



Overview of DOE's Gasification Program

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Technology Manager - Gasification



Presentation Outline

- **History & Gasification Chemistry**
- **Gasification-Based Energy Conversion Systems**
- **Commercial Status**
- **Environmental Benefits**
- **DOE Program Overview**
- **Results of Systems Analysis Study**



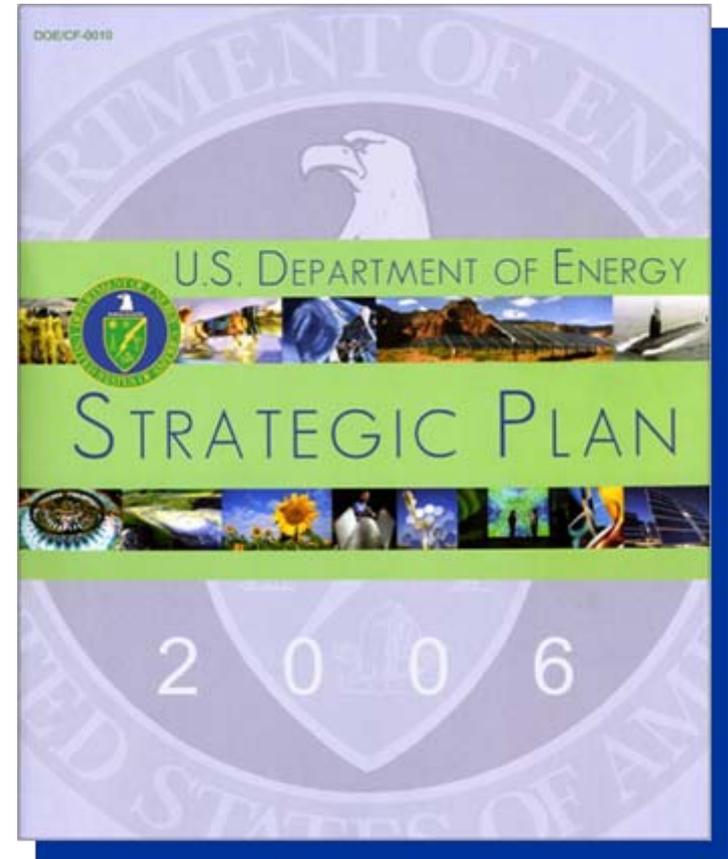
Why the Interest in Gasification?

- **Continuing high price of fuels**
 - Natural gas & Highway transportation fuels
- **Energy Security**
- **Gasification is baseline technology for H₂, SNG, fuels from coal, and capture of CO₂ for sequestration**
- **Excellent environmental performance of IGCCs for power generation**
- **Growing environmental community view of IGCCs as best technology option for coal systems**
- **Uncertainty of carbon management requirements and potential suitability of IGCC for CO₂ controls**
- **Potential for performance guarantees**

U. S. Department of Energy Strategic Plan

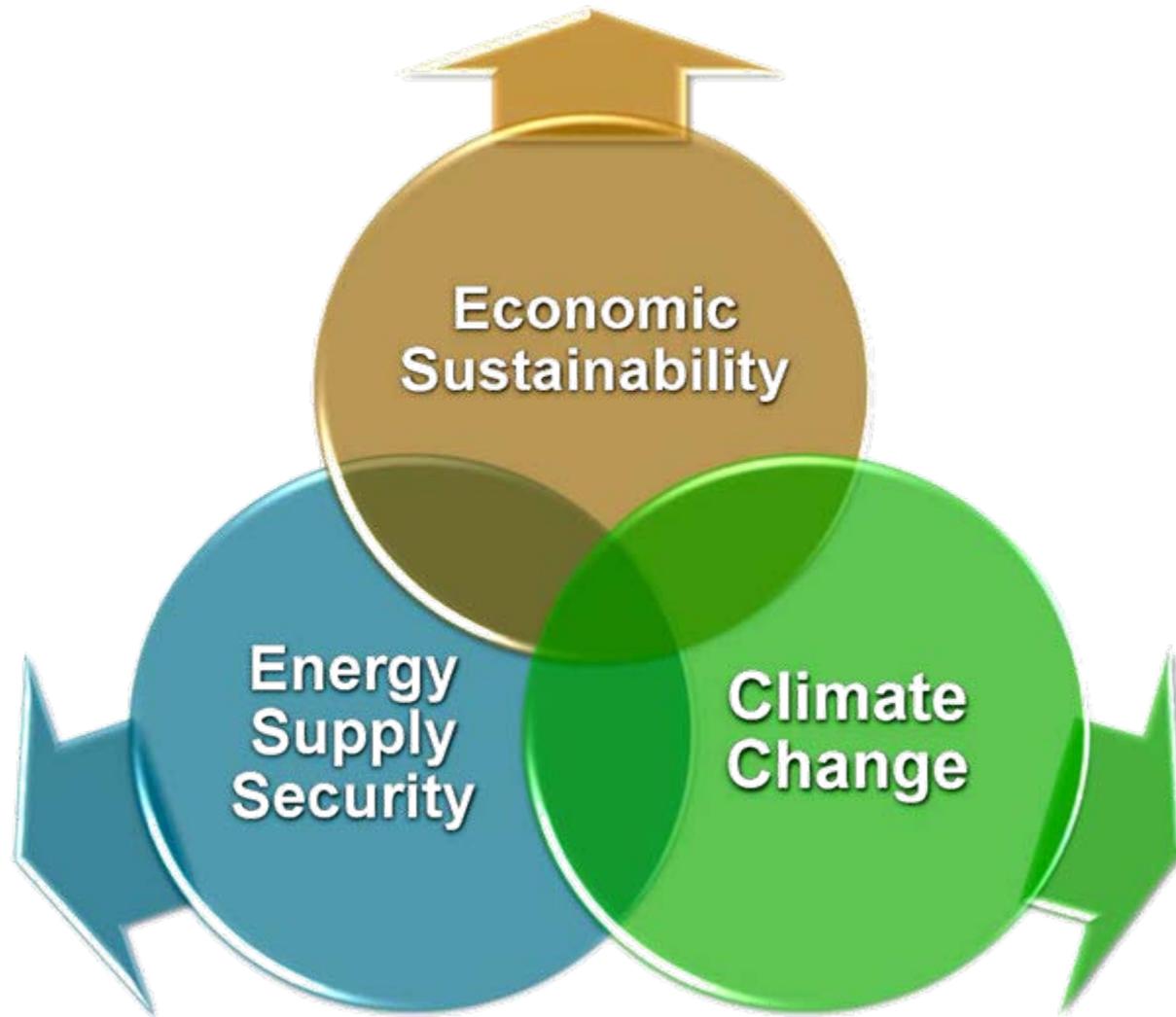
Energy Security - Promoting America's energy security through reliable, clean, and affordable energy

- **Energy Diversity** – Increase our energy options and **reduce dependence on oil**, thereby reducing vulnerability to disruption and increasing the flexibility of the market to meet U.S. needs.
- **Environmental Impacts of Energy** – Improve the quality of the environment by **reducing greenhouse gas emissions** and environmental impacts to land, water, and air from energy production and use.
- **Energy Infrastructure** – Create a more flexible, more reliable, and higher capacity U.S. energy infrastructure.
- **Energy Productivity** – Cost-effectively improve the energy efficiency of the U.S. economy.



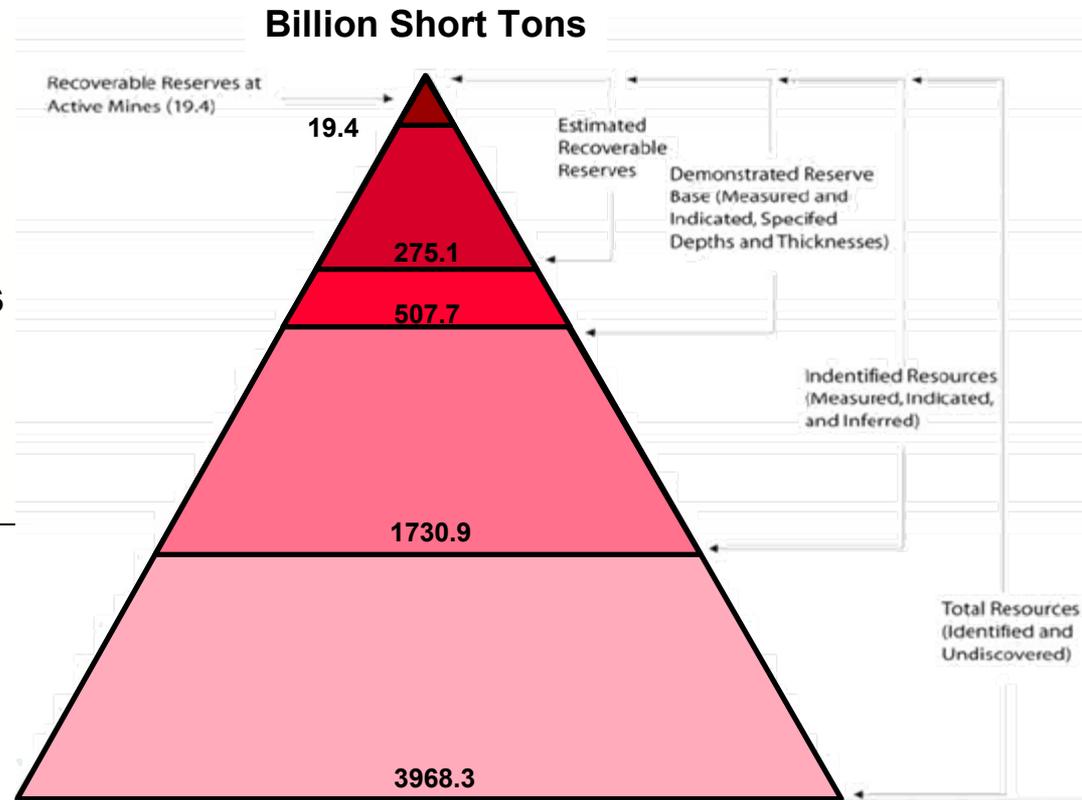
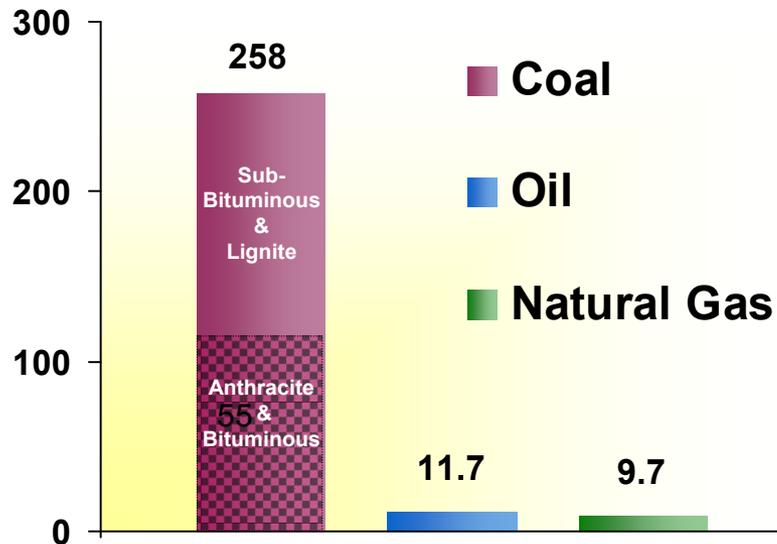
Energy Strategy Complexity

Inter-related Consequences of Energy Strategies

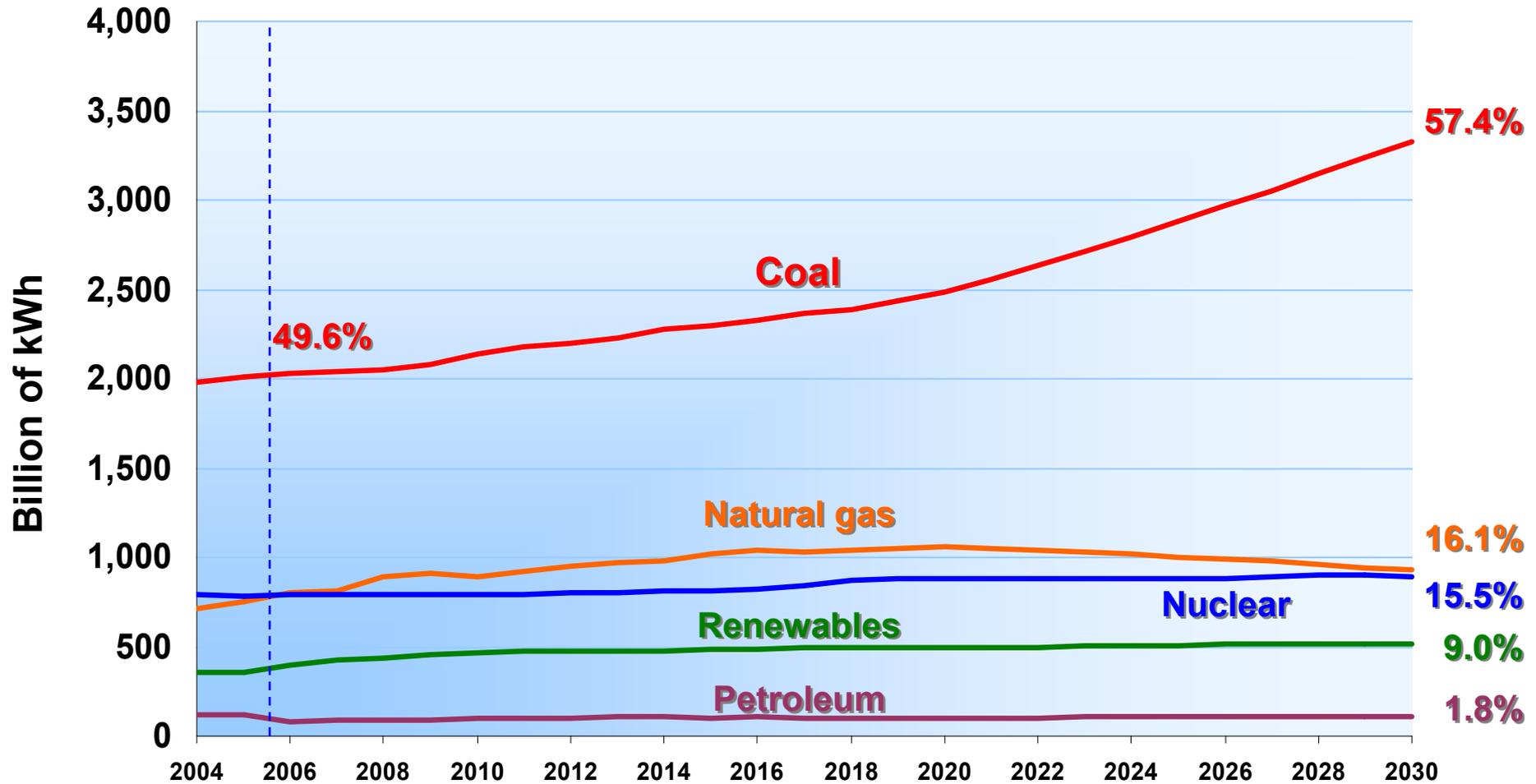


U.S. has a 250 Year Supply of Coal at Current Demand Levels!

U.S. Fossil Fuel Reserves / Production Ratio

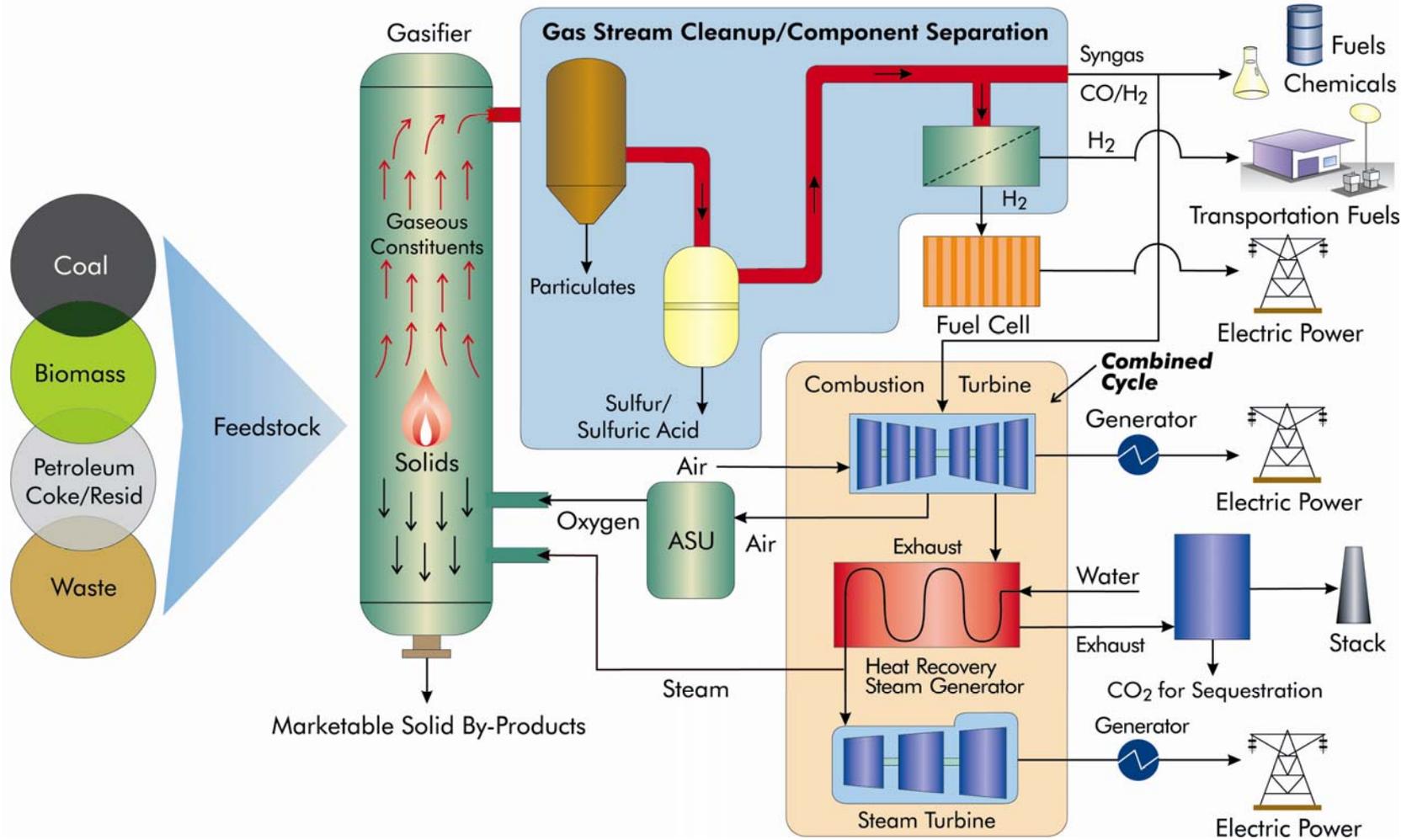


U.S. Domestic Electricity Generation Forecast



Significant growth in share of electricity generated by coal

Overview of Energy Systems Options



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.



Benefits of Gasification

- **Feedstock flexibility**

- A very 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 (SO₂, NO_x, CO, Hg, etc.)
- Reduced water consumption
- Potential solid wastes can be utilized or easily managed
- High efficiency / low CO₂ production
- CO₂ can be easily captured for sale or geologic storage (sequestration)



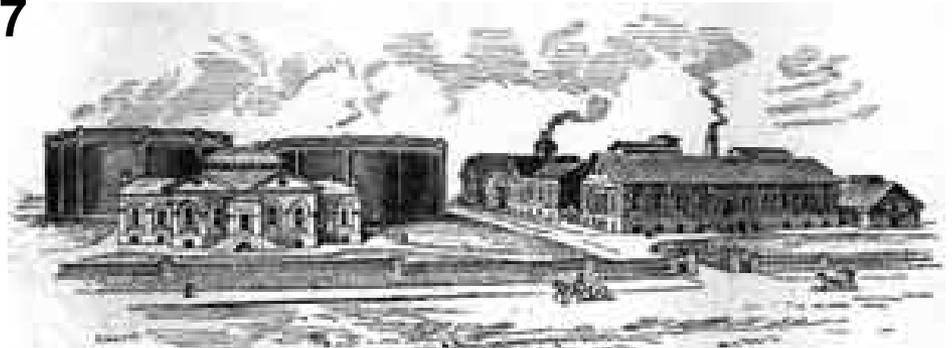
History of Gasification

Town Gas

Town gas, a gaseous product manufactured from coal, supplies lighting and heating for America and Europe.

Town gas is approximately 50% hydrogen, with the rest comprised of mostly methane and carbon dioxide, with 3% to 6% carbon monoxide.

- First practical use of town gas in modern times was for street lighting
- The first public street lighting with gas took place in Pall Mall, London on January 28, 1807
- Baltimore, Maryland began the first commercial gas lighting of residences, streets, and businesses in 1816



History of Gasification

- Used during World War II to convert coal into transportation fuels (Fischer – Tropsch)
- Used extensively in the last 50+ years to convert coal and heavy oil into hydrogen – for the production of ammonia/urea fertilizer
- Chemical industry (1960's)
- Refinery industry (1980's)
- Global power & CTL industries (Today)

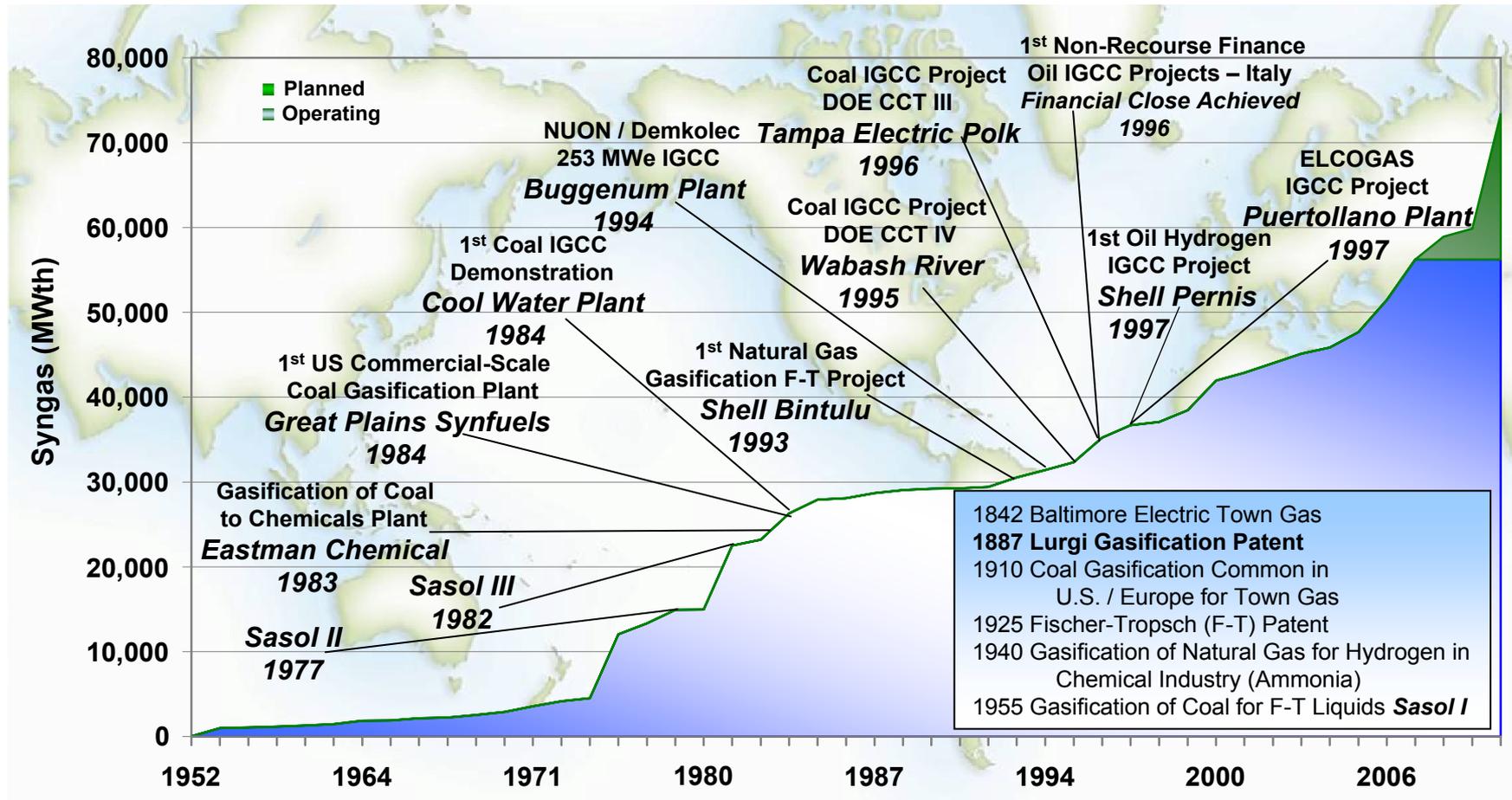


Major Gasification Milestone

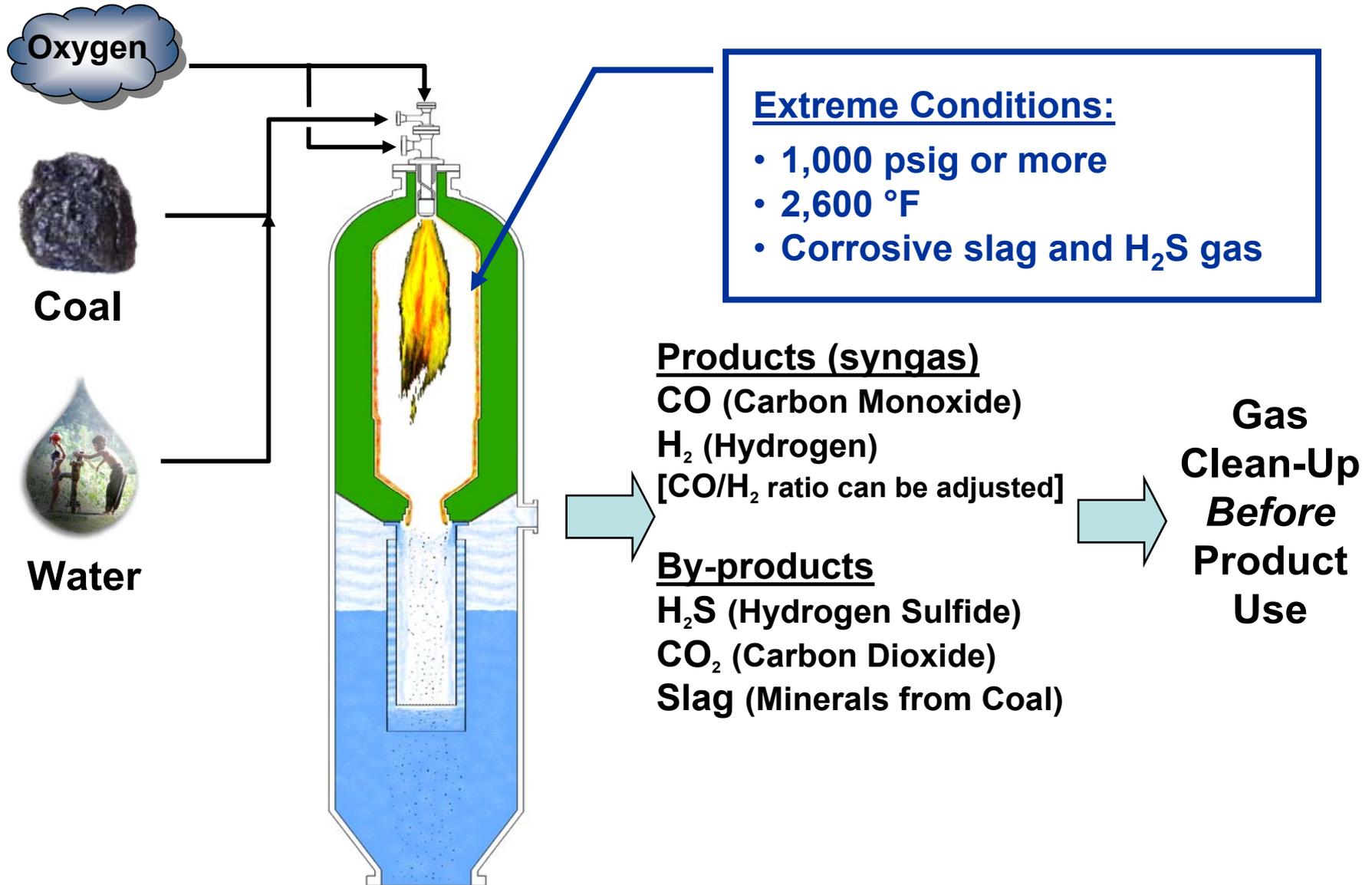
- 1842 Baltimore Electric Town Gas
- 1887 Lurgi Gasification Patent**
- 1910 Coal Gasification Common in U.S. / Europe for Town Gas
- 1940 Gasification of Natural Gas for Hydrogen in Chemical Industry (Ammonia)
- 1950 Gasification of Coal for Fischer-Tropsch (F-T) Liquids (Sasol-Sasolburg)
- 1960 Coal Tested as Fuel for Gas Turbines (Direct Firing)
- 1970's IGCC Studies by U.S. DOE
- 1970 Gasification of Oil for Hydrogen in the Refining Industry
- 1983 Gasification of Coal to Chemicals Plant (Eastman Chemical)
- 1984 First Coal IGCC Demonstration (Cool Water Plant)**
- 1990's First Non-Recourse Project Financed Oil IGCC Projects (Italy)
- 1993 First Natural Gas Gasification F-T Project (Shell Bintulu)
- 1994 NUON/Demkolec's 253 MWe Buggenum Plant Begins Operation
- 1995 PSI Wabash, Indiana Coal IGCC Begins Operation (DOE CCT IV)
- 1996 Tampa Electric Polk Coal IGCC Begins Operation (DOE CCT III)
- 1997 First Oil Hydrogen/IGCC Plant Begin Operations (Shell Pernis)
- 1998 ELCOGAS 283 MWe Puertollano Plant
- 2007 **Clean Coal Power R&D** 250 MWe IGCC Plant Begins Operation (Japan)

Today IGCC is an Accepted Refinery and Coal Plant Option

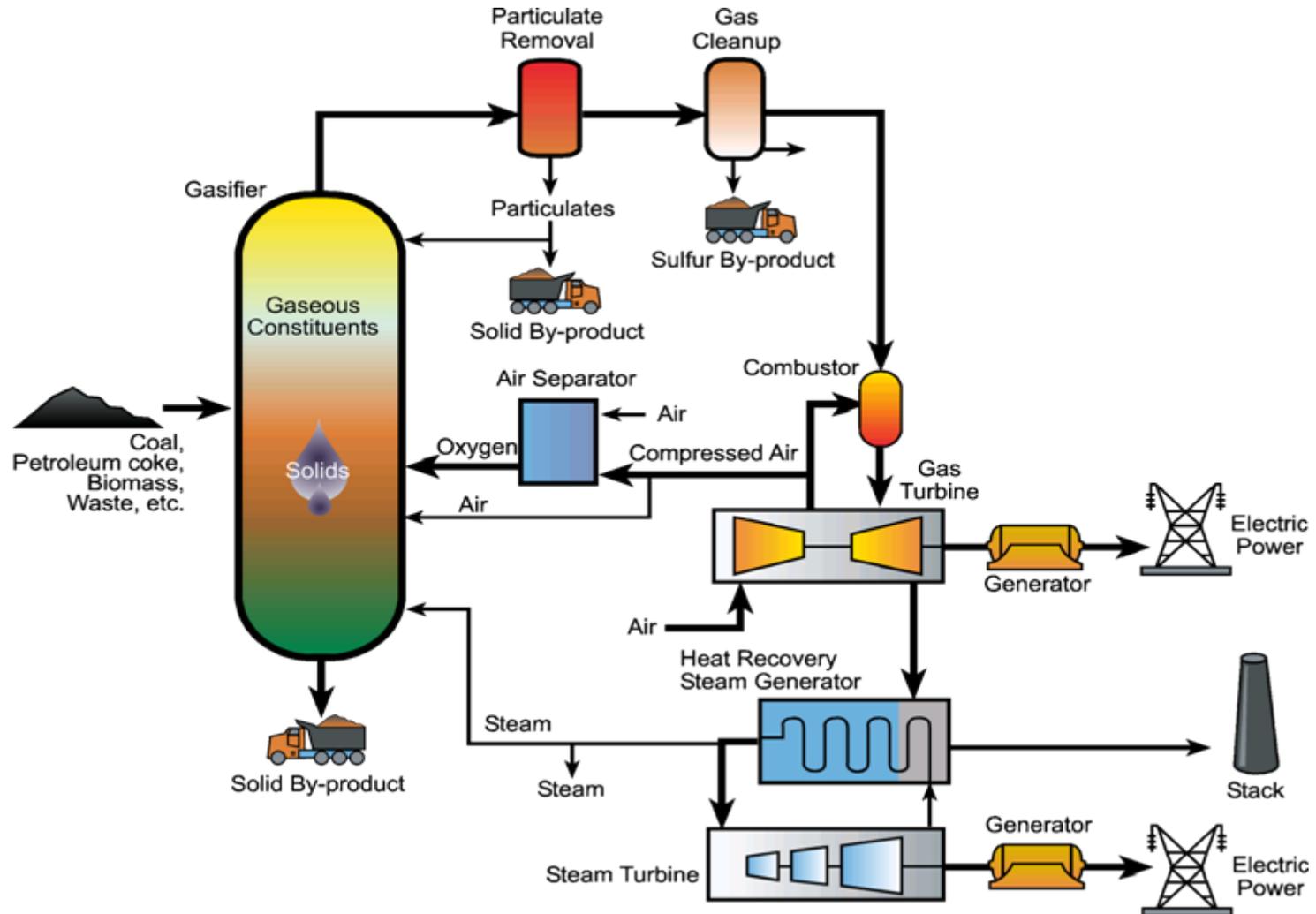
Worldwide Gasification Capacity and Planned Growth Cumulative by Year



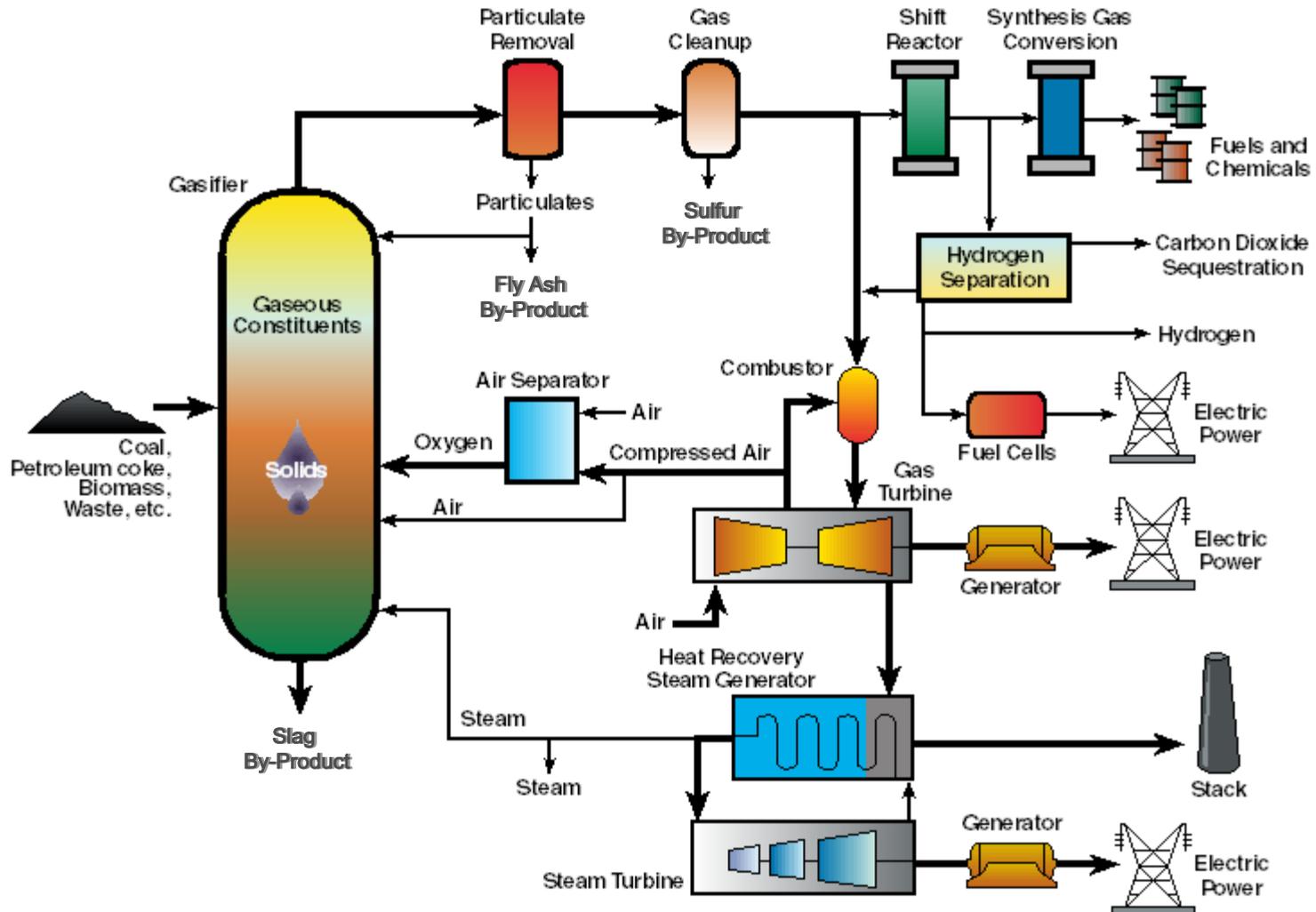
What is Coal Gasification?



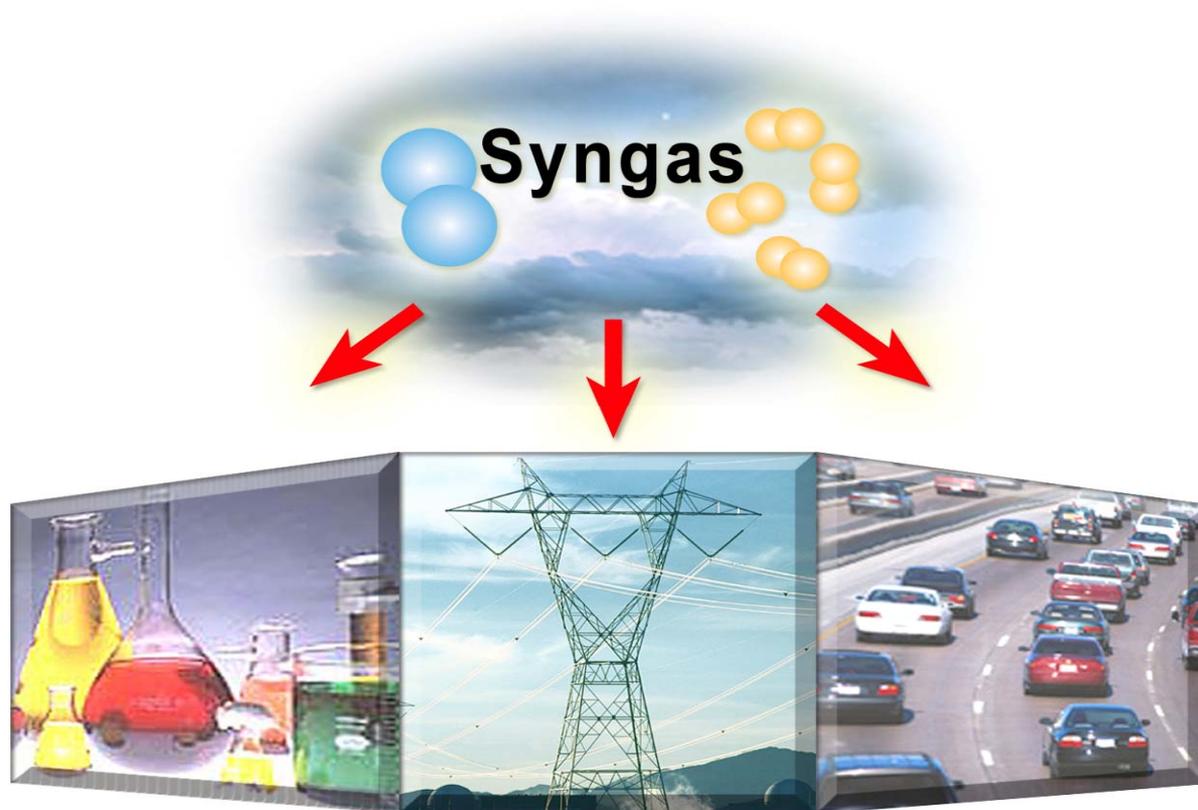
Integrated Gasification Combined Cycle (IGCC)



Gasification-Based Energy Production System Concepts



So what can you do with CO and H₂ ?

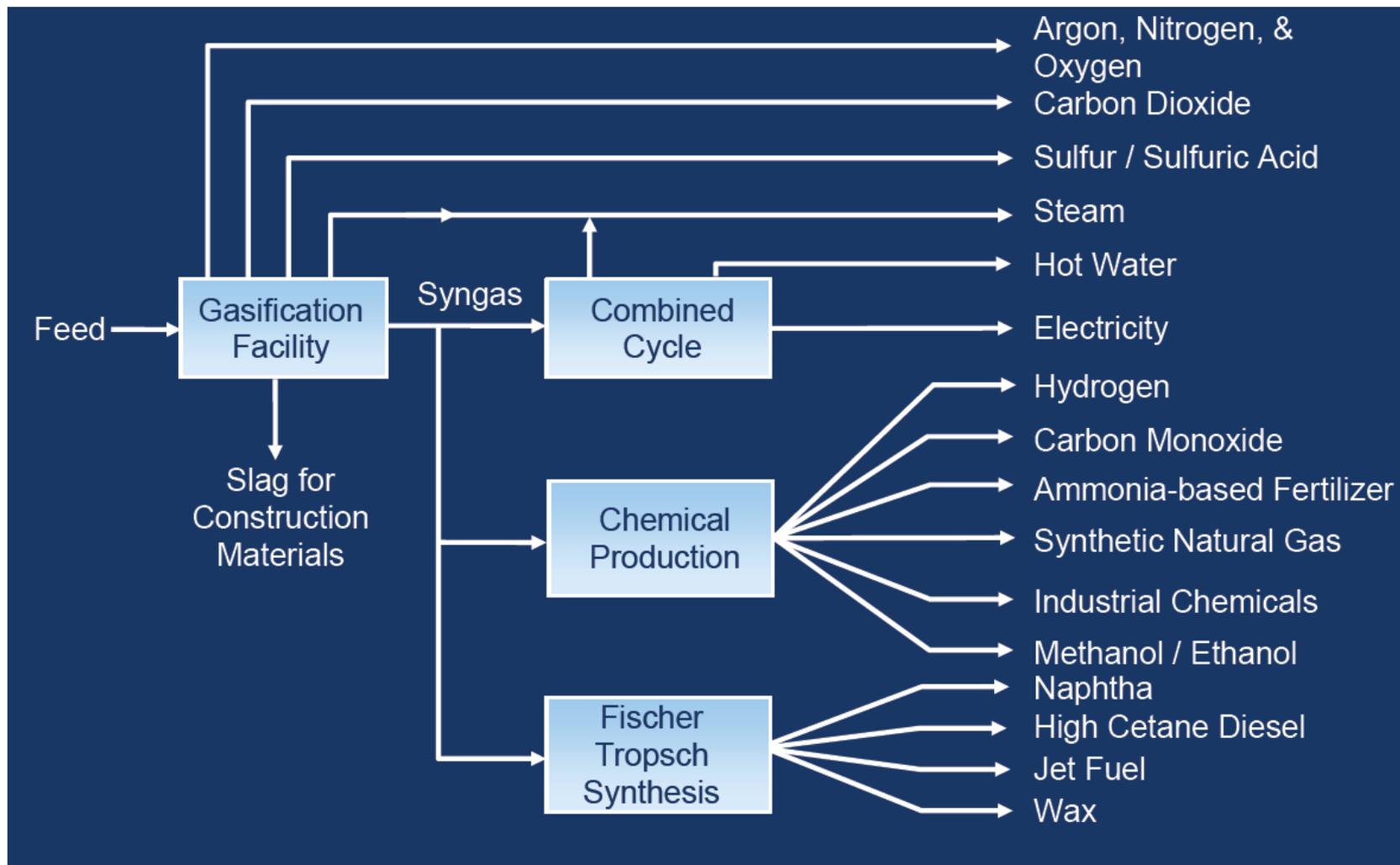


**Building Blocks for
Chemical Industry**

**Clean
Electricity**

**Transportation Fuels
(Hydrogen)**

Gasification Products



Chemicals from Coal - Final Products

It is likely that you have recently used a product based on coal gasification



Acetic Anhydride
Acetic Acid



Gasification Chemistry



Gasification with Oxygen



Combustion with Oxygen



Gasification with Carbon Dioxide



Gasification with Steam



Gasification with Hydrogen



Water-Gas Shift



Methanation



**Gasifier Gas
Composition
(Vol %)**

H ₂	25 - 30
CO	30 - 60
CO ₂	5 - 15
H ₂ O	2 - 30
CH ₄	0 - 5

H ₂ S	0.2 - 1
COS	0 - 0.1
N ₂	0.5 - 4
Ar	0.2 - 1
NH ₃ + HCN	0 - 0.3

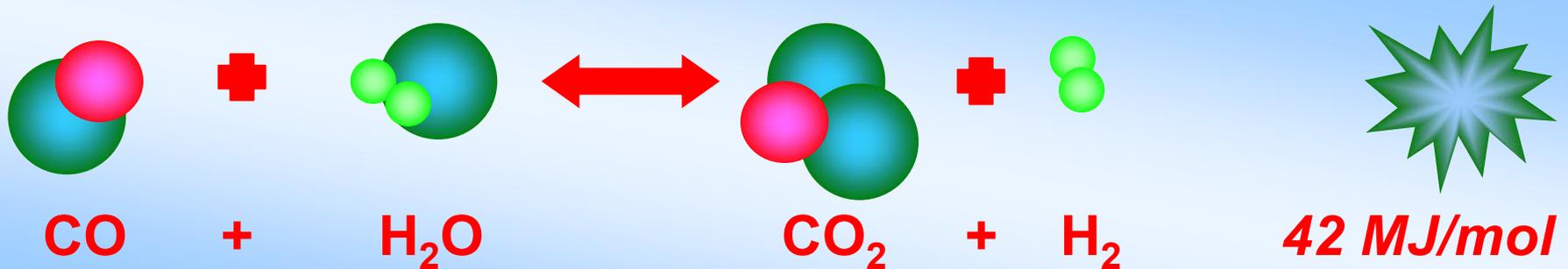
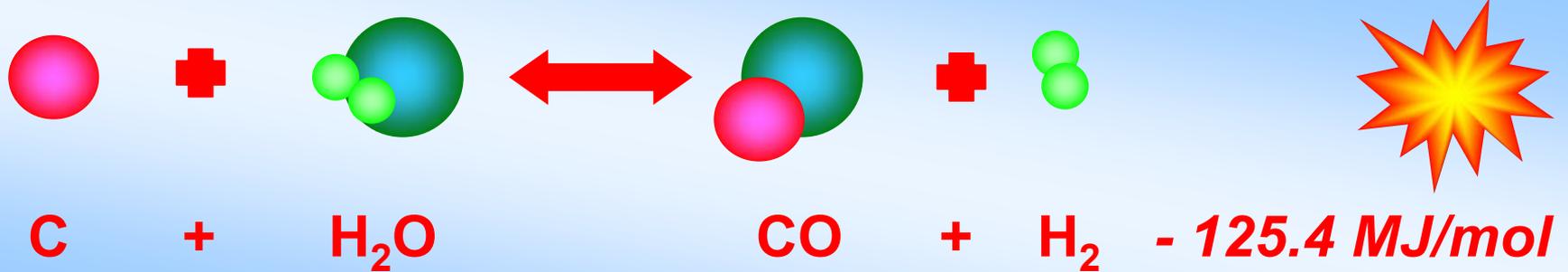
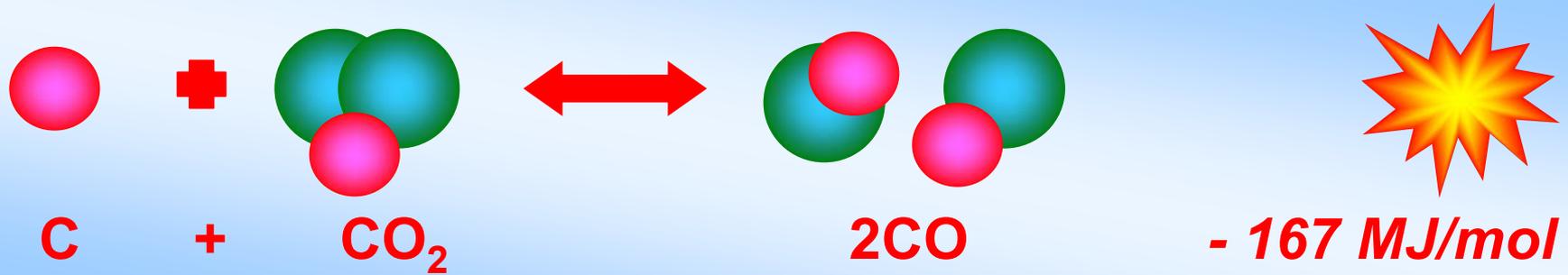
Ash/Slag/PM

Chemical Reactions in Coal Gasification

Reaction	Reaction heat, kJ/(kg·mol)	Process
Solid-gas reactions		
$C + O_2 \rightarrow CO_2$	+ 393,790	Combustion
$C + 2H_2 \rightarrow CH_4$	+ 74,900	Hydrogasification
$C + H_2O \rightarrow CO + H_2$	- 175,440	Steam-carbon
$C + CO_2 \rightarrow 2CO$	- 172,580	Boudard
Gas-phase reaction		
$CO + H_2O \rightarrow H_2 + CO_2$	+ 2,853	Water-gas shift
$CO + 3H_2 \rightarrow CH_4 + H_2O$	+ 250,340	Methanation

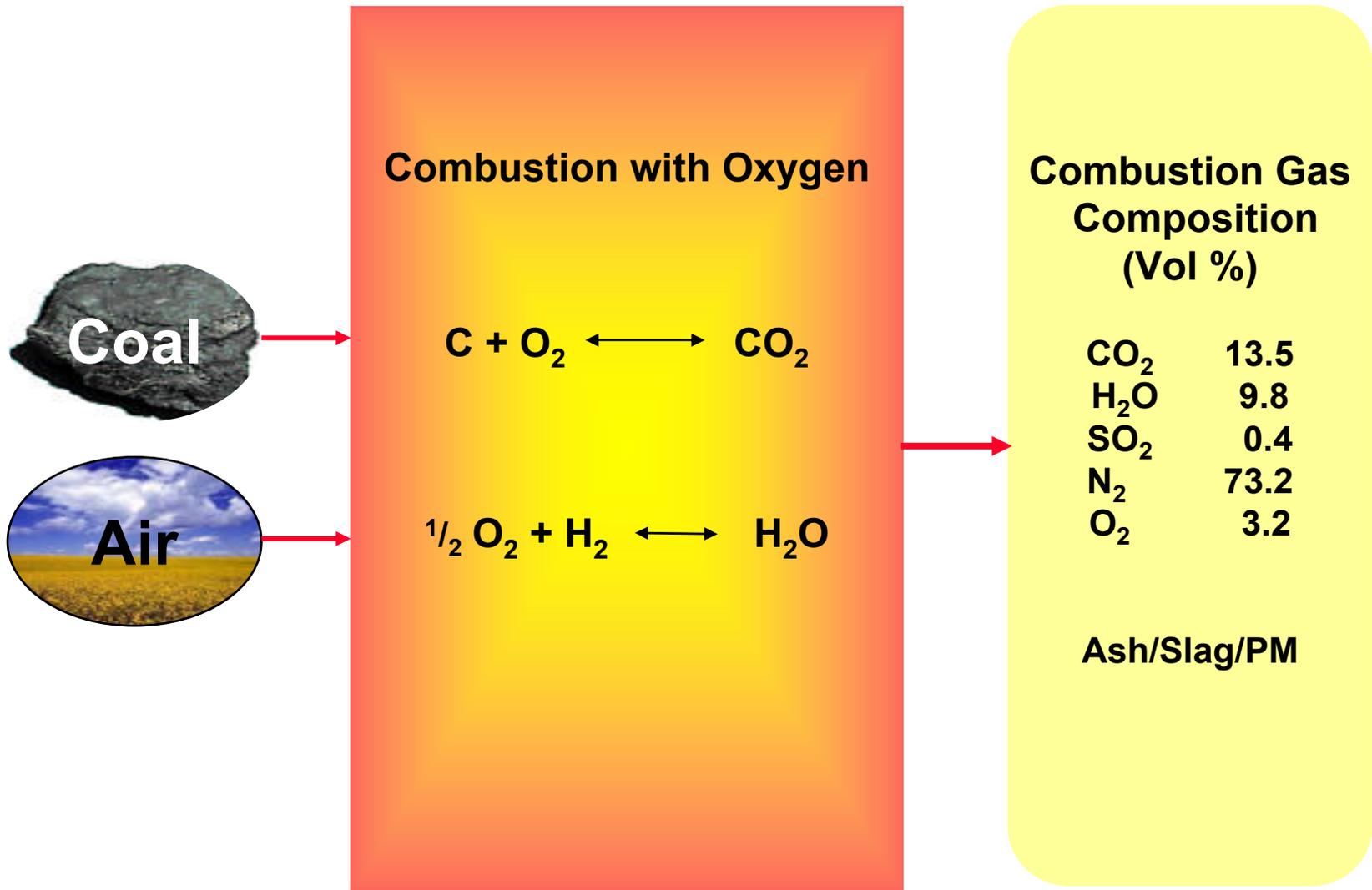
Examples of Important Reactions

Chemical Reactions in Coal Gasification



3 Examples of Important Gasification Reactions

Combustion Chemistry

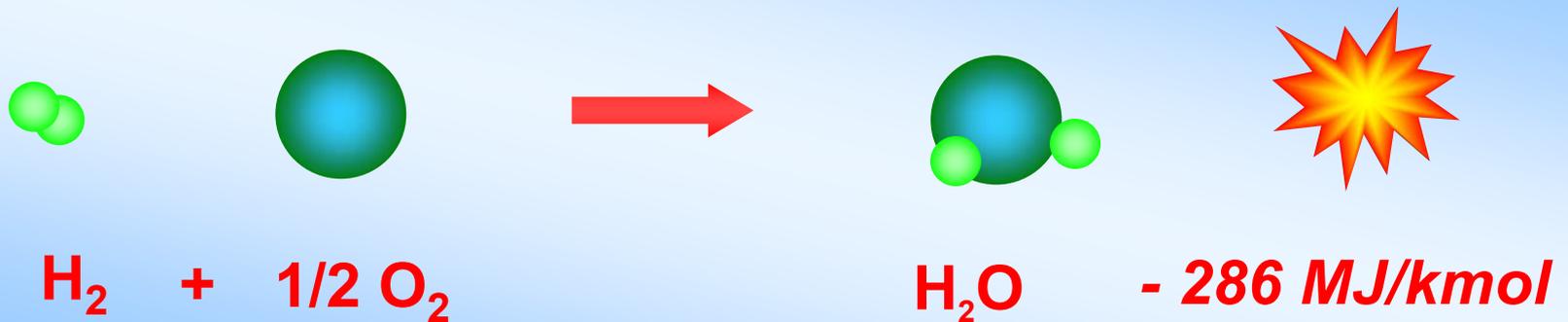
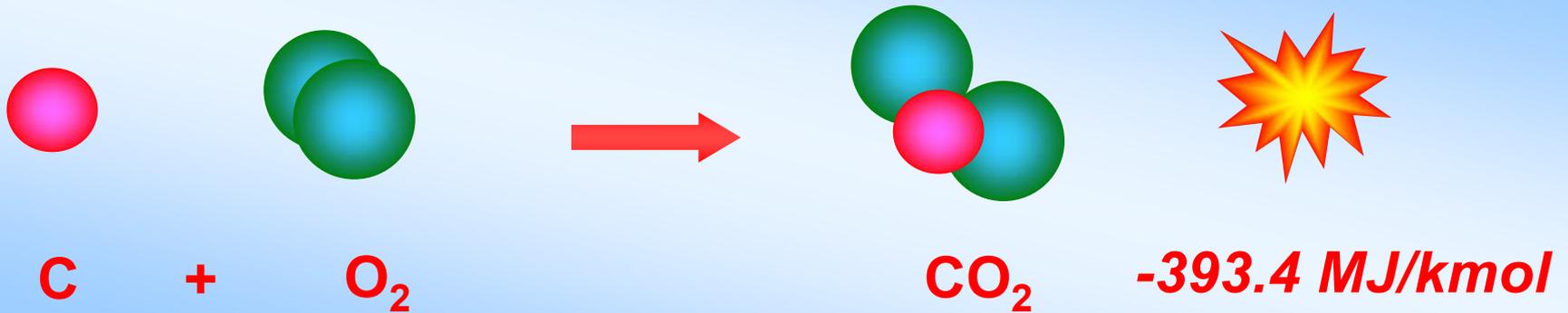


Chemical Reactions in Coal Combustion

Reaction	Reaction heat, kJ/(kg·mol)
$C_{(s)} + CO_{2(g)} \rightarrow 2CO_{(g)}$	+ 172,800
$C_{(s)} + H_2O_{(v)} \rightarrow CO_{(g)} + H_2(g)$	+ 131,800
$C_{(s)} + O_{2(g)} \rightarrow CO_{2(g)}$	- 393,400
$C_{(s)} + \frac{1}{2} O_{2(g)} \rightarrow CO_{(g)}$	- 110,300
$CO_{(g)} + H_2O_{(v)} \rightarrow CO_{2(g)} + H_2(g)$	+ 46,900
$CO_{(g)} + \frac{1}{2} O_{2(g)} \rightarrow CO_{2(g)}$	- 172,580

Examples of Important Reactions

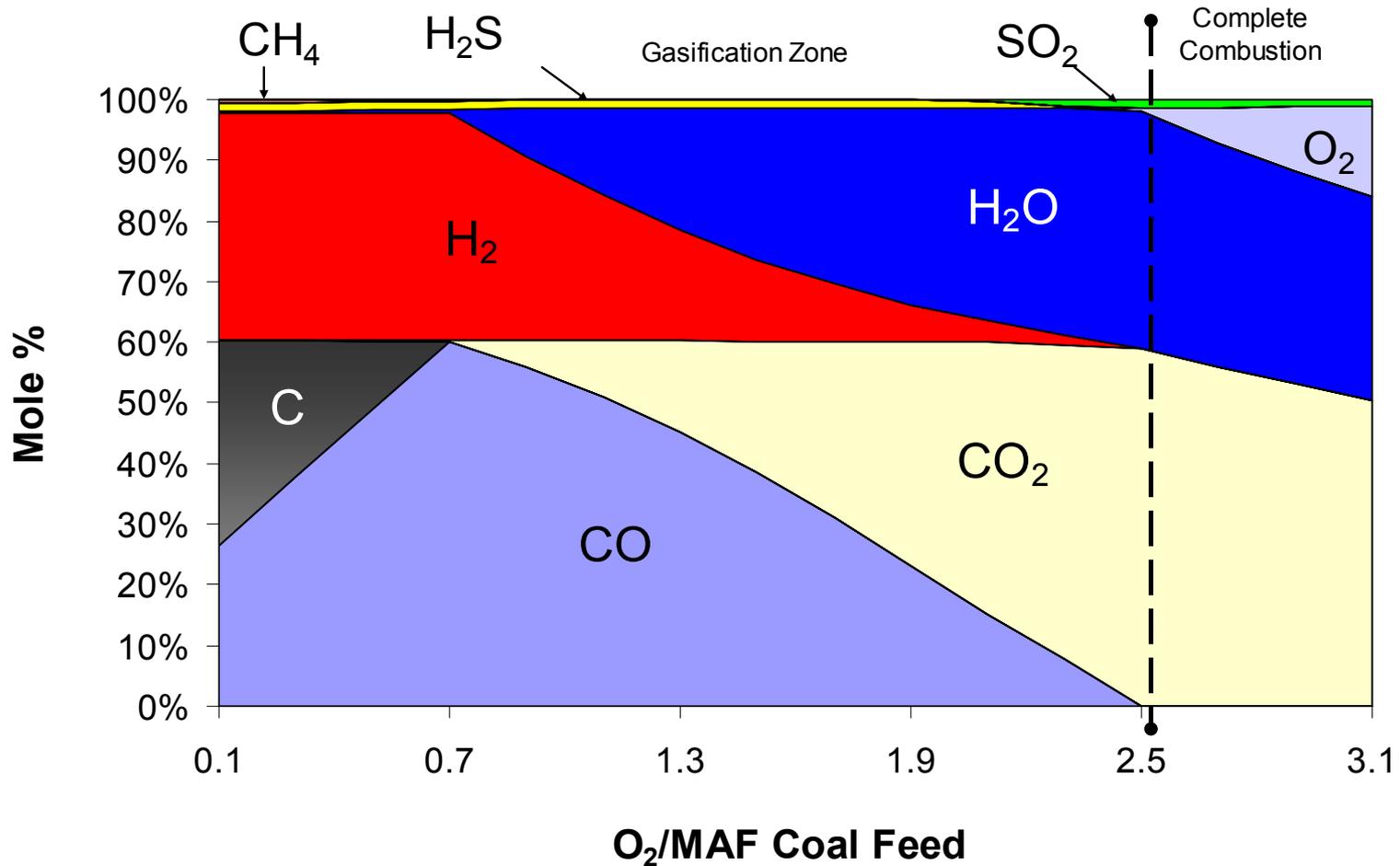
Chemical Reactions in Coal Combustion



Examples of 2 Important Reactions

Gasification Phase Diagram

An Example



Coal: Illinois #6, Dry Feed

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	400-1000 psi	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)	36-41%	35-40%

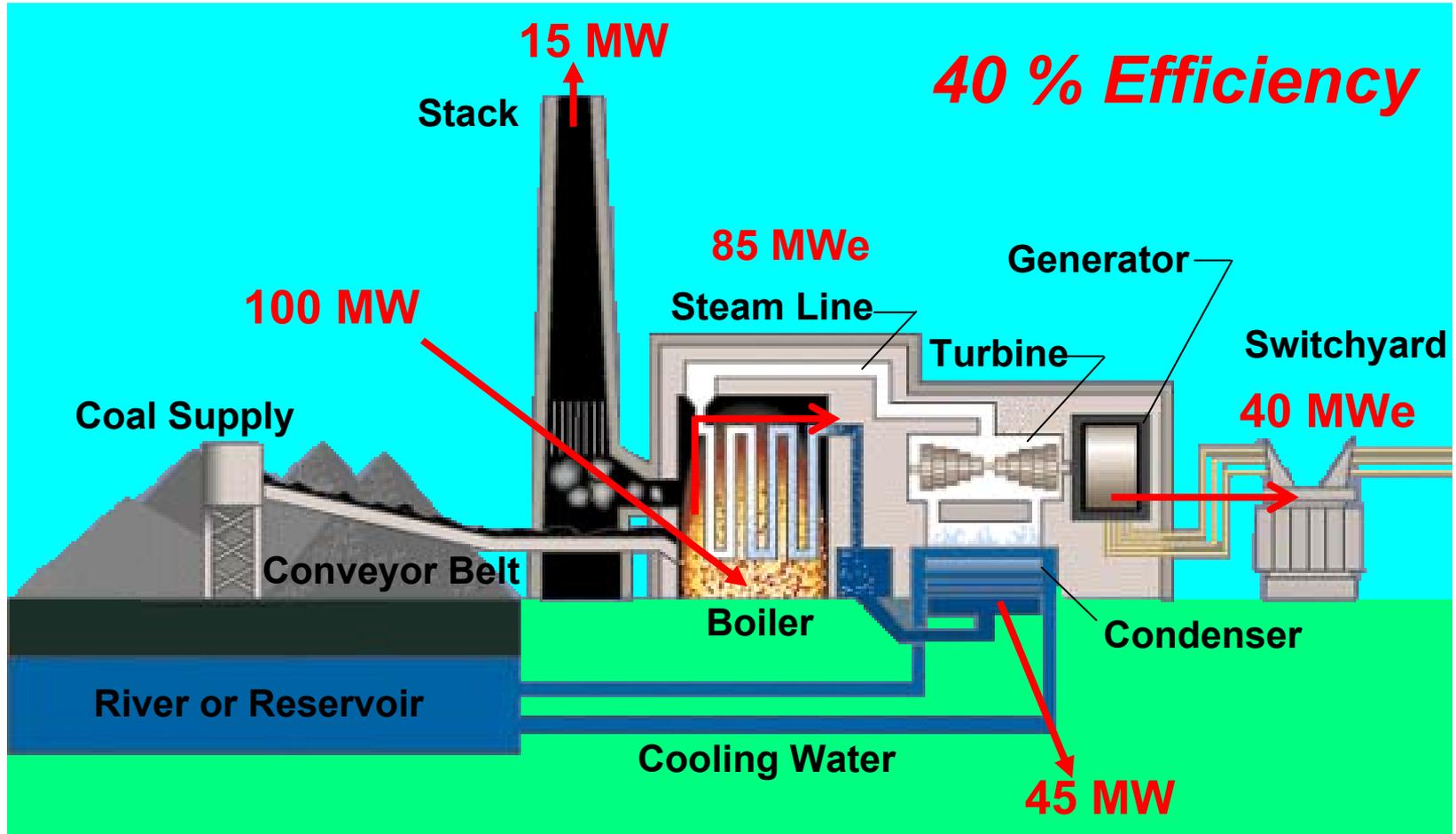
Comparison of Air Emission Controls: *PC vs. IGCC*

	<i>Sulfur</i>	<i>NO_x</i>	<i>PM</i>	<i>Mercury</i>
<i>PC</i>	FGD system	Low-NO _x burners and SCR	ESP or baghouse	Inject activated carbon
<i>IGCC</i>	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



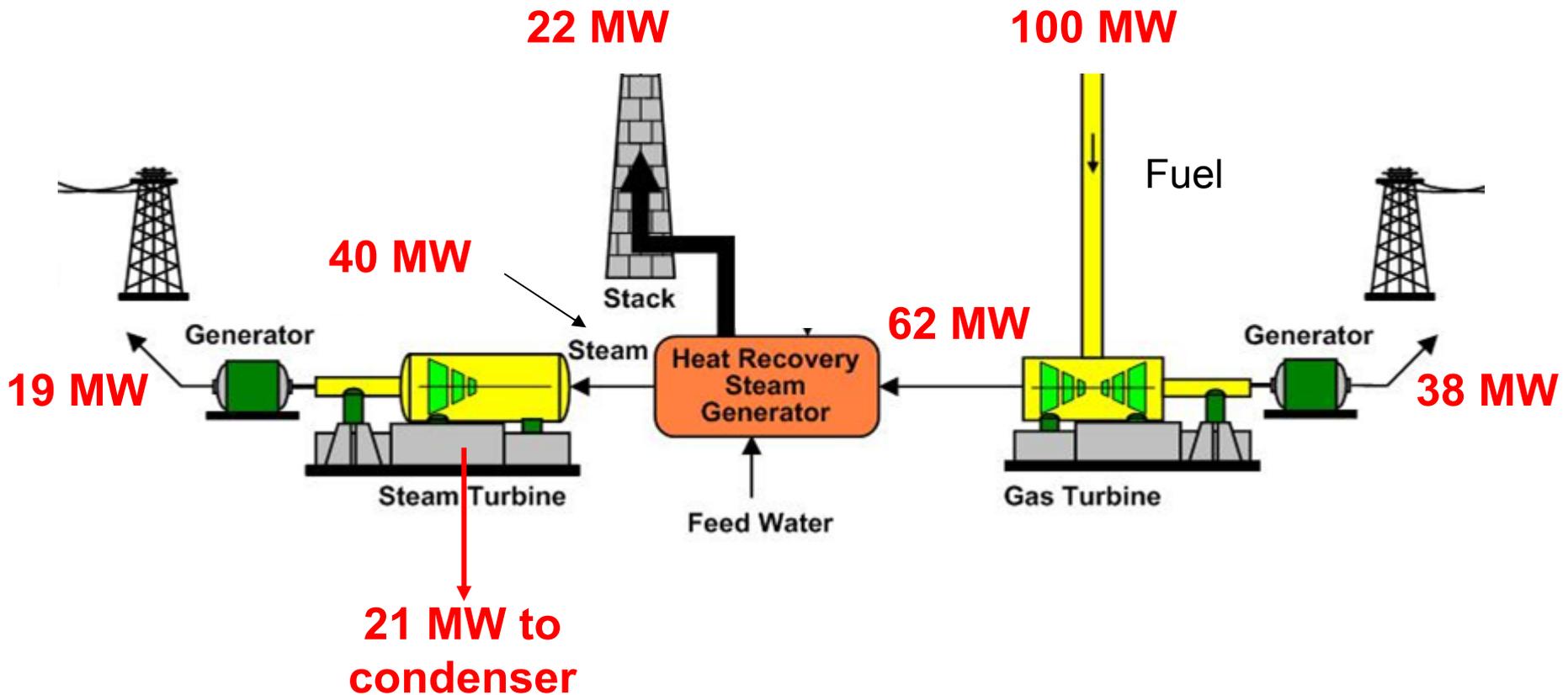
Conventional Coal Plant

(Illustration only)



Combined Cycle (Illustration only)

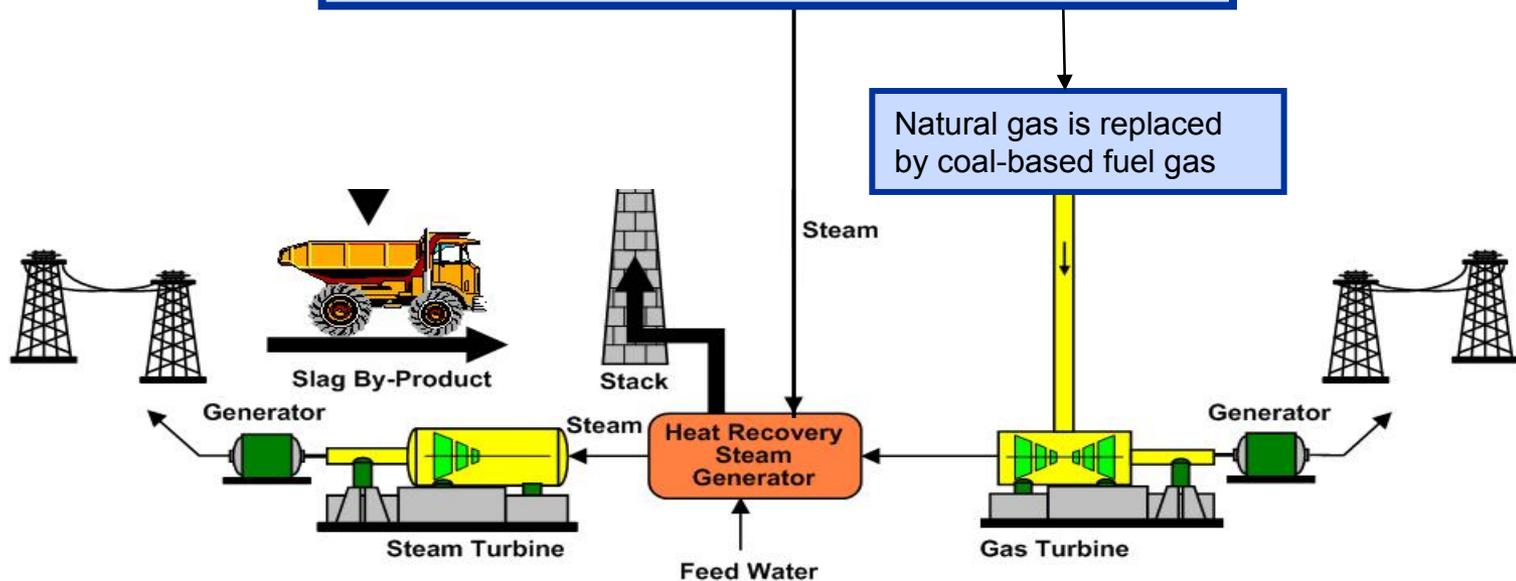
Net Power:
19 + 38 = 57 MW
57% Efficiency



Coal-Based IGCC Power Plant

Gasification Island

- Converts coal to synthesis gas
- Synthesis gas cleaned and conditioned

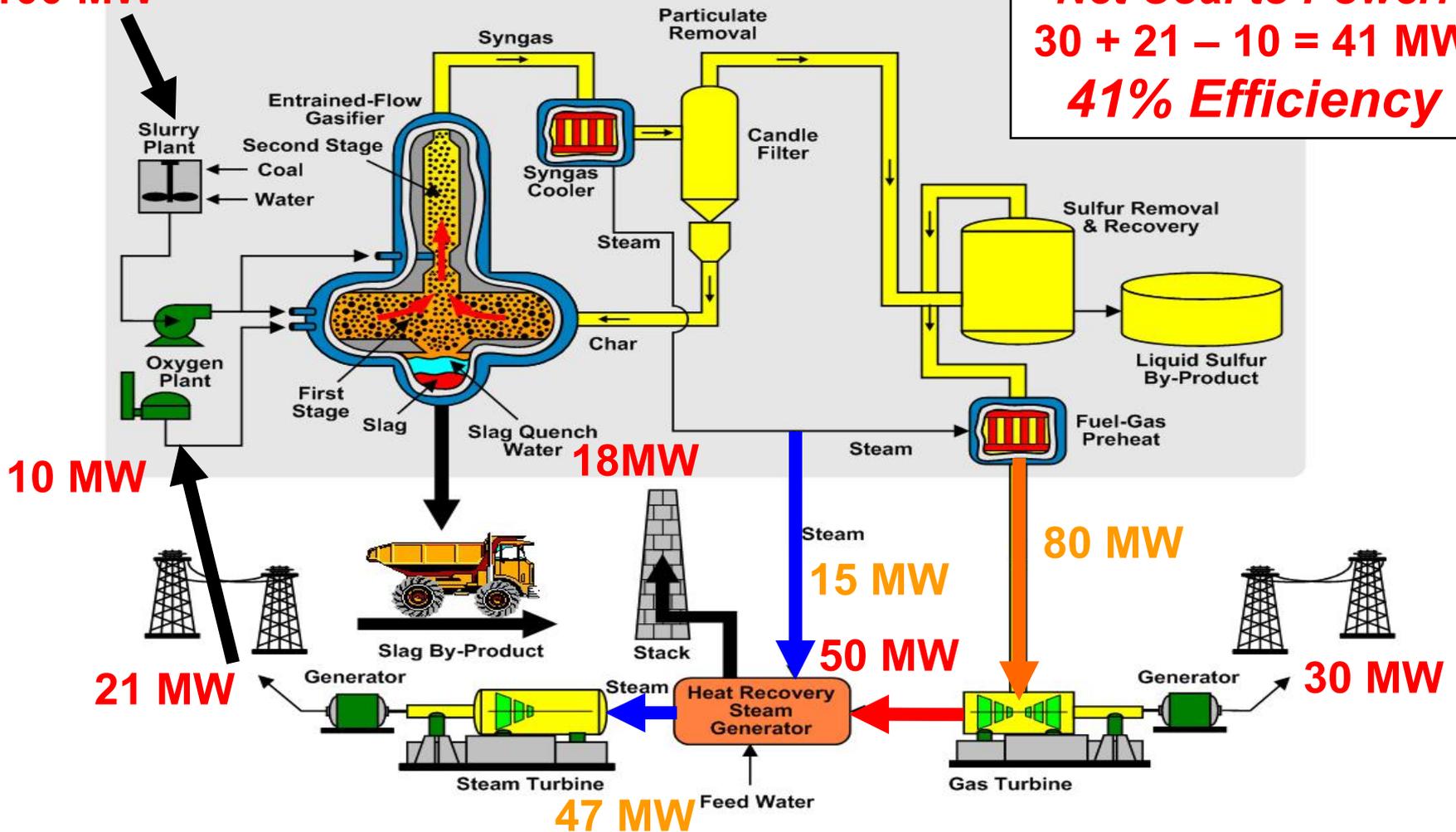


Coal-Based IGCC Power Plant

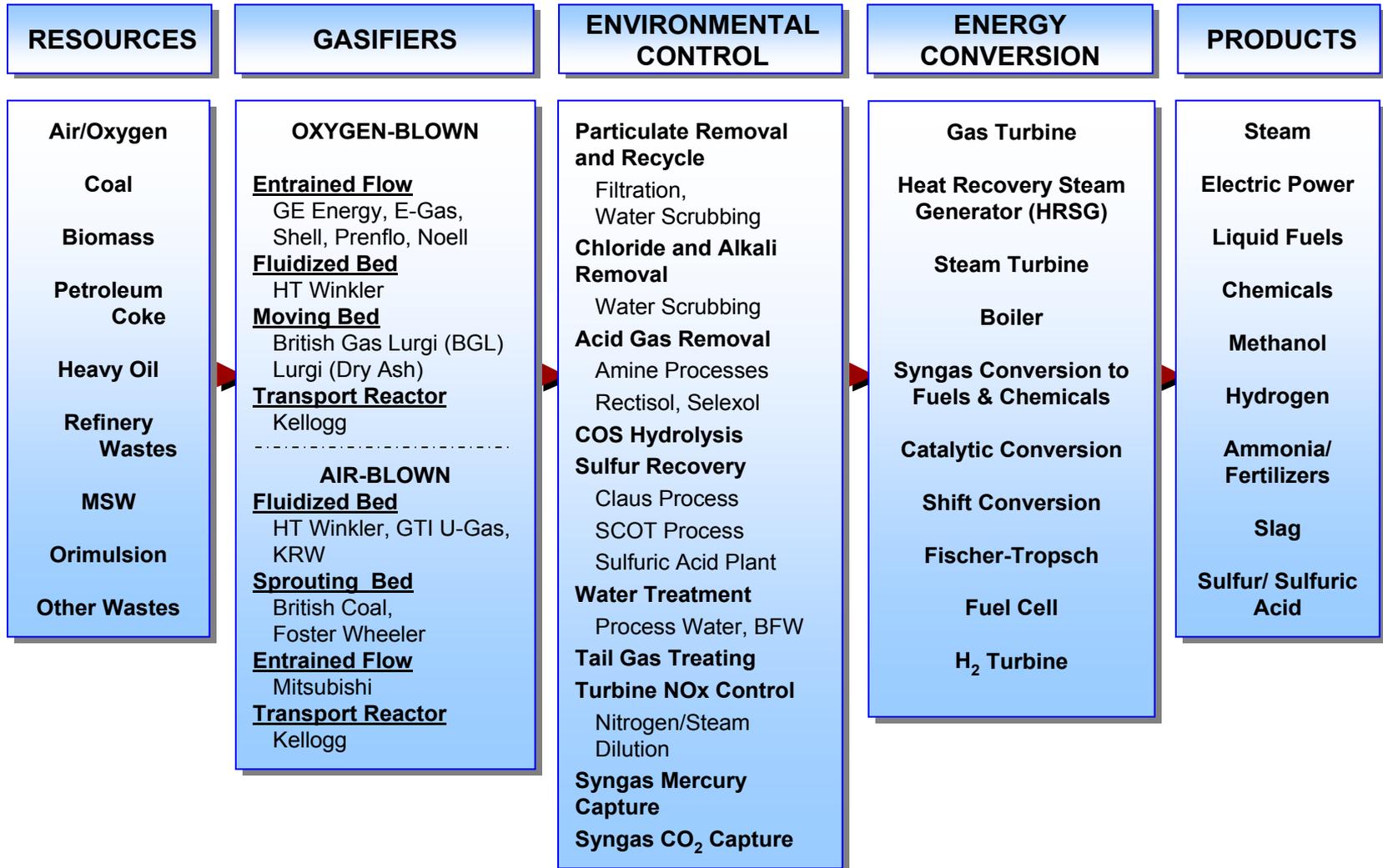
(Illustration only)

100 MW

Net Coal to Power:
 $30 + 21 - 10 = 41 \text{ MW}$
41% Efficiency

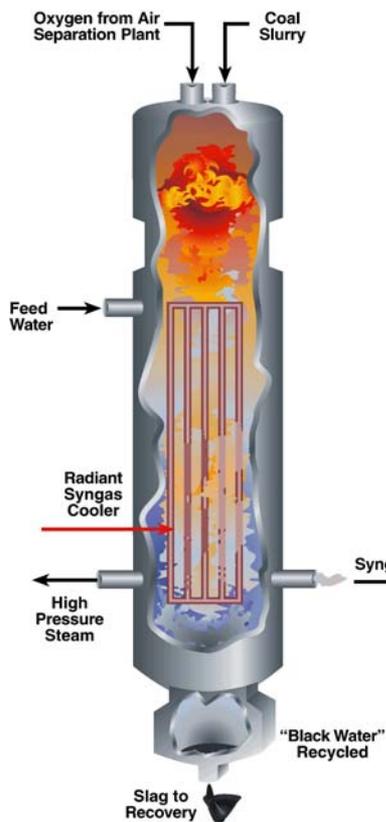


Gasification-Based Energy Conversion Systems

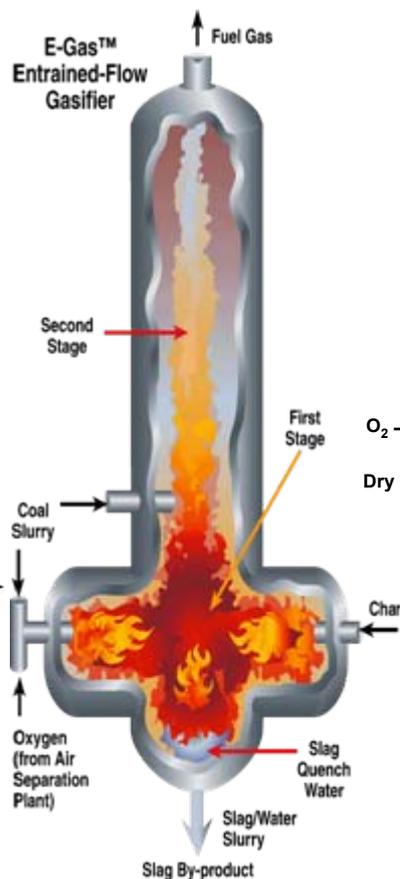


Gasifiers

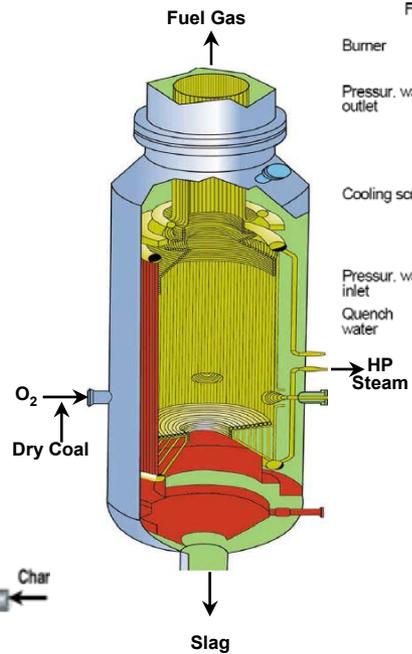
GE Energy
(Chevron-Texaco)



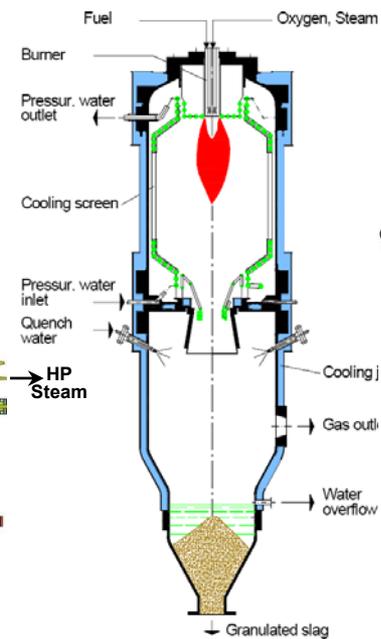
ConocoPhillips
E-Gas



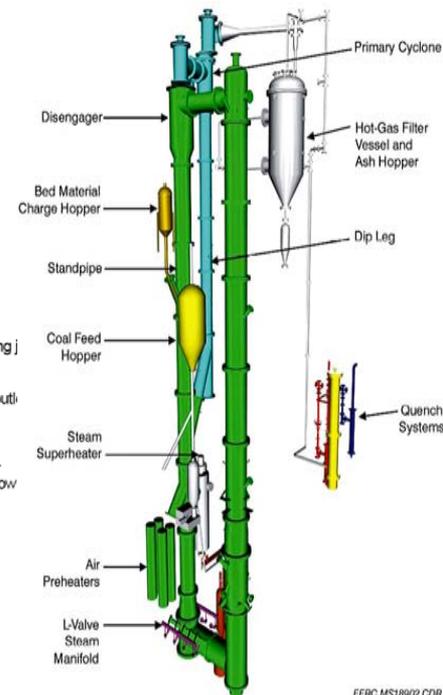
Shell
SCGP



Siemens
(GSP/Noell)



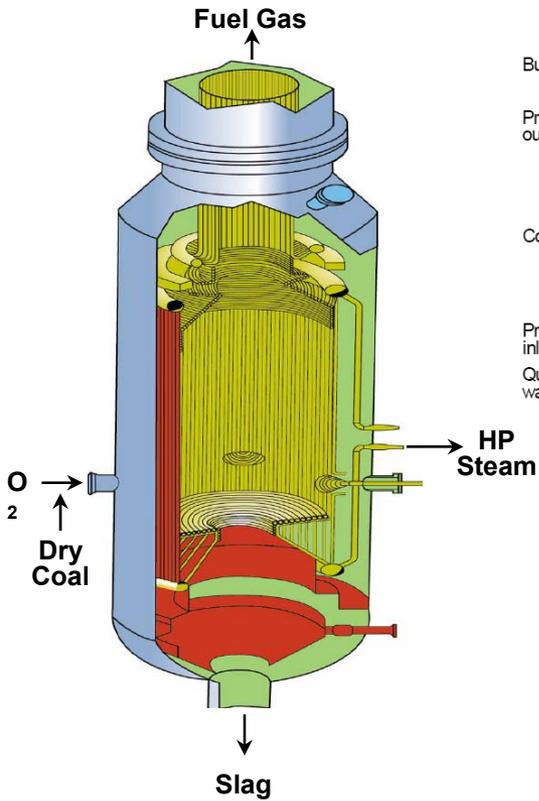
KBR
Transport



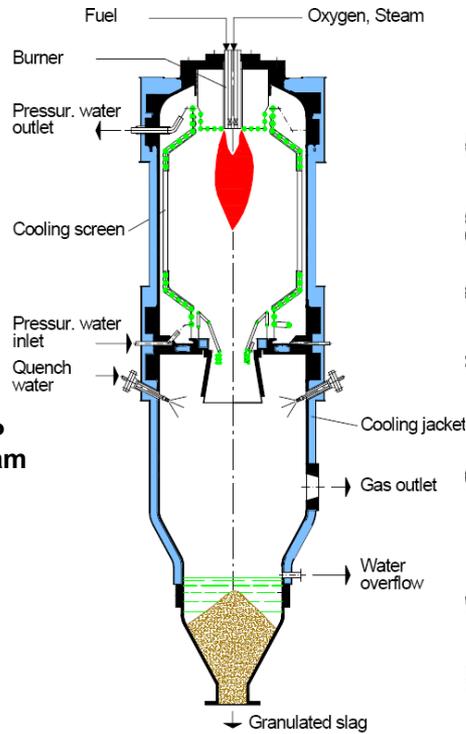
EERC MS18902.CDR

Gasifiers for Low Rank Coal

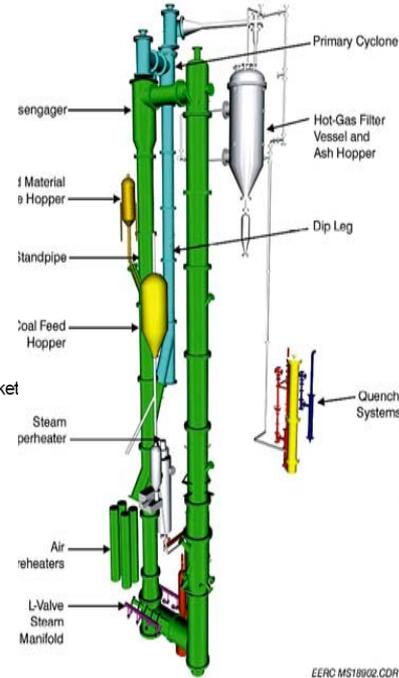
**Shell
SCGP**



**Siemens
(GSP/Noell)**

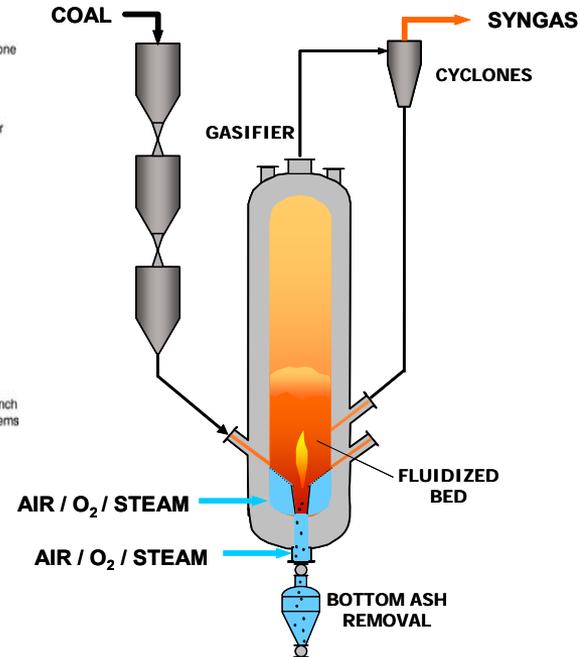


**KBR
Transport**

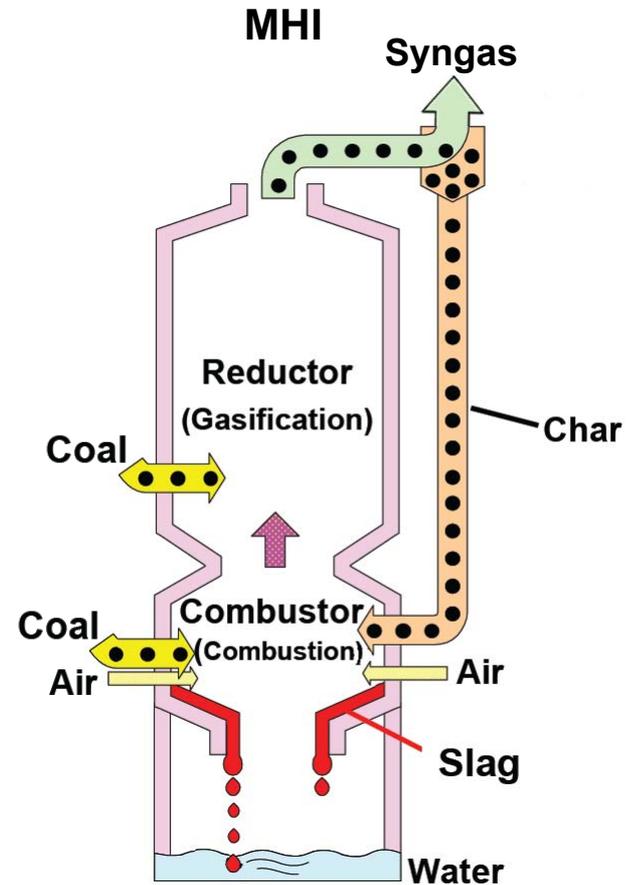
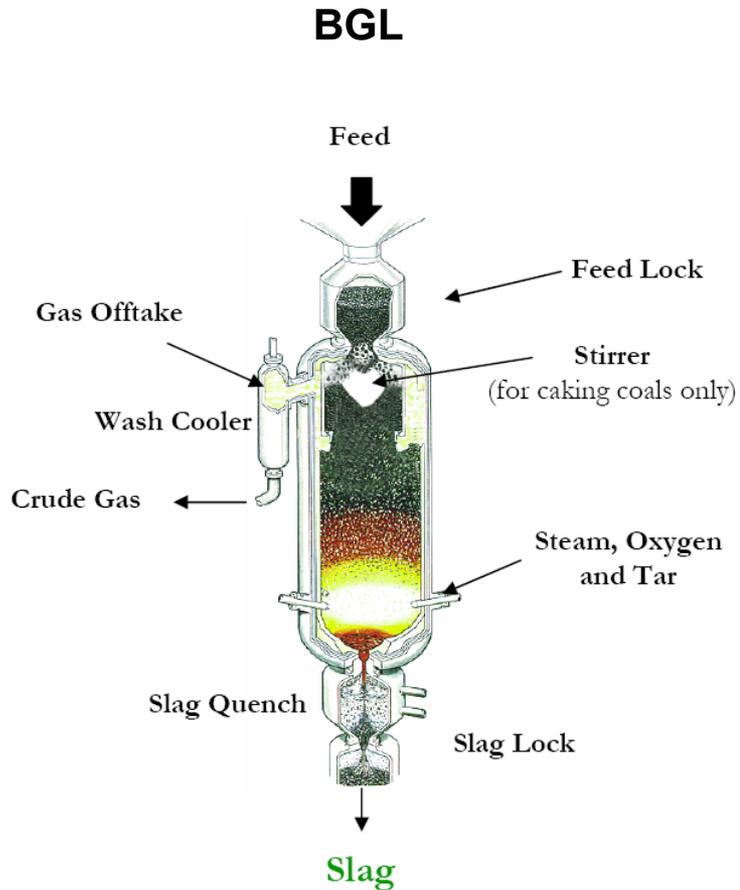


EERC M518902.CDR

**GTI
Fluid Bed**

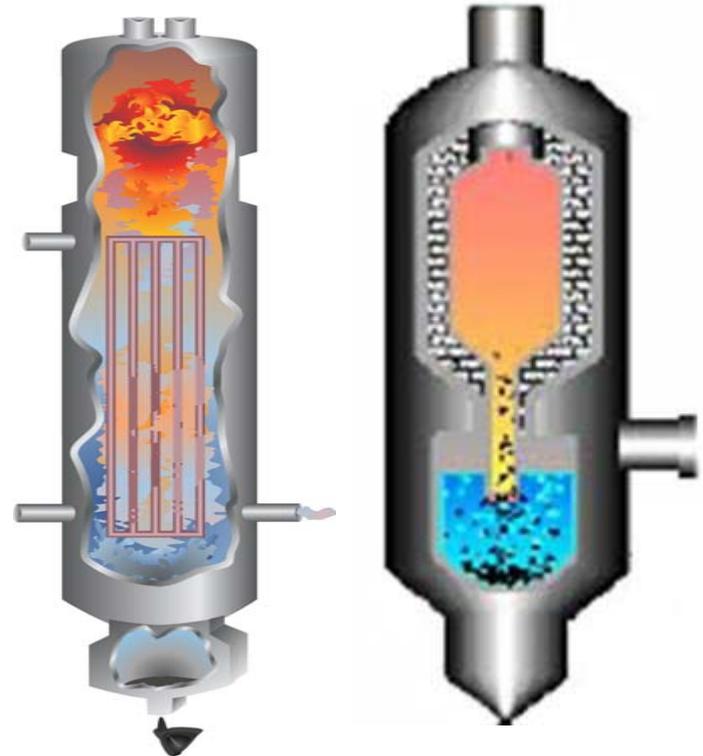


Gasifiers for Low Rank Coal *(continued)*



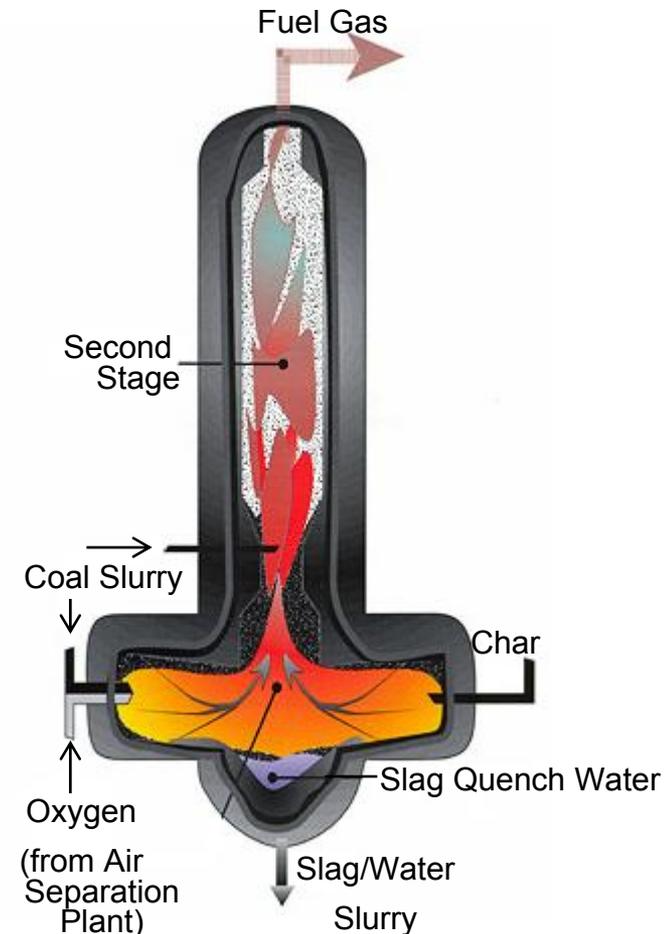
GE Energy Gasifier

- Coal-water slurry feed
- Entrained-flow
- Oxygen-blown
- Refractory-lined gasifier
- Two versions offered
 - Radiant cooler
 - Quench
- Slagging
- Good for bituminous coal, pet coke, or blends of pet coke and low-rank coals
- EPC alliance with Bechtel for guarantees on total IGCC plant
- 64 Plants operating
 - 15,000 MWth Syngas
- 10 Plants in planning



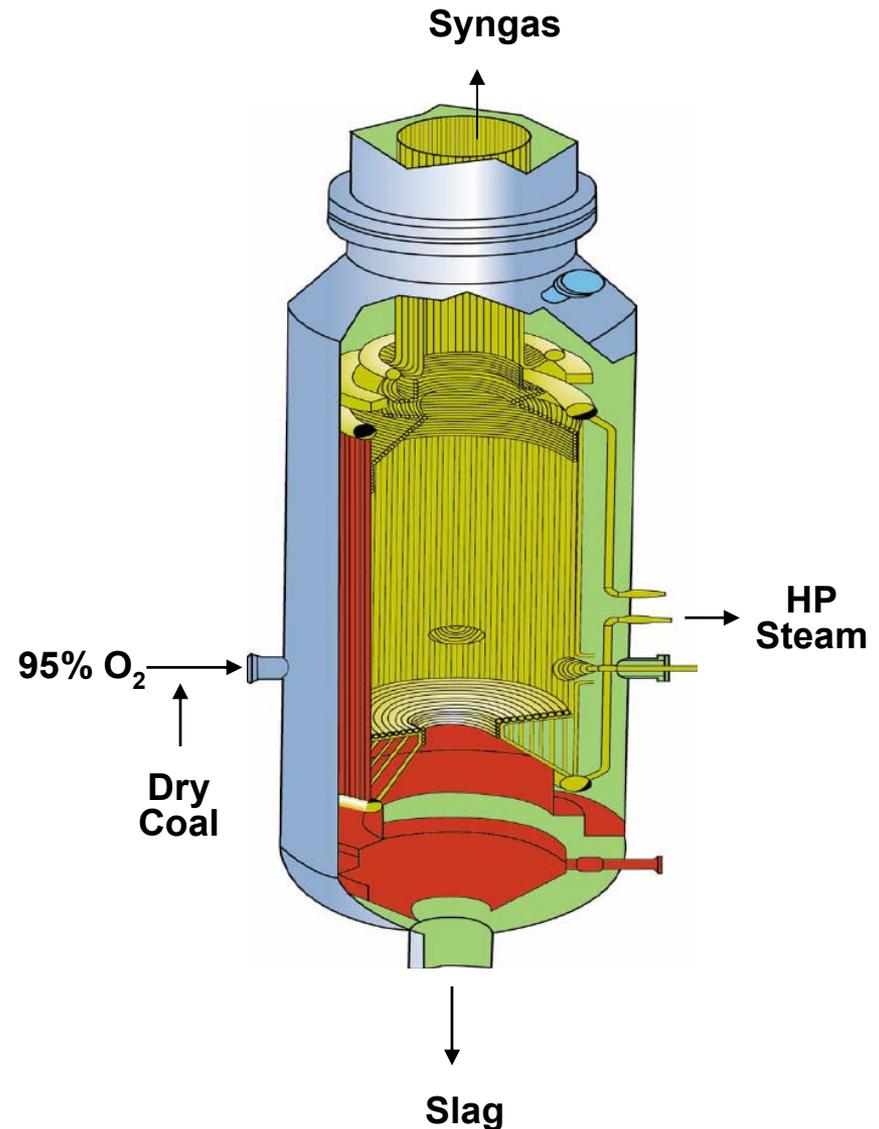
ConocoPhillips (E-Gas) Gasifier

- **Entrained-flow**
- **Two-stage gasifier**
 - 80% of feed to first stage (lower)
 - Advanced E-STR gasifier feeds 100% to second stage (upper)
- **Coal-water slurry feed**
- **Oxygen-blown**
- **Refractory-lined gasifier**
- **Continuous slag removal system, dry particulate removal**
- **Good for a wide range of coals, from pet coke to PRB to Bituminous and blends**
- **Project specific EPC and combined cycle supplier alliances**
- **1 Plant operating - 590 MWth Syngas**
- **4 Plants in planning**



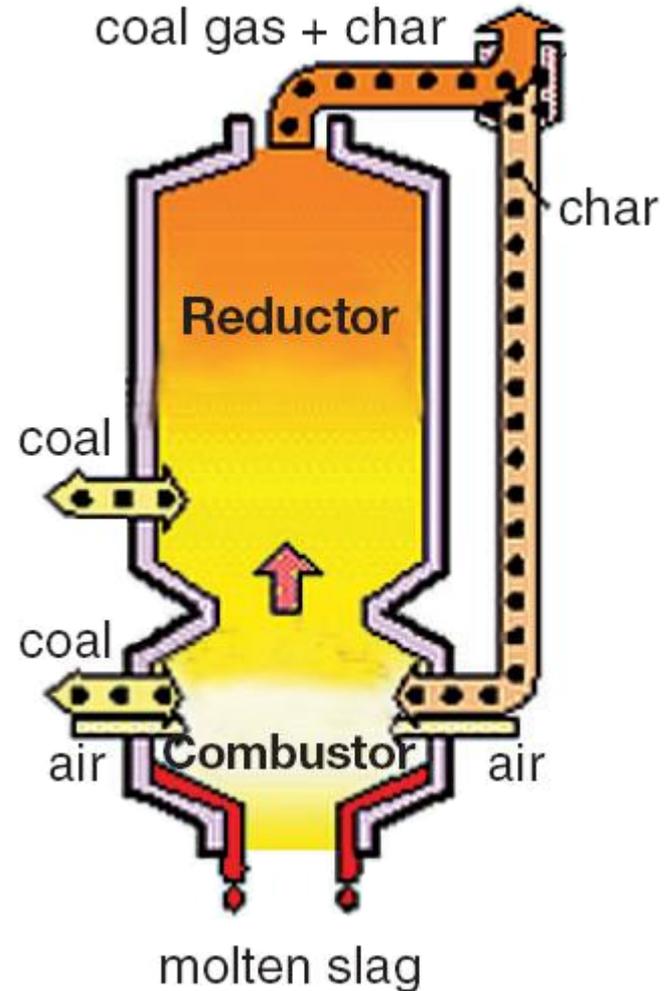
Shell Gasifier

- **Entrained flow gasifier**
- **Dry feed**
 - coal is crushed and dried
- **Oxygen-blown**
- **Waterwall in gasifier**
- **Good for wide variety of feedstocks, from pet coke to low-rank coals**
- **First plants in China operating**
- **8,500 MWth Syngas**
- **Several Plants in planning**



Mitsubishi Gasifier

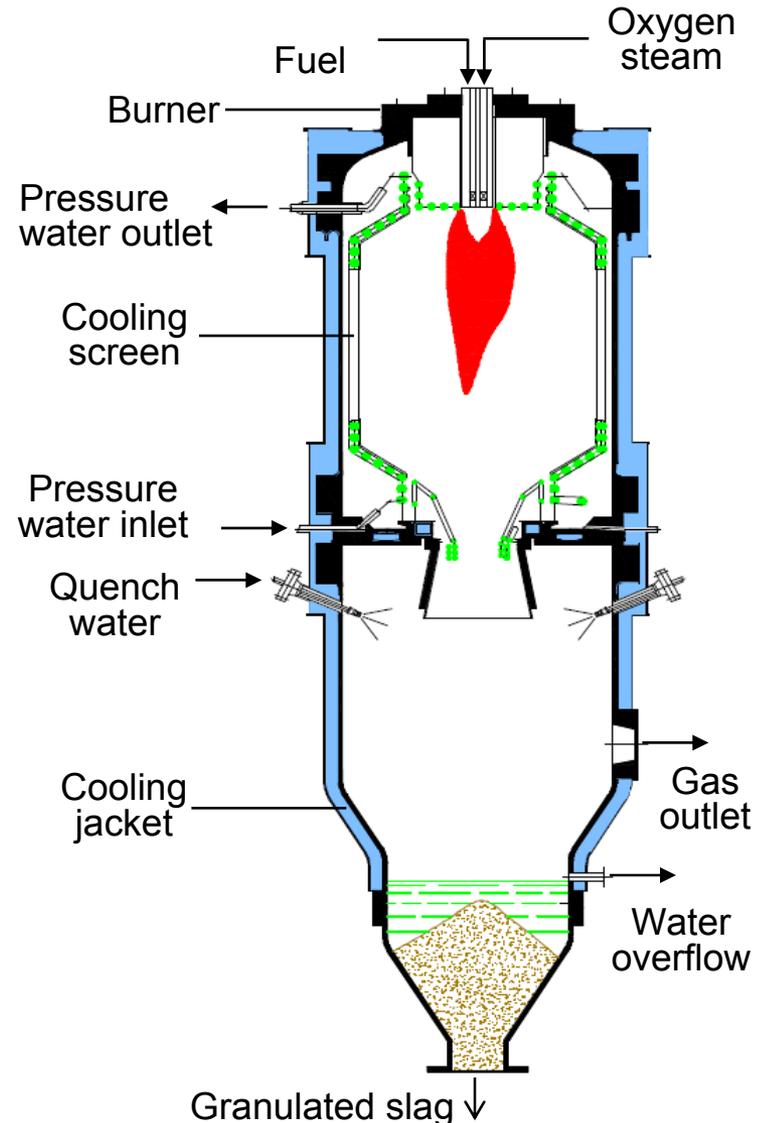
- **Entrained bed**
- **Dry feed system**
- **Suitable for low rank coal with high moisture content**
- **Two-Stage feeding**
- **Air Blown**
- **Membrane waterwall**
- **Slagging**
- **Developed in the 80's by Central Research Institute of the Electric Power Industry Japan**
- **1 Plant in planning**
- **1 Demonstration plant in operation, 250 MWe, Nakoso, Japan, startup Sept 2007**



Siemens GSP Gasifier

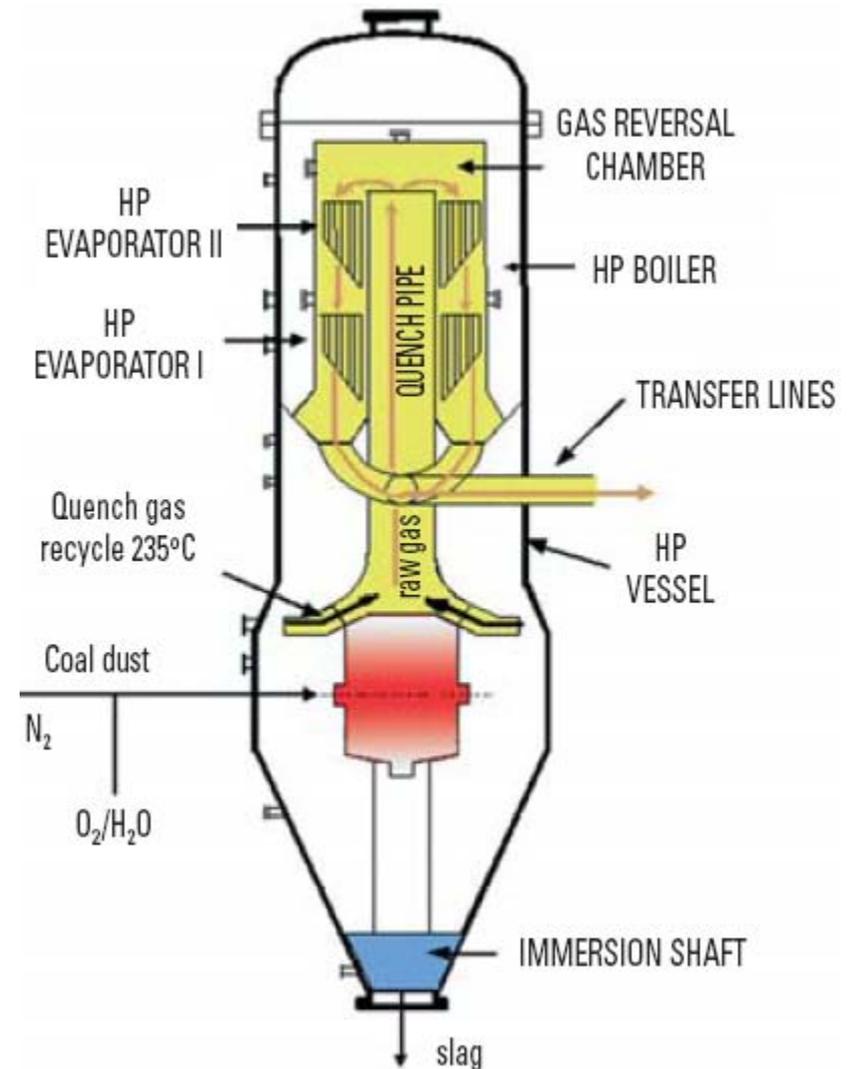
- **Entrained flow gasifier**
- **Dry feed**
- **Oxygen-blown**
- **Top fired reactor**
- **Waterwall screen in gasifier**
- **Good for a wide variety of feedstocks, from bituminous to low-rank coals**
- **Siemens provides gasification island and power block**
- **Freiberg Pilot Plants**
 - cooling wall/screen
 - 3 MW & 5 MW
- **2 Industrial plants:**
 - Schwarze Pumpe*, Vrěsová (oil)
- **9 SFG-500 gasifiers on order or being manufactured**

**no longer operating*



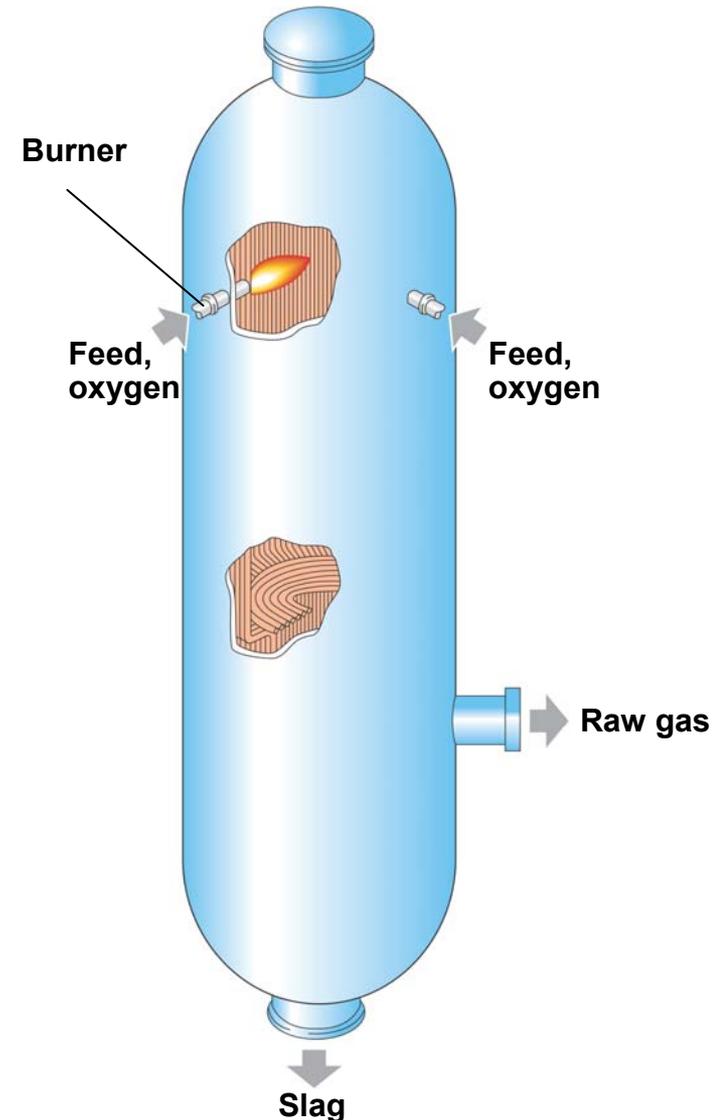
PRENFLO™ Gasifier/Boiler (PSG)

- Pressurized entrained flow gasifier with steam generation
- Uhde
- Oxygen blown
- Dry feed system
- Membrane wall
- Waste heat boiler
- Able to gasify variety of solid fuels
 - hard coal, lignite, anthracite, refinery residues, etc.
- Demonstration plant Fürstenhausen, Germany (48 TPD)
- Used in world's largest solid-feedstock-based IGCC plant in Puertollano, Spain



PRENFLO™ Gasifier (PDQ)

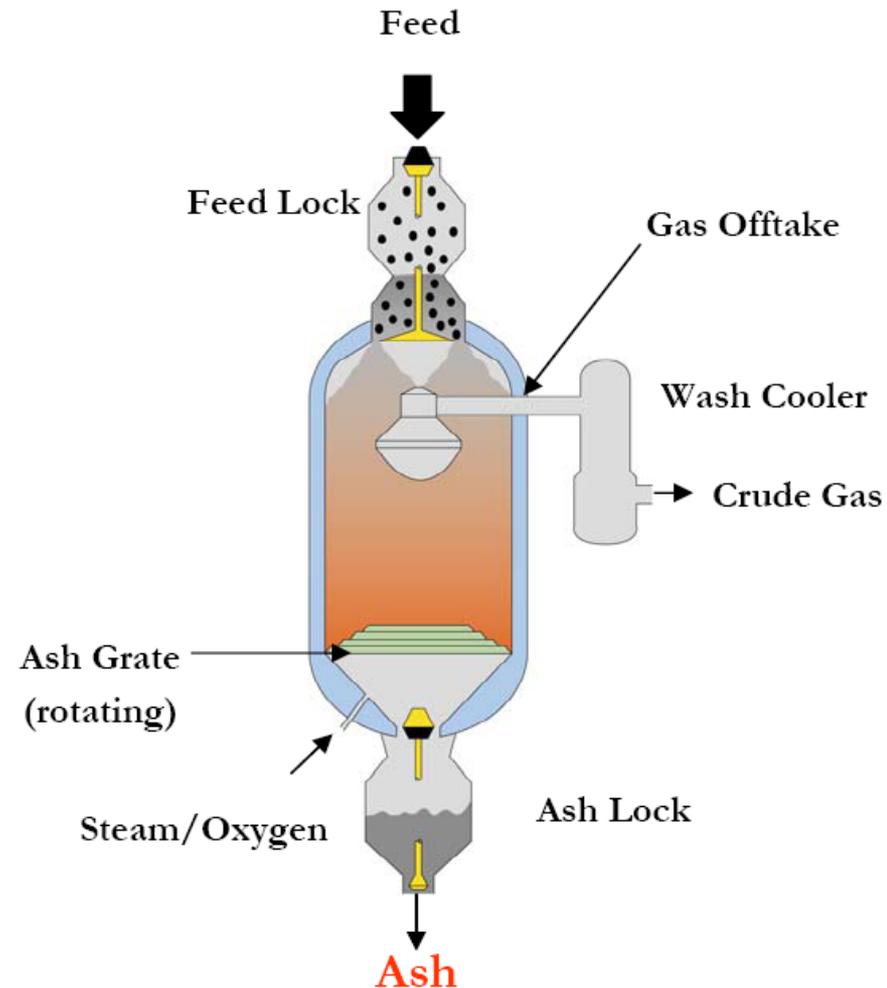
- **Pressurized entrained flow gasifier with direct quench (PDQ)**
- **License, EPCM, process guarantees by Uhde**
- **Oxygen blown**
- **Dry feed system**
- **Membrane wall**
- **Full water quench**
- **Able to gasify a wide variety of solid fuels**
 - hard coal, lignite, anthracite, refinery residues, etc.
- **Based on proven PSG design:**
 - Fürstenhausen, Germany
 - world's largest solid-feedstock-based IGCC plant in Puertollano, Spain
- **Compact design with significant cost savings**
- **First plants under design**



Lurgi Gasifier

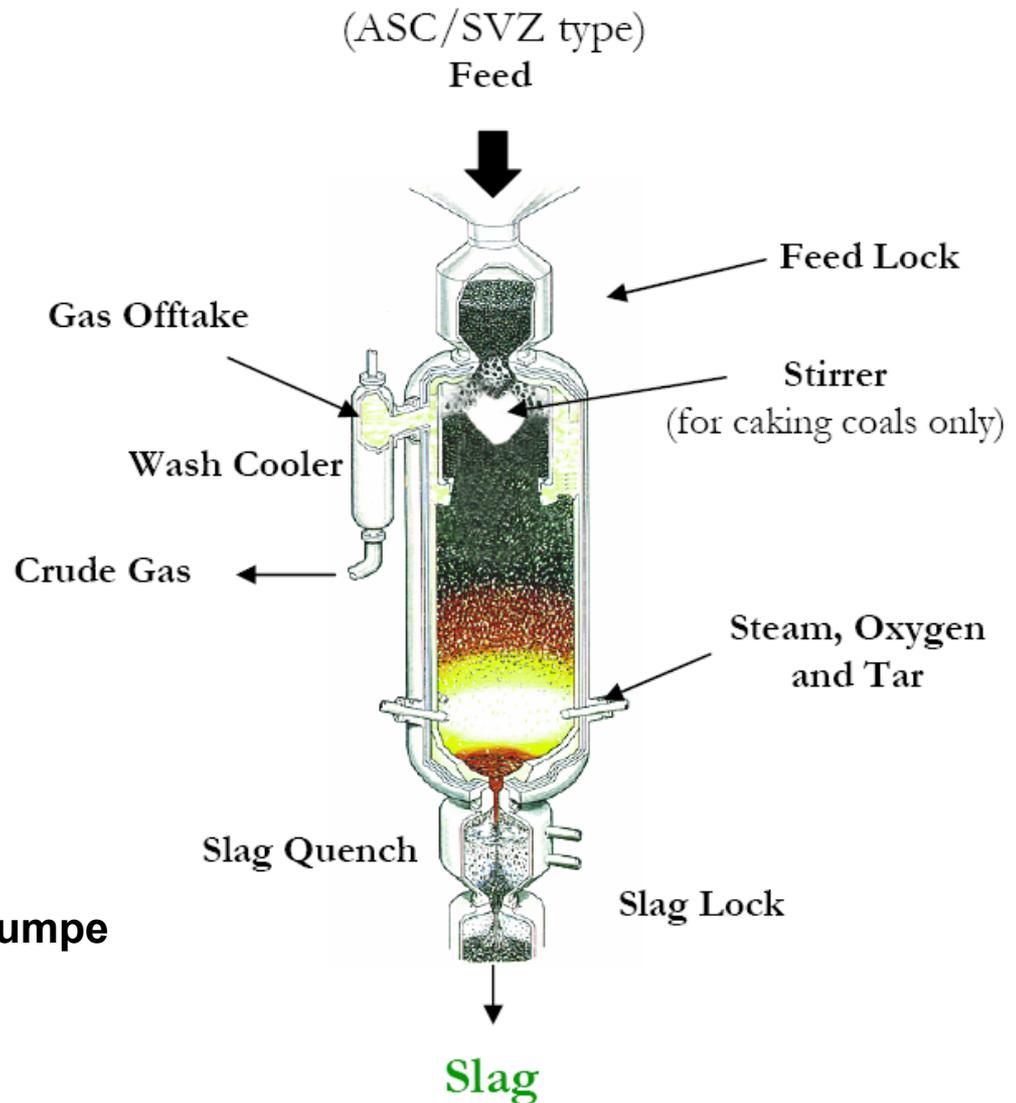
(North Dakota/Sasol type)

- **Moving bed gasifier**
- **Lock hoppers**
 - Distributor
 - Quench cooler
- **Dry feed system**
- **Dry bottom ash**
- **Extensive experience with low rank coals**
- **North Dakota/Sasol type**
- **8 Plants operating**
 - 18,600 MWth Syngas



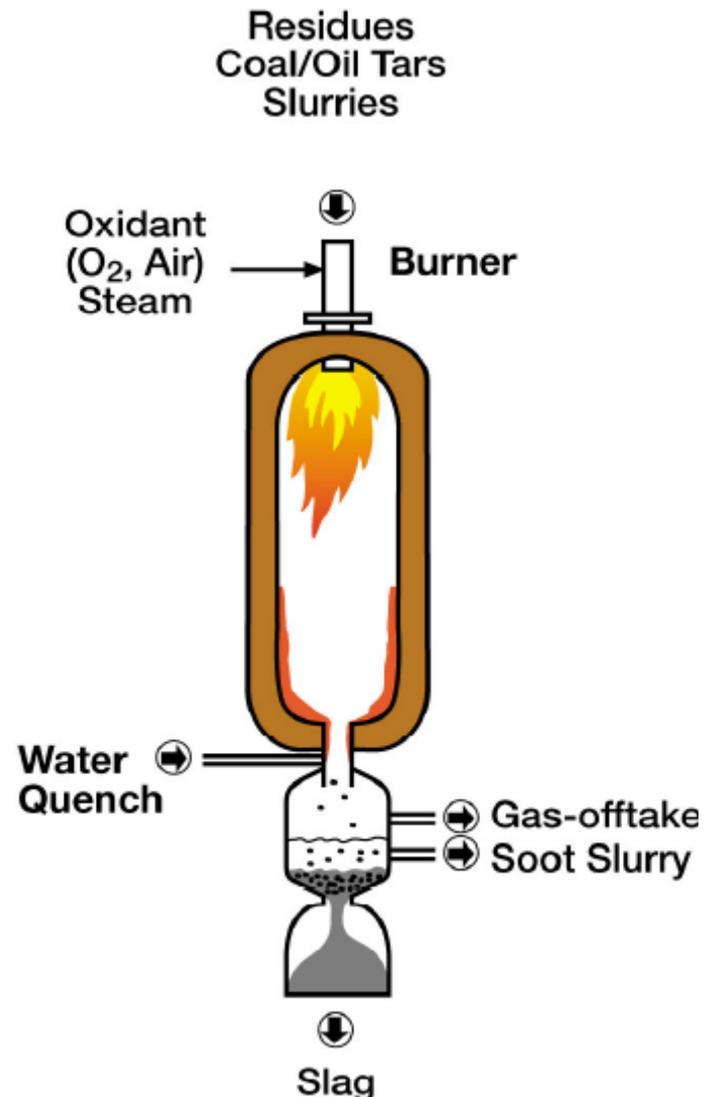
British Gas/ Lurgi (BGL) Gasifier

- Moving bed gasifier
- “Slagging” version of Lurgi
- Dry feed
- Oxygen-blown
- Refractory-lined gasifier
- Good for wide range of coals
- Opportunity fuel blends
 - RDF, tires, wood waste
- Modular design
- Allied Syngas build, own and operate in North American
- Demonstration plant
 - Westfield 1986 – 1990
 - 500 TPD
- 1 Plant in planning
- 1st Commercial plant Schwarze Pumpe
 - operated 2000 -2005
 - BGL-1000



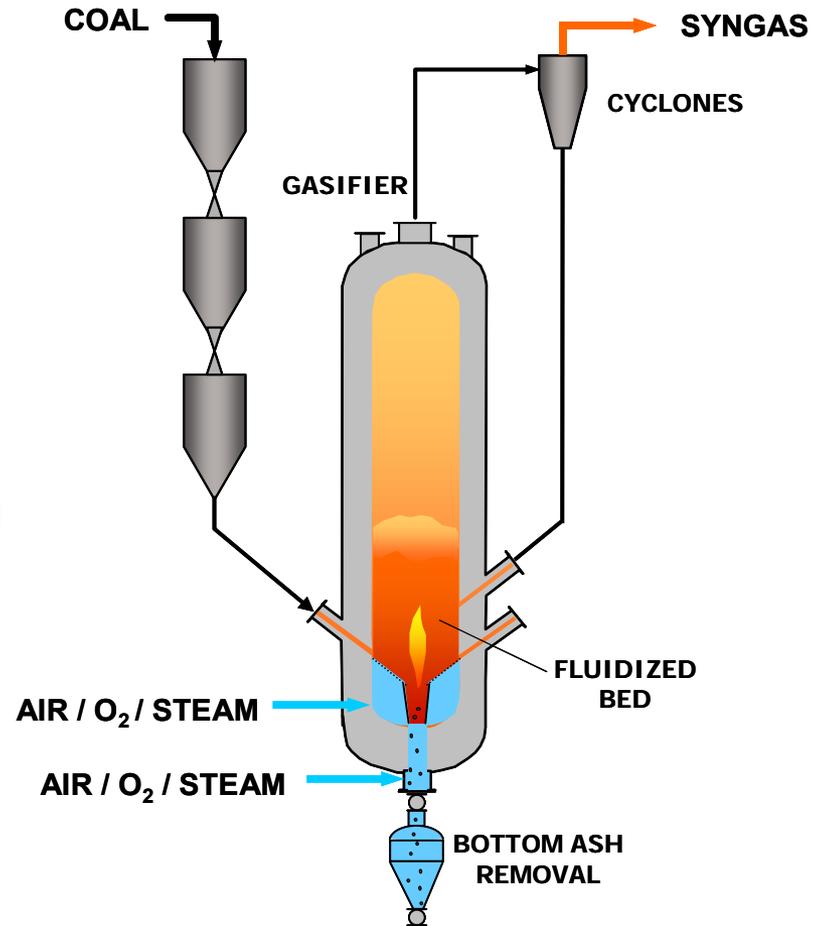
Multi Purpose (MPG) Gasifier

- Moving bed gasifier
- Oxygen-blown
- Good for wide range of feedstocks
 - Petcoke/ coal slurries and waste
- Quench configuration for coal/petcoke feedstock
- MPG technology developed from Lurgi's fixed-bed gasification process
- “Reference plant” (oil)
 - Schwarze Pumpe in operation since 1968



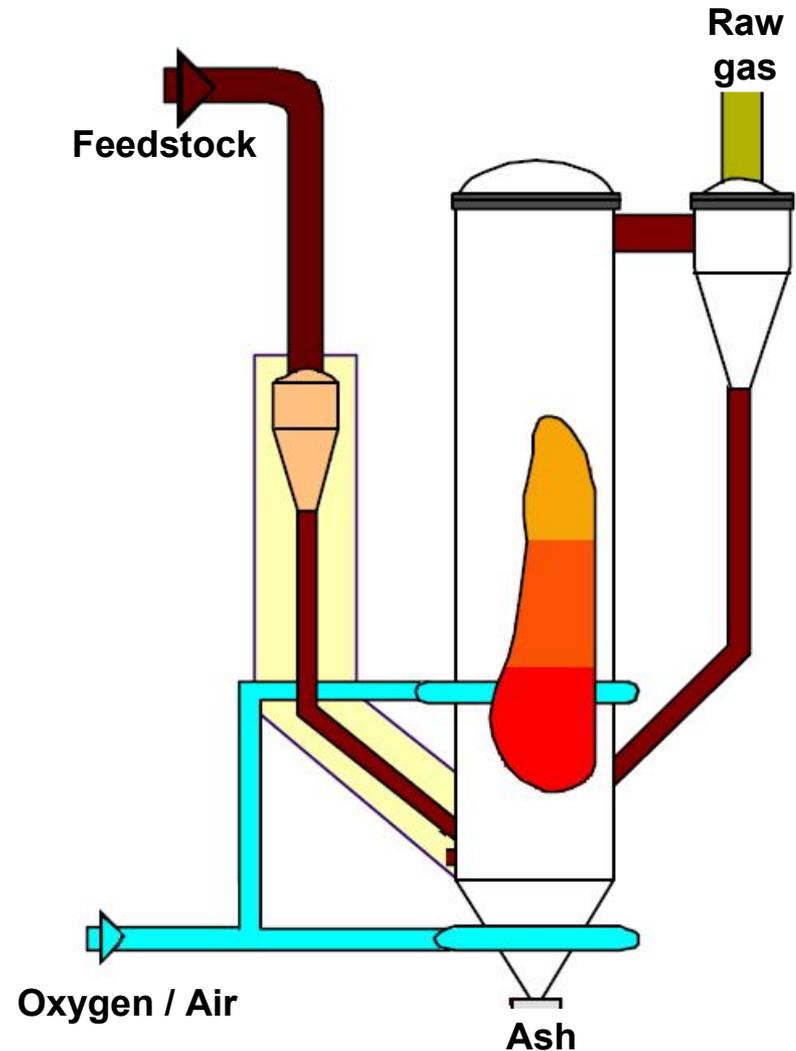
GTI (U-Gas) Gasifier

- Fluidized bed gasifier
- Dry feed system
- Coal and coal/biomass blends
- Highly efficient
- Air or oxygen blown
- Non-slagging/bottom ash
- 30 year license agreement with Synthesis Energy Systems (SES)
- 20+ years experience including plants in Shanghai and Finland
- 2 Plants in operation
 - 520 MWth Syngas



High Temperature Winkler Gasifier

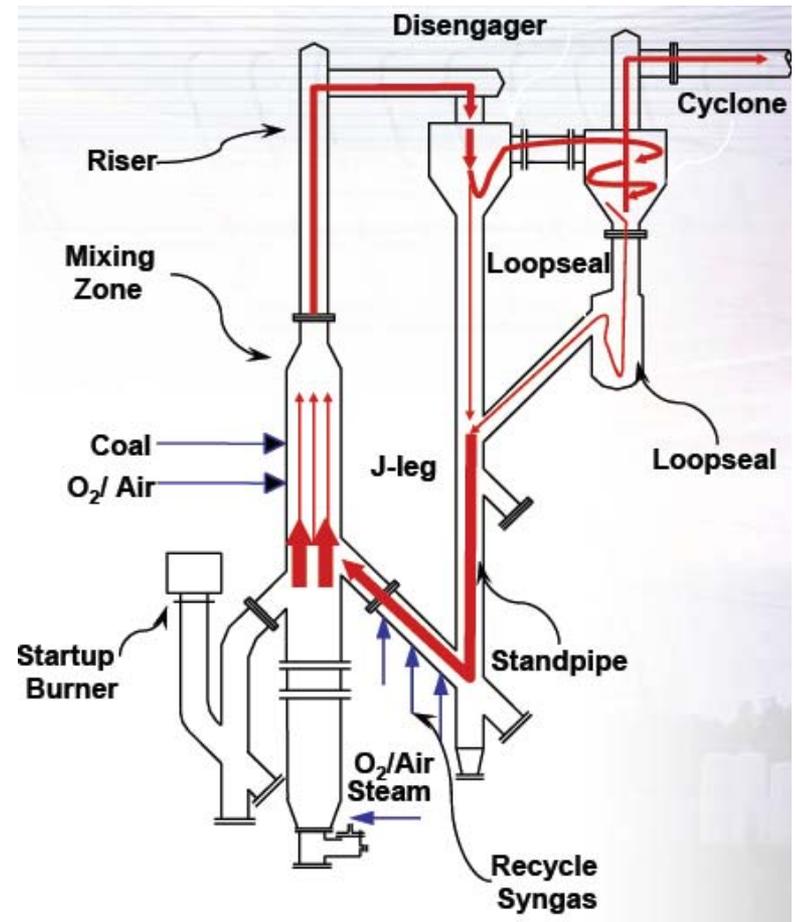
- Fluidized bed gasifier
- Dry feed
- Oxygen or air-blown
- Dry bottom ash
- Developed to utilize lignite coal
- Capable of gasifying broad range of feedstock
- Marketed for waste materials as Uhde PreCon process.
- Berrenrath demonstration plant
 - In operation 1986 - 1997
 - 67,000 operating hours
 - 1.6 million tonnes dry lignite processed to produce 800,000 tonnes methanol



Kellogg Brown & Root (KBR) Gasifier

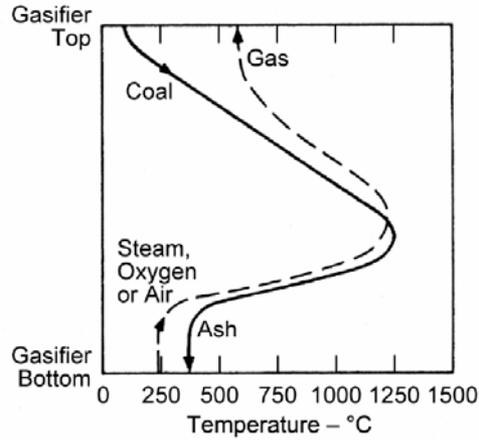
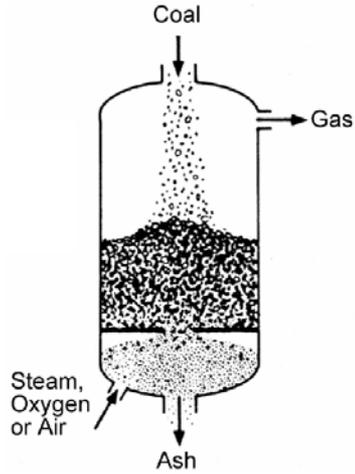
Transport Gasifier

- **Oxygen or air-blown**
 - Air blown for power generation
 - Oxygen for liquid fuels and chemicals
- **High reliability design**
 - Non-slagging
 - No burners
 - Coarse, dry coal feed
- **Planned 560 MWe IGCC with a 2x1 CC owned by Mississippi Power Company in Kemper County, MS**
 - June 2013 COD

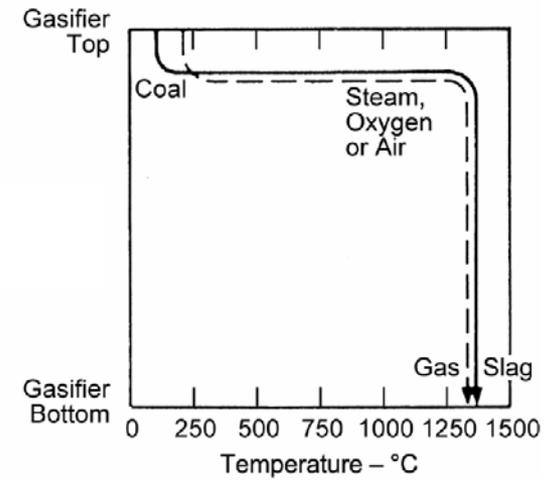
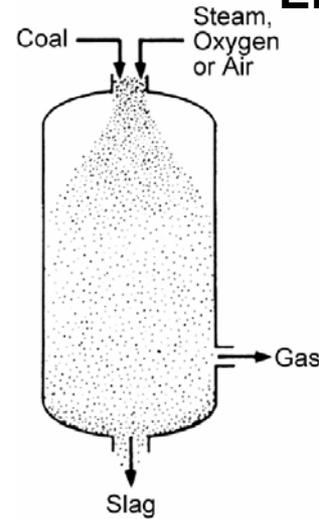


Gasifier Configurations

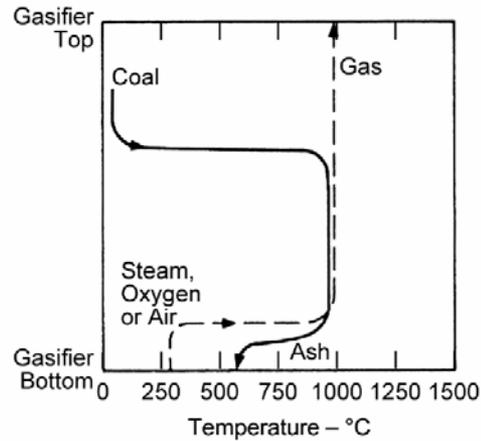
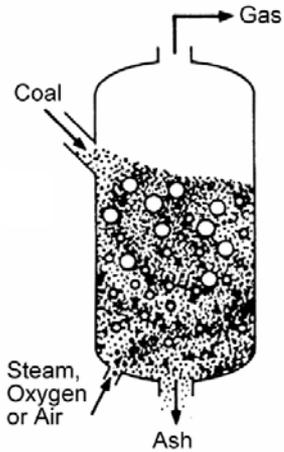
Moving Bed



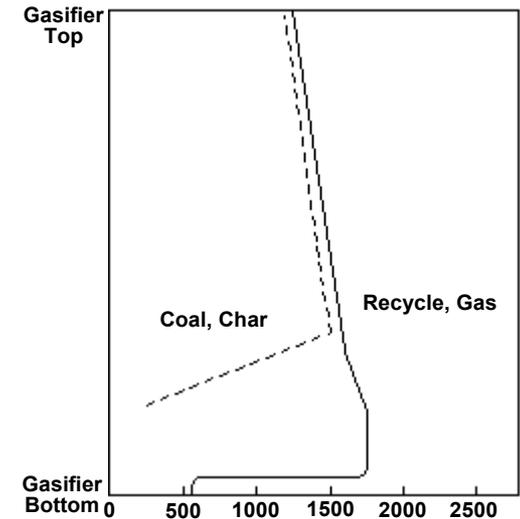
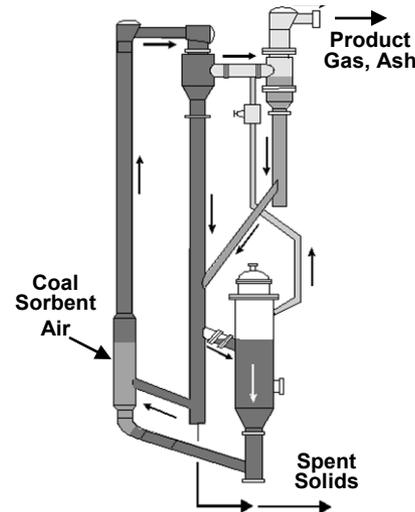
Entrained Flow



Fluidized Bed



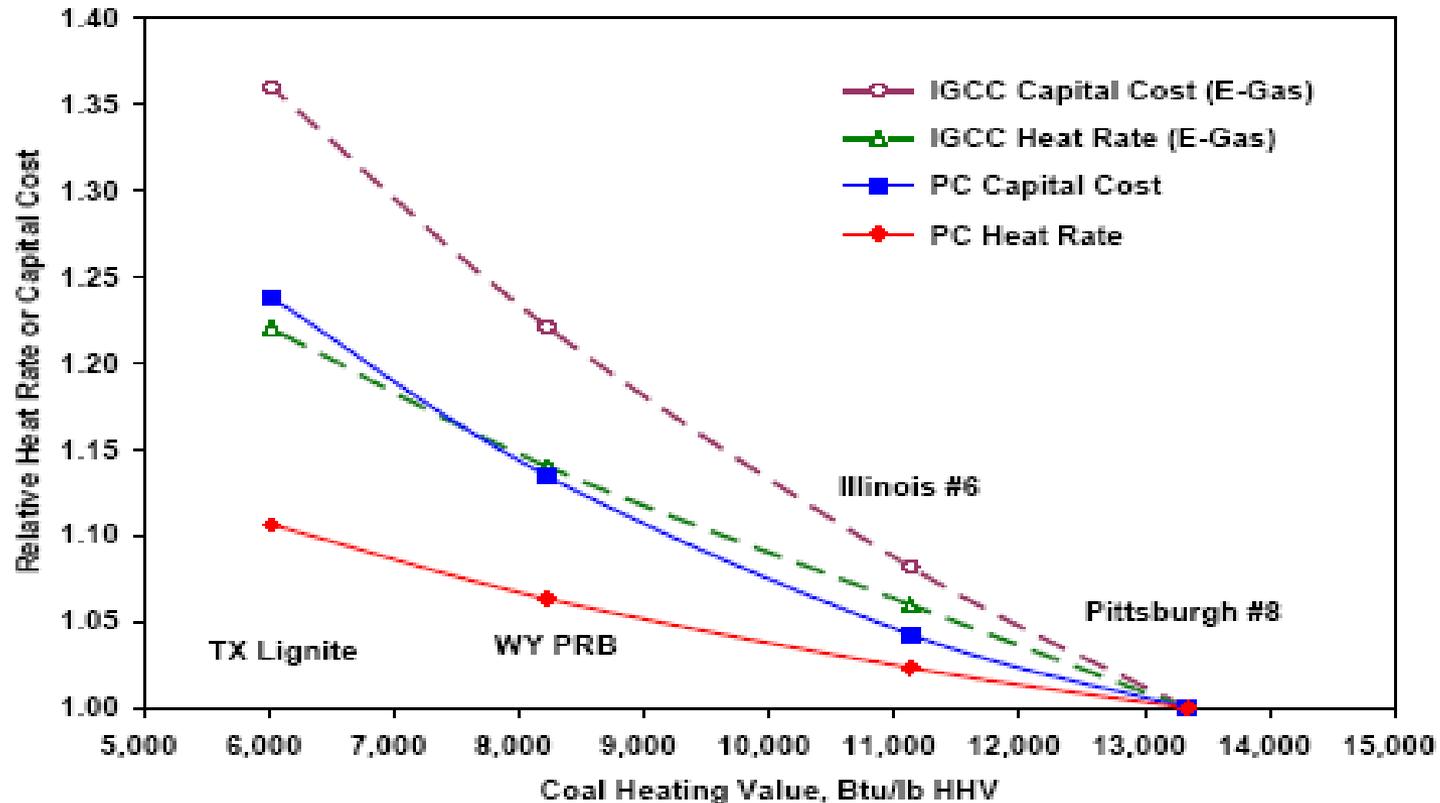
Transport



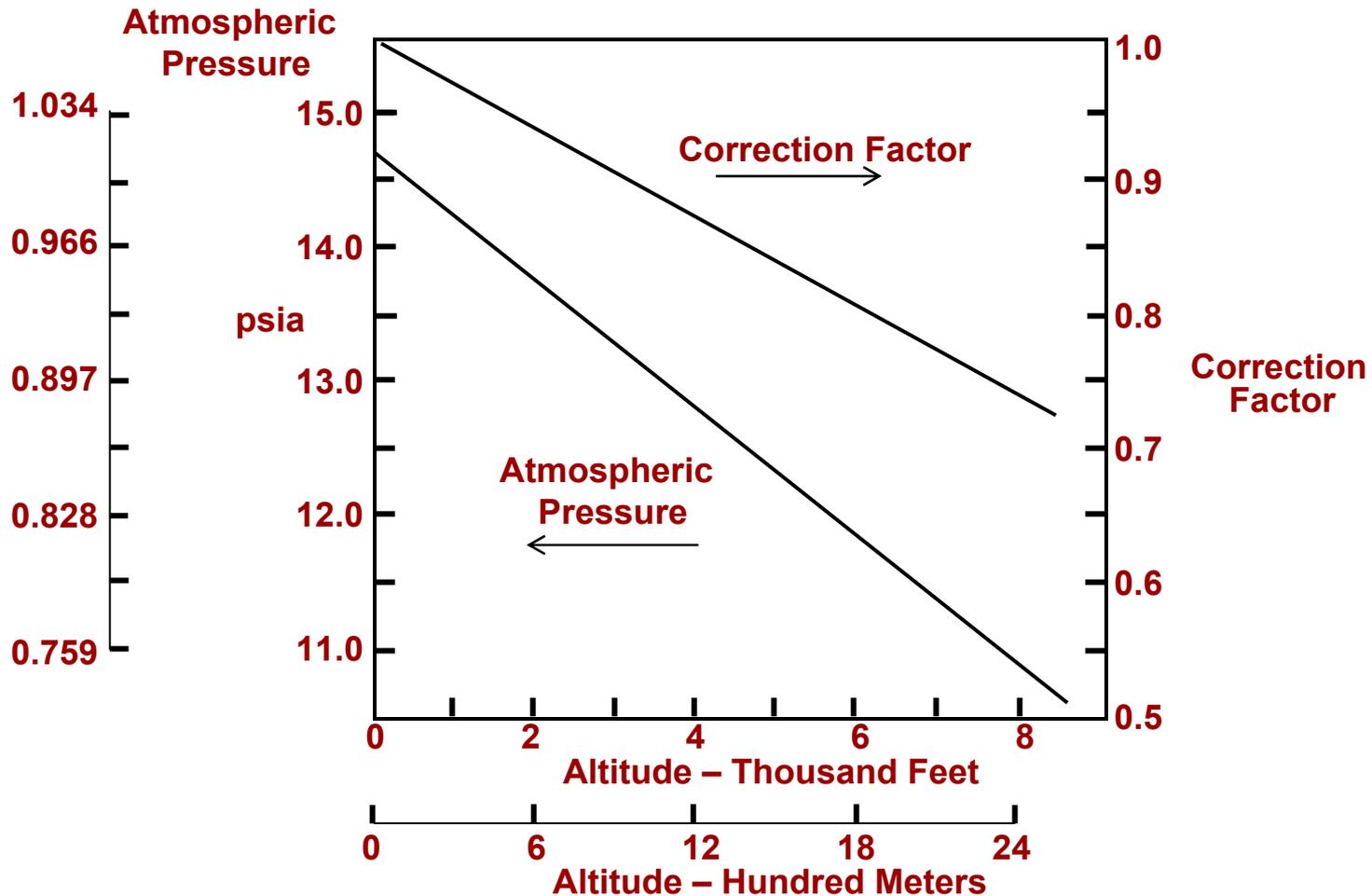
Comparison of Gasifier Characteristics

	Moving Bed		Fluidized Bed		Entrained Flow	Transport Flow
Ash Condition	Dry	Slagging	Dry	Agglomerate	Slagging	Dry
Coal Feed	~ 2 in	~ 2 in	~ 1/4 in	~ 1/4 in	~ 100 Mesh	~1/16in
Fines	Limited	Better than dry ash	Good	Better	Unlimited	Better
Coal Rank	Low	High	Low	Any	Any	Any
Gas Temp. (°F)	800-1,200	800-1,200	1,700-1,900	1,700-1,900	>2,300	1,500-1,900
Oxidant Req.	Low	Low	Moderate	Moderate	High	Moderate
Steam Req.	High	Low	Moderate	Moderate	Low	Moderate
Issues	Fines and hydrocarbon liquids		Carbon conversion		Raw gas cooling	Control carbon inventory and carryover

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



Effect of Altitude on Performance





Polk



Wabash

Gasification A Commercial Reality

Buggenum



Puertollano



Snapshot of IGCC Syngas Fuel Composition & Typical Natural Gas Composition

Syngas	PSI	Tampa	El Dorado	Pernis	ILVA	Schwarze Pumpe	Sarlux	Fife	Exxon Singapore	Valero Delaware	^d	Natural Gas
H₂	24.8	37.2	35.4	34.4	8.6	61.9	22.7	34.4	44.5	32.0	33.4	trace
CO	39.5	46.6	45.0	35.1	26.2	26.2	30.6	55.4	35.4	49.5	42.2	—
CH₄	1.5	0.1	0.0	0.3	8.2	6.9	0.2	5.1	0.5	0.1	0.1	93.9
CO₂	9.3	13.3	17.1	30.0	14.0	2.8	5.6	1.6	17.9	15.8	17.8	14.5
N₂ + Ar	2.3	2.5	2.1	0.2	42.5	1.8	1.1	3.1	1.4	2.2	5.7	48.2
H₂O	22.7	0.3	0.4	—	—	—	39.8	—	0.1	0.4	0.1	0.9
LHV^a												
Btu/ft³	209.0	253.0	242.0	210.0	183.0	317.0	163.0	319.0	241.0	248.0	230.4	134.6
kJ/M³	8224.0	9962.0	9528.0	8274.0	7191.0	12492.0	6403.0	12568.0	9477.0	9768.0	9079.0	5304.0
GT Temperature												
°F	570.0	700.0	250.0	200.0	400.0	100.0	392.0	100.0	350.0	570.0	300.0	—
°C	330.0	371.0	121.0	96.0	204.0	38.0	200.0	38.0	177.0	299.0	149.0	—
H₂/CO ratio	0.63	0.80	0.79	0.98	0.33	2.36	0.74	0.62	1.26	0.65	0.79	0.46
Diluent	Steam	N ₂	N ₂ /Steam	Steam	—	Steam	Moisture	H ₂ O	Steam	H ₂ O/N ₂	N ₂ /H ₂ O	n/a
Equivalent LHV^b												
Btu/ft³	150.0	118.0	113^c	198.0	—	200.0	—	^c	116.0	150.0	115.3	134.6
kJ/M³	5910.0	4649.0	4452.0	7801.0	—	7880.0	—	—	4660.0	5910.0	4543.0	5304.0

^a Pre-diluent, ^b Post-diluent, ^c Always co-fired with 50% natural gas, ^d Confidential

Commercial-Scale Coal IGCC Power Plants

U.S.

- **Southern California Edison's 100 MWe Cool Water Coal Gasification Plant (1984-1988)**
- **Dow Chemical's 160 MWe Louisiana Gasification Technology Inc (LGTI) Project (1987-1995)**
- **PSI Energy's (now Cinergy) 262 MWe Wabash River Generating Station (1995 - present)**
- **Tampa Electric's 250 MWe Polk Power Station (1996-present)**

International

- **NUON/Demkolec's 253 MWe Buggenum Plant (1994-present)**
- **ELCOGAS 283 MWe Puertollano Plant (1998-present)**

IGCC Plants in the U.S.

- **Southern California Edison**
 - 100 MWe Cool Water Coal Gasification Plant (1984-1988)
- **Dow Chemical's Louisiana Gasification Technology Inc (LGTI) Project**
 - 160 MWe (1987-1995)
- **Wabash River Coal Gasification Repowering Project**
 - 262 MWe – Coal/petcoke (1995 - present)
- **Tampa Electric Polk Power Station**
 - 250 MWe - Coal/petcoke (1996 - present)
- **Valero Delaware City**
 - 240 MWe (design) - Petcoke



Coal-based 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 Operating IGCC Projects

<i>PROJECT- LOCATION</i>	<i>COD*</i>	<i>OUTPUT (MWe)</i>	<i>FEEDSTOCK - PRODUCTS</i>
Nuon (Demkolec) - Buggenum, The Netherlands	1994	253	Coal/ biomass - Power
PSI Wabash (Global/Cinergy) - Indiana USA	1995	262	Coal/ petcoke - Power
Tampa Electric - Polk County, Florida USA	1996	250	Coal/ petcoke - Power
SUV - Vresova, Czech Republic	1996	350	Coal/ petcoke - Power & Steam
Shell Refinery - Pernis, The Netherlands	1997	80	Visbreaker tar - Power, H ₂ & Steam
ELCOGAS - Puertollano, Spain	1998	283	Coal/ petcoke - Power
ISAB Energy - Italy	1999	510	Asphalt - Power
Valero (Premcor) - Delaware City, Delaware USA	2000	240	Petcoke - Power
Sarlux/Enron - Sardinia, Italy	2000	550	Visbreaker tar - Power, H ₂ & Steam
API Energia - Falconara, Italy	2001	250	Oil residue - Power & Steam
Exxon Chemical - Singapore	2002	180	Ethylene tar - Power
Nippon Petroleum (NPRC) - Negishi, Japan	2004	350	Asphalt - Power
ENI Sannazzaro - Italy	2006	250	Oil residue - Power
Institute for Clean Coal Technology (ICCT) - Yankuang, China	2006	72	Coal - Power & Methanol
Clean Coal Power - Nakoso, Japan	2007	220	Coal - Power
<i>Total Operating IGCC Output (MW)</i>		4100	

* COD: Commercial Operation Date

IGCCs are using a variety of feedstocks

IGCC Technology in Early Commercialization

U.S. Coal-Fueled Plants

- **Wabash River**
 - 1996 Powerplant of the Year Award*
 - Achieved 77% availability **
- **Tampa Electric**
 - 1997 Powerplant of the Year Award*
 - First dispatch power generator
 - Achieved 90% availability **



**Nation's first commercial-scale
IGCC plants, each achieving
> 97% sulfur removal
≥ 90% NOx reduction**

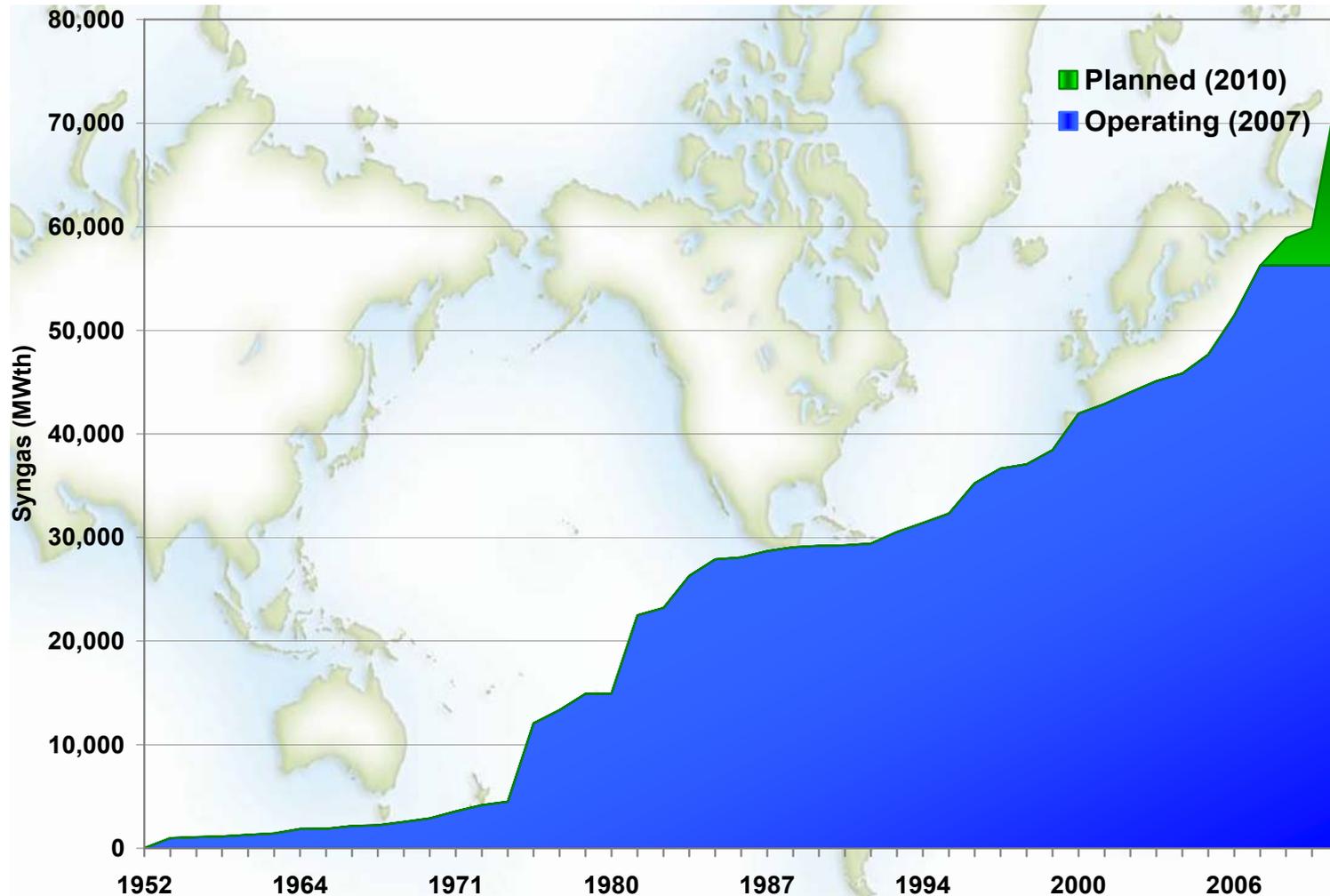


*Power Magazine

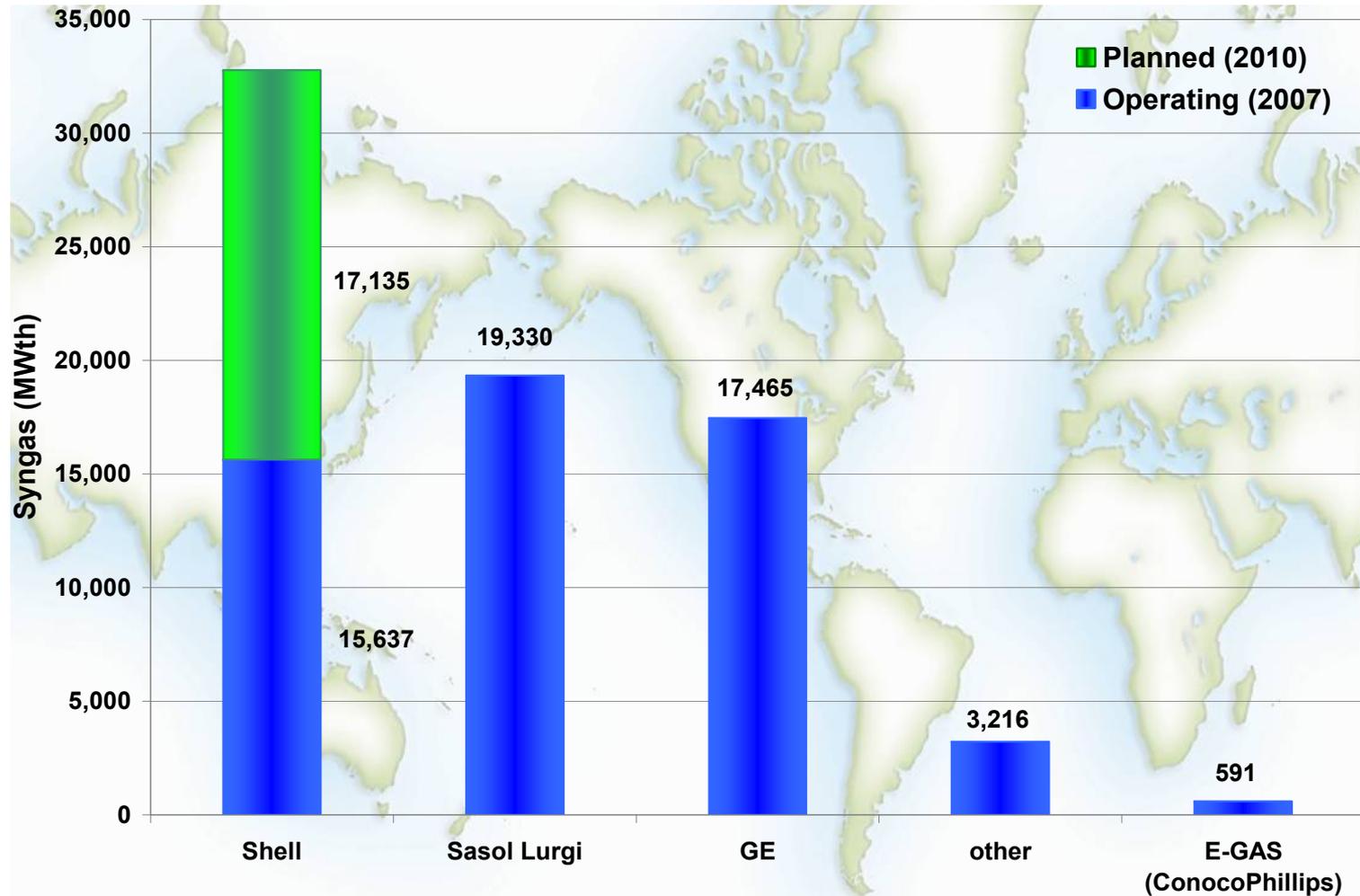
** Gasification Power Block

Worldwide Gasification Capacity and Planned Growth

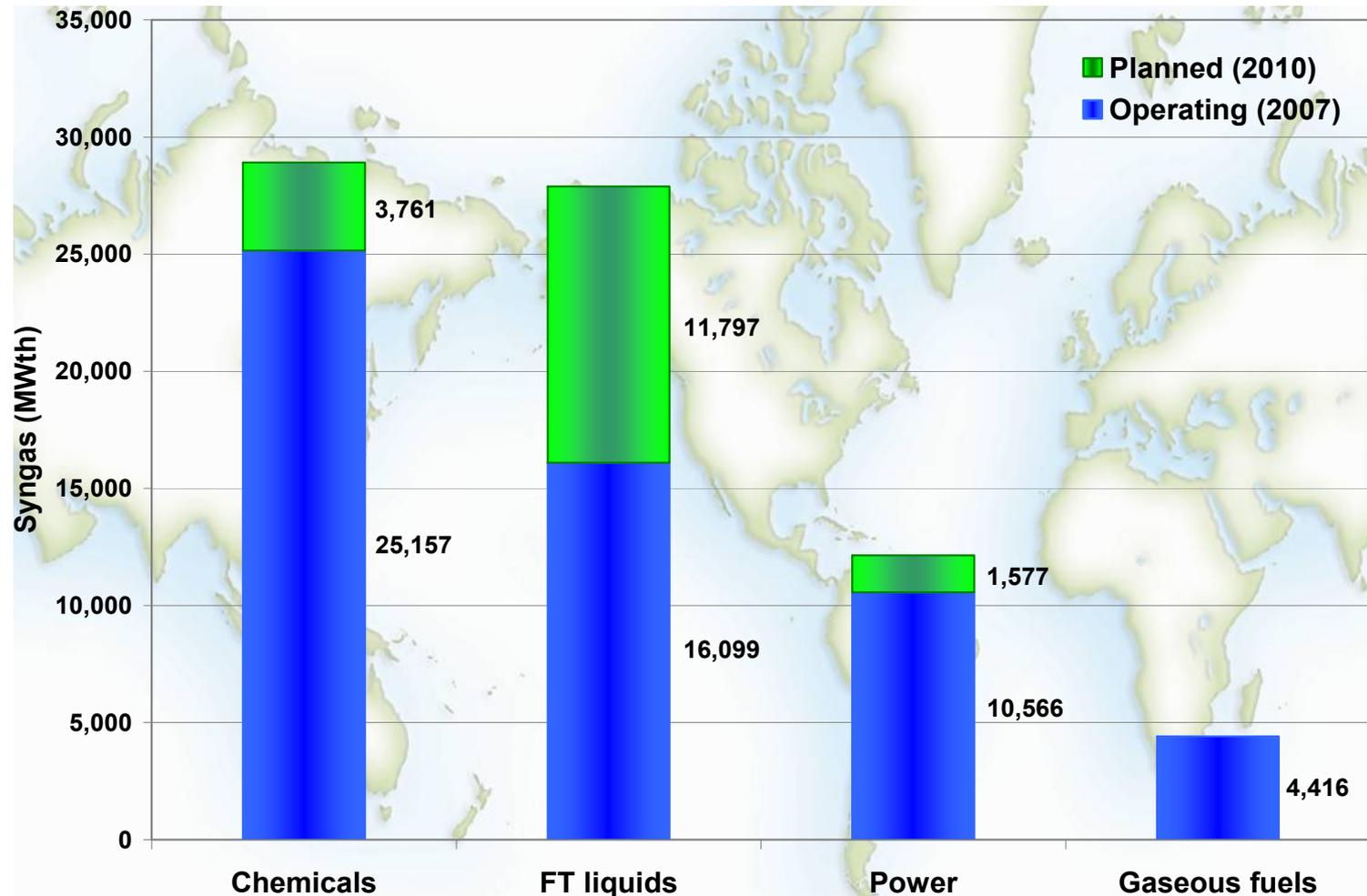
Cumulative by Year



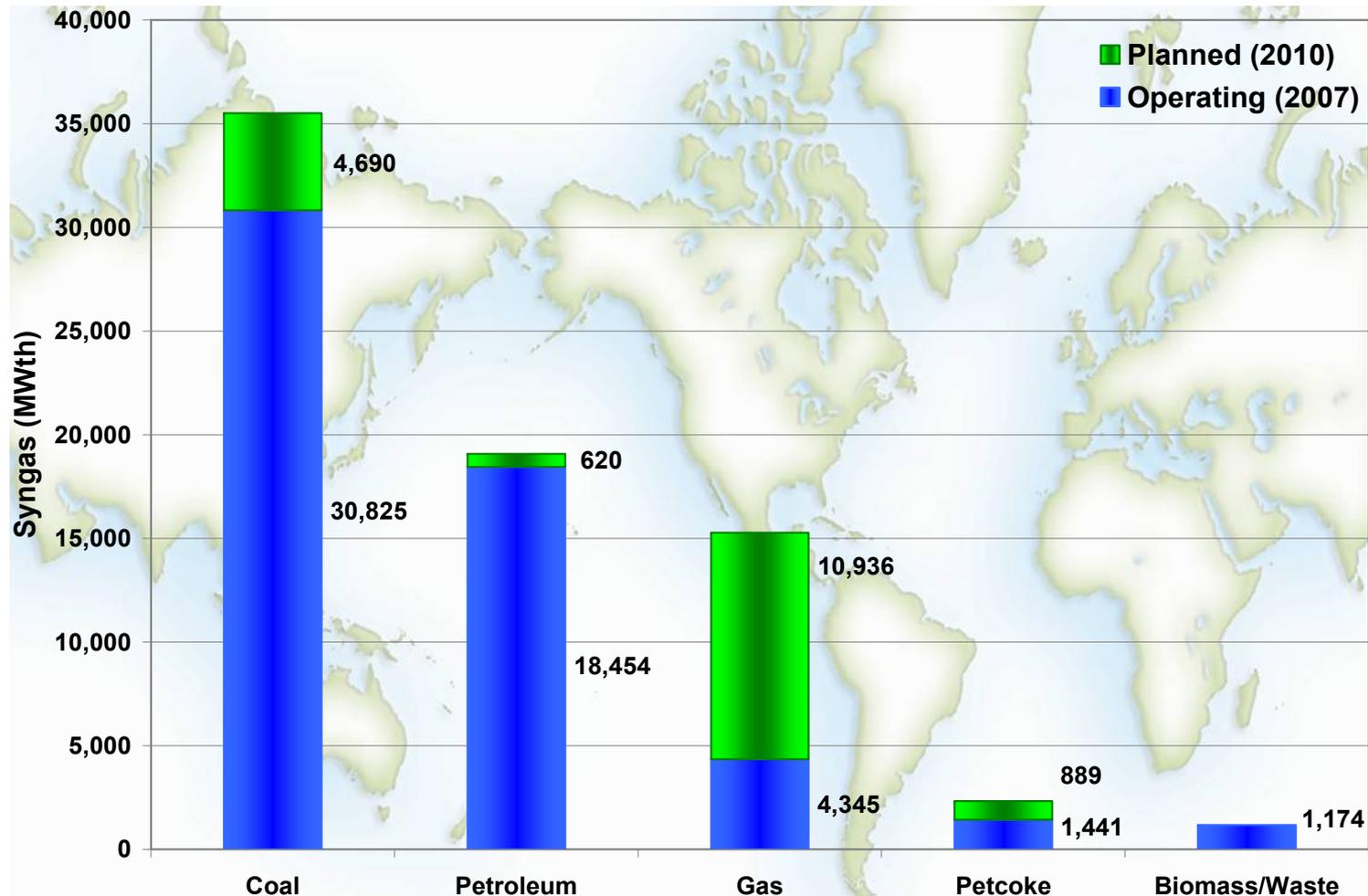
Worldwide Gasification Capacity and Planned Growth *by Technology*



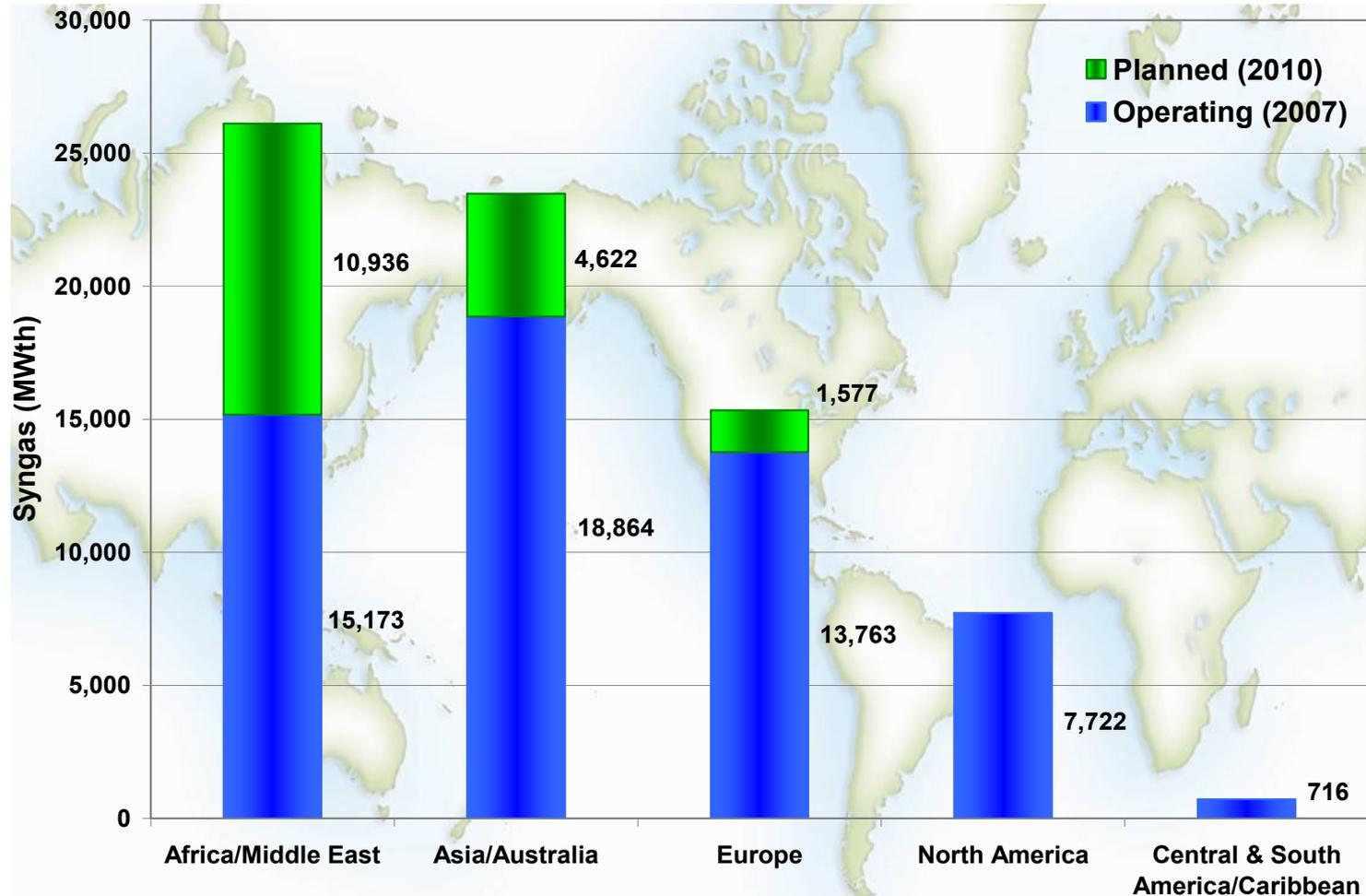
Worldwide Gasification Capacity and Planned Growth by Product



Worldwide Gasification Capacity and Planned Growth by Primary Feedstock



Worldwide Gasification Capacity and Planned Growth by Region



Survey Results

Operating Plant Statistics 2004 vs. 2007

2004

- Operating Plants **117**
- Gasifiers **385**
- Capacity **~45,000 MWth**
- Feeds
 - Coal **49%**
 - Petcoke **36%**
- Products
 - Chemicals **37%**
 - F-T **36%**
 - Power **19%**

2007

- Operating Plants **144**
- Gasifiers **427**
- Capacity **~56,000 MWth**
- Feeds
 - Coal **55%**
 - Petcoke **33%**
- Products
 - Chemicals **45%**
 - F-T **28%**
 - Power **19%**

Cool Water IGCC Demonstration Project

Daggett, California

- **First U.S. IGCC demonstration**
- **Operating period 1984-1989**
- **GE Technology**
(formerly Texaco, ChevronTexaco)
- **Product gas fueled GE 7E combined cycle**
- **1,150 tons/day southern Utah (SUFCO) coal; 100 MWe Net**
- **Co-funded by Texaco, GE, EPRI & Southern California Edison**
- **Considerable information provided for development of full-scale plant**
- **Basis for Tampa Electric Polk Power Station**

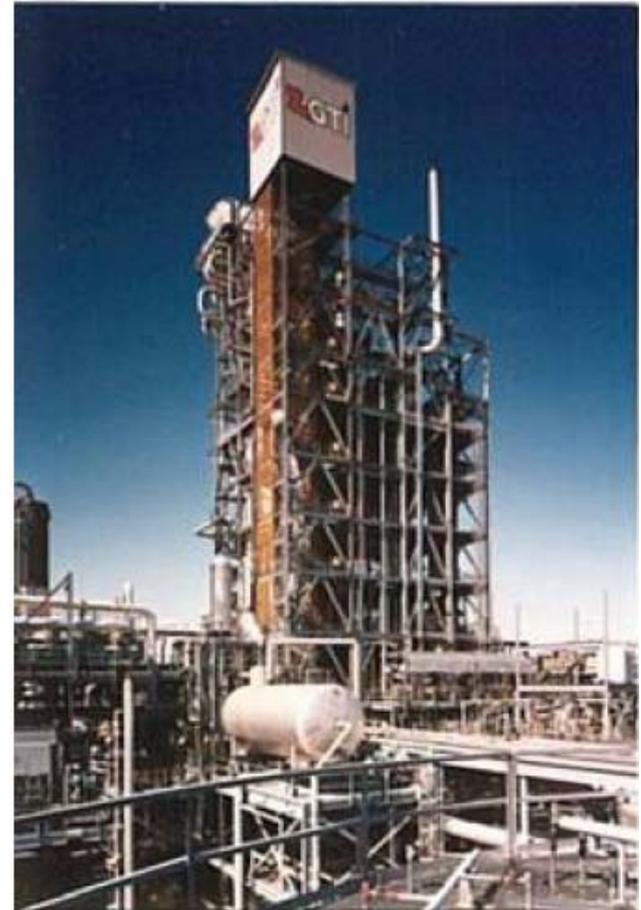


Southern California Edison Site

Louisiana Gasification Technology Inc (LGTI) Project

Dow Chemical Plant — Plaquemine, Louisiana

- **Operating Period 1987-1993**
- **E-Gas Technology (formerly Dow, Dynergy)**
- **2,400 TPD Powder River Basin (PRB) Coal; 160 MWe**
- **Product gas fueled two Westinghouse modified W501D5 gas turbines**
 - 80% syngas
 - 20% natural gas
- **85,000 hours on syngas**
- **160 MWe Net**



Wabash River Generating Station

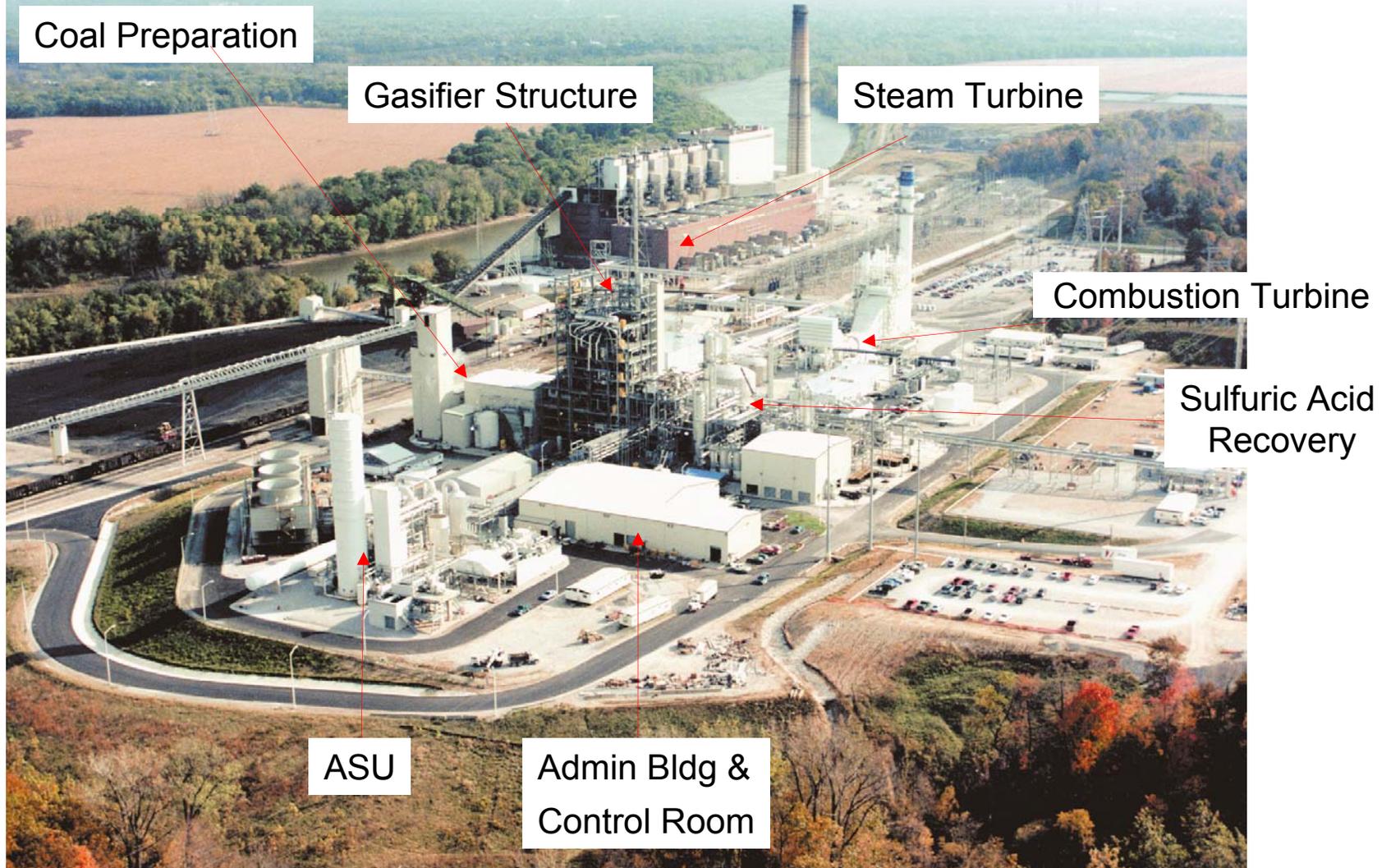
SG Solutions – West Terre Haute, Indiana

- **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

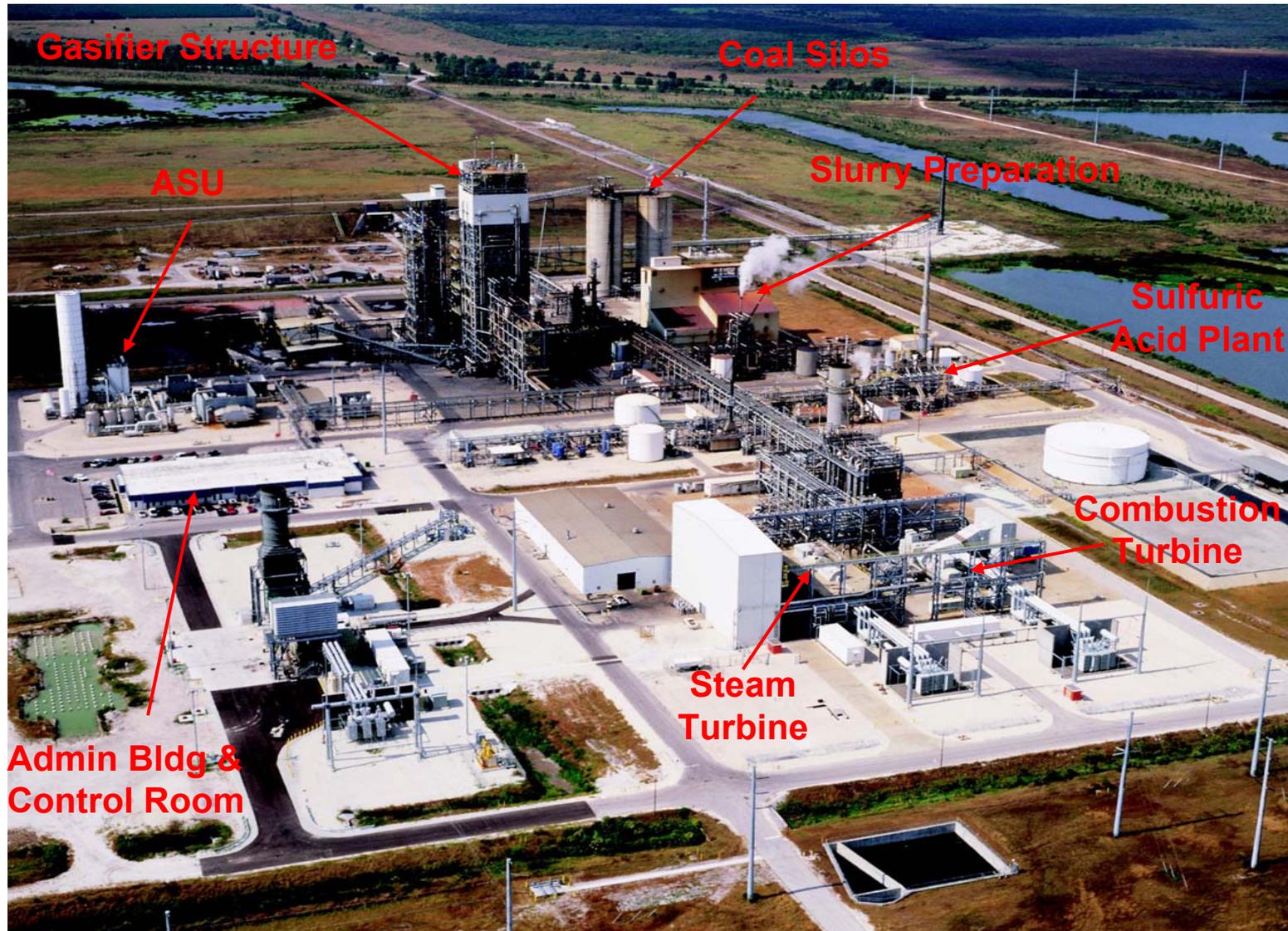
- **GE Gasifier**
 - oxygen blown
 - slurry fed
 - entrained flow
- **Vessel refractory lined**
 - largest built
- **Feedstock 2,200 tons/day**
 - coal and petcoke blend
- **CT is GE 7F**
- **Single train configuration**
 - one gasifier supplying one CT
- **Acid gas removal via**
 - MDEA and COS hydrolysis
- **DOE Clean Coal Technology Program**
 - Plant startup July 1996



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

NATIONAL ENERGY TECHNOLOGY LABORATORY

Polk Power Station Aerial Photo



ELCOGAS

Puertollano, Spain

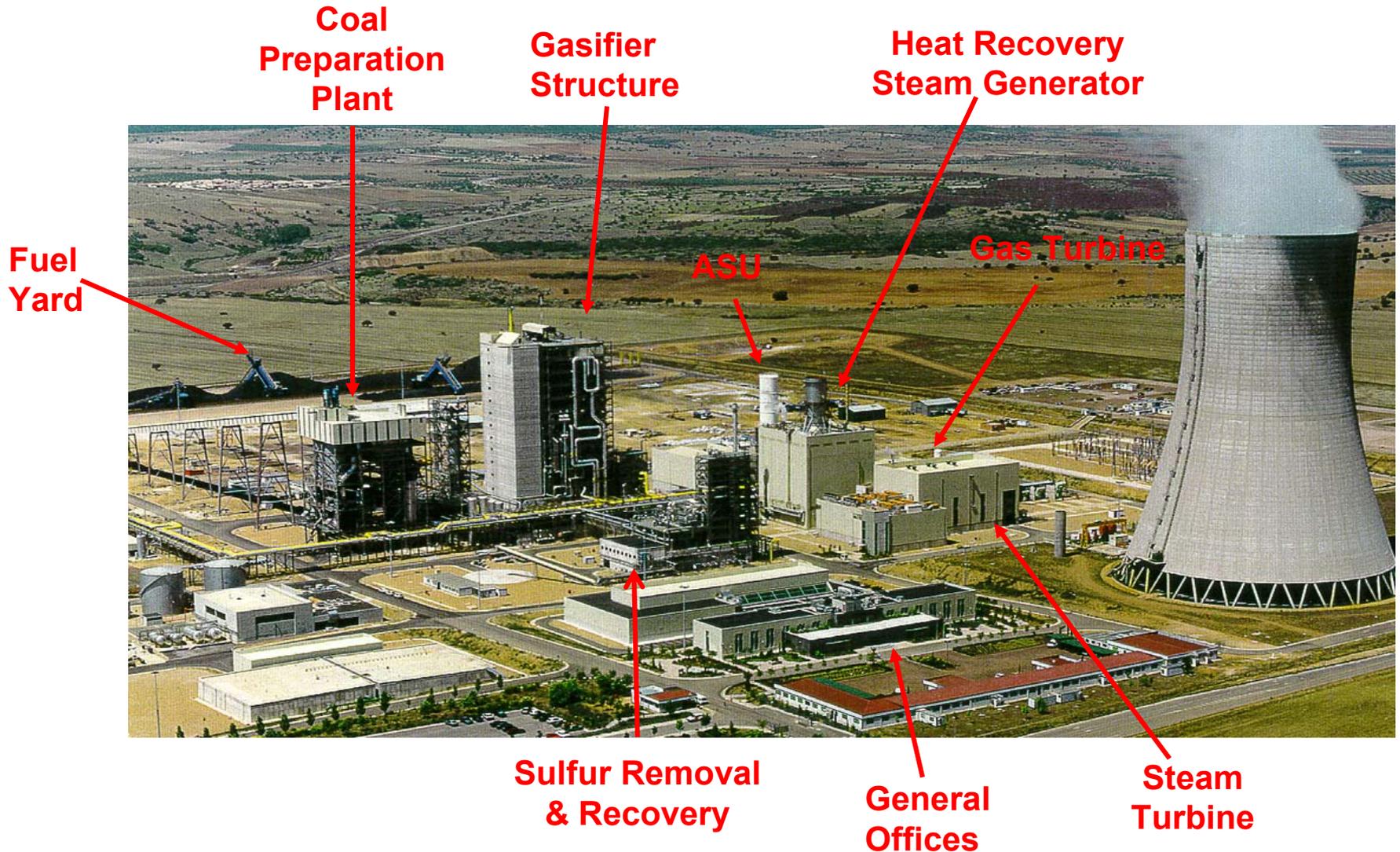
- **PRENFLO gasifier**
 - Pressurized entrained flow gasifier now offered by Uhde
- **Oxygen blown**
- **2,600 tons/day coal and petcoke**
- **Commercial operation began in 1996 w/ natural gas**
- **In 1998 began operating on 50/50 Petroleum coke / local Spanish coal (~ 40% ash)**
- **Siemens V94.3 gas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



IGCC Plant Puertollano, Spain

Power generation	<u>ISO</u>	<u>at site</u>
– Combustion turbine:	200 MW	182.3 MWe
– Steam turbine:		135.4 MWe
– Internal load:	_____	- <u>35.0 MWe</u>
– Net output:	300 MW	282.7 MWe

ELCOGAS Plant Aerial Photo



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**
- ***Only large-scale biomass installation in operation today***



Buggenum IGCC Plant

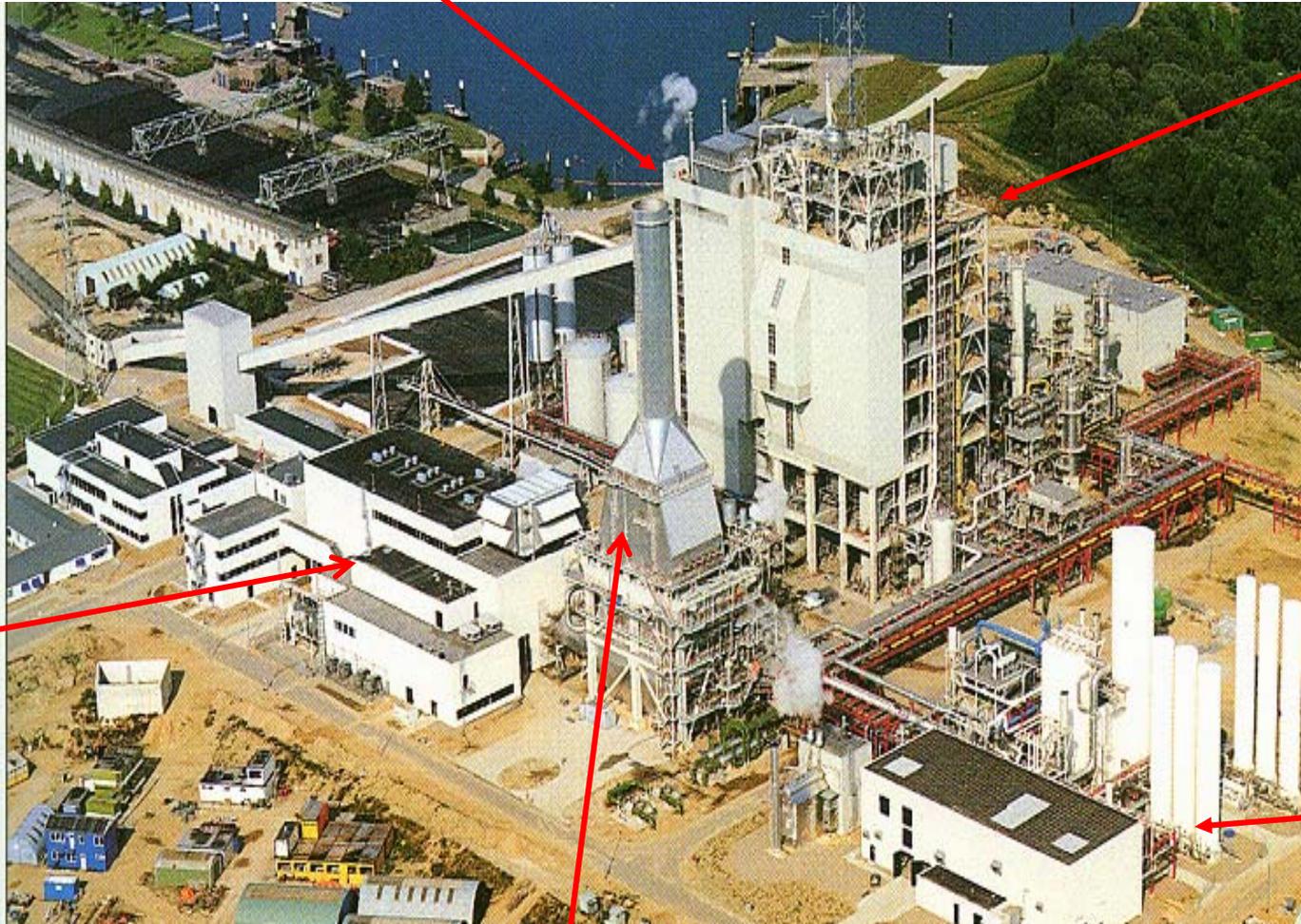
- **Power generation**
 - Combustion turbine: 155 MWe
 - Steam turbine: 128 MWe
 - Internal load: - 30 MWe
 - **Net output: 253 MWe**

Nuon Plant Aerial Photo

Coal Preparation Plant

Gasifier Structure

Gas & Steam Turbine



ASU

Heat Recovery
Steam Generator

Note: Sulfur Removal & Recovery (out of view)

Valero Refinery

Delaware City, Delaware

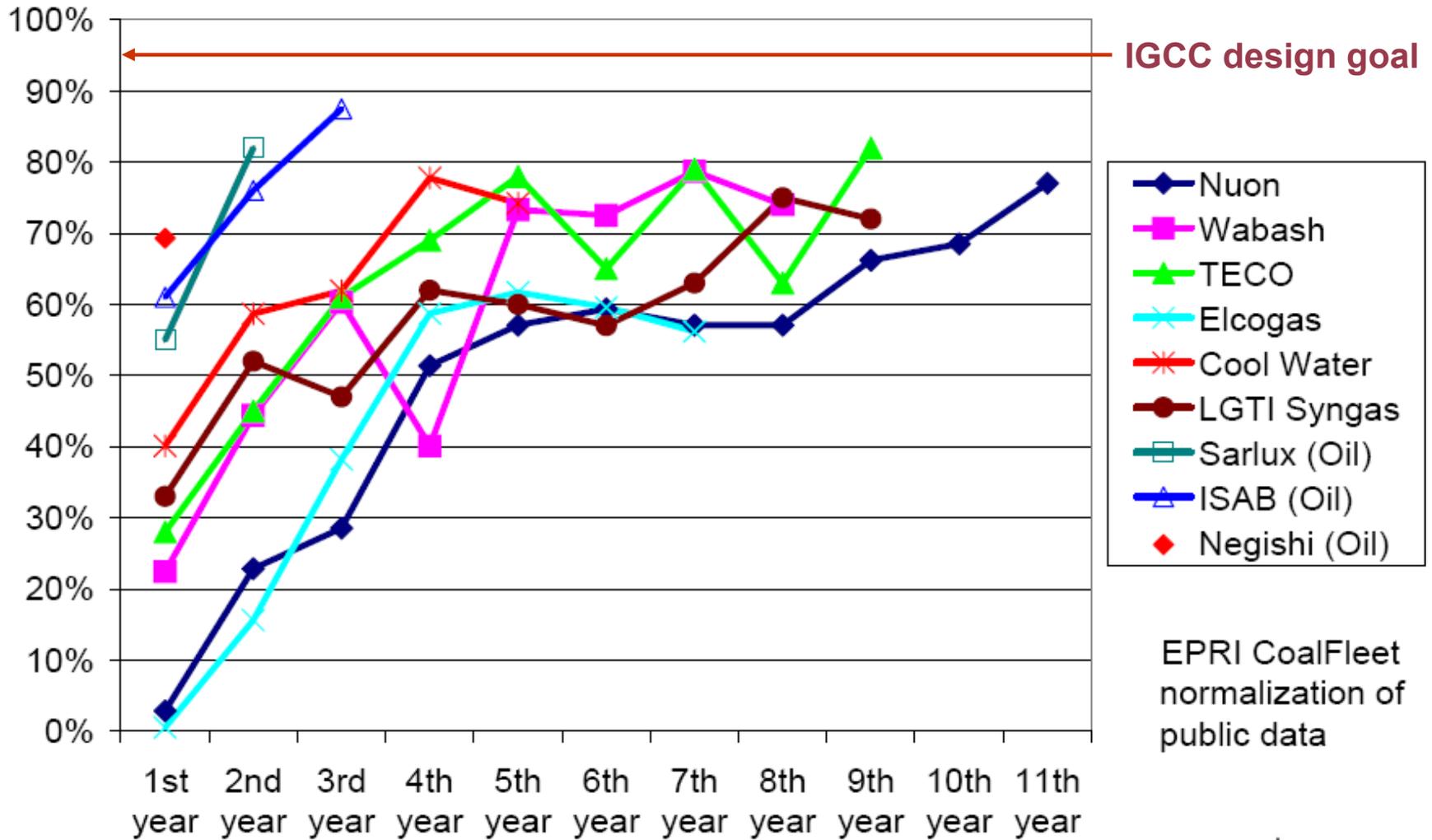
- **2 GE gasifiers**
 - formerly Texaco
- **Oxygen blown**
- **2 Combustion turbines**
 - GE 6FA
- **2,100 tons/day feedstock**
 - petcoke
- **Plant startup July 2002**
- **Power generation**
 - Combustion turbines: 180 MWe
 - Steam turbine: 60 MWe
 - Net output: **240 MWe**



Gasification Facility at Delaware City Refinery

IGCC Availability History

excludes operation on back-up fuel

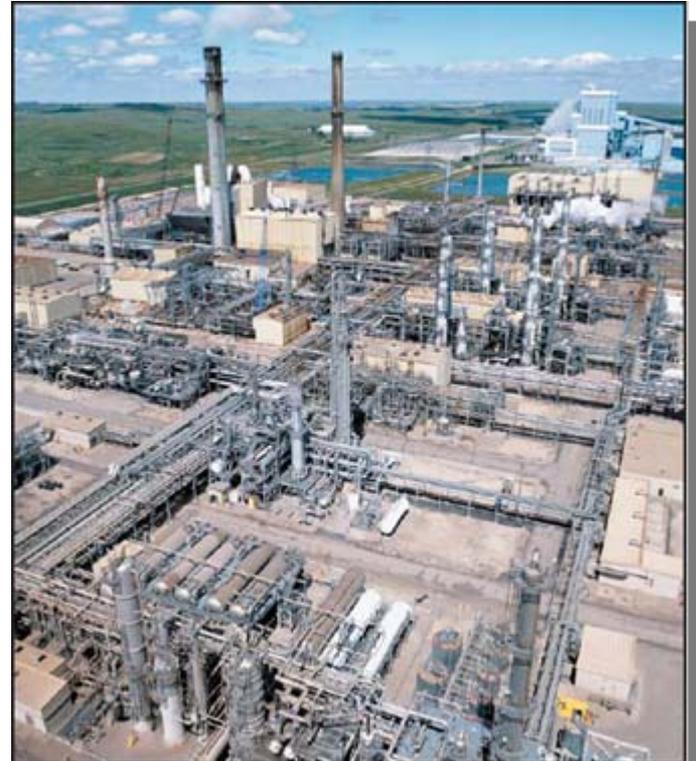


EPRI CoalFleet
normalization of
public data

Dakota Gasification Company - SNG

Beulah, North Dakota

- Part of Basin Electric Power Cooperative
- Plant startup 1984
- Coal consumption exceeds 6 million tons/year
- Produces more than 54 billion standard cubic feet of SNG per year
 - also produces fertilizers, solvents, phenol, carbon dioxide, and other chemical
- 200 mmscfd CO₂ capacity
- EnCana injecting 7,000 tonnes/day
 - increasing oil production by 18,000 barrels/day
- Apache injecting 1,800 tonnes/day



Great Plains Synfuels Plant

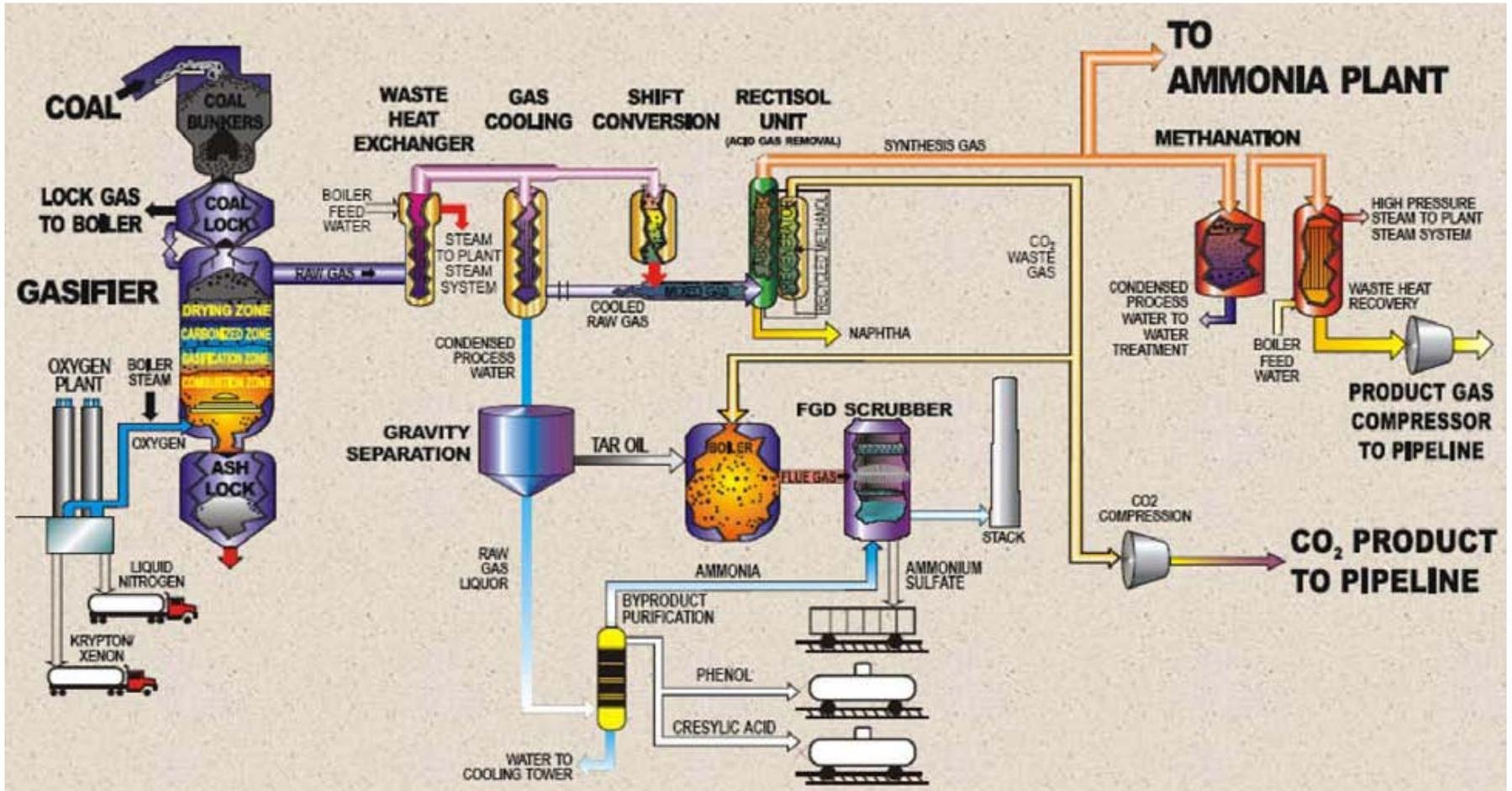
CO₂ is captured, pressurized, and piped 205 miles to Saskatchewan and sold for use in enhanced oil recovery (EOR) by EnCana and Apache Canada

Great Plains Synfuels Plant

Aerial Photo



Dakota Gasification Process Schematic



Eastman Chemical Company

Kingsport, Tennessee

- **“Coal-to-Chemicals” Facility**
- **Plant startup 1983**
- **Texaco gasifiers**
- **Gasifies 1,200 tons/day Central Appalachian medium sulfur coal**
- **Sulfur compounds and ash are removed from the syngas**
- **Syngas is used to make methanol, acetic acid, acetic anhydride, methyl acetate...**



Courtesy: Eastman Chemical Co.

Eastman Chemical Company

Kingsport, Tennessee



**Gasification
Area**

SASOL I

Sasolburg, South Africa

- **Plant startup in 1955**

- 17 Sasol-Lurgi Fixed Bed Dry Bottom (FBDB) gasifiers
- 100% Sub-bituminous coal feedstock
- Fisher-Tropsch process for Liquid Chemicals production

- **Supplies syngas to**

- Sasol Wax to produce
 - Fischer-Tropsch hard waxes
- Sasol Solvents to produce
 - methanol and butanol
- Sasol Nitro to produce
 - ammonia



- ***2004 plant converted from coal gasification to natural gas reforming***

- *Gasifiers decommissioned 2005*
- *Replaced with 2 natural gas autothermal reformers*

SASOL II & III

Secunda, South Africa



- Plant startup in 1974
- **80** Sasol-Lurgi Fixed Bed Dry Bottom (FBDB) gasifiers
- 155,000 bl/d production levels achieved in 2004
- Sub-bituminous coal feedstock, supplemented with natural gas
- Fisher-Tropsch process for Liquid Fuels & Chemicals production

Coffeyville Resources Nitrogen Fertilizers

Coffeyville, Kansas

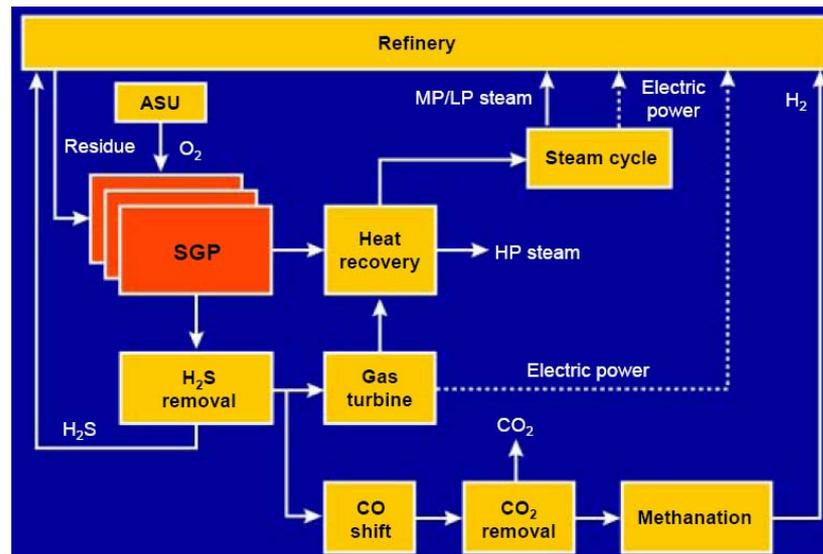
- Plant converted from natural gas to petcoke to reduce costs by adding GE Energy gasifier
- Produces syngas with CO and H₂
- Syngas shifted to CO₂ and H₂
- CO₂ removed, leaving concentrated H₂ stream
- H₂ used to make ammonia for fertilizer
- 326,663 short tons ammonia in 2007



Technology suitable for Carbon Capture

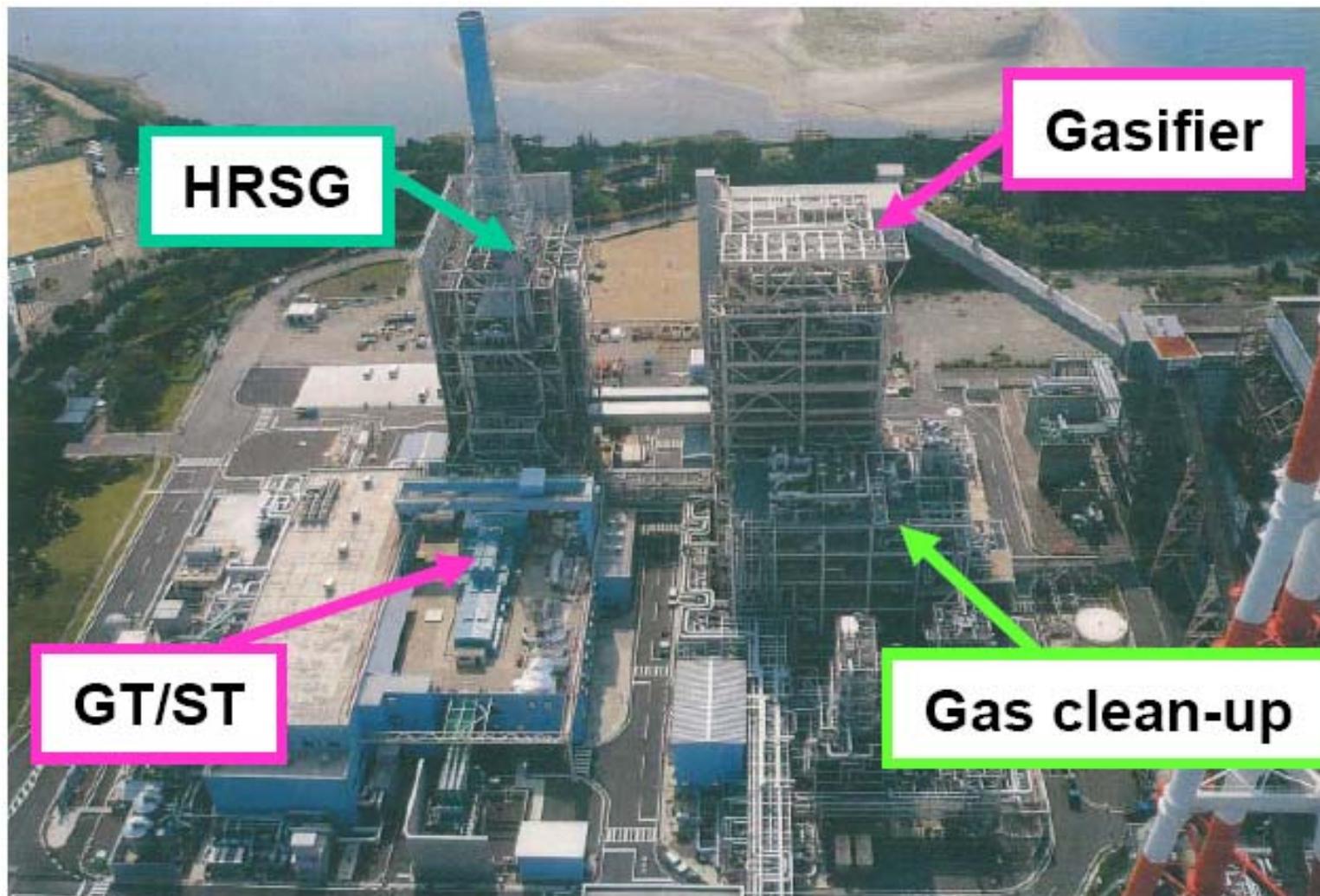
Pernis Refinery IGCC/Hydrogen Project

- Major \$2.2 billion refinery renovation
- Completed May 1997
- Gasifies 1,656 mt/d visbreaker residue
- Produces 118 MMscf/d H₂
- 3 Shell Gasifiers
- Rectisol process for gas cleanup
- 2 General Electric 6B turbines



Clean Coal Power R&D IGCC Demonstration Plant

Aerial Photo



WMPI Coal-to-Clean Fuels & Power Project

Gilberton, PA

- Shell oxygen-blown, entrained flow gasifier
- 4,700 tons/day waste coal
- 5,000 barrels/day ultra-clean transportation fuels
- 41 MWe electricity
- Operational - 2010
- Total project cost:
 - \$612 million (\$100 million DOE)
- Located:
 - Gilberton, Schuylkill County, PA

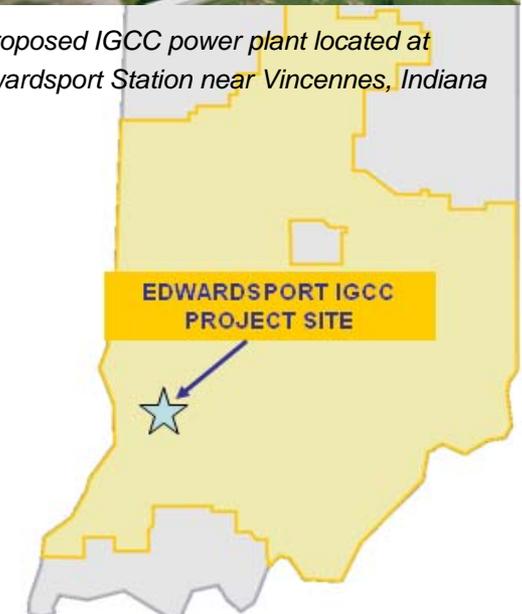


Edwardsport IGCC Project

- **GE Gasifier**
- **630 MWe**
- **1.5 million tons of coal per year**
- **Operational - 2012**
- **Total project cost:**
 - **\$2.35 billion**
 - **\$133.5 million Federal investment tax credit award**
 - **\$460 million in local, state and federal tax incentives**
- **Located:**
 - **Knox County, Indiana**



Rendering of the proposed IGCC power plant located at Duke Energy's Edwardsport Station near Vincennes, Indiana



Environmental Benefits



Air Permitting

IGCC and Gasification Plants

- **Emission controls for IGCC and gasification**
- **Applicable regulations for IGCC**
- **Comparing IGCC with PC and NGCC**
- **New Source Performance Standards**
- **IGCC emission rate comparison**
- **Startup and shutdown emissions**

IGCC New Source Performance Standards (NSPS)

<i>Emission</i>	<i>NSPS</i>	<i>NSPS on Gasifier Input Basis (calculated)</i>
NO_x	1.0 lb/MWh*	0.143 lb/MMBtu
SO₂	1.4 lb/MWh* and minimum 95% removal	0.2 lb/MMBtu
Particulate Matter	Lesser of 0.14 lb/MWh* or 0.015 lb/MMBtu**	0.011 lb/MMBtu
Mercury (bituminous coal)	20 x 10⁻⁶ lb/MWh*	2.87 lb/TBtu

* Output-based standards are on a gross generation basis

** Gas turbine heat input basis, filterable PM only

Emission Rate Units

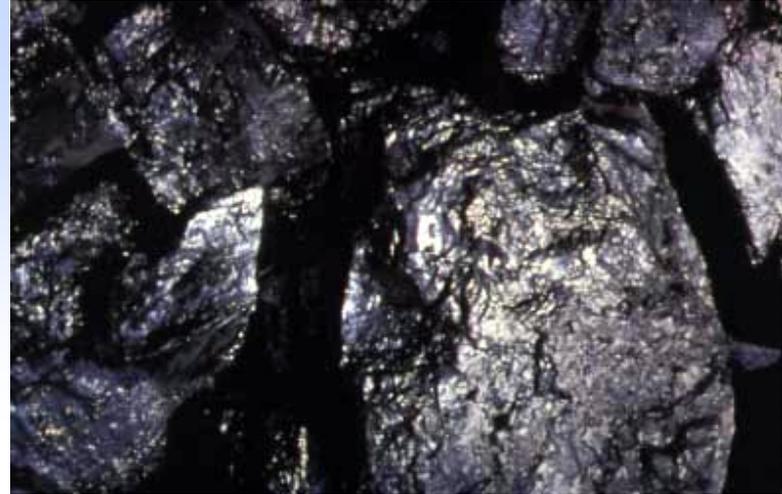
- **IGCC permits list emission rates as lb/MMBtu of:**
 - Gasifier (coal) heat input, or
 - Gas turbine heat input basis
- **EPA's comments on the new NSPS addressed this:**

“The heat input for an IGCC facility is the heat content of the syngas burned in the stationary combustion turbine and not the heat content of the coal fed to the gasification facility. The gasification facility is not part of the affected source under subpart Da, only the stationary combustion turbine are covered.”
- **Emission rates are to be expressed on basis of:**
 - Syngas input to the gas turbine
- **Permit applications or permits can list “equivalents”**
 - on gasifier input basis, and
 - lb/hr and ppm

Important to specify heat input basis in permit application

Potential Feedstocks

- IGCC isn't necessarily "coal" gasification, other feedstocks could include:
 - Petroleum coke
 - Biomass
 - Blends of the above

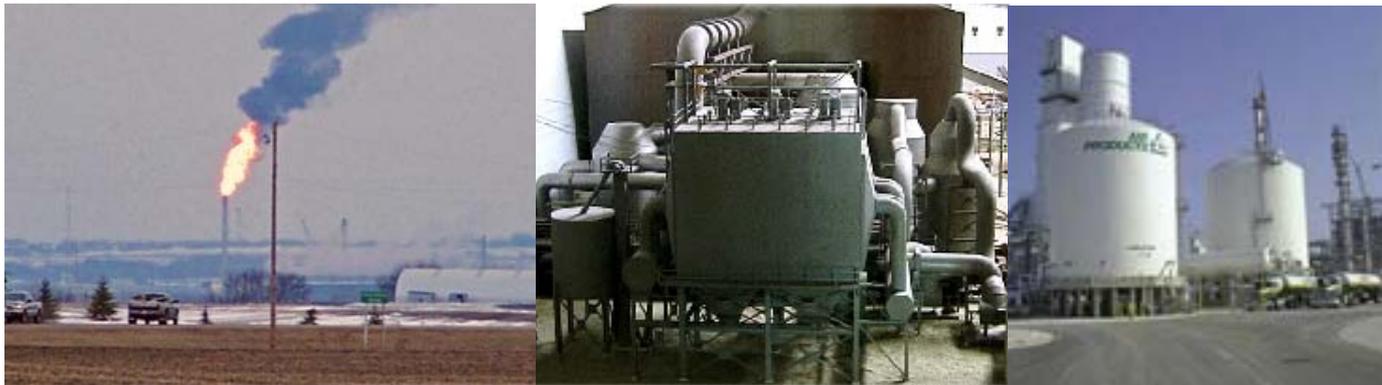


All Potential Feedstocks Should Be Included in Permit Application



Air Emissions

- **Unique emission points depend on technology provider, may include:**
 - Flare
 - Sulfur recovery unit tail gas incinerator
 - Sulfuric acid plant stack
 - Tank vent incinerators
 - Air separation unit cooling tower



Air Permitting

- **For air permit application:**
 - Preliminary engineering required to provide sufficient information for permit application
 - Emission inventory has to be developed
 - Startup, shutdown and emergency emissions must be calculated for ambient air quality modeling
 - Emissions from flare must be determined
 - Raw syngas
 - Clean syngas
 - Duration
 - Number of flare events per year

What About SCR for IGCC?

- **Technical issues**

- The fuel is syngas, not natural gas as in NGCC
- Ammonium sulfate/bisulfate deposit in the HRSG, causing corrosion and plugging, requiring numerous washdowns
- No coal-based IGCC system in the world uses SCR

- **Economic Issues**

- No commercial guarantees yet with syngas
- Deep sulfur removal, i.e. Selexol, is required, with higher capital cost



Use of SCR on IGCC Plants

- SCR has been *proposed* on some units:
 - As BACT for NO_x
 - As an Innovative Control Technology to reduce emissions beyond diluent injection
 - As a trial/experiment, with emission limits only for natural gas use
 - To evaluate SCR with a syngas-fired combined cycle unit
 - To minimize NO_x emissions in order to reduce costs for NO_x allowances

Use of SCR on IGCC Plants cont.

- EPA addressed SCR in 2006 report
- Noted technical problems with using SCR on IGCC plant
 - Noted SCR issues with IGCC plants using liquid feedstocks
 - Evaluated SCR with Selexol for deep sulfur removal

Final Report

Environmental Footprints and Costs of Coal-Based Integrated Gasification Combined Cycle and Pulverized Coal Technologies



- **Concluded that:**
 - Even with Selexol, SCR problems are not solved
 - Additional cost and reduced output are negative impacts to IGCC
 - BACT will continue to be a case by case issue

Air Emission Rate Comparisons

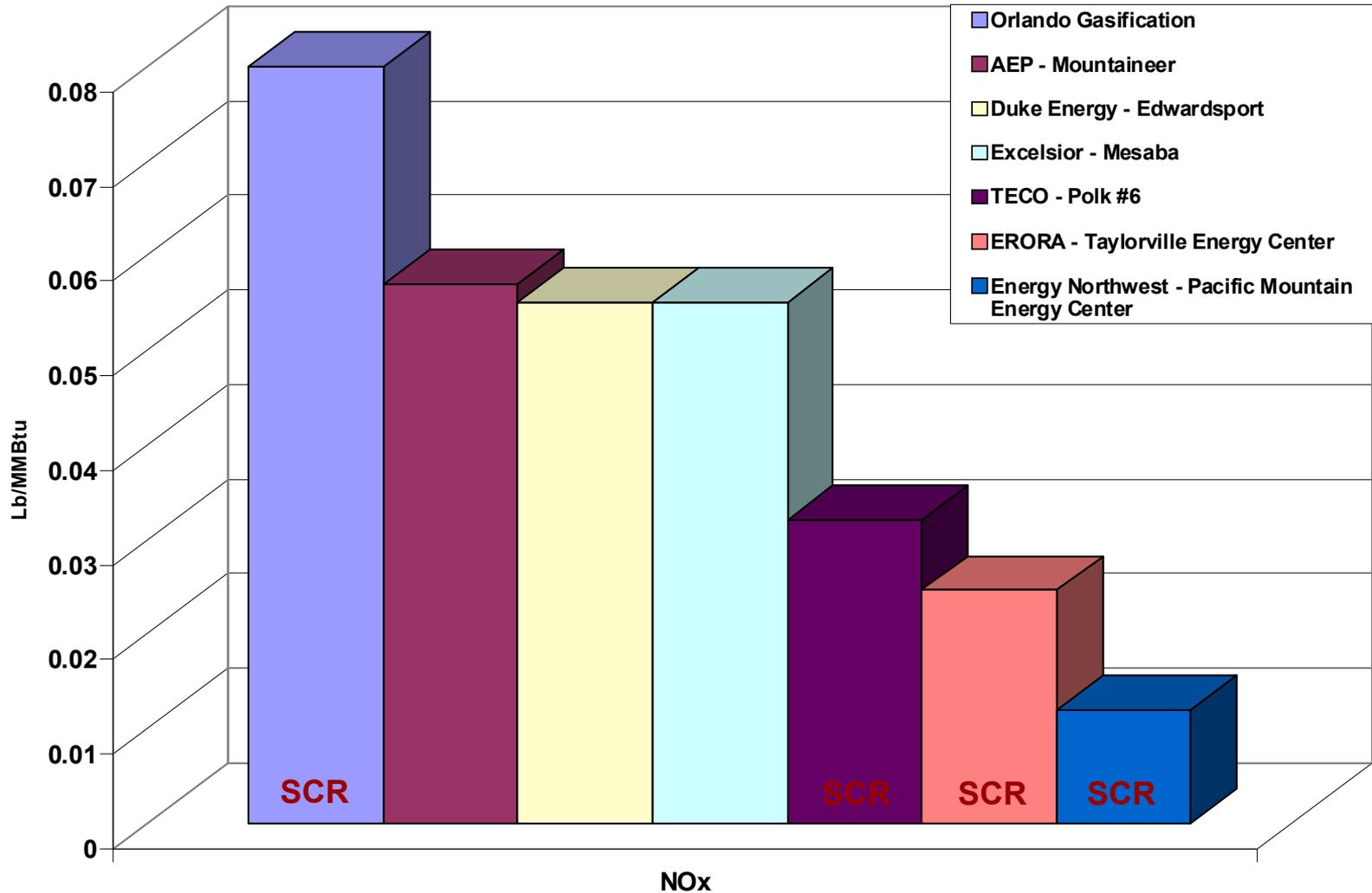
- **NO_x and SO_x data is from publicly available information:**
 - Permit applications
 - Draft permits
 - Final permits
 - Submittals to other agencies
- **Data provided on gasifier and gas turbine heat input basis**
 - Calculated when not provided in data sources

IGCC plants included in charts:

- **AEP Mountaineer**
 - Permit application
- **Duke Energy Indiana Edwardsport**
 - Permit application
- **Energy Northwest Pacific Mountain Energy Center**
 - Permit application
- **ERORA Taylorville Energy Center**
 - Final permit
- **Excelsior Energy Mesaba**
 - Permit application
- **Orlando Gasification**
 - Final permit
- **Tampa Electric Company Polk Unit #6**
 - Permit application

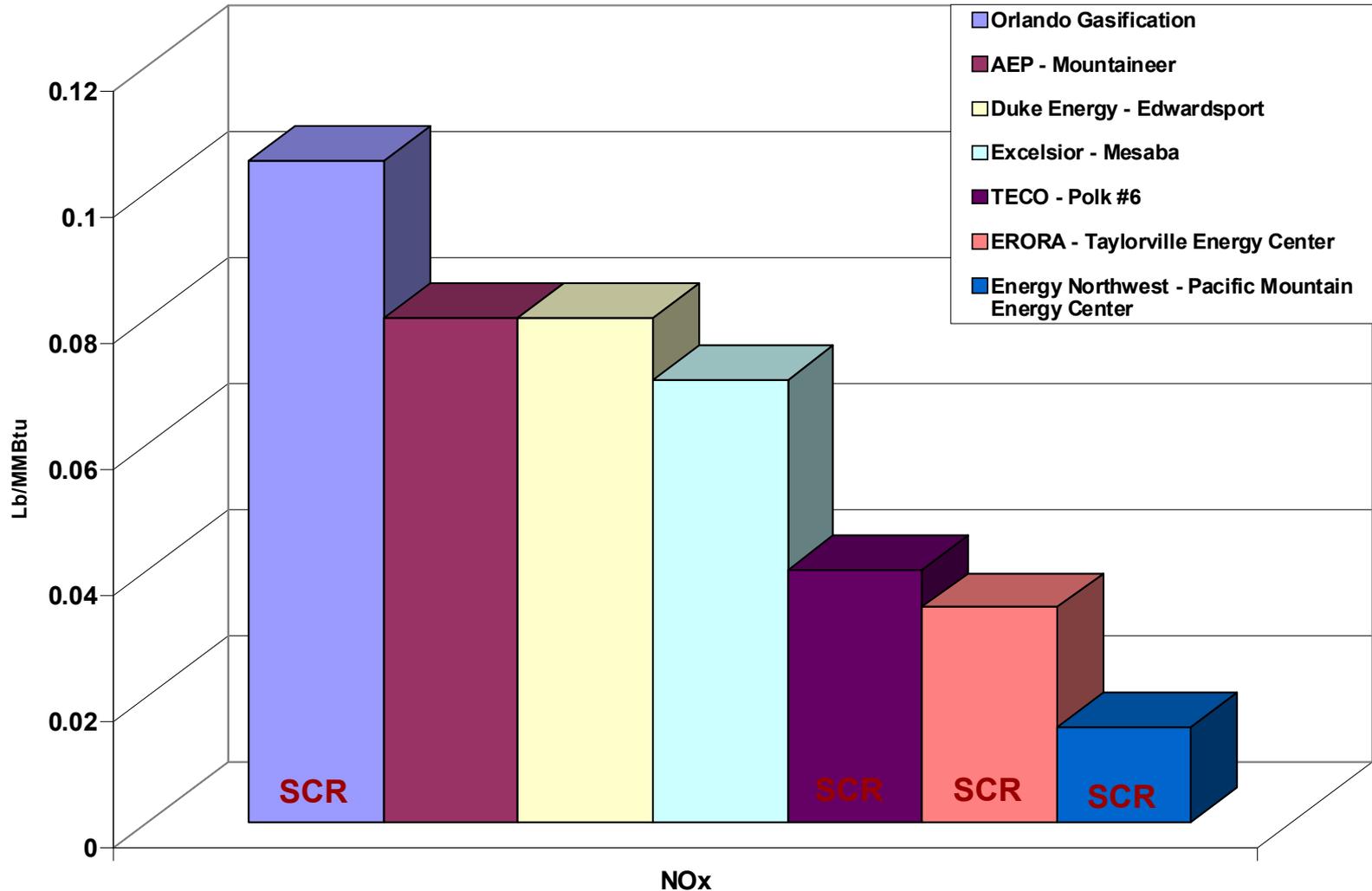
NOx Emission Rate Comparisons

Gasifier Heat Input Basis



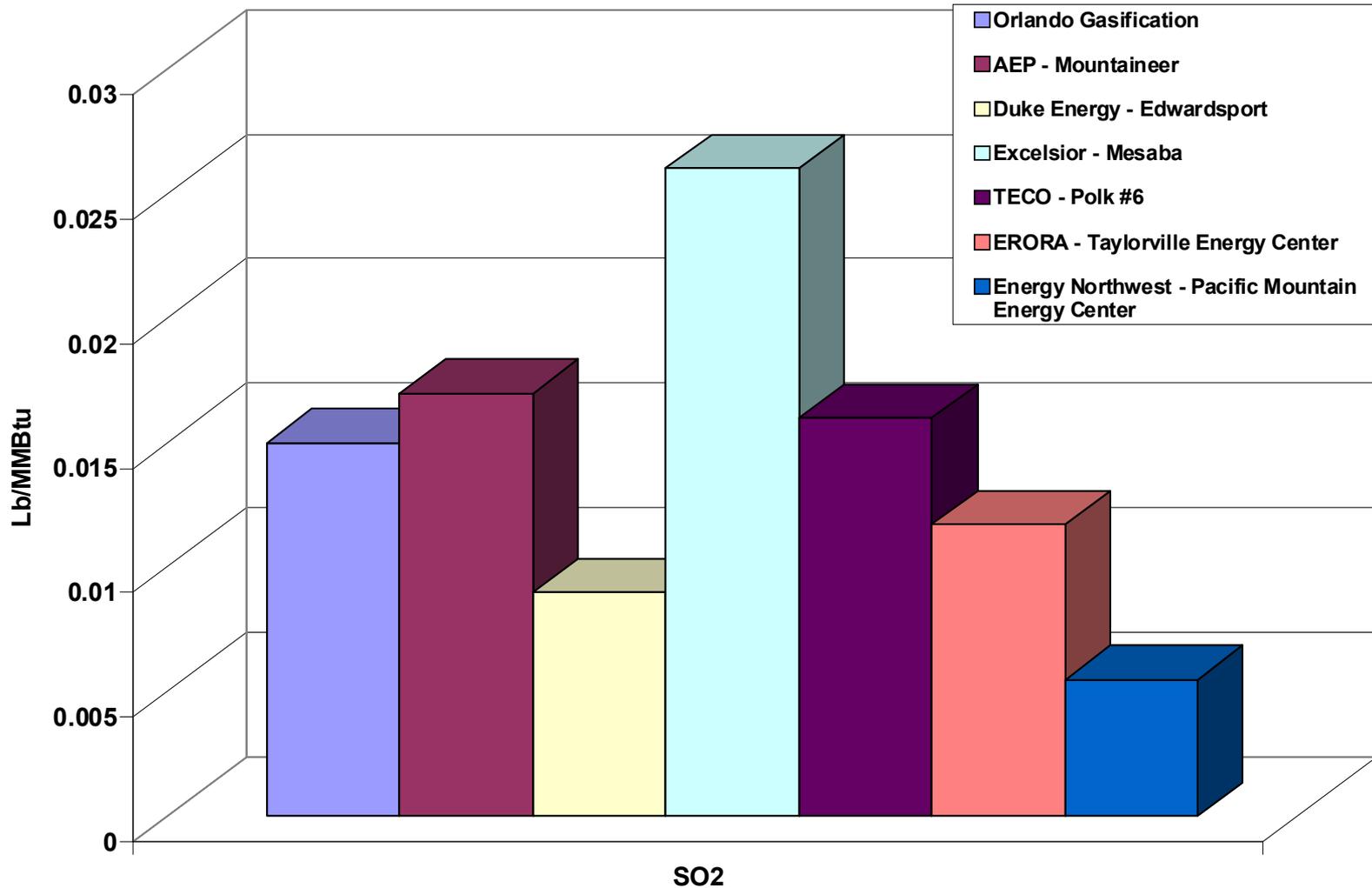
NOx Emission Rate Comparisons

Gas Turbine Heat Input Basis



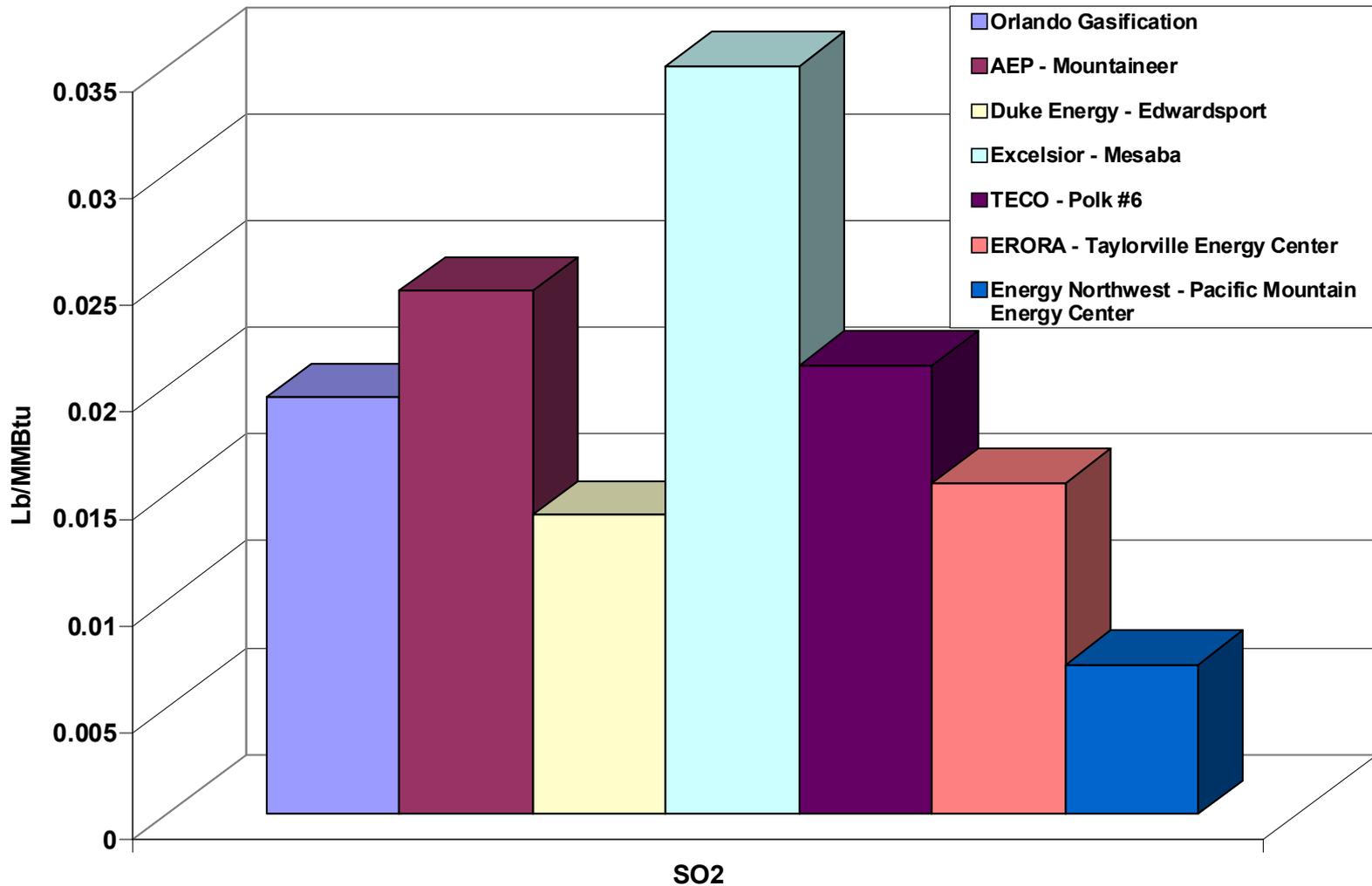
SO₂ Emission Rate Comparisons

Gasifier Heat Input Basis



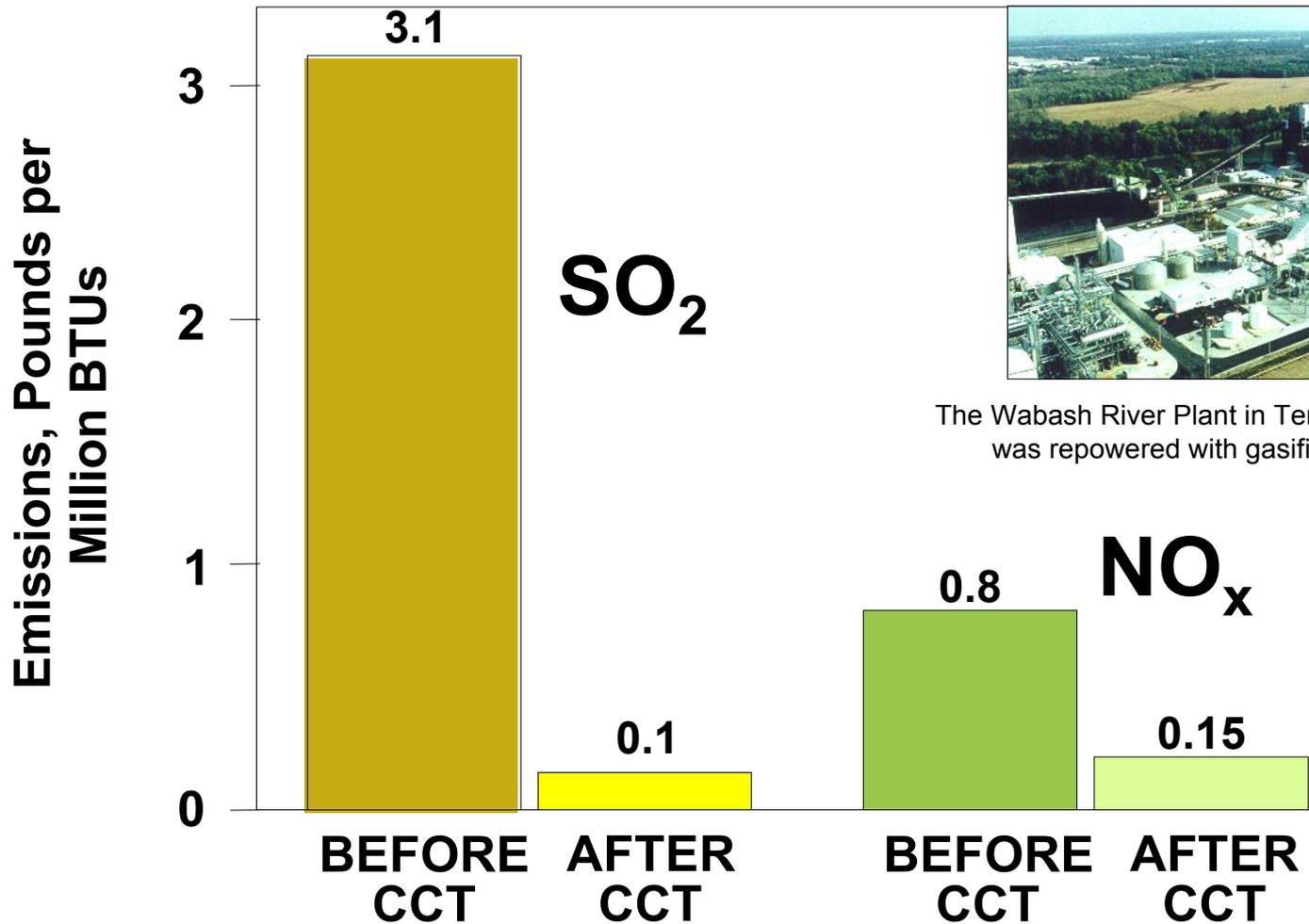
SO₂ Emission Rate Comparisons

Gas Turbine Heat Input Basis



Wabash River Clean Coal Project

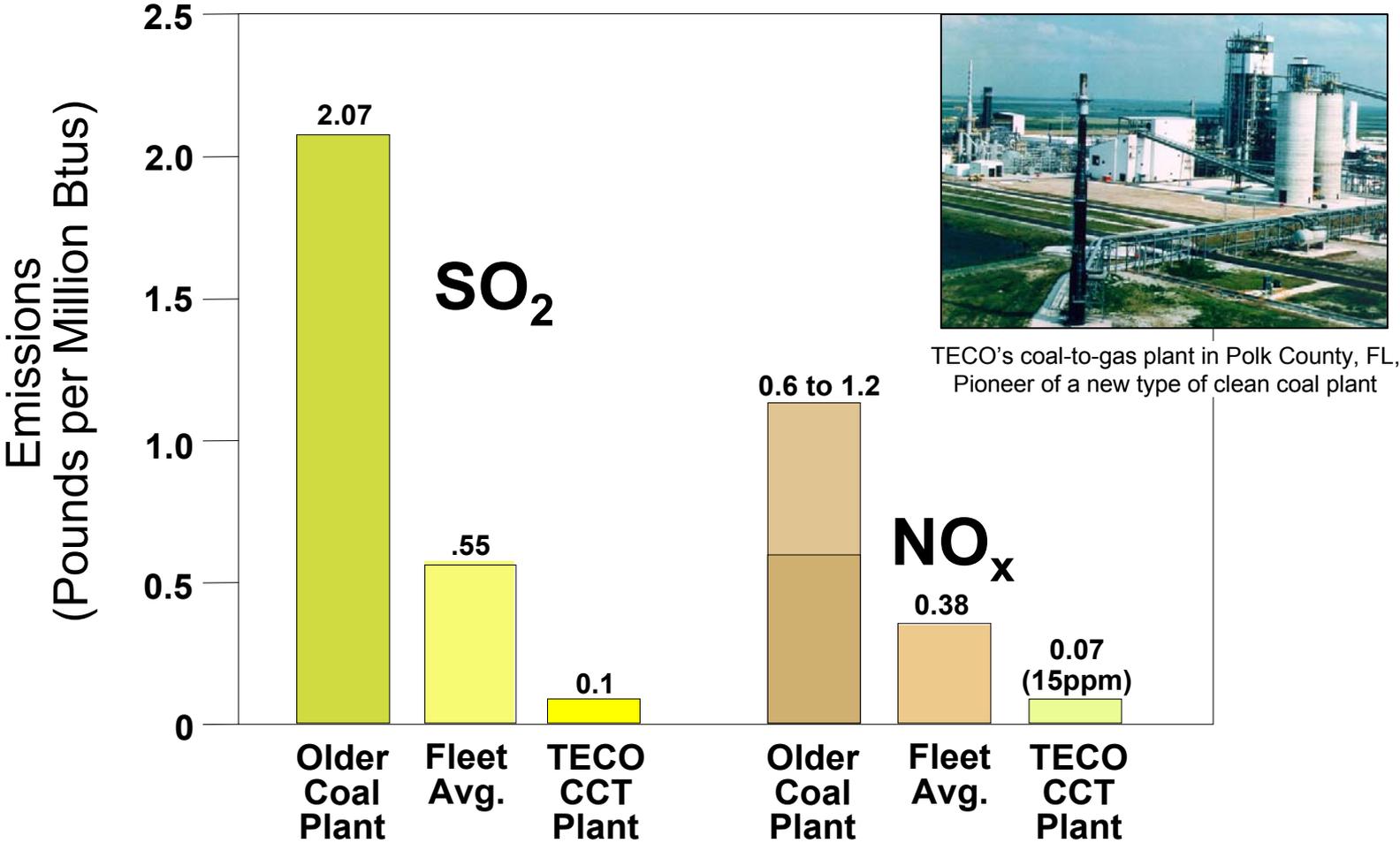
A Case Study for Cleaner Air



The Wabash River Plant in Terre Haute, Indiana, was repowered with gasification technology

Tampa Electric (TECO) Clean Coal Project

A Case Study for Cleaner Air



Proposed U.S. Gasification Plants - /GCC

<i>Project</i>	<i>State</i>	<i>Feedstock</i>	<i>MWe</i>	<i>MFG.</i>	<i>Capture</i>	<i>In Service</i>
Edwardsport IGCC Project	Indiana	coal	630	GE	STUDY	2012
Taylorville Energy Center	Illinois	coal	630	GE	NO	2014
Cash Creek Generation*	Kentucky	coal	720	GE	EOR	2012
Hydrogen Energy California project (HECA)**	California	petcoke	390	GE	2 MTY	2012
Mesaba	Minnesota	coal	600	E-Gas	READY	2011
Mississippi IGCC project	Mississippi	coal	600	KBR	READY	2013
WMPI Coal-to-Clean Fuels & Power Project***	Pennsylvania	waste coal	41	Shell	NO	
Great Lakes Energy and Research Park ***	Michigan	coal	250	E-Gas	4 MTY	2012
Hyperion Energy Center (HEC)**	South Dakota	petcoke			READY	2014
Genesee IGCC Project	Alberta	coal	270	Siemens	.25 MTY EOI	2011
Luminant IGCC Commercial Demonstration	Texas	coal	630		YES	
Luminant IGCC Commercial Demonstration	Texas	coal	630		YES	
<i>On Hold</i>						
AEP IGCC Project Mountaineer Plant	West Virginia	coal	630	GE	READY	2012
AEP IGCC Project Great Bend	Ohio	coal	630	GE	READY	2012
Lima Energy IGCC	Ohio	coal	540		NO	2012-2014
Southern Illinois Clean Energy Center	Illinois	coal	545	E-Gas		
Twin River Energy Center	Maine	coal	700			
"unnamed plant" Xcel Energy	Colorado	coal	300-350		YES	
Wallula Energy Resource Center	Washington	coal	700	MHI	65%	2013
Pacific Mountain Energy Center	Washington	petcoke	680		NO	
Lower Columbia Clean Energy Center	Oregon	coal	520		READY	
Dodds Roundhill Clean Coal Project	Canada	coal		Siemens	EOR	

*SNG project also

**H₂ project also

***CTL project also

Proposed U.S. Gasification Plants – CTL & Chemicals

<i>Project</i>	<i>State</i>	<i>Feed stock</i>	<i>Product</i>	<i>Capacity</i>	<i>Unts</i>	<i>MFG</i>	<i>Capture</i>	<i>In Service</i>
Great Lakes Energy and Research Park	Michigan	coal	transportation fuels	10,000	BPD	ConPh	YES	2012
Northern Appalachia Fuel LLC	West Virginia	coal	methanol	720,000	tonnes/y	U-GAS	YES	2012
Many Stars Coal-to-Liquids Plant	Montana	coal	liquid fuels	50,000	BPD		95% EOR	
Alter NRG	Alberta	coal	diesel fuel	40,000	BPD	WPC	85% EOR	2014
Clean Coal Power Operations	TBD (Kentucky)	coal	liquid fuels	<200,000	BPD		YES	
WMPI Coal-to-Clean Fuels & Power Project	Pennsylvania	waste coal	transportation fuels	5,000	BPD	Shell	NO	
Illinois Clean Fuels project	Illinois	coal	transportation fuels	400	Mgal/Y		YES	2012
Rentech Strategic Fuels Center	Mississippi	coal	transportation fuels	28,000	BPD		EOR	2011
Medicine Bow Fuel & Power LLC	Wyoming	coal	MTG	20,000	BPD	GE	EOR	2013
Malmstrom AFB CTL project	Montana	coal	jet fuels	25,000	BPD		EOR	
American Lignite Energy	North Dakota	coal	transportation fuels	32,000	BPD			
Power County Advanced Energy Center	Idaho	coal	fertilizer	3,100	TPD	E-Gas	EOR	2012
Ohio River Clean Fuels, LLC	Ohio	coal	jet fuels	53,000	BPD	Shell	85%	
Kentucky CTL project	Kentucky	coal	transportation fuels	30,000	BPD			2010
Beaumont Gasification Project	Texas	petcoke	chemicals	70	Mgal/Y	GE	EOR	2011
Faustina Hydrogen Products LLC	Louisiana	petcoke	chemicals	4,600	TPD		EOR	2010
CTL Diesel Fuel Production Plant (FFI)	Kentucky	coal	diesel fuel	72	Mgal/Y	WPC		2010
Rentech Product Demonstration Unit	Colorado	coal	diesel fuel	420	GPD			8/7/2008
Mingo Hybrid Energy Center LLC	West Virginia	forest residue noncompliant coal	liquid fuels	1,700	TPD			
Beluga Coal to Liquids Project	Alaska	coal	liquid fuels	80,000	BPD		EOR	
<i>On Hold</i>								
Rentech Energy Midwest Facility	Illinois	coal	transportation fuels					
Twin River Energy Center	Maine	coal	clean diesel fuel	9,000	BPD			

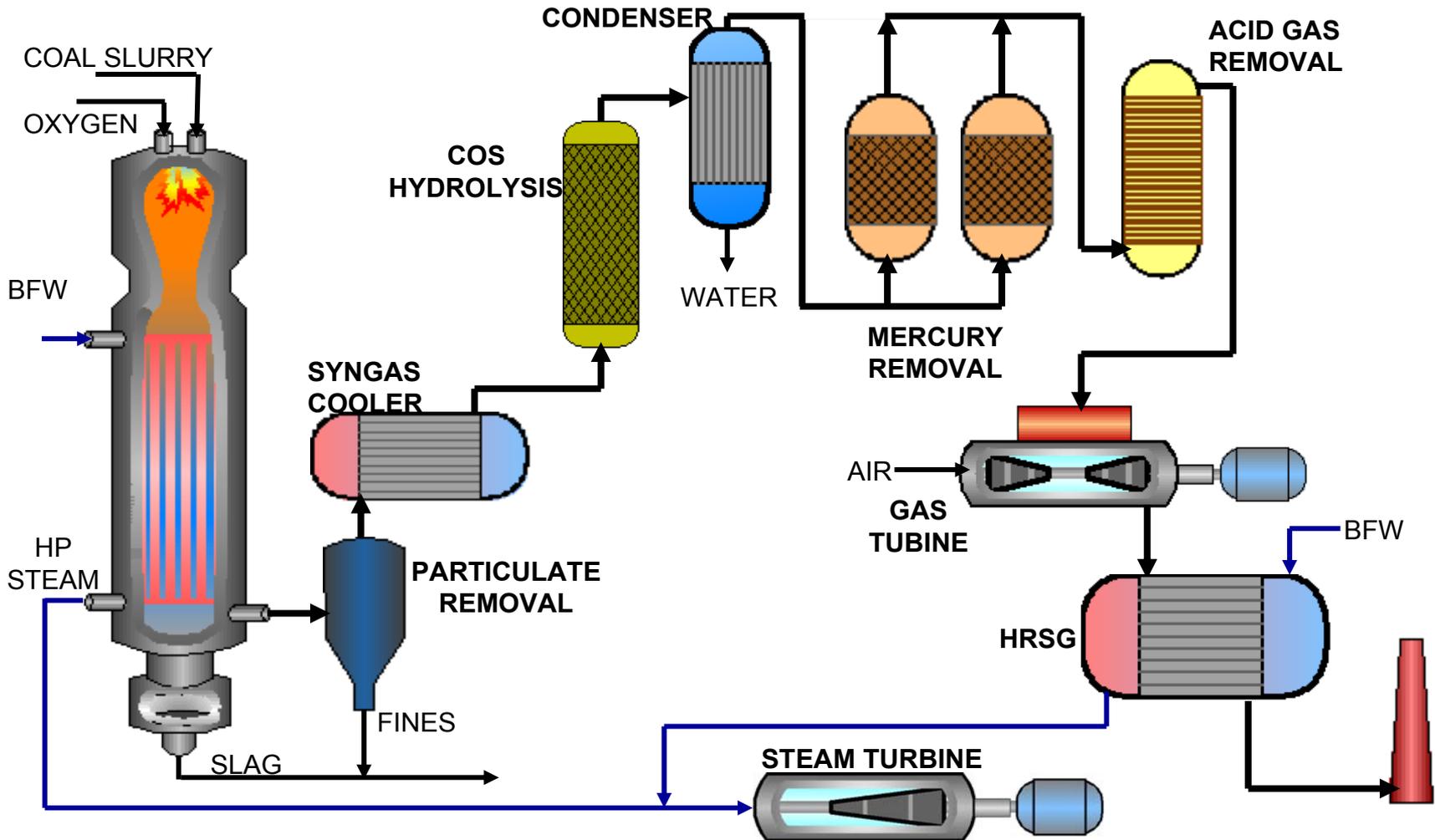
Proposed U.S. Gasification Plants - SNG

<i>Project</i>	<i>State</i>	<i>Feedstock</i>	<i>Capacity</i>	<i>Unts</i>	<i>MFG</i>	<i>Capture</i>	<i>In Service</i>
Kentucky Syngas	Kentucky	coal	50-70	BSCF/year	E-Gas	READY	
Hunton Energy Freeport Plant	Texas	petcoke	180	MMSCF/day		100%	2012
South Heart	North Dakota	coal	100	MMCF/day	BGL	YES	
Indiana SNG Project	Indiana	coal	40	BSCF/year			
Scriba Coal Gasification Plant	New York	coal	400,000	dekatherms			2010
Lake Charles Cogeneration	Louisiana	petcoke				EOR	2013
Cash Creek Generation*	Kentucky	coal			GE	EOR	2012
Lackawanna Clean Energy	New York	petcoke	85	MMSCF/day		EOR	2012
Pilot Gasification Project "Bluegas"	Massachusetts	coal, petcoke, biomass					2008
<i>On Hold</i>							
Southern Illinois Clean Energy Center	Illinois	coal	95.0	MNscfd	E-Gas		
Secure Energy Decatur Gasification	Illinois	coal	20	BSCF/year	Siemens		2009
Southern Illinois Coal-to-SNG facility	Illinois	coal	50	BSCF/year	GE	YES	
<i>*also power project</i>							



Great Plains Synfuels Plant Aerial Photo

IGCC with Mercury Removal



Mercury Removal System

Performance and Cost

- Remove >90% of mercury
- Stable adsorption of mercury in carbon beds as mercury sulfide
- Incremental capital costs of \$4 – 8/kW for carbon-bed removal system
- Incremental cost of electricity of \$0.16 – 0.32/MWh for O&M and capital repayment
 - <0.4% of the cost of electricity (COE) for an IGCC plant where COE is \$75 - 80/MWh
 - Estimated cost of mercury removal in IGCC compares favorably (<10%) to costs of 90% removal in conventional PC power plant



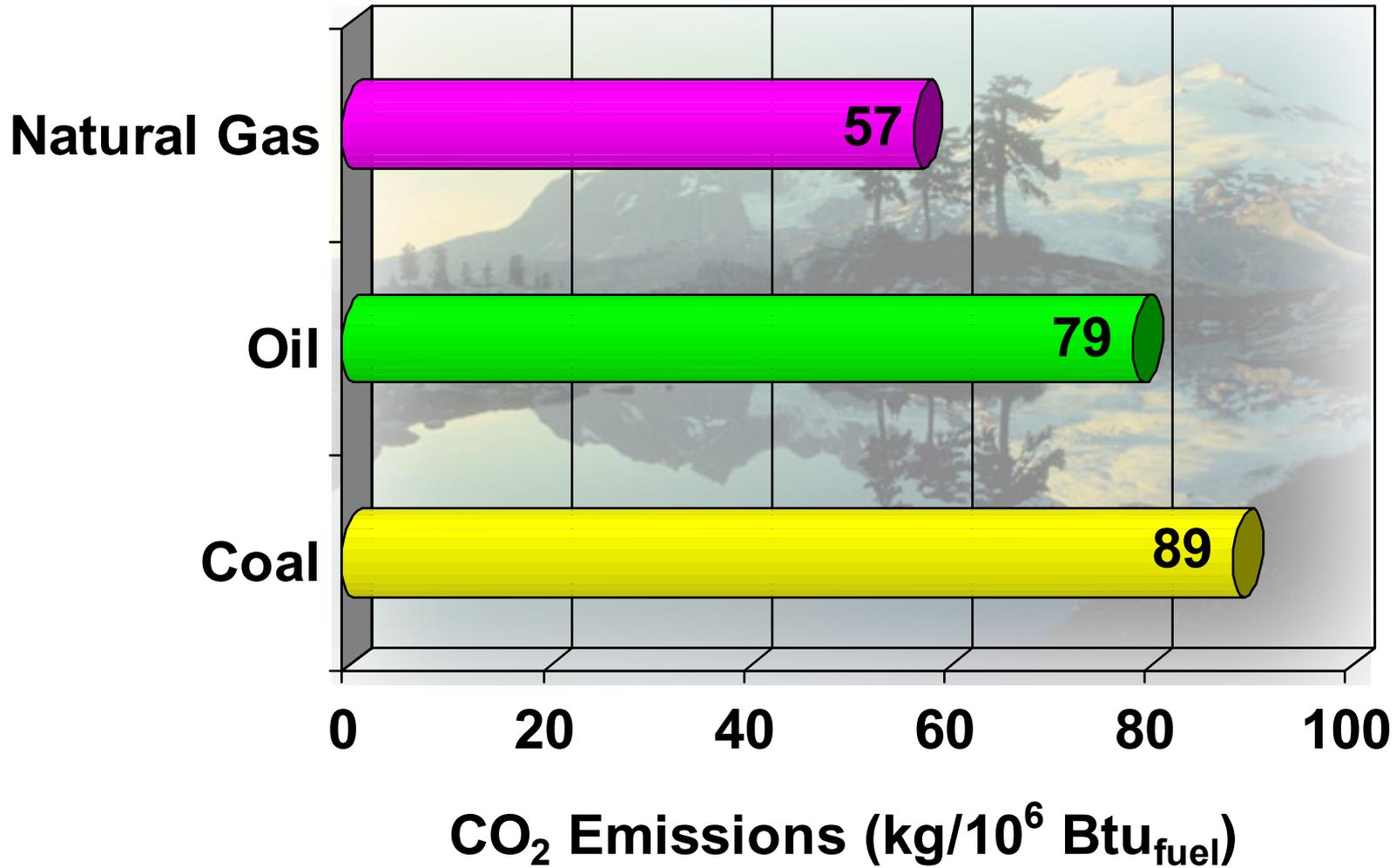
*Estimates for IGCC plant based on the 640 MWe nominal plants used in NETL's "Cost and Performance Baseline for Fossil Energy Power Plants" study**

Gasifier Slag

- Very similar to slag from coal-fired boilers
- It is not regulated as a coal combustion byproduct under RCRA; does not have the same Bevill exclusion from Subtitle C (hazardous wastes)
- Gasification slag does have a Bevill exclusion as a mineral processing waste
- Mineral processing wastes, as listed in 40 CFR 261.4(b)(7) include:
 - “Gasifier ash from coal gasification”



Fossil Fuel CO₂ Emissions



Uncontrolled CO₂ Emissions – Comparison of Fossil-Fired Power Generation Technologies

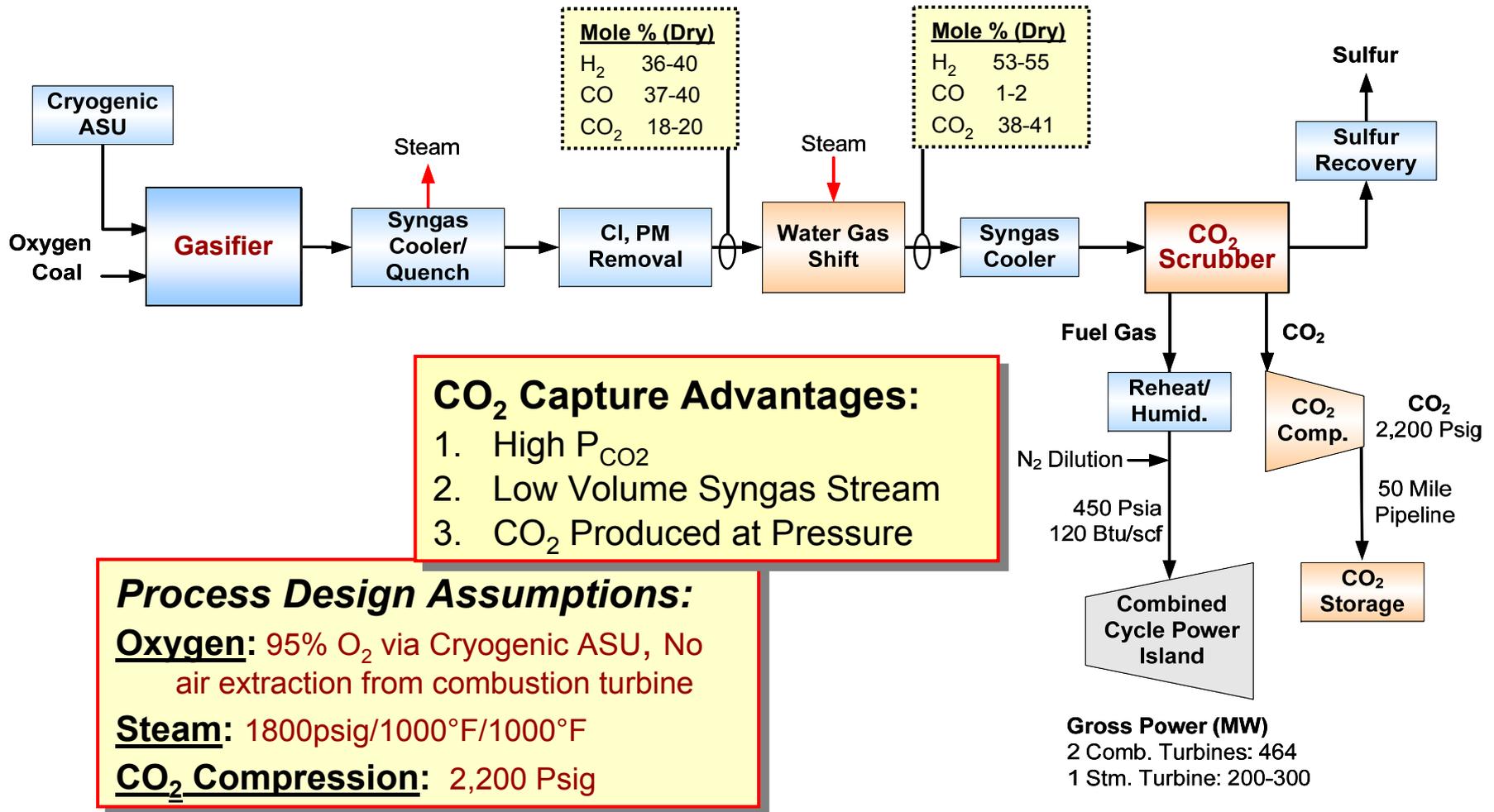
<i>Power Generation Technology</i>	<i>Heat Rate, Btu/kWh</i>	<i>CO₂ Emission, lb/kWh</i>
Conventional Pulverized Coal-Fired with FGD	9,800	2.00
Pressurized Fluidized Bed Combustion	8,700	1.81
Integrated Gasification Combined Cycle (IGCC)	8,700	1.74
Natural Gas Combustion Turbine (Simple Cycle)	11,000	1.27
Advanced Gasification-Fuel Cell	6,000	1.20
Natural Gas Combined Cycle (NGCC)	7,500	0.86

Volume of CO₂ Produced

- **1 million metric tons of liquid CO₂:**
 - Every year would fill a volume of 32 million cubic feet
 - *Close to the volume of the Empire State Building*
- **U.S. emits roughly 6 billion tons (gigatons) of CO₂ per year**
 - Under an EIA reference case scenario cumulative CO₂ emissions 2004-2100 are expected to be 1 trillion tons
 - *Almost enough to fill Lake Erie twice by the end of the century!*



Pre-Combustion Current Technology IGCC Power Plant with CO₂ Scrubbing



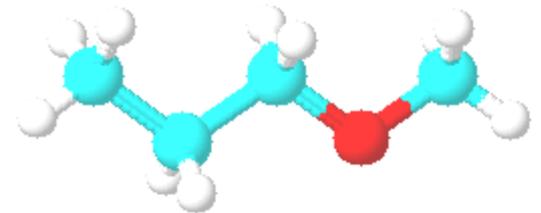
CO₂ Capture via Selexol Scrubbing

Advantages

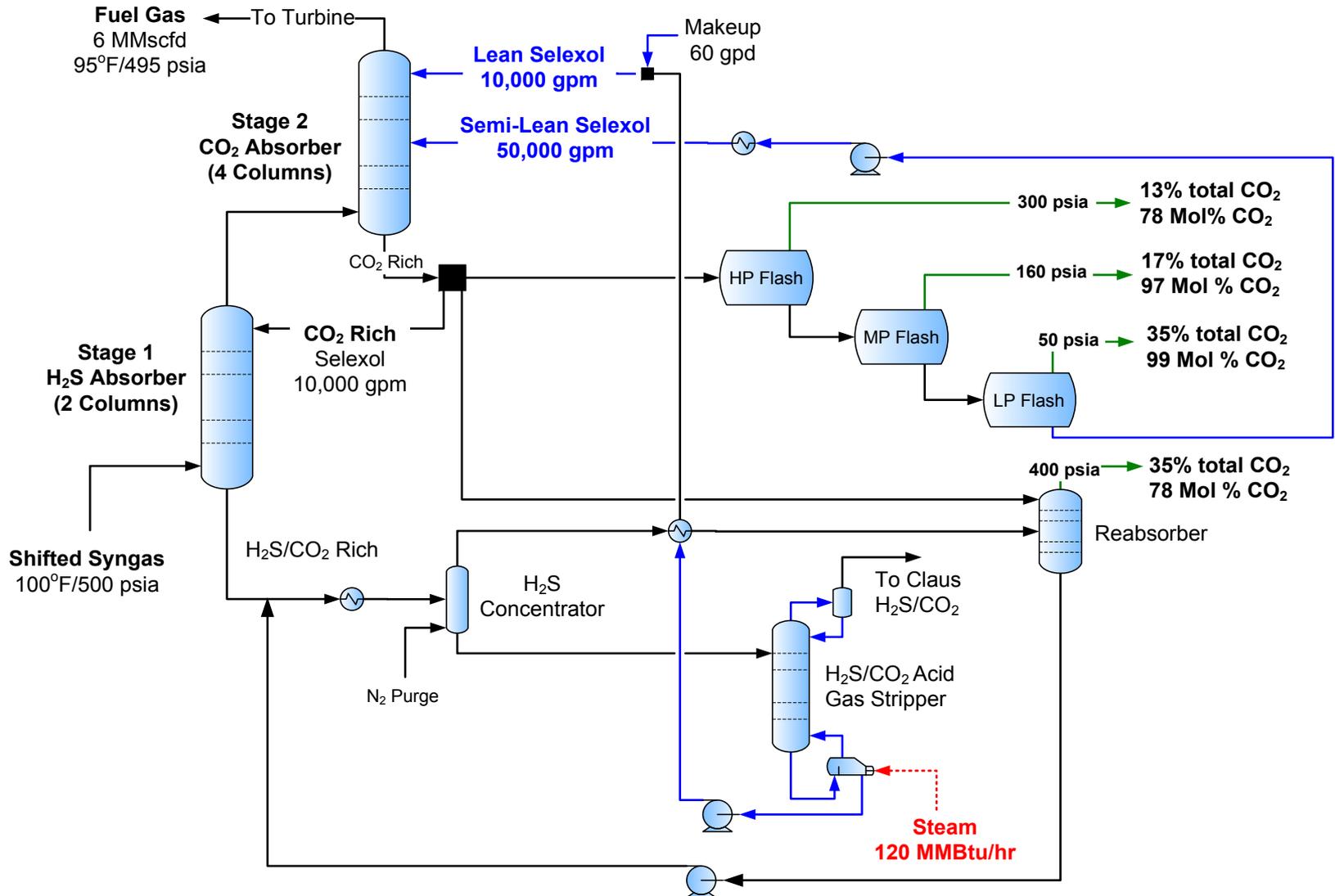
- Physical Liquid Sorbent → High loadings at high CO₂ partial pressure
- Highly selective for H₂S and CO₂ → No need for separate sulfur capture system
- No heat of reaction (ΔH_{rxn}), small heat of solution
- Chemically and thermally stable, low vapor pressure
- 30+ years of commercial operation (55 worldwide plants)

Disadvantages

- Requires Gas Cooling (to ~100°F)
- CO₂ regeneration by flashing



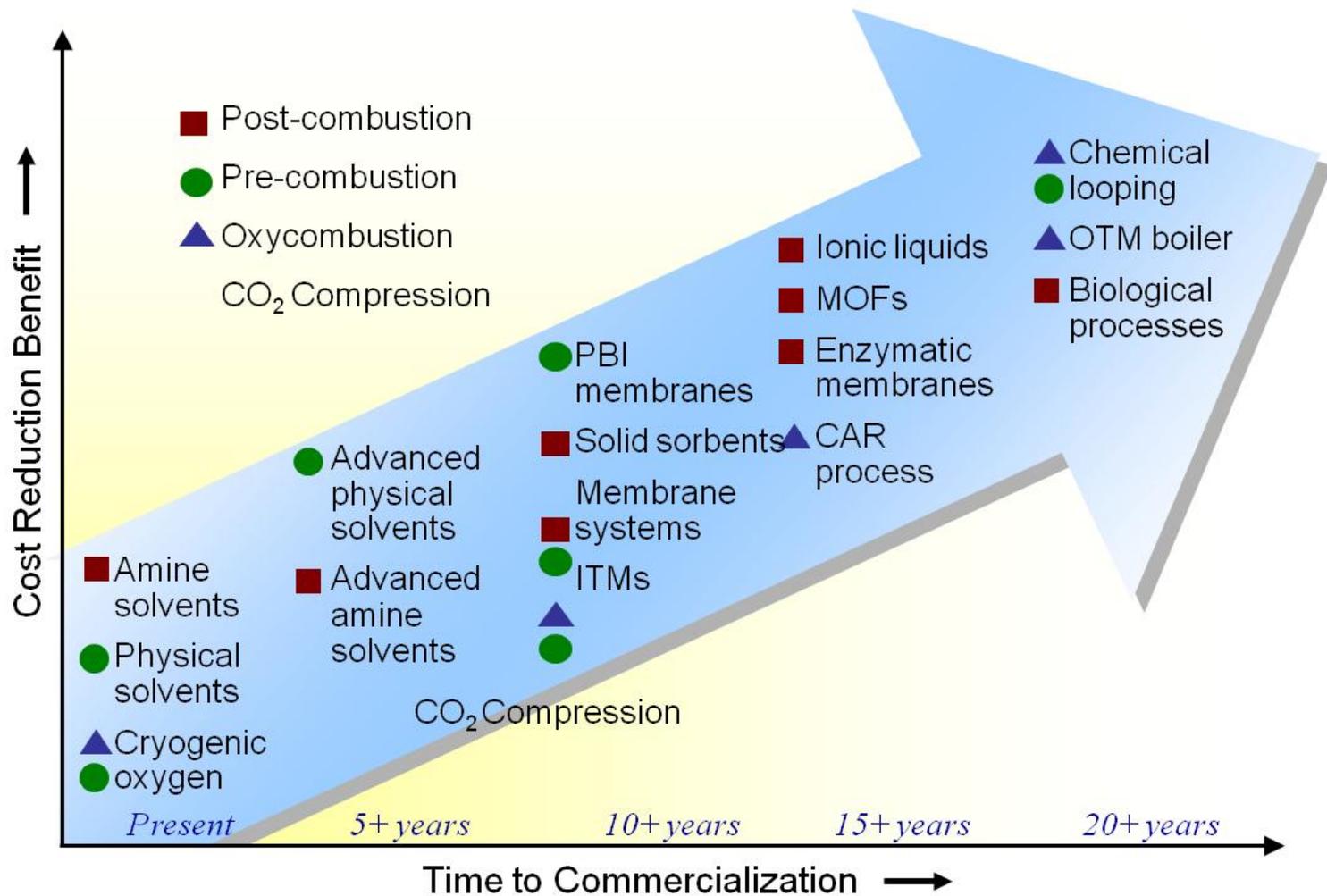
Selexol™ Scrubbing



CO₂ Capture via Rectisol Scrubbing

- **Based on low-temperature (refrigerated methanol)**
- **Capable of deep total sulfur removal as well as CO₂ removal**
- **Most expensive AGR process**
- **Predominantly used in chemical synthesis gas applications**
 - As low as < 0.1 ppmv total sulfur requirements
- **Proposed for use in IGCC for CO₂ removal but no published cost studies**

Technology Advances for Carbon Capture



Sample CO₂ Quality Specification

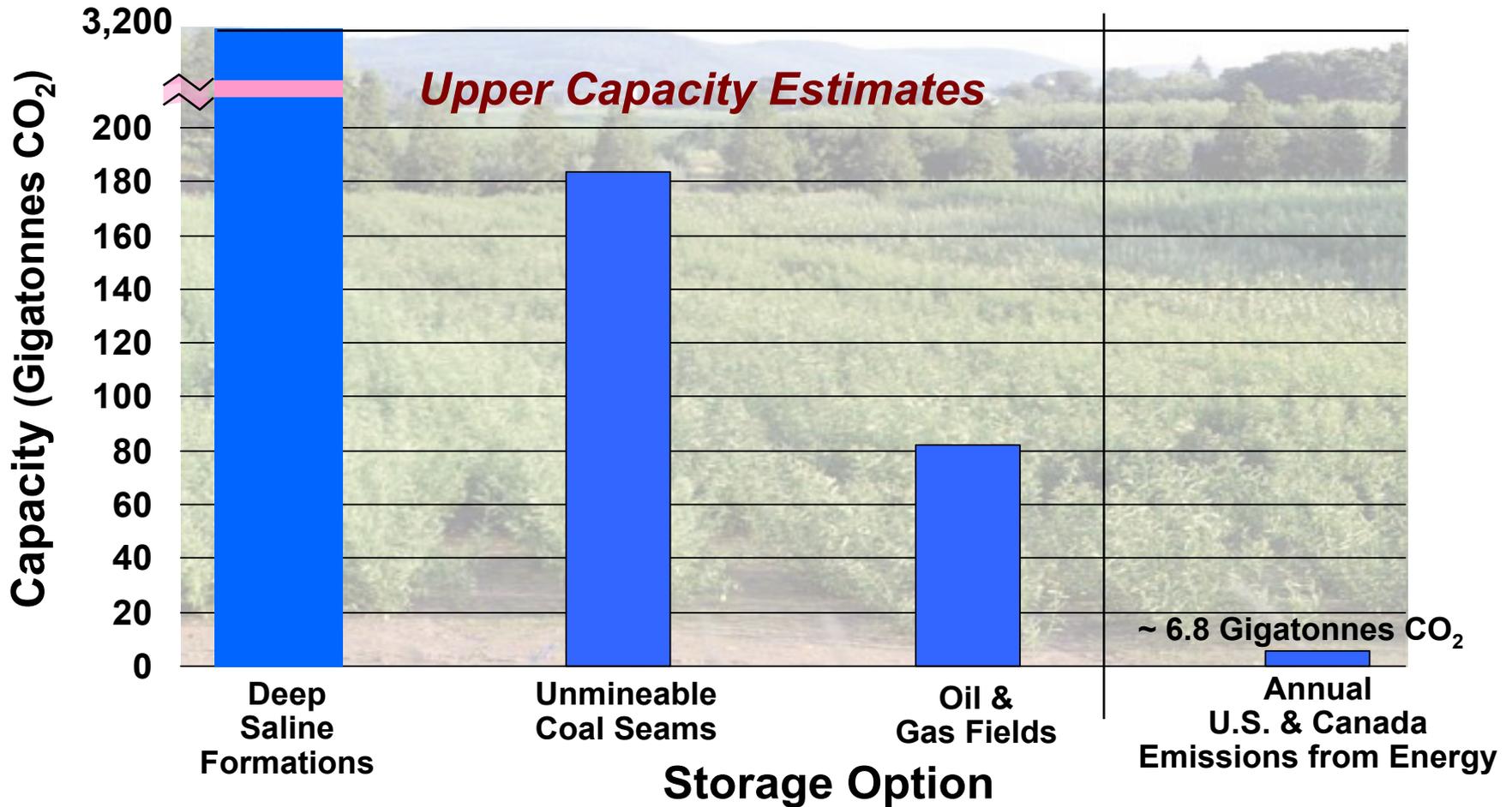
Component	IPCC, 2005	IPCC, 2005; APGTF, 2002	Dakota Gasification	Kinder Morgan, 2006; Elsam A/S et al., 2003	Dixon Consulting; EOR, 2001	Industry Working Group, 2005	Canyon Reef EOR, 2005
CO₂ (mole%)	> 95%	> 96%	> 96%	> 95%		> 95%	> 95%
N₂ (ppmv)	< 40,000	< 300	< 6,000	< 40,000	< 20,000	< 40,000	< 40,000
CH₄ (ppmv)	< 50,000	< 7,000	< 20,000	< 50,000	< 10,000	< 50,000	< 50,000
H₂S (ppmv)	< 1,061	< 9,000	< 20,000	< 200	< 100 (ppmv)	< 200	< 1,500
O₂ (ppmv)	< 7.5	< 50	< 100	< 10	< 2 (ppmv)	< 100	< 10
H₂O (ppmv)	< 641	< 20	< 2	< 480	< -5C DP at 300 psia	< -40C DP	< 28lb/MMCF

Comparison of CO₂ Storage Options

<i>Characteristics</i>	<i>EOR</i>	<i>Saline Aquifers</i>	<i>Depleted Oil & Gas Reservoirs</i>	<i>Coal Beds</i>
Experience Base	Permian Basin	Learning	Learning	To date, one failure
Storage Capacity	Moderate	Very high (10-100 x EOR)	Unknown	Low
Leakage Risk	Very low	Low	Very low	High
Accessibility to CO₂ Source	Limited	Extensive	Limited	Very Limited
Likelihood of Success	100%	High	100%	Very low
Economics	Oil production could offset some cost	Gov't incentive required	Gov't incentive required	Gov't incentive required
Overall Risk	Very low	Low	Very low	High
Other Comments	Most EOR projects do not have sufficient demand for CO ₂ for one coal fired plant (30 years)	Largest storage capacity opportunity	CO ₂ capacity needs to be quantified	Significant technical uncertainty

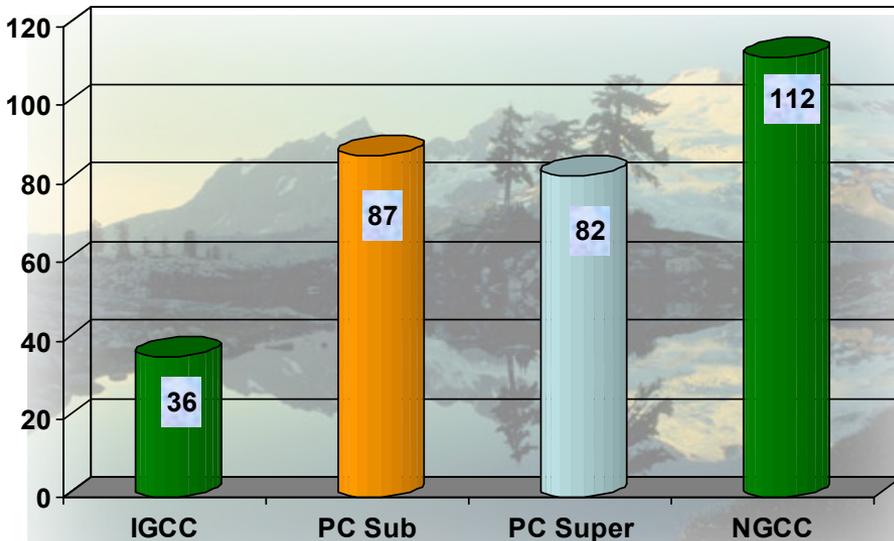
North America Geologic Storage Capacity

(> 500 Year Potential Storage Capacity for U.S. & Canada)

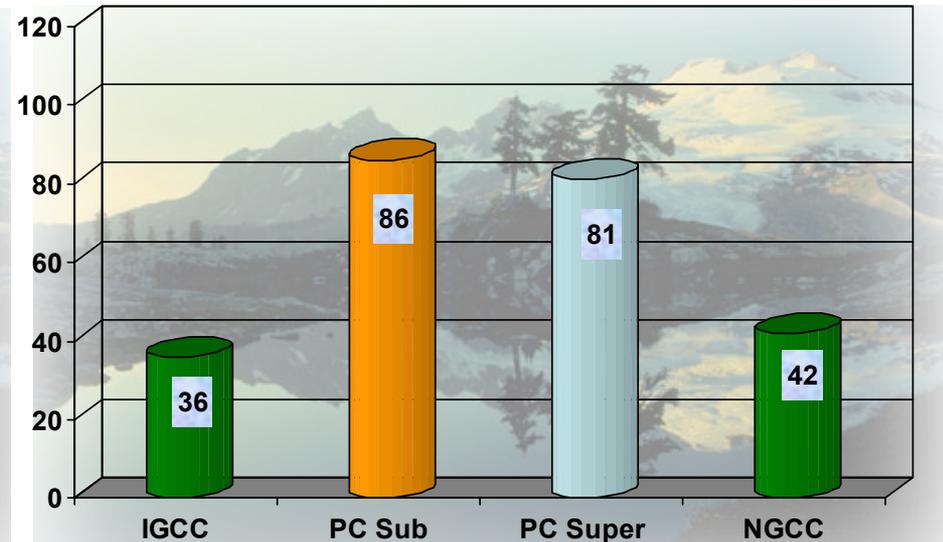


Impact of CO₂ Capture

Effect of CO₂ Capture on Capital Cost
(% Increase Resulting From CO₂ Capture)



Effect of CO₂ Capture on Levelized Cost of Electricity
(% Increase Resulting From CO₂ Capture)



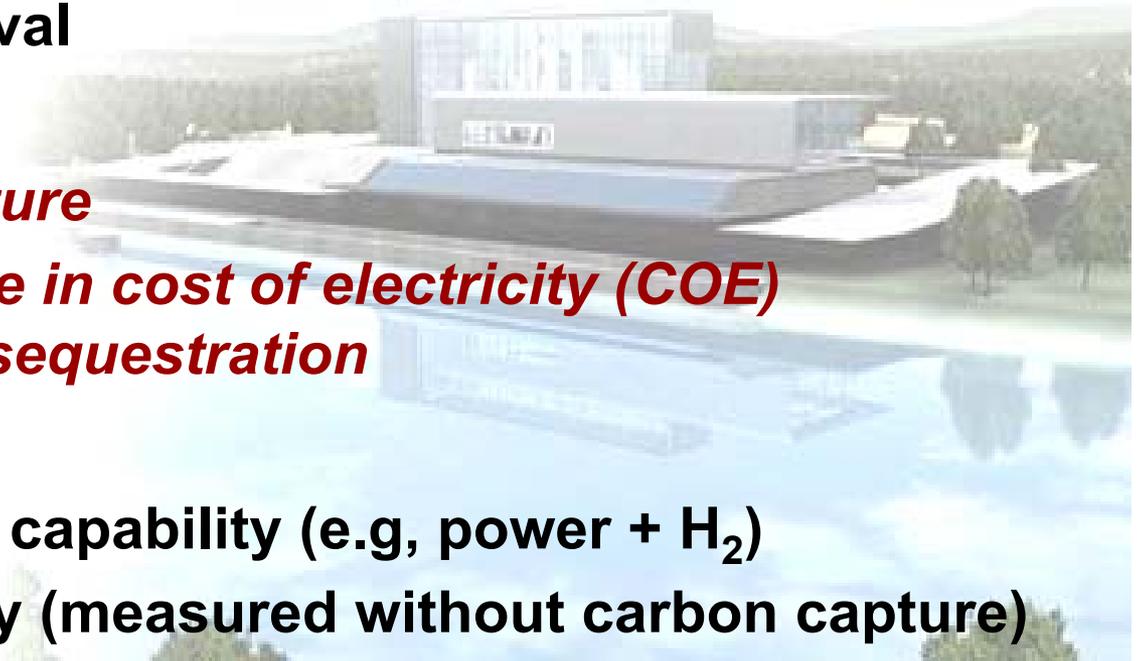
January 2007 Dollars, 85% Capacity Factor,
16.4% (no capture) 17.5% (capture) Capital Charge Factor,
Coal cost \$1.80/106Btu, Natural Gas cost \$6.75/106Btu

DOE Gasification Program Overview



Advanced Power Systems Goal

- **2010:**
 - **45-50% Efficiency (HHV)**
 - **99% SO₂ removal**
 - **NO_x < 0.01 lb/MM Btu**
 - **90% Hg removal**
- **2012:**
 - **90% CO₂ capture**
 - **<10% increase in cost of electricity (COE) with carbon sequestration**
- **2015:**
 - **Multi-product capability (e.g, power + H₂)**
 - **60% efficiency (measured without carbon capture)**



Advanced Power Systems Program

2012 Goal

Complete R&D to integrate this technology with CO₂ separation, capture, and sequestration into a “**near-zero**” emission configuration that can provide electricity with less than 10 percent increase in cost.

Near- Zero	
SO₂	>99% removal
H₂S	50 ppbw
NH₃	10 ppm
HCl	10 ppb
Hg	5 ppbw (>90% removal)
As	5 ppbw (>90% removal)
Se	0.2 ppmw
P	<20 ppbw
Cd	30 ppb
CO₂	>90% removal

Note: Controlling NO_x emissions is the responsibility of the turbine program.

Advanced Power Systems Roadmap

Challenges

Optimization of Coal Use with

- Zero emissions
- High efficiency
- Low cost plants

for production of

- *Electric power*
- *Fuels*
- *Chemicals*
- *Hydrogen*

Reduction of Power Plant Pollutants (NO_x, SO_x, Hg, As, Cd, Se, PM)

Reduction of CO₂ Emissions

Maintain Low Cost of Electricity to the Public through diversified mix of indigenous fuels

R&D Pathways

By 2010

- Transport gasifiers
- Advanced materials & instrumentation
- Dry feed pump
- Warm gas cleaning (all contaminants including Hg)
- 7FB gas turbines
- ITM oxygen
- 85% capacity factor
- 98% carbon conversion

By 2015

All of 2010 improvements
Plus:

- Chemical looping gasifiers
- Hydrogen gas turbines
- SOFC topping cycle
- 90% capacity factor
- CO₂ capture & sequestration

Targets

By 2010

- Efficiency 45-50% (HHV)
- Capital \$1000/kW*

By 2012

- Increase COE < 10% w/CO₂ capture

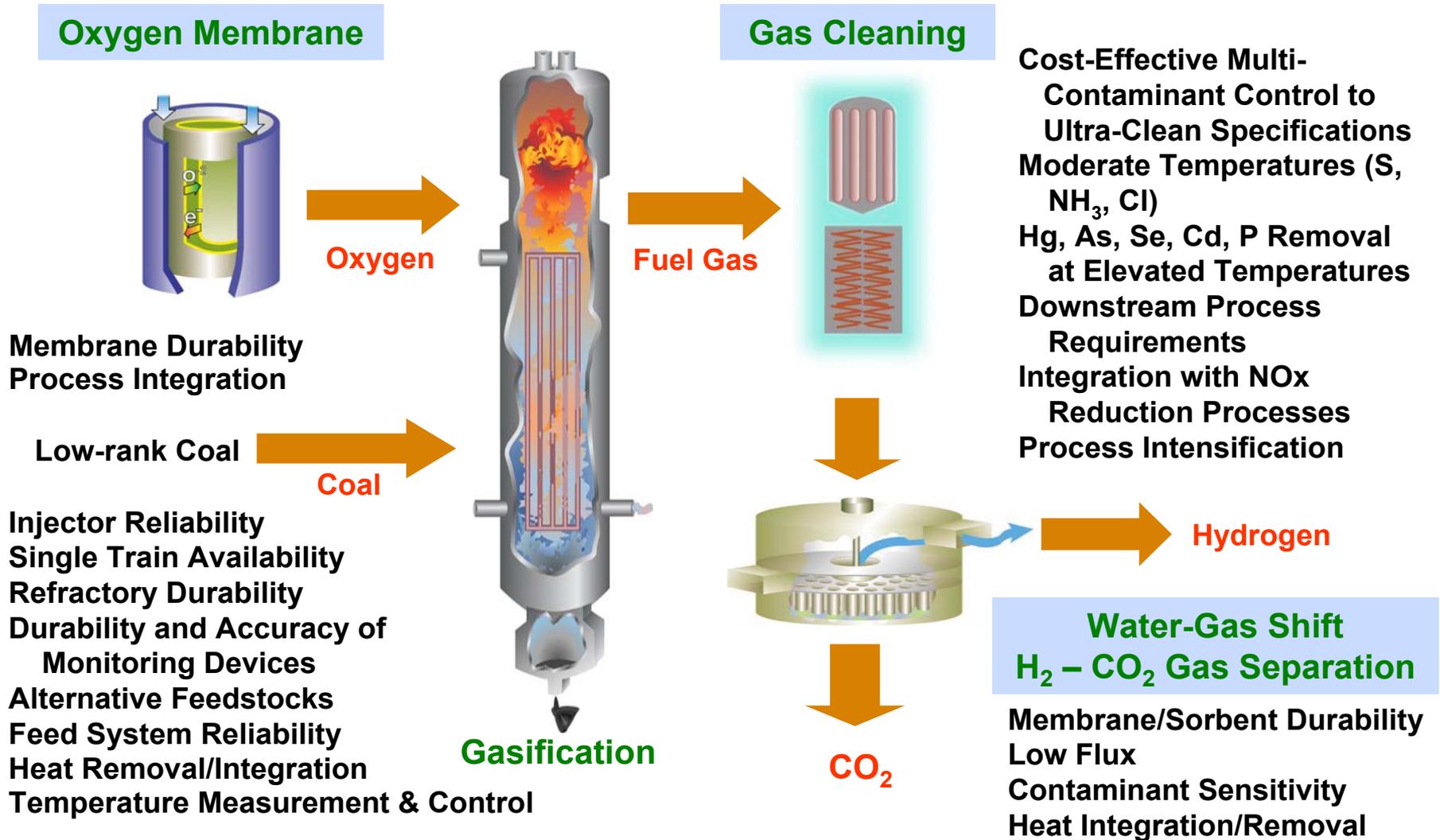
By 2015**

- Efficiency 50-60% (HHV)
- Capital \$900/kW*

*Cost in 2002\$

**Targets for Plants w/o Carbon Capture

Major Technology Issues



Gasification R&D Program

Power Systems Development Facility (PSDF)

Wilsonville, AL



- Southern Company
 - Kellogg, Brown & Root
 - Siemens Power Generation
 - Southern Research Institute
 - Electric Power Research Institute
 - Burlington Northern Railroad
 - Peabody Energy
 - Lignite Energy Company

Development and demonstration of modular industrial scale gasification-based processes and components

Gasification Systems

NETL **Office of Research and Development**

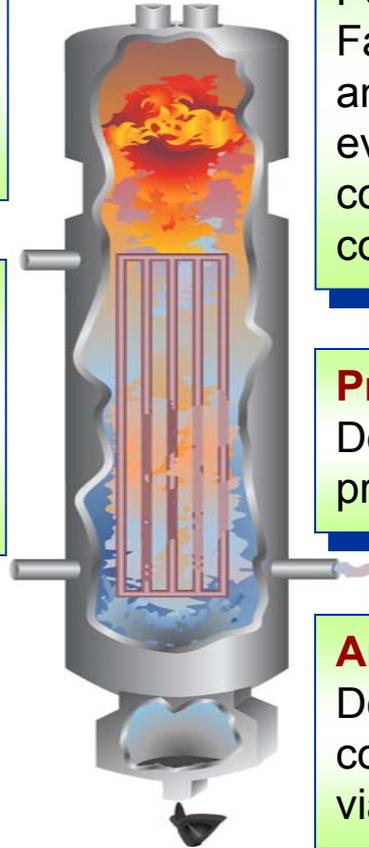
On going investigations into the co-gasification of coal and biomass including biomass feed preparation

NETL **Office of Research and Development**

Addressing the most critical technology development problems for commercial use of Underground Coal Gasification

Research Triangle Institute

Development of a novel cost-effective approach to the coproduction of SNG and electricity



Southern Company Services

Power Systems Development Facility (PSDF) – A development and research facility to test, evaluate and accelerate advanced coal-based power system components and technologies

Pratt & Whitney Rocketdyne

Development and testing of a high pressure coal feed pump

Arizona Public Service

Development of a system for coproduction of SNG and electricity via coal hydrogasification

Power Systems Development Facility (PSDF)

Project Goal:

- Accelerate the development and deployment of advanced coal-based power systems, components, technologies, and processes
- PSDF serves as a proving ground for performing integrated systems, process, and component testing



Power Systems Development Facility

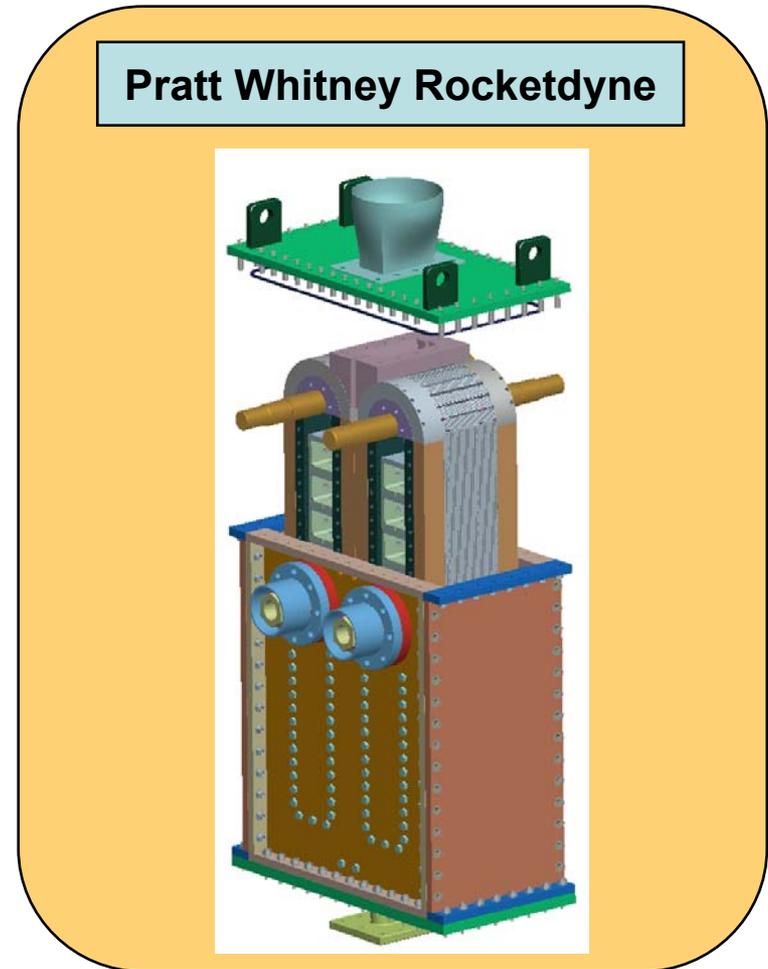
Status:

- >11,000 hours of coal gasification
- High moisture lignite test successfully completed
 - >540 operating hours; carbon conversions up to 98.9%
- High sodium lignite successfully tested
 - >300 hours of operation; carbon conversion increased from 84% to 95%
 - Kaolin effective in preventing agglomeration
- Bituminous coal testing completed (237 hr)
- Commissioned high Moisture Coal Drying System
- Off-line Coal Feed Test Facility
 - Pressure Decoupled Advanced Coal (PDAC) Feeder
 - Rotary table to be installed to demonstrate operability to 500 psig
- Advanced syngas cleanup slipstream
 - Modifications to support fuel cell & H₂ membranes
- Provide key data for Mississippi CCPI Demonstration

High Pressure Solids Pump

Benefit:

- Reduce heat penalties with slurry feed and high-moisture (western) low-rank coals
- **Two approaches:**
 - Stamet: cylindrical flow geometry
 - Pratt Whitney Rocketdyne: linear flow geometry
- **Common principle:**
 - Uses pulverized coal under mechanical pressure to maintain high pressure seal to gasifier
- **Status:**
 - **Stamet purchased by GE (6/8/07)**
 - PWR to construct and test a 400 ton/day pump



Gasifier Performance and Capital Cost Summary

with and without coal feed pump

	Shell Gasifier		Transport Gasifier		GE Energy R/C Gasifier	
Coal Type / Feed Type	Eastern		Western		Eastern	
Coal Preparation for Feed	Drying	Pump	Drying	Pump	Slurry	Pump
Auxiliary Power, MWe	43.2	44.2	35.8	39.9	49.0	44.0
Net Plant Efficiency (HHV)	40.6%	40.9%	40.5%	40.7%	40.4%	40.9%
Net Heat Rate (Btu/kWhr)	8,410	8,345	8,416	8,386	8,456	8,335
Total Coal Prep Capital Cost (\$x1000)	\$45,590	\$17,898	\$59,594	\$33,279	\$12,766	\$9,751
Total Coal Prep Capital Cost (\$/kW)	\$176	\$69	\$197	\$111	\$46	\$37
Total Gasifier Island Cost (\$/kW)	\$611	\$501	\$438	\$352	\$449	\$463

Coal Feed Pump Favorable

Coal Feed Pump Less Favorable

Advanced Hydrogasification Process

Arizona Public Service

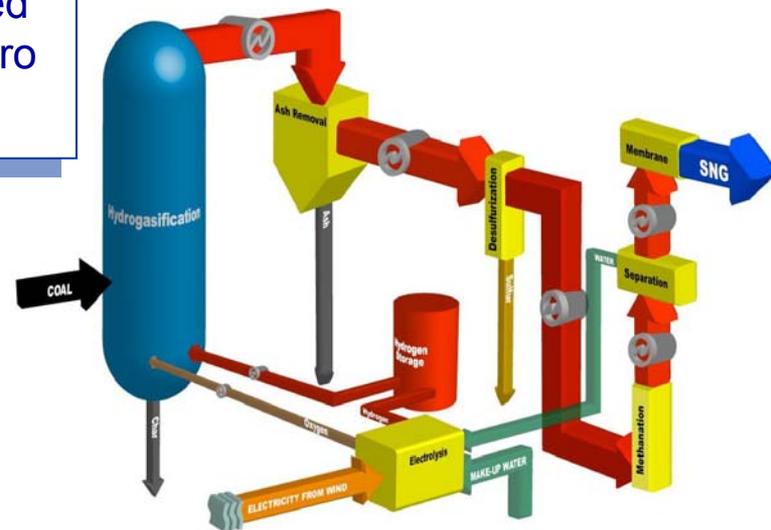
Objective:

Develop and demonstrate a coal hydrogasification based process to co-produce SNG and electricity with near-zero emissions

Accomplishments:

- Completed bench scale reactor design, site layout, auxiliary equipment specification and test plan
- Field test of carbon recycling concept to flue gas feed closed-system algae farm* (Algae growth: average - 98 g/m²/d, peak - 174 g/m²/d)

* > **Twice growth rate reported in the literature**



Proposed APS Advanced Hydrogasification Process

Future Plans:

- Evaluate effect of temperature, feed rate, and coal on hydrogen mass flow with batch-sc
- Perform batch-scale hydrogasification tests to evaluate effects of temperature, coal, and feed rate on hydrogen mass flow
- Revise Systems Study and Cost Analysis for process including algae for carbon reutilization

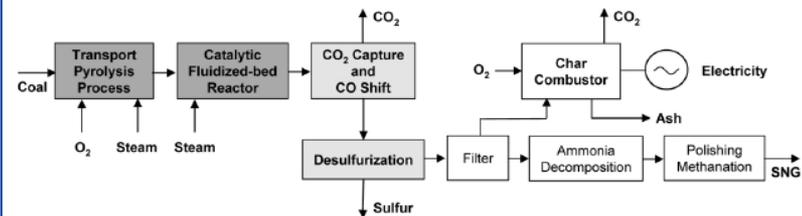
Co-Production of SNG and Electricity via Catalytic Coal Gasification

Goal:

Develop a commercial application for co-production of electricity and SNG at a cost <\$5 per MMBtu and near-zero emissions

Accomplishments:

- Multi-cycle parametric testing of RTI's regenerable CO₂ sorbent for >90% CO₂ removal completed
- Testing demonstrated technical feasibility of the sorbent
- Preliminary char combustion experiments results indicate >75% of the heavy metals in the char derived from the coal remain trapped in the ash during combustion



Proposed Process for the Co-Production of SNG and Electricity via Catalytic Coal Gasification

**Center for Energy Technology
RTI International**

Benefits:

Efficient SNG production will help to reduce the U.S. dependence on natural gas and provide supply and price stability

Underground Coal Gasification

*Addressing the **most critical** technology development problems for commercial use of Underground Coal Gasification (UCG)*

Research and Development Project Areas

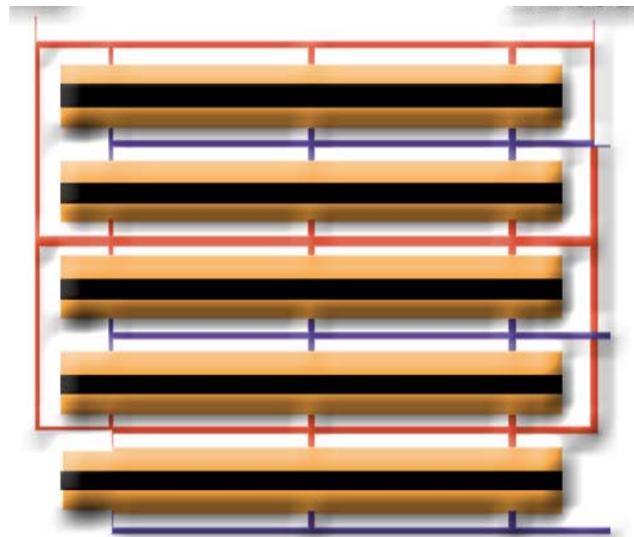
- Environmental Aspects
- Resource assessment
- Models validation for the gasification process
- Life cycle analysis -- costs and environmental
- Lab scale UCG experiments
- Collaboration with LLNL -- model development

Underground Coal Gasification Database

- Proposed and current UCG projects
- Completed tests & project reports
- Patent & literature collection



Advanced Gas Separation



Eltron Research

- CoorsTek
- NORAM Engineering & Constructors
- Praxair

Developing materials to separate hydrogen from syngas

Air Products and Chemicals, Inc.

Developing and demonstrating ion transport membranes (ITM) for oxygen production

Research Triangle Institute

Development of novel chemical looping technology for co-production of hydrogen and electricity

Ohio State University

Development of novel iron-based chemical looping technology for IGCC and Fischer-Tropsch Applications

Ion Transport Membrane Air Separation



0.5 TPD Modules

*Air Products & Chemicals
Ion Transport Membrane
“ITM Oxygen”*

(ITM capacity: 4,550 sTPD oxygen)



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

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

ITM Benefits: IGCC plant specific capital cost reduced by 9%, plant efficiency increase by 1.2%, with ~25% cost savings in oxygen production

Ion Transport Membrane Air Separation Air Products & Chemicals “ITM Oxygen”

Benefits: IGCC plant specific capital cost reduced by 9%; plant efficiency increase by 1.2%; ~25% cost savings in oxygen production



0.5 TPD Modules



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

- **Testing of 5 TPD unit**
 - Operated under full driving force conditions
 - Met/exceeded wafer performance for flux and purity
 - Cycled modules from idle to operating conditions w/o loss of performance
- **Proved feasibility of full integration with large frame GTs**
- **Phase 3 for 150 TPD in unit signed in February 2007**
- **Planning Phase 4**
 - 1,500 to 2,500 TPD unit

APCI Air Separation ITM Modules

- **Testing of 5 TPD SEP unit**
 - Operated under full driving force conditions
 - Met/exceeded wafer performance for flux and purity
 - Cycled modules from idle to operating conditions w/o loss of performance
- **Proved feasibility of full integration with large frame GTs**
- **Phase 3 for 150 TPD unit signed February 2007**
- **Planning Phase 4**
 - 1,500 to 2,500 TPD unit



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



0.5 TPD Modules

Test membrane modules
FY06 – 5 TPD (successfully completed)
FY10 – 150 TPD
Offer commercial air separation modules
Post FY10 - demos of IGCC

Membrane Air Separation Advantages

Air Products

(ITM capacity: 4,550 sTPD oxygen)

	ITM Oxygen	Cryo ASU	Δ %
IGCC Net Power (MWe)	627	543	+15
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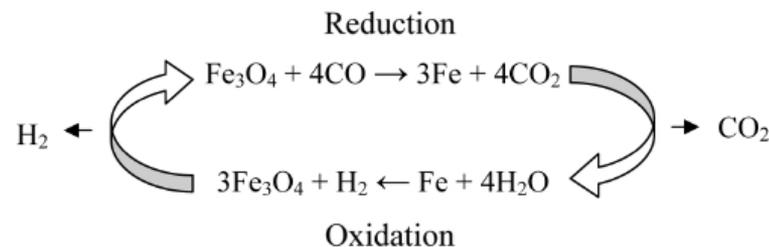
Co-Production of Electricity and Hydrogen Using a Novel Iron-Based Catalyst

Goal:

Develop a highly efficient steam-iron process technology for the co-production of electricity and hydrogen in an integrated gasification combined cycle (IGCC) power plant

Accomplishments:

- Iron (FE)-based catalysts synthesized and compositions have been manipulated to improve hydrogen production
- Synthesized catalysts were tested in a fluidized-bed microreactor system
- A performance evaluation was performed and an optimal catalyst composition selected



Hydrogen produced by steam-iron redox cyclone

**Center for Energy Technology
RTI International**

Benefits:

Enable co-production of high purity hydrogen and electricity from an IGCC at an economic level

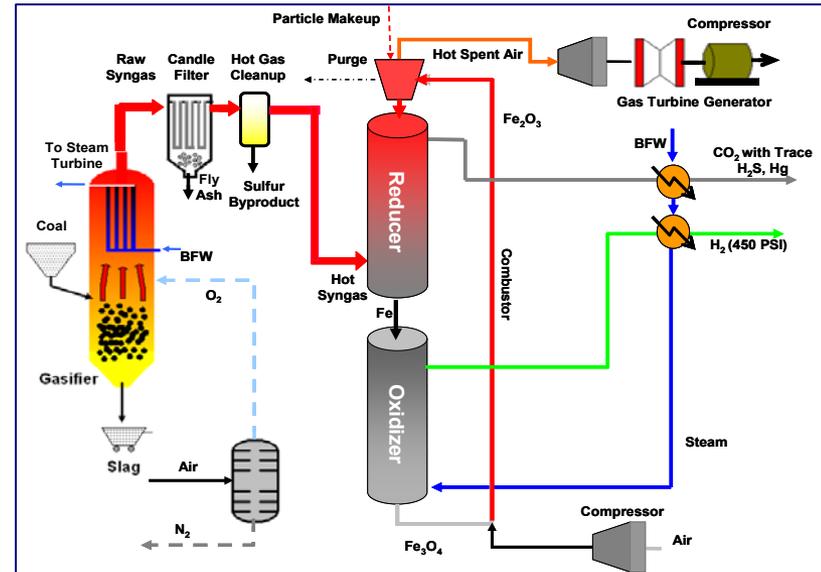
Enhanced Hydrogen Production Integrated with CO₂ Separation

Goal:

Develop a process that produces a pure hydrogen stream and a concentrated CO₂ stream in two separate reactors — avoiding additional CO₂ separation cost

Benefits:

Enable co-production of high purity hydrogen and electricity from an IGCC at an economic level

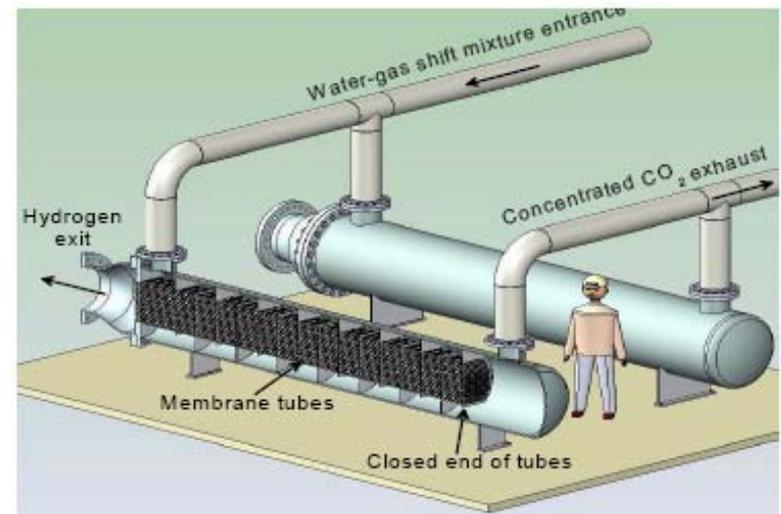
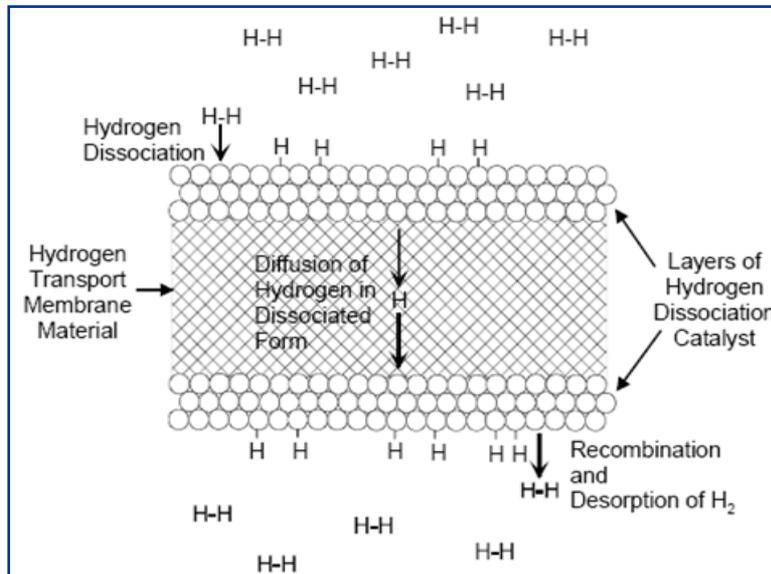


Simplified schematic of the Syngas Chemical Looping Process for H₂ production from coal

Ohio State University

ELTRON Hydrogen Membrane

- Allows capture of high pressure CO₂
- High hydrogen permeate pressure
- High hydrogen recoveries — >90%
- Essentially 100% pure hydrogen
- Low cost
- Long membrane life
- Target: 4 tpd module in 2013 / 2014



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



• Status

- Seeking development partner ↗
- Current testing at 1.5 lb/d ←
- Scale-up to 220 lb/d - 2010

Progress Towards DOE-FE Targets

<i>Performance Criteria</i>	<i>2005 Target</i>	<i>2010 Target</i>	<i>2015 Target</i>	<i>Current Eltron Membrane</i>
Flux (sccm/cm²/100 psi ΔP)	50	100	150	160
Operating Temperature (°C)	400-700	300-600	250-500	300-400
S Tolerance (ppmv)	N/A	2	20	20 (early)
System Cost (\$/ft²)	1000	500	<250	<200
ΔP Operating Capability (psi)	100	400	800-1000	1,000
Carbon Monoxide Tolerance	Yes	Yes	Yes	Yes
Hydrogen Purity (%)	95	99.5	99.99	>99.999
Stability/Durability (years)	1	3	>5	0.9
Permeate Pressure (psi)	N/A	N/A	N/A	270

Improving Process Control

Modeling & Monitoring Systems in Harsh Environments

NETL

Office of Research and Development

Development of new refractory materials

NETL

Office of Research and Development

Development of an IGCC Dynamic Simulator

Virginia Polytechnic Institute

Development of a single crystal sapphire optical fiber sensor for reliable temperature measurements in slagging coal gasifiers

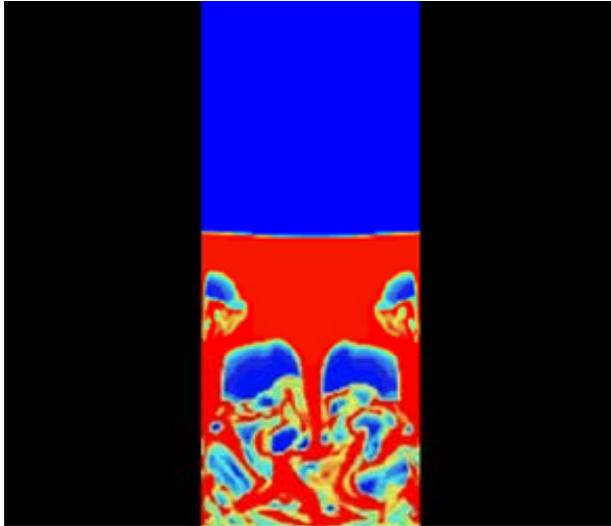
Gas Technology Institute (GTI)

Development of an optical sensor for monitoring coal gasifier flame characteristics

NETL

Office of Research and Development

Computational Fluid Dynamics (CFD)
modeling of advanced gasifiers



*Hydrodynamics in the Bubbling
Fluidized Oxidation Reactor*

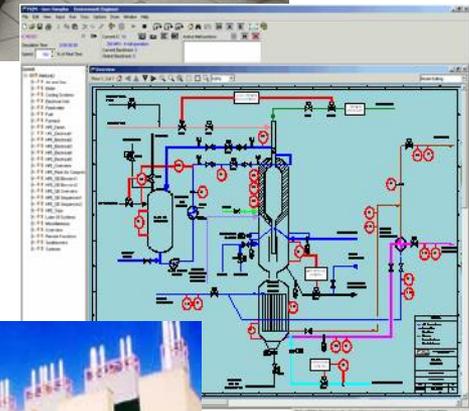
IGCC Dynamic Simulator & Research Center

Office of Research and Development

- **IGCC Simulator**
 - Full-scope, high-fidelity, real-time
 - Generic IGCC plant with carbon capture
- **IGCC DS&R Center**
 - IAES Collaboratory for Process & Dynamic Systems Research
 - WVU's NRCCE
- **R&D Collaborations**
 - Enginomix, FCS, WVU
 - Software/services vendor
- **Industry Participation**
- **Schedule**
 - 1QFY09 Initiate simulator development
- **Future Directions**
 - Site-specific IGCC simulators
 - Extension to other advanced systems (e.g., polygeneration)



*IGCC
DS&R
Center*



*WVU's
NRCCE*

Advanced Refractories for Gasifiers

Office of Research and Development

Target is a refractory material that can last years, rather than months, and to achieve 90 percent + on-line availability

Licensed to Harbison-Walker – Aurex 95P



Conventional refractory after rotary slag testing



Phosphate modified high-chrome oxide refractory material



Rotary Slag Test

New refractory chemistry:

- Increases mechanical durability
- Reduces slag penetration

Future

- Reduce/eliminate chrome content and achieve long refractory life

Real-Time Flame Monitoring Sensor

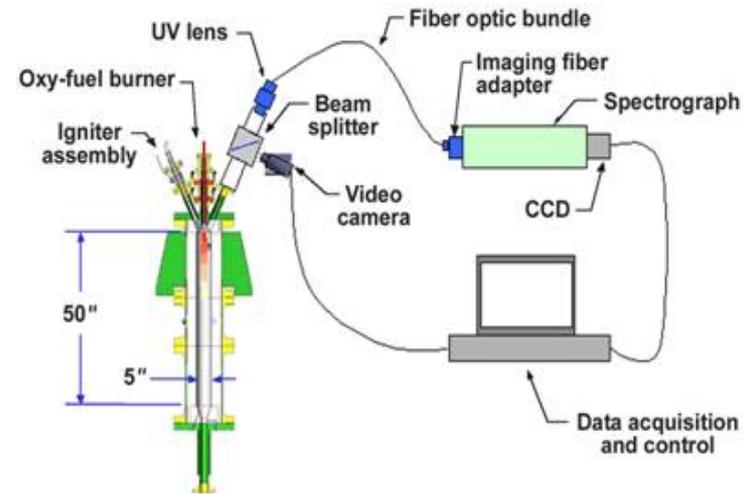
Gas Technology Institute

Field Test Objective:

Develop a reliable, practical, and cost-effective means of monitoring coal gasifier feed injector flame characteristics 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



Instrumentation used for accessing CETC gasifier flames using fiber optic coupling

Future Work:

Field demonstration tests at the Wabash River gasifier (2009)

Single Point Sapphire Temperature Sensor

Virginia Polytechnic Institute

Objective:

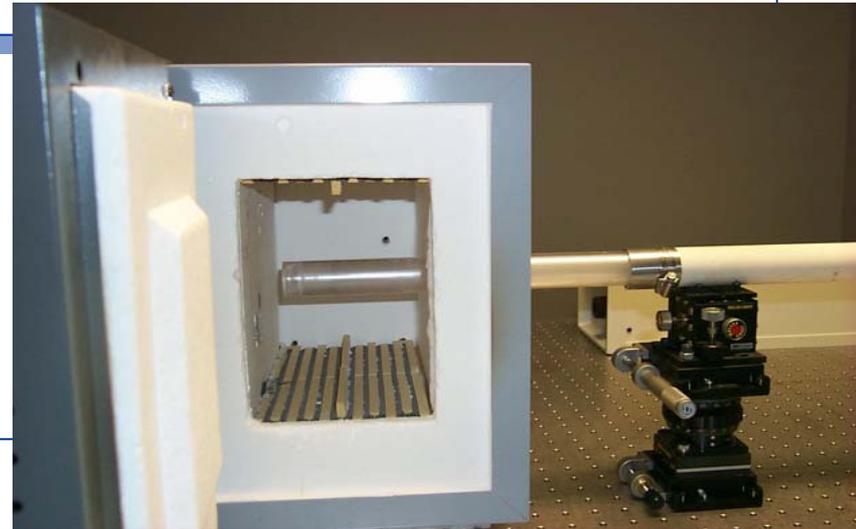
Development of a reliable sensor for real-time temperature monitoring in slagging coal gasifiers using a single-crystal sapphire for optically-based measurement

Accomplishments:

- Accurate readings up to 1600°C
- Full-scale testing at TECO
 - 7 months of continuous operation

Next Step:

- IP licensing being evaluated by Virginia Tech
- Considering testing on turbines (combustor section)
- Additional long-term testing

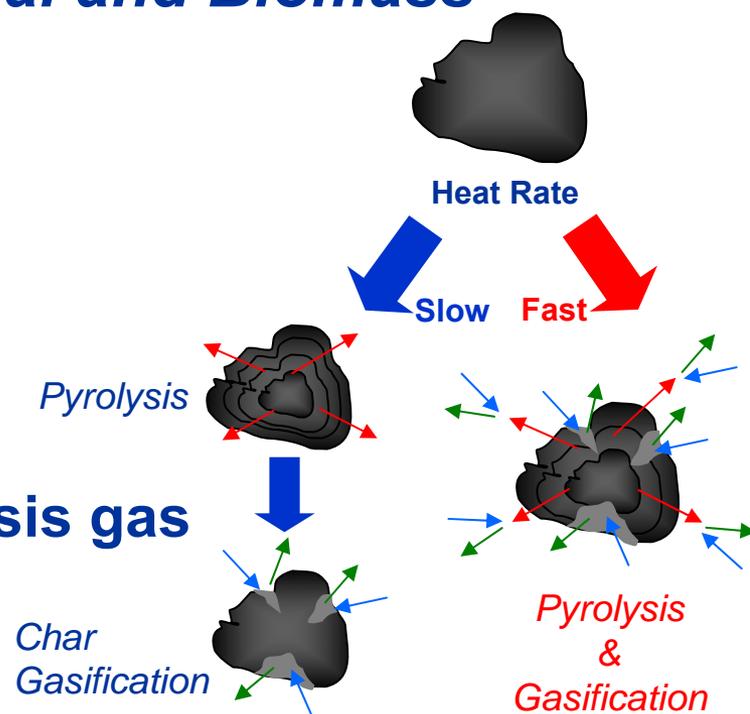


Advanced Energy Systems R&D

Objective: Address uncertainties in coal and biomass co-gasification

Thermochemical Conversion of Coal and Biomass activities include:

- Feed preparation development
- Pyrolysis evaluation
- Char production and evaluation
- Gasification for CO₂ reduction
- Purification and upgrading of synthesis gas
- CBTL baseline catalyst studies



Projects in Ultra Gas Cleaning

(Clean to Near-Zero at Warm-Gas Temperatures)

TDA Research

Development of single sorbent process for removal of multiple trace metals

- Hg, As, Se, Cd

NETL Office of Research and Development

Developing an integrated humid gas cleaning technology approach for next generation IGCC systems

University of North Dakota Energy Environmental Research Center

- Corning
- Developing a multi-contaminant control process using a sorbent-impregnated monolith fixed honeycomb structure

RTI International

- Nexant
- SRI
- SudChemie
- URS

Bulk removal of H₂S, COS, NH₃, and HCl in transport reactor to sub-ppm levels followed with fixed bed polishing plus trace heavy metals removal to near-zero

Gas Technology Institute

- University of California at Berkeley
 - ConocoPhillips
- Integrated multi-contaminant process removing H₂S, NH₃, and HCl and heavy metals (Hg, As, Se, Cd) in single process reactor - - Includes high pressure conversion of H₂S to elemental sulfur

TDA's Novel Sorbent-Based Process for Trace Metals Removal

Field Test Objective:

Develop a chemical sorbent-based process for trace metals removal (Hg, As, Se, and Cd) in a single process step at high temperature (500°F)

Preliminary Slipstream Test Results, PSDF:

- Two sorbent beds tested
 - 96 hr test duration
 - 28,850 scf coal-derived syngas treated
 - Nearly 100% Hg removal at 500°F

Future Plans:

- Chemical analysis to determine removal efficiency of other trace metals
- Expanded 12-month test period with syngas derived from other coal ranks.



Prototype test system for field evaluations at PSDF

Integrated Multi-Contaminant Removal Process

Gas Technology Institute

Field Test Objective:

Scale-up the solvent-based high pressure **University of California Sulfur Recovery Process** (UCSRP-HP) and integrate it with **GTI's** multi-contaminant (ammonia, Cl, Se, As, Cd, and Hg) removal process

Preliminary Slipstream Test Results:

- Converts H_2S to elemental sulfur at 285-300°F
 - Formation of 99.2% pure sulfur
- Successfully completed 1,000 hrs of solution stability testing
- Catalyst stability confirmed

Future Plans:

- Conduct preliminary economic analysis
- Design fully integrated pilot-scale unit



*High pressure bench-scale test unit
(design temperature - 450°F, design
pressure - 1000 psig)*

Warm Gas Cleanup Progress

RTI Process Development Testing at Eastman Chemical

Field Test Objective:

Successfully test warm-gas multi-contaminant cleanup technologies – while creating pure sulfur product – using coal-derived syngas

Preliminary Slipstream Test Results:

- >3,000 hrs of sulfur removal – as low as 1 ppm
- Equally effective on H₂S and COS
- Stable solids circulation at 300-600 psig
- Low sorbent attrition
- >500 hrs pure sulfur production from process off gas
- Tested multi-contaminant removal for NH₃, Hg, and As

Future Plans:

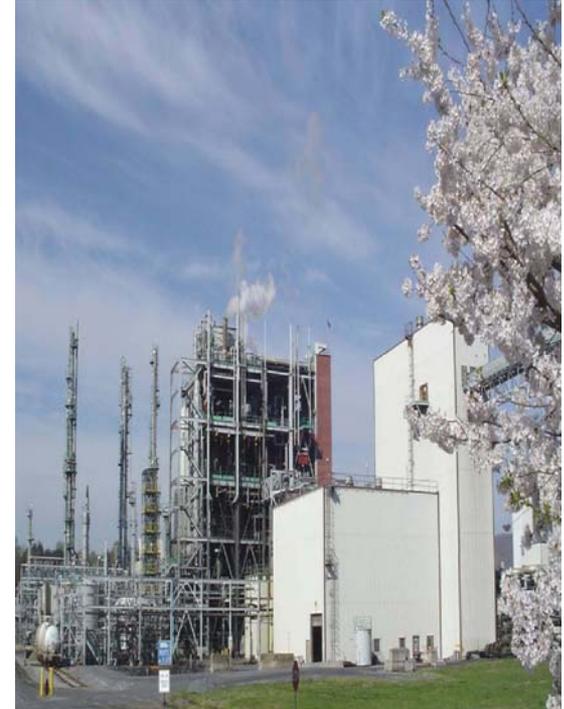
- 25-50 MWe slip stream demonstration unit
- NETL economic analysis show potential:
 - ✓ 2.3% improved plant efficiency
 - ✓ 4% reduction in COE



WGDS Operations Summary

September 2006 to November 2007

- **Reached Steady State Regeneration within 10 hours of startup on 9/5/06**
- **3017 hours of Syngas Operations**
 - 346 hr longest continuous run
 - 61-81% On-Stream
 - Most downtime caused by support equipment
- **116 hours of DSRP operation with >90% sulfur removal**
- **Guard Bed**
 - 2541 hr bypassing Guard Bed
 - 476 hr using Guard Bed
 - No detectable difference in WGDS performance



*RTI Desulfurization Unit /
DSRP at Eastman Plant*

WGCU/DSRP

Nexant Preliminary Study

	IGCC Base Case <i>LTGC + SELEXOL + CLAUS + SCOT</i>	IGCC RTI Case <i>RTI WGCU/DSRP</i>
Coal Feed, STPD (AR)	5,763	5,763
Electric Power, MW	554	618
Total Plant Aux. Consumption, MW	137	126
HHV, %	35.8	39.9
Total Installed Cost (TPC), \$MM (2006)	1,127.7	1,096.8
Installed Cost, \$/Net kW	2,036	1,775

Transport Desulfurization Modeling

Office of Research and Development

Objective:

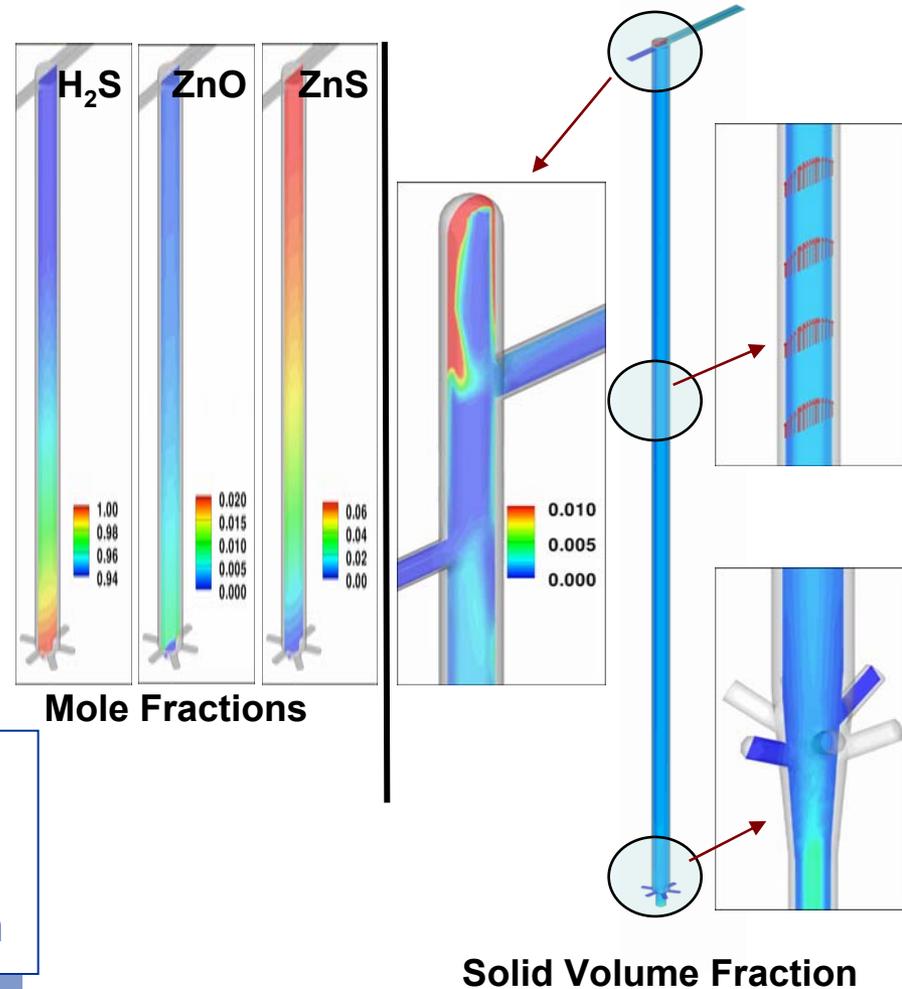
- Model sorbent-based sulfur capture systems
 - For absorption and regeneration

Status:

- Developed absorption model;
 - Applied to NETL transport reactor experiments
- Identified several candidate reaction models for regeneration

Future Work:

- Complete absorption model development
- Refine regeneration model
- Perform simulations of the RTI-Eastman system



Monolith Traps for Mercury and Trace Metal Control

University of North Dakota EERC

Goal:

Develop a system that removes trace metals from syngas in one step and at a higher temperature than conventional processes

Benefits:

- Increase gas cleanup process efficiency
- Reduces cost

Accomplishments:

- Removal of Hg and As at 400°F
- High-pressure test apparatus has been constructed

Next:

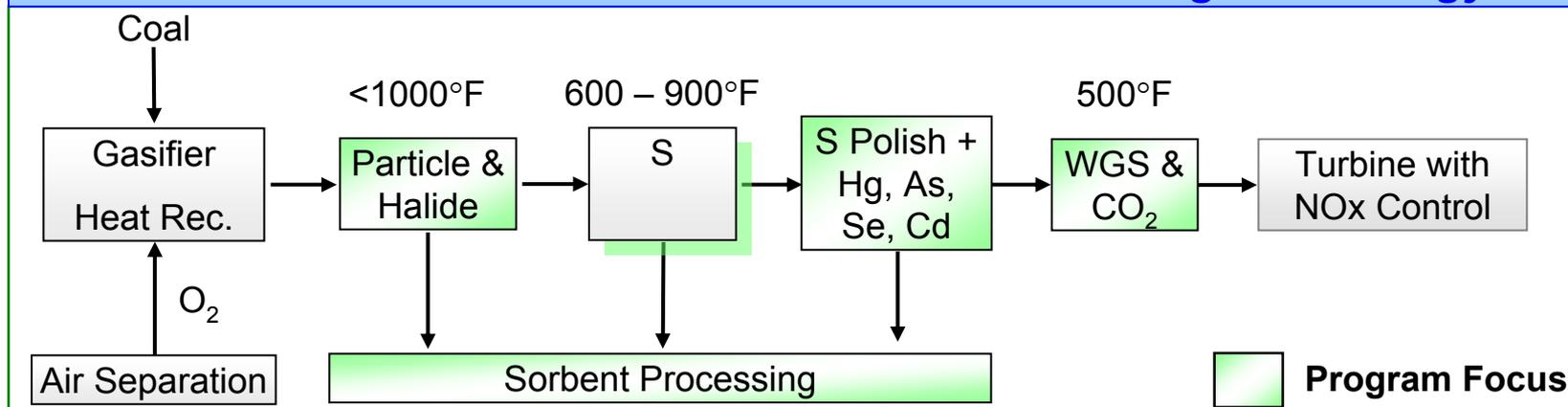
- Test removal of Hg, As, and Se at $\geq 400^\circ\text{F}$ and ≥ 600 psi



Sulfur-impregnated carbon honeycomb monoliths

Multi-Contaminant Removal for Coal Derived Syngas

*Research that Focuses on
...the Next Generation IGCC Plant Humid Gas Cleaning Technology*



Program Focus Areas

- Particle & Halide
- Sorbent Processing
- Desulfurization
- Trace Metal Removal
- CO₂ Capture

*NETL's Office of
Research and Development*

Multi-Contaminant Removal for Coal Derived Syngas

**Research that Focuses on
...the Next Generation IGCC Plant Humid Gas Cleaning Technology**

Projects Include:

- Polishing Desulfurization with Regenerative ZnO-Based Sorbents in Fixed-Bed Systems
- Dechlorination with a Regenerative Sorbent in Fixed-Bed or Moving-Bed Systems
- Ammonia Removal with Once-Through or Regenerative Sorbents in Fixed-Bed Systems
- Trace Metal Removal (Hg, As, Se) Using Regenerative Precious Metal Sorbents in Fixed-Bed Systems
- Simultaneous Removal of HCl and H₂S Using Regenerative Sorbents in Fixed-Bed or Moving-Bed Systems
- CO₂ Capture Using Magnesium-Based Sorbents in Fluid-Bed or Moving-Bed Systems
- CO₂ Capture Using Solvent (Fluorinated Hydrocarbons or Ionic Liquids) in Absorber-Stripper System
- CO₂ Separation in Supported Ionic Liquid Membrane Systems

**NETL's Office of
Research and Development**

DOE Gasification Program Budget

DOE/CF-030
Volume 7

Department of Energy



FY 2009 Congressional Budget Request

Fossil Energy Research and Development

Advanced Integrated Gasification Combined Cycle

February 2008

Office of Chief Financial Officer

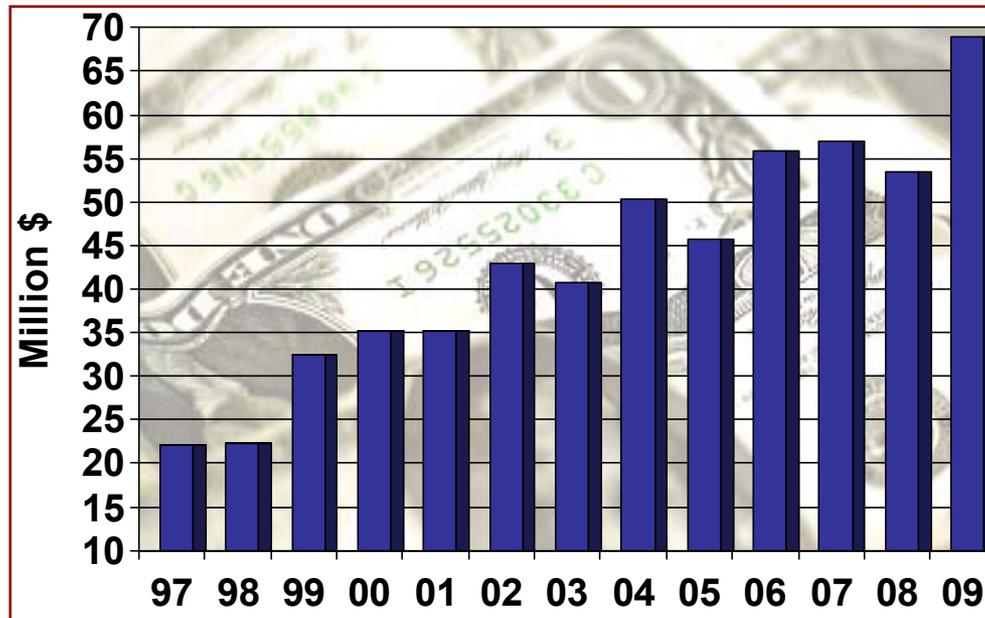
Volume 7

FY08 Gasification Technology Program

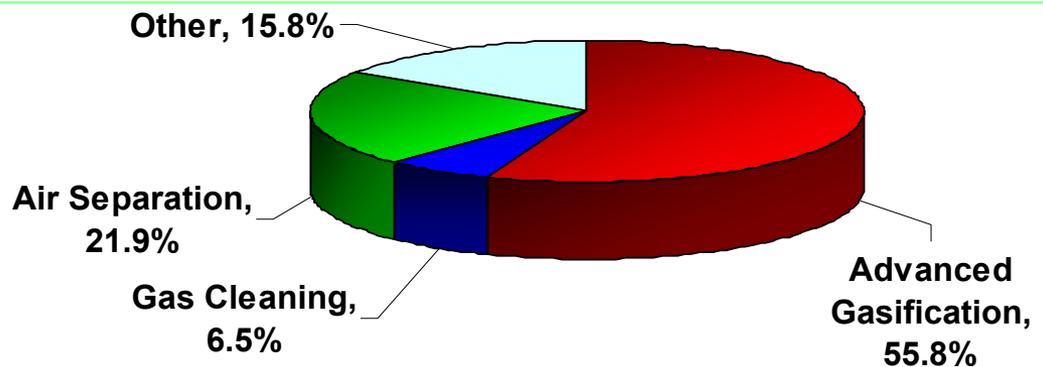
27 Projects

Organizations

• Industry	13
• University	1
• National Laboratories	1
• Non-Profit	3
Total	18

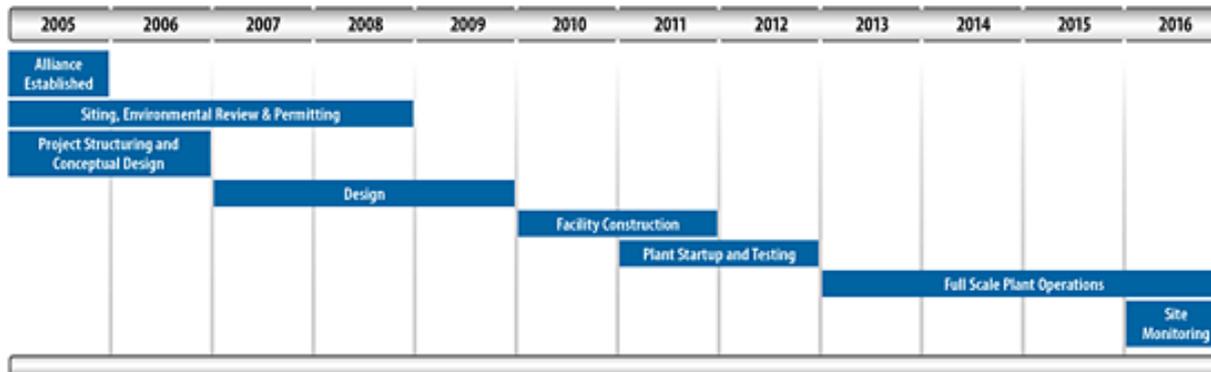
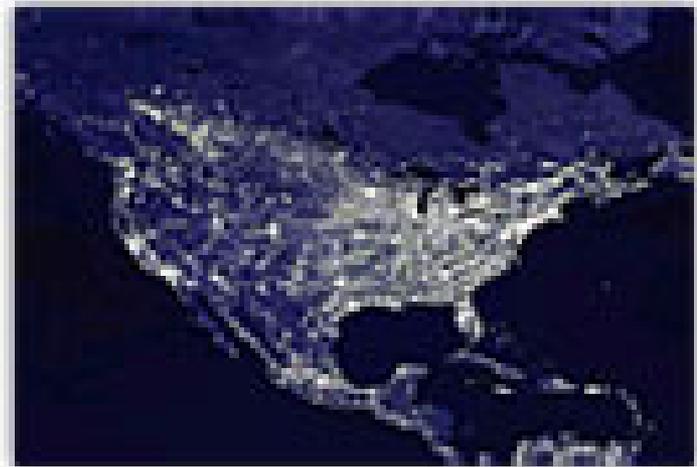
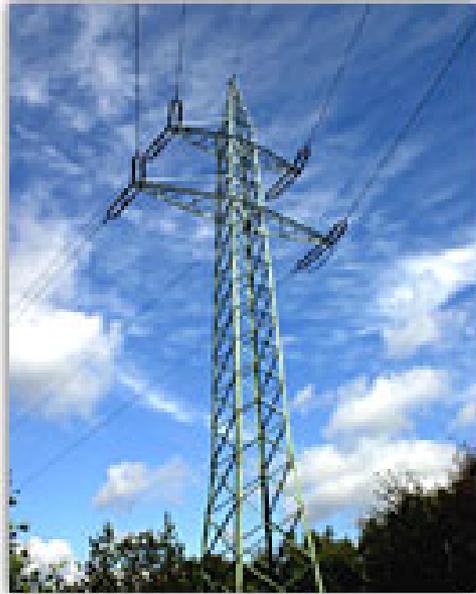


FY08 Budget Allocation

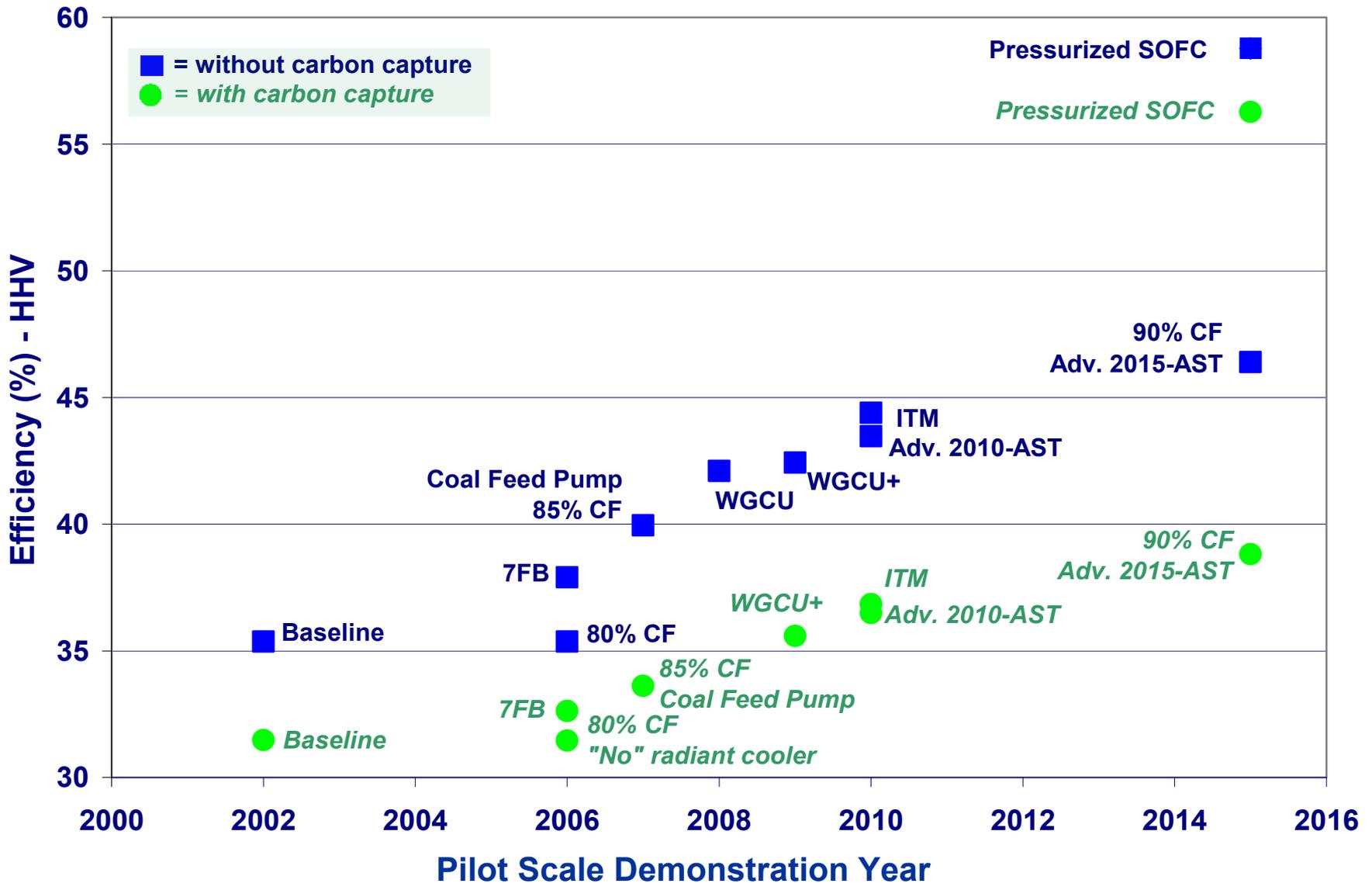


Annual Budget

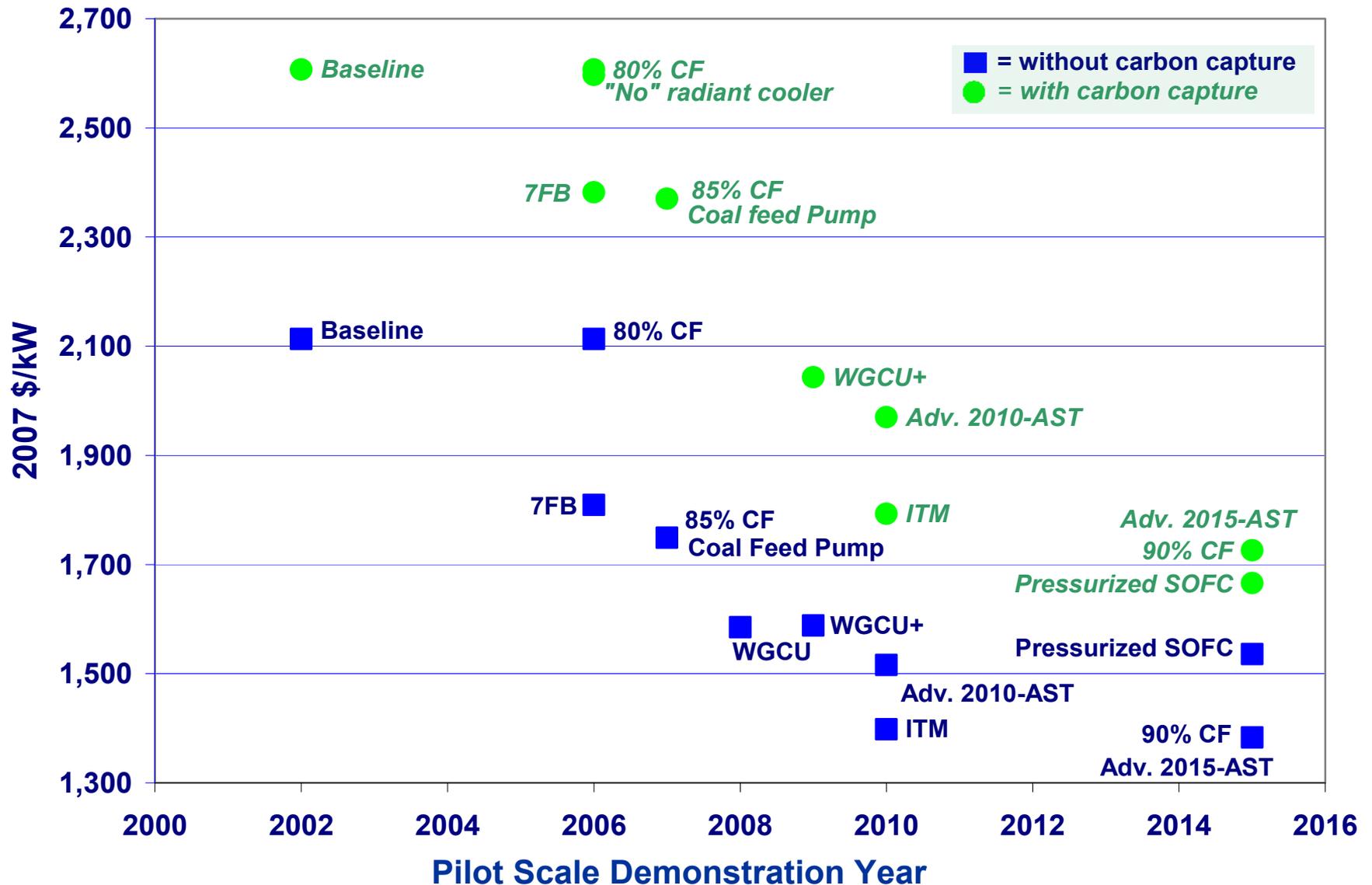
Technology Roadmap Timeline



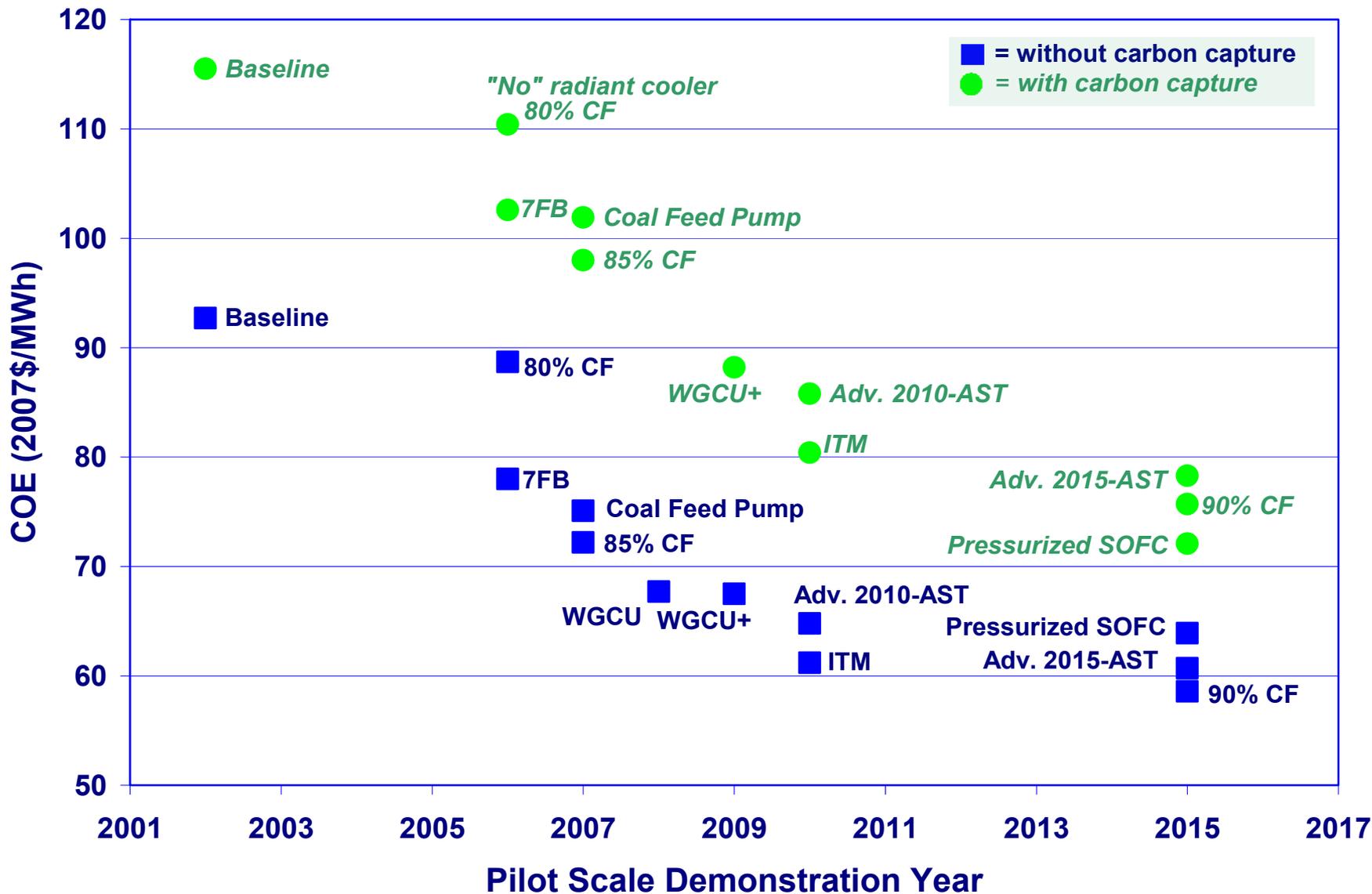
Efficiency Timeline



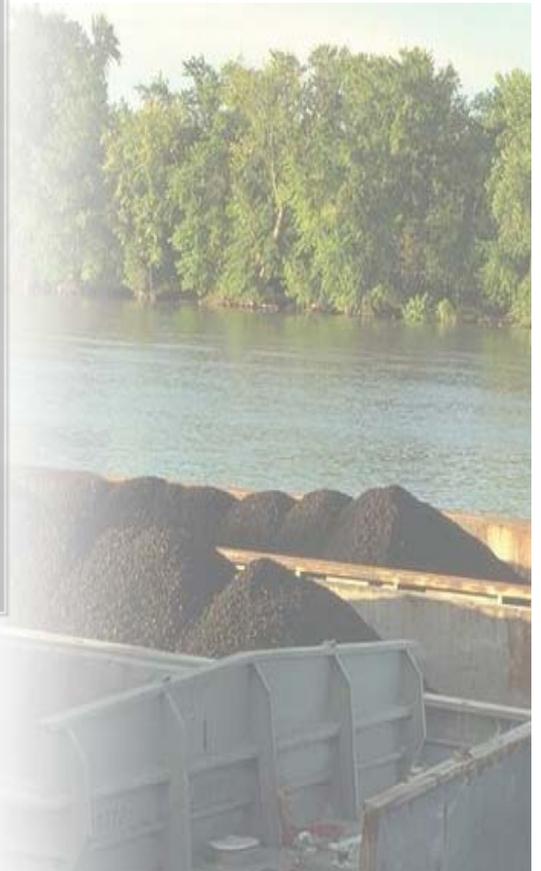
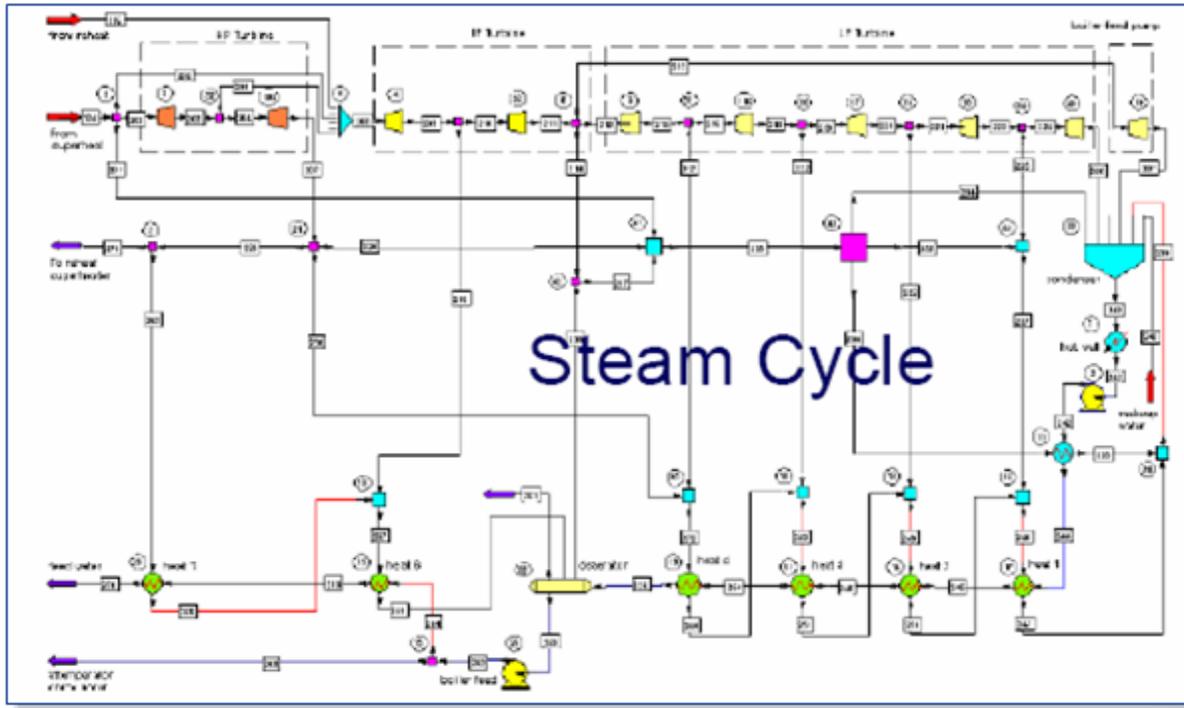
Capital Cost Timeline



COE Timeline



Baseline Analysis



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)	F Class	GE	Selexol / - / Claus	
				Selexol / Selexol / Claus	90%
	CoP E-Gas		MDEA / - / Claus		
			Selexol / Selexol / Claus	88% ¹	
	1800/1000/1000 (CO ₂ capture cases)		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	2400/1050/950	F Class	HRSG		
				- / Econamine / -	90%

¹ CO₂ capture is limited to 88% by syngas CH₄ content

GEE – GE Energy
CoP – Conoco Phillips

Design Basis: Coal Type

Illinois #6 Coal Ultimate Analysis (weight %)

	As Rec'd	Dry
Moisture	11.12	0
Carbon	63.75	71.72
Hydrogen	4.50	5.06
Nitrogen	1.25	1.41
Chlorine	0.29	0.33
Sulfur	2.51	2.82
Ash	9.70	10.91
Oxygen (by difference)	6.88	7.75
	100.0	100.0
HHV (Btu/lb)	11,666	13,126

Environmental Targets

Pollutant	IGCC ¹	PC ²	NGCC ³
SO ₂	0.0128 lb/MMBtu	0.085 lb/MMBtu	< 0.6 gr S /100 scf
NO _x	15 ppmv (dry) @ 15% O ₂	0.07 lb/MMBtu	2.5 ppmv @ 15% O ₂
PM	0.0071 lb/MMBtu	0.017 lb/MMBtu	Negligible
Hg	> 90% capture	1.14 lb/TBtu	Negligible

¹ Based on EPRI's CoalFleet User Design Basis Specification for Coal-Based IGCC Power Plants

² Based on BACT analysis, exceeding new NSPS requirements

³ Based on EPA pipeline natural gas specification and 40 CFR Part 60, Subpart KKKK

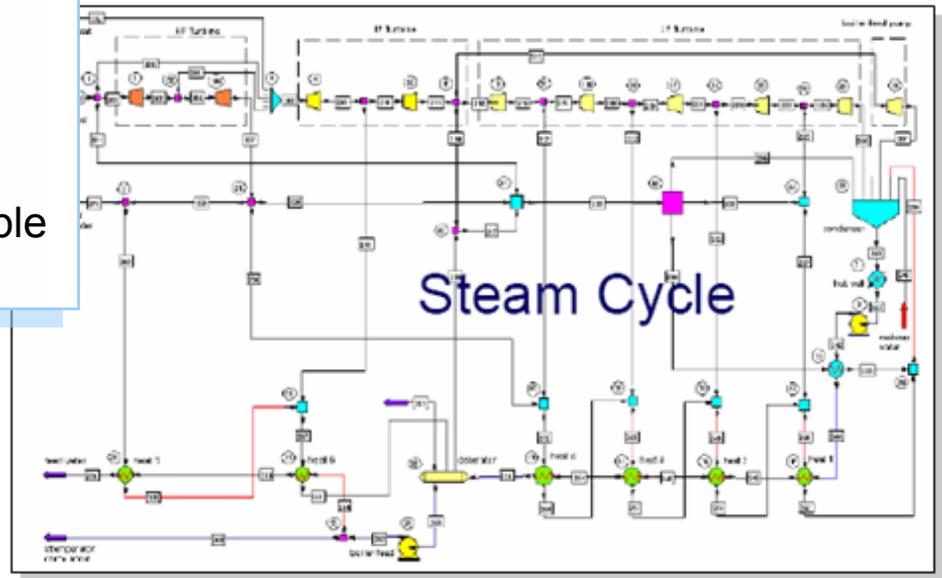
Technical Approach

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/Temperature)
- Sources
 - Parsons
 - Vendor sources where available
- Follow DOE Analysis Guidelines



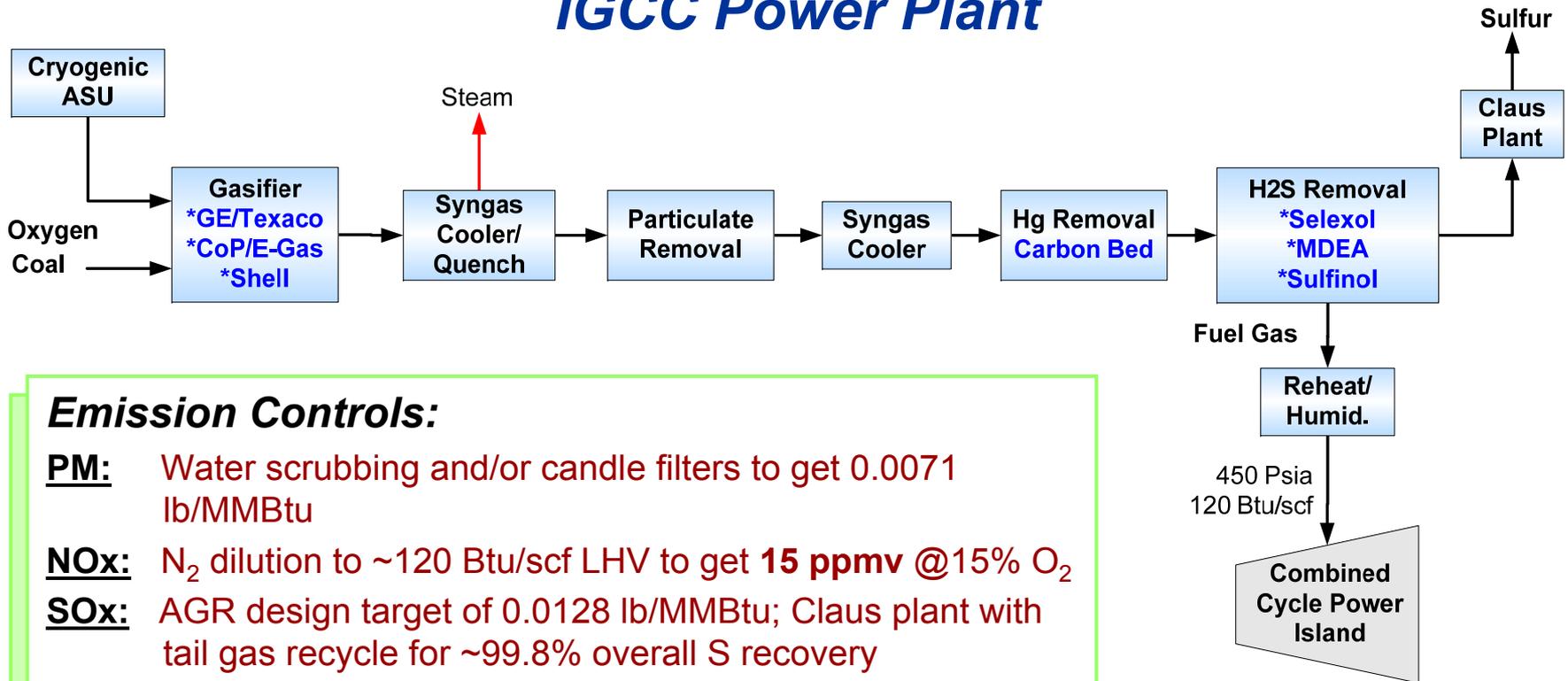
Study Assumptions

- **Capacity Factor = Availability**
 - IGCC capacity factor = 80% w/ no spare gasifier
 - PC and NGCC capacity factor = 85%
- **GE gasifier operated in radiant/quench mode**
- **Shell gasifier with CO₂ capture used water injection for cooling (instead of syngas recycle)**
- **Nitrogen dilution was used to the maximum extent possible in all IGCC cases and syngas humidification/steam injection were used only if necessary to achieve approximately 120 Btu/scf syngas LHV**
- **In CO₂ capture cases, CO₂ was compressed to 2200 psig, transported 50 miles, sequestered in a saline formation at a depth of 4,055 feet and monitored for 80 years**
- **CO₂ transport, storage and monitoring (TS&M) costs were included in the levelized cost of electricity (COE)**

IGCC Power Plant

Current State-of-the-Art

Current Technology IGCC Power Plant



Emission Controls:

PM: Water scrubbing and/or candle filters to get 0.0071 lb/MMBtu

NO_x: N₂ dilution to ~120 Btu/scf LHV to get **15 ppmv @15% O₂**

SO_x: AGR design target of 0.0128 lb/MMBtu; Claus plant with tail gas recycle for ~99.8% overall S recovery

Hg: Activated carbon beds for ~95% removal

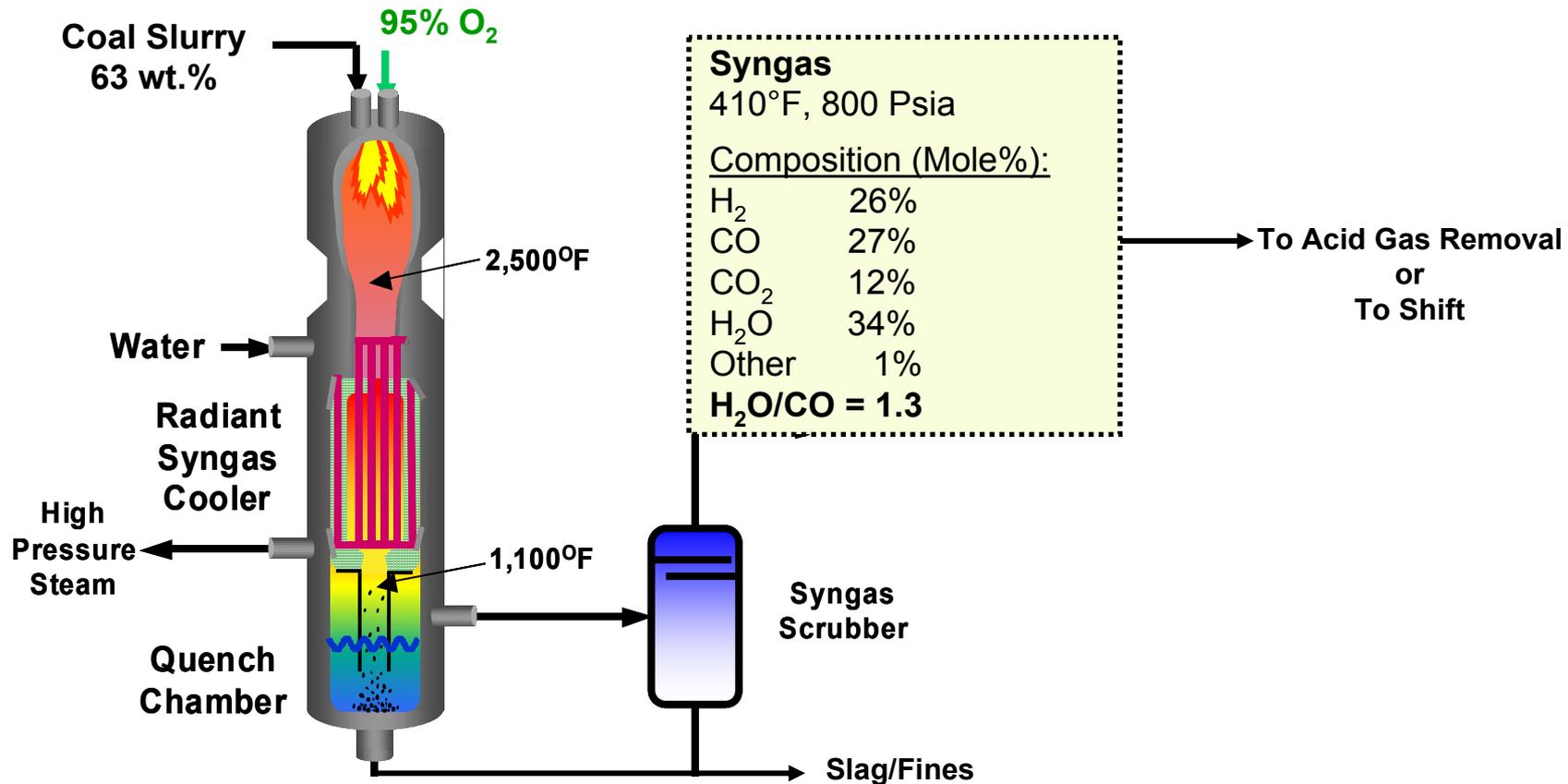
Advanced F-Class CC Turbine: 232 MWe

Steam Conditions:

1800 psig/1050°F/1050°F (non-CO₂ capture cases)

1800 psig/1000°F/1000°F (CO₂ capture cases)

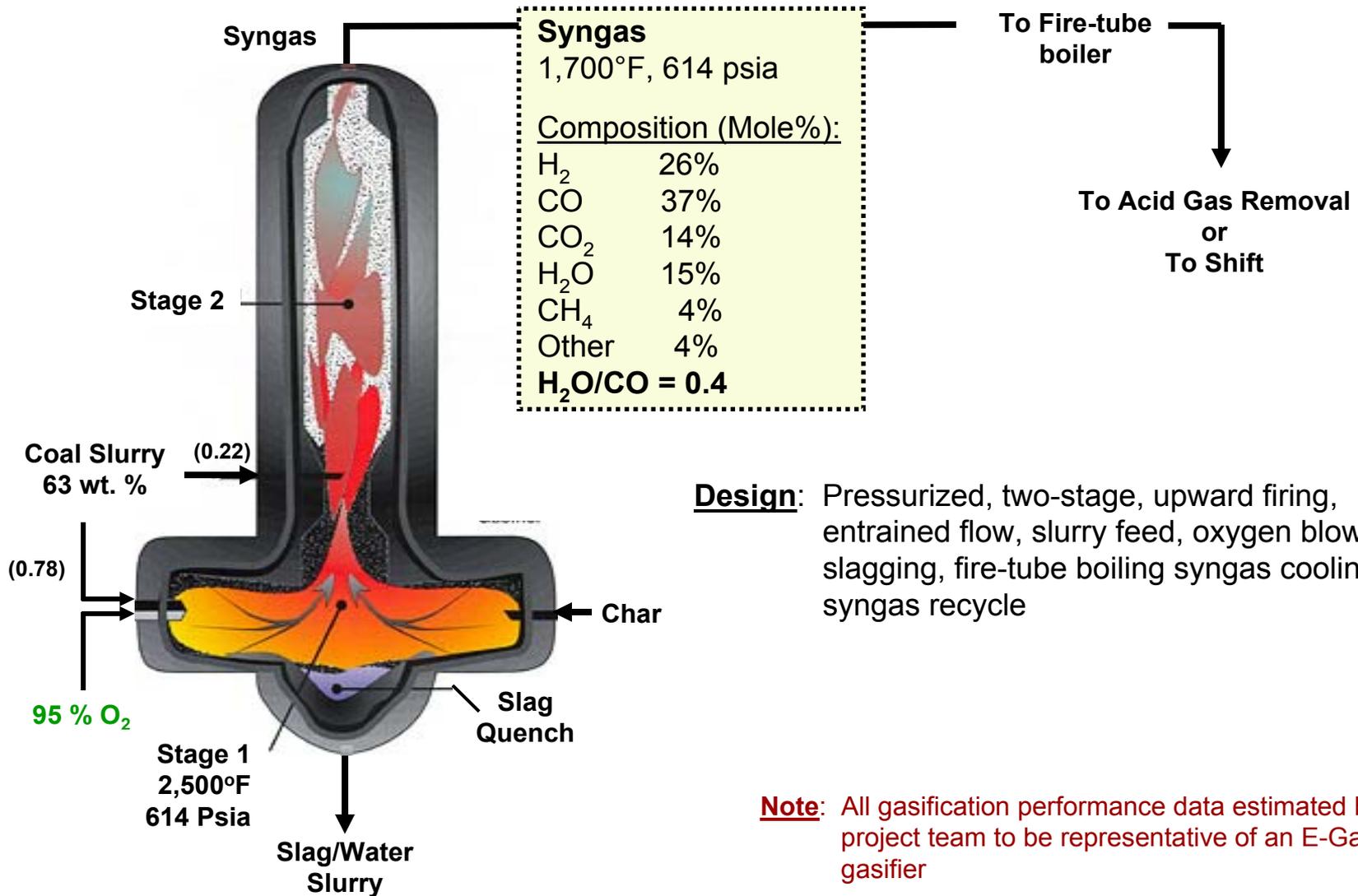
GE Energy Radiant



Design: Pressurized, single-stage, downward firing, entrained flow, slurry feed, oxygen blown, slagging, radiant and quench cooling

Note: All gasification performance data estimated by the project team to be representative of GE gasifier

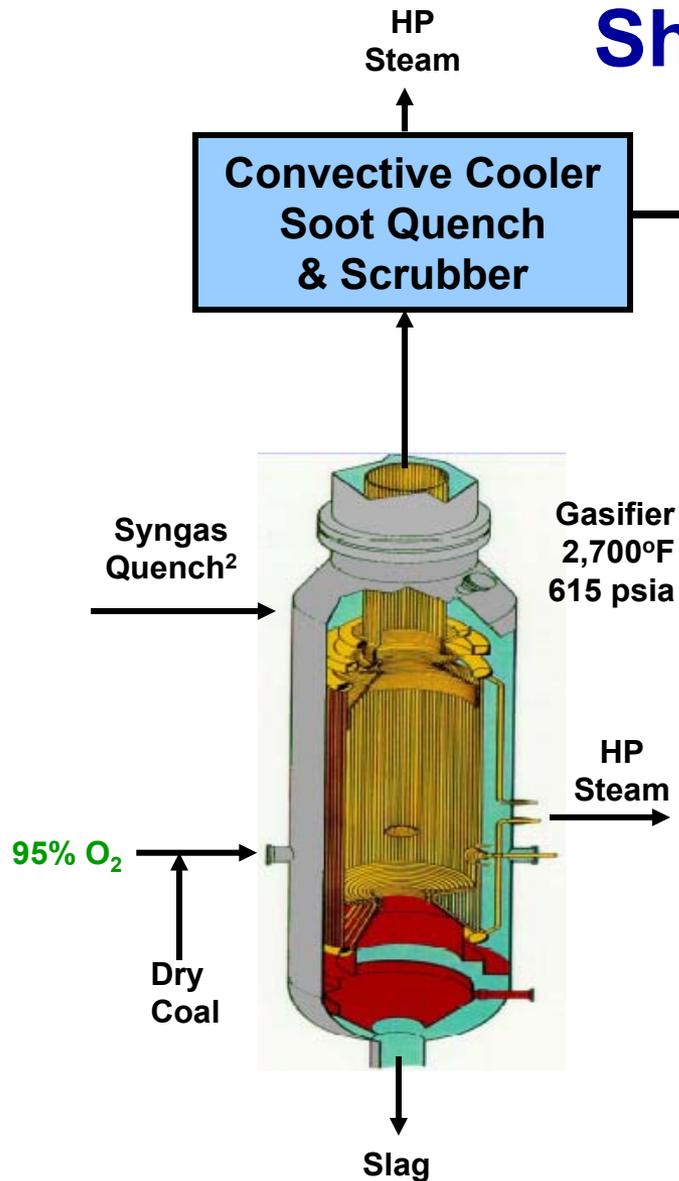
ConocoPhillips E-Gas™



Design: Pressurized, two-stage, upward firing, entrained flow, slurry feed, oxygen blown, slagging, fire-tube boiling syngas cooling, syngas recycle

Note: All gasification performance data estimated by the project team to be representative of an E-Gas gasifier

Shell Gasification



Design: Pressurized, single-stage, downward firing, entrained flow, dry feed, oxygen blown, convective cooler

Notes:

1. All gasification performance data estimated by the project team to be representative of Shell gasifier.
2. CO₂ capture incorporates full water quench instead of syngas quench.

Syngas	
350°F, 600 Psia	
Composition (Mole%):	
H ₂	29%
CO	57%
CO ₂	2%
H ₂ O	4%
Other	8%
H₂O/CO = 0.1	

To Acid Gas Removal
or
To Shift

IGCC Performance Results

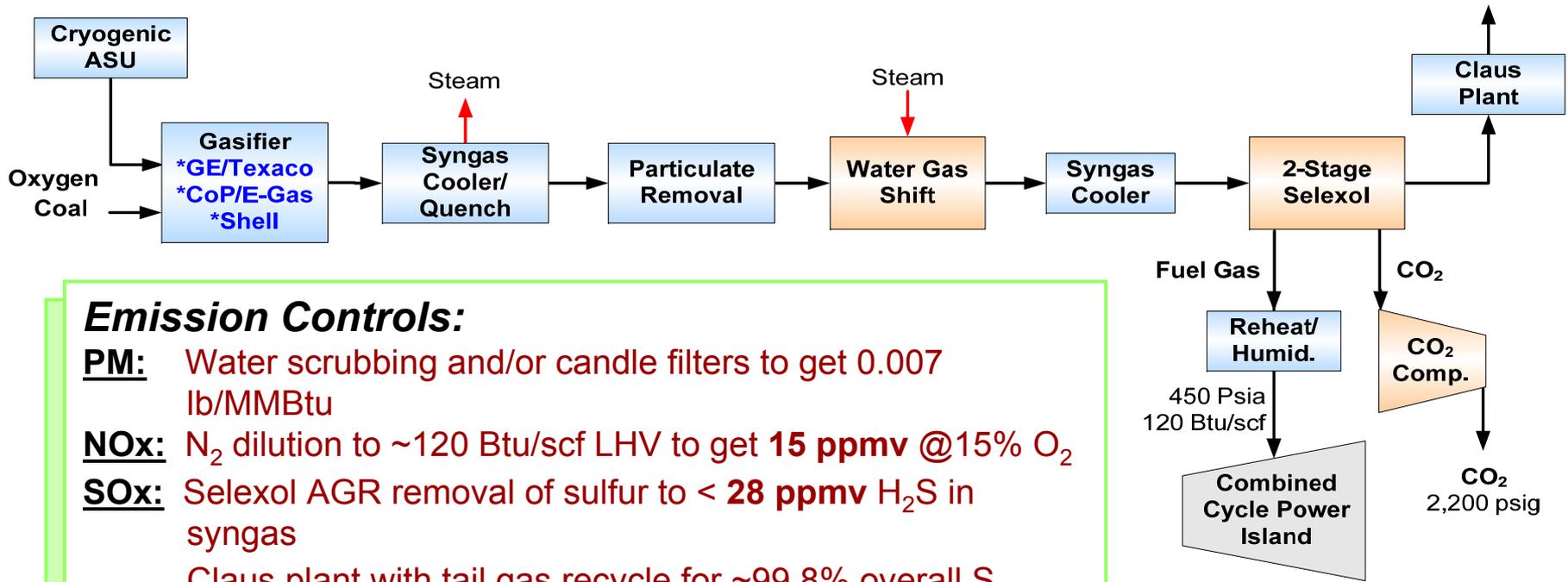
No CO₂ Capture

	GE Energy	E-Gas	Shell
Gross Power (MW)	770	742	748
Auxiliary Power (MW)			
Base Plant Load	23	25	21
Air Separation Unit	103	91	90
Gas Cleanup	4	3	1
Total Aux. Power (MW)	130	119	112
Net Power (MW)	640	623	636
Heat Rate (Btu/kWh)	8,922	8,681	8,306
Efficiency (HHV)	38.2	39.3	41.1

IGCC Power Plant With CO₂ Capture

Current Technology

IGCC Power Plant with CO₂ Scrubbing



Emission Controls:

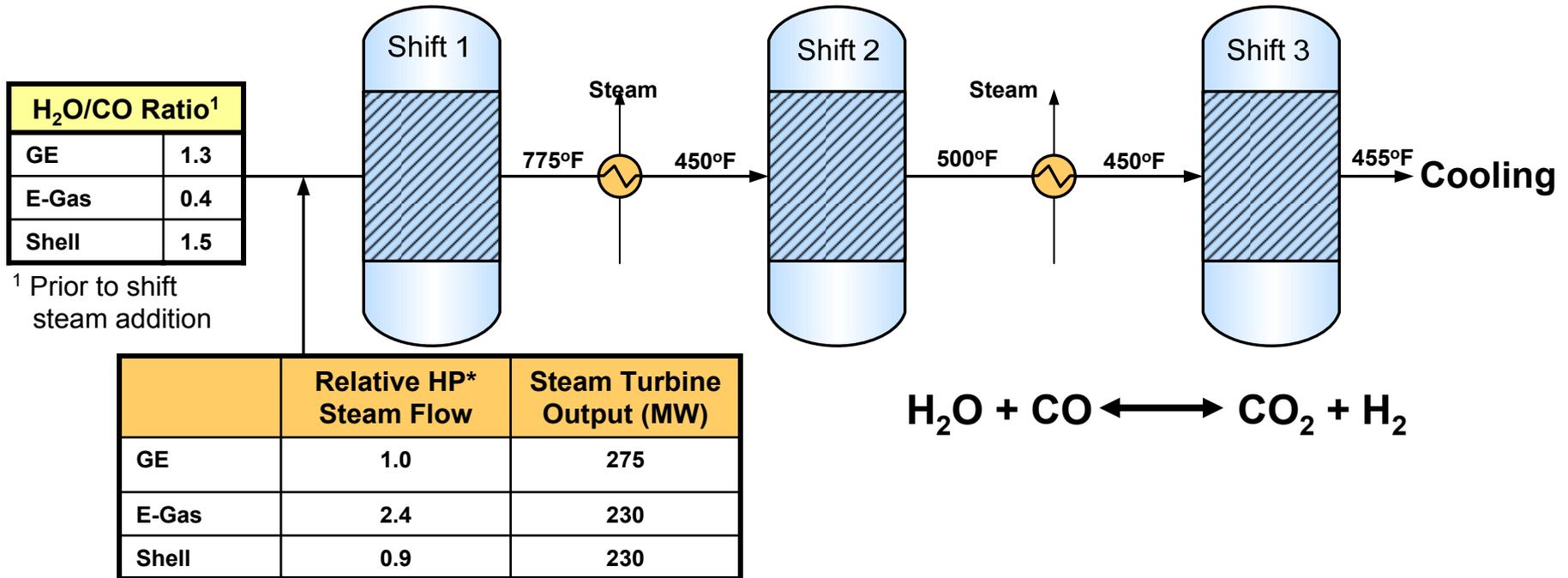
- PM:** Water scrubbing and/or candle filters to get 0.007 lb/MMBtu
- NO_x:** N₂ dilution to ~120 Btu/scf LHV to get **15 ppmv @15% O₂**
- SO_x:** Selexol AGR removal of sulfur to < **28 ppmv H₂S** in syngas
Claus plant with tail gas recycle for ~99.8% overall S recovery
- Hg:** Activated carbon beds for ~95% removal
- Advanced F-Class CC Turbine:** 232 MWe
- Steam Conditions:** 1800 psig/1000°F/1000°F

Gross Power (MW)
 2 Comb. Turbines: 464
 1 Stm. Turb: 230-275
Total Gross: 690-750

Water-Gas Shift Reactor System

Design:

- Haldor Topsoe SSK Sulfur Tolerant Catalyst
- Up to 97.5% CO Conversion
- 2 stages for GE and Shell, 3 stages for E-Gas
- $H_2O/CO = 2.0$ (Project Assumption)
- Overall $\Delta P = \sim 30$ psia



*High Pressure Steam

IGCC Performance Results

	GE Energy	
CO ₂ Capture	NO	YES
Gross Power (MW)	770	745
Auxiliary Power (MW)		
Base Plant Load	23	23
Air Separation Unit	103	121
Gas Cleanup/CO ₂ Capture	4	18
CO ₂ Compression	-	27
Total Aux. Power (MW)	130	189
Net Power (MW)	640	556
Heat Rate (Btu/kWh)	8,922	10,505
Efficiency (HHV)	38.2	32.5
Energy Penalty¹	-	5.7

Steam for Selexol

↑ in ASU air comp.
load w/o CT
integration

Includes H₂S/CO₂
Removal in Selexol
Solvent

¹CO₂ Capture Energy Penalty = Percent points decrease in net power plant efficiency due to CO₂ Capture

IGCC Performance Results

	GE Energy		E-Gas		Shell	
CO₂ Capture	NO	YES	NO	YES	NO	YES
Gross Power (MW)	770	745	742	694	748	693
Auxiliary Power (MW)						
Base Plant Load	23	23	25	26	21	19
Air Separation Unit	103	121	91	109	90	113
Gas Cleanup/CO ₂ Capture	4	18	3	15	1	16
CO ₂ Compression	-	27	-	26	-	28
Total Aux. Power (MW)	130	189	119	176	112	176
Net Power (MW)	640	556	623	518	636	517
Heat Rate (Btu/kWh)	8,922	10,505	8,681	10,757	8,306	10,674
Efficiency (HHV)	38.2	32.5	39.3	31.7	41.1	32.0
Energy Penalty¹	-	5.7	-	7.6	-	9.1

¹CO₂ Capture Energy Penalty = Percent points decrease in net power plant efficiency due to CO₂ Capture

IGCC Key Points

IGCC

- HHV efficiency = 38-41% (Supercritical PC is 39.1%)

IGCC with CO₂ Capture

- CO₂ capture reduces efficiency by 6-9 percentage points
- 5-7 percentage points higher than PC with CO₂ capture
- 11-12 percentage points lower than NGCC with CO₂ capture

R&D can increase competitiveness and reduce costs

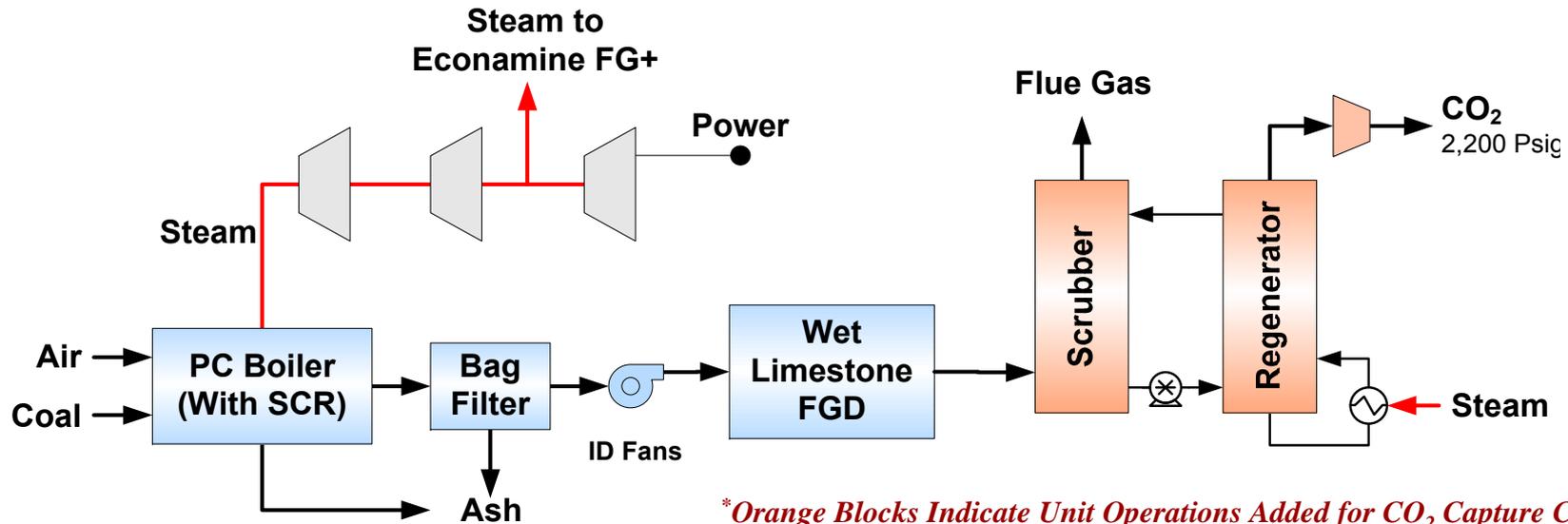
- Reduced ASU cost (membranes)
- Warm gas cleaning for sulfur removal
- Improved gasifier performance
 - carbon conversion, throughput, RAM
- Advanced carbon sorbents and solvents
- High-temperature membranes for shift and CO₂ separation
- Co-sequestration

Comparison to PC and NGCC

Current State-of-the-Art

Current Technology

*Pulverized Coal Power Plant**



PM Control: Baghouse to achieve 0.013 lb/MMBtu (99.8% removal)

SO_x Control: FGD to achieve 0.085 lb/MMBtu (98% removal)

NO_x Control: LNB + OFA + SCR to maintain 0.07 lb/MMBtu

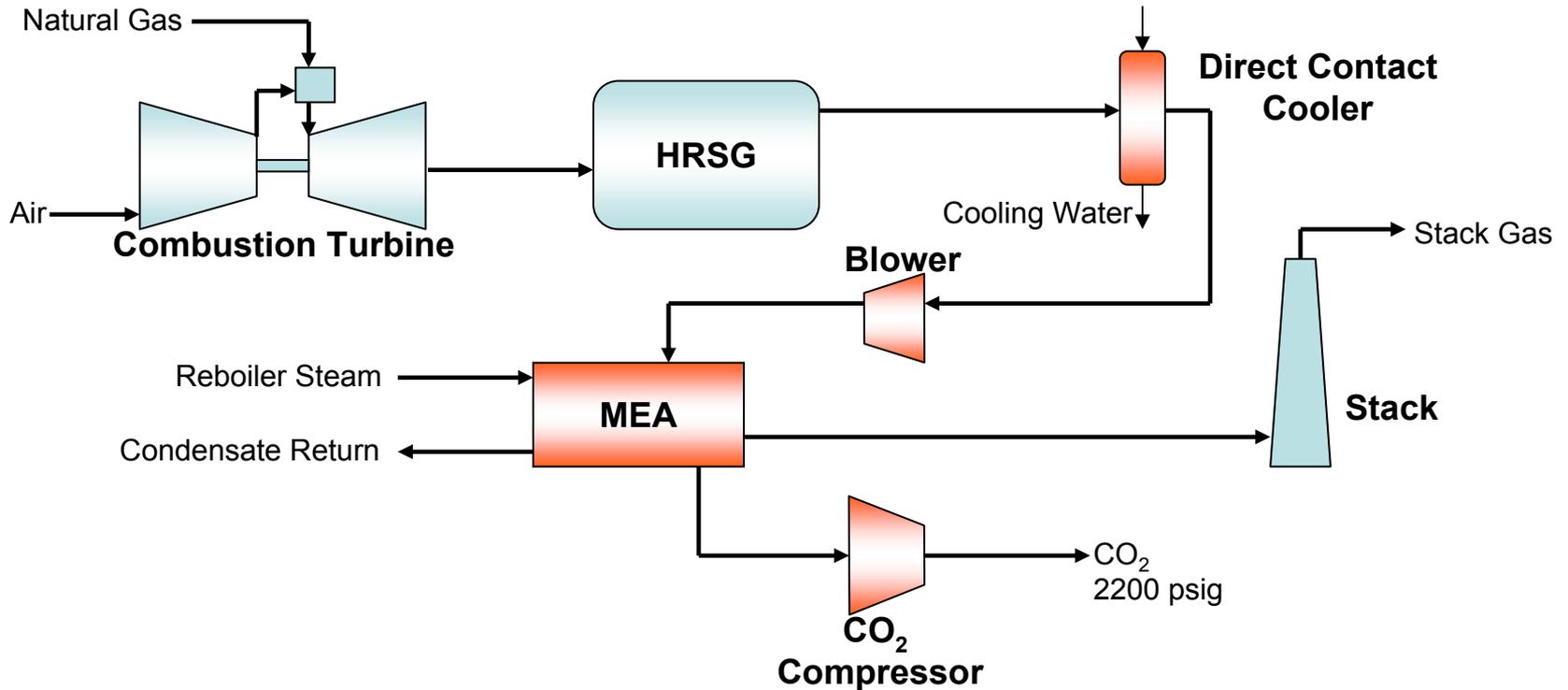
Mercury Control: Co-benefit capture ~90% removal

Steam Conditions (Sub): 2400 psig/1050°F/1050°F

Steam Conditions (SC): 3500 psig/1100°F/1100°F

Current Technology

Natural Gas Combined Cycle*



**Orange Blocks Indicate Unit Operations Added for CO₂ Capture Case*

NO_x Control: LNB + SCR to maintain 2.5 ppmvd @ 15% O₂

Steam Conditions: 2400 psig/1050°F/950°F

PC and NGCC Performance Results

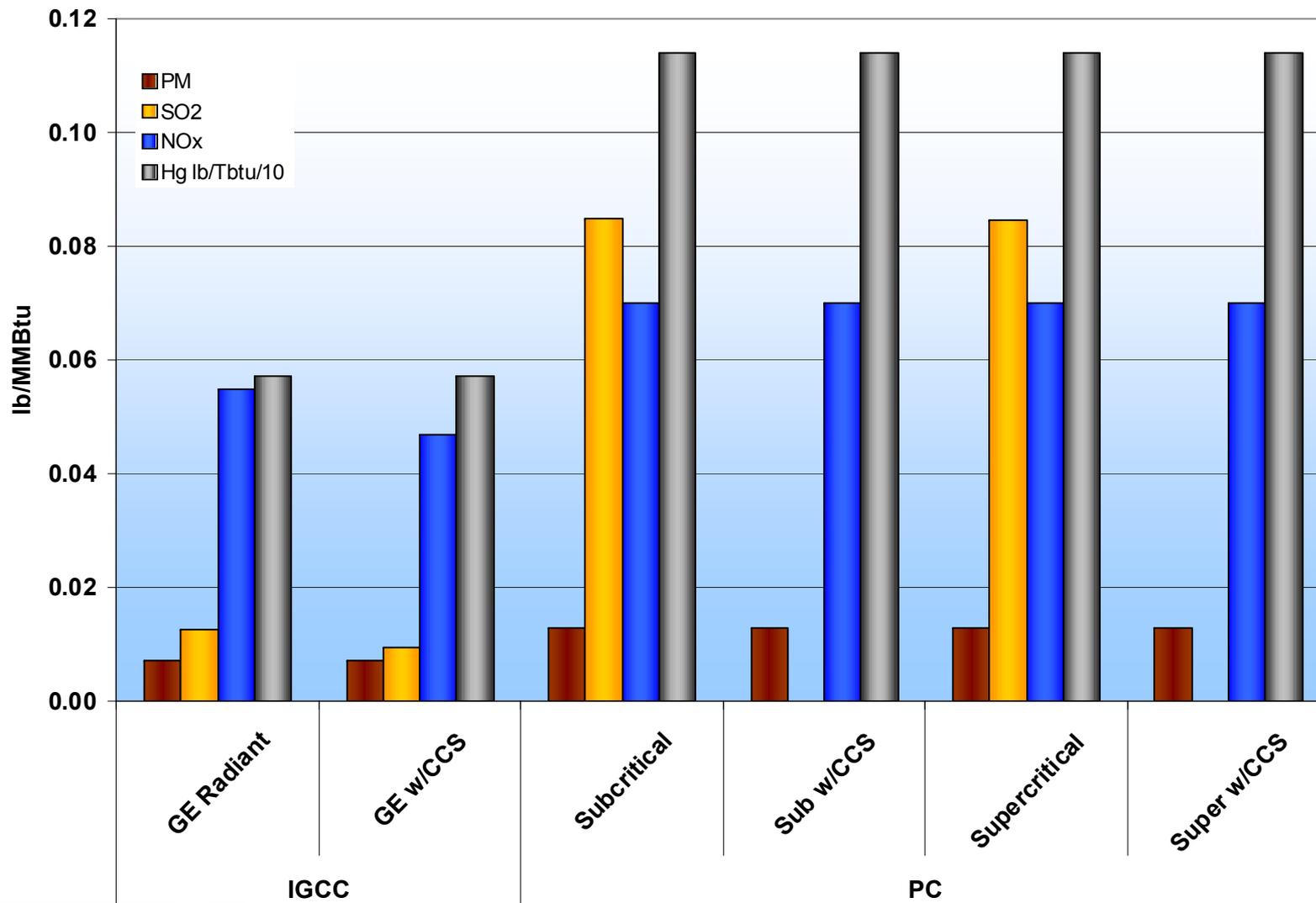
	Subcritical		Supercritical		NGCC	
CO ₂ Capture	NO	YES	NO	YES	NO	YES
Gross Power (MW)	583	680	580	663	570	520
Base Plant Load	29	48	26	43	10	13
Gas Cleanup/CO ₂ Capture	4	30	4	27	0	10
CO ₂ Compression	-	52	-	47	0	15
Total Aux. Power (MW)	33	130	30	117	10	38
Net Power (MW)	550	550	550	546	560	482
Heat Rate (Btu/kWh)	9,276	13,724	8,721	12,534	6,720	7,813
Efficiency (HHV)	36.8	24.9	39.1	27.2	50.8	43.7
Energy Penalty¹	-	11.9	-	11.9	-	7.1

¹CO₂ Capture Energy Penalty = Percent points decrease in net power plant efficiency due to CO₂ Capture

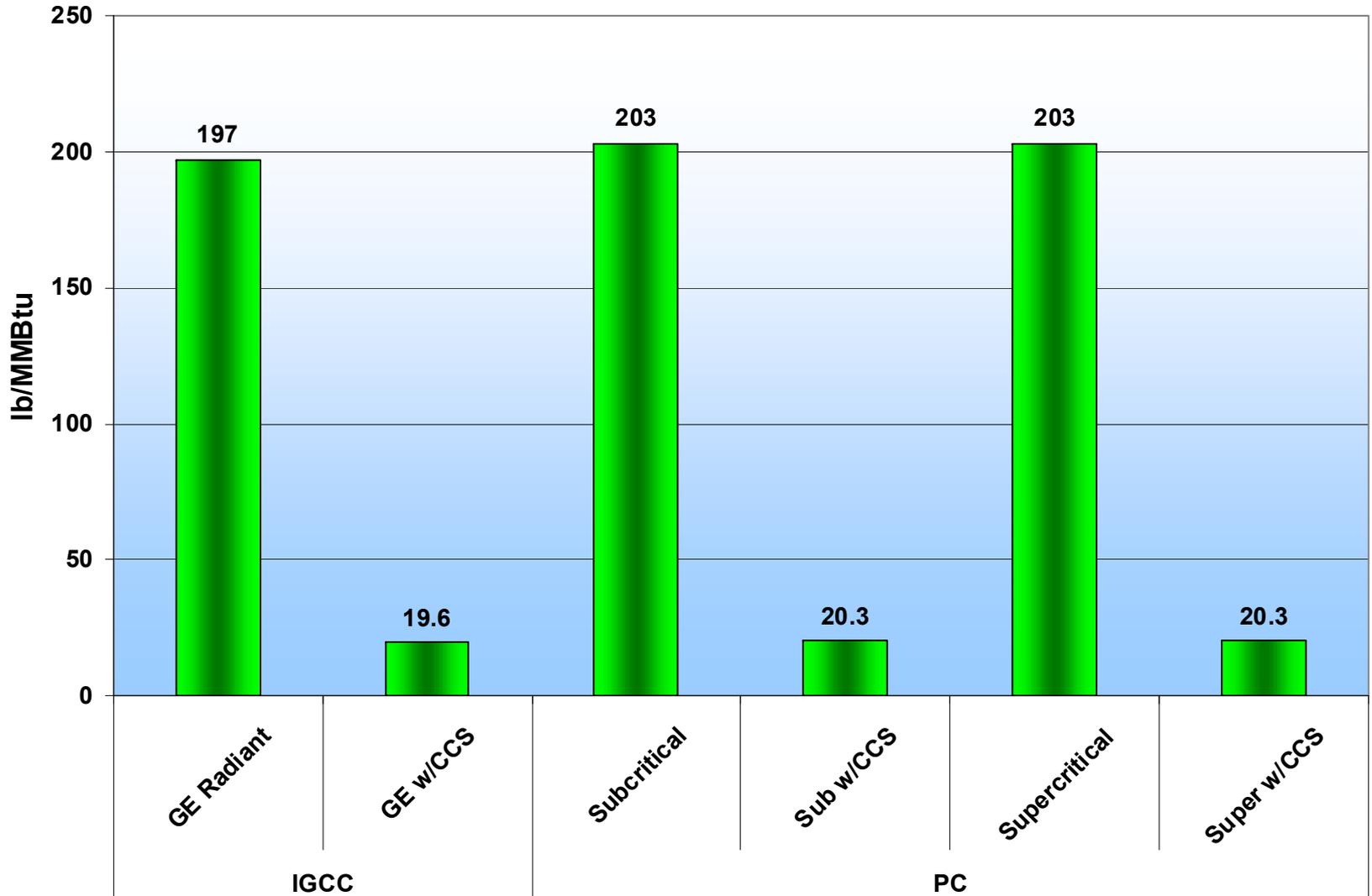
Environmental Performance Comparison

IGCC, PC and NGCC

Criteria Pollutant Emissions for All Cases



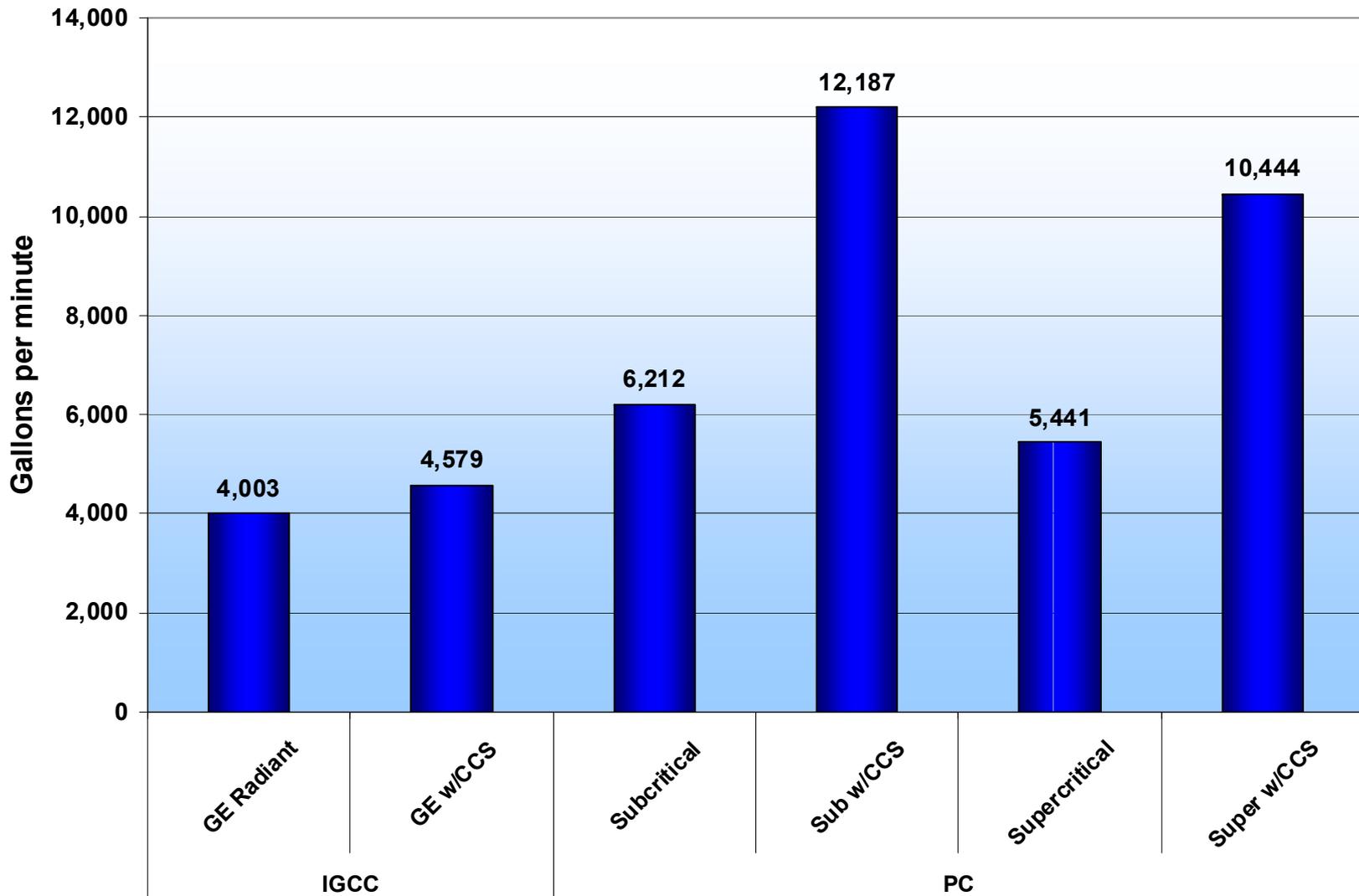
CO₂ Emissions for All Cases



Raw Water Usage Comparison

IGCC, PC and NGCC

Raw Water Usage Comparison



Economic Results for All Cases

Economic Assumptions

Startup	2010
Plant Life (Years)	20
Capital Charge Factor	
High Risk	
(All IGCC, PC/NGCC with CO₂ capture)	17.5
Low Risk	
(PC/NGCC without CO₂ capture)	16.4
Dollars (Constant)	2007
Coal (\$/MM Btu)	1.80
Natural Gas (\$/MM Btu)	6.75
Capacity Factor	
IGCC	80
PC/NGCC	85

IGCC Economic Results

No CO₂ Capture

	GE Energy	E-Gas	Shell
Plant Cost (\$/kWe)¹			
Base Plant	1,323	1,272	1,522
Air Separation Unit	287	264	256
Gas Cleanup	203	197	199
Total Plant Cost (\$/kWe)	1,813	1,733	1,977
Capital COE (¢/kWh)	4.53	4.33	4.94
Variable COE (¢/kWh)	3.27	3.19	3.11
Total COE² (¢/kWh)	7.80	7.52	8.05

¹Total Plant Capital Cost (Includes contingencies and engineering fees)

²January 2007 Dollars, 80% Capacity Factor, 17.5% Capital Charge Factor, Coal cost \$1.80/10⁶Btu

IGCC Economic Results

	GE Energy		E-Gas		Shell	
CO ₂ Capture	NO	YES	NO	YES	NO	YES
Plant Cost (\$/kWe)¹						
Base Plant	1,323	1,566	1,272	1,592	1,522	1,817
Air Separation Unit	287	342	264	329	256	336
Gas Cleanup/CO ₂ Capture	203	414	197	441	199	445
CO ₂ Compression	-	68	-	69	-	70
Total Plant Cost (\$/kWe)	1,813	2,390	1,733	2,431	1,977	2,668
Capital COE (¢/kWh)						
Capital COE (¢/kWh)	4.53	5.97	4.33	6.07	4.94	6.66
Variable COE (¢/kWh)	3.27	3.93	3.20	4.09	3.11	3.97
CO₂ TS&M COE (¢/kWh)	0.00	0.39	0.00	0.41	0.00	0.41
Total COE² (¢/kWh)	7.80	10.29	7.53	10.57	8.05	11.04
Increase in COE (%)	-	32	-	40	-	37
\$/tonne CO₂ Avoided	-	35	-	45	-	46

¹Total Plant Capital Cost (Includes contingencies and engineering fees)

²January 2007 Dollars, 80% Capacity Factor, 17.5% Capital Charge Factor, Coal cost \$1.80/10⁶Btu

PC and NGCC Economic Results

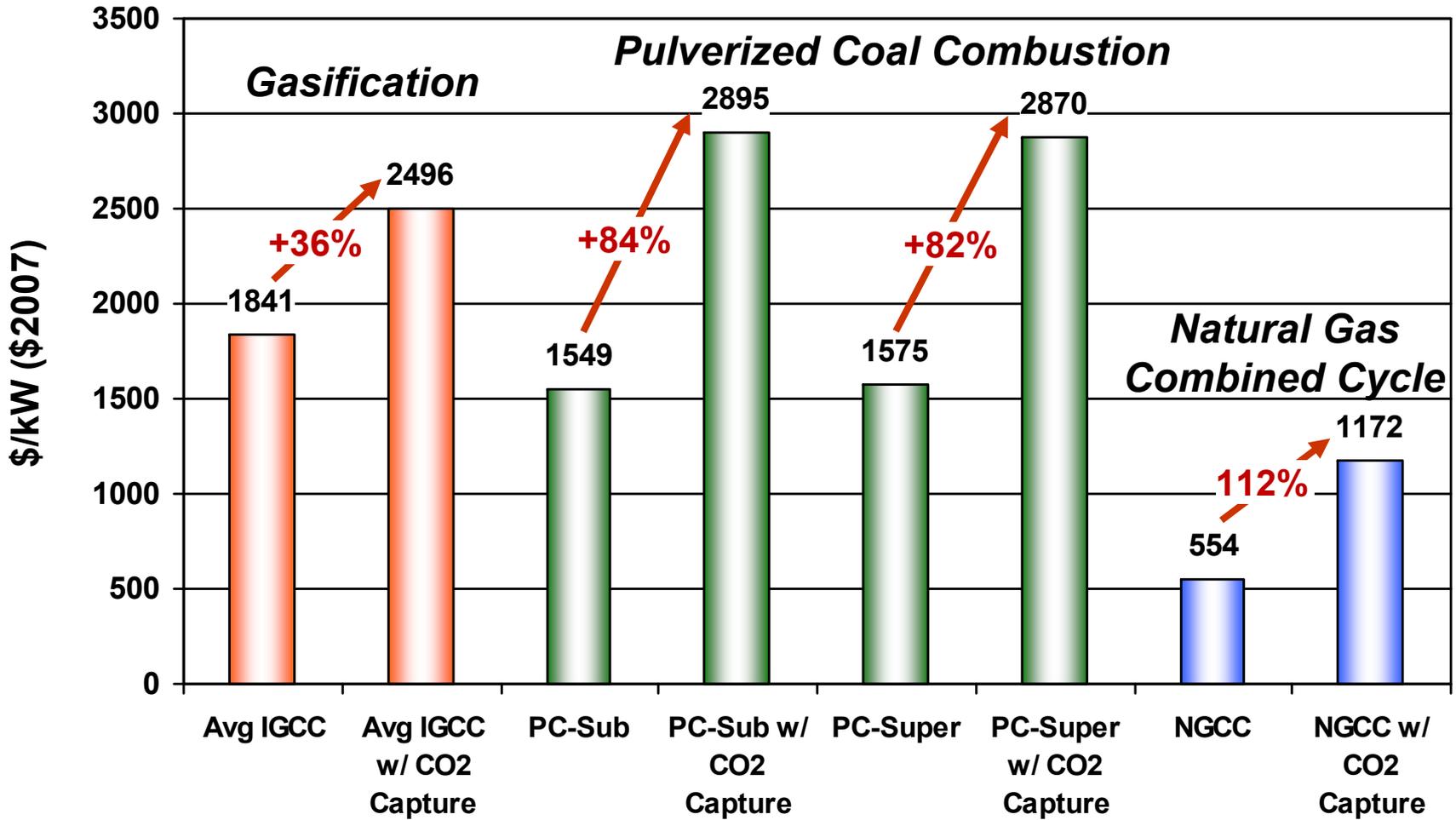
	Subcritical		Supercritical		NGCC	
CO ₂ Capture	NO	YES	NO	YES	NO	YES
Plant Cost (\$/kWe)¹						
Base Plant	1,302	1,689	1,345	1,729	554	676
Gas Cleanup (SOx/NOx)	246	323	229	302	-	-
CO ₂ Capture	-	792	-	752	-	441
CO ₂ Compression	-	89	-	85	-	52
Total Plant Cost (\$/kWe)	1,549	2,895	1,575	2,870	554	1,172
Capital COE (¢/kWh)						
Capital COE (¢/kWh)	3.41	6.81	3.47	6.75	1.22	2.75
Variable COE (¢/kWh)	2.99	4.64	2.86	4.34	5.62	6.70
CO₂ TS&M COE (¢/kWh)	0.00	0.43	0.00	0.39	0.00	0.29
Total COE² (¢/kWh)	6.40	11.88	6.33	11.48	6.84	9.74
Increase in COE (%)	-	85	-	81	-	43
\$/tonne CO₂ Avoided	-	75	-	75	-	91

¹Total Plant Capital Cost (Includes contingencies and engineering fees)

²January 2007 Dollars, 85% Capacity Factor, 16.4% (no capture) 17.5% (capture) Capital Charge Factor, Coal cost \$1.80/10⁶Btu, Natural Gas cost \$6.75/10⁶Btu

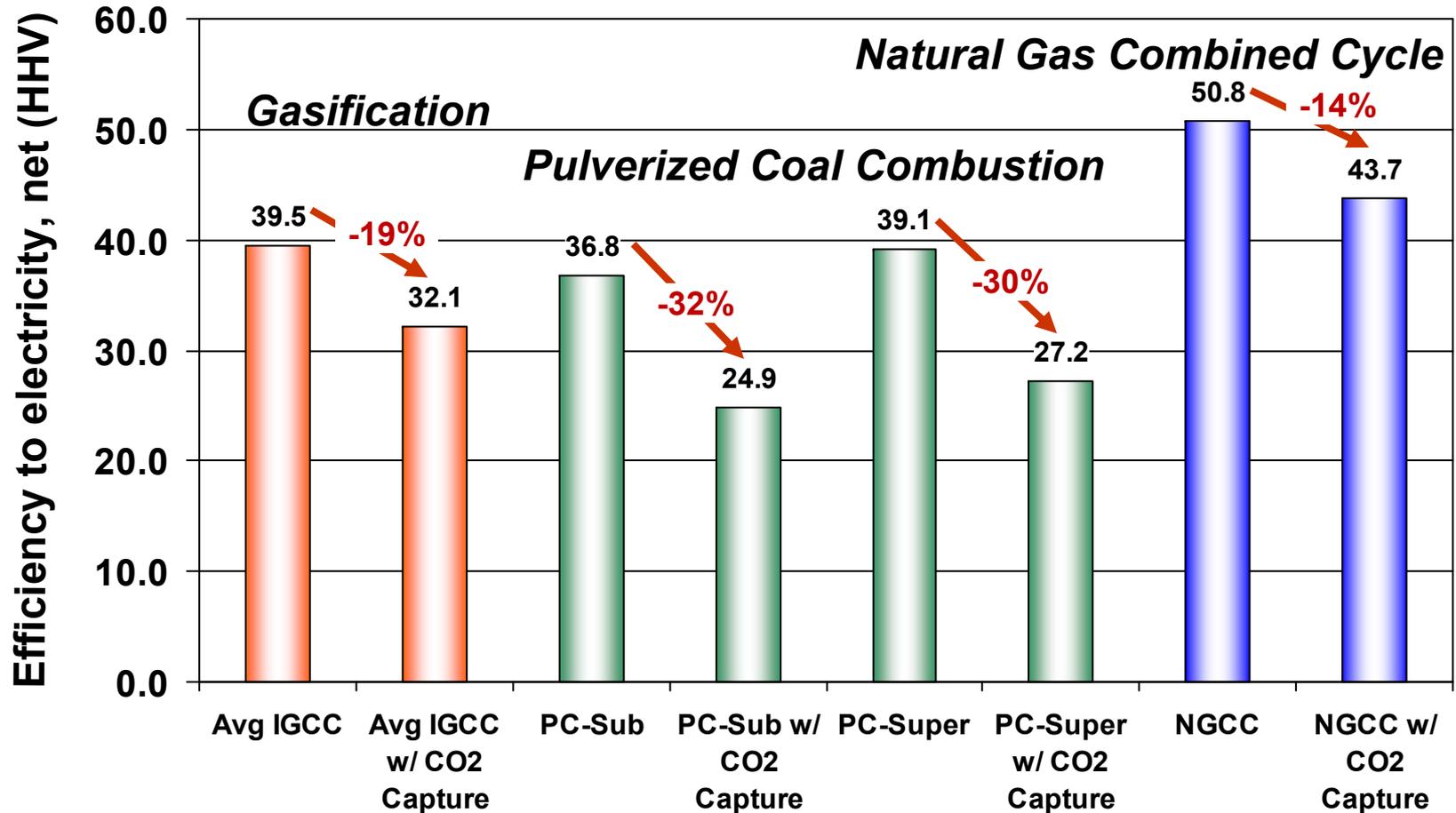
Capturing CO₂ with Today's Technology is Expensive

Total Plant Cost Comparison



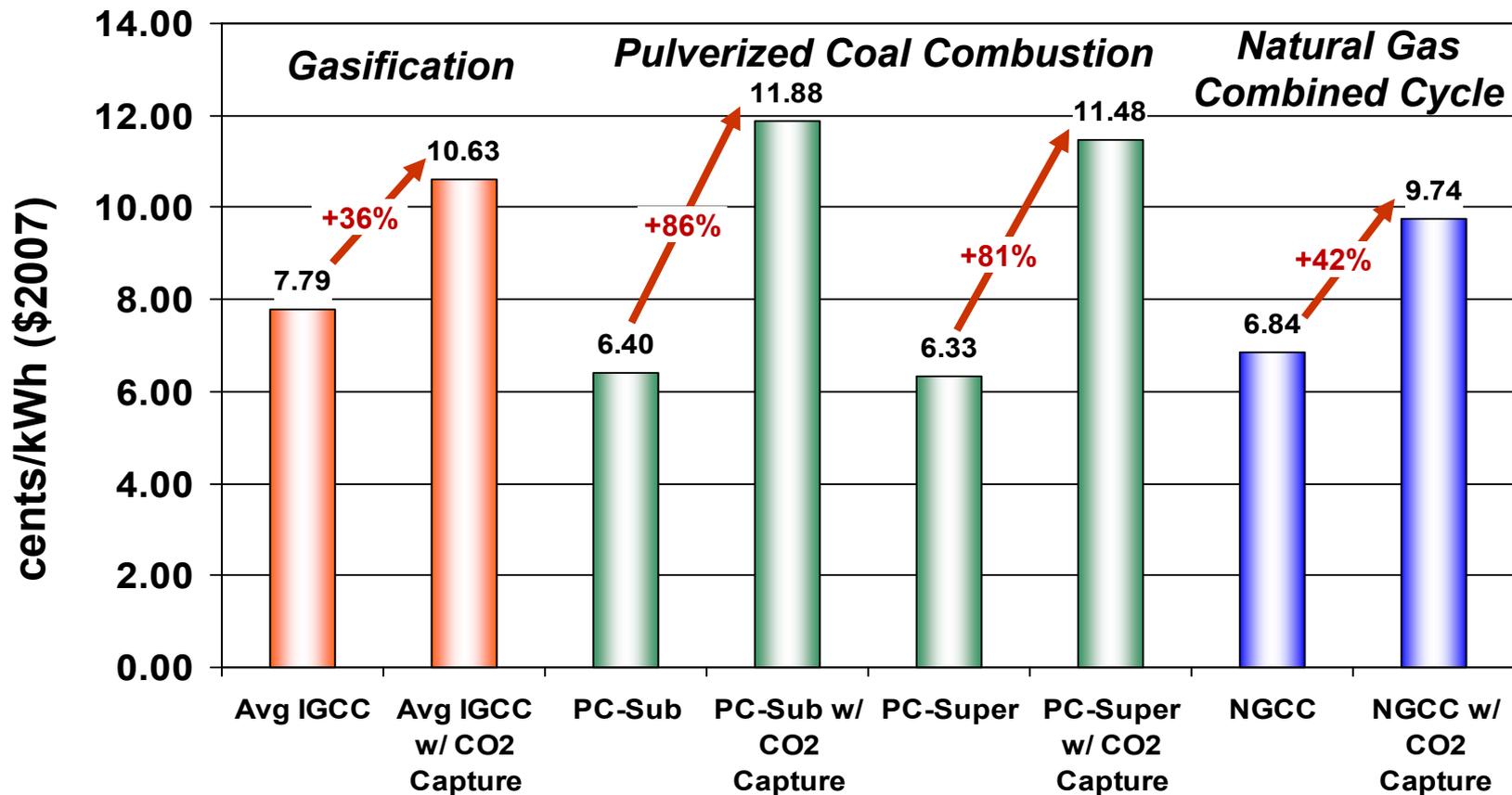
Total Plant Capital Cost includes contingencies and engineering fees

Capturing CO₂ with Today's Technology Significantly Reduces Plant Efficiency



Capturing CO₂ with Today's Technology is Expensive

Cost of Electricity Comparison



... the Benefits

GASIFICATION

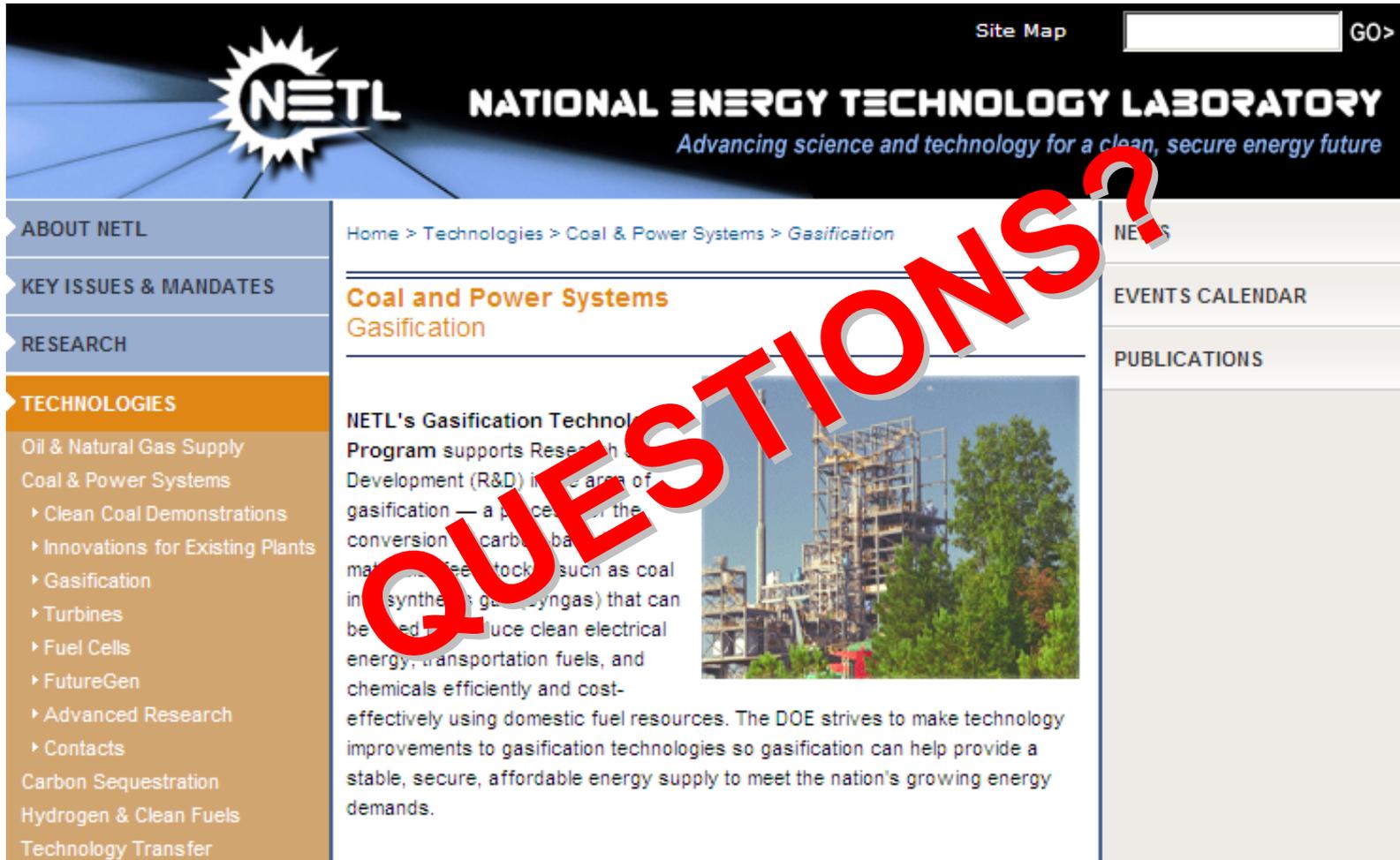
- **Stable, affordable, high-efficiency energy supply with a minimal environmental impact**
- **Feedstock Flexibility/Product Flexibility**
- **Flexible applications for new power generation, as well as for repowering older coal-fired plants**

BIG PICTURE

- **Energy Security -- Maintain coal as a significant component in the US energy mix**
- **A Cleaner Environment (reduced emissions of pollutants)**
 - **The most economical technology for CO₂ capture**
- **Ultra-clean Liquids from Coal -- Early Source of Hydrogen**

Visit NETL Gasification Website

www.netl.doe.gov/technologies/coalpower/gasification/index.html



The screenshot shows the NETL website interface. At the top, the NETL logo is on the left, and the text "NATIONAL ENERGY TECHNOLOGY LABORATORY" and "Advancing science and technology for a clean, secure energy future" is on the right. A "Site Map" link and a search box with "GO" are also visible. The left sidebar contains a navigation menu with categories: ABOUT NETL, KEY ISSUES & MANDATES, RESEARCH, TECHNOLOGIES (highlighted), Oil & Natural Gas Supply, Coal & Power Systems (with sub-items: Clean Coal Demonstrations, Innovations for Existing Plants, Gasification, Turbines, Fuel Cells, FutureGen, Advanced Research, Contacts), Carbon Sequestration, Hydrogen & Clean Fuels, and Technology Transfer. The main content area shows a breadcrumb trail: Home > Technologies > Coal & Power Systems > Gasification. Below this is the heading "Coal and Power Systems Gasification" and a photograph of an industrial gasification plant. The text below the photo reads: "NETL's Gasification Technology Program supports Research and Development (R&D) in the area of gasification — a process for the conversion of carbon-based materials (feedstock) such as coal into synthetic gas (syngas) that can be used to produce clean electrical energy, transportation fuels, and chemicals efficiently and cost-effectively using domestic fuel resources. The DOE strives to make technology improvements to gasification technologies so gasification can help provide a stable, secure, affordable energy supply to meet the nation's growing energy demands."

QUESTIONS?