NATIONAL ENERGY TECHNOLOGY LABORATORY

Gasification Systems Program – Slide Library

Jenny B. Tennant

Technology Manager - Gasification

U.S. DEPARTMENT OF ENERGY

Slide Library

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Gasification 101

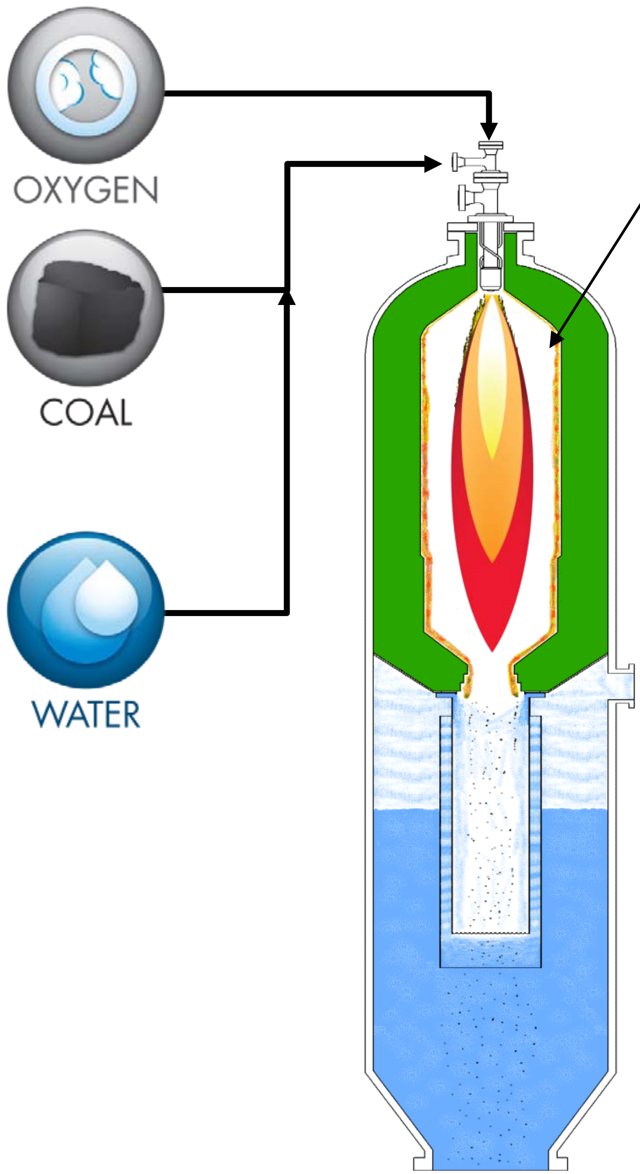
What is Gasification?

Gasification converts any carbon-containing material into synthesis gas, composed primarily of carbon monoxide and hydrogen (referred to as syngas)

Syngas can be used as a fuel to generate electricity or steam, as a basic chemical building block for a large number of uses in the petrochemical and refining industries, and for the production of hydrogen

Gasification adds value to low- or negative-value feedstocks by converting them to marketable fuels and products

The Gasifier



Extreme Conditions:

415 psia or more
2,600 F
Corrosive slag and H_2S gas

Products (syngas)

CO (Carbon Monoxide)
H_2 (Hydrogen)
[CO/H_2 ratio can be adjusted]

Gas Clean-Up before Product Use

By-products

H_2S (Hydrogen Sulfide)
CO_2 (Carbon Dioxide)
Slag (Minerals from Coal)

Courtesy: Eastman Chemical

Gasification – Differences from Combustion

Add water and high pressure

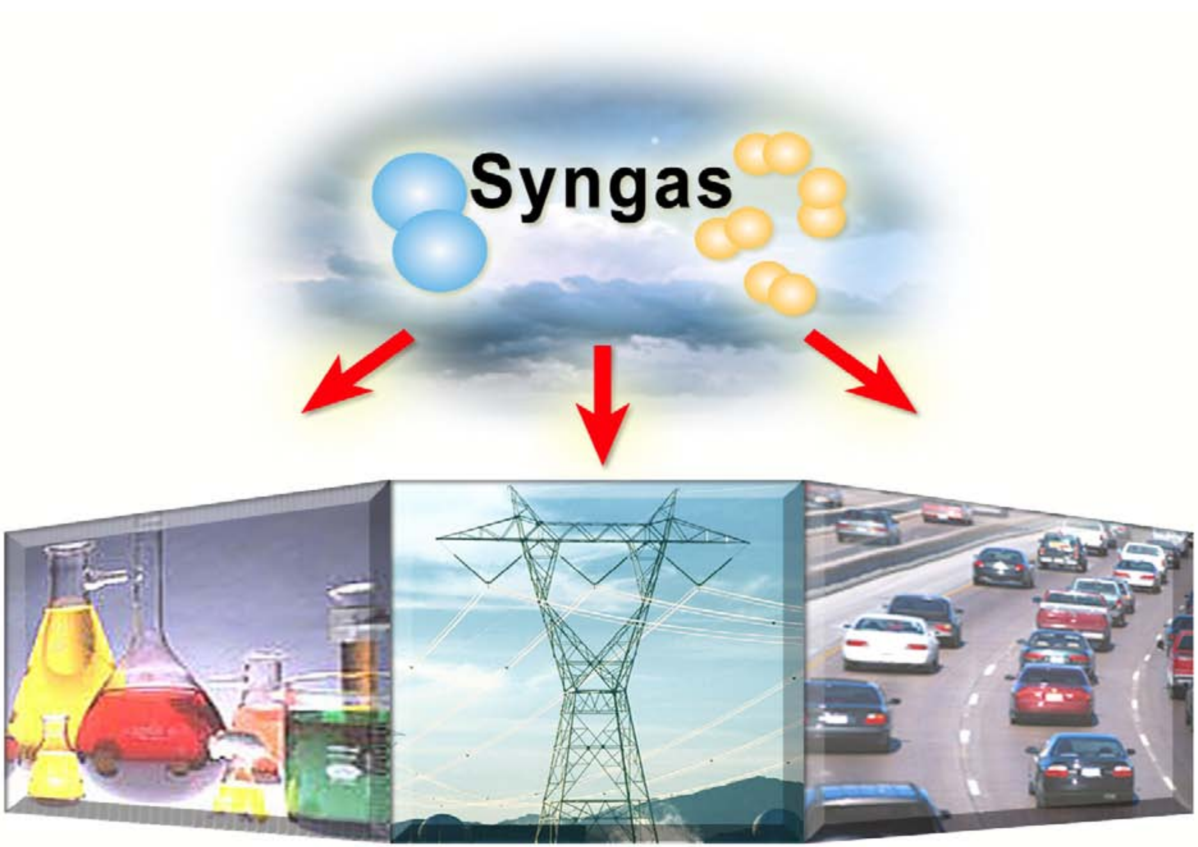
Use less air or oxygen

Gasification exit gases are at high pressure, so smaller volume, smaller reactors

Combustion makes heat + CO_2 + H_2O

Gasification makes less heat + carbon monoxide + hydrogen ($CO + H_2$); called Syngas

So what can you do with CO and H_2 ?



Building Blocks for Chemical Industry

Clean Electricity

Transportation Fuels (Hydrogen)

Water-Gas-Shift (WGS) Reaction

Dry syngas is ~ 40% CO + 50% H_2

– For each CO molecule the WGS reaction creates one H_2 molecule and one CO_2 molecule

$$CO + H_2O + \textit{catalyst} \longrightarrow CO_2 + H_2$$

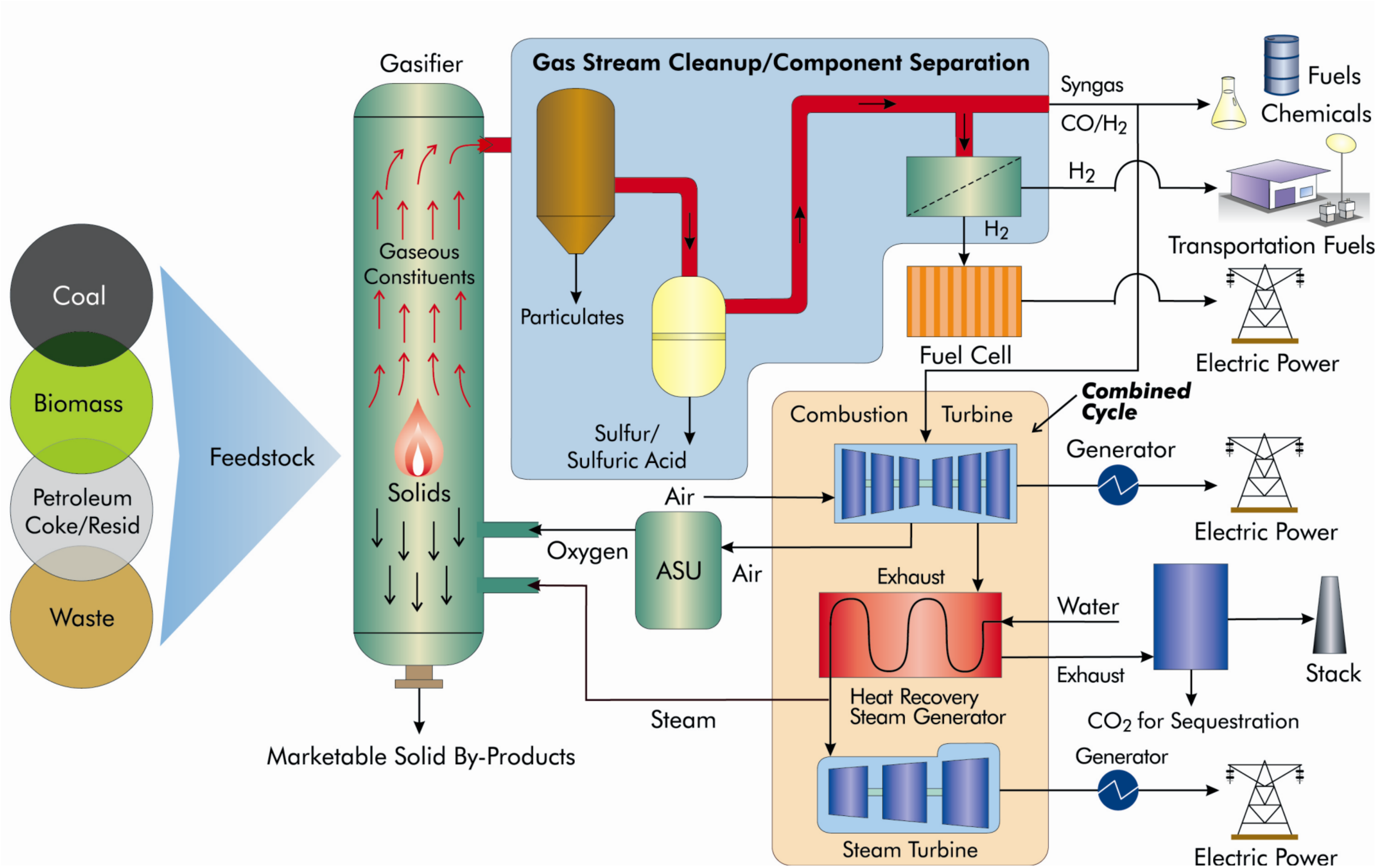
After the WGS reaction, the CO_2 and H_2 can be separated

High pressure CO_2 results in lower cost sequestration

Hydrogen can be burned to make power

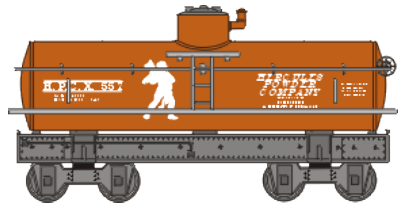
$$2H_2 + O_2 \longrightarrow 2H_2O$$

Overview of Energy Systems Options



Chemicals and Products from Gasification

Syngas



Acetic Anhydride
Acetic Acid

Methanol

Ammonia

Fertilizer (Urea)

Liquid Fuels (Diesel)

Hydrogen

Courtesy: Eastman Chemical

Benefits of Gasification

- Feedstock flexibility
  - Wide range of coals, petcoke, liquids, wastes, biomass can be utilized
- Product flexibility
  - Syngas can be converted to high valued products: electricity, steam, hydrogen, liquid transportation fuels, SNG, chemicals
- Environmental superiority
  - Pollutants can be economically controlled to extremely low levels (SO_2, NO_X, CO, Hg, etc.)
  - Reduced water consumption
  - Potential solid wastes can be utilized or easily managed
  - High efficiency / low CO_2 production
  - CO_2 can be easily captured for sale or geologic storage (sequestration)

Program Slides

Why the Interest in Coal Gasification?

Continuing fuel price fluctuation – natural gas and transportation fuels

Energy security – the U.S. has a lot of coal

Gasification can be used to make hydrogen (H_2), synthetic natural gas (SNG), fertilizer, chemicals and transportation fuels from coal

Can be the lowest cost option to make power with carbon dioxide (CO_2) capture and storage

Excellent environmental performance for power generation

Gasification Systems Program Goal

The goal of the Gasification Systems Program is to reduce the cost of electricity, while increasing power plant availability and efficiency, and maintaining the highest environmental standards

"Federal support of scientific R&D is critical to our economic competitiveness"

Dr. Steven Chu, Secretary of Energy
November 2010

Gasification Systems Program

Focus to reduce the cost of gasification, while increasing plant availability and efficiency, and maintaining the highest environmental standards

FE Program Target: IGCC with CSS that has less than 10% increase in COE and 90% capture

Increasing focus on low rank coal (LRC) gasification

- EIA forecasts significant growth in western coal production; low rank western coal cost per Btu will stay at about half that of eastern coal
- Industry interest in cost-sharing LRC R&D
- Potential for economic boost to U.S. regions with LRC reserves

Gasification Systems Program

Key Research Areas

Gasifier Optimization

- Improve reliability
- Expand fuel flexibility
- Increase efficiency

Gas Cleanup

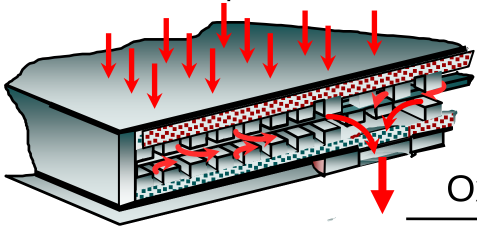
- Control multi-contaminants to extremely low levels

Gas Separation

- Oxygen separation
- Hydrogen and carbon dioxide separation

Key Gasification Systems R&D Areas

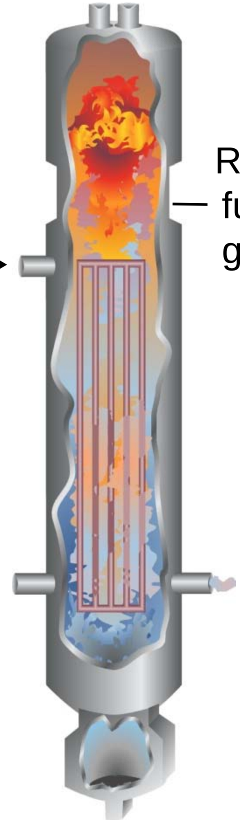
Hot Compressed Air



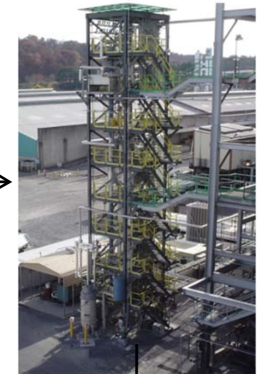
Oxygen

Gas Separation

– Oxygen from Air



Raw fuel gas



Gas Cleaning

– Control multi-contaminants to extremely low levels

Clean fuel gas

Feedstock

Water Gas Shift

H_2 rich stream

CO_2

Gasifier Optimization

– Improve reliability
– Expand fuel flexibility
– Increase efficiency

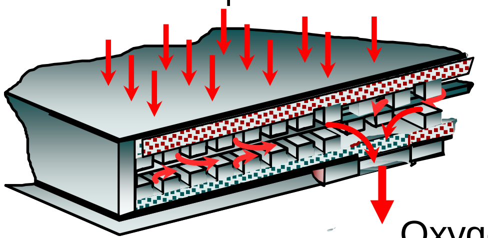
Gas Separation

– CO_2 from Hydrogen

Gasification Systems Projects

Anticipated Benefits

Hot Compressed Air



Oxygen

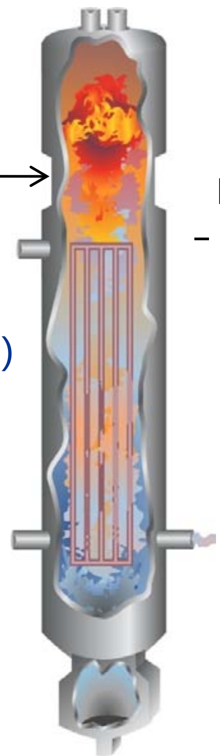
APCI Oxygen Membrane

- 6.9% capital cost reduction (36.0% O_2 plant capital cost reduction)
- 5.0% COE reduction

Feedstock

PWR Coal Feed Pump

- 1.0% COE reduction



Raw Fuel Gas

Clean Fuel Gas

RTI Warm Gas Cleaning

in combination with

Eltron H_2-CO_2 Membrane

- 2.6 % pt efficiency increase
- 12.0% COE decrease

Water Gas Shift

- Process improvement and intensification

H_2 Rich Stream

CO_2

Gasifier Optimization

Low-rank Coal Alternative Feedstocks

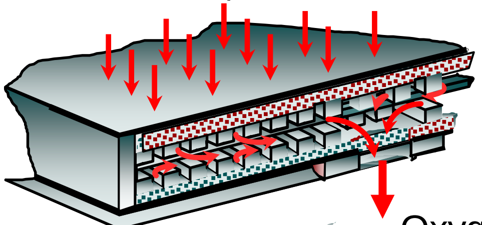
- Energy security
- Carbon footprint reduction

Improve RAM

- Refractory durability
- Feed system reliability
- Heat removal/integration
- Temperature control & measurement
- Dynamic simulator
- CFD gasifier modeling
- Slag model development

Gasification Systems Project Benefits

Hot Compressed Air



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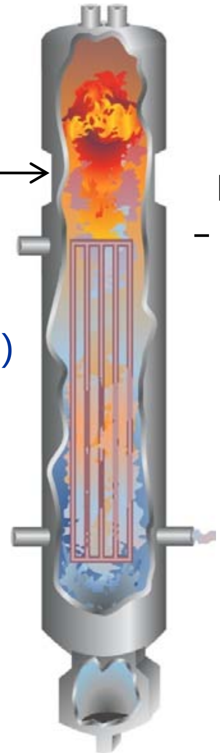


Raw Fuel Gas

Clean Fuel Gas

Water Gas Shift

NCCC WGS Optimization

ORD Pd Sorbent

RTI Warm Gas Cleaning

in combination with

Eltron H_2-CO_2 Membrane

- 2.6 % pt efficiency increase
- 12.0% COE decrease

H_2 Rich Stream

CO_2

Gasifier Optimization

Low-rank Coal Alternative Feedstocks

Goal is competitive use of LRC

Improve RAM

Goal is 10% Improvement

Low Rank Coal Program Pathway

Why It's the Right Time

Gasification industry interviews show interest in low rank coal

- Most projects are cost shared with industry
- Industry use is objective of Gasification Program R&D

Low rank coals present unique challenges *and* opportunities for gasification and IGCC

- High inherent moisture, high in alkali metals (Na, K, Ca)
- High oxygen content, high reactivity, low sulfur and <u>Low Cost</u>

NETL systems analysis has shown low rank coal gasification has the potential to be economically competitive

- Altitude vs Shipping
- Limited gasifier types

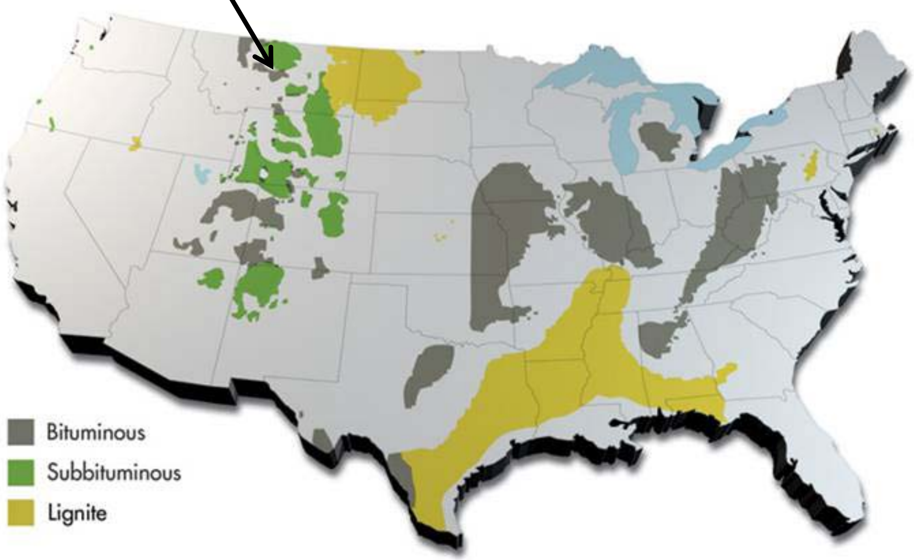
About half of world, and U.S., coal reserves are low rank -- a global market opportunity for advanced IGCC technology

U.S. Low Rank Coal Resources and Prices

Low rank: lignite and sub-bituminous coal

- About 50% of the U.S. coal reserves
- Nearly 50% of U.S. coal production
- Lower sulfur

Year	Lignite Price ($/ST)	PRB Price ($/ST)	Bitum. Price ($/ST)
2010	16.77	13.93	53.40
2011	16.41	13.15	51.87
2015	16.67	13.00	48.70
2020	17.31	13.92	48.23
2025	17.83	15.31	49.03

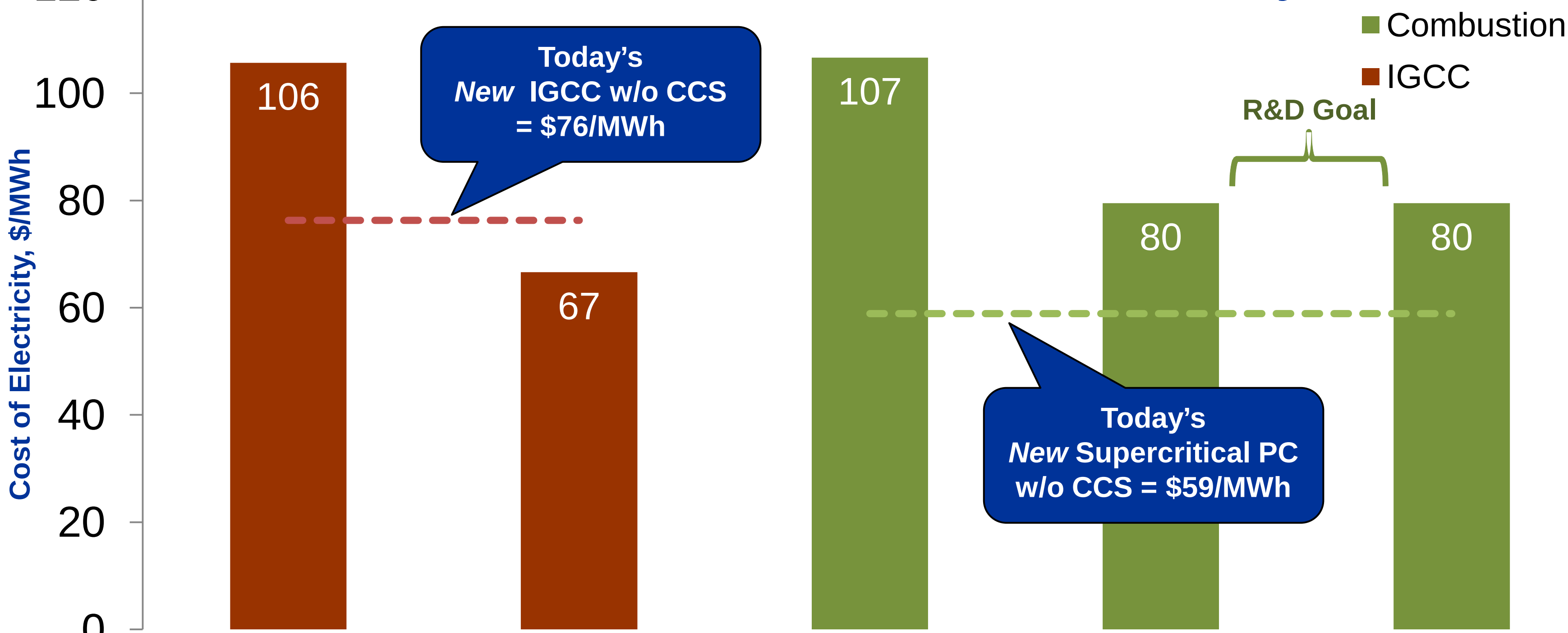


EIA forecasts significant growth in western coal production; declining eastern coal production

Low rank western coal cost per Btu will stay at about half that of eastern coal

Anticipated Results from Established Research

New Plants - R&D Goals for 2nd Gen CCS Systems



IGCC w/CCS R&D Progress to Date
- Adv F turbine
- 80% Availability

2nd Gen IGCC w/CCS
- Coal pump
- WGCU
- H_2 membrane
- ITM
- Adv H_2 turbine-2 (>2600 F TIT) *2 on 1 configuration*
- 85% Availability

Today's Supercritical PC w/CCS
- Air-fired
- 3500 psig/ 1100F/1100F
- Wet FGD
- Amine absorber for CO_2 separation
- 85% Availability

2nd Gen Advanced Oxy-Combustion PC w/CCS

Potential technology mix to meet 35% goal:
- Oxy-fired combustion
- Boiler-integrated ITM
- USC steam cycle (4000 psig / 1350F / 1400 F)
- Compact oxyfuel-specific boiler
- SO_x co-sequestration
- 85% Availability

2nd Gen Advanced Post-Combustion PC w/CCS

Potential technology mix to meet 35% goal
- Advanced solvents, sorbents or membranes
- USC steam cycle
- Advanced CO_2 compression
- 85% Availability

Key Assumptions:
- June 2007 dollars (equivalent to January 2010 dollars per Chemical Engineering Plant Cost Index)
- Capital cost component includes owner's costs
- $1.64/MMBtu coal price
- "R&D Progress to Date" and "Today's SCPC" cases based on Rev 2 of Bituminous Baseline Study
- "2nd Gen IGCC w/CCS" case based on NETL's IGCC Pathway study, Volume 2, Rev 2 DRAFT

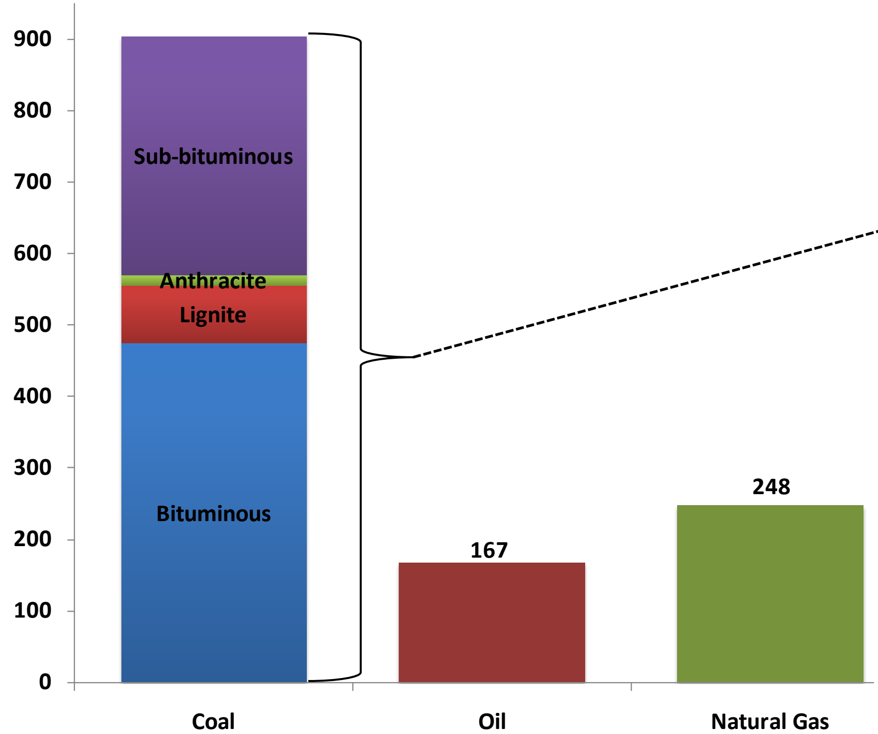
TIT = turbine inlet temperature WGCU = warm gas cleanup ITM = ion transport membrane USC = Ultra supercritical FGD = Flu Gas Desulfurization

Energy Outlook

U.S. Fossil Fuel Resources

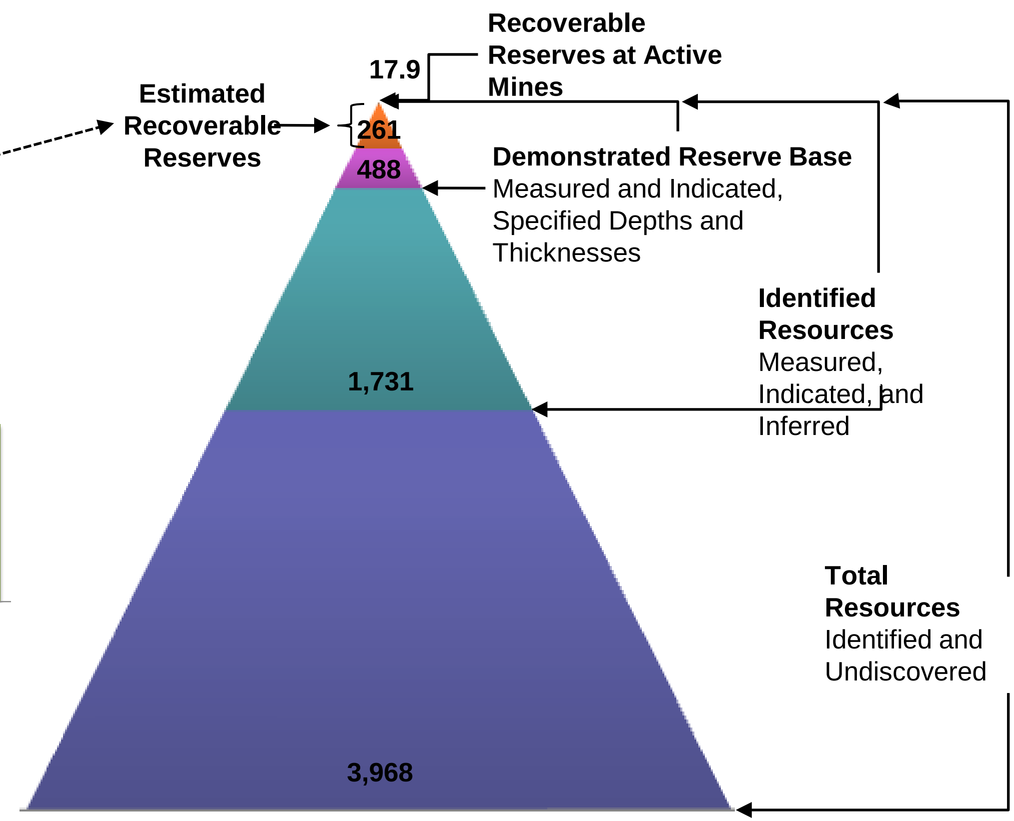
U.S. Fossil Fuel Reserves and Resources

barrels of oil equivalent



U.S. Coal Resources

billion short tons



Sources: Chart - Whitney, Gene et al., U.S. Fossil Fuel Resources: Terminology, Reporting, and Summary, Congressional Research Service, October 2009 p14

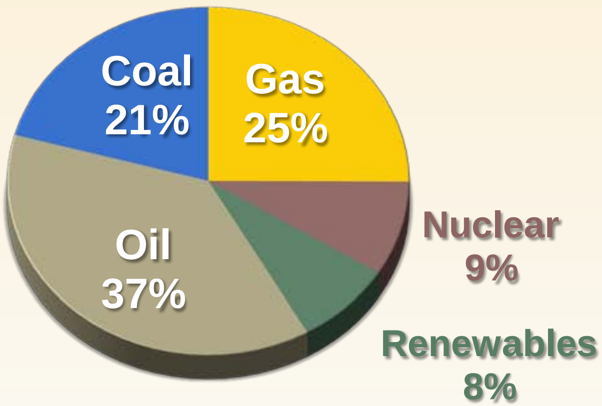
Pyramid figure - U.S. Energy Information Administration, Form EIA-7A, Coal Production Report, February 2009

Energy Demand 2009

Energy Demand 2035

United States

95 QBtu / Year
83% Fossil Energy

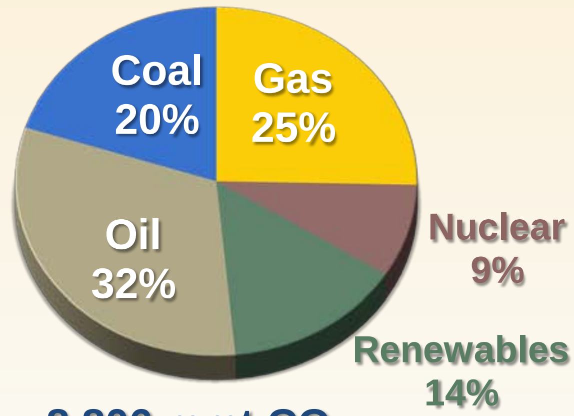


5,425 mmt CO_2

+ 14%

United States

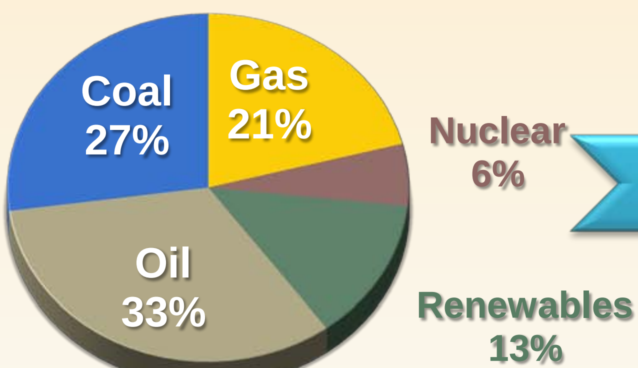
108 QBtu / Year
77% Fossil Energy



8,806 mmt CO_2

World

481 QBtu / Year
81% Fossil Energy

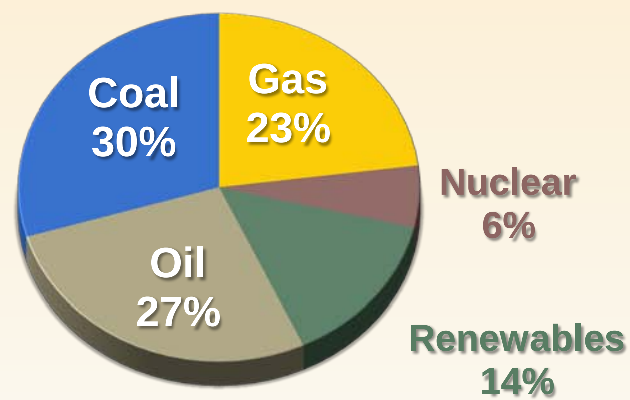


28,844 mmt CO_2

+ 51%

World

726 QBtu / Year
80% Fossil Energy



43,320 mmt CO_2

Sources: U.S. data from EIA, Annual Energy Outlook 2012er: World data from IEA, World Energy Outlook 2011

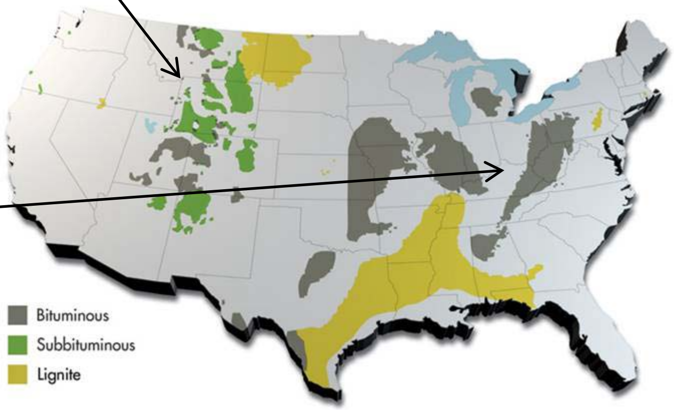
U.S. Coal Resources

Low rank: lignite and sub-bituminous coal

- About 50% of the U.S. coal reserves
- Nearly 50% of U.S. coal production
- Lower sulfur

Bituminous coal

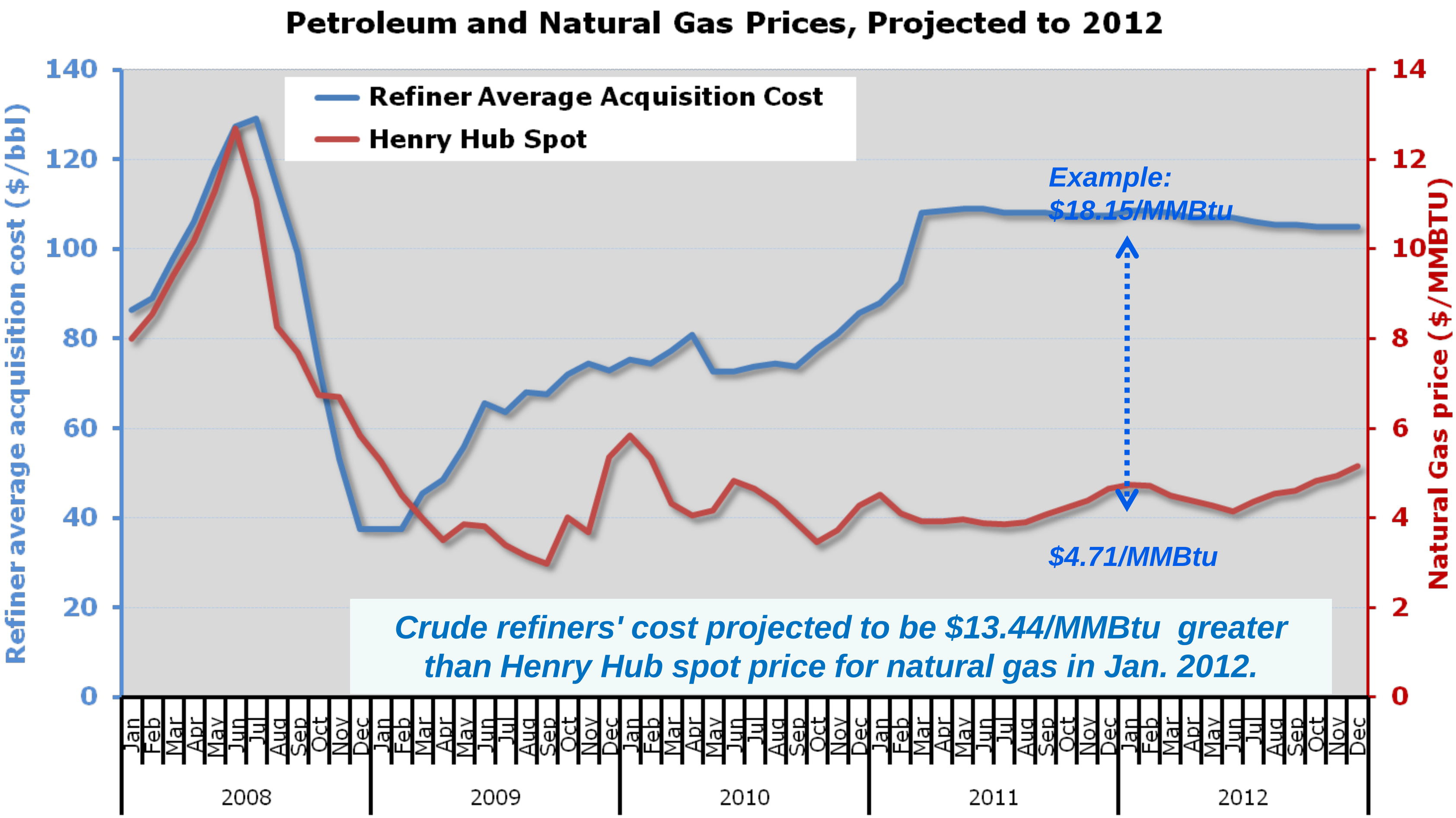
- About 50% of the U.S. coal reserves
- Higher heating value
- Lower moisture and mineral content



EIA forecasts significant growth in western coal production; declining eastern coal production

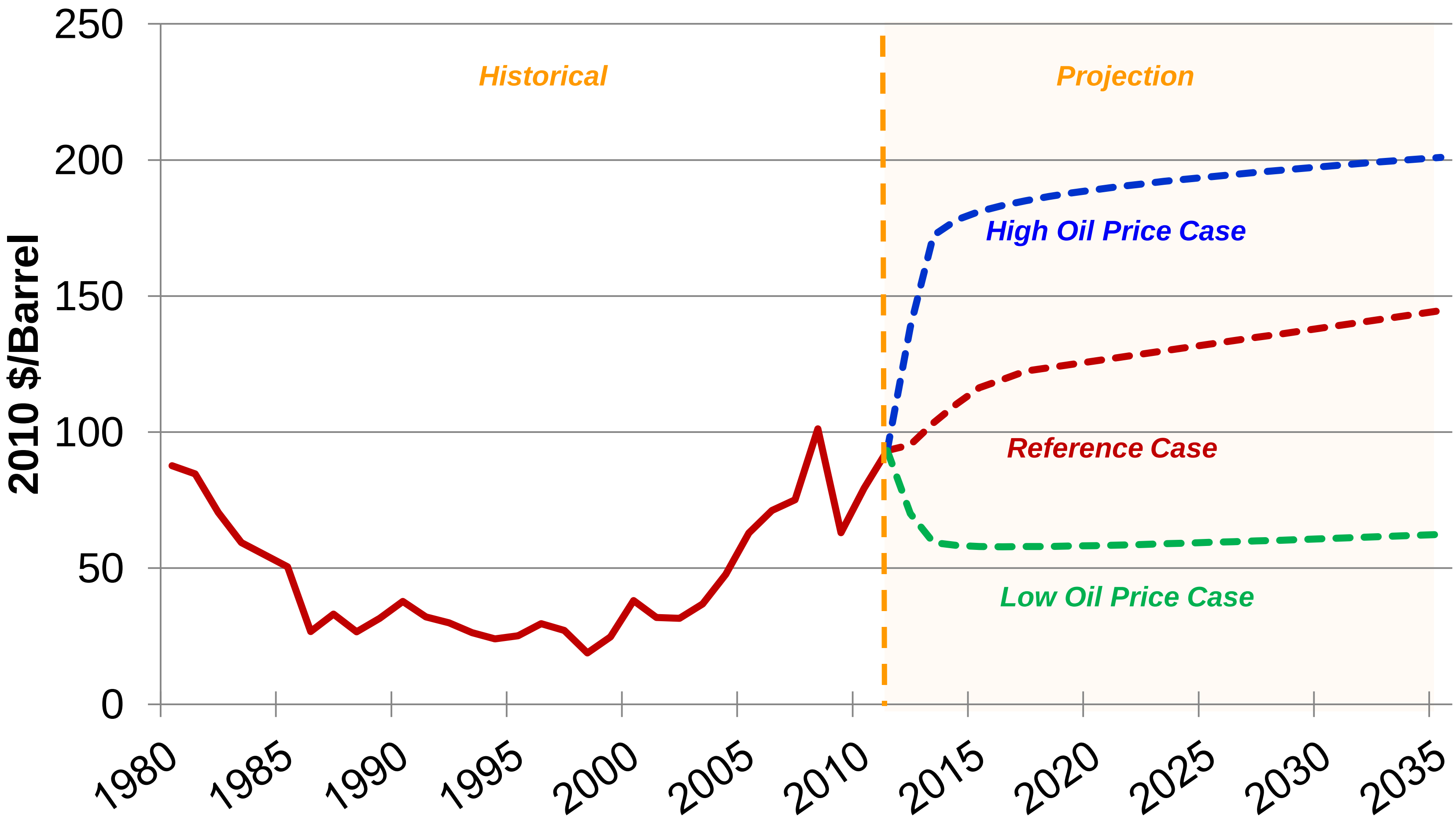
Low rank western coal cost per Btu will stay at about half that of eastern coal

Oil and Gas Price Comparison



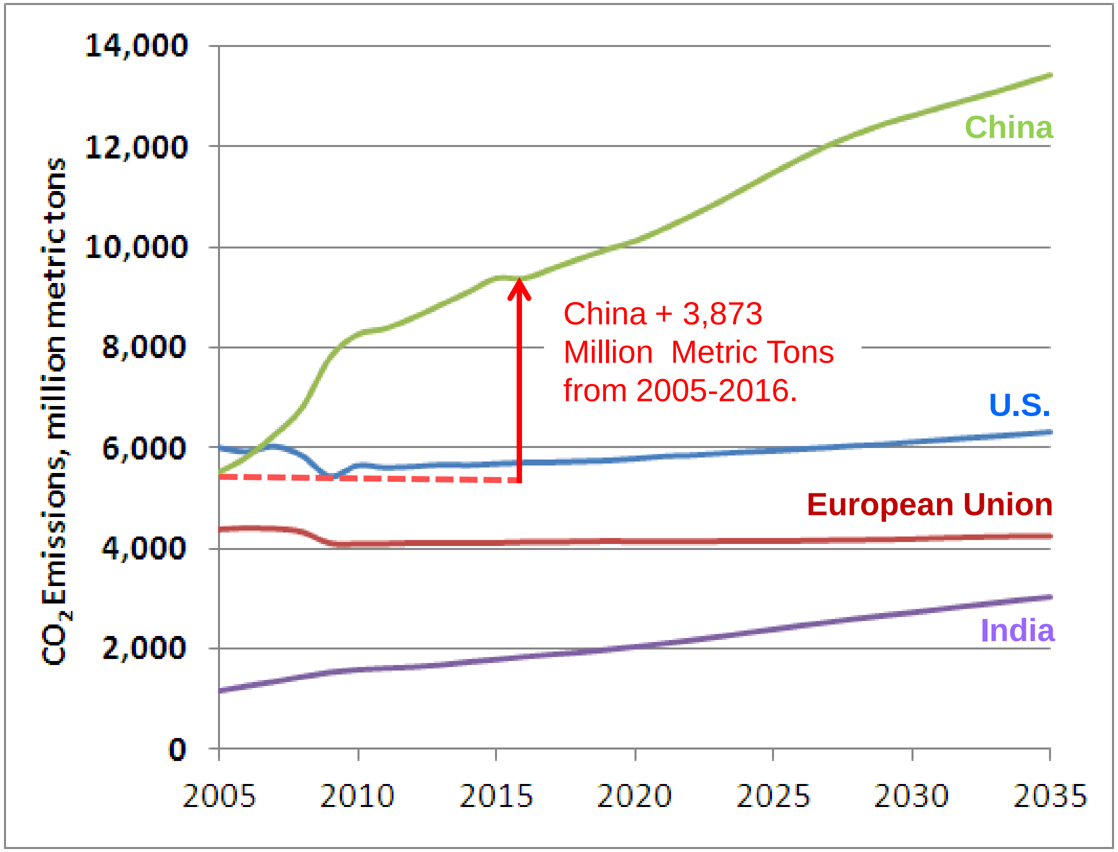
Source: EIA's Short Term Energy Outlook, Table 2

Average World Oil Price Projections



Source: EIA AEO 2012 (early release), Figure 5

Carbon Capture is a Global Issue

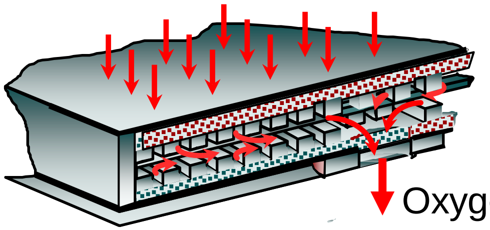


- **The European Union are anticipated to maintain level of CO_2 release through 2035; 2020 for U.S.**
- **China and India CO_2 emissions will substantially increase into 2035**
- **By 2020, China's CO_2 emissions will eclipse U.S. and the European Union, combined**
- **By 2015, China aims to cut CO_2 emissions per unit economic growth by 16 percent of 2011 levels**

Source: *IEA World Energy Outlook 2010, Current Policies Scenario*

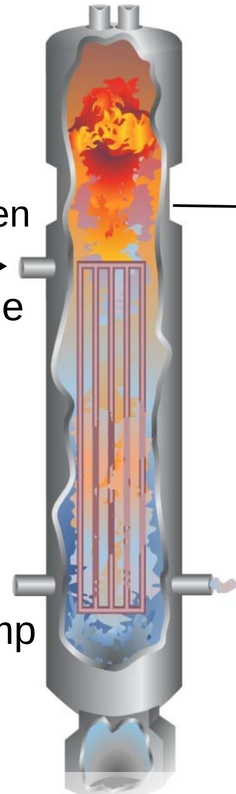
Active DOE Cooperative Agreements

Gasification Systems Program Projects



Oxygen

APCI Ion Transport Membrane



RTI Warm Gas Cleanup
ORD Pd Sorbent
APCI Sour PSA
 – scoping study

TDA Integrated CO_2 Removal and WGS*
 – scoping study

Eltron H_2/CO_2 Membrane

PWR Dry Coal Feed Pump
GE Posimetric Pump*
 – scoping study
EPRI CO_2-Coal Slurry*
 – scoping study

Water Gas Shift

H_2 rich stream

CO_2

NCCC WGS Optimization

Gasification Optimization

<u>Improve RAM</u>

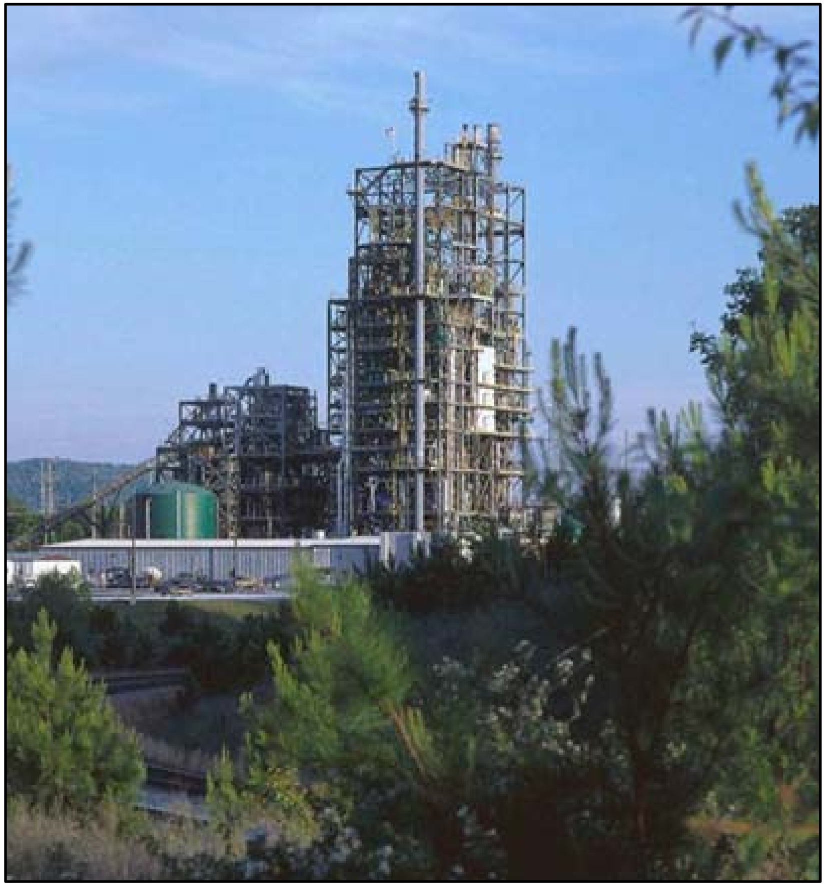
VPI Temperature Sensor
REI Syngas Cooler Fouling
GTI Real-Time Flame Monitor Sensor
GE Improve Availability and Reduce Costs
ORD Improve Refractory
ORD Conversion and Fouling

***Low-rank Coal Alternative Feedstocks**

NCCC Transport Gasifier Optimization
ORD Low Rank Coal Optimization

National Carbon Capture Center at the Power Systems Development Facility (PSDF)

Southern Company Services



Location: Wilsonville, AL

Subcontractors

- American Electric Power
- Arch Coal
- Electric Power Research Institute
- Luminant
- NRG
- Peabody Energy
- Rio Tinto

Development and commercial scale-up of modular industrial scale gasification-based processes and components

National Carbon Capture Center

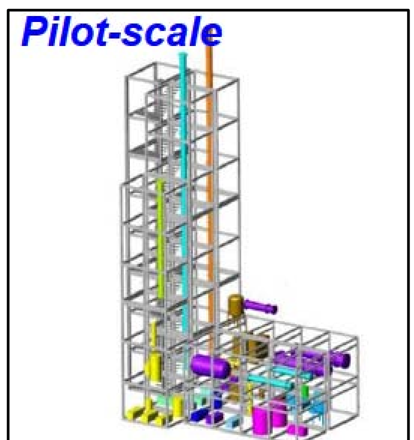
Southern Company Services

Goal: Accelerate path to cost-effective CO_2 capture technology for all 3 major areas of CO_2 Capture; post combustion, pre-combustion, oxy-combustion

Technology: Flexible testing facilities for scale-up from bench to engineering-scale

Project tasks

Modifications underway to enhance and enlarge pre-combustion CO_2 capture testing infrastructure to enable testing of membranes, sorbents and solvents



National Carbon Capture Center (NCCC)

Advanced Gasification and H_2 Separation

Fuel flexibility, filter materials, sensor development - 1000 hour gasification test using PRB coal

- Evaluated new gasifier temperature control scheme
- Continued long-term evaluation of hot gas filter elements
- Conducted sensor development involving sapphire thermowell for gasifier service, coal-flow measurement device, and vibration type level detector
- 996 hour test of PRB sub-bituminous coal completed through Dec. 2011

Carbon capture - Modifications continue to enhance and enlarge pre-combustion CO_2 capture testing infrastructure to enable testing of membranes, sorbents, and solvents. Conducted evaluations of:

- Hydrogen and CO_2 membranes
- High-temperature palladium-based mercury sorbent
- CO_2 capture testing with new solvents
- Water-gas shift catalyst performance

Power Systems Development Facility (PSDF)

Project History - Accomplishments

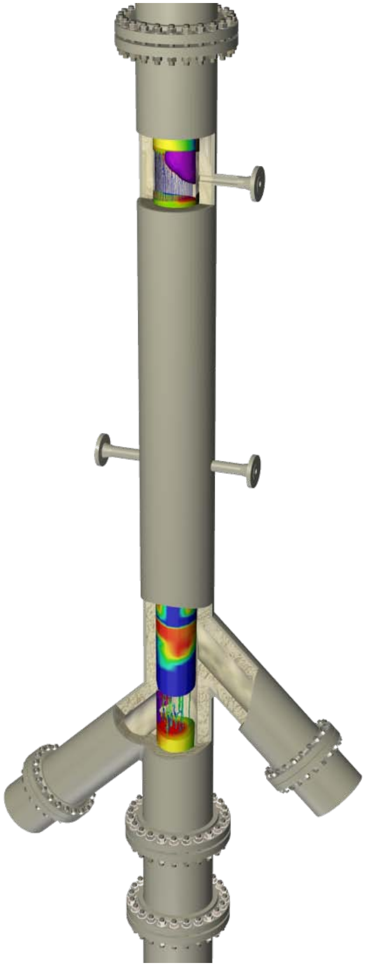
History - Established by DOE in early '90s

- To accelerate development of more efficient advanced coal-based power plant technologies
- Research centered around high-temperature, high-pressure filtration
- Signed over 115 non-disclosure agreements (NDA)s with developers to support advancement of their technologies
- Air-blown Transport Gasifier commenced operation in 1999

Accomplishments - Results through December 31, 2011 include:

- 28 major gasification test campaigns
- 16,000 hours of gasification operation
- Successful engineering scale demonstration of advanced power systems technologies, including:

  Hot gas particulate control device, advanced syngas cleanup systems, and high-pressure solids handling systems
- Developed gasifier suitable for low-rank fuels use
- Extensive successful operation on a variety of coals including: subbituminous, bituminous, and lignite
- TRIG™ technology being used in CCPI demonstration, Kemper County



Ion Transport Membrane (ITM)

Air Products and Chemicals, Inc. (APCI)

Goal: Low cost oxygen production

Technology: O_2 separation from air utilizing peroskovite ceramic membrane technology

Project tasks (planned completion date 9/30/2015)

- Perform module testing utilizing the 5 TPD Test System to evaluate lifetime performance against target values, and obtain membrane module performance data (complete)
- Construct ~100 TPD pilot system to demonstrate integrated operability and performance of ITM system, (construction continuing)
- Construct and start-up the ceramic wafer and module manufacturing [commercial scale] facility (equipment orders placed)
- Conduct process modeling and conceptual design of 2,000 TPD ITM oxygen production plant

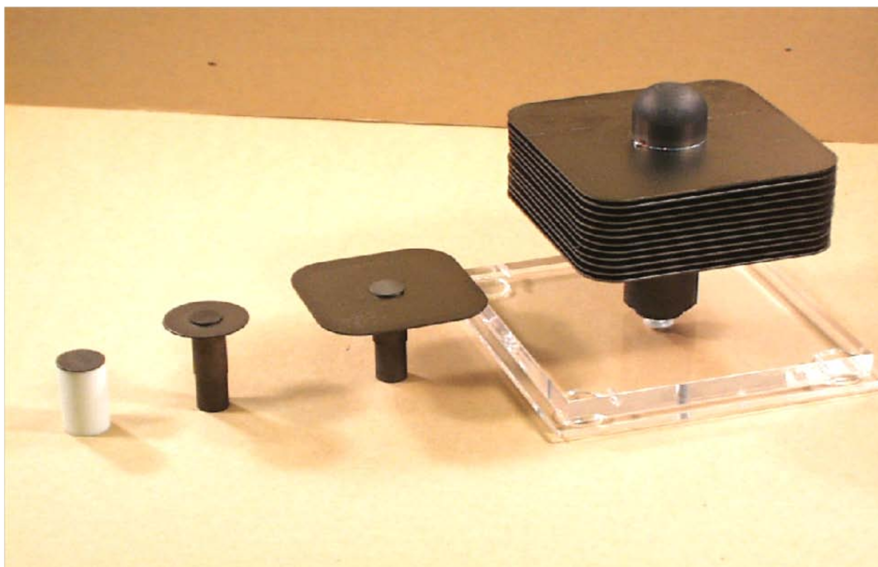
Ion Transport Membrane (ITM)

Development of ITM Oxygen Technology

1.0 TPD Stack

0.5 TPD Stack

Progression to commercial size wafers

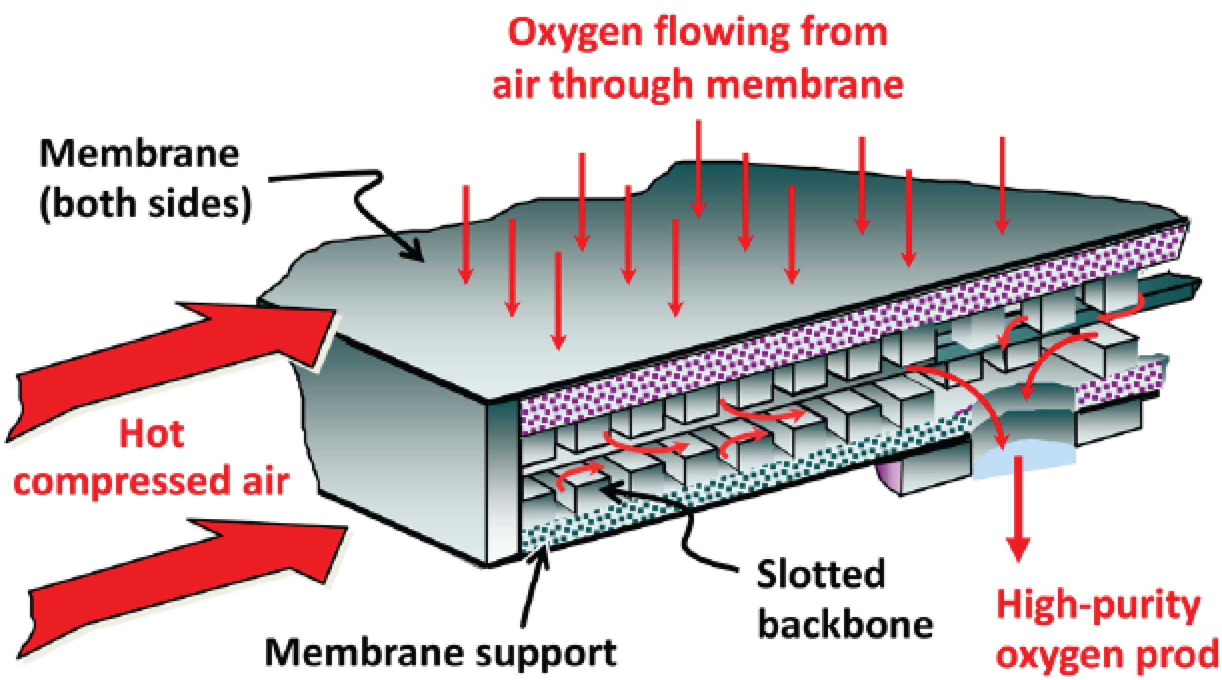


Ion Transport Membrane (ITM)

Air Products and Chemicals, Inc. (APCI)

Ion Transport Membrane (ITM)

– Supported thin-film, ceramic planar devices
– Fast, solid state electrochemical transport of oxygen
– Pressure-driven; compact
– All the layers are composed of the same ceramic material



½-TPD module (multiple membranes)

Membrane Air Separation Advantages

Cryo-ASU vs. ITM in IGCC

IGCC Efficiency	Cryo-ASU	ITM with F-Class GT	ITM with G-Class GT
No CCS	BASE	0.8%	2.9%
With CCS	BASE	0.3%	2.2%

Improved Efficiency

Oxygen Plant Cost	Cryo-ASU	ITM with F-Class GT	ITM with G-Class GT
No CCS	BASE	-24.9%	-34.8%
With CCS	BASE	-24.5%	-36.3%

Better Economics

Levelized Cost of Electricity	Cryo-ASU	ITM with F-Class GT	ITM with G-Class GT
No CCS	BASE	-1.6%	-5.0%
With CCS	BASE	-2.1%	-4.9%

G-Class cases include full air-side integration of advanced gas turbine and oxygen plant

Source: Air Products and Chemicals, Inc.

High Pressure Solids Pump

Pratt & Whitney Rocketdyne

Goal: Reliable and consistent dry feed for high pressure IGCC leading to lower cost

Technology: Bulk solids form multiple stable “bridges” between parallel moving walls to feed dry solids across 1,000+ psi pressure gradient

Project tasks (planned completion date 12/31/2012)

- Complete performance and durability tests
- Perform pump cost benefit analysis

High Pressure Solids Pump

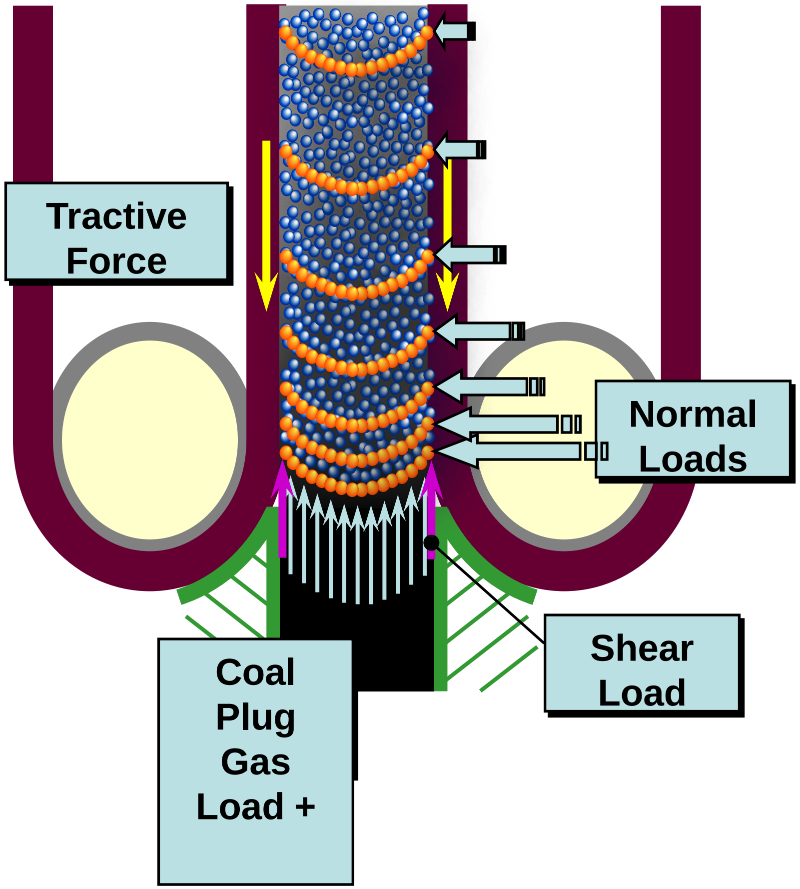
Pratt & Whitney Rocketdyne

Pump operation relies on ability of bulk solids to form multiple stable “bridges” or arch between parallel wall structure, bridges can support very large loads

Increasing load is transferred to sidewalls, making the bridge more stable, further increasing load will ultimately fail the sidewall

Extrusion or “pumping” occurs when sidewalls are moved mechanically and material is released by separating the walls

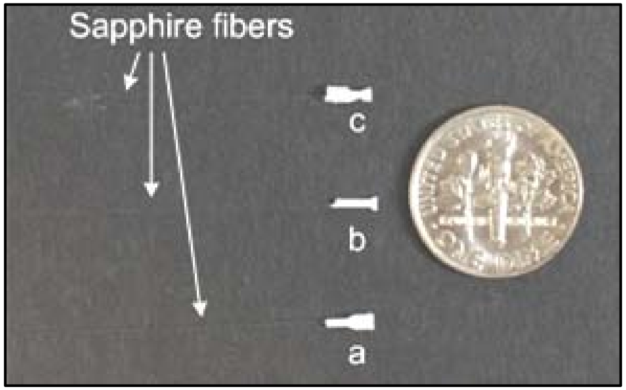
In “lock-up” there is no “slip” or relative motion between material and moving walls, device exhibits “positive displacement” with a volumetric displacement of unity



Single Point Sapphire Temperature Sensor

Virginia Polytechnic Institute

A temperature measurement system based using a sapphire optical sensor that is accurate and reliable for use in the extreme harsh environment of a coal gasifier



Accomplishments

– Accurate readings up to 1600 °C

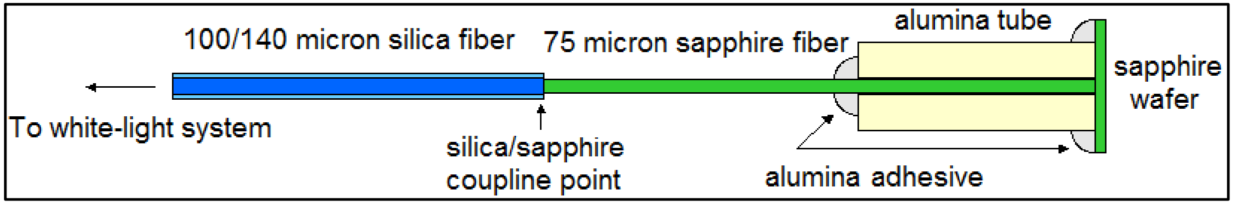
– Full-scale testing at TECO

– 7 months of operation

Future Work

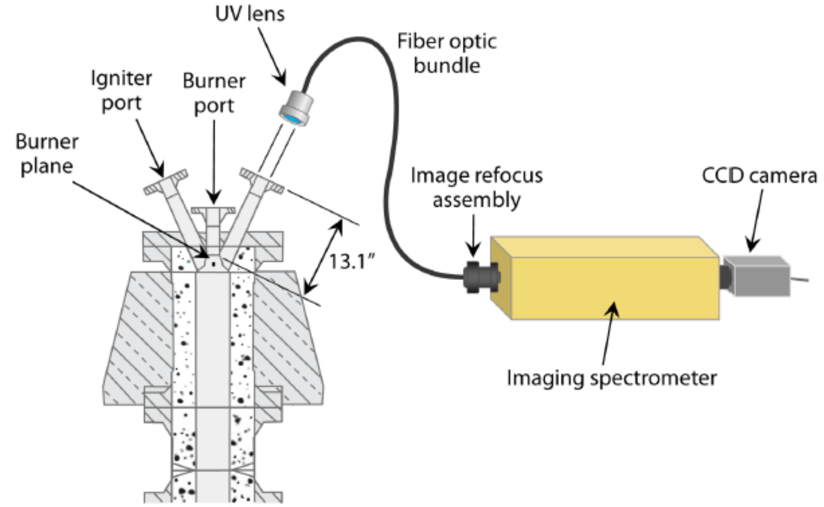
– Validate sensor design for flexible but robust packaging for in situ gasifier monitoring

– Complete bench scale testing sensor probe for combustion turbine monitoring



Real-Time Flame Monitoring Sensor

Gas Technology Institute



Description

– Develop a reliable, practical, and cost-effective means of monitoring coal gasifier conditions (flame characteristics, slag, temperature) using an optical flame sensor

Accomplishments

– Modified sensor to detect UV, visible, and/or near IR wavelengths

– Successfully completed lab-scale testing with natural gas flames

– Successfully tested the sensor on a natural gas mockup of an oxygen-fired, high pressure pilot-scale slagging gasifier

– Performed successful tests at Wabash River IGCC and Pratt & Whitney Rocketdyne pilot gasifier

Future Work

– Initiate full scale testing at Wabash River gasifier to demonstrate long term operation and ability to measure temperature.

Model Based Optimal Sensor Network Design

General Electric Global Research

Goal: Develop an advanced model-based optimal sensor network to monitor the condition of the gasification section in an IGCC plant, focusing on gasifier refractory degradation and radiant syngas cooler fouling

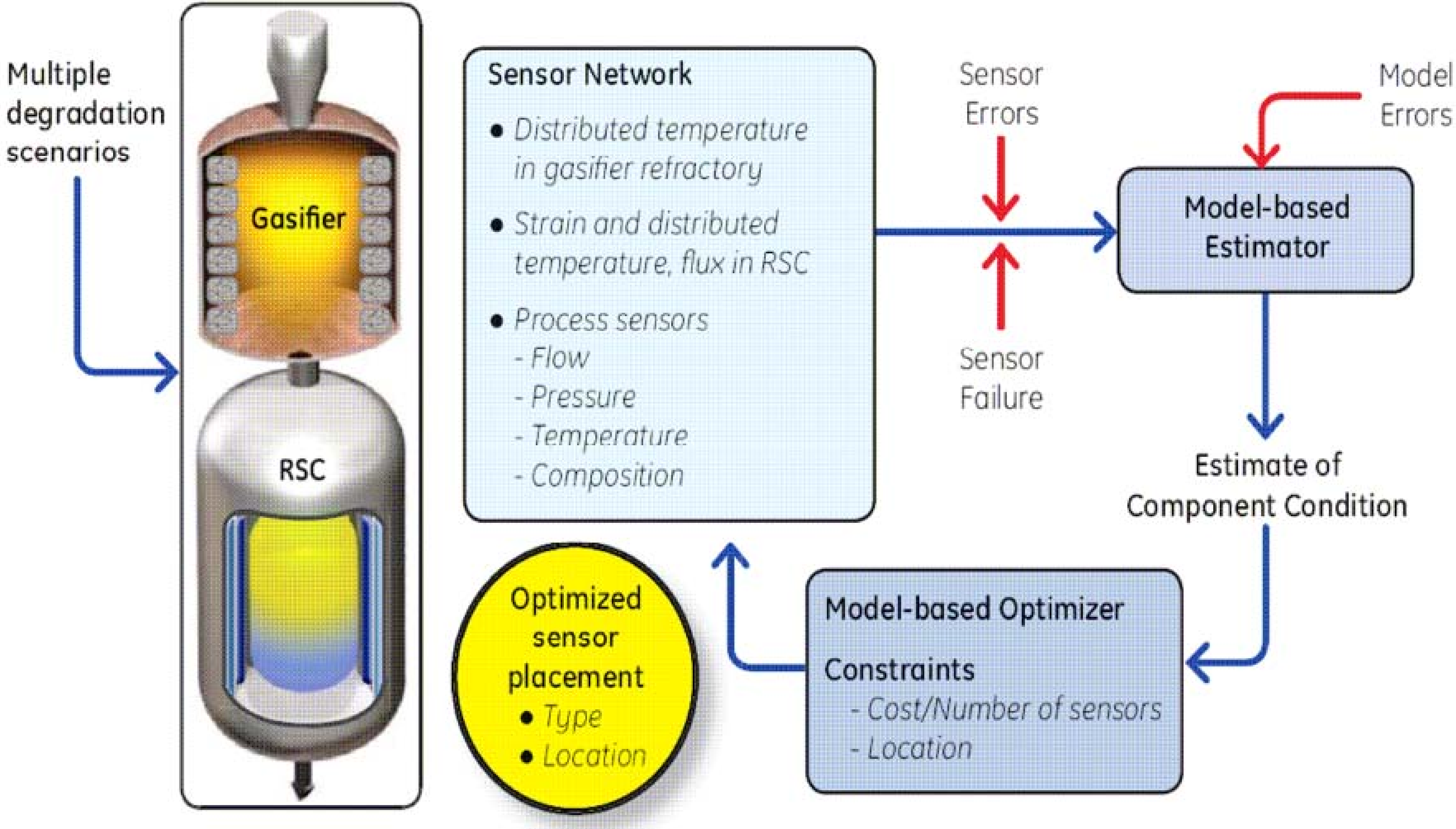
Technology: Combination of model-based nonlinear estimation and optimization software

Project tasks (planned completion date 12/31/2012)

- Develop systematic model-based computational approach for optimal sensor placement
- Computer simulation demonstration on gasifier and radiant syngas cooler

Model Based Optimal Sensor Network Design

General Electric Global Research



Schematic of online monitoring integration with predictive controls model

Warm Gas Cleanup

Research Triangle Institute (RTI)

Goal: Higher efficiency, ultra clean syngas cleanup

Technology: Highly reactive sorbent in integrated transport reactor system

Project tasks (planned completion date 9/30/2015)

- Design and construct a 50 MWe prototype system (FEED completed)
- Operate at commercial conditions
- Optimize water gas shift
- Capture 90% carbon in syngas, up to 300,000 TPY CO_2, via integration of water-gas shift (WGS) and aMDEA into process
- Perform CO_2 sequestration with monitoring and verification

Warm Gas Cleanup – RTI

Previous Testing at Eastman Chemical

RTI Warm Gas Cleanup Technologies

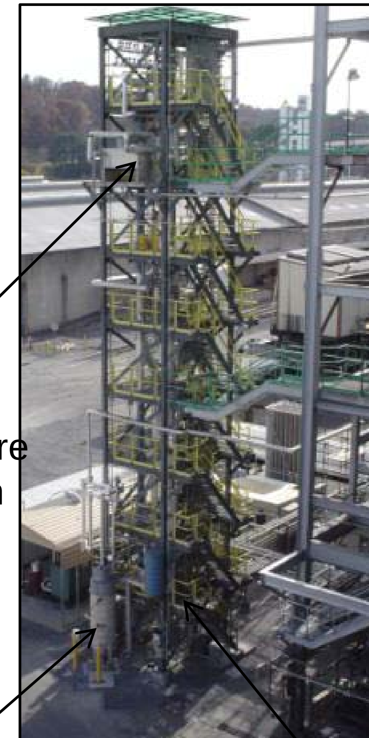
- Cleans multi-contaminants from coal-derived syngas while creating pure sulfur product

High Temperature Desulfurization Process

- > 99.9 % removal of both H_2S and COS (to < 5 ppmv levels)
- > 3,000 hours of operation at 0.3 MWe

Direct Sulfur Recovery Process

- > 99.8 % SO_2 conversion to elemental sulfur
- 96 % ammonia removal
- 90 % mercury and arsenic removal



Pilot Plant Operation at Eastman's Gasification Facility, Kingsport, TN

Hydrogen Transport Membrane (HTM)

Eltron Research, Inc.

Goal: Lower cost H_2 separation and CO_2 capture for IGCC

Technology: Dense metal membrane to separate H_2 from shifted syngas, leaving CO_2 at high pressure

Project tasks (planned completion date 9/30/2015)

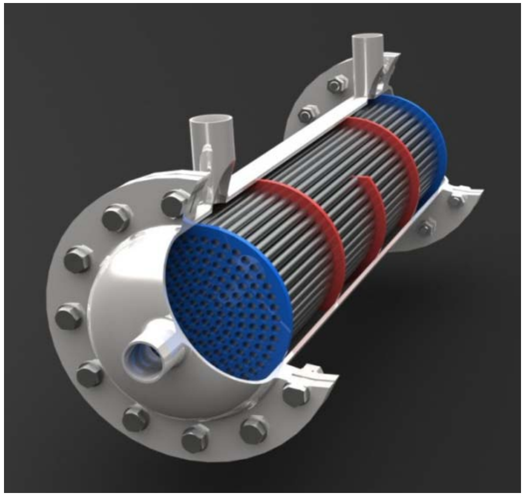
- Complete testing of lab- and bench-scale units at Eltron (ongoing)
- Complete testing of 5-12 lb/day H_2 production unit using real coal-derived synthesis gas (ongoing)
- Design, construct, and evaluate performance of nominally 250 lb/day prototype development unit
- Design, construct and test a nominally 4-10 TPD pre-commercial module

Hydrogen Transport Membrane (HTM)

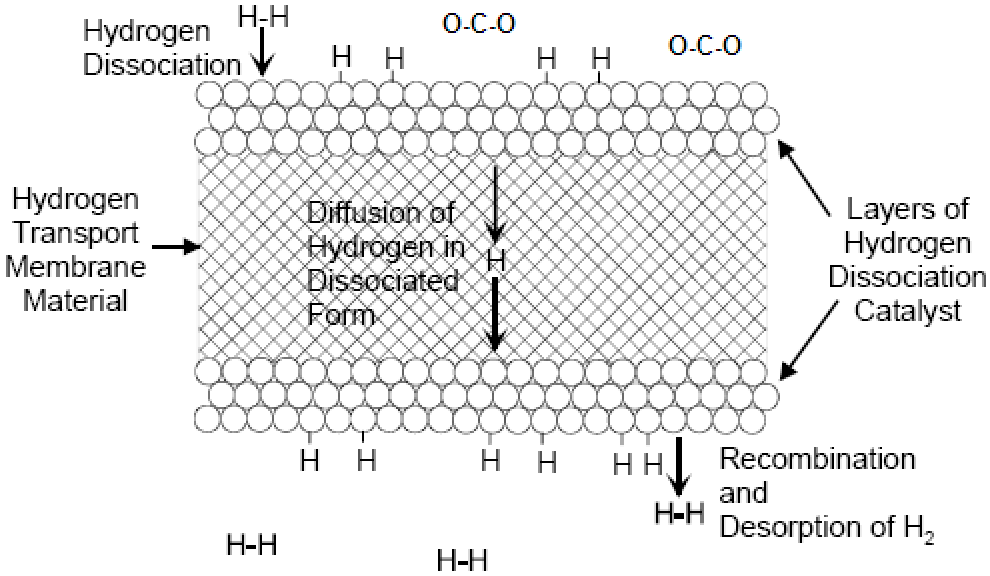
Eltron Research, Inc.

Hydrogen Transport Membrane

- High CO_2 retentate pressure
- Allows capture of high pressure CO_2
- High hydrogen recoveries >90%
- Essentially 100% pure hydrogen
- Low cost, long membrane life



Conceptual design of commercial membrane unit



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

Low Rank Coal R&D

Recently Awarded Projects

Liquid CO_2 Slurry for Feeding Low Rank Coal (LRC) Gasifiers (Electric Power Research Institute, Inc.)

- Measurements of rheological properties including viscosity and solids loading with three low rank coals for both LCO_2 and water slurries
- Preliminary design and cost estimate of mixing system

Advanced CO_2 Capture Technology for LRC IGCC Systems (TDA Research)

Demonstrate technical/economic potential for integrated CO_2 scrubber/water gas shift (WGS) catalyst by:

- Optimizing sorbent/catalyst and process design
- Assessing integrated system in bench-scale & slipstream field demonstration

Scoping Studies to Evaluate the Benefits of an Advanced Dry Feed System on the Use of LRC in IGCC Technologies (GE)

- Completing techno-economic studies of IGCC – with and without dry feeder

Sour PSA for Separation of CO_2,Sulfur, and Impurities from LRC (Air Products and Chemicals, Inc.)

- Extensive testing in PSA and TSA modes
- Using experimental results to generate a high-level pilot process design
- Techno-economic assessment of applicability for low-rank coal use

CO_2 Slurry Feed

Electric Power Research Institute, Inc. (EPRI)

Liquid CO_2 Slurry for Feeding Low Rank Coal (LRC) Gasifiers

Study potential advantages of CO_2 slurries of low-rank coal by:

- Conducting plant-wide technical and economic simulations
- Developing a preliminary design and cost estimate of a slurry preparation and mixing system
- Performing laboratory tests of rheological properties of liquid CO_2/LRC slurry and maximum solids loading capability for 3 coals

Project Duration: 12 months

Team Members:

- Electric Power Research Institute
- Dooher Institute of Physics and Energy
- Worley Parsons Group, Inc.
- Columbia University

Integrated CO_2 Scrubber and Water Gas Shift

TDA Research, Inc

Advanced CO_2 Capture Technology for Low Rank Coal IGCC Systems

Demonstrate technical and economic potential for an integrated CO_2 scrubber/ water gas shift catalyst by:

- Optimizing sorbent/catalyst and process design
- Assessing integrated system, in bench-scale & slipstream field demonstration using actual coal-derived synthesis gas
- Use results to feed a techno-economic analysis

Project Duration: 12 months

Team Members:

- TDA Research, Inc.
- University of California at Irvine
- Southern Company
- ConocoPhillips

Benefits of Dry Feed System

General Electric Company

Scoping Studies to Evaluate the Benefits of an Advanced Dry Feed System on the Use of Low Rank Coal in IGCC Technologies

Evaluate and demonstrate the benefits of novel dry-feed technologies to effectively, reliably, and economically feed low-rank coal into commercial IGCC systems by:

- Completing comparative techno-economic studies of two IGCC power plant cases, (with and without advanced dry feed technologies)

Project Duration: 12 months

Team Members:

- General Electric Company
- Eastman Chemical Company

Advanced Acid Gas Separation Technology for the Utilization of Low Rank Coals

Air Products and Chemicals, Inc. (APCI)

Sour Pressure Swing Adsorption (PSA) for Separation of CO_2, Sulfur, and Impurities from Low Rank Coals

Objective:

- Test performance of APCI Sour PSA on syngas produced from gasification low rank coals
- Achieve resulting cost reduction of >10% in capital scope at 90% CO_2 capture and >95% CO_2 purity
- Determine the ability of adsorbents in handling impurities resulting from the gasification of low rank coals

Scope of Work:

- Extensive testing in PSA and temperature swing adsorption (TSA) modes
- Using experimental results to generate a high-level pilot process design
- Preparing techno-economic assessment of applicability for low-rank coal use

Project Team:

- Air Products and Chemicals, Inc. (APCI)
- University of North Dakota Energy and Environmental Research Center (EERC)

Reliability, Availability & Maintainability R&D

Recently Awarded Projects

Mitigation of Syngas Cooler Plugging and Fouling (Reaction Engineering International)

- Experimental Testing: Deposit bond strength and characterization
- Modeling: Investigate deposit behavior in the syngas cooler section, evaluate process conditions and equipment designs for mitigation of syngas cooler plugging and fouling
- Field Test: Validate specific means to implement mitigation methods

Feasibility Studies to Improve Plant Availability and Reduce Total Installed Cost in IGCC Plants (GE)

Work on tasks, with broad applicability to the IGCC industry

- Integrated operations philosophy
- Modularization of gasification/IGCC plant
- Active fouling removal
- Improved slag handling

Mitigation of Syngas Cooler Plugging & Fouling

Reaction Engineering International

Objective:

- Improve the availability of IGCC plants through improving the performance of the Syngas Cooler (SC) through reduced plugging and fouling by:
  - Gaining a better understanding of ash deposition onto refractory and metal surfaces associated with SC
  - Evaluating fouling and plugging of SC designs
  - Evaluate and develop methods to mitigate SC fouling and plugging
  - Validate defined SC mitigation technology through field tests

Scope Of Work:

- *Experimental Testing* – deposit bond strength and characterization
- *Modeling* – investigate deposit behavior in the SC section, evaluate process conditions and equipment designs for mitigation of SC plugging/fouling
- *Field Test* – Validate specific means to implement mitigation methods

Team Members:

- Reaction Engineering International, Salt Lake City
- University of Utah, Salt Lake City

IGCC Affordability and Availability

General Electric Company

Feasibility Studies to Improve Plant Availability and Reduce Total Installed Cost in IGCC Plants

Objective: Work on tasks, with broad applicability to the IGCC industry

- Integrated operations philosophy
- Modularization of gasification/IGCC plant
- Active fouling removal
- Improved slag handling

Project Duration: 36 months

Team Members:

- General Electric Company
- Eastman Chemical Company

NETL In-House R&D (ORD-RUA)

NETL Office of Research & Development
Gasification Projects

Refractory Improvement

- Develop improved performance refractory liners that are carbon feedstock flexible (coal, western coal, petcoke)
- Model gasifier slag for refractory interactions, downstream phases and material interactions (syngas coolers)
- Manage slag viscosity and refractory wear, evaluate additives

Conversion and Fouling

- In slagging gasifiers using coal, petcoke or mixtures of them to:
  - Improve the carbon conversion efficiency to syngas
  - Reduce convective syngas cooler fouling
- Collaborate with industry to ensure proper technology development and transfer

NETL Office of Research & Development
Gasification Projects

Low-Rank Coal Optimization

- Pretreatment and kinetic co-feed experimental efforts to support and validate the development of a hierarchy of device scale gasifier models with uncertainty quantification (UQ).
- Demonstrate the models with UQ for the NCCC/TRIG under co-feed conditions and optimize co-feed performance.

Warm Syngas Cleanup

- Conduct both lab and pilot-scale R&D for cost efficient sorbents for trace contaminant capture of high efficiency coal gasification plant

Advanced Virtual Energy Simulation Training And Research (AVESTAR™) Center

- Training Center: 3D virtual simulation of IGCC plant
- Establish the world-class center for addressing key operational and control challenges arising in IGCC plants with carbon capture.

Refractory Improvement

NETL Office of Research and Development

Refractory Development for Mixed Feedstock Use

- Determine mechanisms of wear in NETL refractory materials under development.
- Determine refractory corrosion mechanisms in current generation commercial refractory liner materials exposed to coal slag, important for understanding how to overcome limitations in current refractory liner materials.

Slag Management (Current Emphasis)

- Determine critical information needed for slag management in gasifiers, which will be tracked in commercial gasifiers and predicted in models to increase gasifier RAM.

Advanced Refractory For Gasifiers

Rotary Slag Test

New refractory chemistry
– Increases mechanical durability
– Reduces slag penetration

Conventional refractory after rotary slag testing

Phosphate modified high-chrome oxide refractory material

Advanced Refractories for Gasifiers

NETL Office of Research and Development

Current refractory goal is to refine/evaluate composition in commercial gasifiers

Cr^{+6} formation in high Cr_2O_3 refractories is thermodynamically predicted not to be an issue with current carbon feedstock

- Low oxygen partial pressure results in low Cr^{+6} formation
- Gasification environment has O_2 partial pressure about 10^{-8}

Conversion and Fouling

NETL Office of Research and Development

Modeling

- Evaluate and validate sub-models for particle-slag interaction, particle fragmentation, and mineral matter chemistry (sulfur release) and implement into CFD model
- Develop and evaluate reduced order model to predict mineral matter split between slag and fly ash for entrained-flow gasifier

Convective Syngas Cooler Fouling

- Literature survey of deposition models
- Investigate gasifier ash deposits to determine problematic ash characteristics

Kinetics

- Effect of pressure on pyrolysis kinetics
- Preliminary gasification kinetics at high pressure

Slag Characterization

- Continue to characterize coal and petcoke blends, characterize ash and slag, begin studies of FeS and VOx behavior in slag

Control of Ash in IGCC

Regional University Alliance

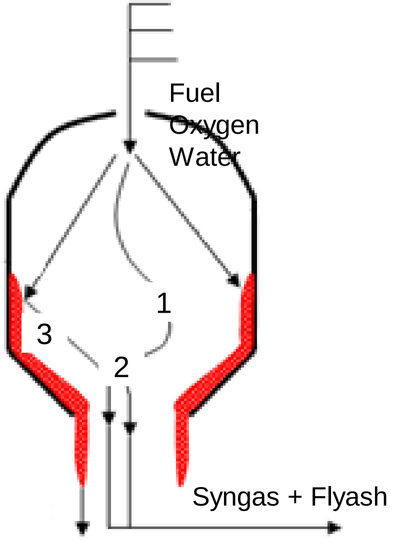
Goal: Solutions to IGCC Ash Management Problems

- Unconverted carbon in gasification flyash
- Syngas cooler fouling

Development of Models and Techniques to improve IGCC plant operations

- Adaption of "Particle Population Model" used for predicting CFB ash splits
- Inorganic transformations and char/slag interactions
- Particle trajectories and deposition modeling
- Gasification kinetics

Coordinate and leverage R&D in 3 universities (PSU, CMU and WVU) and NETL



1. Particles contact and coalesce with slag
2. Particles do not contact slag
3. Particles contact but do not coalesce with slag

Low Rank Coal Optimization

NETL Office of Research and Development

Kinetics

- Development of NETL's Carbonaceous Chemistry for Computational Modeling (C3M) software to bridge coal kinetics software (PCCL, CPD, etc) and available kinetic experiments with CFD software (MFIX, Fluent, Barracuda), other models
- Provide modelers and experimentalist with a virtual kinetic laboratory

Fuel Pretreatment

- Expand and further test the grinding laws developed in FY11
- Correlate the NETL lab scale results with large scale grinding energies

Multiphase Models

- NETL's open source suite of multiphase solvers such as MFIX-DEM, MFIX continuum, MFIX-PIC and multiphase Reduced Order Models will be used to aid in the design and optimization of operating conditions and establishing performance trends in the NCCC/TRIG with uncertainty quantification

Warm Syngas Cleanup

NETL Office of Research and Development

Elevated temperatures results in higher IGCC thermal efficiency

Palladium-based sorbents are currently among the most promising candidates for high-temperature capture of mercury, arsenic, selenium, phosphorus and the other trace elements

Progress:

- 2007 - License agreement between the NETL and sorbent manufacturer Johnson Matthey
- 2008 - The technology received the R&D 100 award
- 2009 to present - Over 99% removal of mercury, arsenic, and selenium from dirty syngas slipstreams at 550ºF over several weeks testing at the National Carbon Capture Center
- Present - Identifying an optimum form of the palladium sorbent (loading, support, alloy)

Advanced Virtual Energy Simulation Training And Research (AVESTAR™) Center

NETL Office of Research and Development

– R&D, Training, and Education for the Operation and Control of Advanced Energy Systems with CO_2 Capture and Storage

– Real-time Dynamic Simulators with Operator Training System (OTS) Capabilities

– 3D Virtual Immersive Training Systems (ITS)

Benefits

– OTS for normal and faulted operations, plant start-up, shutdown, and load following/shedding

– ITS for added dimension of plant realism

– OTS/ITS for training both control room and plant field operators, promoting teamwork

– Work force development in IGCC plant and CO_2 capture operations

– Advanced R&D in process dynamics, model predictive control, sensors, RT optimization, 3D virtual plants, and more

AVESTAR™

For more information on AVESTAR and IGCC training courses, please send email to AVESTAR@netl.doe.gov

Congressionally Directed Projects

Arrowhead Center to Promote Prosperity and Public Welfare (PROSPER)

New Mexico State University

Congressionally Directed Project

Conduct research analyzing the relationships between the fossil-fuel energy sector and economic development issues in New Mexico

Actively engage stakeholders in the research process

Provide a timely, focused economic research product on the inter-relationships between fossil-fuel energy, the economy, and the environment, especially applicable to the State of New Mexico

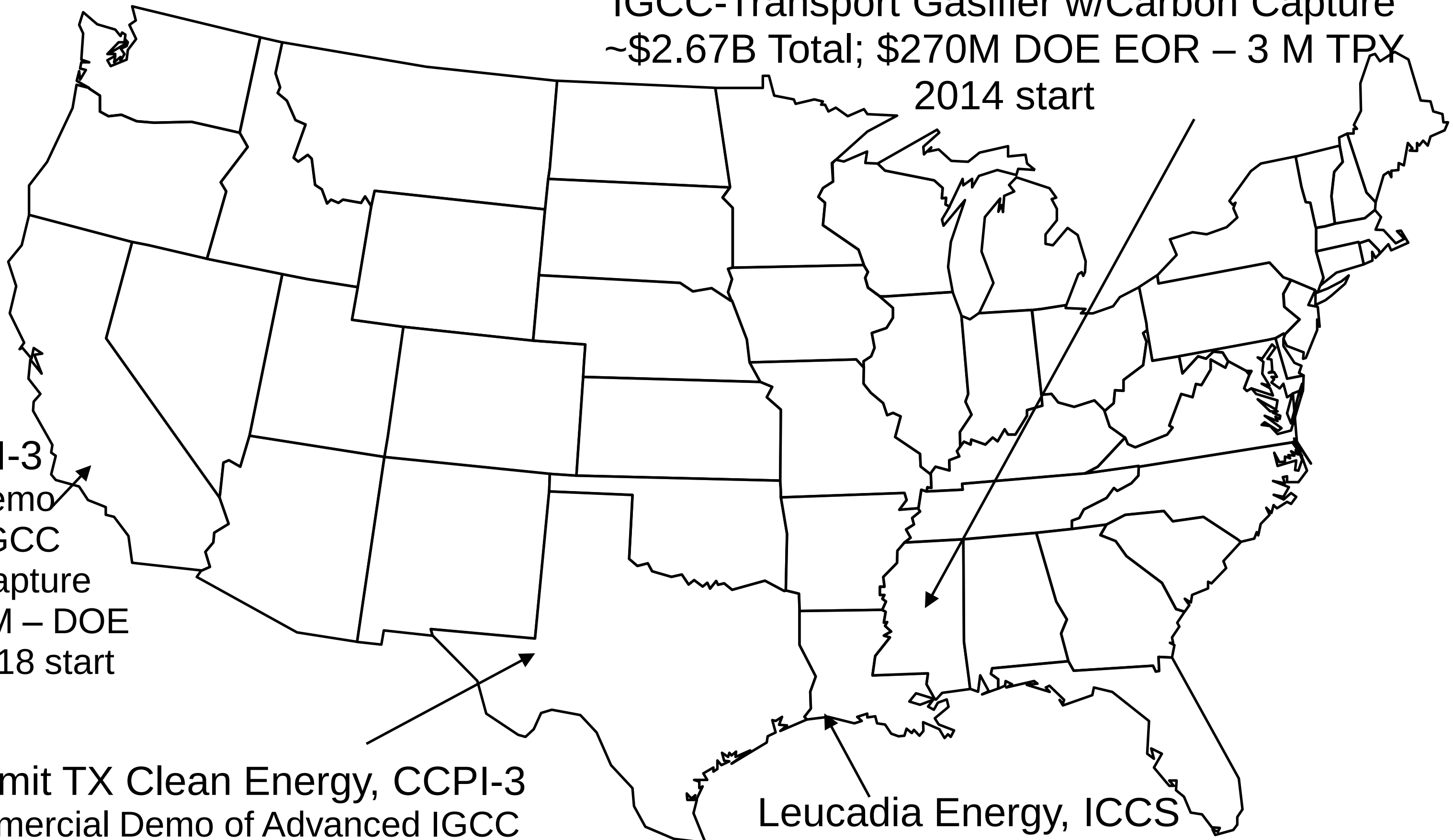
Outreach activities to provide public sector and industry policy-makers with the information and analysis needed to enhance New Mexico's energy economy

DOE Supported Gasification Demonstration Projects

Gasification-Focused Projects

Clean Coal Power Initiative, Industrial Capture & Storage

Southern Company, CCPI-2 Kemper County
IGCC-Transport Gasifier w/Carbon Capture
~$2.67B Total; $270M DOE EOR – 3 M TPY
2014 start



HECA, CCPI-3
Commercial Demo
of Advanced IGCC
w/ Full Carbon Capture
~$4B – Total, $408M – DOE
EOR – 3M TPY 2018 start

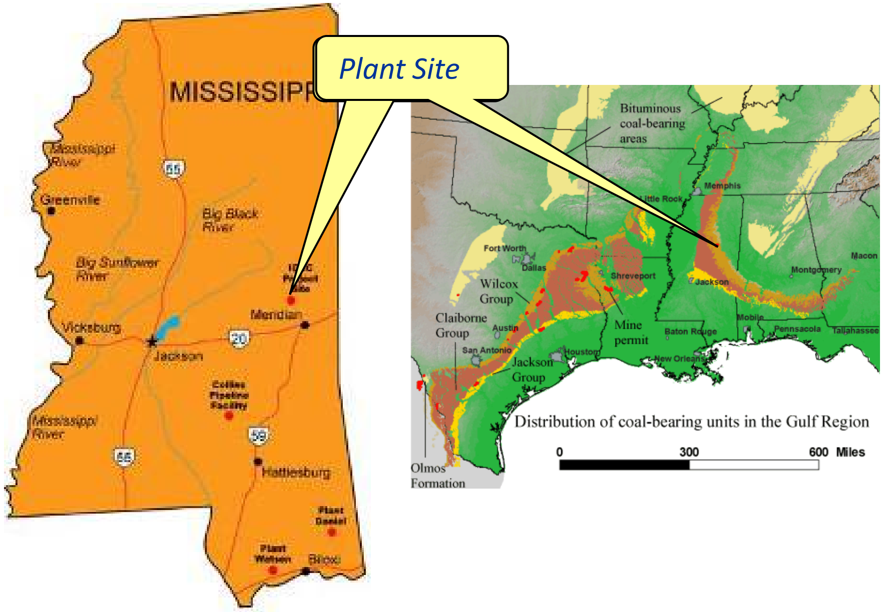
Summit TX Clean Energy, CCPI-3
Commercial Demo of Advanced IGCC
w/ Full Carbon Capture
~$1.7B – Total, $450M – DOE
EOR – 3M TPY 2018 start

Leucadia Energy, ICCS
CO_2 Capture from Methanol Plant
EOR in Eastern TX Oilfields
$436M - Total, $261M – DOE
EOR – 4.5 M TPY 2015 start

Southern Company Services, Inc. CCPI-2

Advanced IGCC with CO_2 Capture

- **Kemper County, MS**
- **582 MWe (net) IGCC: 2 KBR Transport Gasifiers, 2 Siemens Combustion Turbines, 1 Toshiba Steam Turbine**
- **Mississippi Lignite Fuel**
- **65% CO_2 capture (Selexol® process) 3,000,000 tons CO_2/year**
- **EOR Sequestration site TBD (Start 2014)**
- **Total Project: $2.01 Billion**
  DOE Share: $270 Million (13%)



Key Dates

- Project Awarded: Jan 2006
- Project moved to MS: Dec 2008
- Construction: Jul 2010
- NEPA ROD: Aug 2010
- Operations: May 2014

Status

- NEPA Record of Decision: 8/19/2010
- Construction initiated: 9/16/2010
- Process equipment installation underway

Hydrogen Energy California

Advanced IGCC-Polygen

- **Kern County, CA**
- **Up to 280 MWe (net) IGCC, 1.0 million tons/yr Urea/UAN**
- **90% CO_2 capture – 2,500,000 tons CO_2/year**
- **EOR - Elk Hills oil field (Start: TBD)**
- **Fuels: Bituminous Coal/Petcoke**
- **Maximize use of non-potable water for power production**
- **Recycle all IGCC/project wastewater with 100% zero liquid discharge**
- **Total Project: $4.0 Billion DOE - $408 Million (10%)**

IGCC Poly-generation with Integrated Carbon Capture & Sequestration

Key Dates

- **Project Awarded: 9/30/2009**
- **Project Being Re-baselined**

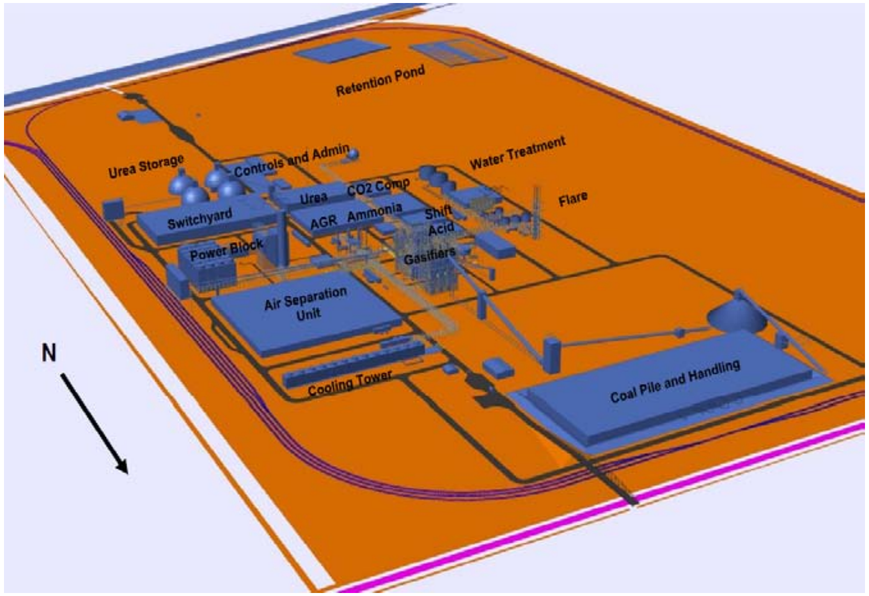
Status

- **New Owner, SCS Energy: 9/2011**
- **FEED initiated: 9/21/2011**
- **Sulfur recovery unit process design: 9/27/2011**
- **NEPA public scoping meeting scheduled: 7/12/2012**

Summit Texas Clean Energy, LLC CCPI-3

Advanced IGCC-Polygen

- **Penwell, Ector County, TX**
- **400 MWe (gross) Greenfield IGCC with Siemens Gasification and Power Block**
  - SFG-500 gasifiers (2 x 50%)
  - High H_2 SGCC6-5000F combined cycle (1 x 1)
- **PRB sub bituminous coal fuel**
- **90% CO_2 capture – 3,000,000 tons CO_2/yr**
  - 2-stage Water Gas Shift
  - Linde Rectisol® AGR
- **Permian Basin EOR (Start: 2014)**
- **Total Project: $1.727 Billion**
  DOE Share: $450 Million (26%)



Key Dates

- **Project Awarded: Jan 2010**
- **Construction: Jun 2012**
- **Financial Close: 1st Q FY2012**
- **Operation: Jul 2014**

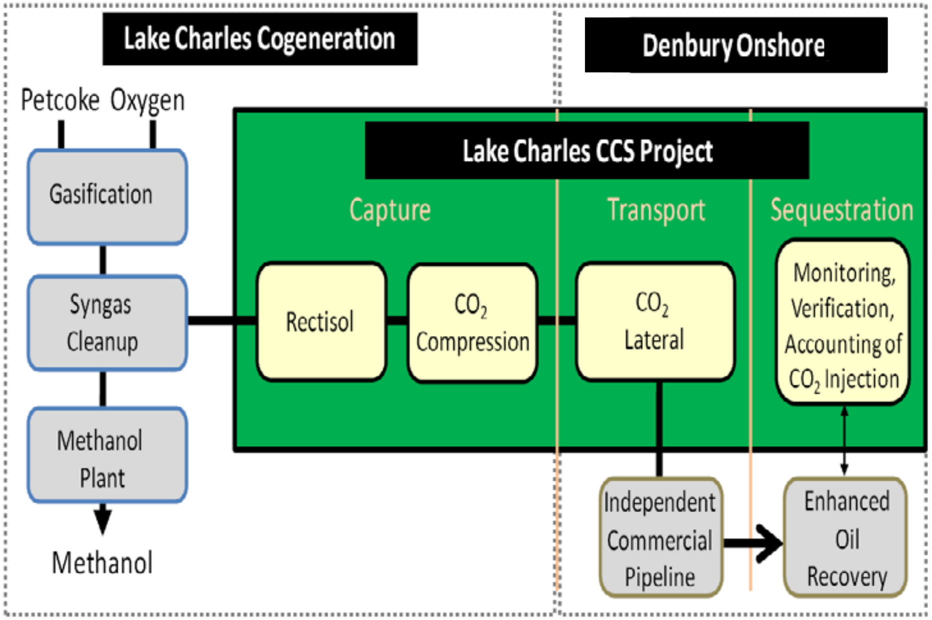
Status

- **Air permit: Dec 2010**
- **Urea contract: Jan 2011**
- **CO_2 contract (60% of total): May 2011**
- **Record of Decision: Sep 2011**
- **Power off-take agreement executed: Dec 2011**

Leucadia Energy, LLC ICCS Area 1

Petcoke Gasification to Methanol

- Lake Charles, LA
- GE Energy Gasification (4 gasifiers: 3 hot/1 spare)
- 730 Million gallons/year methanol
- 90% CO_2 capture (Rectisol® process); 4,000,000 tons CO_2/year
- CO_2 to Denbury pipeline for EOR in Texas at the West Hastings oil field (Start 2015)
- Total Project: $436 Million
  DOE Share: $261 Million (60%)



Key Dates

- Phase 2 Awarded: Jun 17, 2010
- Complete FEED: Jul 2011
- Construction: Oct 2012
- Operation: Jun 2015

Status

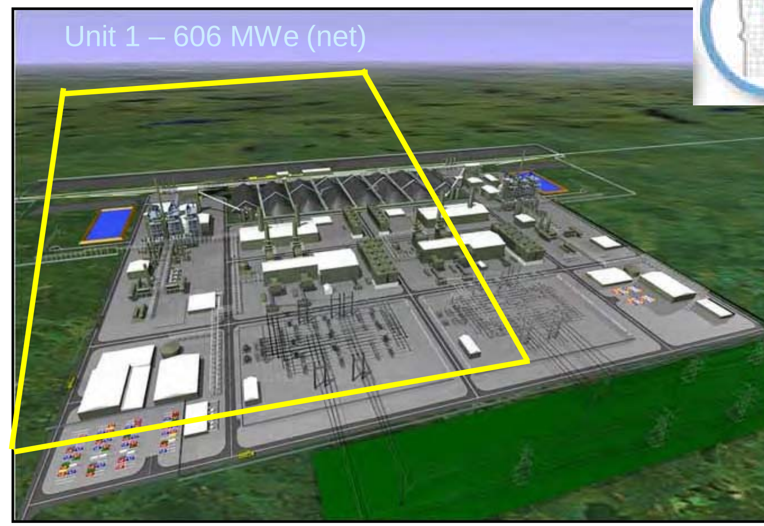
- FEED completed
- NEPA EIS in progress
- Negotiating product off-take agreements

Mesaba Energy Project CCPI-2

Advanced IGCC

- Taconite, Minnesota
- No Sequestration
- 606 MWe(net)
- ConocoPhillips E-Gas^{TM} technology
  – 2 operating gasifiers + 1 spare
- 2 GE 7FB turbines and 1 steam
- Bituminous and/or blend of sub-bituminous and pet-coke
- Status:
  – Notice of Availability (NOA) for the Final EIS Issued Nov. 2009
  – Completing pre-construction permitting

EXCELSIOR ENERGY



- Permits Approved
  – Large Electric Power Generating Plant Site
  – High Voltage Transmission Line
  – Route Permit Pipeline Route

Systems Analysis

Gasification Systems Program

NETL's Program Analysis Support

On-going and Planned Gasification Studies

Low Rank Coal:

Parallel screening studies for Gasification FY11 awards

Cost and Performance Baseline for TRIG™

- PRB and ND Lignite Air Blown IGCC
- Texas Lignite Air and Oxygen Blown IGCC
    - Co-feeding of biomass to meet 90% equivalent CCS

IGCC with CCS Pathway Study: Low Rank Coal

Co-production assessments

Altitude versus shipping sensitivity analysis

IGCC availability studies:

Identifying gaps for conventional technologies

Setting targets for advanced technologies

General advanced technology assessments:

IGCC with CCS Pathway: Bituminous Coal, Updates

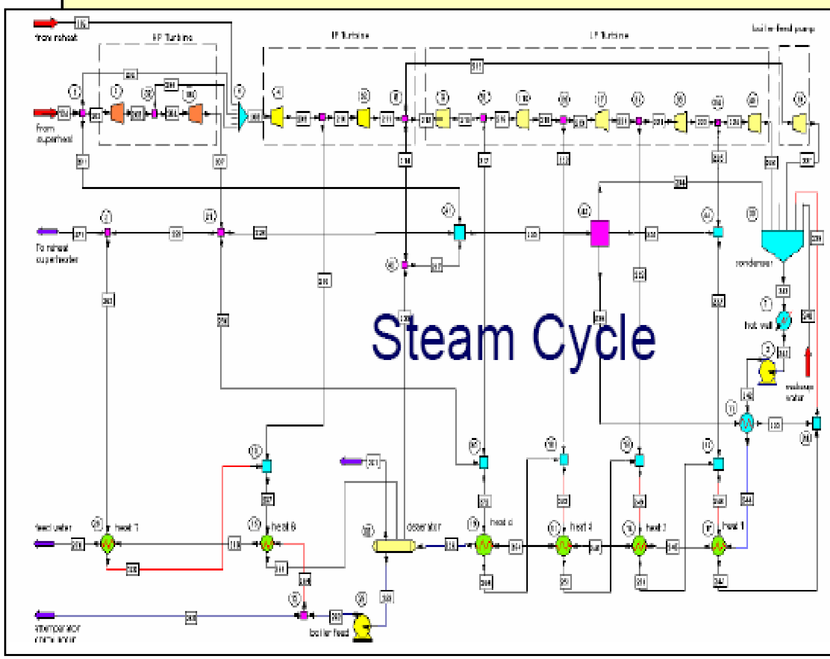
- DOE IGCC portfolio + PWR compact gasifier assessment
- Pressure sensitivity analysis

Updated WGCU assessment - learnings from TECO design

Technical Approach

1. Extensive Process Simulation (ASPEN)

- All major chemical processes and equipment are simulated
- Detailed mass and energy balances
- Performance calculations (auxiliary power, gross/net power output)



2. Cost Estimation

- **Inputs from process simulation** (Flow Rates/Gas Composition/Pressure/Temp.)
- **Sources for cost estimation**
  - WorleyParsons
  - Vendor sources where available
- **Follow DOE Analysis Guidelines**

Systems Analysis

Bituminous Baseline Study

Full presentation available at:

http://www.netl.doe.gov/energy-analyses/baseline_studies.html

Study Matrix

Plant Type	ST Cond. (psig/°F/°F)	GT	Gasifier/ Boiler	Acid Gas Removal/ CO_2 Separation / Sulfur Recovery	CO_2 Cap
IGCC	1800/1050/1050 (non-CO_2 capture cases) 1800/1000/1000 (CO_2 capture cases)	F Class	GEE	Selexol / - / Claus	
				Selexol / Selexol / Claus	90%
			CoP E-Gas	MDEA / - / Claus	
				Selexol / Selexol / Claus	90%
			Shell	Sulfinol-M / - / Claus	
				Selexol / Selexol / Claus	90%
PC	2400/1050/1050		Subcritical	Wet FGD / - / Gypsum	
				Wet FGD / Econamine / Gypsum	90%
	3500/1100/1100		Supercritical	Wet FGD / - / Gypsum	
				Wet FGD / Econamine / Gypsum	90%
NGCC	2400/1050/1050	F Class	HRSG		
				- / Econamine / -	90%

GEE – GE Energy
CoP – Conoco Phillips

IGCC Performance Results

	GE Energy		E-Gas		Shell	
CO_2 Capture	**NO**	**YES**	**NO**	**YES**	**NO**	**YES**
Gross Power (MW)	**748**	**734**	**738**	**704**	**737**	**673**
Auxiliary Power (MW)						
Base Plant Load	25	26	24	28	22	25
Air Separation Unit	98	115	86	111	85	103
Gas Cleanup/CO_2 Capture	3	19	3	20	1	19
CO_2 Compression	-	31	-	31	-	30
Total Aux. Power (MW)	126	191	113	190	108	177
Net Power (MW)	622	543	625	514	629	497
Heat Rate (Btu/kWh)	8,756	10,458	8,585	10,998	8,099	10,924
Efficiency (HHV)	**39.0**	**32.6**	**39.7**	**31.0**	**42.1**	**31.2**
Energy Penalty[1]	**-**	**6.4**	**-**	**8.7**	**-**	**10.9**

[1]CO_2 Capture Energy Penalty = Percent points decrease in net power plant efficiency due to CO_2 Capture

PC and NGCC Performance Results

	Subcritical		Supercritical		NGCC	
CO_2 Capture	**NO**	**YES**	**NO**	**YES**	**NO**	**YES**
Gross Power (MW)	**583**	**673**	**580**	**663**	**565**	**511**
Base Plant Load	28	45	25	41	10	12
Gas Cleanup/CO_2 Capture	5	29	5	27	0	10
CO_2 Compression	-	49	-	45	-	15
Total Aux. Power (MW)	**33**	**123**	**30**	**113**	**10**	**37**
Net Power (MW)	550	550	550	550	555	474
Heat Rate (Btu/kWh)	9,277	13,046	8,687	12,002	6,798	7,968
Efficiency (HHV)	**36.8**	**26.2**	**39.3**	**28.4**	**50.2**	**42.8**
Energy Penalty[1]	**-**	**10.6**	**-**	**10.9**	**-**	**7.4**

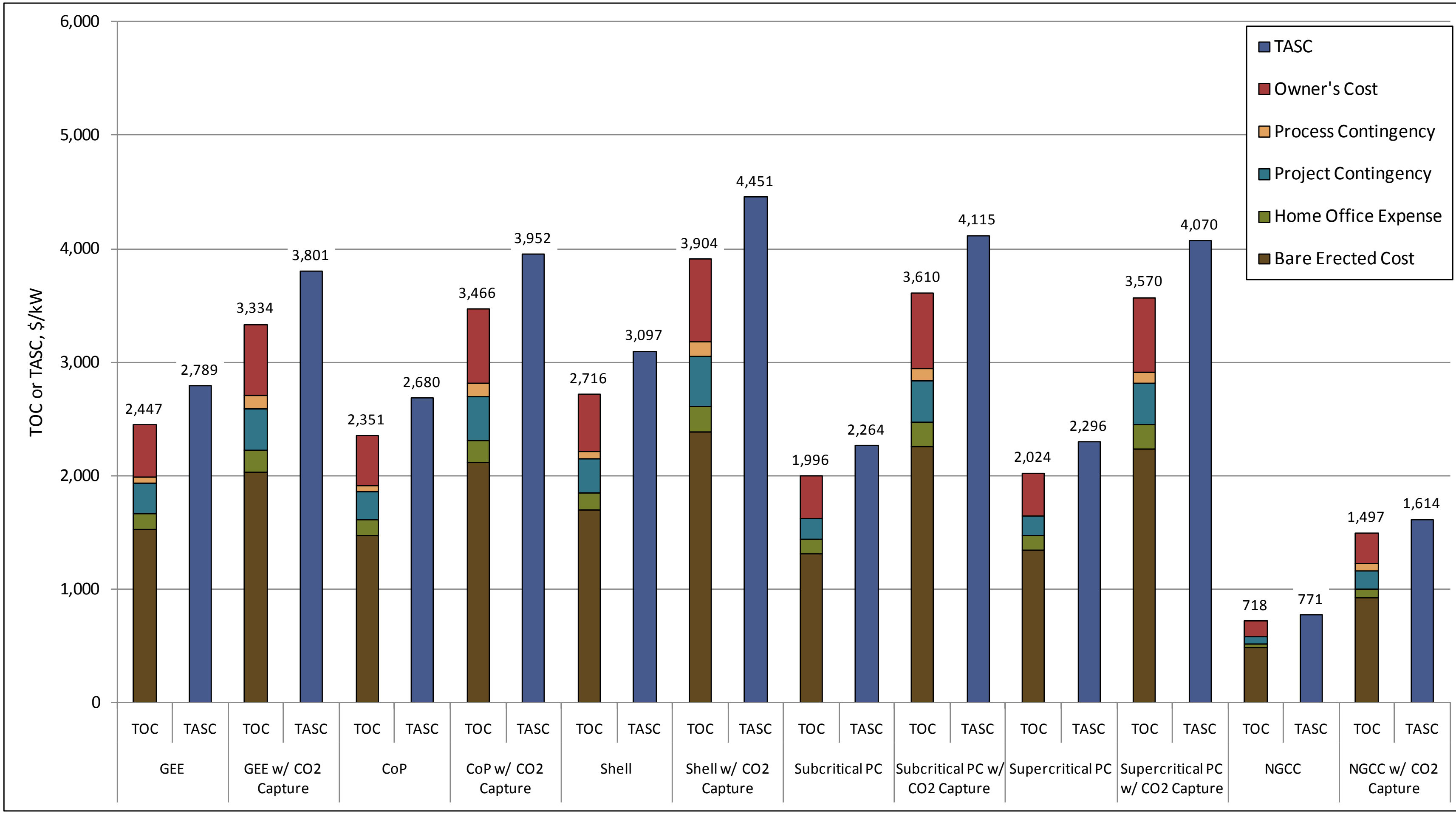
[1] CO_2 Capture Energy Penalty = Percent points decrease in net power plant efficiency due to CO_2 Capture

IGCC Economic Results

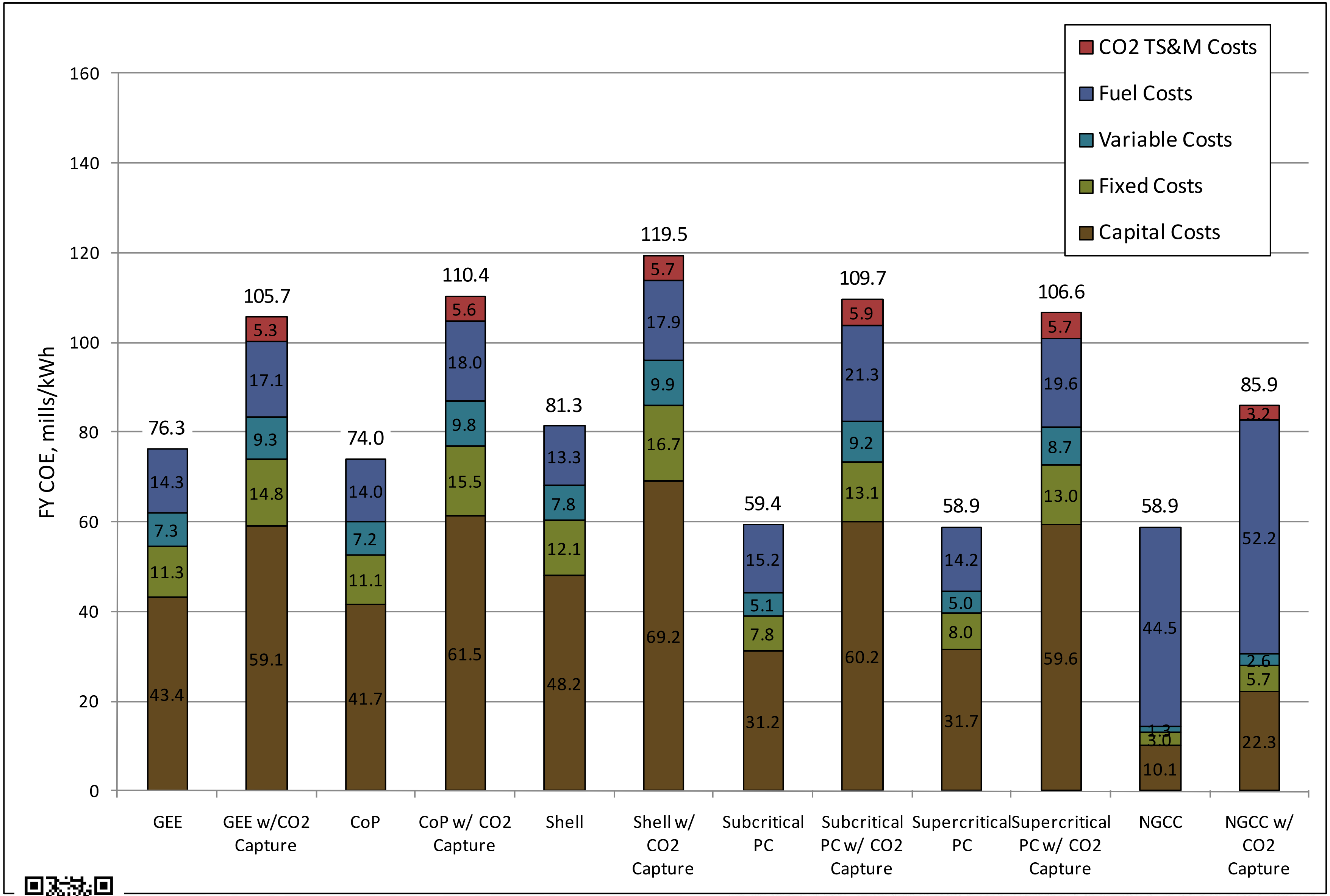
	GE Energy		E-Gas		Shell	
CO_2 Capture	**NO**	**YES**	**NO**	**YES**	**NO**	**YES**
Plant Cost ($/kWe)[1]						
Base Plant	1,426	1,708	1,423	1,804	1,719	2,164
Air Separation Unit	312	429	281	437	285	421
Gas Cleanup/CO_2 Capture	249	503	209	500	213	521
CO_2 Compression	-	71	-	76	-	75
Total Plant Cost ($/kWe)	**1,987**	**2,711**	**1,913**	**2,817**	**2,217**	**3,181**
Capital COE ($/MWh)	43.4	59.1	41.7	61.5	48.2	69.2
Fixed COE ($/MWh)	11.3	14.8	11.1	15.5	12.1	16.7
Variable COE ($/MWh)	7.3	9.3	7.2	9.8	7.8	9.9
Fuel COE ($/MWh)	14.3	17.1	14.0	18.0	13.3	17.9
CO_2 TS&M COE ($/MWh)	0.0	5.2	0.0	5.5	0.0	5.6
Total COE[2] ($/MWh)	**76.3**	**105.6**	**74.0**	**110.3**	**81.3**	**119.4**
CO_2 Avoided B v A ($/ton)	-	54	-	68	-	77
CO_2 Avoided B v SCPC ($/ton)	-	82	-	91	-	108

[1]Total Plant Capital Cost (Includes contingencies and engineering fees but not owner's costs)
[2]80% Capacity Factor, 17.73% Capital Charge Factor, Coal cost $1.64/10^6 Btu

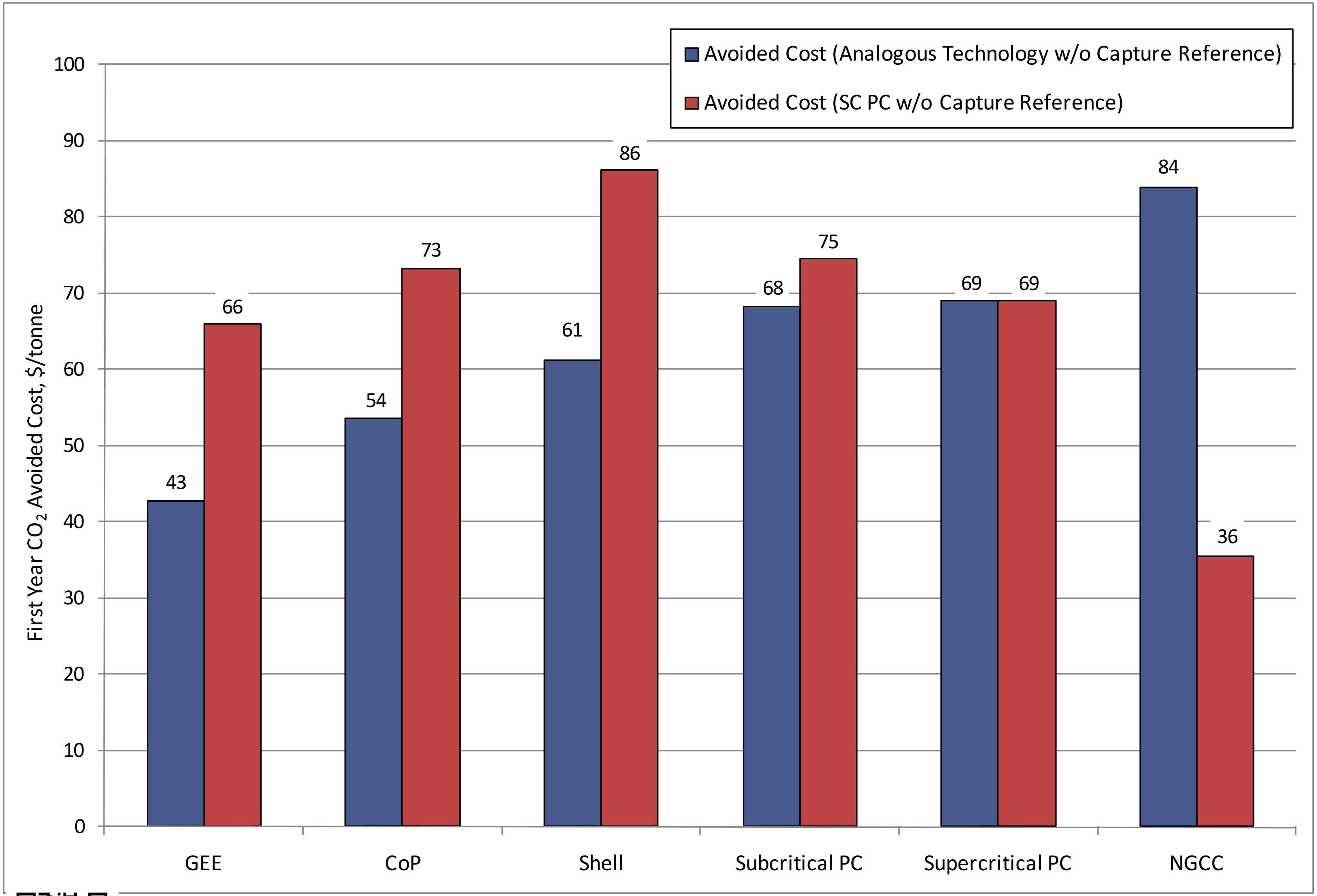
Plant Cost Comparison



Cost of Electricity Comparison



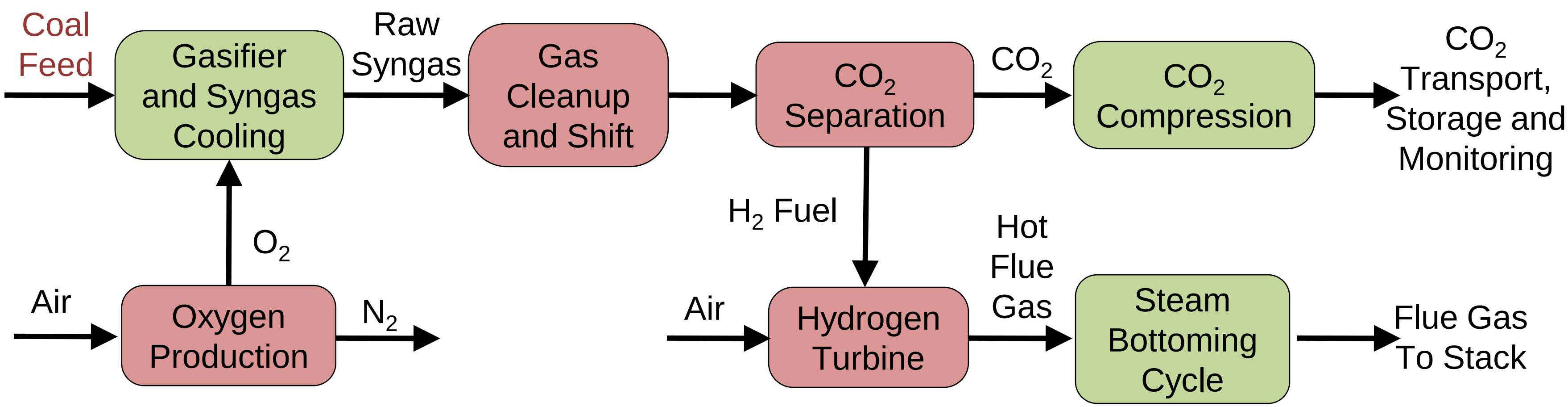
CO_2 Avoided Costs



Systems Analysis

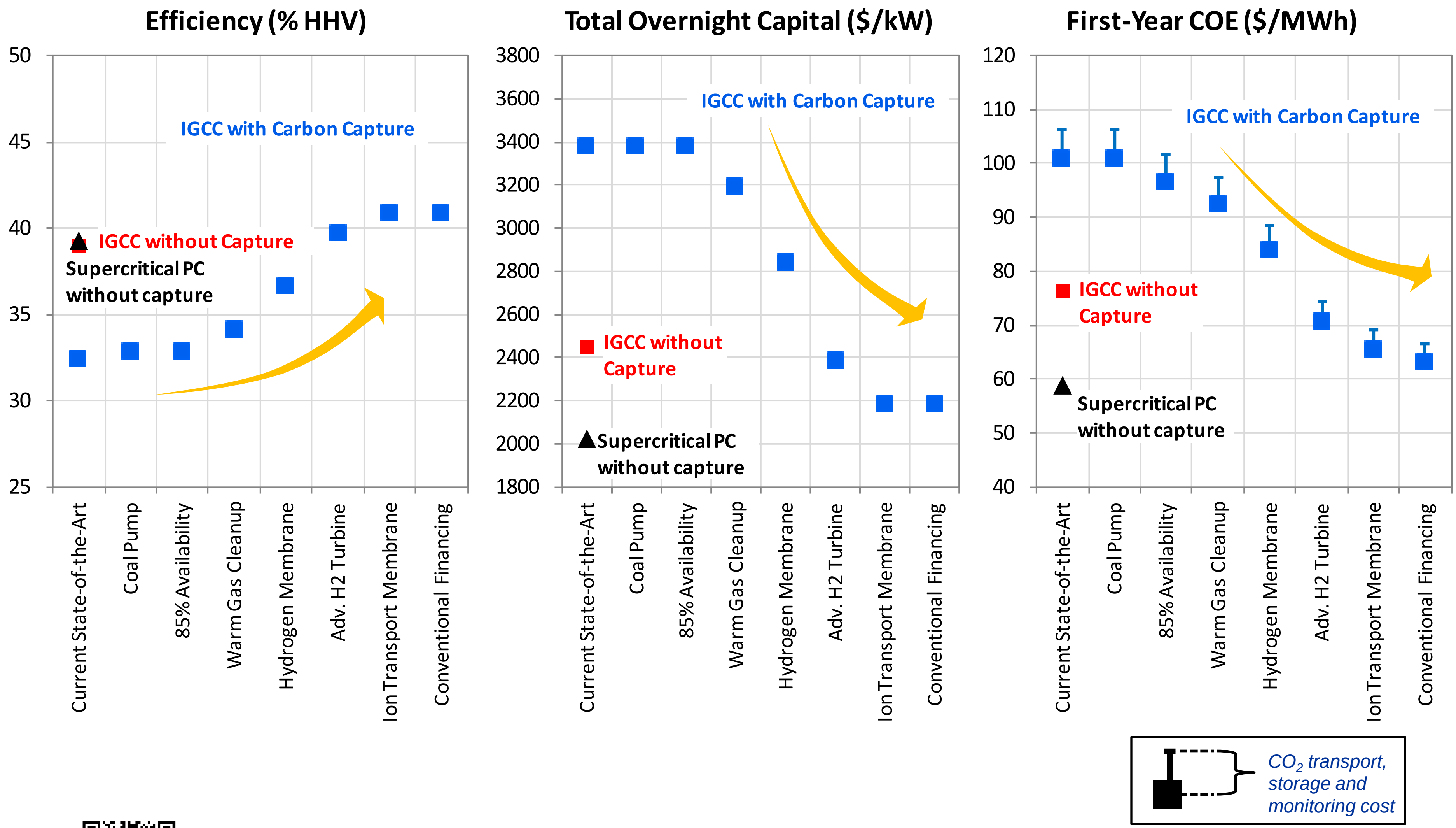
Bituminous IGCC Pathway Study

IGCC Advanced Technology Assessments



	Technology Advancements				
Coal Feed System	Slurry Feed		→		Coal Feed Pump
Oxygen Production	Cryogenic Air Separation		→		Ion Transport Membrane
Gas Cleanup	Selexol		→		Warm Gas Cleanup
Turbine	Adv F Turbine	→	Adv H_2 Turbine	→	Next Gen Adv Turbine
CO_2 Separation	Selexol		→		H_2 Membrane
Capacity Factor	80%	→	85%	→	90%

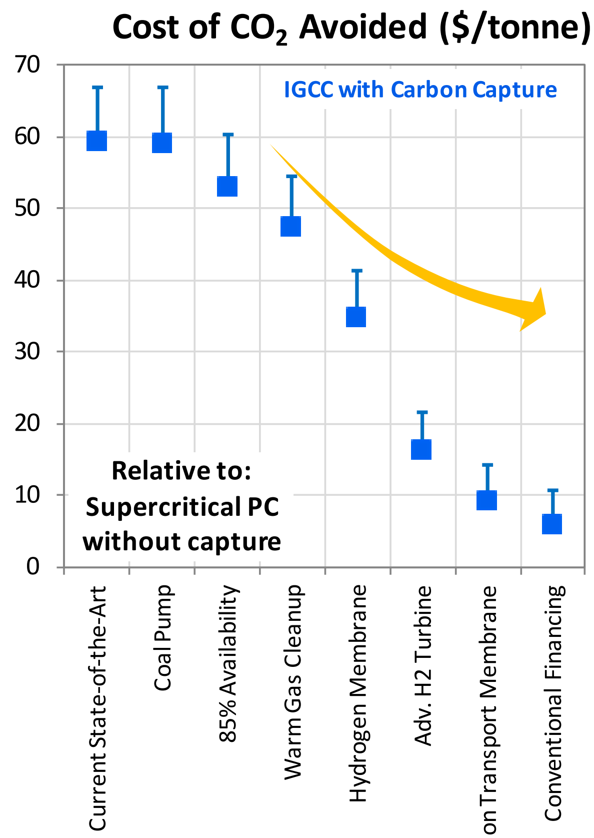
Advanced IGCC Systems
Driving Down the Cost

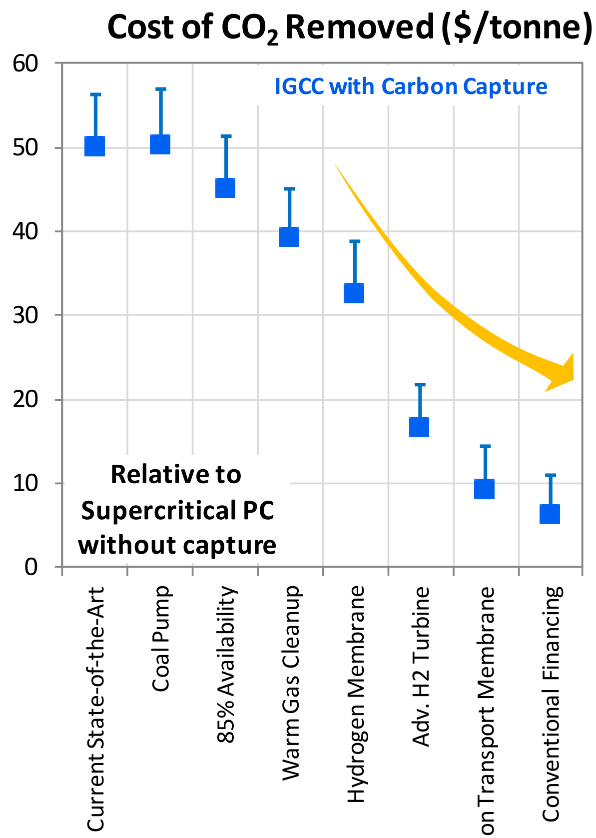


PRELIMINARY RESULTS – SUBJECT TO CHANGE

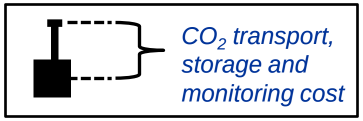
Advanced IGCC Systems

Driving Down the Cost





- CO_2 emissions value to incentivize CCS drops from $65 to $10 per tonne with successful R&D
  - Measured by cost of CO_2 avoided with CO_2 TS&M
- CO_2 power plant gate sales price for CO_2-EOR to incentivize CCUS drops from $50 to $5 per tonne with successful R&D
  - Measured by cost of CO_2 removed excluding CO_2 TS&M

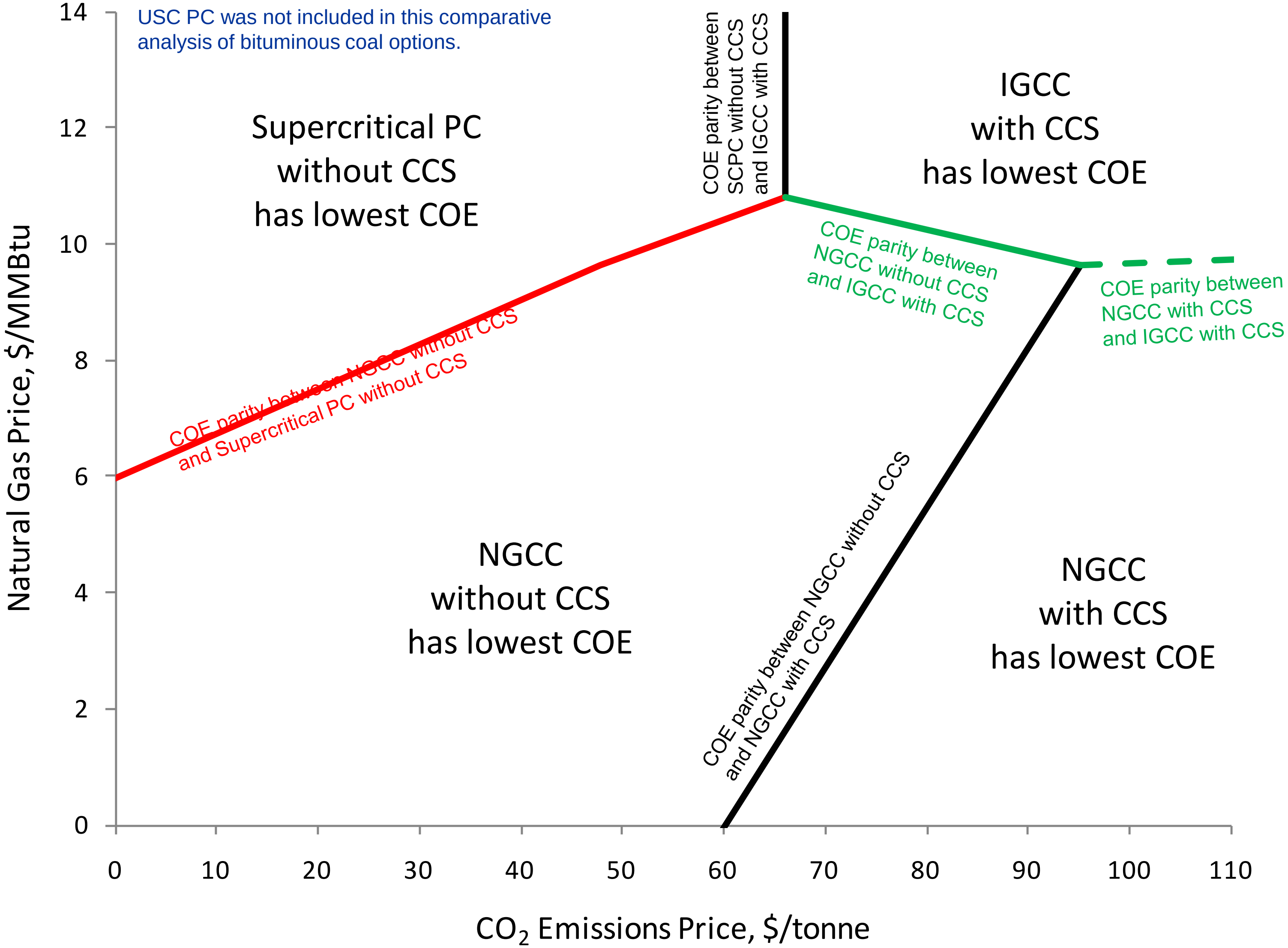


TS&M: Transportation, storage, and monitoring

PRELIMINARY RESULTS – SUBJECT TO CHANGE

Lowest Cost Power Generation Options

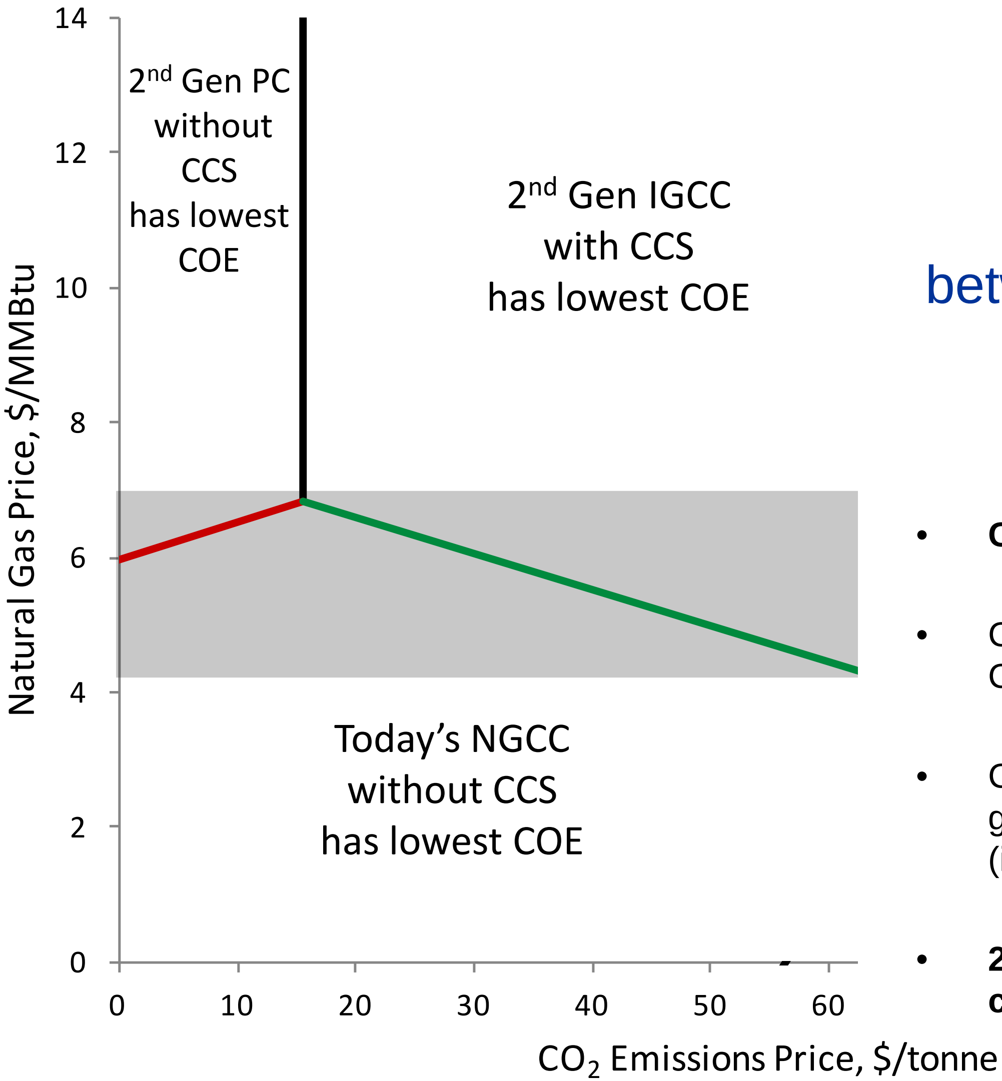
MIDWEST (sea level): *Today's NGCC versus Today's Coal (Bituminous)*



Assumes capacity factor = availability (i.e. all plants including NGCC are base load).
Assumes bituminous coal at delivered price of $1.64/MMBtu

Lowest Cost Power Generation Options

MIDWEST (sea level): *Today's NGCC versus 2^{nd} Generation Coal (Bituminous)*



Given a first-year CO_2 emission price between $0 and $60/tonne, ***and using 2^{nd}-Gen technology***:

- **CCS becomes economically viable**
- Coal <u>with CCS</u> is preferred at first-year CO_2 prices of $15/tonne or higher
- Coal is preferred over natural gas at gas prices above $7/MMBtu (instead of $11/MMBtu)
- **2^{nd}-Gen technology for natural gas could increase CCS market space**

Assumes capacity factor = availability (i.e. all plants including NGCC are base load).
Assumes coal price of $1.64/MMBtu

PRELIMINARY RESULTS – SUBJECT TO CHANGE

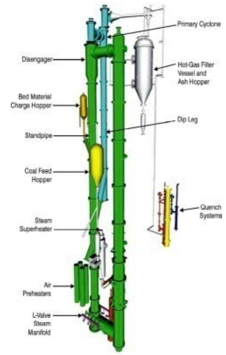
Systems Analysis

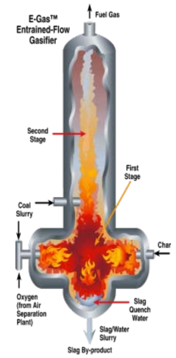
Low Rank Coal Baseline Study: IGCC Cases

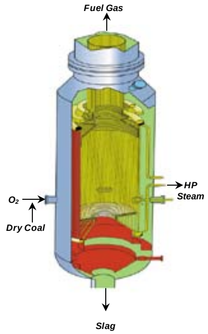
Full presentation available at:

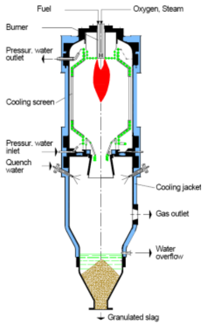
http://www.netl.doe.gov/energy-analyses/baseline_studies.html

IGCC Cases: Technical Design Basis



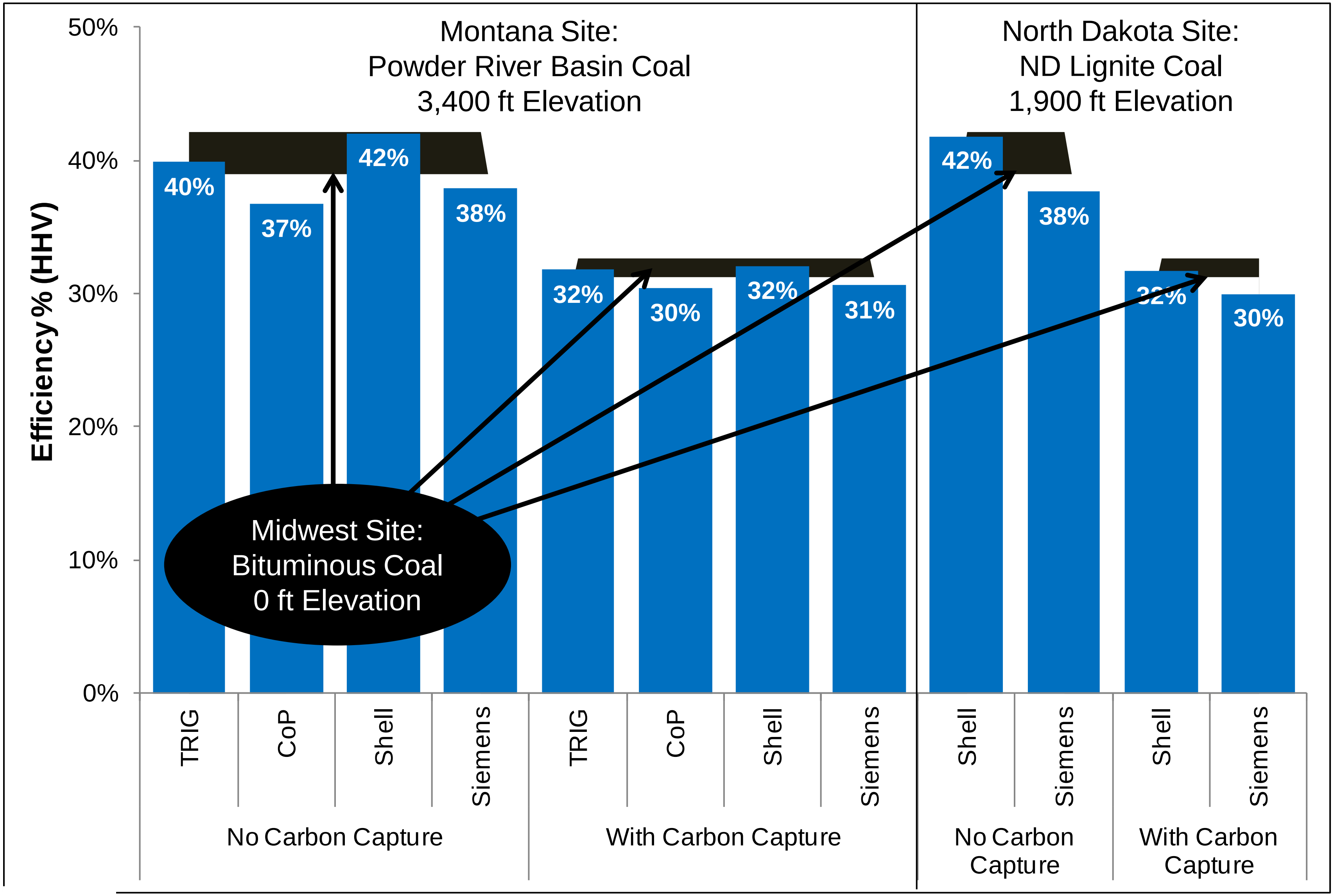




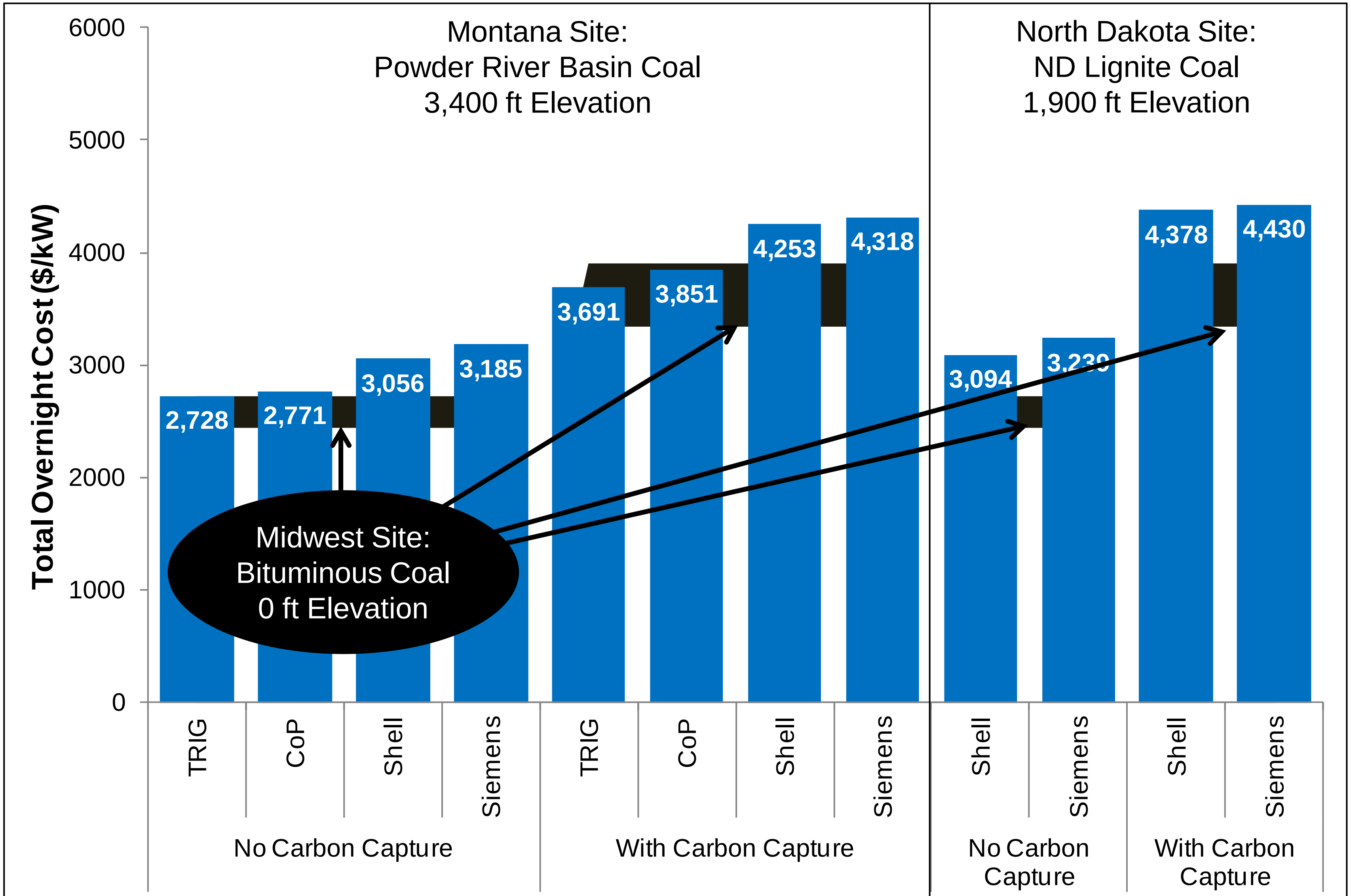


	Southern Company TRIG	ConocoPhillips E-Gas	Shell SCGP	Siemens (GSP/Noell)
Gasifier	Transport	Slurry; entrained	Dry-fed entrained	
Coal Type	PRB		PRB & ND Lignite	
Location/Elevation	Montana/3400 ft		PRB: Montana/3400 ft Lignite: ND/1900 ft	
Coal Drying	Indirectly heated fluidized bed	NA	WTA process	
Oxidant	Oxygen			
AGR for CO2 capture plants	2-Stage Selexol			
Gas Turbine	Advanced F-class (Nitrogen dilution and air integration maximized)			
Steam Cycle (psig/F/F)	1800/1050/1050 (non-CO_2 capture cases) 1800/1000/1000 (CO_2 capture cases)			
Carbon Capture	83%	90%		
Availability	80%			

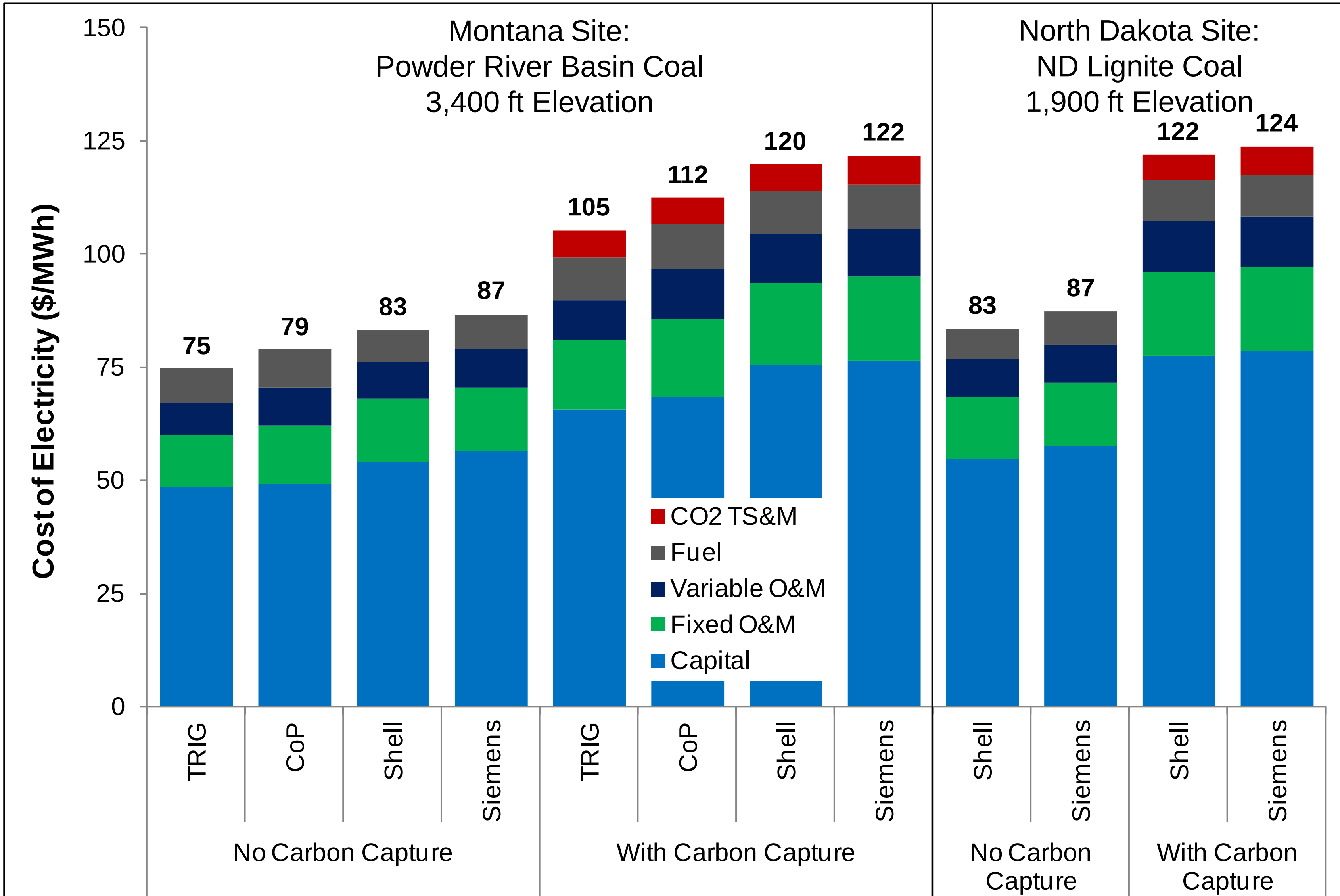
IGCC Efficiency: Bituminous Coal Comparison



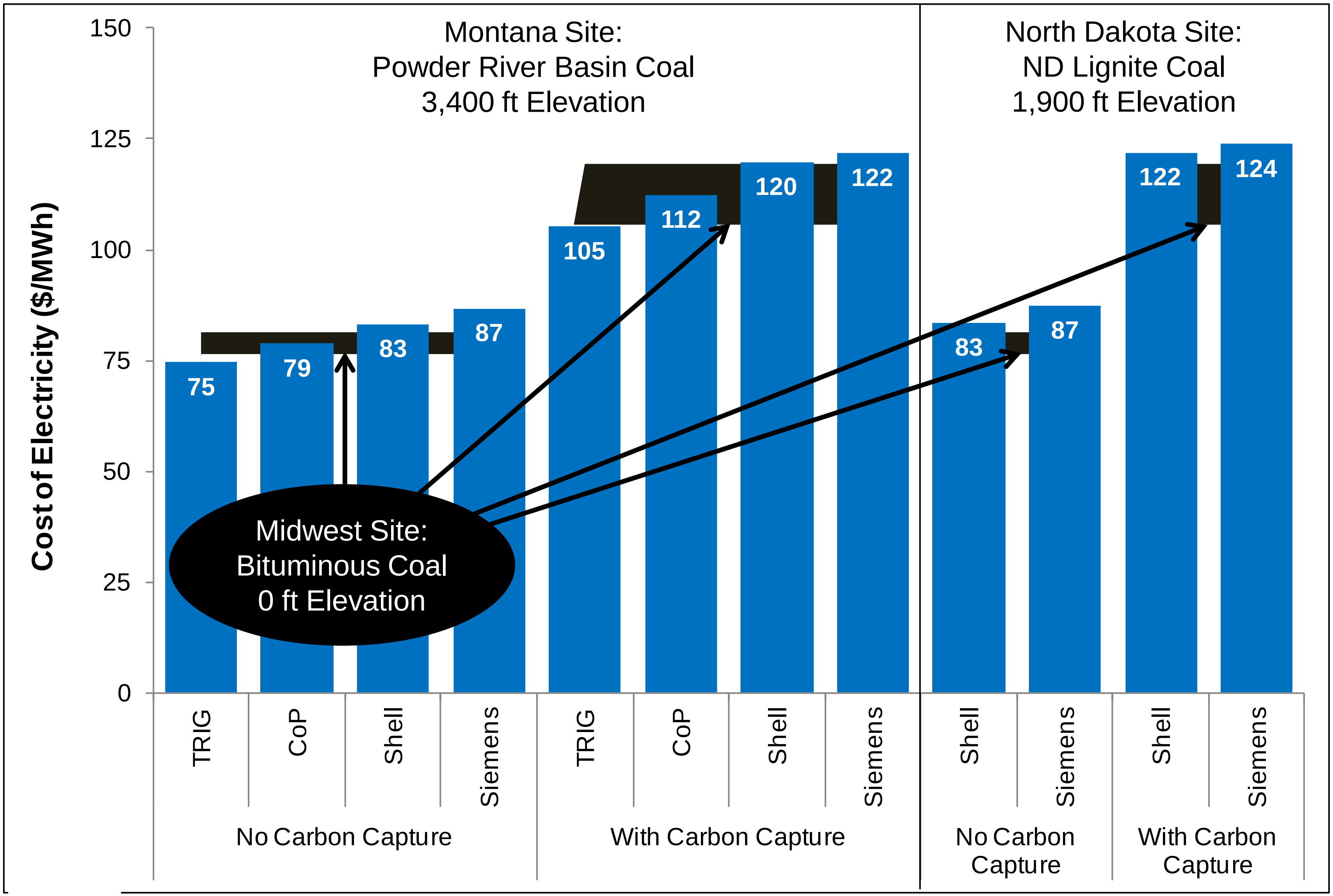
IGCC Plant Cost: Bituminous Coal Comparison



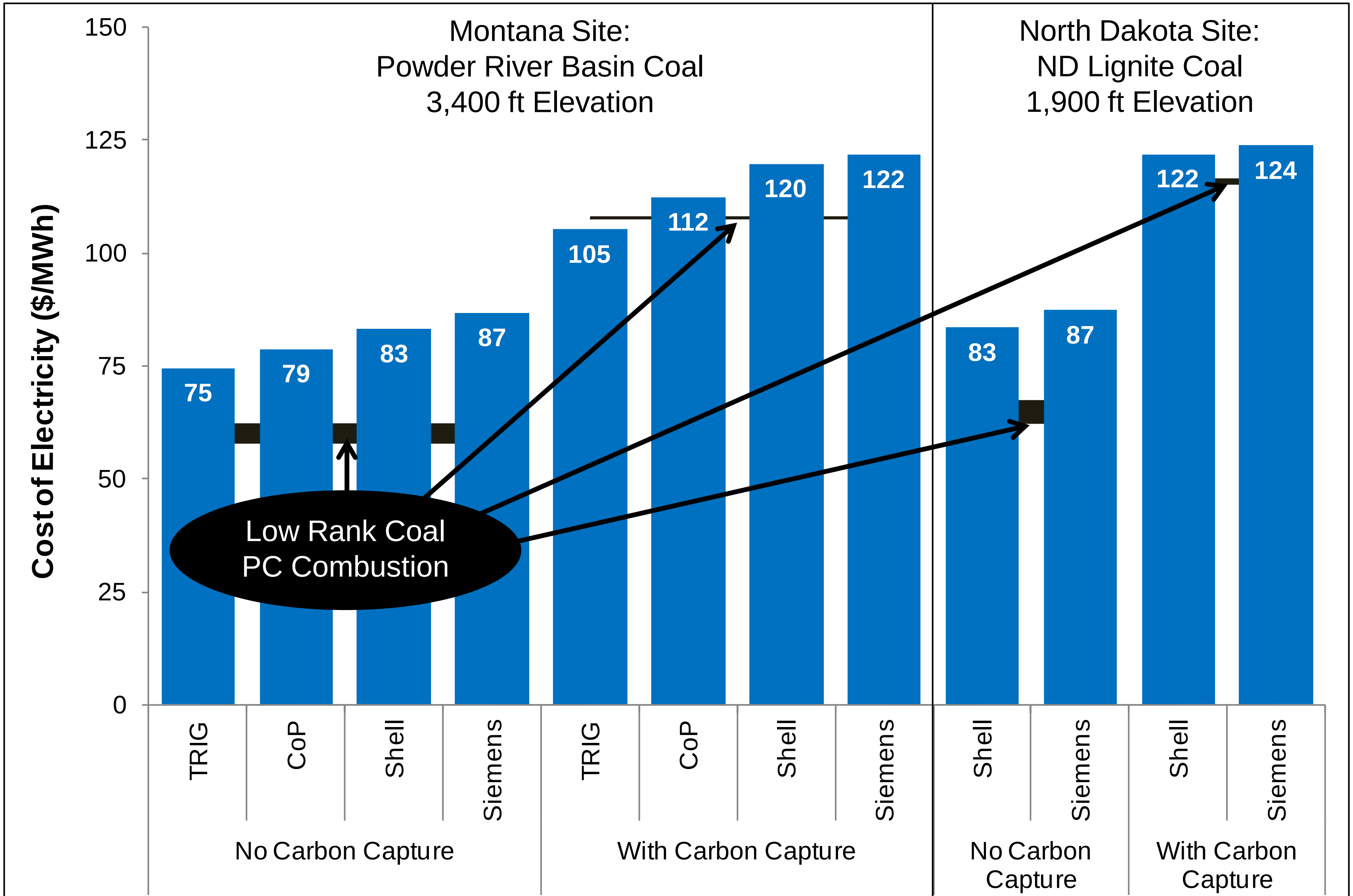
Conventional IGCC: COE



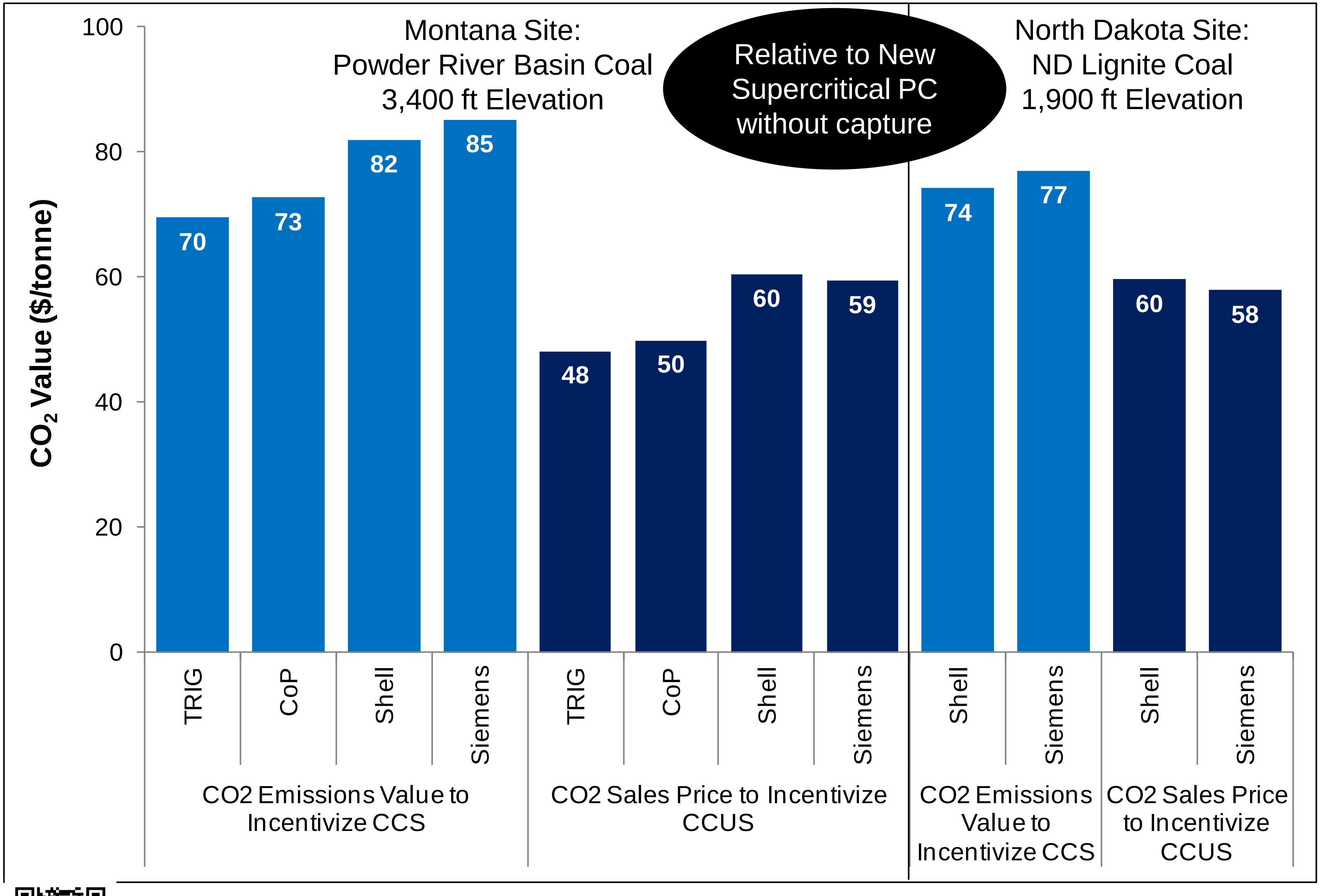
IGCC COE: Bituminous Coal Comparison



IGCC COE: Comparison to PC Plants



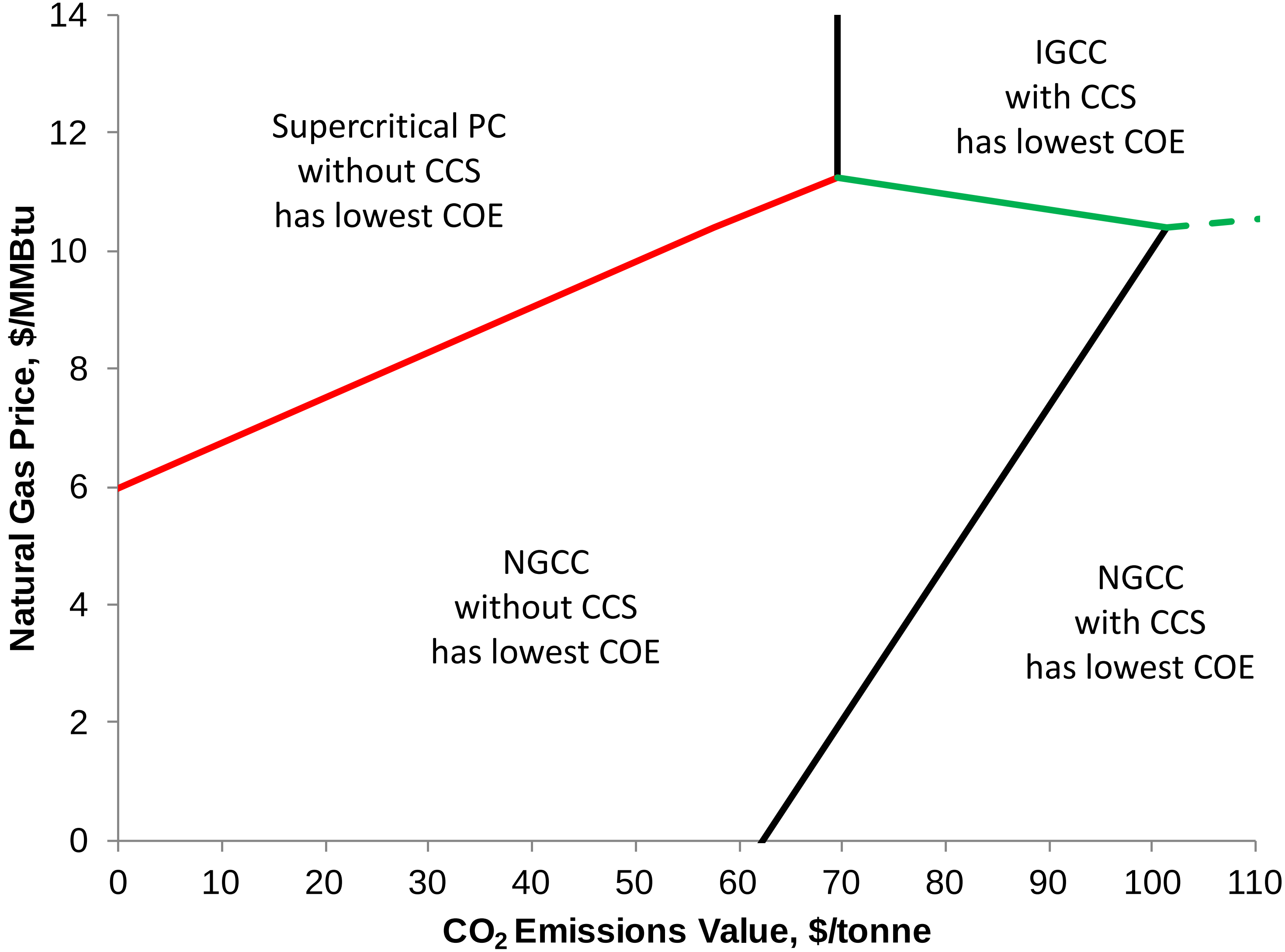
Conventional IGCC: CO_2 Capture Cost



CCUS = Carbon capture, utilization and storage

Lowest Cost Power Generation Options

Western (3400 ft): Today's NGCC versus Today's Coal (PRB)



Assumes capacity factor = availability (i.e. all plants including NGCC are base load).

Key Findings & Next Steps

- **Transport gasifier provides low cost IGCC power**
- **Slurry-fed gasification still competitive for high-moisture PRB coal**
- **Western location/low rank coal gasification COE on par with midwest/bituminous coal gasification**
- **IGCC with carbon capture COE essentially equivalent to PC PRB**
- **All coal systems, with and without carbon capture, face challenges competing in today's U.S. market**
  - No carbon policy
  - Current natural gas prices
- **Opportunities for IGCC**
  - State-of-the-Art: Co-production, CO_2 utilization via enhanced oil recovery
  - 2nd Gen: R&D and demonstration for advanced technologies

Systems Analysis

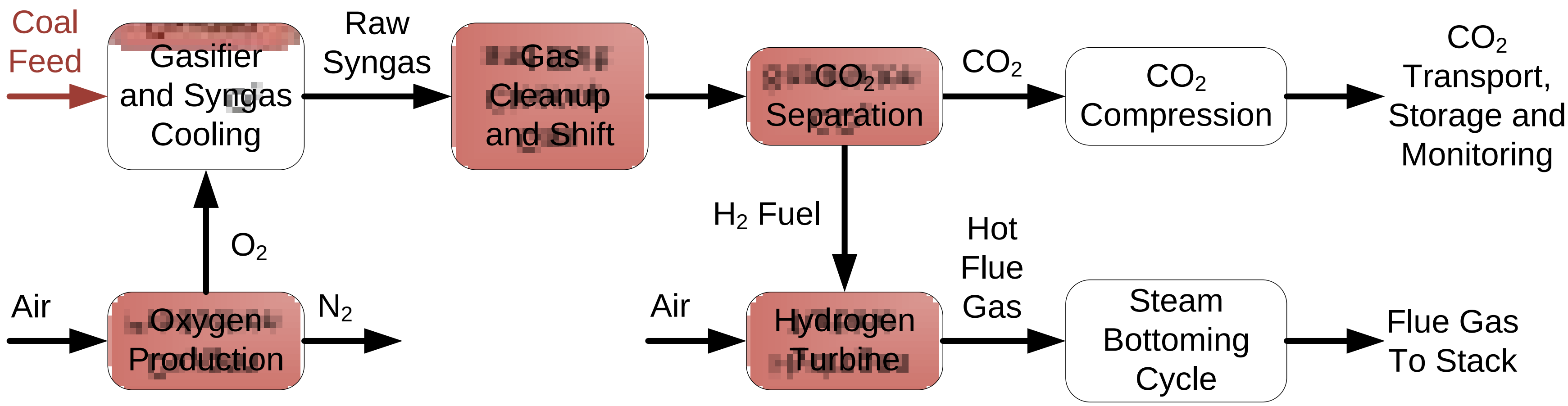
Low Rank Coal IGCC Pathway Study

Systems Analyses for Advanced IGCC

- **Objectives:**
  - Evaluate improved performance and cost resulting from DOE-funded R&D
  - Identify enabling technologies within the portfolio
  - Show relative contribution of different R&D efforts
  - Identify/highlight gaps for low rank coal R&D pathway

- **Approach:**
  - Begin with established cost and performance of conventional IGCC
    - CoP E-Gas selected as reference plant
  - Substitute conventional technologies with advanced technologies in a cumulative fashion assuming successful R&D
  - Evaluate cost and performance in a manner consistent with baseline studies

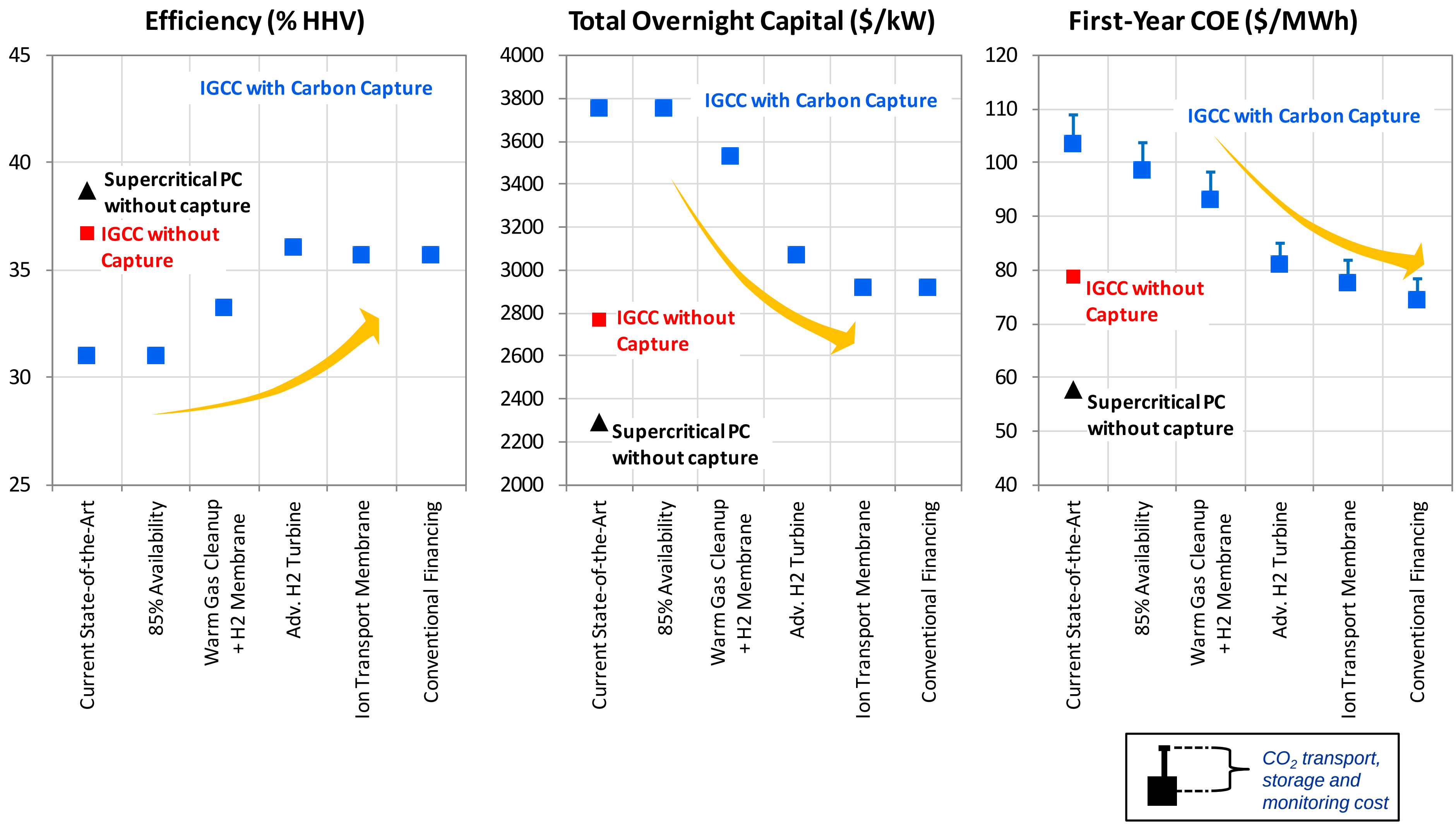
Advanced Technology Progression



	Technology Progression				
Gas Cleanup	Physical Solvent		→		Warm Gas Cleanup (WGCU)
CO_2 Separation	Physical Solvent		→		H_2 Membrane
Gas Turbine	Advanced F-Class		→		Advanced Hydrogen Turbine
Oxygen Production	Cryogenic Air Separation		→		Ion Transport Membrane (ITM)
Availability	80%	→	85%	→	90%

Advanced IGCC Systems – PRB Coal

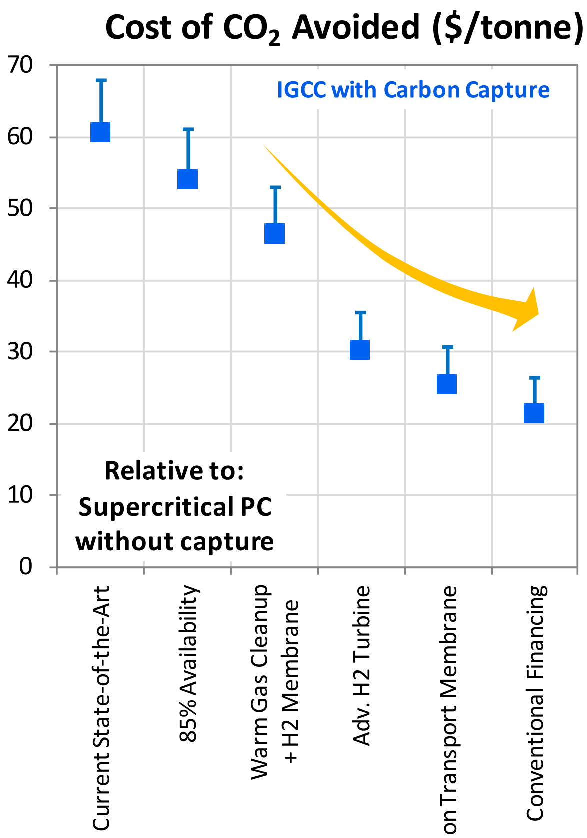
Driving Down the Cost

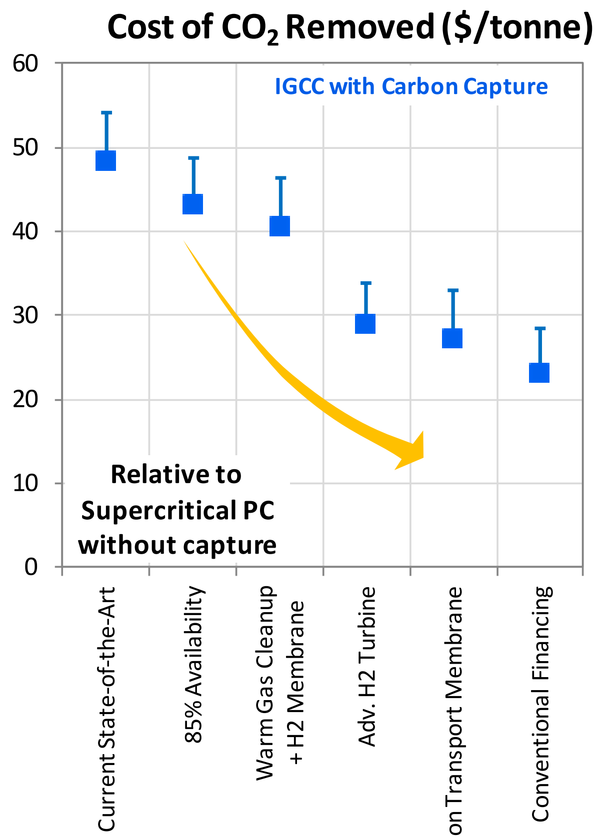


PRELIMINARY RESULTS – SUBJECT TO CHANGE

Advanced IGCC Systems – PRB Coal

Driving Down the Cost





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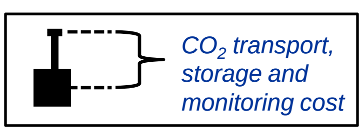
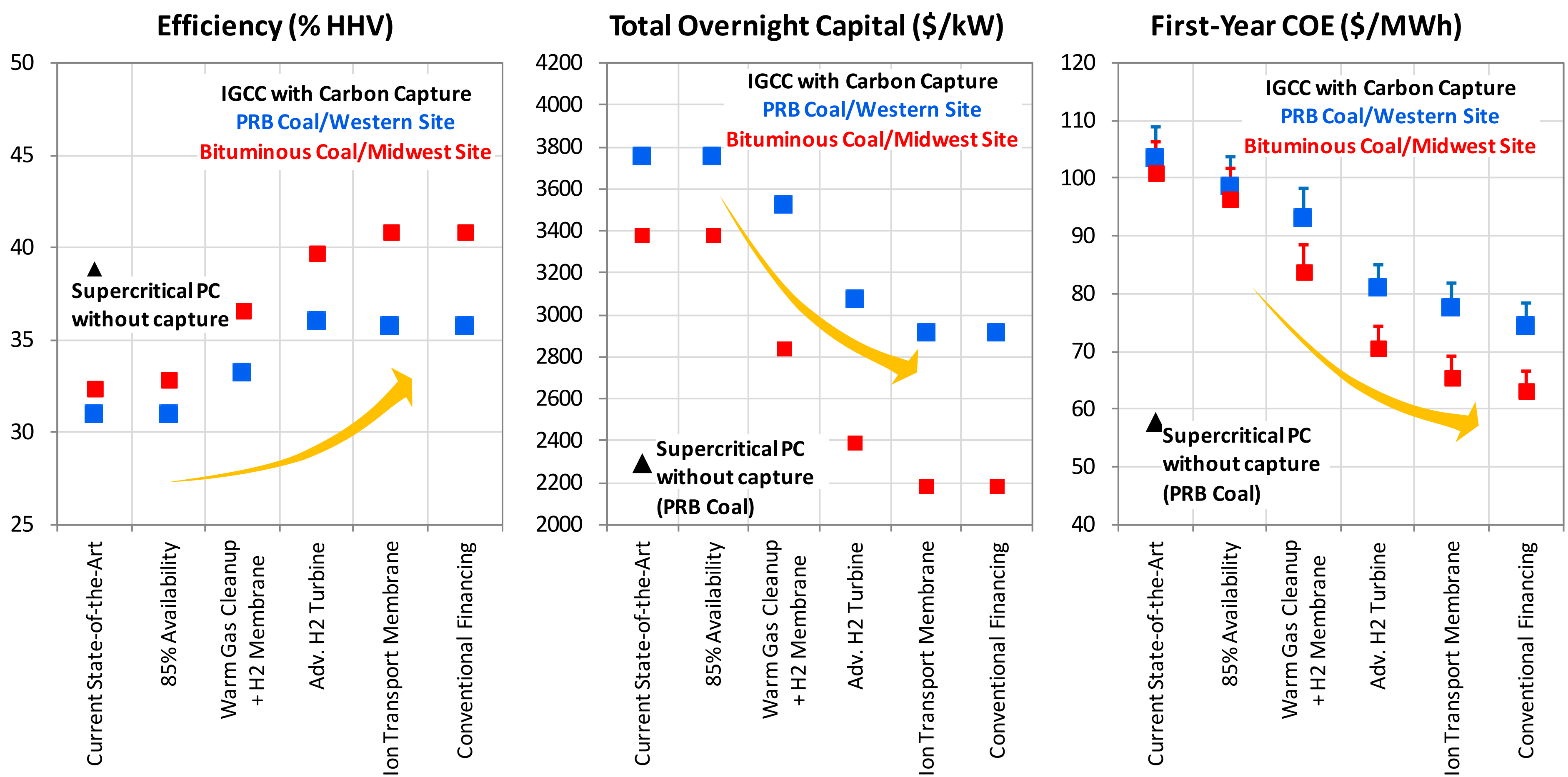
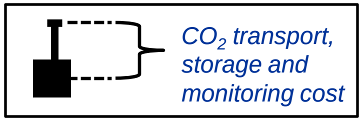


PRELIMINARY RESULTS – SUBJECT TO CHANGE

Advanced IGCC Systems

Driving Down the Cost

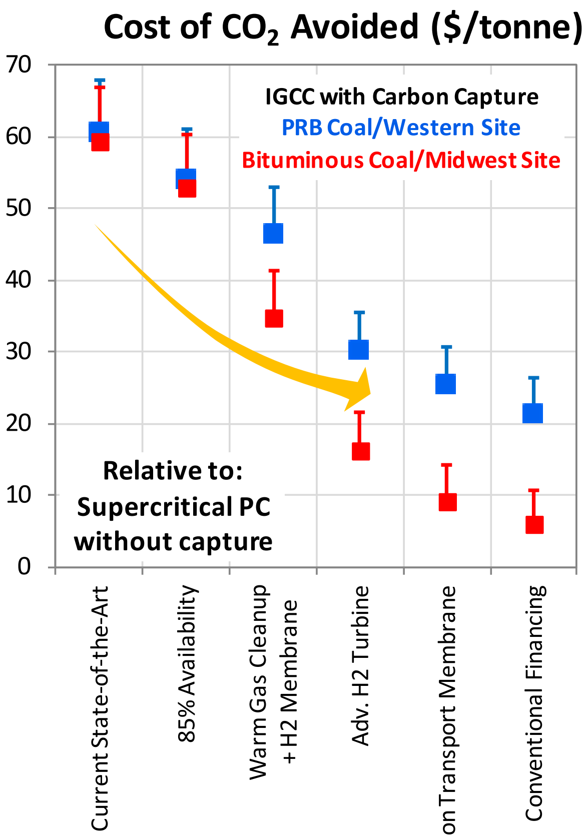


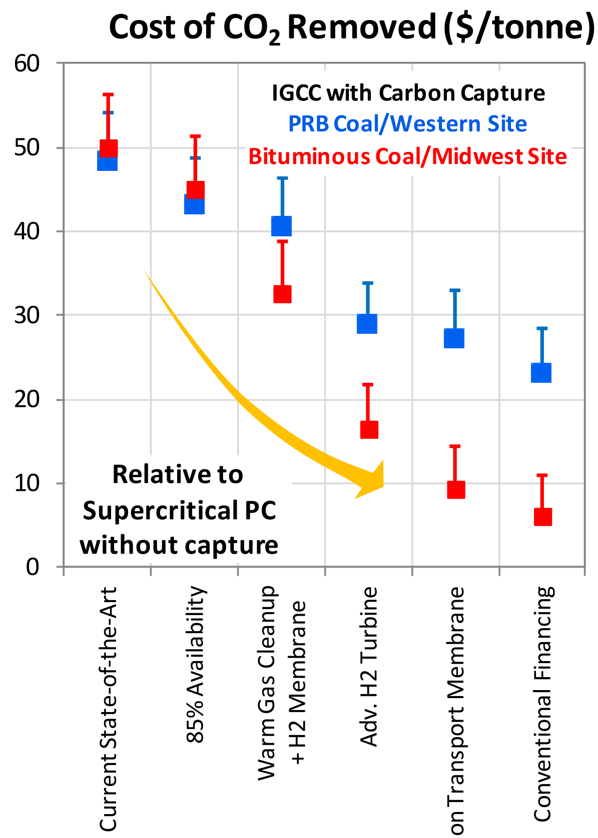


PRELIMINARY RESULTS – SUBJECT TO CHANGE

Advanced IGCC Systems

Driving Down the Cost





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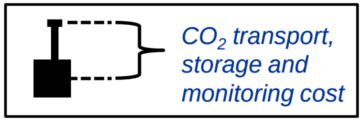
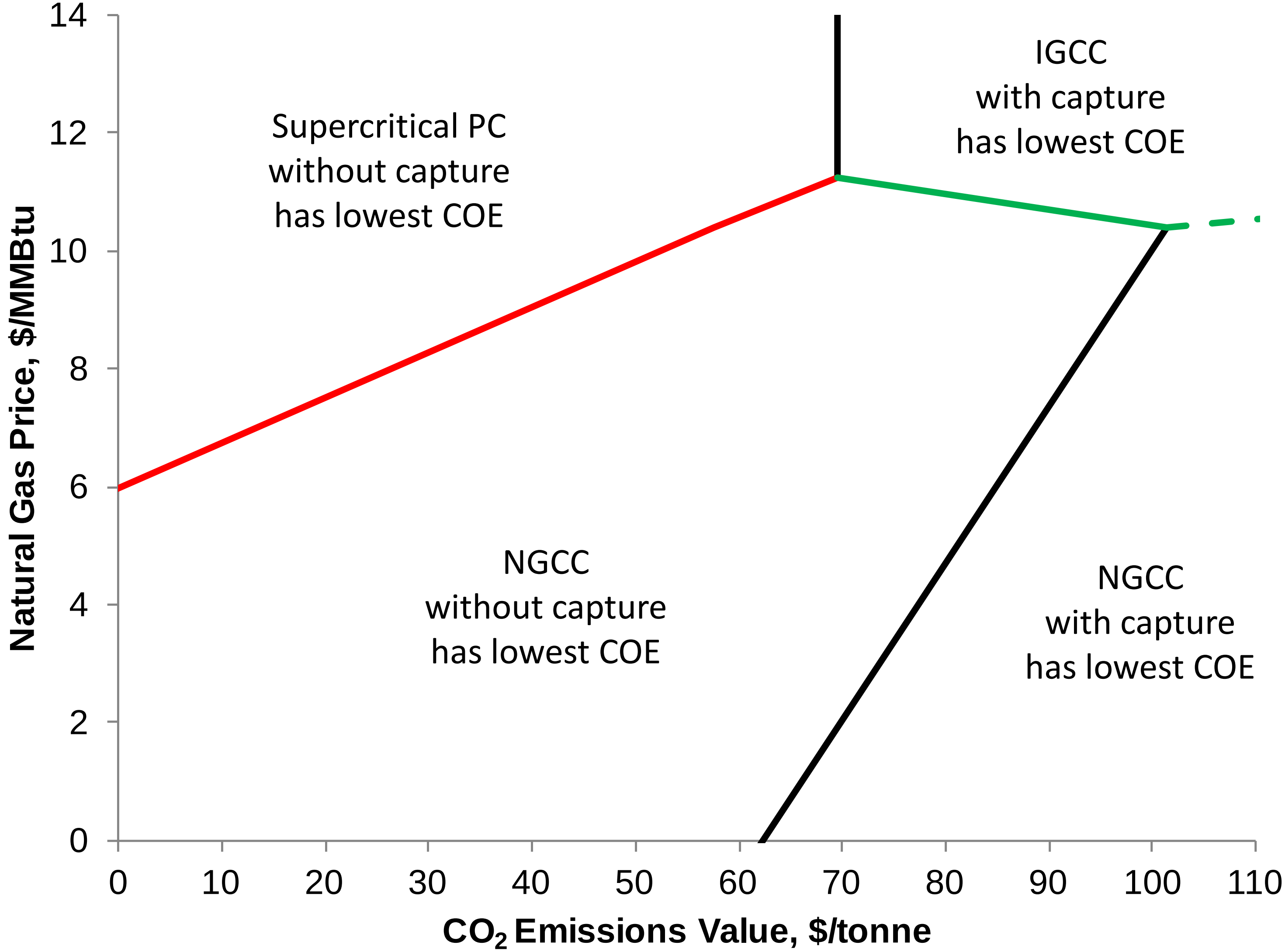


PRELIMINARY RESULTS – SUBJECT TO CHANGE

Lowest Cost Power Generation Options

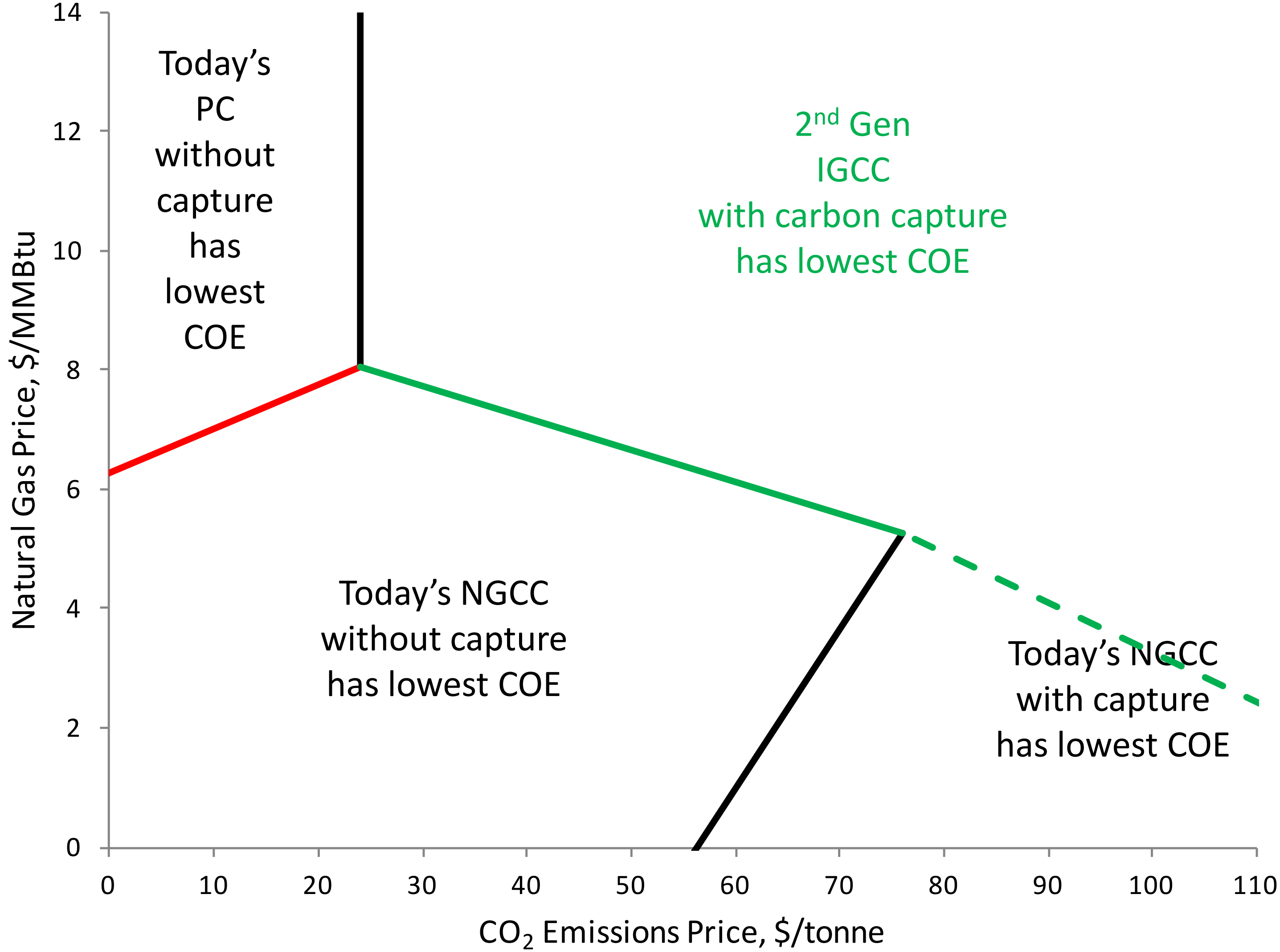
Western (3400 ft): Today's NGCC versus Today's Coal (PRB)



Assumes capacity factor = availability (i.e. all plants including NGCC are base load).

Lowest Cost Power Generation Options

Western (3400 ft): Today's NGCC versus 2nd Gen IGCC (PRB)



Assumes capacity factor = availability (i.e. all plants including NGCC are base load).

Findings of Study and Gaps

- **Current DOE portfolio provides 5 points efficiency gain, 30% reduction in COE relative to today's IGCC with CCS**
- **High pressure gasification may be needed to enable advanced technologies in current R&D portfolio**
  - Managing WGCU pressure drop, hydrogen membrane driving force, meeting fuel gas pressure needs for advanced hydrogen turbine
- **Evaluation of alternatives to slurry-fed gasification for 2nd Gen IGCC recommended**

Conventional IGCC Compared to PC and NGCC

Fundamental Comparison of IGCC with Advanced PC-Fired Plant

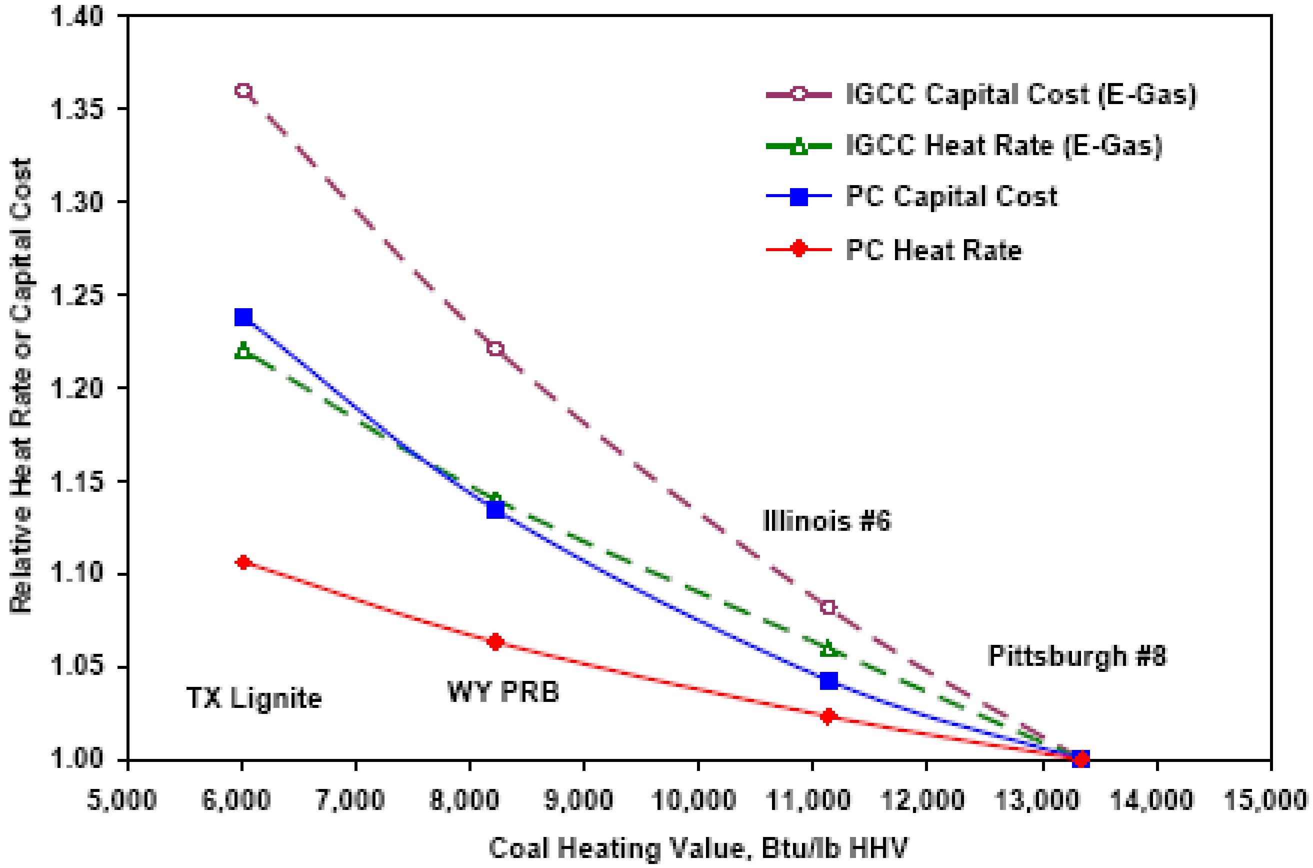
	IGCC	PC
Operating Principles	Partial Oxidation	Full Oxidation
Fuel Oxidant	Oxygen	Air
Temperature	≤ 3000 F	≤ 3200 F
Pressure	415-1000 psia	Atmospheric
Sulfur Control	Concentrate Gas	Dilute Gas
Nitrogen Control	Not Needed	Pre/Post Combustion
Ash Control	Low Vol. Slag	Fly/Bottom Ash
Trace Elements	Slag Capture	ESP/Stack
Wastes/By-products	Several Markets	Limited Markets
Efficiency (HHV)	39-42%	37-40%

Comparison of Air Emission Controls: PC vs. IGCC

	Sulfur	NO_x	PM	Mercury
PC Post Combustion	FGD system	Low-NO_x burners and SCR	ESP or baghouse	Inject activated carbon
IGCC Pre Combustion	Chemical and/or physical solvents	Syngas saturation and N_2 diluent for GT and SCR	Wet scrubber, high temperature cyclone, barrier filter	Pre-sulfided activated carbon bed

Steve Jenkins 2009 GTC Workshop http://www.gasification.org/uploads/downloads/Workshops/2009/Kingsport/02Jenkins.pdf

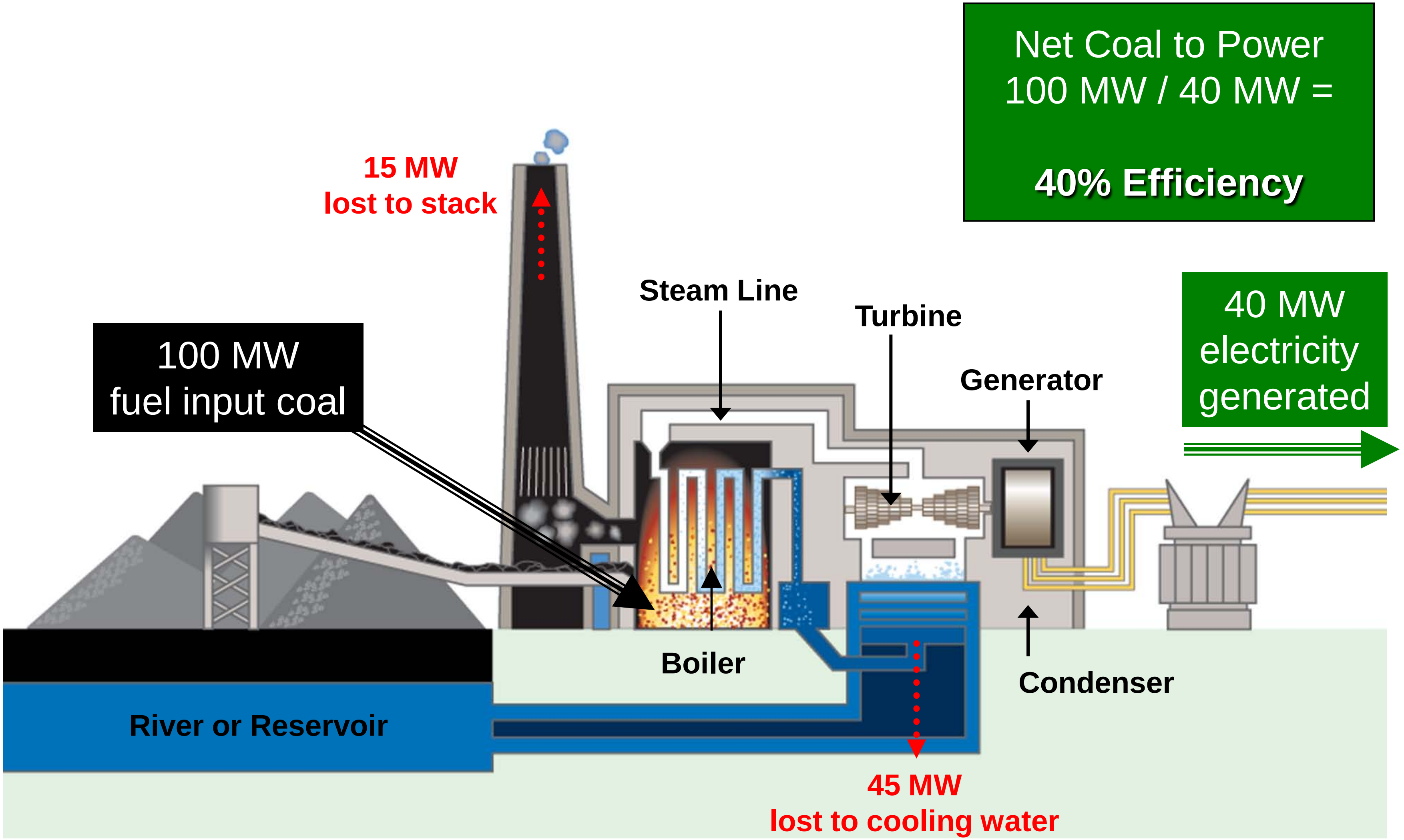
Effect of Coal Quality on PC and IGCC Plant Heat Rates and Capital Costs



Source: EPRI (Booras and Holt), "Pulverized Coal and IGCC Plant Cost and Performance Estimates", GTC Conference, October 2004

Conventional Coal Plant

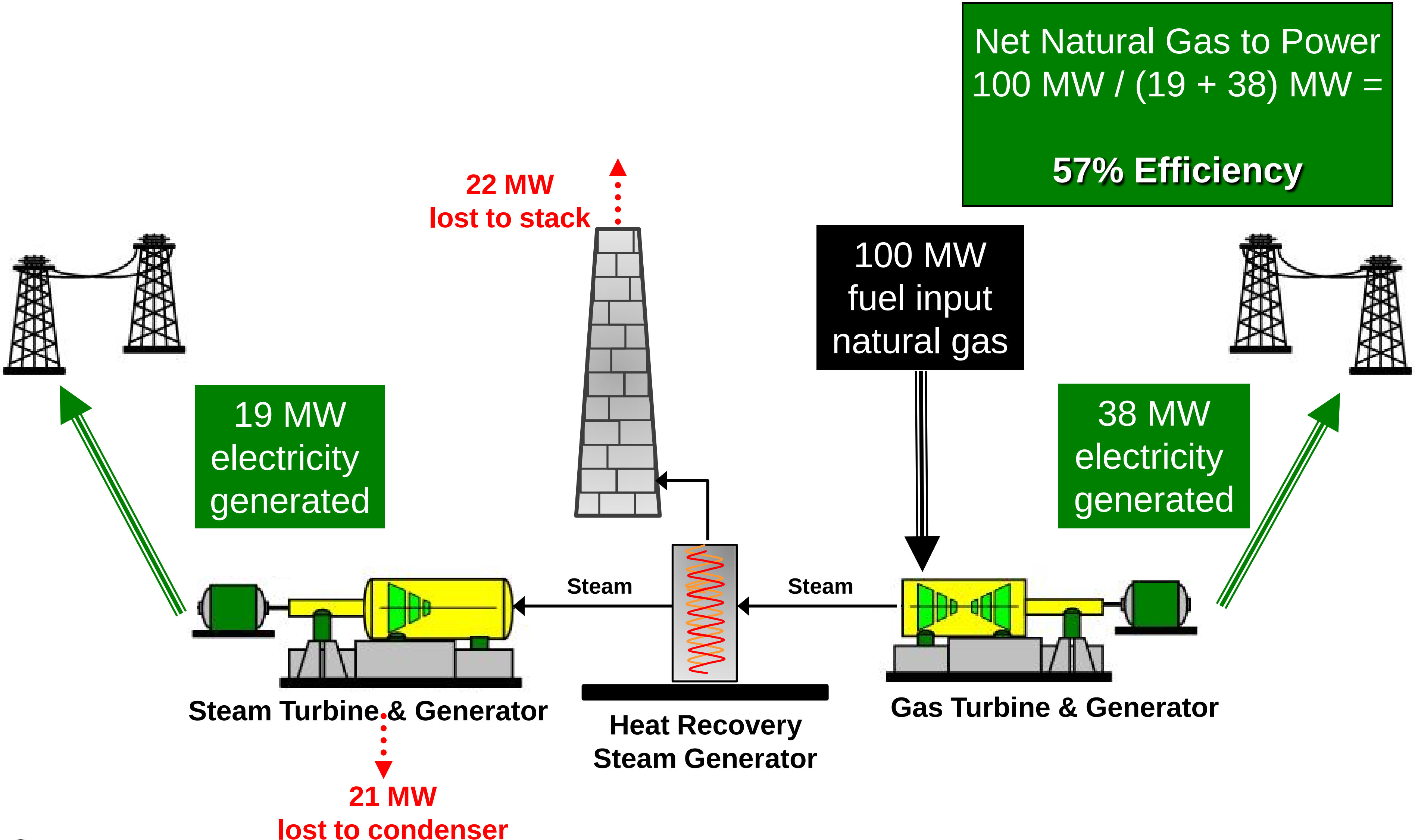
(Illustration only)



Source: EPRI

Natural Gas Combined Cycle

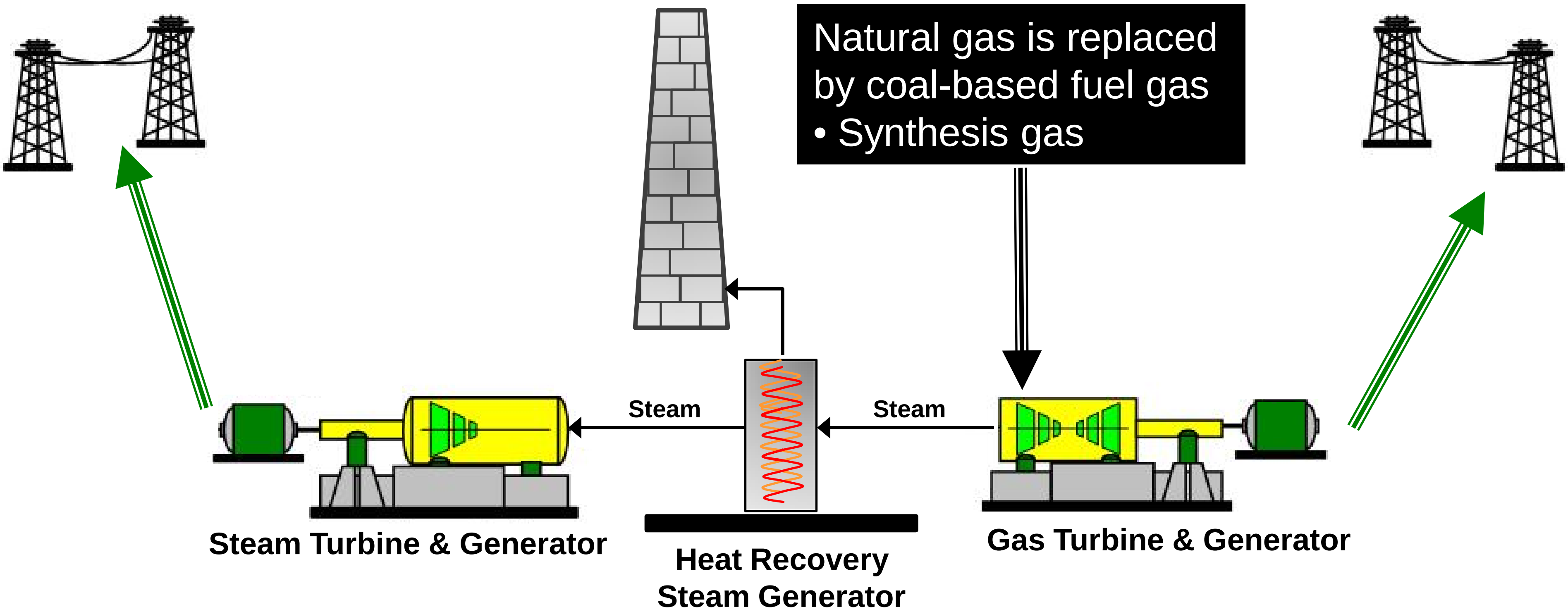
(Illustration only)



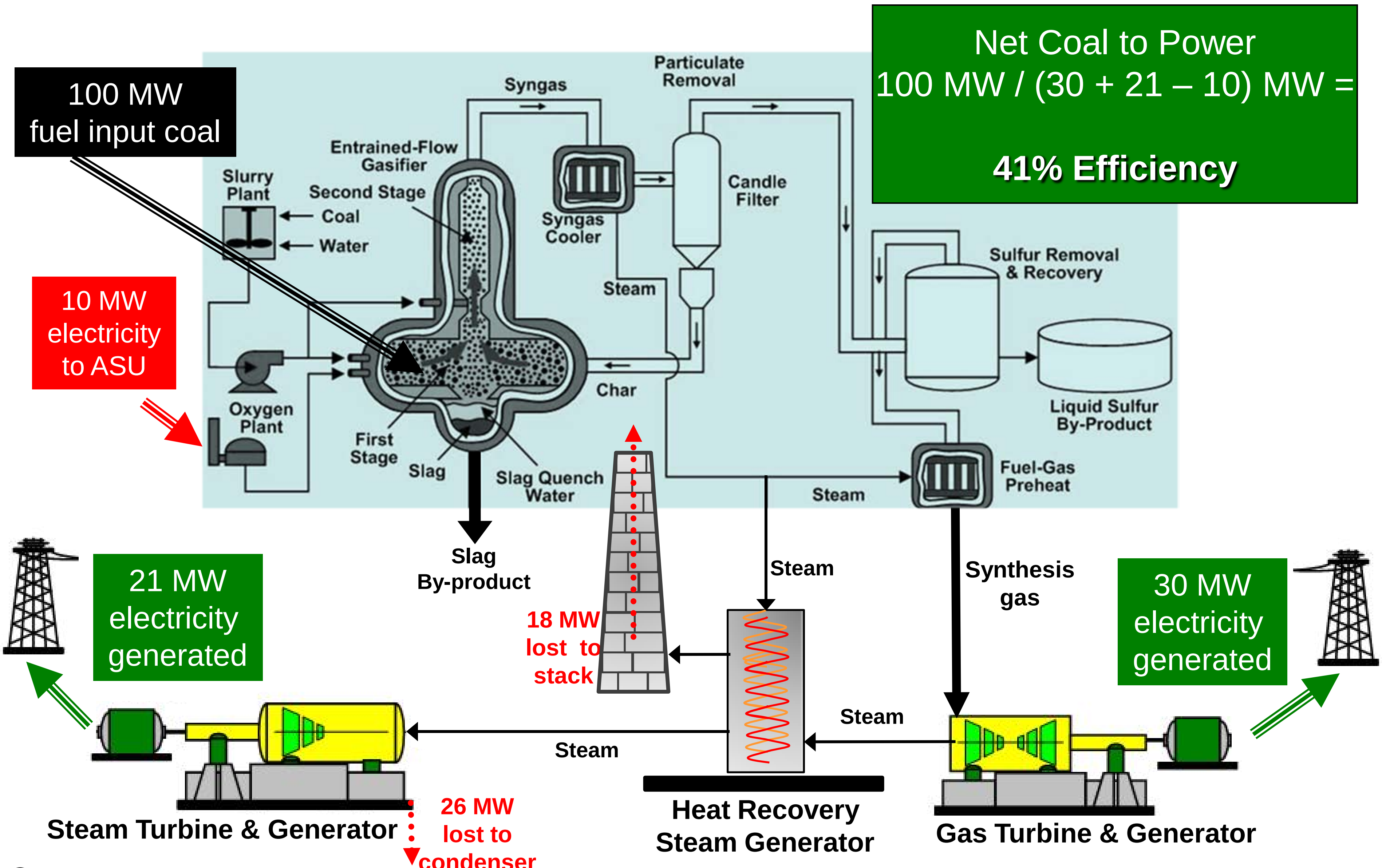
Coal-Based IGCC Power Plant

<u>Gasification Island</u>

- Converts coal to synthesis gas
- Cleans & conditions synthesis gas



Coal-Based IGCC Power Plant



Gasification-Based Energy Conversion Systems

RESOURCES

- Air/Oxygen
- Coal
- Biomass
- Petroleum Coke
- Heavy Oil
- Refinery Wastes
- MSW
- Orimulsion
- Other Wastes

GASIFIERS

OXYGEN-BLOWN

Entrained Flow
GE Energy, E-Gas, Shell, Prenflo, Noell, Huaneng CERI, OMB

Fluidized Bed
HT Winkler, U-Gas

Moving Bed
British Gas Lurgi (BGL)
Lurgi (Dry Ash)

Transport Reactor
KBR

AIR-BLOWN

Fluidized Bed
HT Winkler, GTI U-Gas, KRW

Sprouting Bed
British Coal, Foster Wheeler

Entrained Flow
Mitsubishi

Transport Reactor
KBR

ENVIRONMENTAL CONTROL

Particulate Removal and Recycle
- Filtration, Water Scrubbing

Chloride and Alkali Removal
- Water Scrubbing

Acid Gas Removal
- Amine Processes
- Rectisol, Selexol

COS Hydrolysis

Sulfur Recovery
- Claus Process
- SCOT Process
- Sulfuric Acid Plant

Water Treatment
- Process Water, BFW

Tail Gas Treating

Turbine NOx Control
- Nitrogen/Steam Dilution
- SCR

Syngas Mercury Capture

Syngas CO_2 Capture

ENERGY CONVERSION

- Gas Turbine
- Heat Recovery Steam Generator (HRSG)
- Steam Turbine
- Boiler
- Syngas Conversion to Fuels & Chemicals
- Catalytic Conversion
- Shift Conversion
- Fischer-Tropsch
- Fuel Cell
- H_2 Turbine

PRODUCTS

- Steam
- Electric Power
- Liquid Fuels
- Chemicals
- Methanol
- SNG
- Hydrogen
- Ammonia/ Fertilizers
- Slag
- Sulfur/ Sulfuric Acid

Commercial IGCC Plants

Commercial IGCC Plants in the U.S.

Active and Under Construction

(excluding DOE supported demonstration projects)

Wabash River Coal Gasification Repowering Project
- 262 MWe coal/petcoke (1995 - present)

Tampa Electric Polk Power Station
- 250 MWe coal/petcoke (1996 - present)

Duke Energy's Edwardsport Integrated Gasification Combined Cycle Station
- 630 MWe coal (2012 start up)

Wabash River IGCC

SG Solutions – West Terre Haute, Indiana

Plant startup July 1995

E-Gas gasifier

- ConocoPhillips

2,500 tons/day coal or petcoke

Bituminous coal

- 1995 thru August 2000

Petcoke

- 2000 thru Present

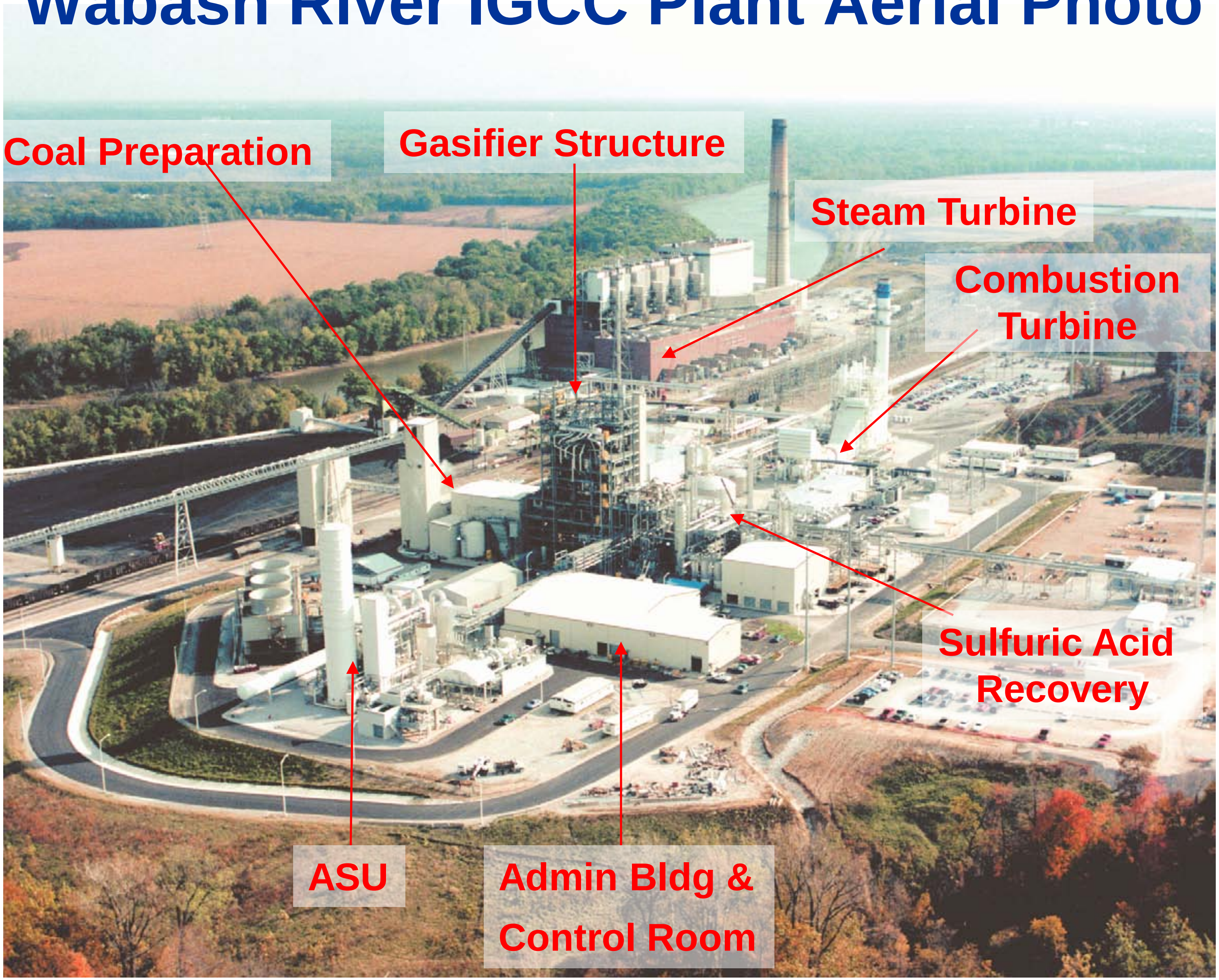
DOE CCT Round IV

- Repowering project

Power generation

- Combustion turbine: 192 MWe
- Steam turbine: 105 MWe
- Internal load: -35 MWe
- Net output: **262 MWe**

Wabash River IGCC Plant Aerial Photo



Polk Power Station Unit 1

Tampa Electric Co. − Mulberry, FL

- GE Gasifier
  - – Oxygen blown
  - – Slurry fed
  - – Entrained flow
  - – Refractory lined
- Feedstock 2,200 tons/day
  - – Coal and petcoke blend
- CT is GE 7F
- Single train configuration
  - – One gasifier supplying one CT
- Acid gas removal via
  - – MDEA and COS hydrolysis
- DOE Clean Coal Technology Program
  - – Plant startup July 1996

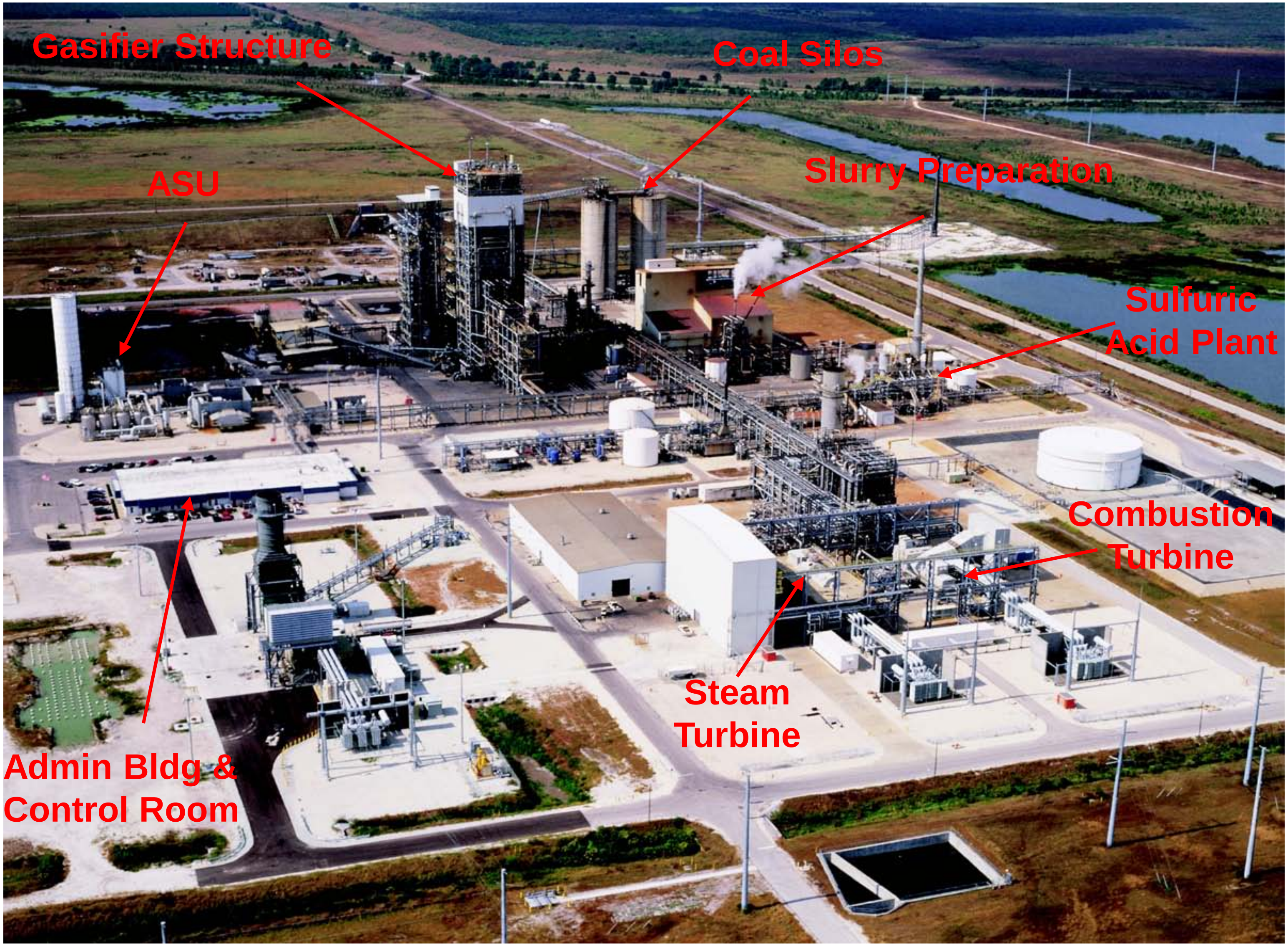
Polk Power Station, Unit

Power generation

– Combustion turbine:	192 MWe
– Steam turbine:	123 MWe
– Internal load:	- 55 MWe
– Other auxiliaries:	- 10 MWe
– **Net output**	**250 MWe**

Courtesy: Tampa Electric Co.

Polk Power Station Aerial Photo

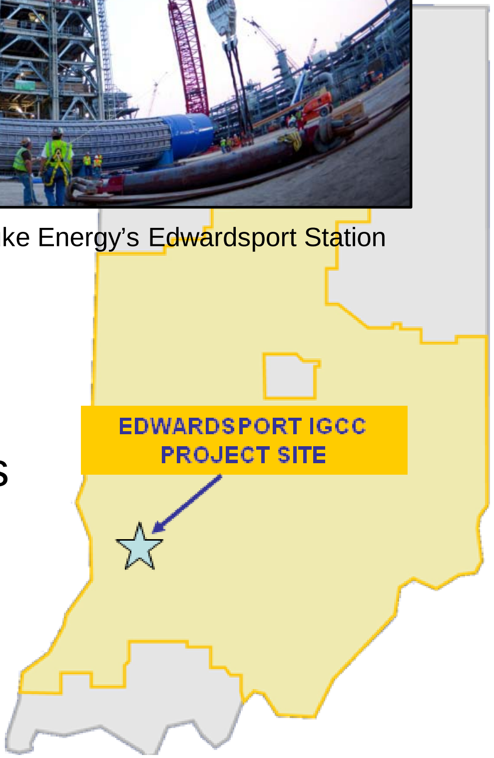


Edwardsport 630 MW IGCC Project

Duke Energy

- 2 x GE Gasifier
- 2 x GE 7 FB combustion turbines
  - 232 MWe each
- GE steam turbine
  - 320 MWe
- 1.5 million tons of coal per year
- Total project cost:
  - $ 2.98 billion
  - $133.5 million Federal investment tax credit award
  - $460 million in local, state and federal tax incentives

Gasifier being installed at Duke Energy's Edwardsport Station



Projected Startup Late 2012

Image courtesy of Duke Energy Indiana

ELCOGAS

Puertollano, Spain

- PRENFLO gasifier
  - Pressurized entrained flow gasifier now offered by Uhde
- Oxygen blown
- 2,600 tons/day coal and petcoke
- Commercial operation began in 1996 with natural gas
- In 1998 began operating on 50/50 Petroleum coke / local Spanish coal (~ 40% ash)
- Siemens V94.3 gas turbine
- Independent power project without a power purchase agreement (PPA)

IGCC Plant Puertollano, Spain

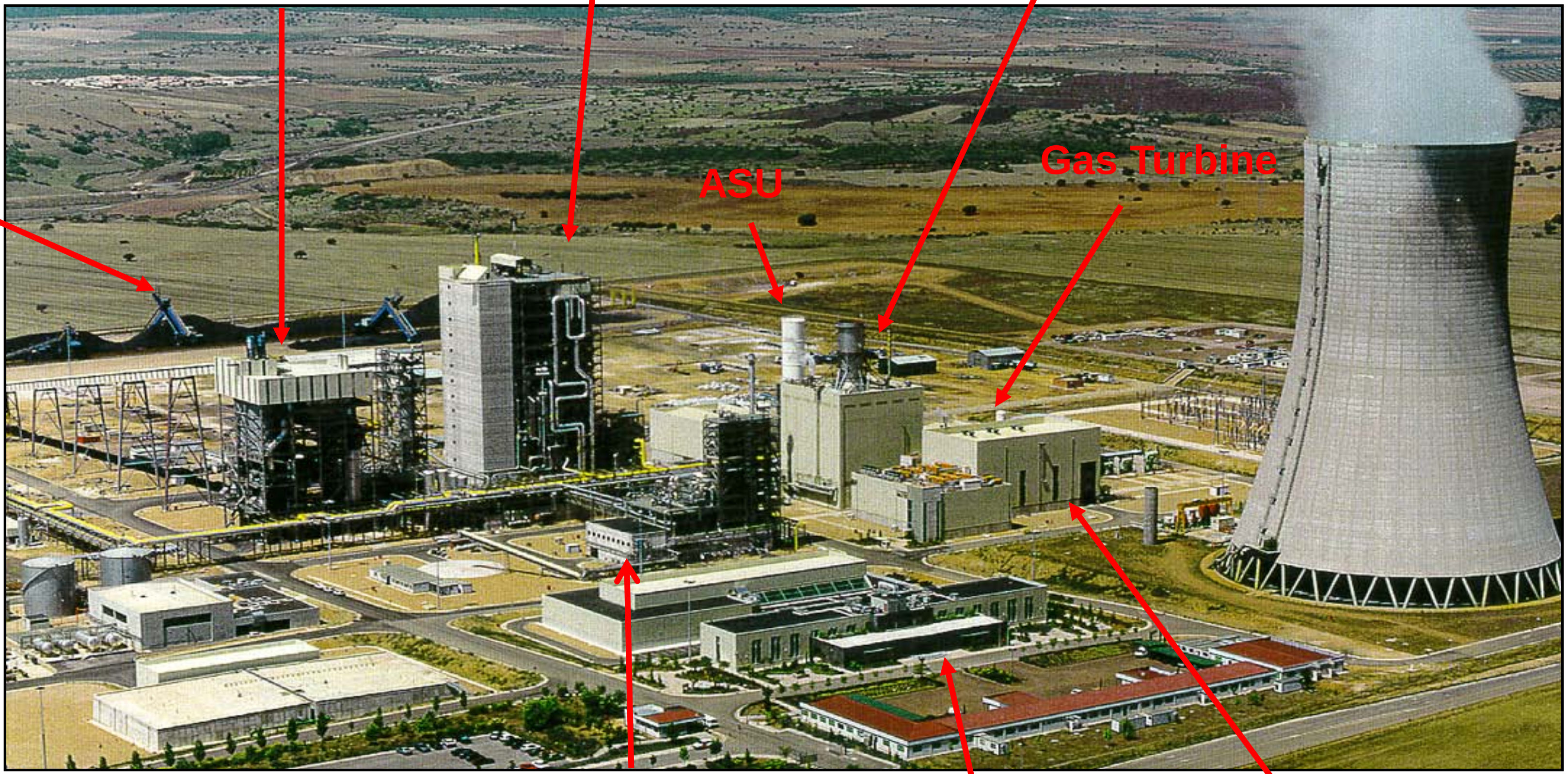
Power generation

– Combustion turbine	182.3 MWe
– Steam turbine	135.4 MWe
– Internal load	- 35.0 MWe
– Net output	282.7 MWe

Source: "Integrated gasification combined cycle technology: IGCC – Its actual application in Spain: ELCOGAS, Puertollanl" Manuel Treviño Coca

Image Source: www.elcogas.es/shared/enter_img2_r1_c1.jpg

ELCOGAS Plant Aerial Photo



Vresova IGCC Power Plant

Vřesová, Czech Republic

- 1970 Town Gas Production
- 1996 Converted to IGCC
- 26 Lurgi Gasifiers – Entrained flow
  - Dry coal feed - Lignite
- 1 Siemens SFG-200 – Entrained
  - Added 2007
  - Oxygen blown – Full quench
  - Feedstock: Phenols, tars, petrol, etc. created during gasification
- 2 GE Combustion turbines
  - FRAME 9 E (9171 E)
- ABB ES Steam turbine

Vřesová IGCC Plant, Czech Republic

Power generation

– Combustion turbine:	309 MWe
– Steam turbine:	114 MWe
– Internal load:	- 25 MWe
– Net output:	398 MWe

http://www.gasification.org/Docs/2005_Papers/05CHHO.pdf

Nuon IGCC Plant
Buggenum, The Netherlands

- Shell Gasification
  - – Offered jointly with Krupp Uhde
- Gas turbine: Siemens V94.2
- 2,000 tons/day feedstock
  - – Bituminous coal
  - – Biomass
- Plant startup 1993

Buggenum IGCC Plant

Power generation

– Combustion turbine:	155 MWe
– Steam turbine:	128 MWe
– Internal load:	- <u>30 MWe</u>
– Net output:	253 MWe

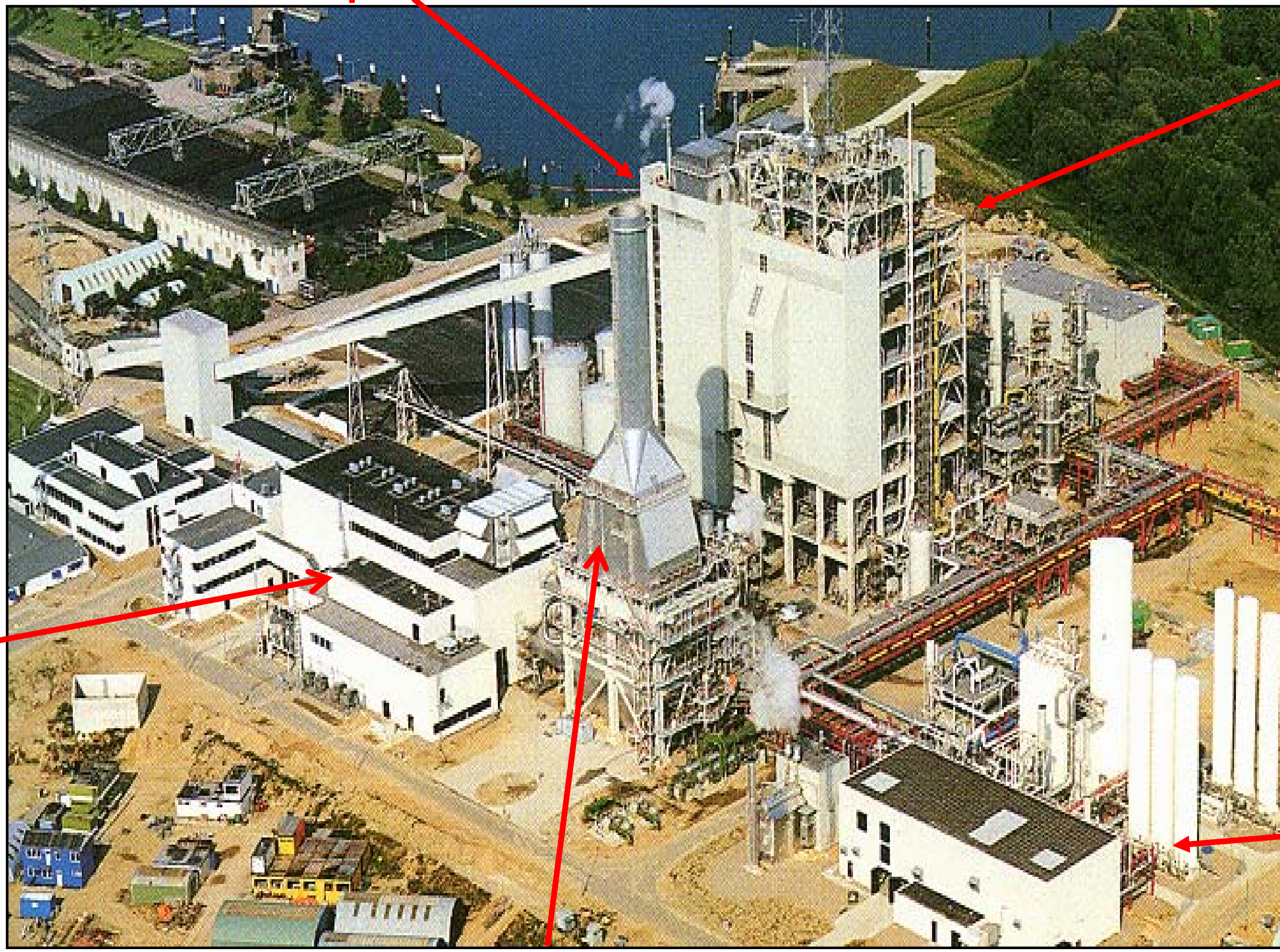
Only large-scale biomass installation in operation today

http://www.gasification.org/Docs/2005_Papers/05CHHO.pdf

Nuon Plant Aerial Photo

Coal Preparation Plant

Gasifier Structure



Gas & Steam Turbine

ASU

Heat Recovery Steam Generator

Note: Sulfur Removal & Recovery (out of view)

Courtesy: Nuon

Clean Coal Power R&D IGCC Demonstration Plant

Nakoso, Japan

Mitsubishi Gasifier
- 250 MWe
- Air-blown
- Entrained flow
- Dry coal feed

1,700 tons/day coal
- Suited to wide range of coals

Water wall structure

Gas clean-up
- MDEA chemical absorption

Plant startup September 2007

Clean Coal Power R&D
Joint project of
- Mitsubishi Heavy Industries,
- Ministry of Economy, Trade and Industry, and
- Several EPC companies

Clean Coal Power R&D IGCC Demonstration Plant

Aerial Photo

Heat Recovery Steam Generator

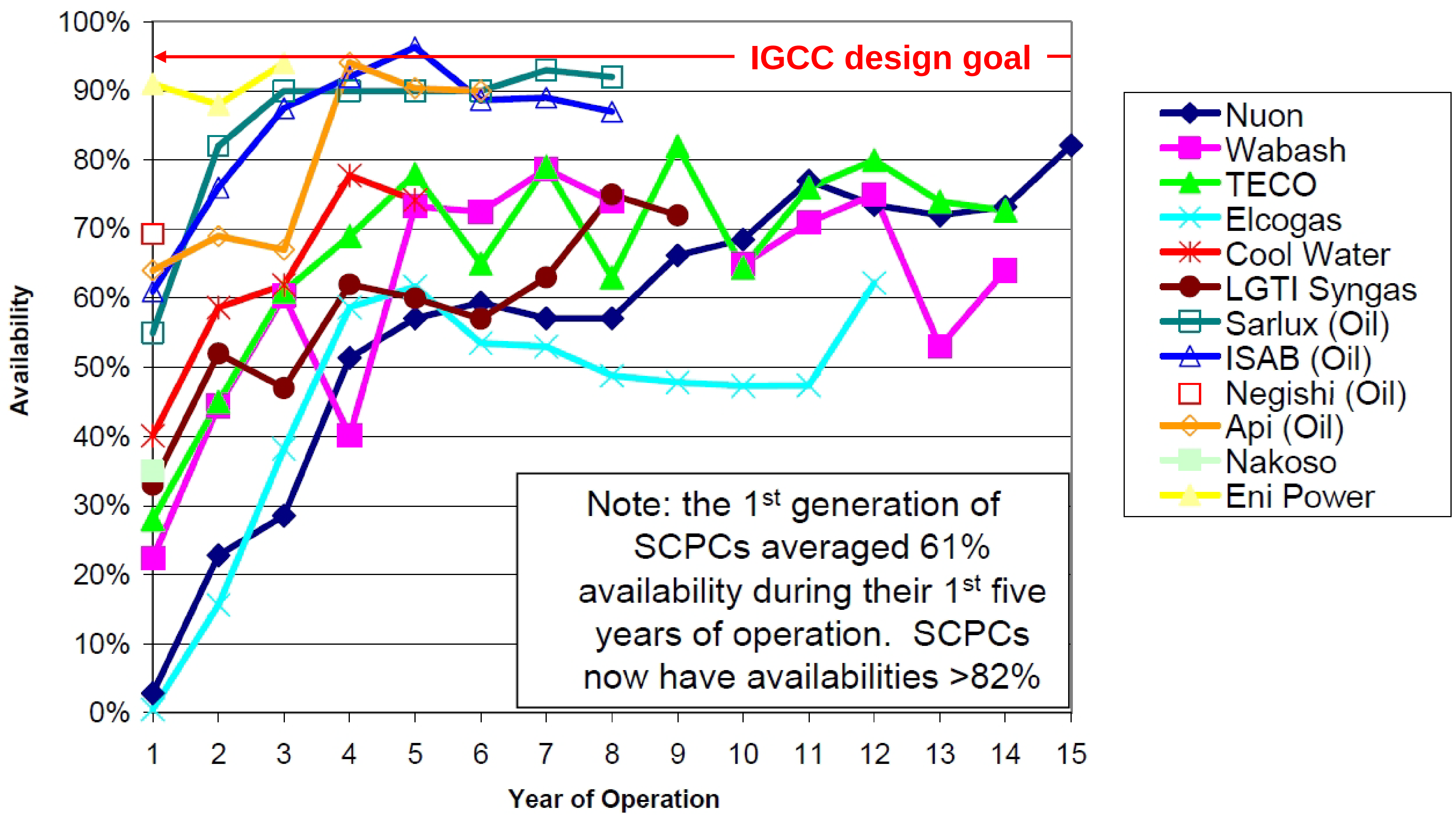
Gasifier

Gas Clean-up

Gas & Steam Turbine

Photo: BLOOMBERG NEWS

IGCC Availability History



Excludes impact of operation on back-up fuel

*Source: **Dr. Jeff Phillips** Sr. Program Manager, Advanced Coal, EPRI*
http://www.gasification.org/uploads/downloads/Workshops/2010/02phillips%20-%20IGCC%20101e.pdf

IGCC Plants in the U.S.

No Longer Operating

Southern California Edison’s Cool Water Coal Gasification Plant

- – 100 MWe coal (1984-1988)

Dow Chemical's Louisiana Gasification Technology Inc (LGTI) Project

- – 160 MWe coal (1987-1995)

Valero Delaware City Refinery’s Delaware Clean Energy Cogeneration Project

- – 160 MWe (& steam) petcoke (2002 – 2009)

IGCC Technology in Early Commercialization

Nation's 1st Commercial-scale IGCC plants

Each achieving: > 97% sulfur removal > 90% NO_X reduction

Wabash River

- ConocoPhillips Gasifier
- 1996 Power plant of the Year Award*
- Achieved 77% availability **

Tampa Electric

- General Electric Gasifier
- 1997 Power plant of the Year Award*
- First dispatch power generator
- Achieved 90% availability **

Power Magazine*   * Gasification Power Block*

Coal/Petcoke-Based U.S. IGCC Plants

Operational Performance

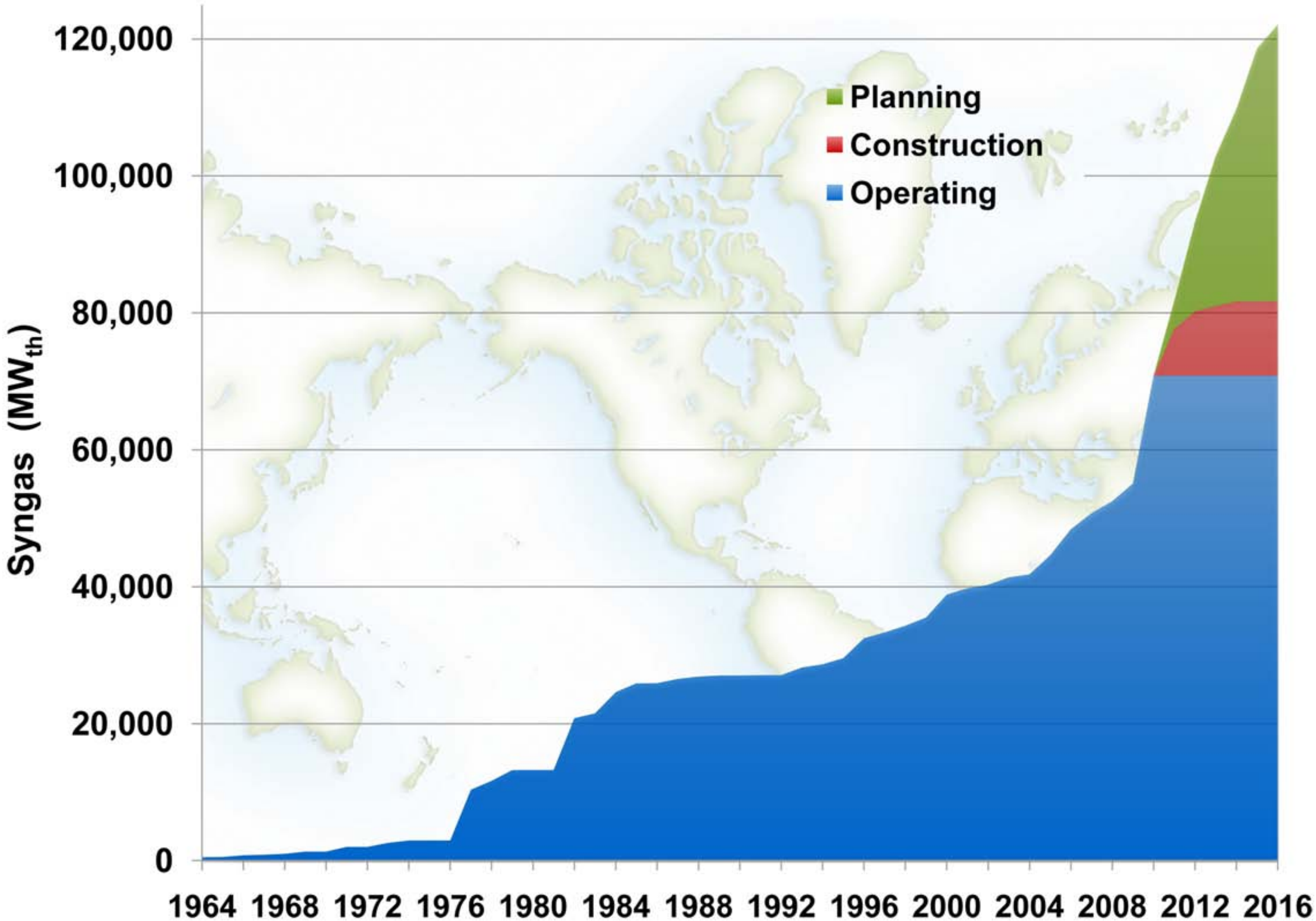
	Cool Water California	LGTI Louisiana	Wabash River Indiana	Tampa Electric Florida	Valero Delaware
Net Power Output MWe	100	160	262	250	240
Efficiency, % (HHV basis)		37.5	40.2	37.5	
Gasification Technology	GE	E-Gas	E-Gas	GE	GE
Feedstock	Bituminous	Low sulfur subbituminous	Petcoke	Coal and petcoke blend	Petcoke
Gas Turbine	GE 107E	2 x Siemens SGT6-3000E	GE 7FA	GE 107FA	2 x GE 7FA
Firing Temp, ˚F (˚C) on natural gas*		2350 (1287)	2350 (1287)	2350 (1287)	
NO_X Control	Steam dilution to combustion turbine	Steam dilution to combustion turbine	Steam dilution to combustion turbine	Nitrogen and steam dilution to combustion turbine	Nitrogen and steam dilution to combustion turbine

* *Syngas firing is usually 100-200˚F lower*

Worldwide Gasification Database

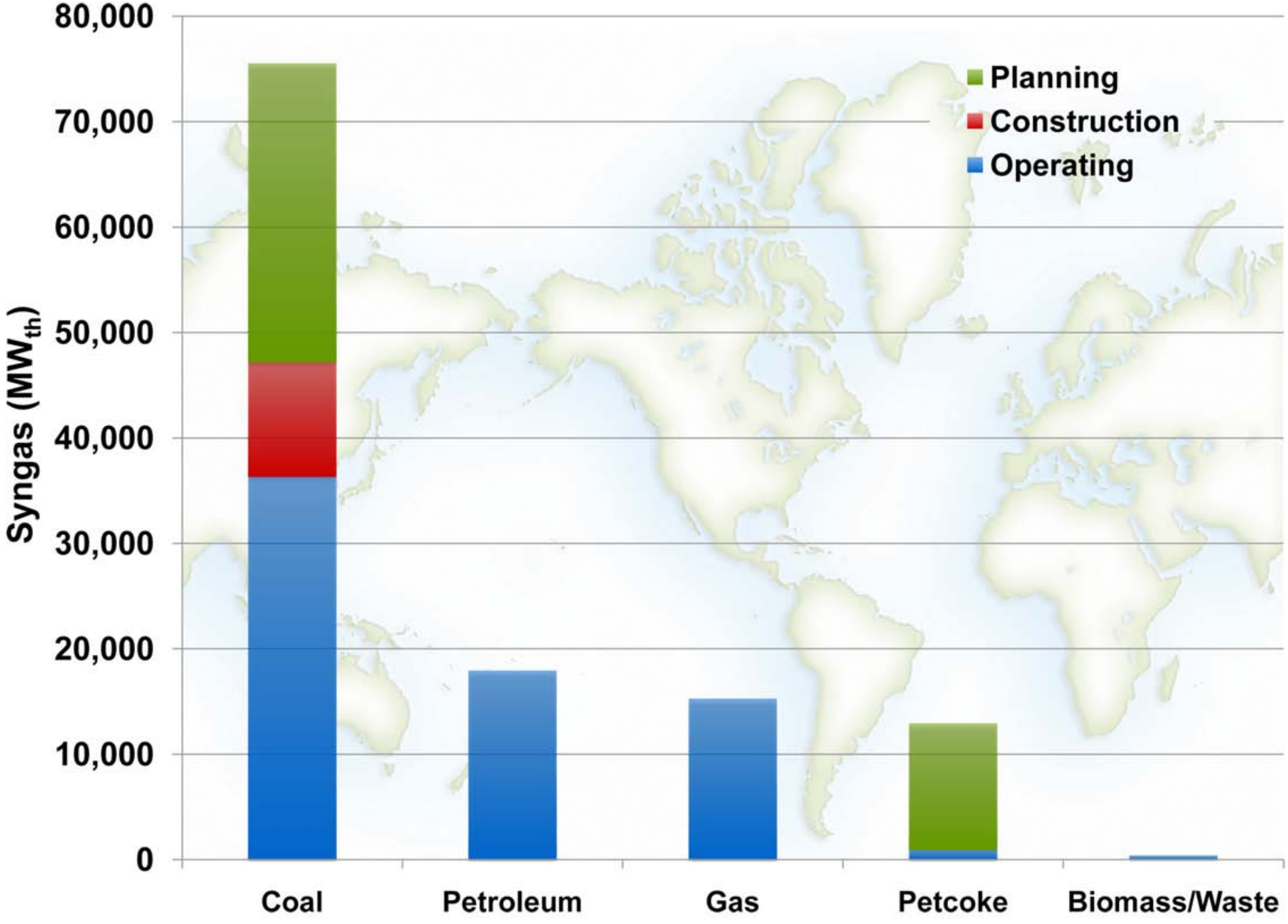
Worldwide Gasification Capacity & Planned Growth

Cumulative by Year



Based on: 2010 Worldwide Gasification Database
http://www.netl.doe.gov/technologies/coalpower/gasification/worlddatabase/index.html

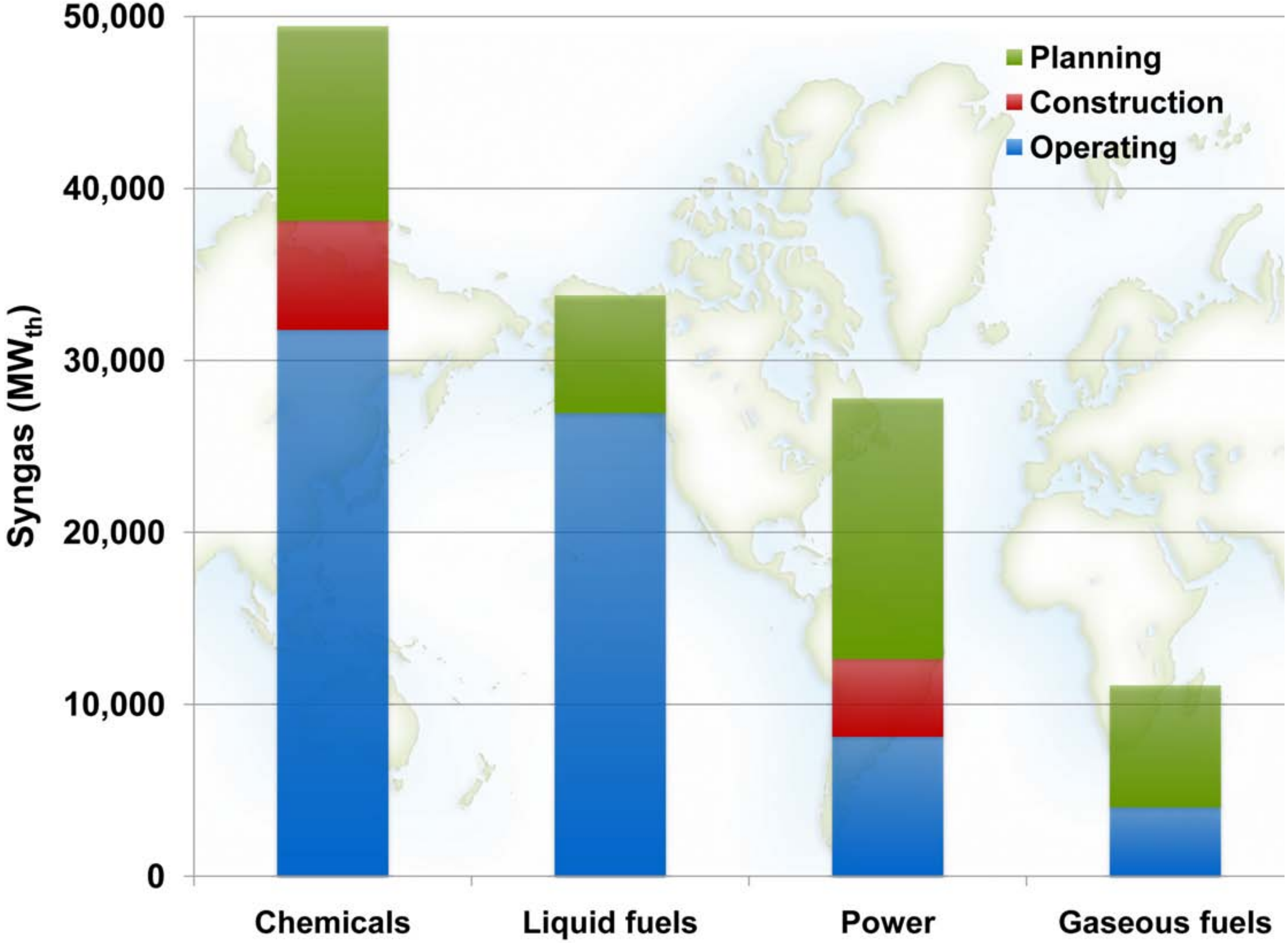
Worldwide Gasification Capacity & Planned Growth
by Feedstock



Based on: 2010 Worldwide Gasification Database
http://www.netl.doe.gov/technologies/coalpower/gasification/worlddatabase/index.html

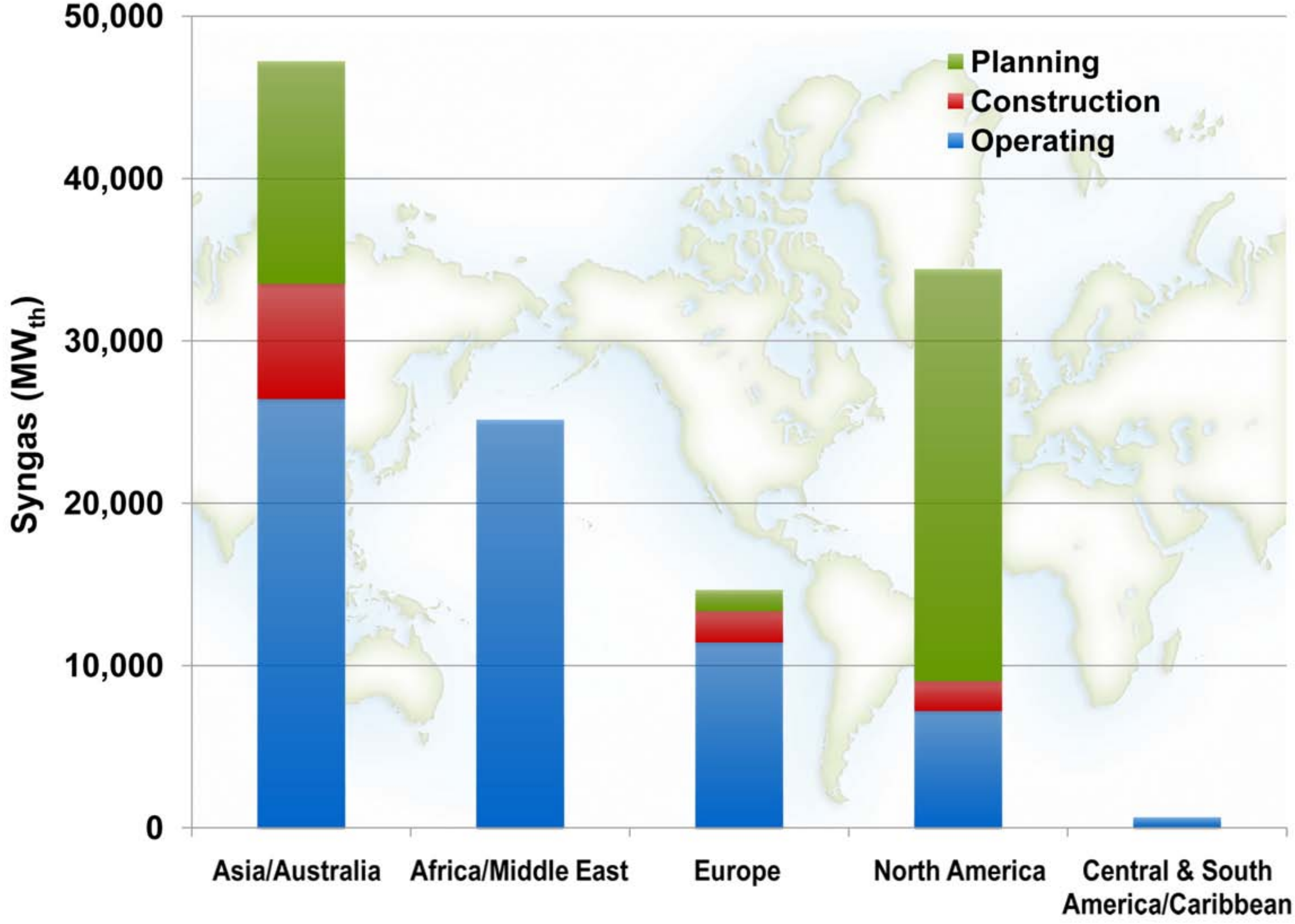
Worldwide Gasification Capacity & Planned Growth

by Product



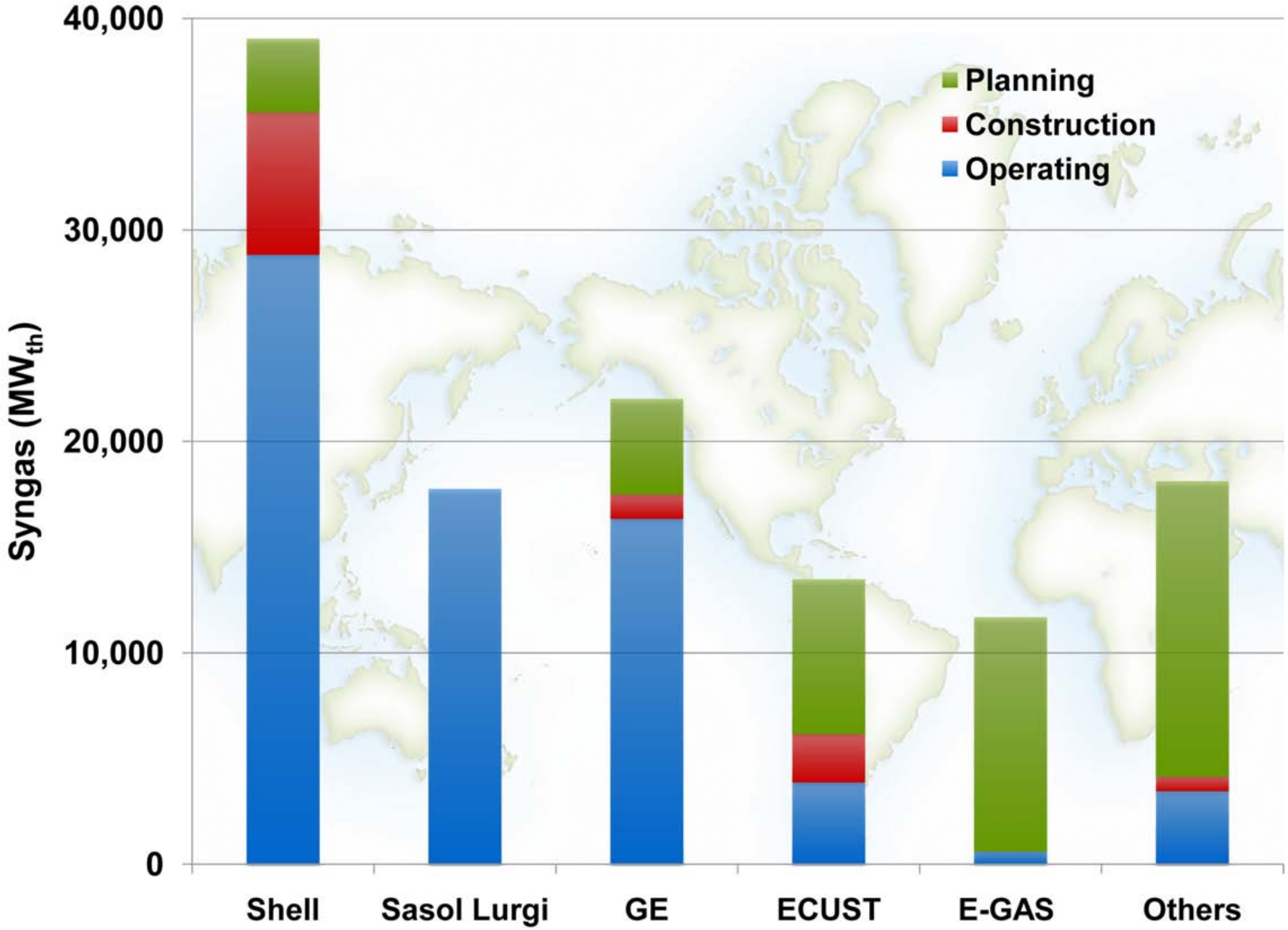
Based on: 2010 Worldwide Gasification Database
http://www.netl.doe.gov/technologies/coalpower/gasification/worlddatabase/index.html

Worldwide Gasification Capacity & Planned Growth *by Region*



Based on: 2010 Worldwide Gasification Database
http://www.netl.doe.gov/technologies/coalpower/gasification/worlddatabase/index.html

Worldwide Gasification Capacity & Planned Growth
by Technology



NATIONAL ENERGY TECHNOLOGY LABORATORY

Based on: 2010 Worldwide Gasification Database
http://www.netl.doe.gov/technologies/coalpower/gasification/worlddatabase/index.html

Closing

… the Benefits

GASIFICATION

- Stable, affordable, high-efficiency energy supply with a minimal environmental impact
- Feedstock Flexibility/Product Flexibility
- Flexible applications for new power generation, as well as for repowering older coal-fired plants

BIG PICTURE

- Energy Security -- Maintain coal as a significant component in the U.S. energy mix
- A Cleaner Environment (reduced emissions of pollutants)
- The most economical technology for CO_2 capture
- Ultra-clean Liquids from Coal -- Early Source of Hydrogen

Visit NETL Gasification Website

www.netl.doe.gov/gasification-portal.html

Google the term "Gasifipedia" Google Gasifipedia Search