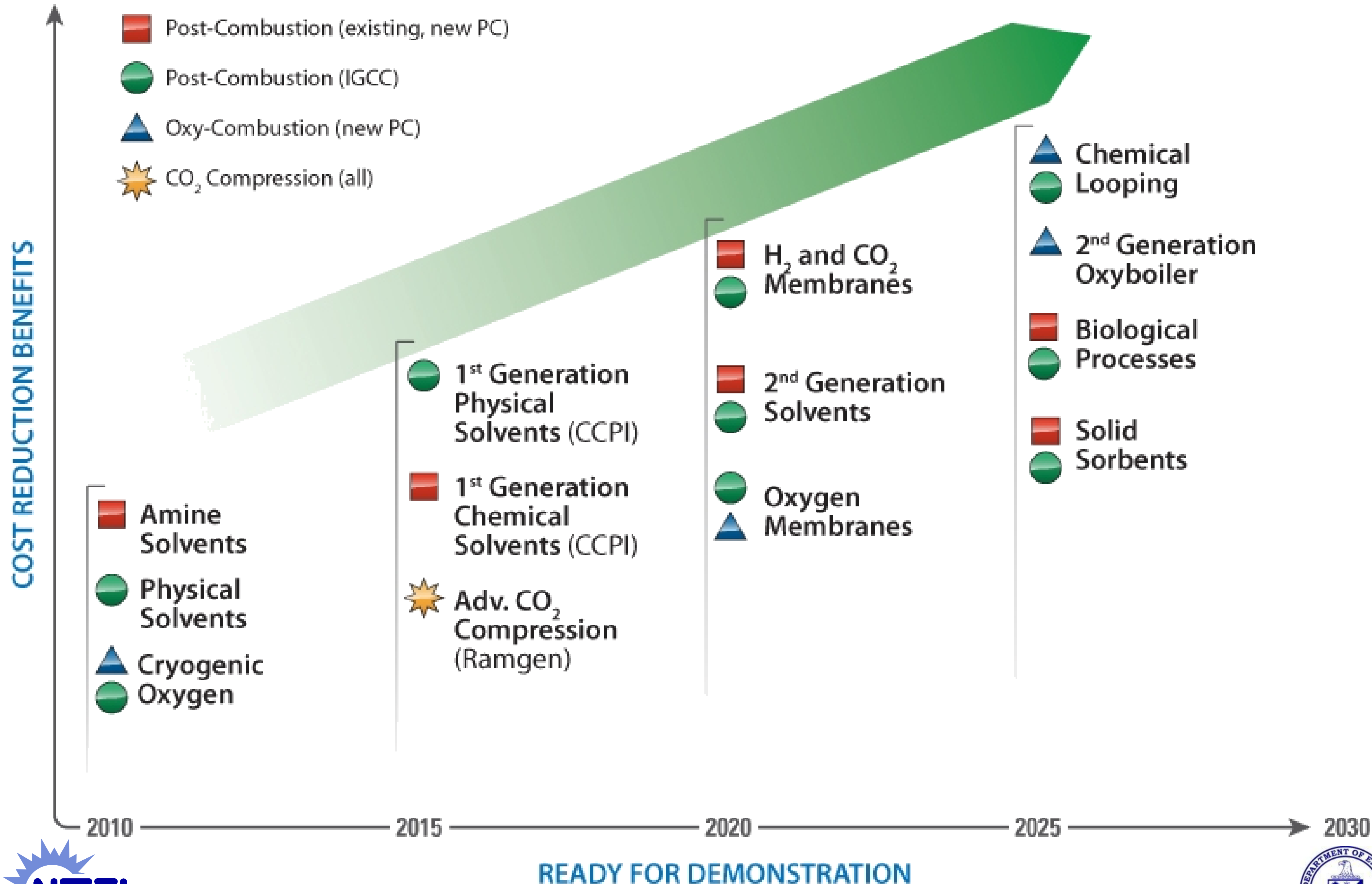
Sorbent Technologies

- Metal Organic Frameworks
- Supported Amines
- Metal Organic Framework (MOF)
- Carbon-based
- Alumina
- Water-Gas Shift (IGCC)
- Sorbent Systems Development

Membrane Technologies

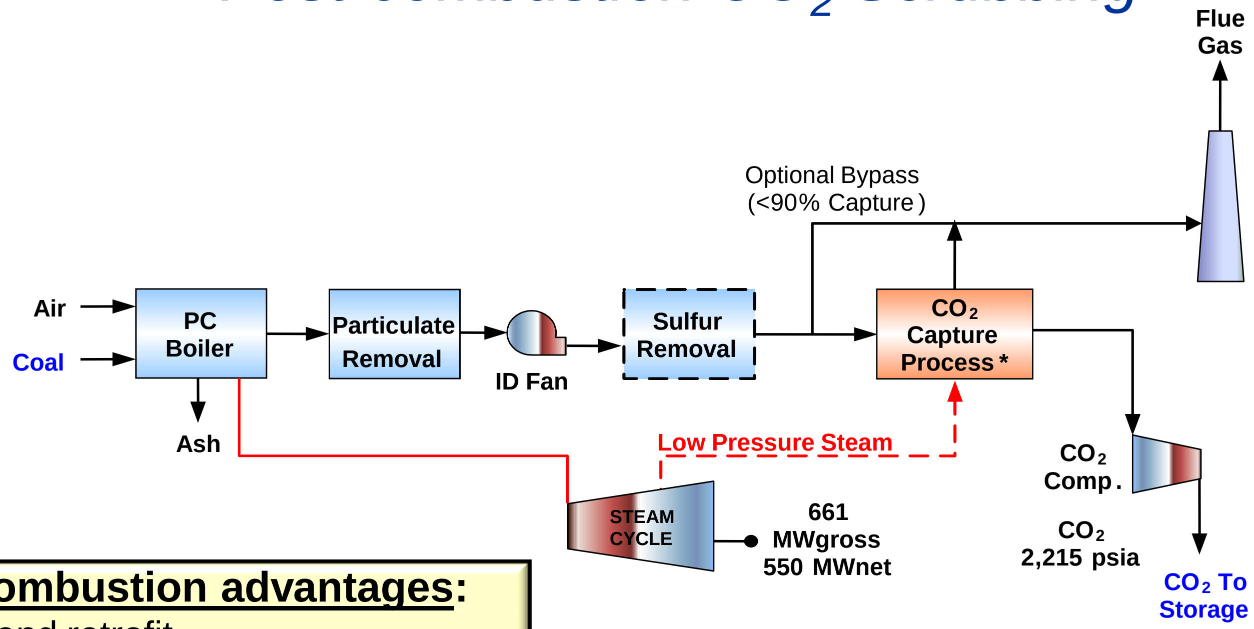
- Spiral wound & hollow fiber
- Cryogenic membrane separation
- Membrane/Solvent Hybrid
- Fuel Cell Hybrid
- Integrated Water-Gas Shift
- H_2 Selective Zeolite
- High Temperature Polymer
- Nanoporous
- PSA/Membrane Hybrid
- Palladium Alloys

Fossil Energy CO_2 Capture Solutions



Pulverized Coal Power Plant System

Post-combustion CO_2 Scrubbing



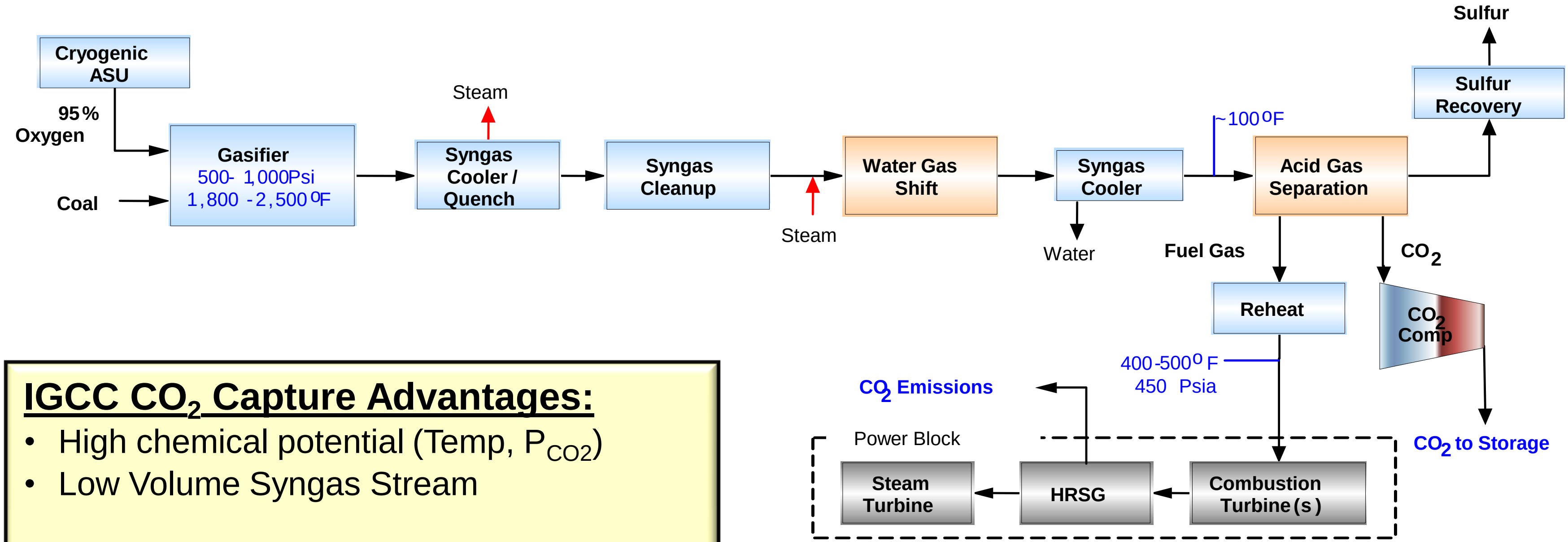
<u>Post-combustion advantages</u>:
- Back-end retrofit
- Slip-stream (0 to 90% capture)

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

<u>Key Challenges</u>:
- 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

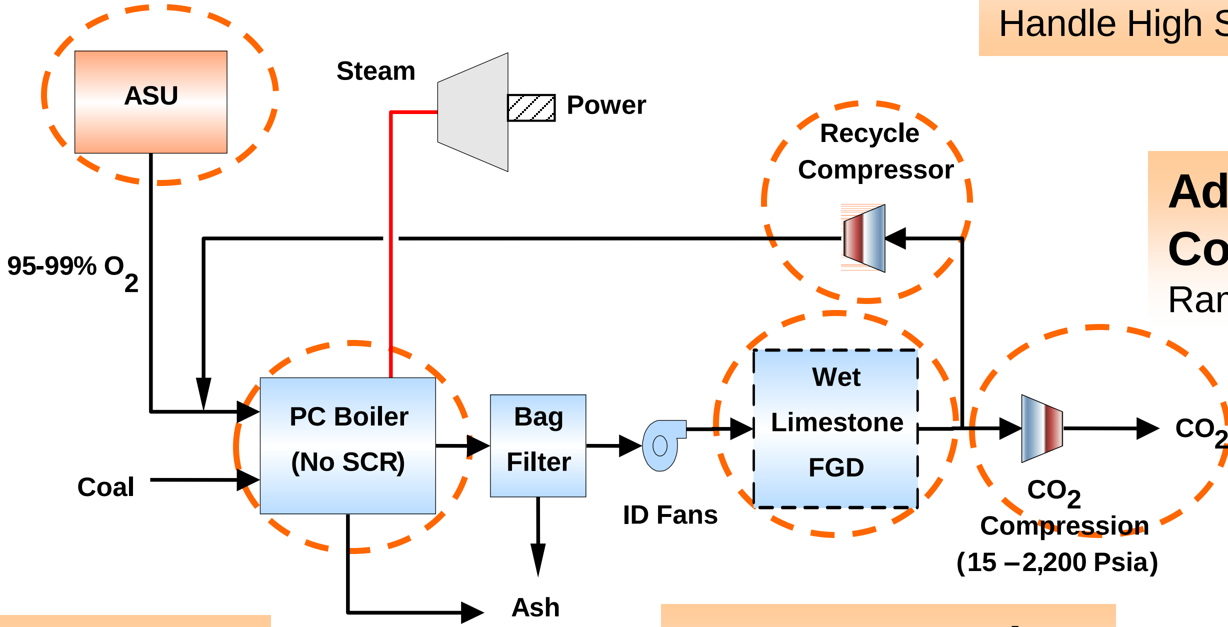
Pulverized Coal Oxyfuel Combustion

Technology Opportunities

Cheap Oxygen
Oxygen Membra

Coal + O_2 → $CO_2 + H_2O$

Advanced MOC*
Reduce CO_2 Recycle
Handle High Sulfur Con.



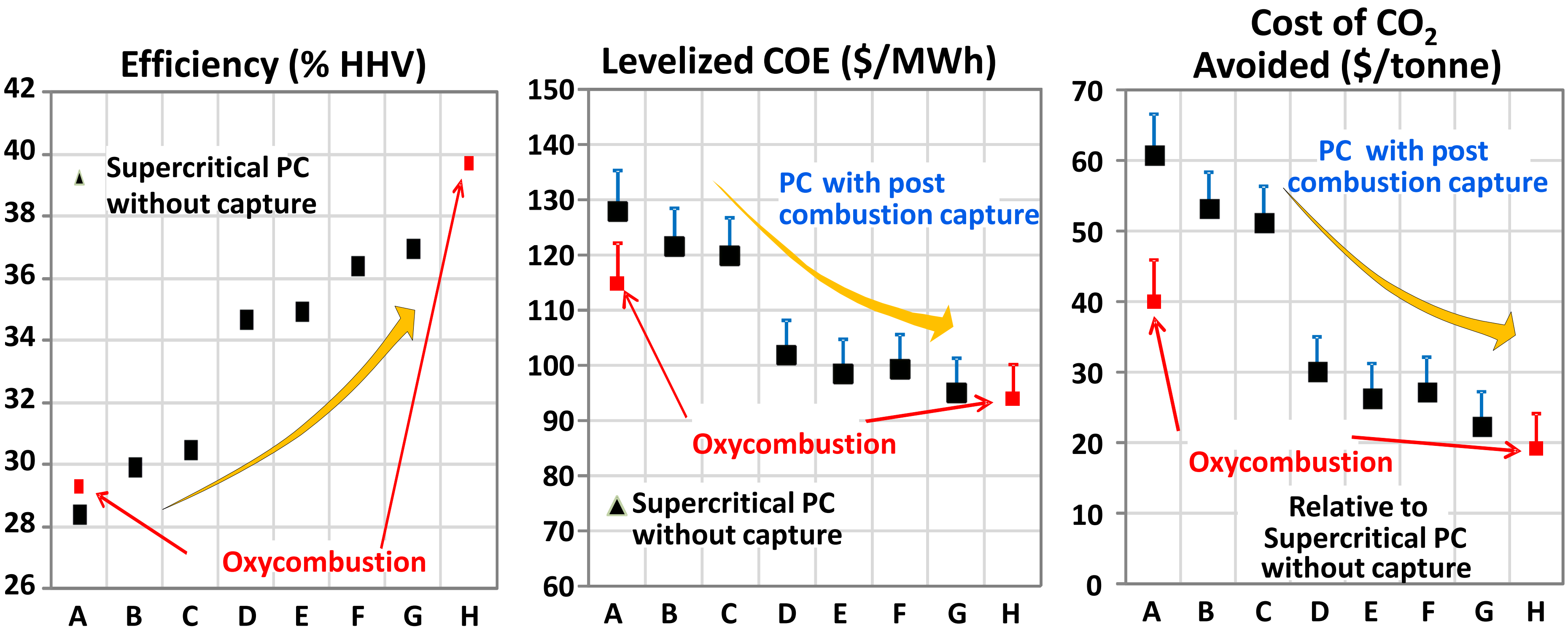
Advanced Compression
Ramgen, SwRI

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

Co-Sequestration
Multi-pollutant capture

*Materials of Construction

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.

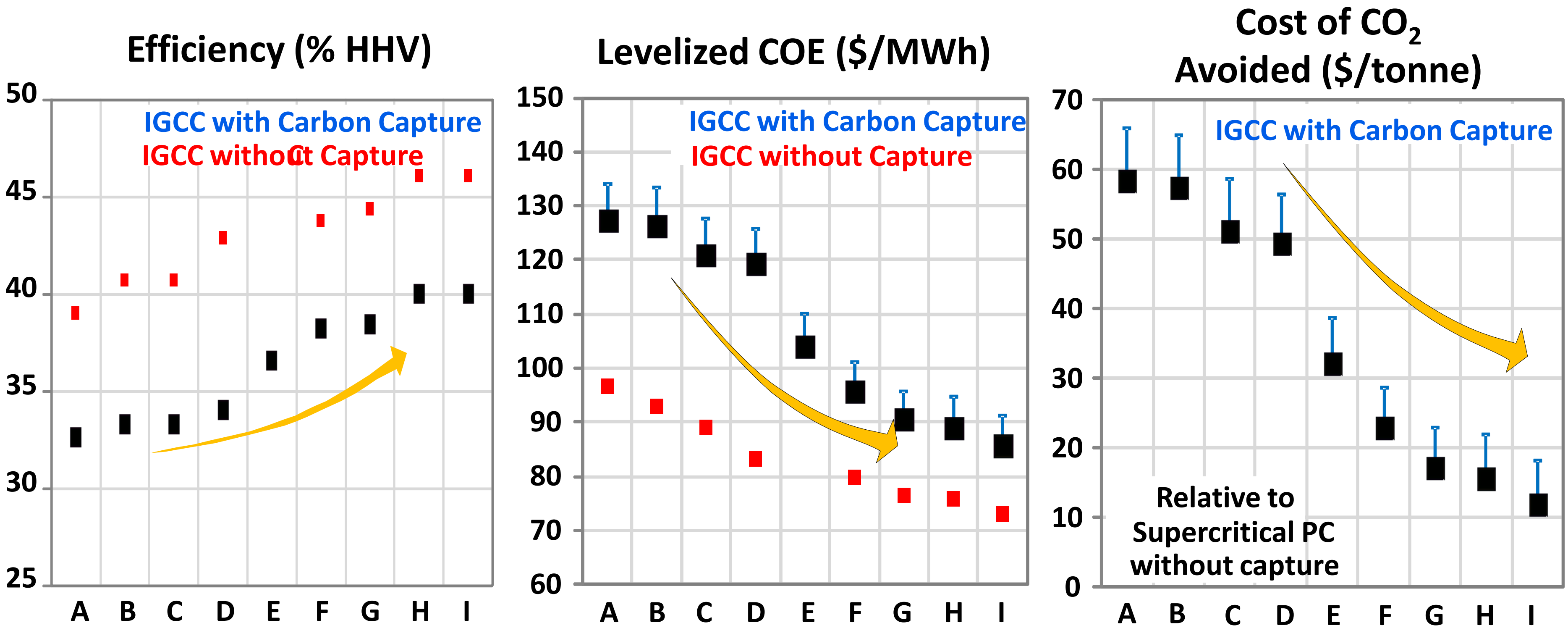
H – Advanced Oxycombustion

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)

European Technology Platform for Zero Emission Fossil Fuel Power Plants Key Conclusions

- Post 2020, CCS will be cost-competitive with other low-carbon energy technologies
- CCS is applicable to both coal- and natural gas-fired power plants
- All three CO_2 capture technologies could be competitive once
- successfully demonstrated
- Early strategic planning of large-scale CO_2 transport infrastructure
- is vital to reduce costs
- A risk-reward mechanism is needed to realize the significant aquifer potential
- for CO_2 storage
- CCS requires a secure environment for long-term investment

http://www.zeroemissionsplatform.eu/library/publication/165-zep-cost-report-summary.html

European Technology Platform for Zero Emission Fossil Fuel Power Plants CCS Costs

•**CO_2 Capture**

Hard coal-fired power plants without capture have an LCOE of ~€48/MWh (excluding EUA costs), rising to €65-70/MWh[9] with capture for an OPTI plant.

Natural gas-fired power plants without capture have an LCOE of ~€70/MWh, rising to ~€90/MWh with capture.

•**CO_2 Transport**

Typical costs for a short onshore pipeline (180 km) and a small volume of CO_2 (2.5 Mtpa) are just over €5/tonne of CO_2. This reduces to ~€1.5/tonne of CO_2 for a large system (20 Mtpa).

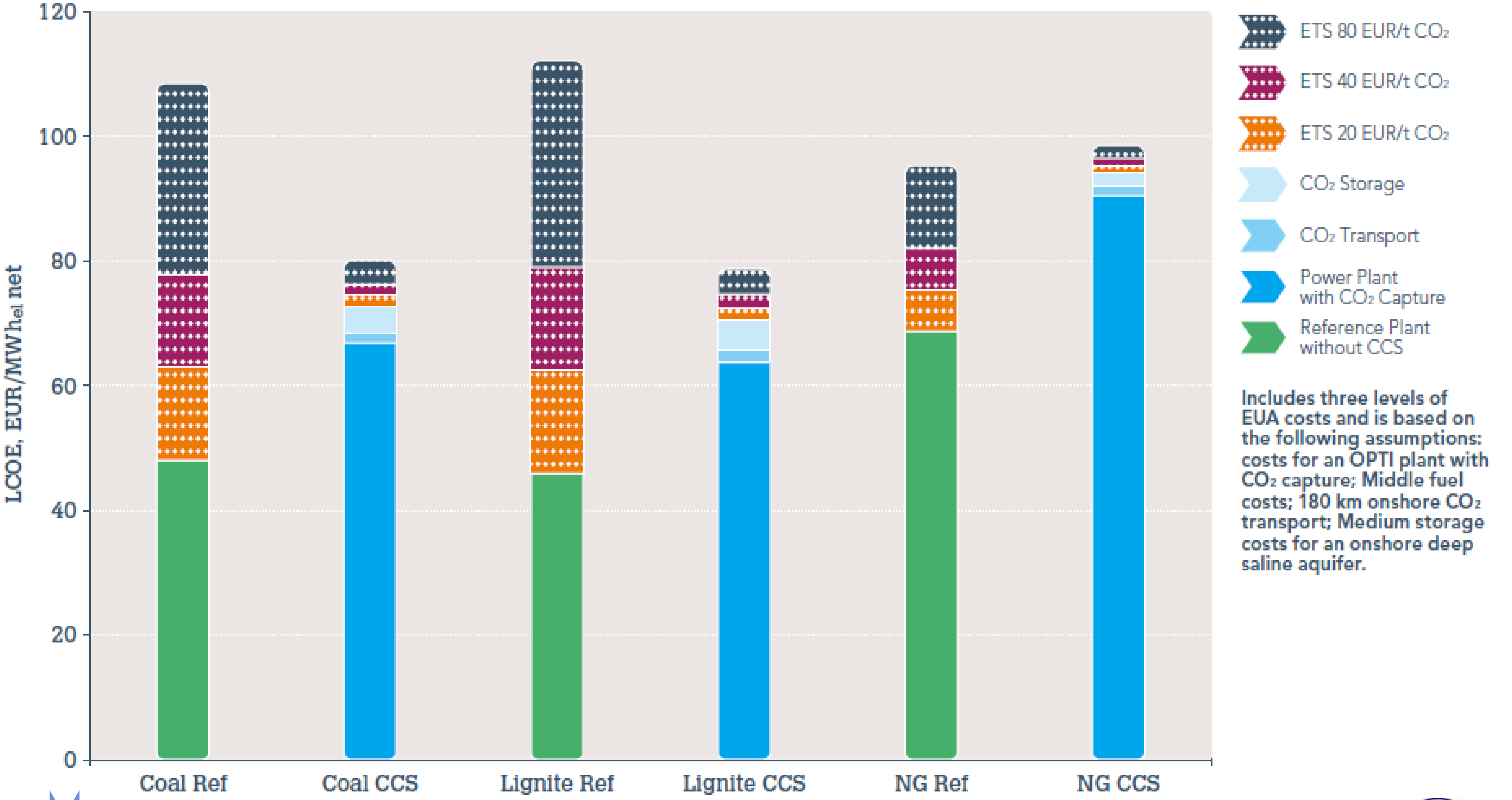
Offshore pipelines are more expensive at ~€9.5 and €3.5/tonne of CO_2 respectively, for the same conditions. If length is increased to 500 km, an onshore pipeline costs €3.7/tonne of CO_2 and an offshore pipeline ~€6/tonne of CO_2.

•**CO_2 Storage**

The cost range is large – from €1 to €20/tonne of CO_2.

http://www.zeroemissionsplatform.eu/library/publication/165-zep-cost-report-summary.html

The LCOE Of Integrated CCS Projects Compared To The Reference Plants W/O CCS

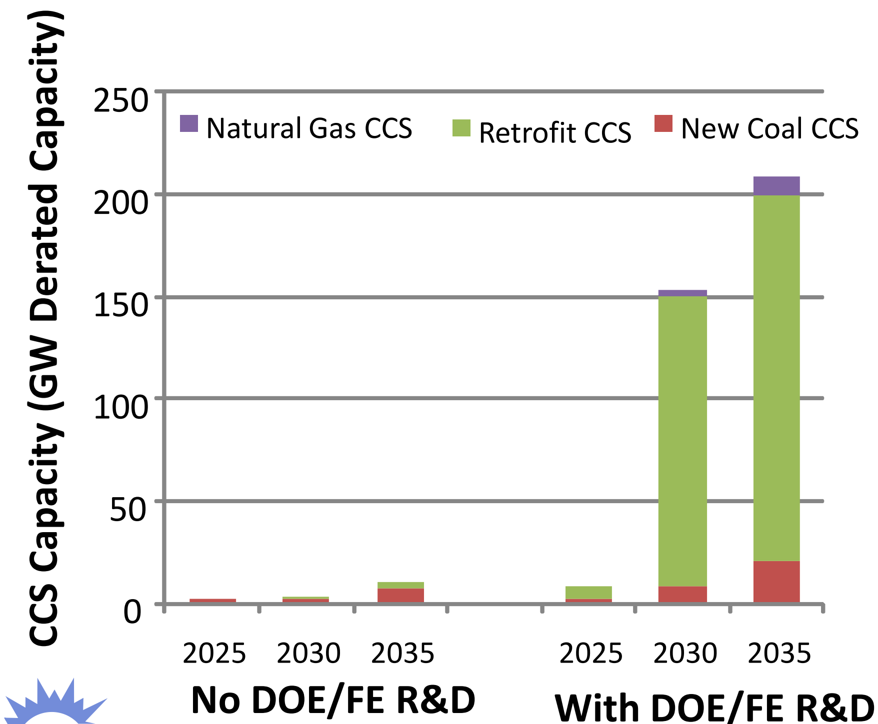


Office of Fossil Energy

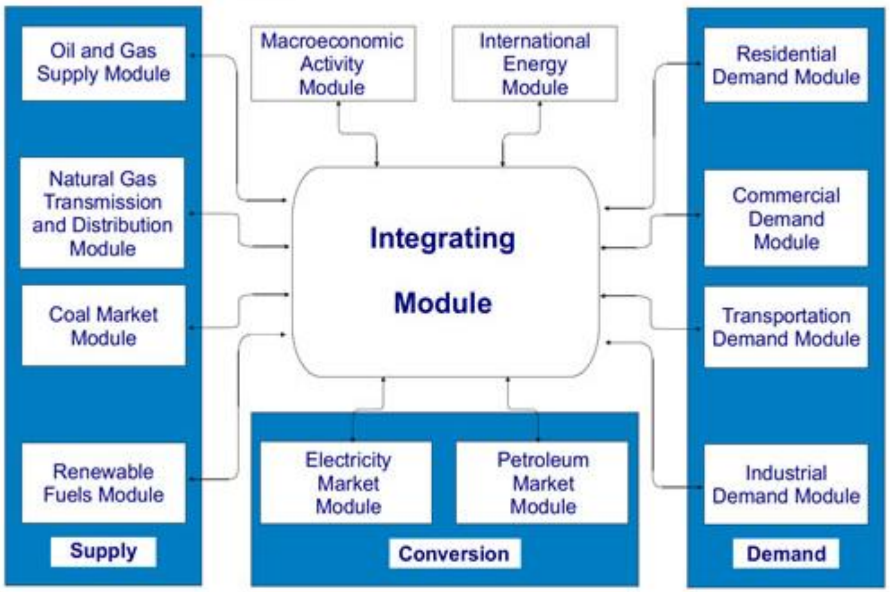
http://www.zeroemissionsplatform.eu/library/publication/165-zep-cost-report-summary.html

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!

Advanced Technology Benefits

- Increased Power Plant Efficiency
- Minimal Increase in Cost of Electricity (COE)
- Avoided Costs
- Reduced Consumption of Fossil Fuels
- Better Environment
- Improvement in Quality of Life for All

Areas For International Cooperation

- OEDC Capture, Transport and Storage Technology Partnerships
- Transfer of Technology to Non-OEDC Countries
- Development and Demonstration of Advanced CO_2 Capture Technologies
- Large-Scale Demonstration of CO_2 Storage
- Global Geological Storage Database
- Global Risk Assessment Partnership
- Public Outreach and Education

For Additional Information

Charles Taylor
+1- 412-386-6058 –or– **+1-304-285-0232**
charles.taylor@netl.doe.gov

Office of Fossil Energy
www.fe.doe.gov

NETL
www.netl.doe.gov