NATIONAL ENERGY TECHNOLOGY LABORATORY

Gasification — Versatile Solutions

DOE's Gasification Program Overview – v1

Gary J. Stiegel

Gasification Technology Manager

Presentation Outline

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

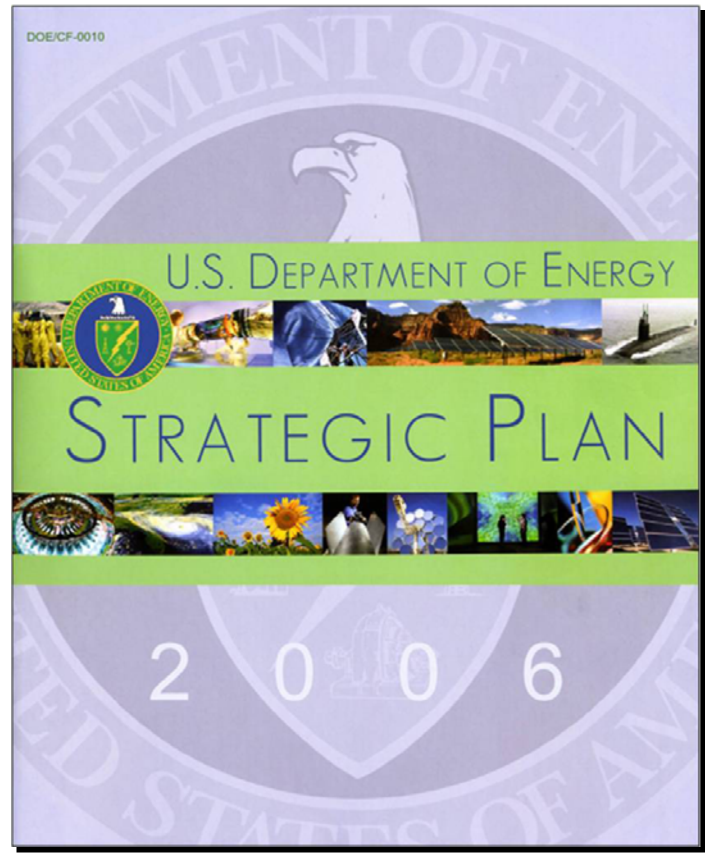
Why the Interest in Gasification?

- **Continuing high price of fuels**
  - Natural gas & Highway transportation fuels
- **Energy Security**
- **Gasification is baseline technology for H_2, SNG, fuels from coal, and capture of CO_2 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 CO_2 controls**
- **Potential for performance guarantees**

U. S. Department of Energy Strategic Plan

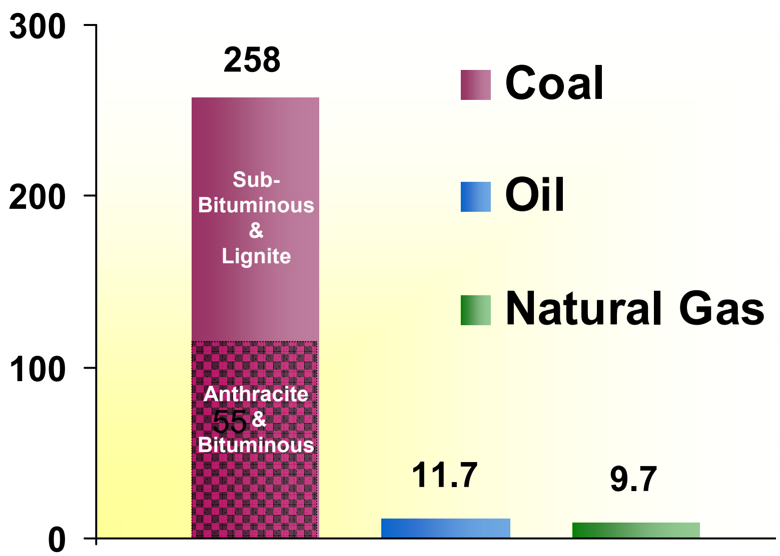
Energy Security - Promoting America's energy security through reliable, clean, and affordable energy

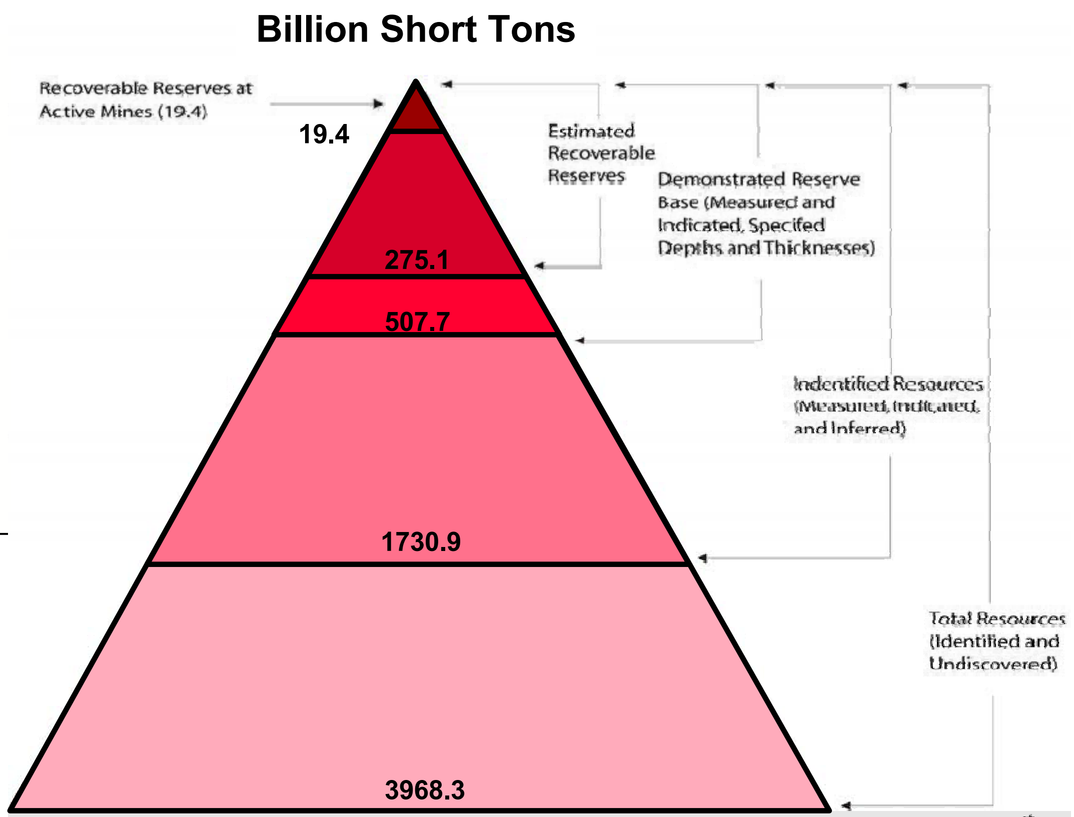
- ***Energy Diversity*** – Increase our energy options and reduce dependence on oil, thereby reducing vulnerability to disruption and increasing the flexibility of the market to meet U.S. needs.
- ***Environmental Impacts of Energy*** – Improve the quality of the environment by reducing greenhouse gas 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.



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

U.S. Fossil Fuel Reserves / Production Ratio





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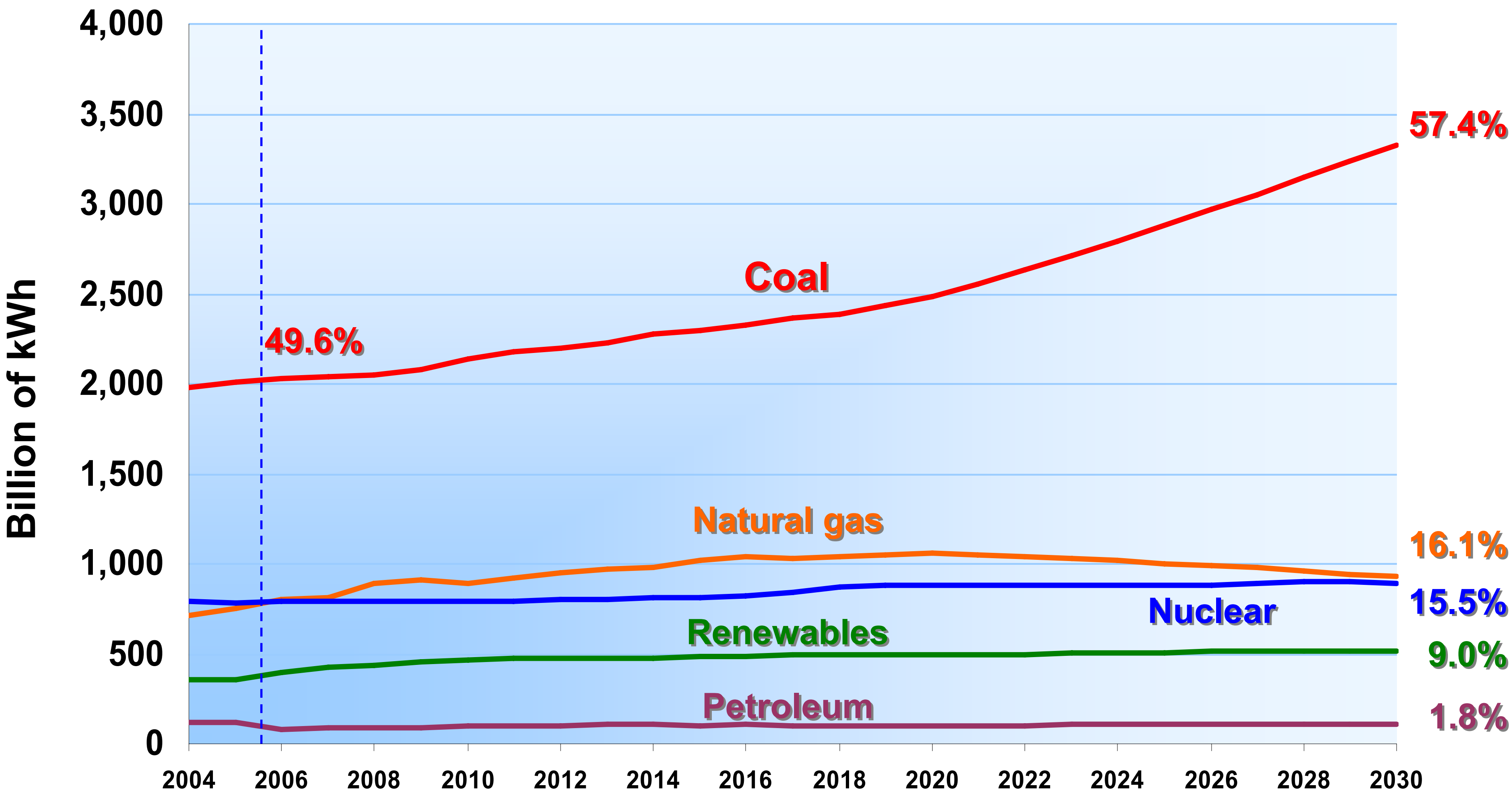
Sources: BP Statistical Review, June 2004, - for coal reserves data – World Energy Council; EIA, Advance Summary U.S. Crude Oil, Natural Gas, and Natural Gas Liquids Reserves, 2003 Annual Report, September 22, 2004 - for oil and gas reserves data
Pyramid figure: NRC – "COAL: Research and Development to Support National Energy Policy", Summer 2007

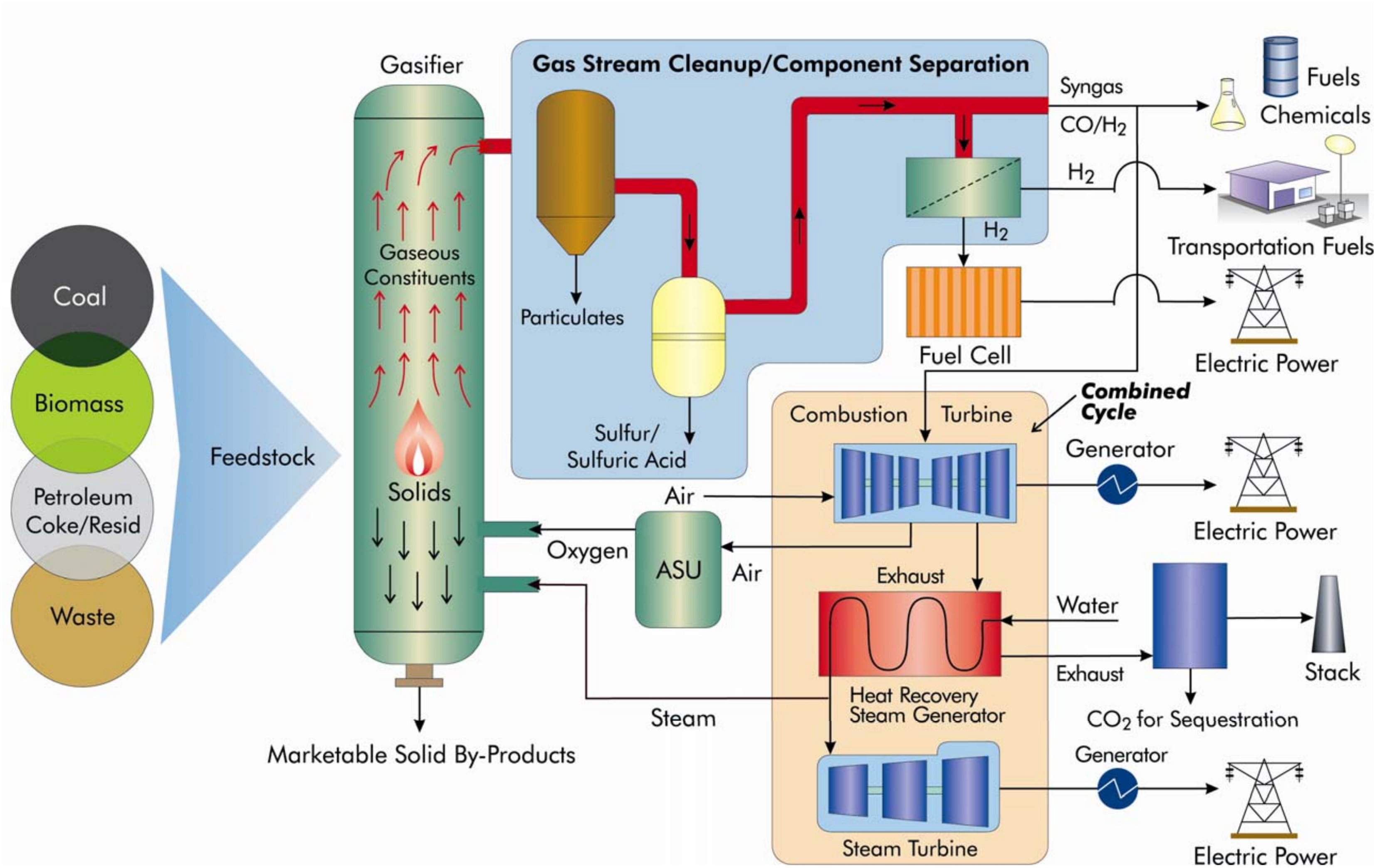
U.S. Domestic Electricity Generation Forecast



Significant growth in share of electricity generated by coal

Annual Energy Outlook 2007early release, December 5, 2006

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.

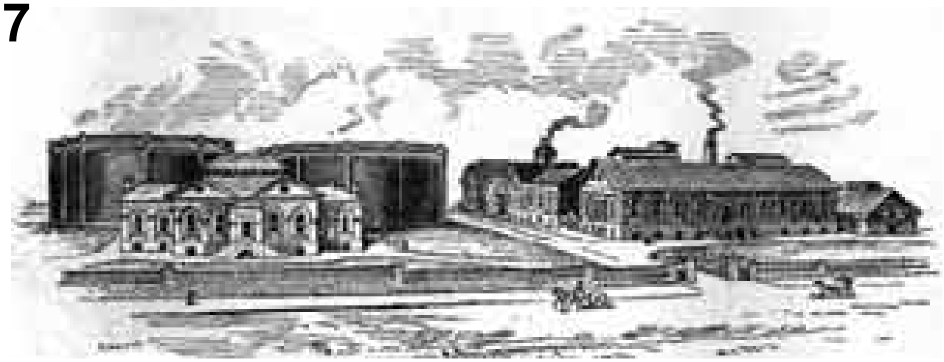
History of Gasification

Town Gas

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

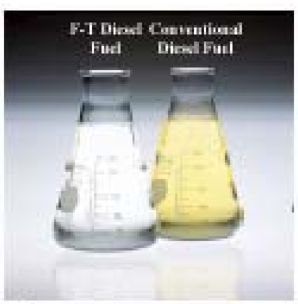
Town gas is approximately 50% hydrogen, with the rest comprised of mostly methane and carbon dioxide, with 3% to 6% carbon monoxide.

- **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)



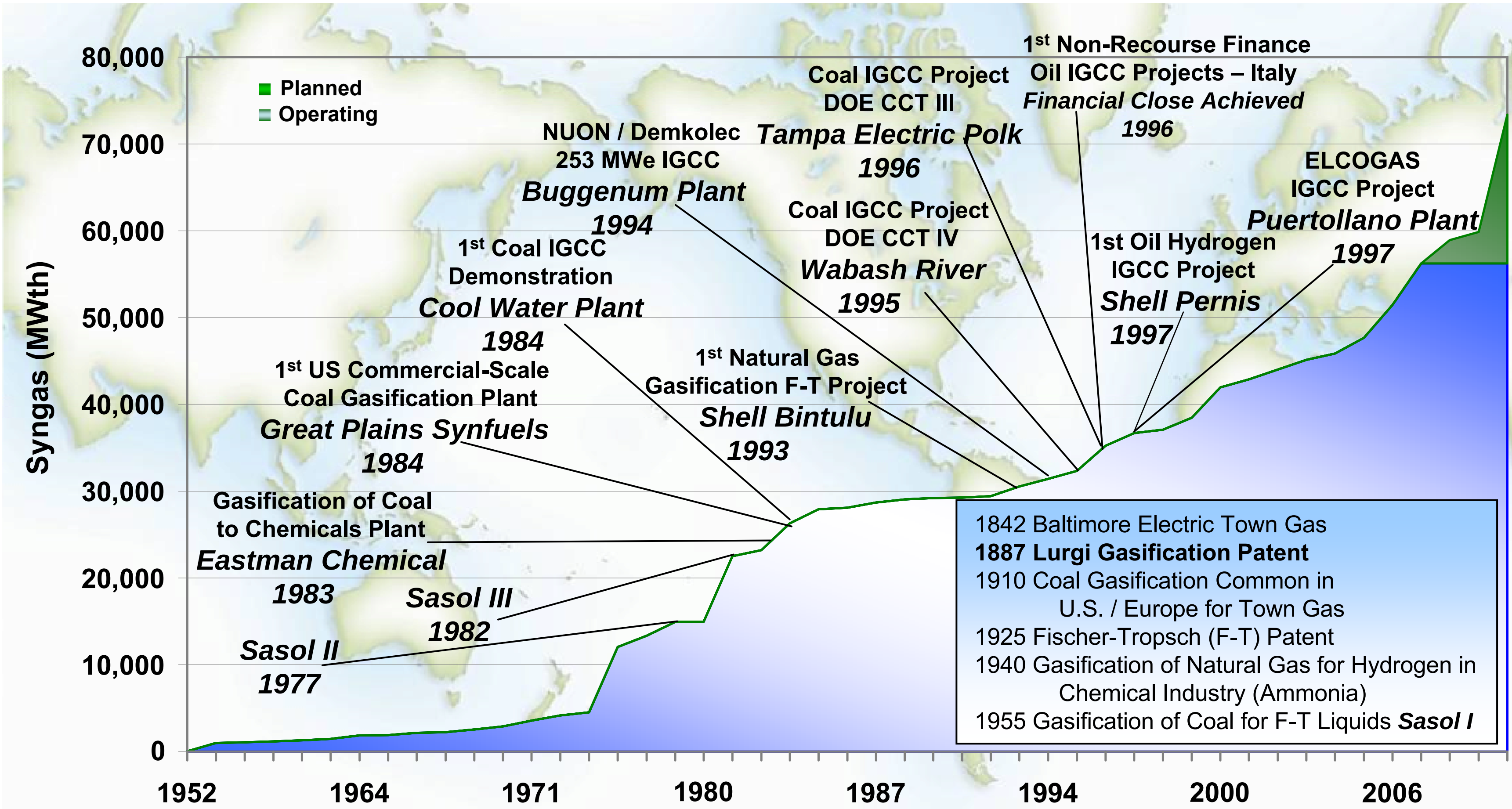
Major Gasification Milestone

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)

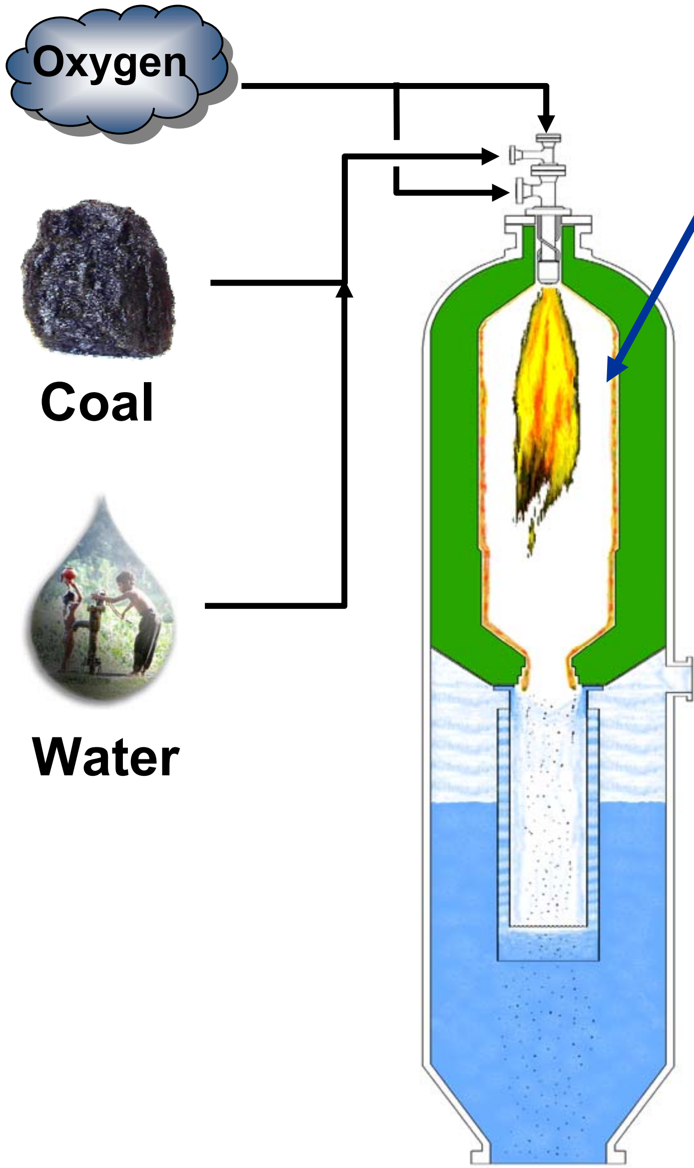
Today IGCC is an Accepted Refinery and Coal Plant Option

Worldwide Gasification Capacity and Planned Growth

Cumulative by Year



What is Coal Gasification?



Extreme Conditions:

- 1,000 psig or more
- 2,600 °F
- Corrosive slag and H_2S gas

Products (syngas)

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

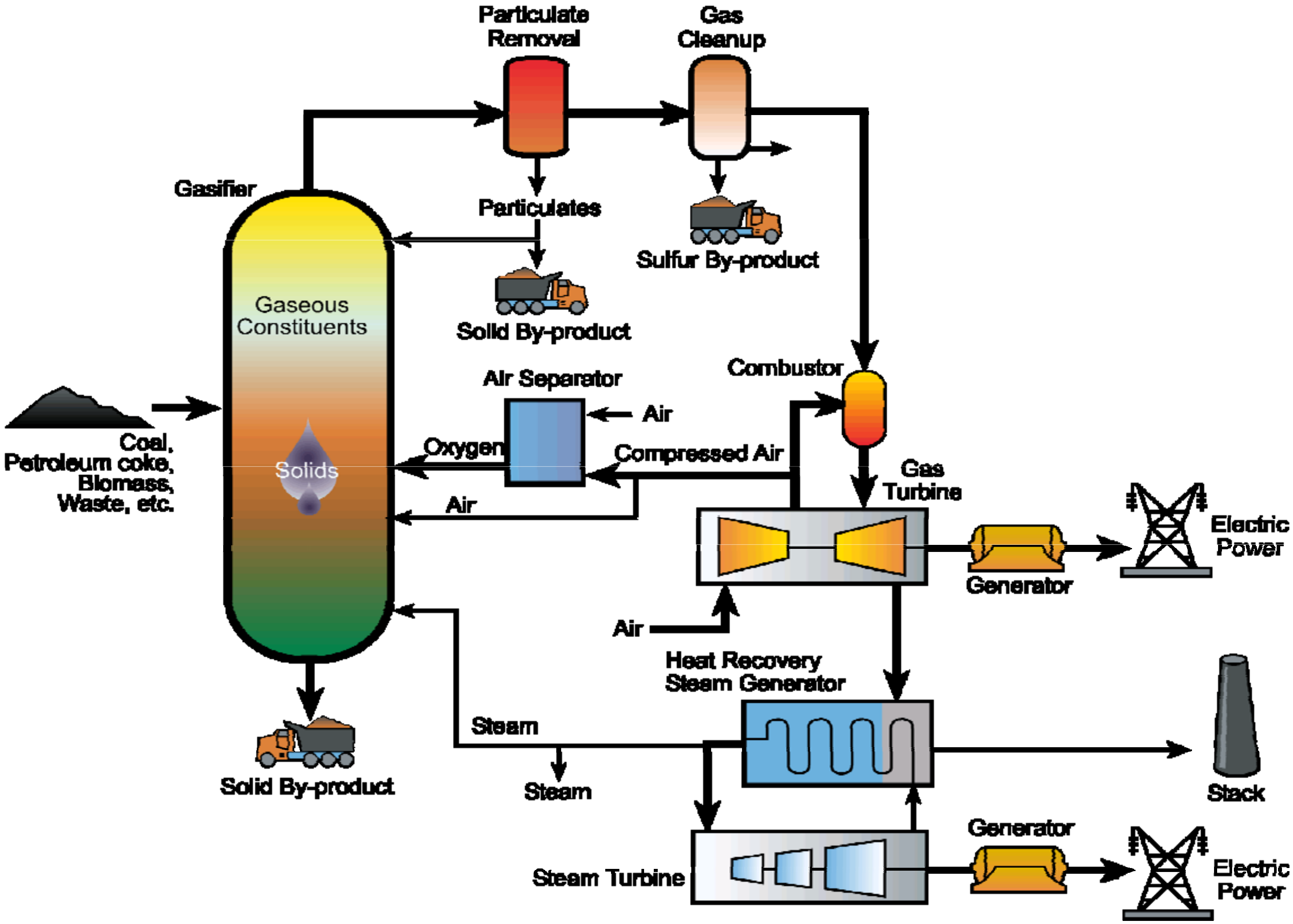
By-products

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

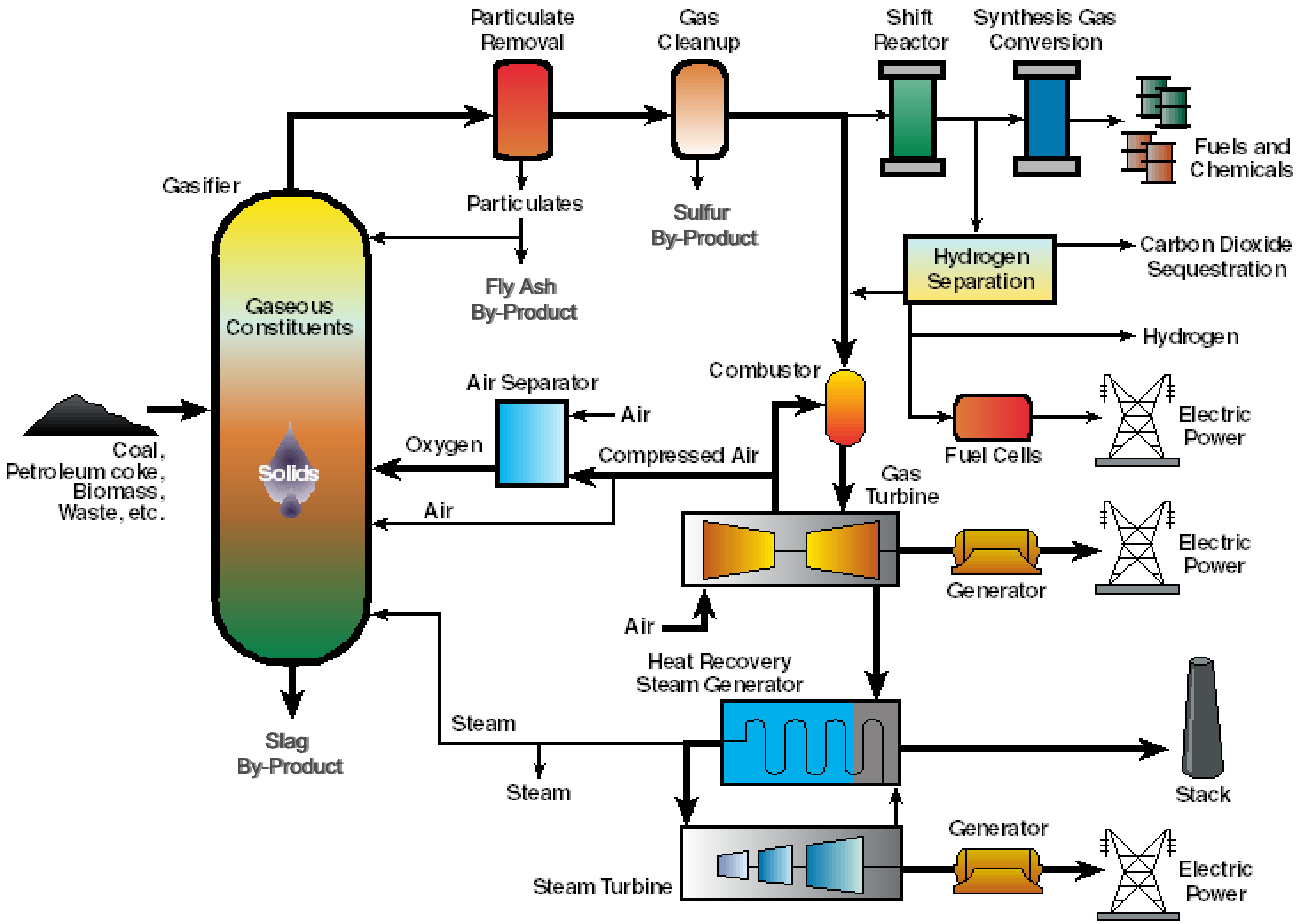
Gas Clean-Up *Before* Product Use

Courtesy: Eastman Chemical

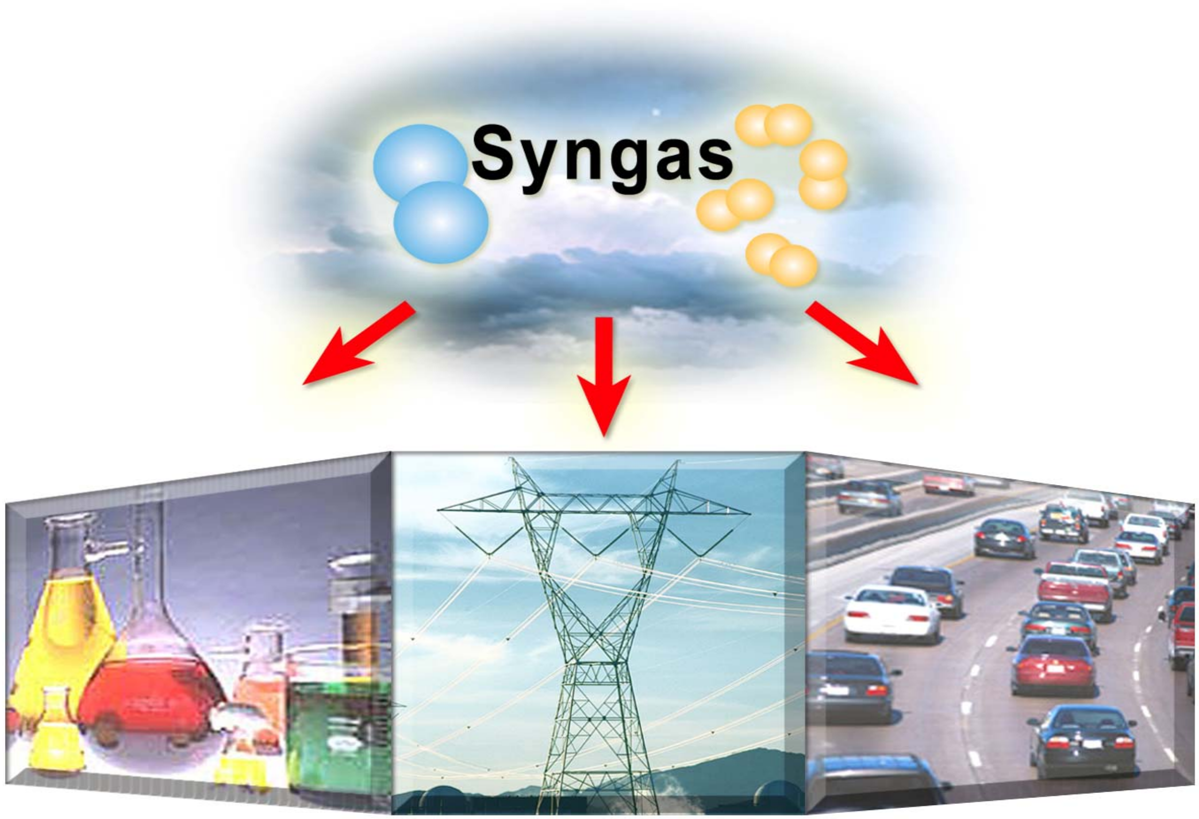
Integrated Gasification Combined Cycle (IGCC)



Gasification-Based Energy Production System Concepts



So what can you do with CO and H_2 ?

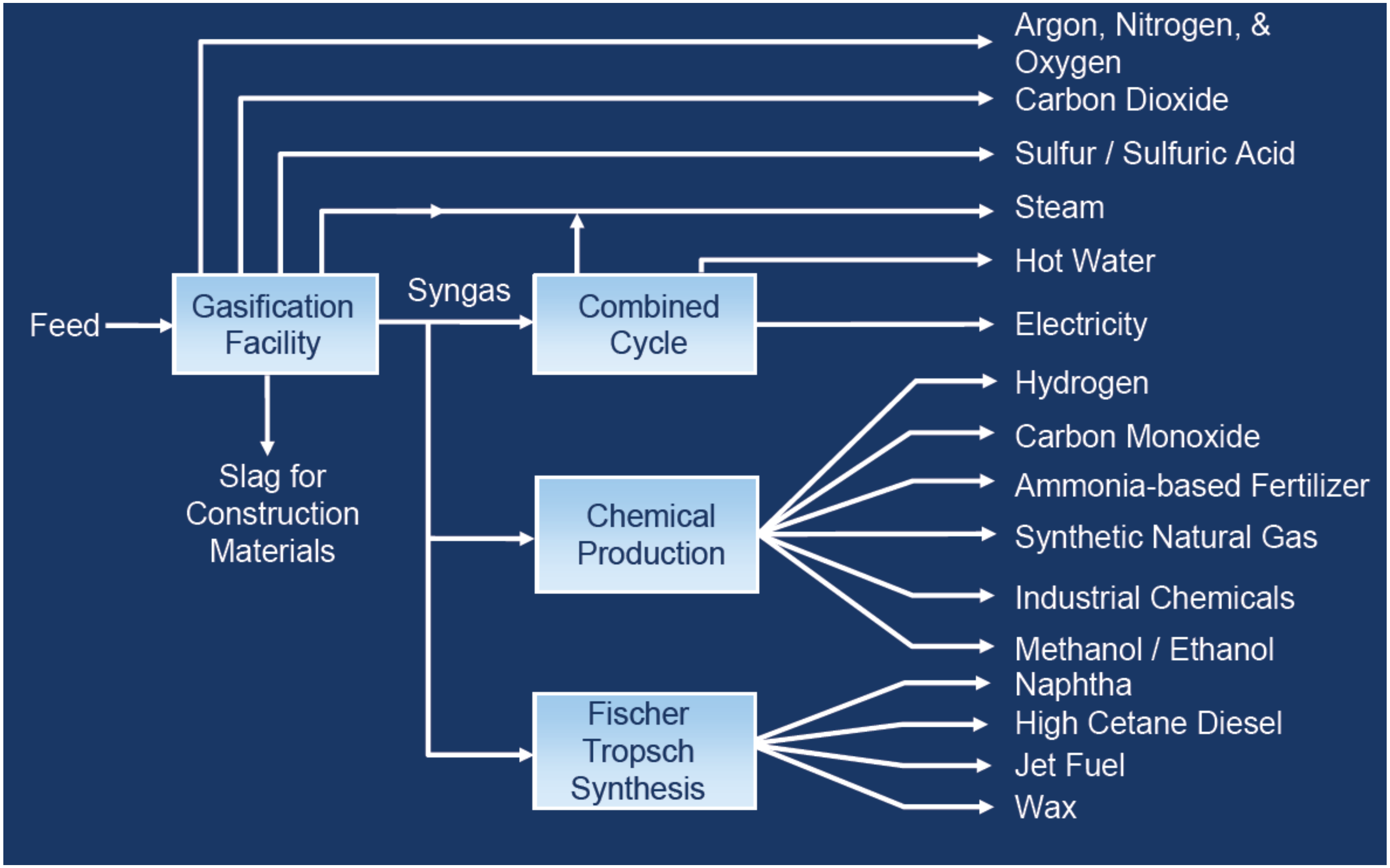


Building Blocks for Chemical Industry

Clean Electricity

Transportation Fuels (Hydrogen)

Gasification Products



Source: FLUOR®

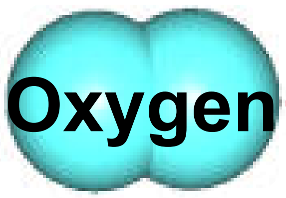
Chemicals from Coal - Final Products

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

Acetic Anhydride
Acetic Acid

Source: Eastman Gasification Services Company

Gasification Chemistry



Gasification with Oxygen

$C + {}^{1}/_{2}\, O_2 \longleftrightarrow CO$

Combustion with Oxygen

$C + O_2 \longleftrightarrow CO_2$

Gasification with Carbon Dioxide

$C + CO_2 \longleftrightarrow 2CO$

Gasification with Steam

$C + H_2O \longleftrightarrow CO + H_2$

Gasification with Hydrogen

$C + 2H_2 \longleftrightarrow CH_4$

Water-Gas Shift

$CO + H_2O \longleftrightarrow H_2 + CO_2$

Methanation

$CO + 3H_2 \longleftrightarrow CH_4 + H_2O$

Gasifier Gas Composition (Vol %)

H_2	25 - 30
CO	30 - 60
CO_2	5 - 15
H_2O	2 - 30
CH_4	0 - 5
H_2S	0.2 - 1
COS	0 - 0.1
N_2	0.5 - 4
Ar	0.2 - 1
NH_3 + HCN	0 - 0.3

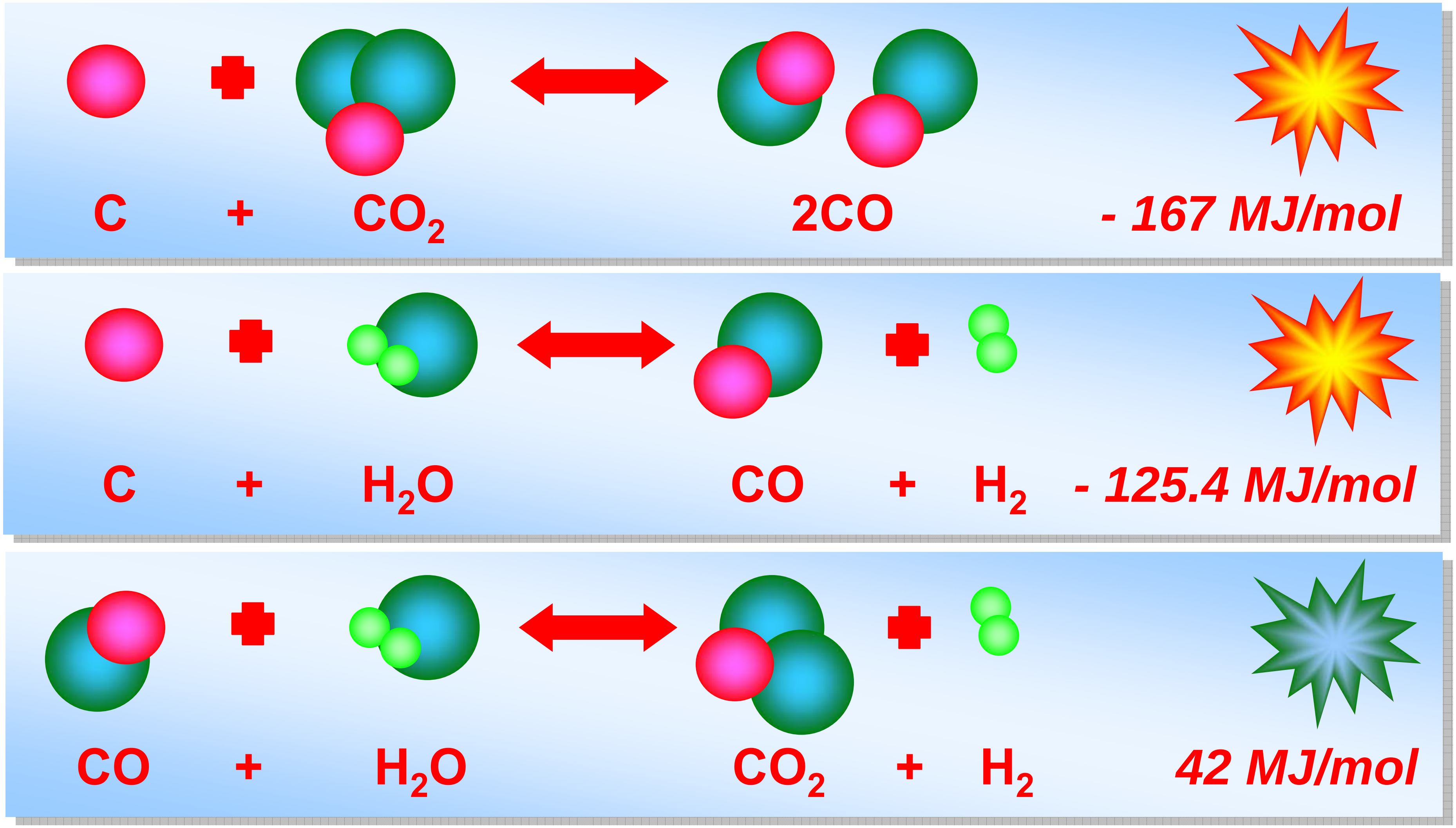
Ash/Slag/PM

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

Combustion with Oxygen

$C + O_2 \longleftrightarrow CO_2$

$^1/_2\, O_2 + H_2 \longleftrightarrow H_2O$

Combustion Gas Composition (Vol %)

CO_2	13.5
H_2O	9.8
SO_2	0.4
N_2	73.2
O_2	3.2

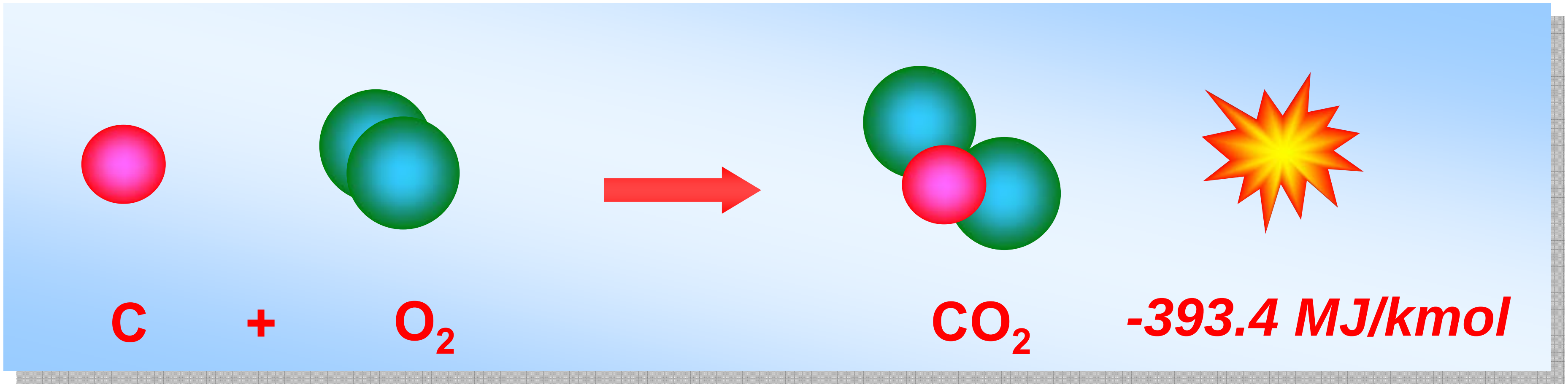
Ash/Slag/PM

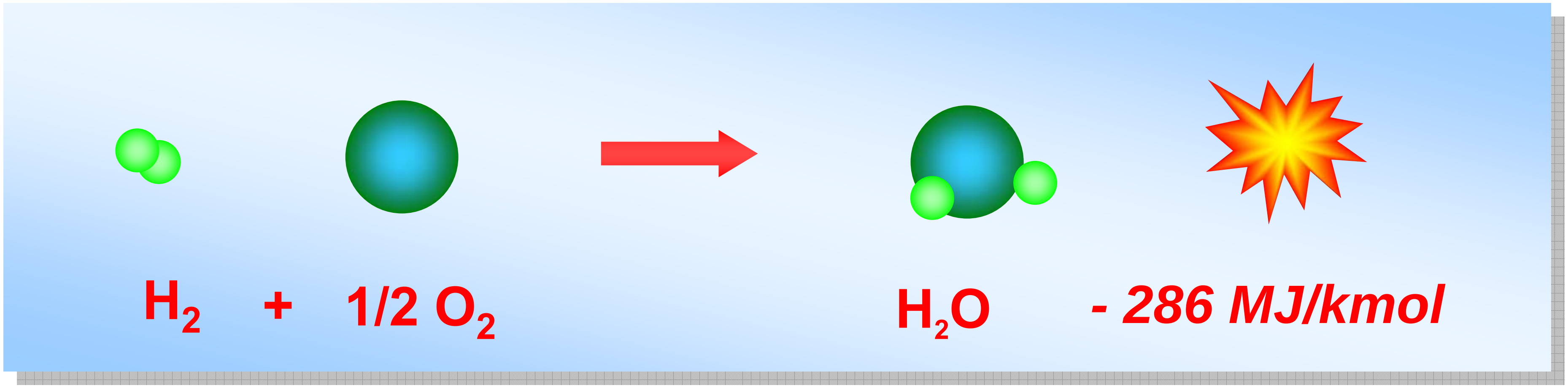
Chemical Reactions in Coal Combustion

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
$C_{(s)} + ½\ O_{2(g)} \rightarrow CO_{(g)}$	– 110,300
$CO_{(g)} + H_2O_{(v)} \rightarrow CO_{2(g)} + H_{2(g)}$	+ 46,900
$CO_{(g)} + ½\ O_{2(g)} \rightarrow CO_{2(g)}$	– 172,580

Examples of Important Reactions

Chemical Reactions in Coal Combustion

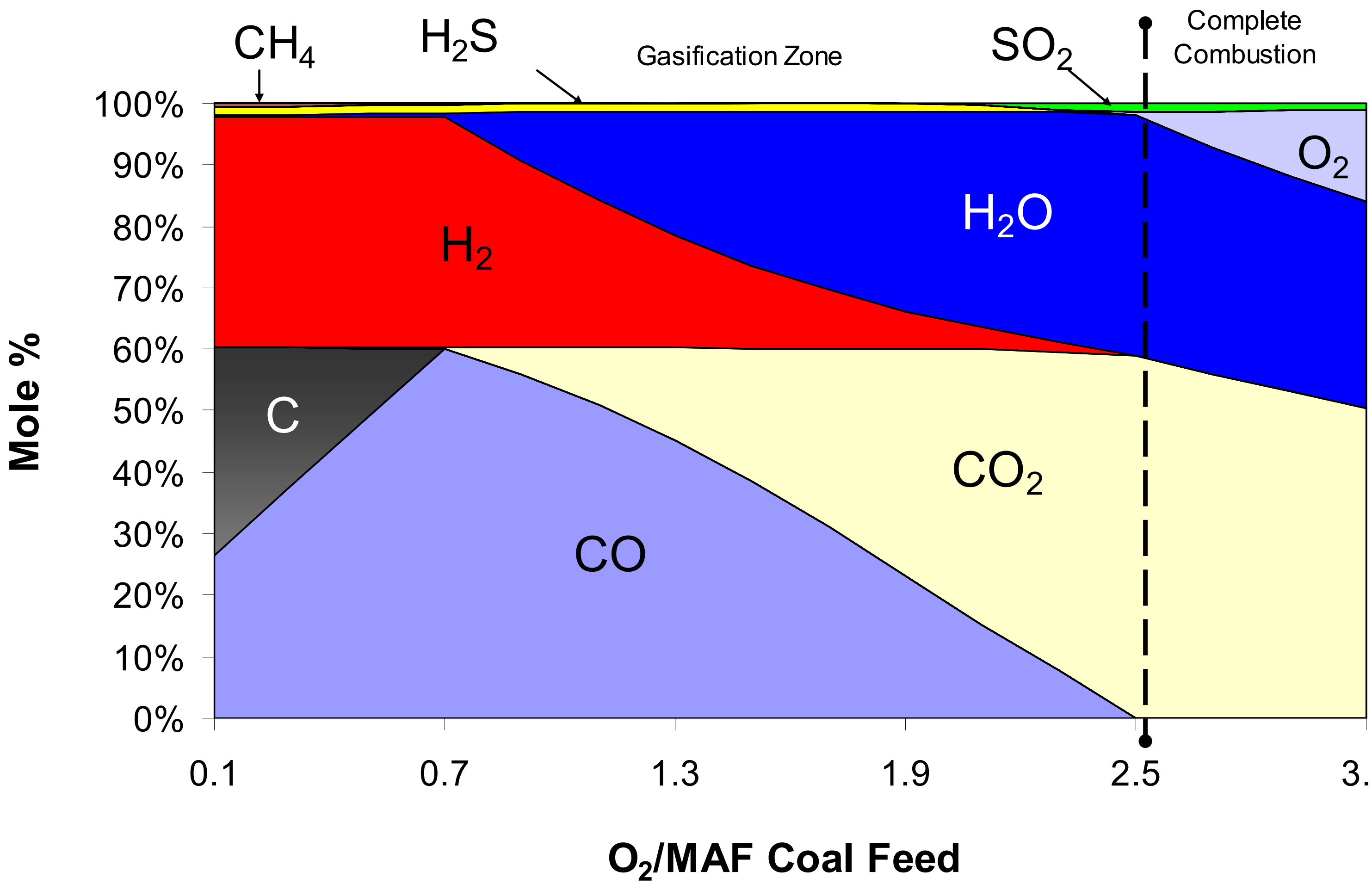




Examples of 2 Important Reactions

Gasification Phase Diagram

An Example



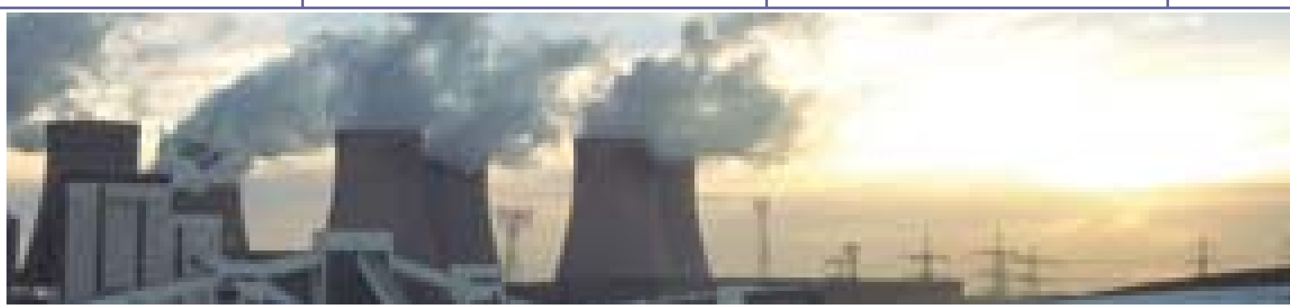
Coal: Illinois #6, Dry Feed

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%

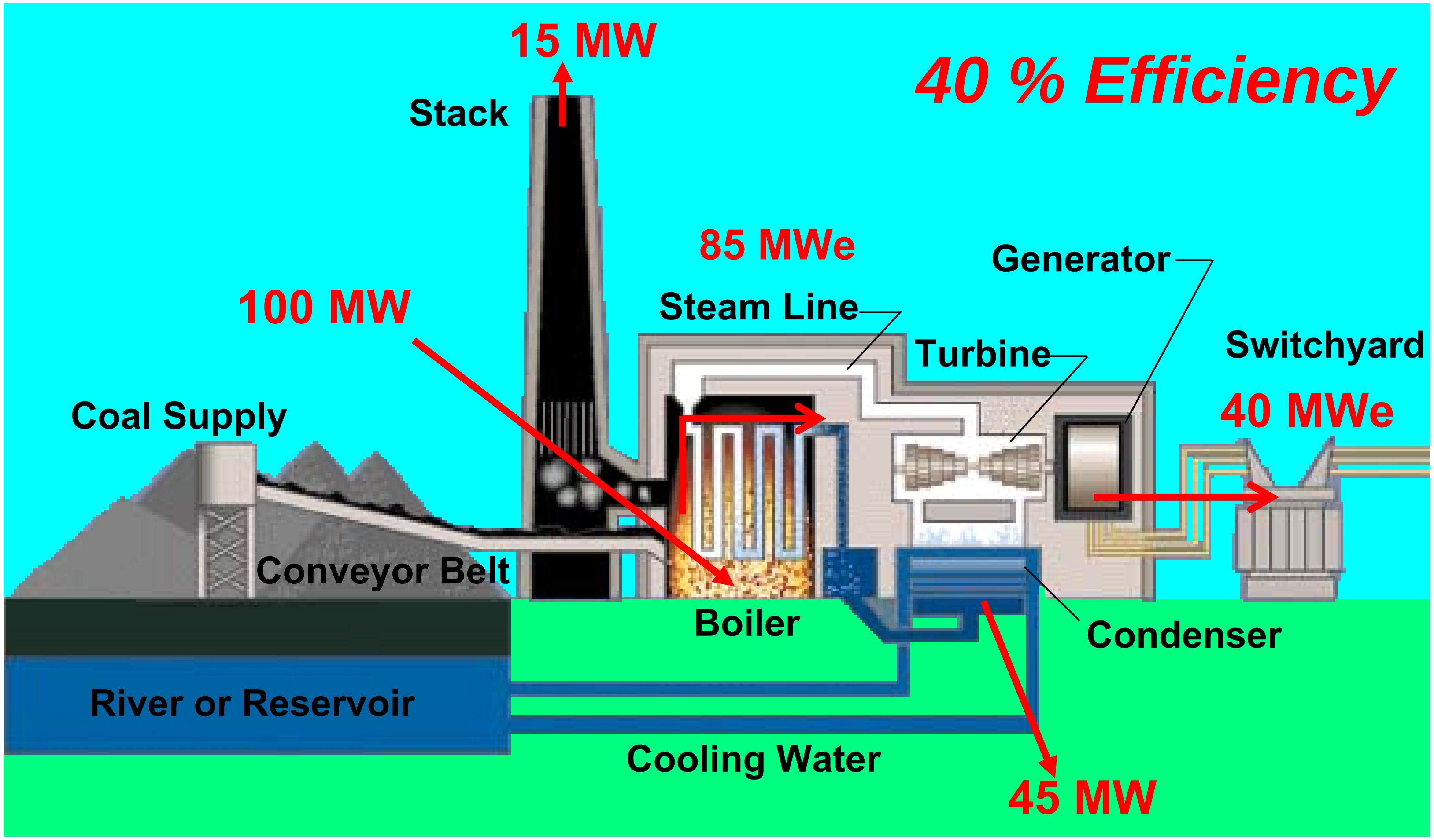
Comparison of Air Emission Controls: *PC vs. IGCC*

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



Steve Jenkins 2007 GTC Conference http://www.gasification.org/Docs/2007_Papers/22JENK.pdf

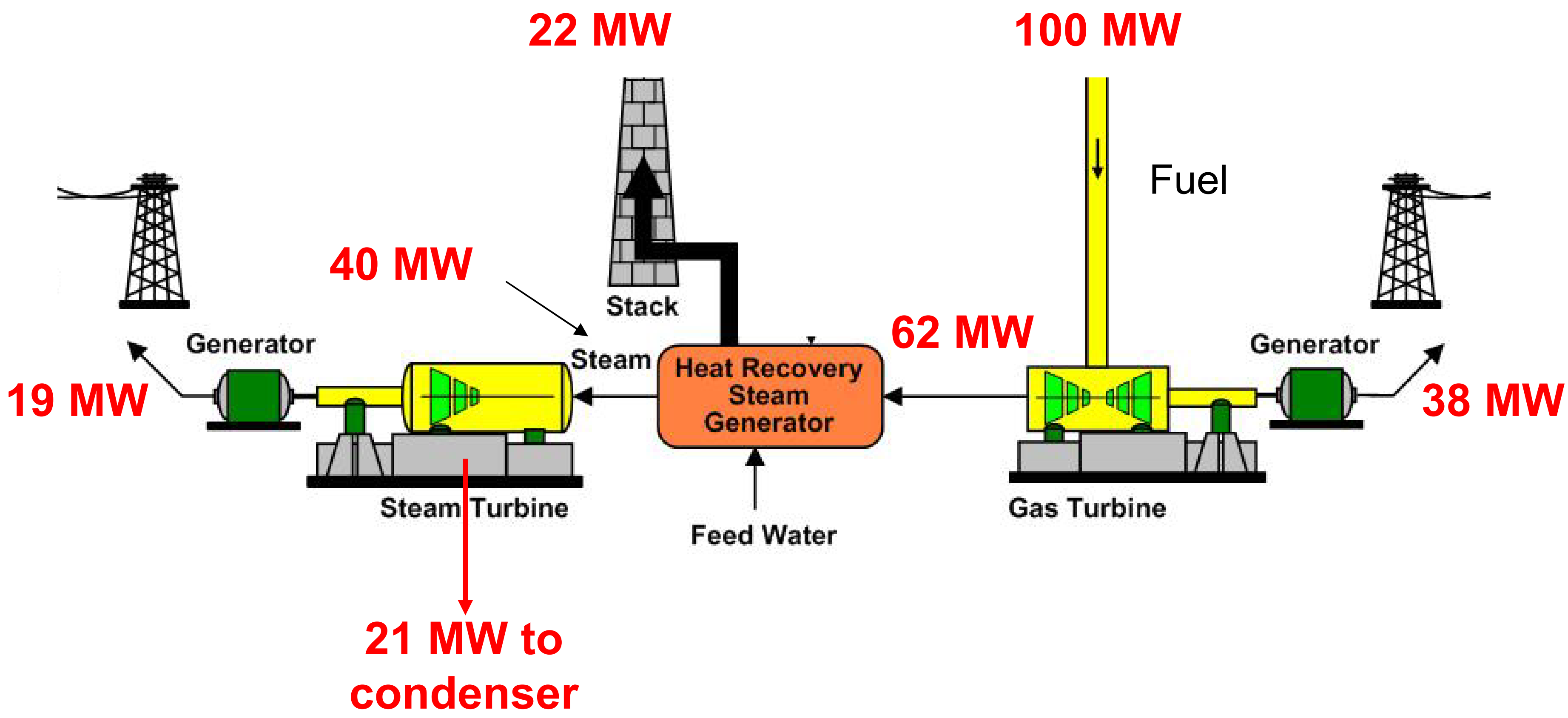
Conventional Coal Plant
(Illustration only)



Source: EPRI

Combined Cycle
(Illustration only)

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

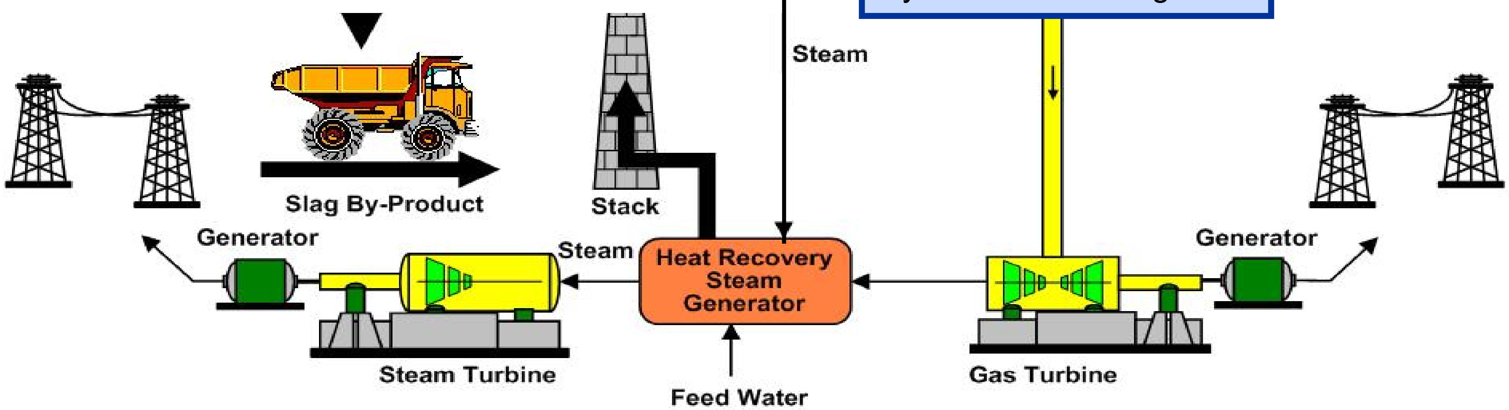


Coal-Based IGCC Power Plant

Gasification Island

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

Natural gas is replaced by coal-based fuel gas



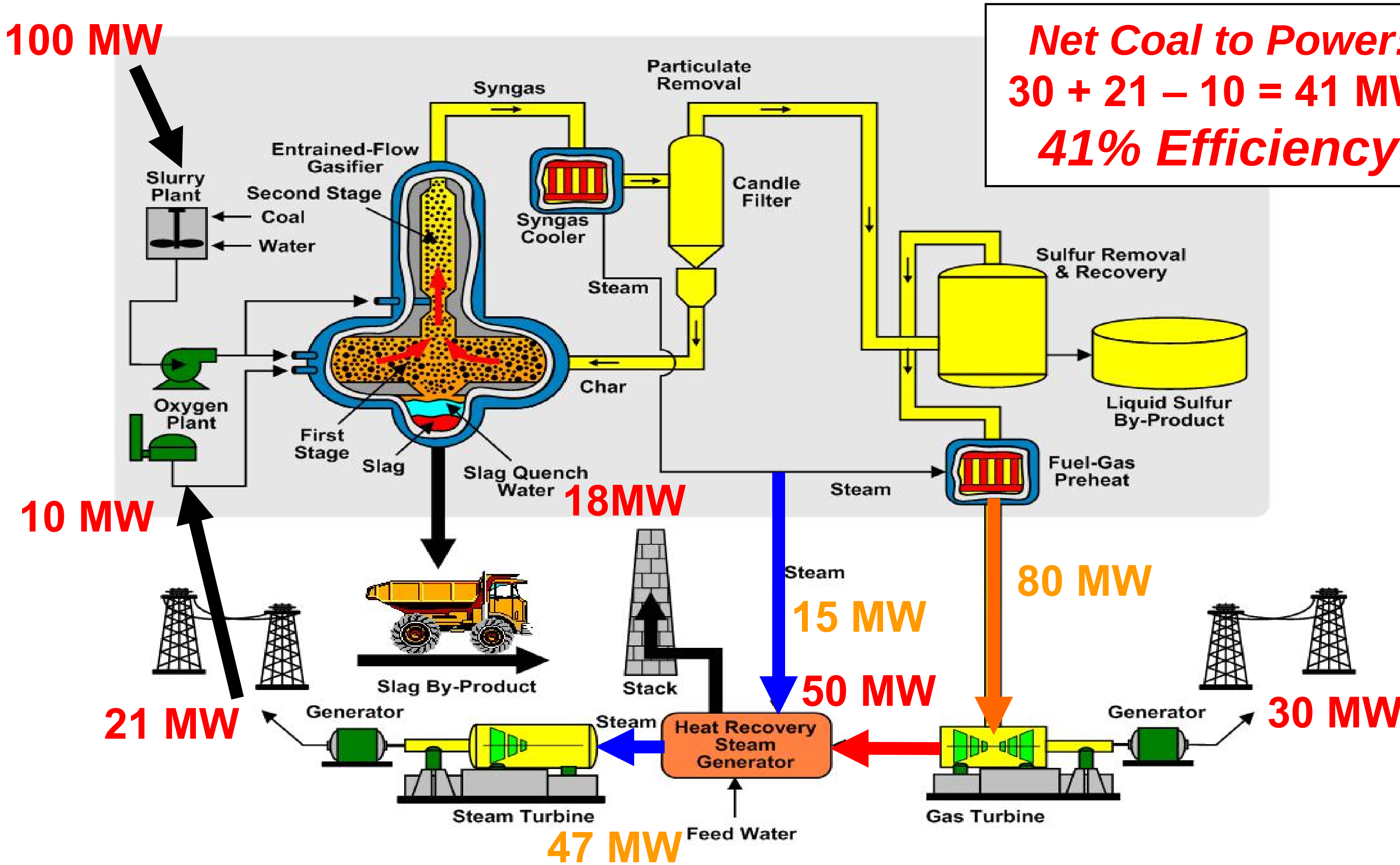
Coal-Based IGCC Power Plant

(Illustration only)

Net Coal to Power:

30 + 21 – 10 = 41 MW

41% Efficiency



Gasification-Based Energy Conversion Systems

RESOURCES

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

GASIFIERS

OXYGEN-BLOWN

Entrained Flow
GE Energy, E-Gas, Shell, Prenflo, Noell

Fluidized Bed
HT Winkler

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

Transport Reactor
Kellogg

AIR-BLOWN

Fluidized Bed
HT Winkler, GTI U-Gas, KRW

Sprouting Bed
British Coal, Foster Wheeler

Entrained Flow
Mitsubishi

Transport Reactor
Kellogg

ENVIRONMENTAL CONTROL

Particulate Removal and Recycle
Filtration, Water Scrubbing

Chloride and Alkali Removal
Water Scrubbing

Acid Gas Removal
Amine Processes
Rectisol, Selexol

COS Hydrolysis

Sulfur Recovery
Claus Process
SCOT Process
Sulfuric Acid Plant

Water Treatment
Process Water, BFW

Tail Gas Treating

Turbine NOx Control
Nitrogen/Steam Dilution

Syngas Mercury Capture

Syngas CO_2 Capture

ENERGY CONVERSION

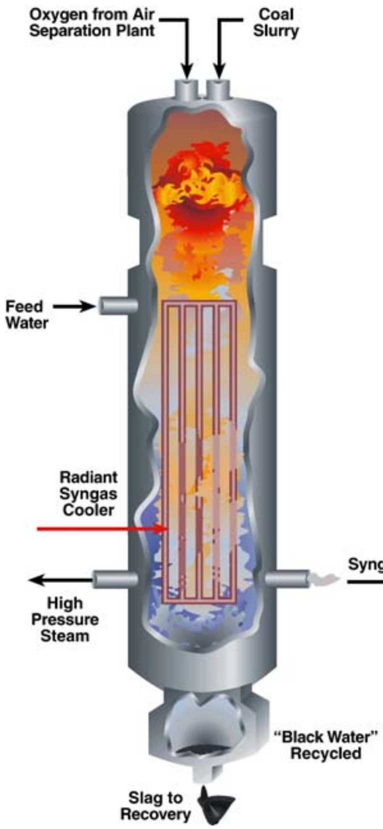
- Gas Turbine
- Heat Recovery Steam Generator (HRSG)
- Steam Turbine
- Boiler
- Syngas Conversion to Fuels & Chemicals
- Catalytic Conversion
- Shift Conversion
- Fischer-Tropsch
- Fuel Cell
- H_2 Turbine

PRODUCTS

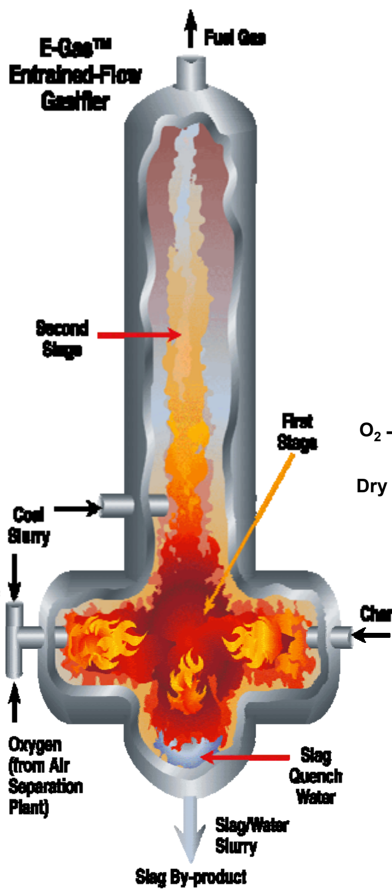
- Steam
- Electric Power
- Liquid Fuels
- Chemicals
- Methanol
- Hydrogen
- Ammonia/ Fertilizers
- Slag
- Sulfur/ Sulfuric Acid

Gasifiers

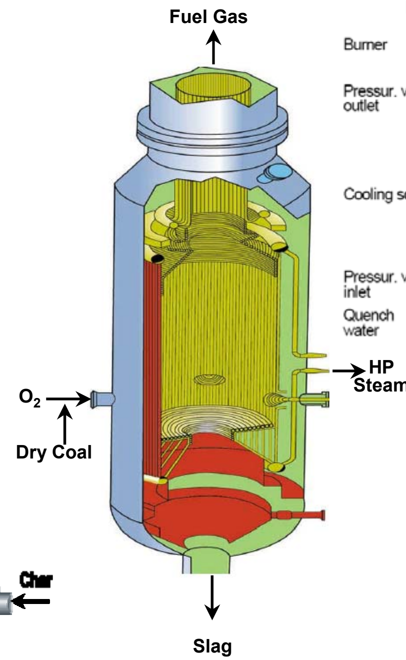
GE Energy
(Chevron-Texaco)



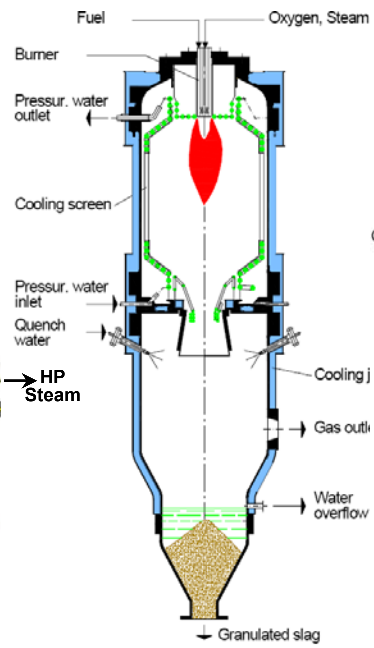
ConocoPhillips E-Gas



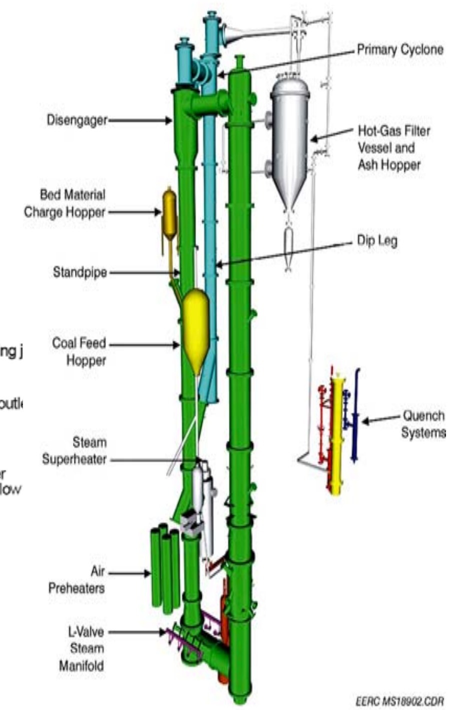
Shell SCGP



Siemens
(GSP/Noell)

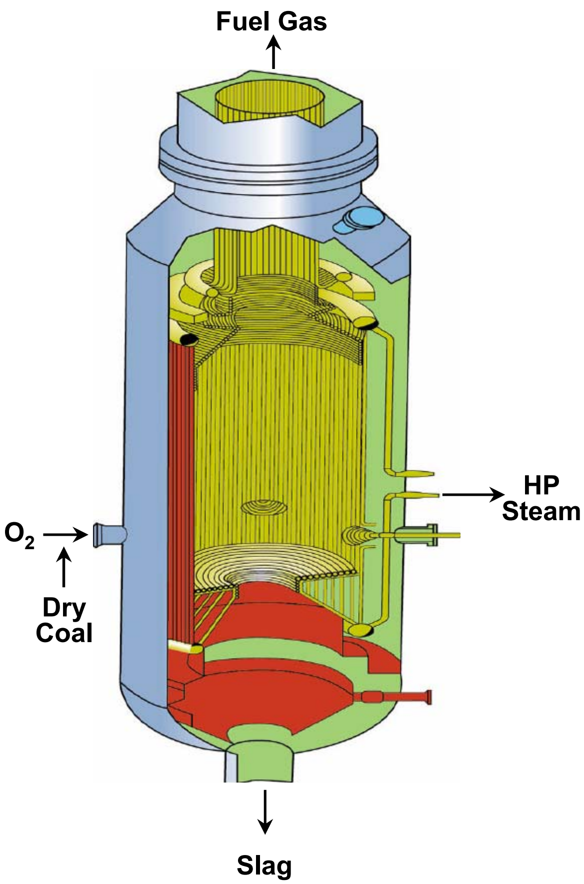


KBR Transport

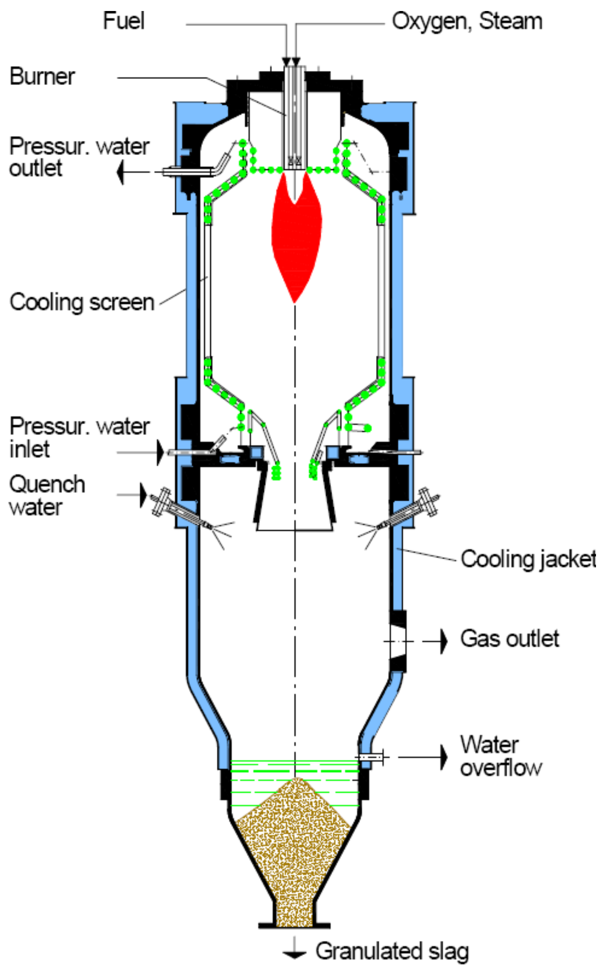


Gasifiers for Low Rank Coal

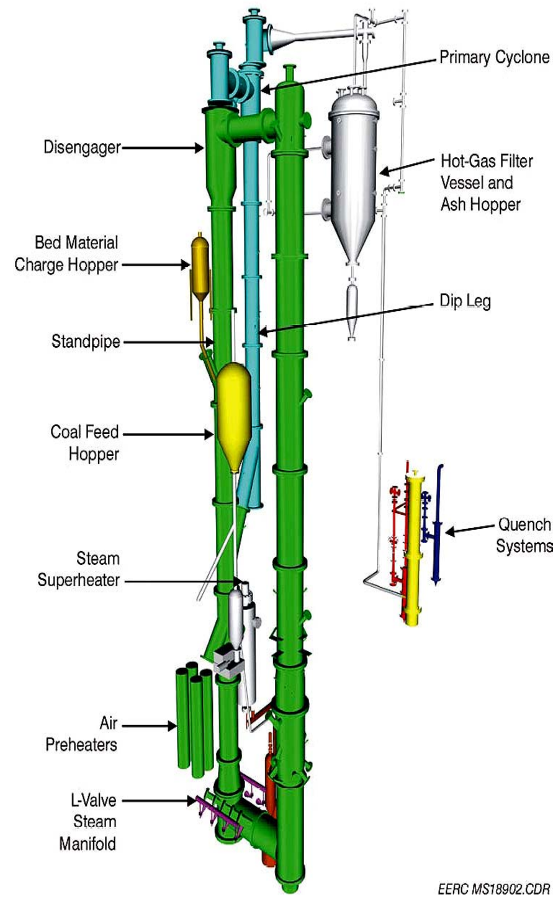
Shell SCGP



Siemens (*GSP/Noell*)

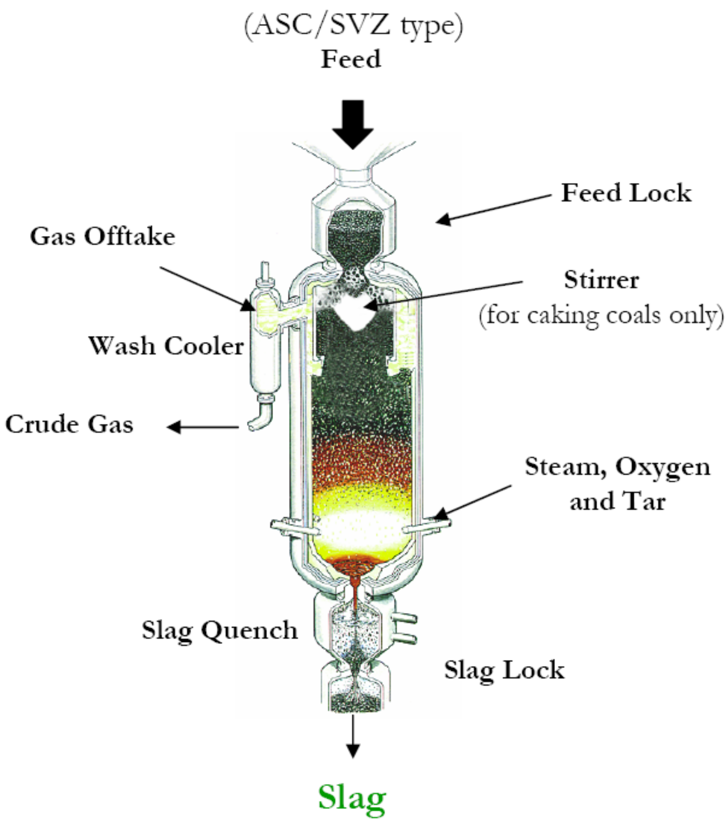


KBR Transport

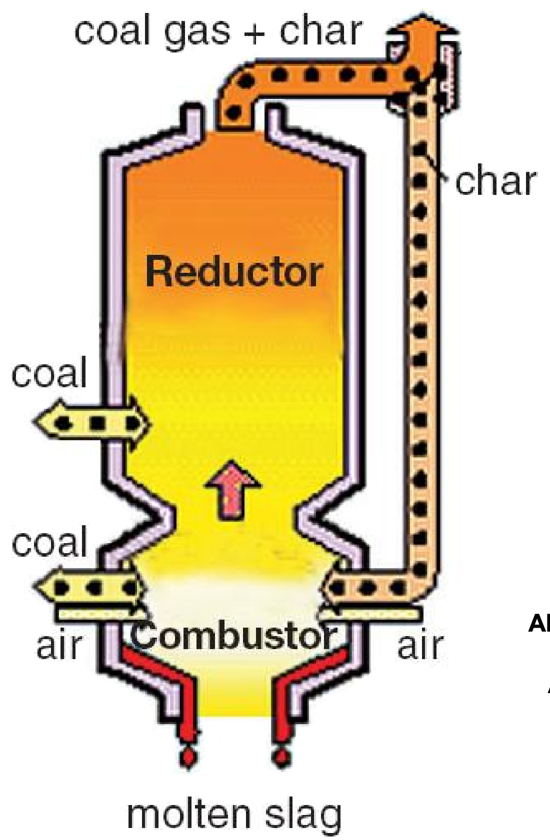


Gasifiers for Low Rank Coal *cont.*

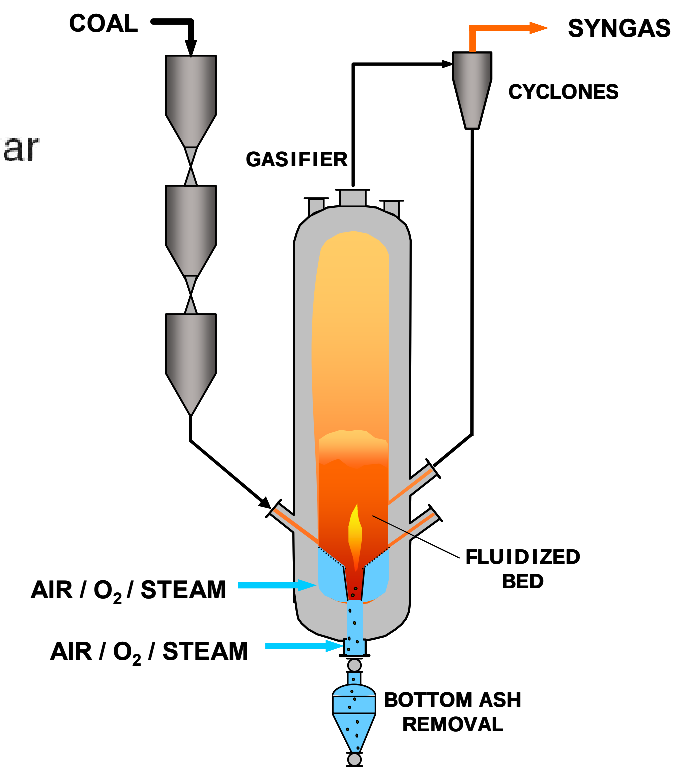
BGL



MHI

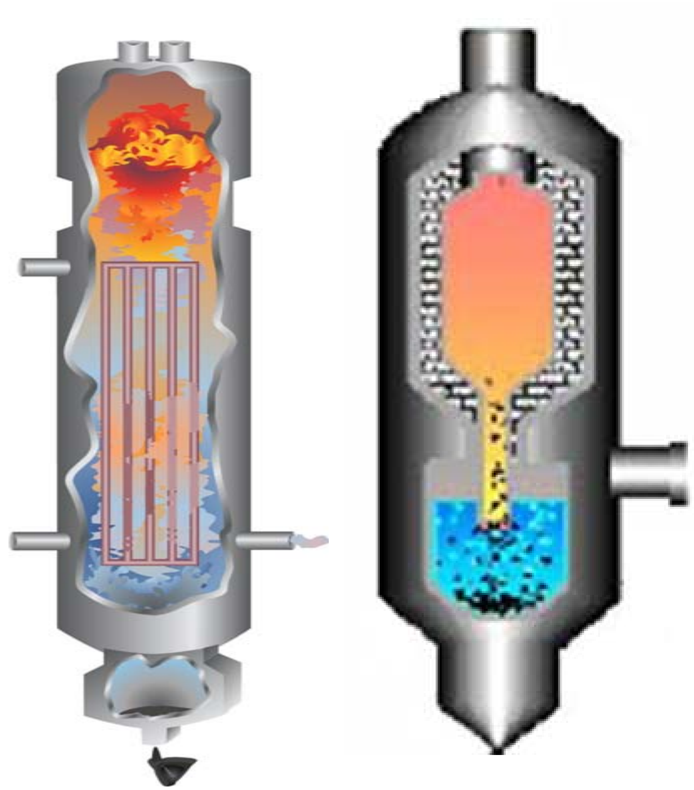


U-Gas



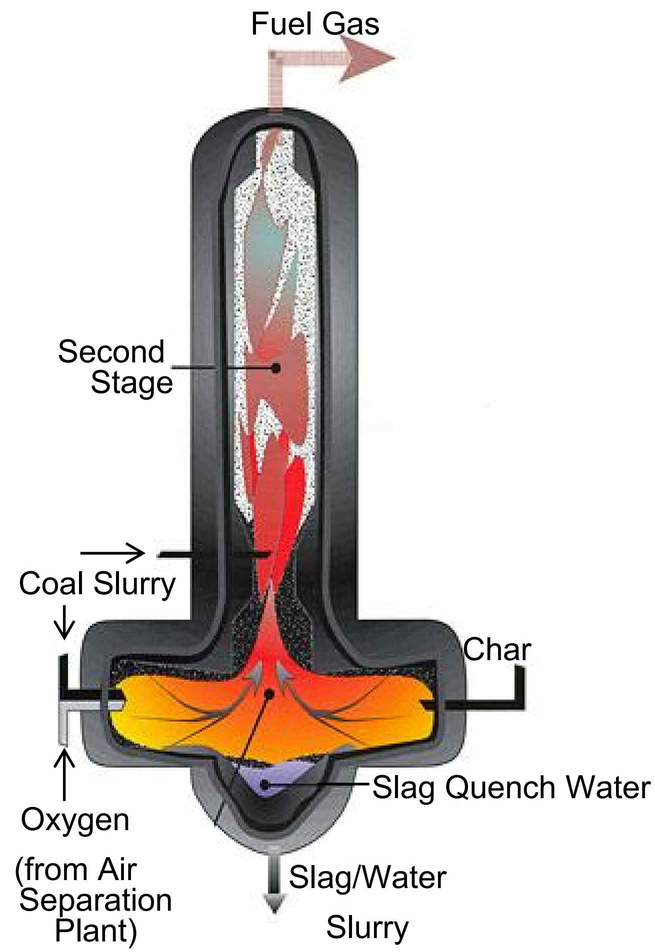
GE Energy Gasifier

- **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**



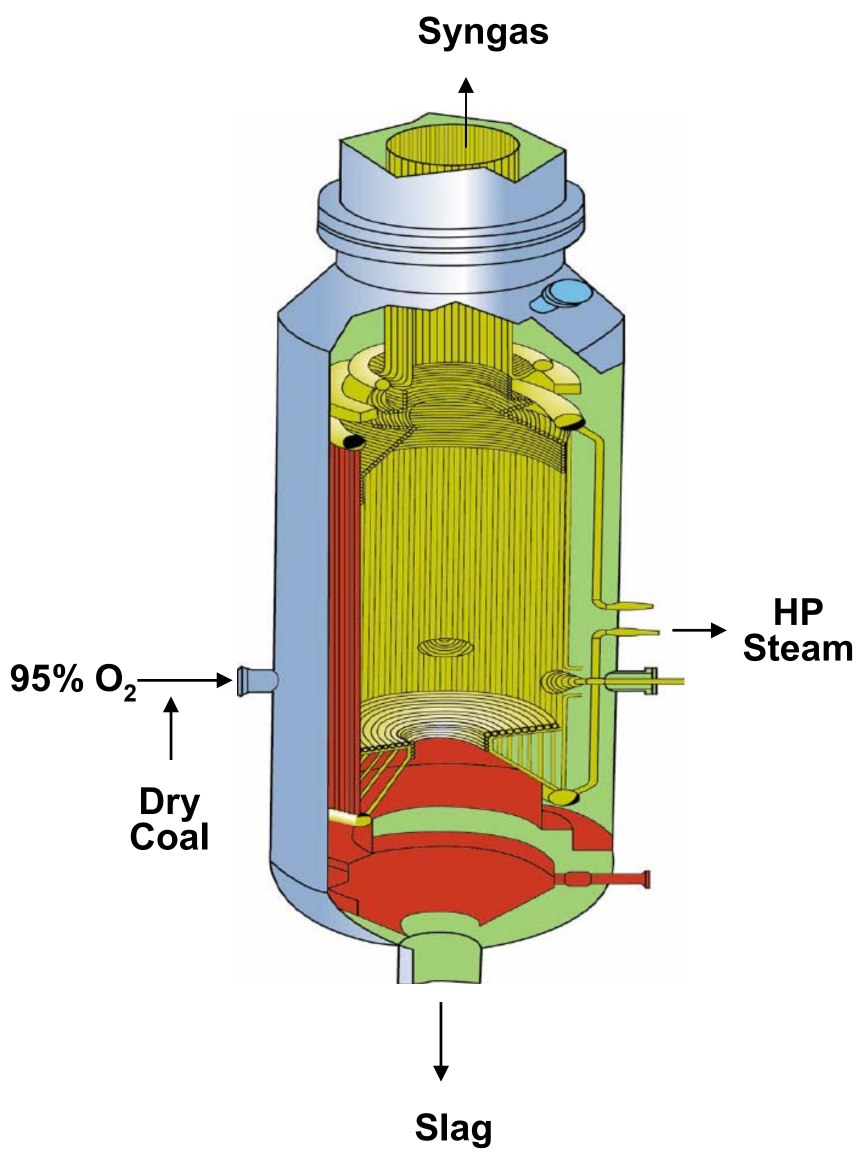
ConocoPhillips (E-Gas) Gasifier

- **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**



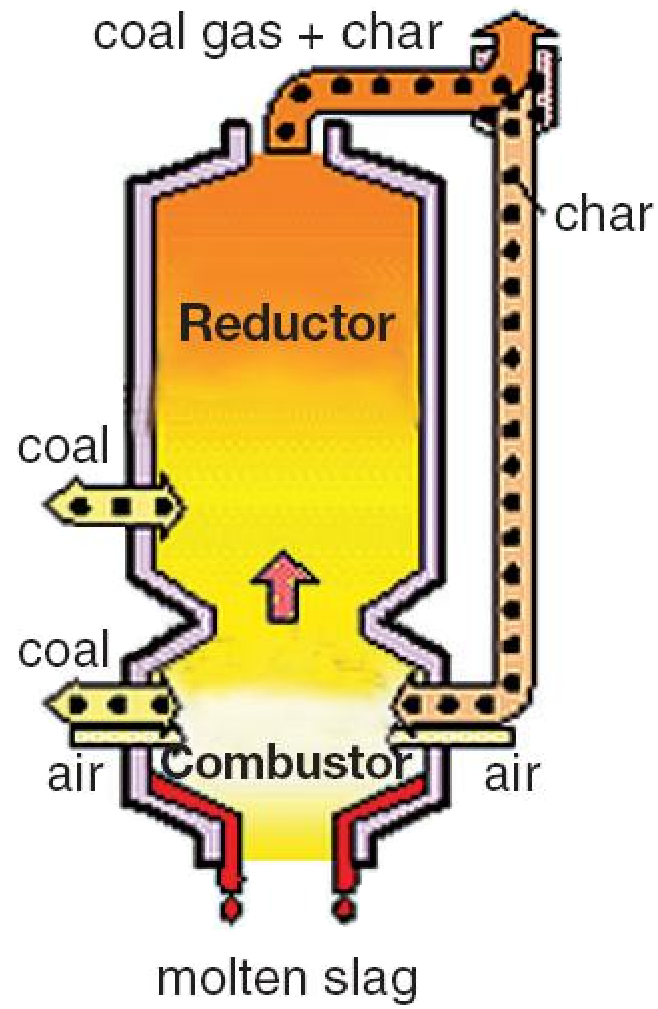
Shell Gasifier

- **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

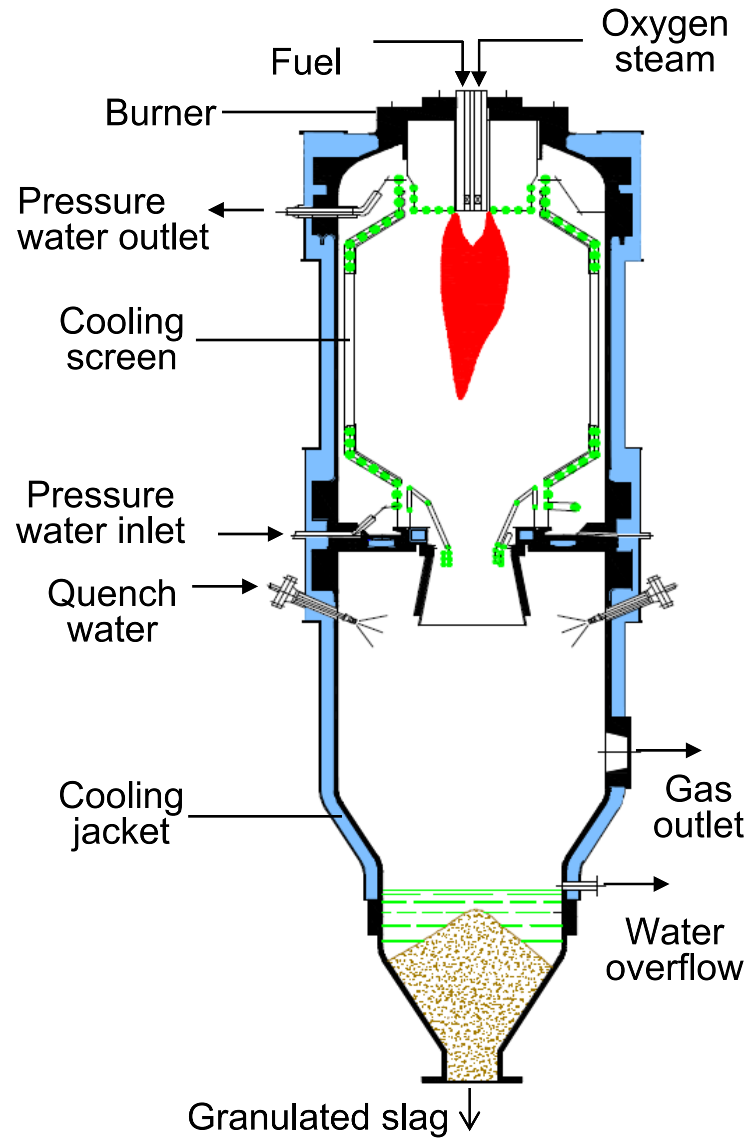
- Entrained bed
- Dry feed system
- Suitable for low rank coal with high moisture content
- Two-Stage feeding
- Air Blown
- Membrane waterwall
- Slagging
- Developed in the 80's by Central Research Institute of the Electric Power Industry Japan
- 1 Plant in planning
- 1 Demonstration plant in operation,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



Siemens GSP Gasifier

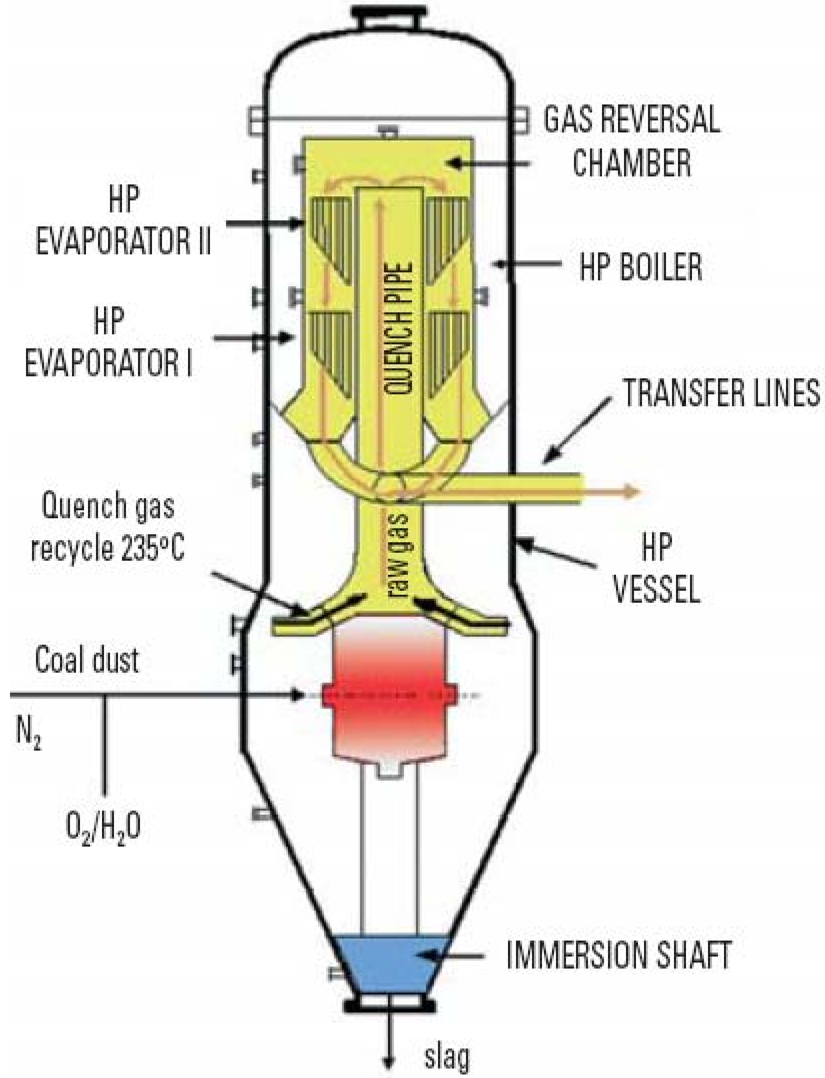
- **Entrained flow gasifier**
- **Dry feed**
- **Oxygen-blown**
- **Top fired reactor**
- **Waterwall screen in gasifier**
- **Good for a wide variety of feedstocks, from bituminous to low-rank coals**
- **Siemens provides gasification island and power block**
- **Freiberg Pilot Plants**
  - cooling 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)

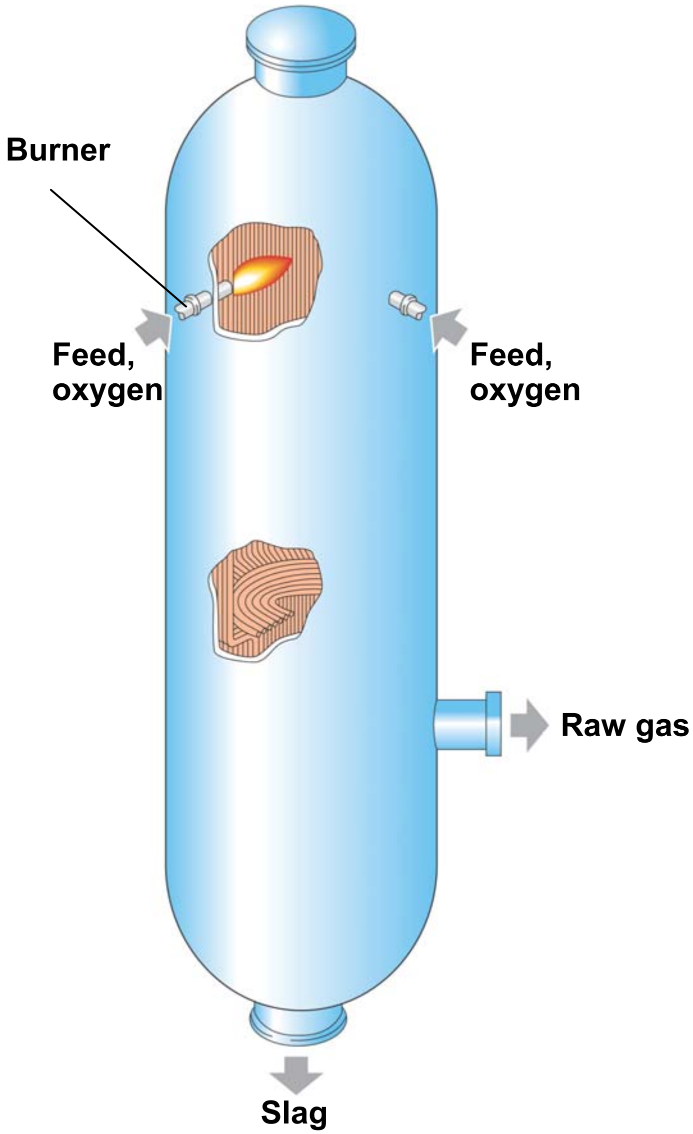
- **Pressurized entrained flow gasifier with steam generation**
- **Uhde**
- **Oxygen blown**
- **Dry feed system**
- **Membrane wall**
- **Waste heat boiler**
- **Able to gasify variety of solid fuels**
  - hard coal, lignite, anthracite, refinery residues, etc.
- **Demonstration plant Fürstenhausen,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



Integrated Gasification Combined Cycle Technology: IGCC It's Actual Application in Spain: ELCOGAS, Puertollano. Manuel Treviño Coca

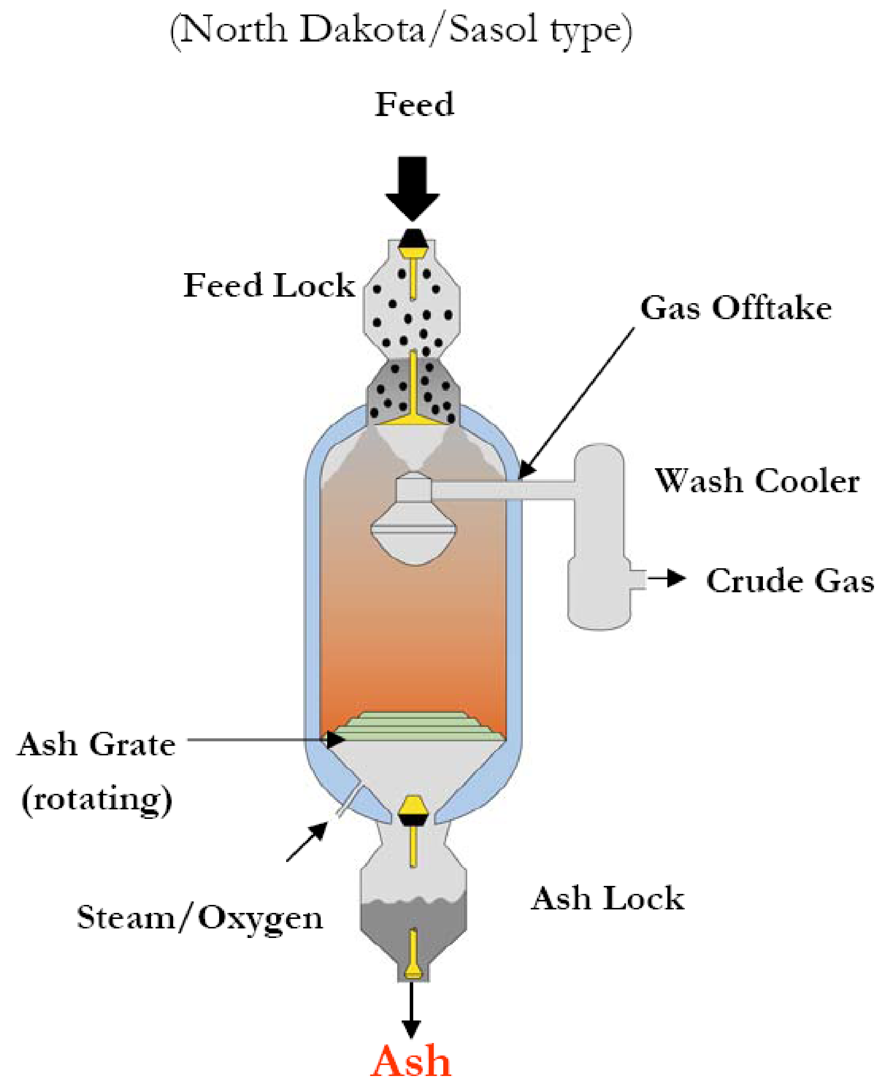
PRENFLO™ Gasifier (PDQ)

- **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**



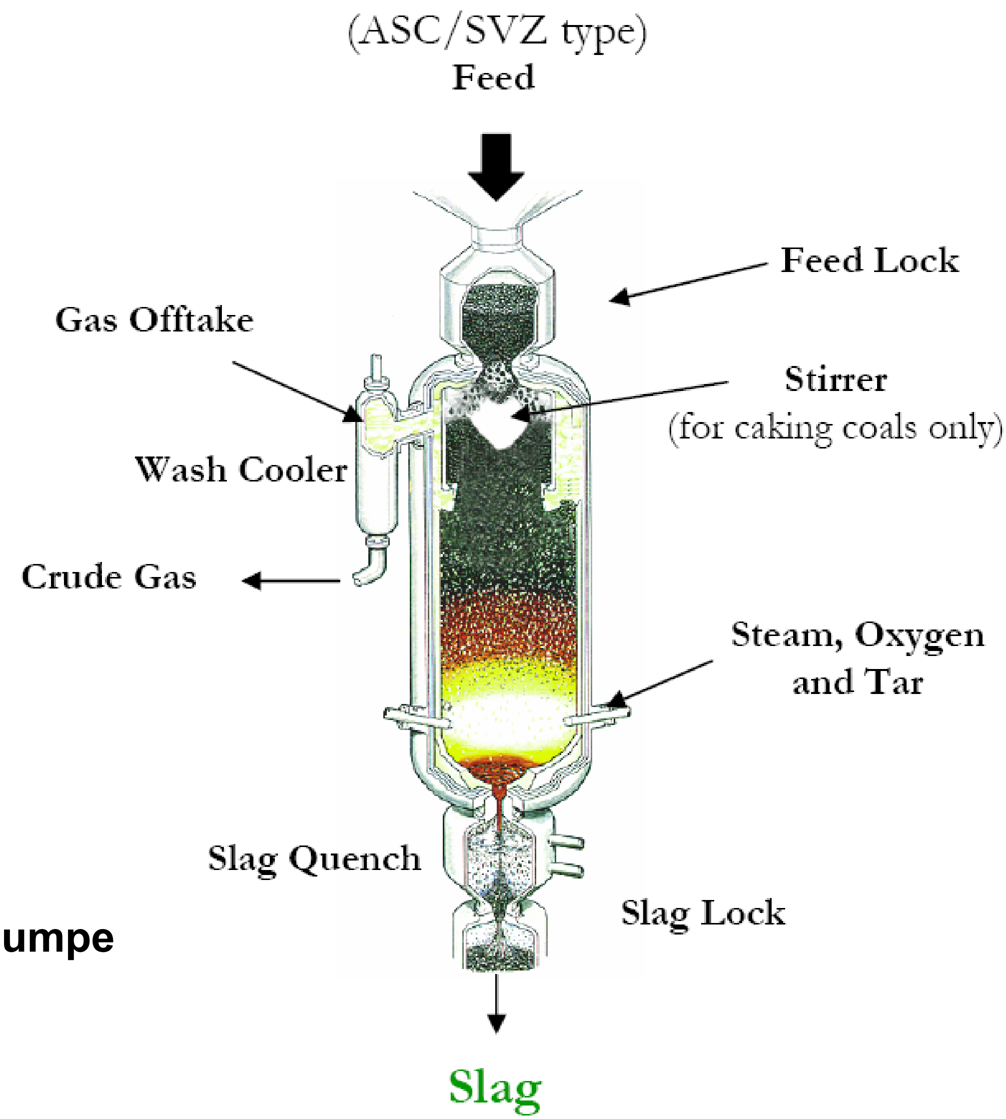
Lurgi Gasifier

- **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



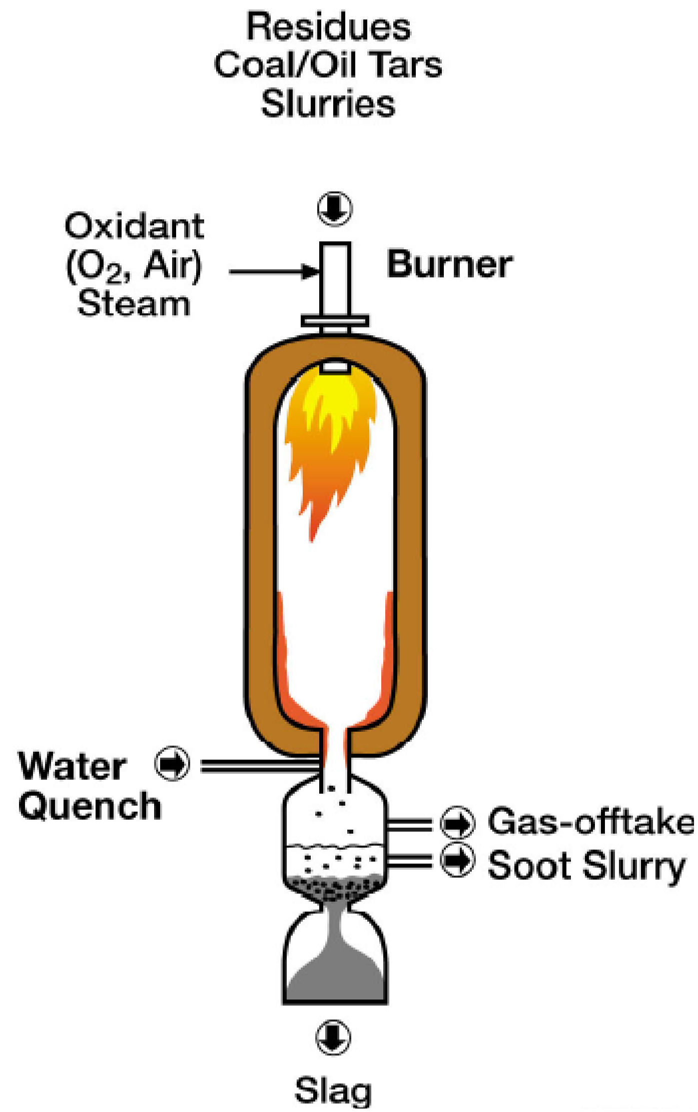
British Gas/ Lurgi (BGL) Gasifier

- 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



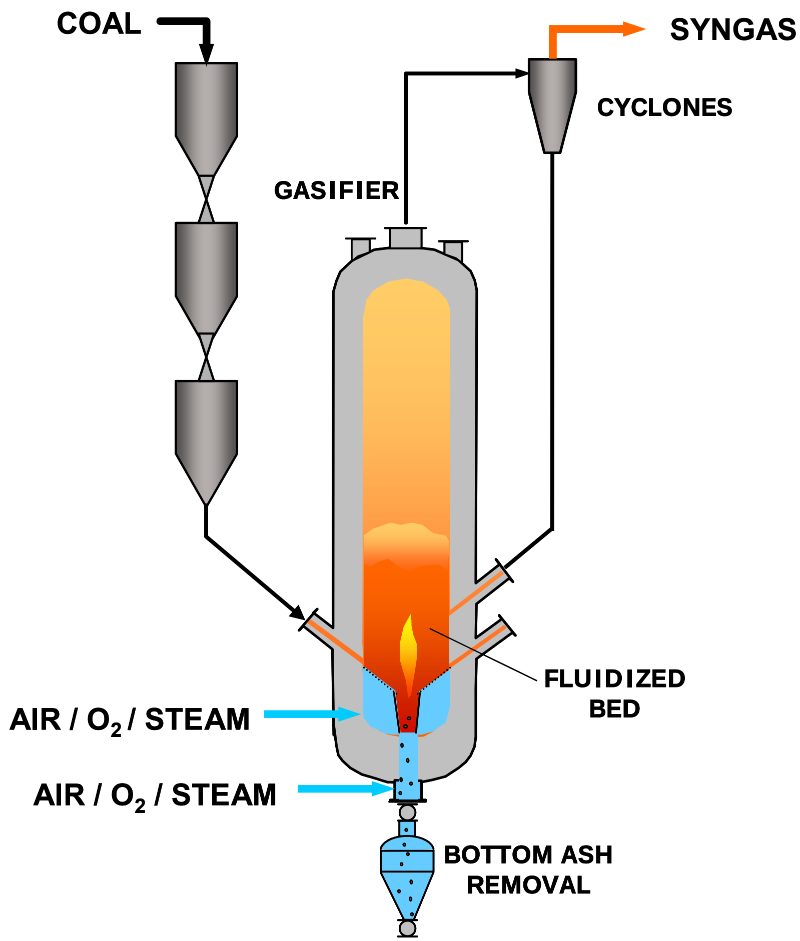
Multi Purpose (MPG) Gasifier

- **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



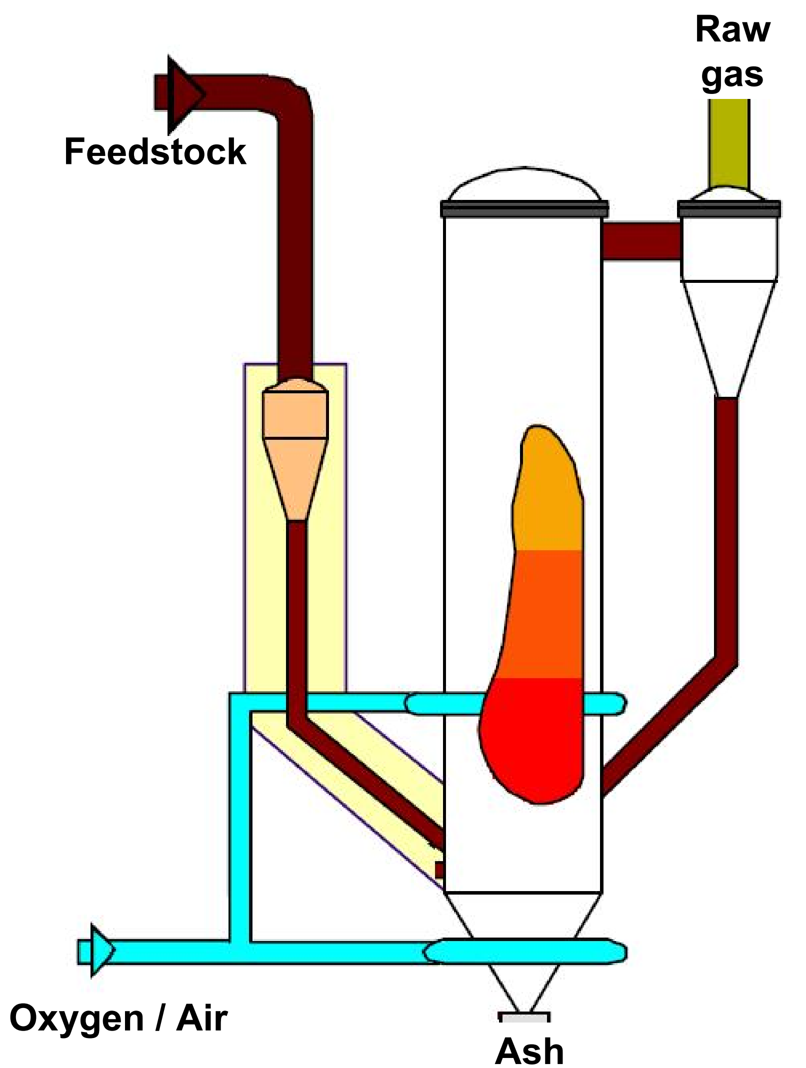
GTI (U-Gas) Gasifier

- **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

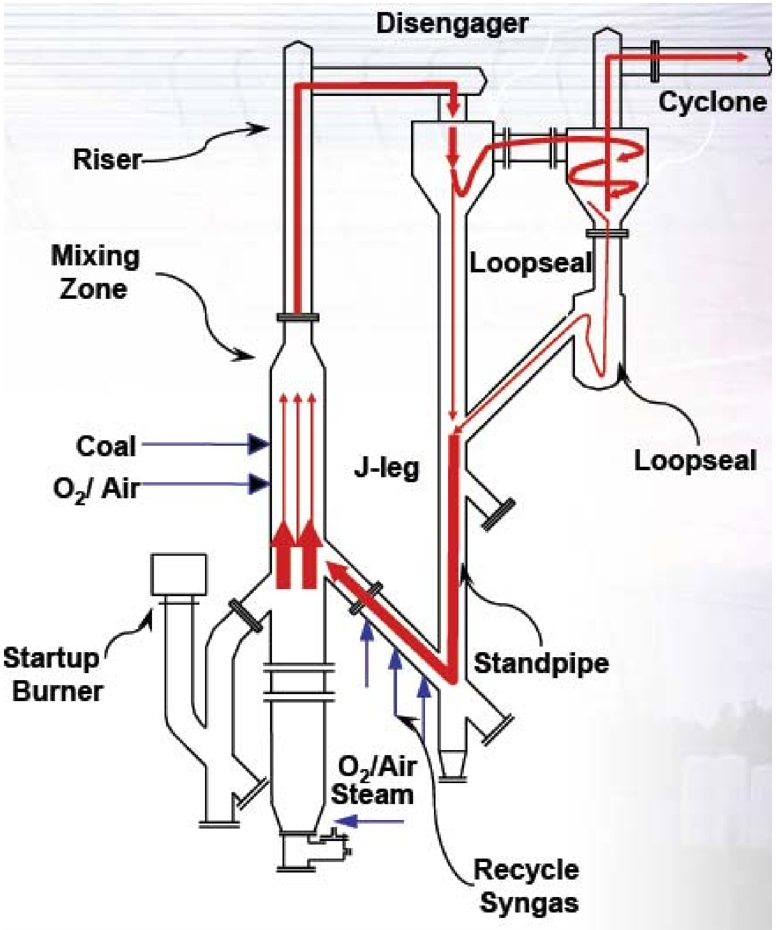
- **Fluidized bed gasifier**
- **Dry feed**
- **Oxygen or air-blown**
- **Dry bottom ash**
- **Developed to utilize lignite coal**
- **Capable of gasifying broad range of feedstock**
- **Marketed for waste materials as Uhde PreCon process.**
- **Berrenrath demonstration plant**
  - In operation 1986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



Kellogg Brown & Root (KBR) Gasifier

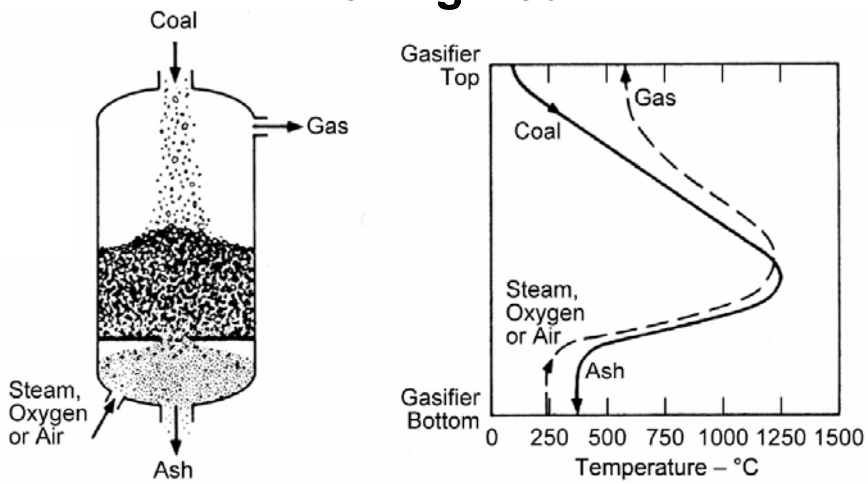
Transport Gasifier

- **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

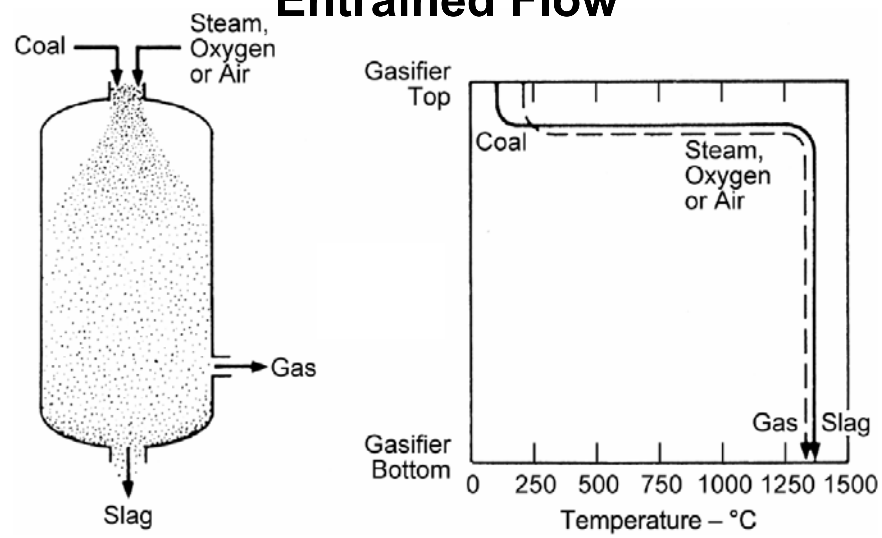


Gasifier Configurations

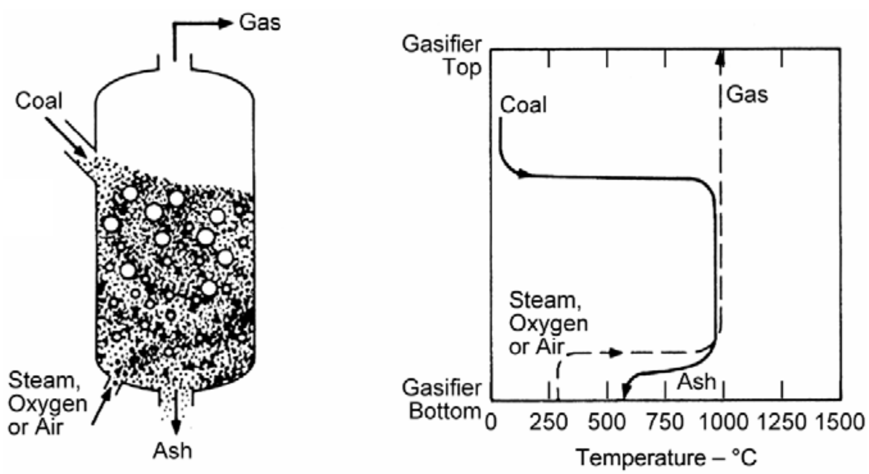
Moving Bed



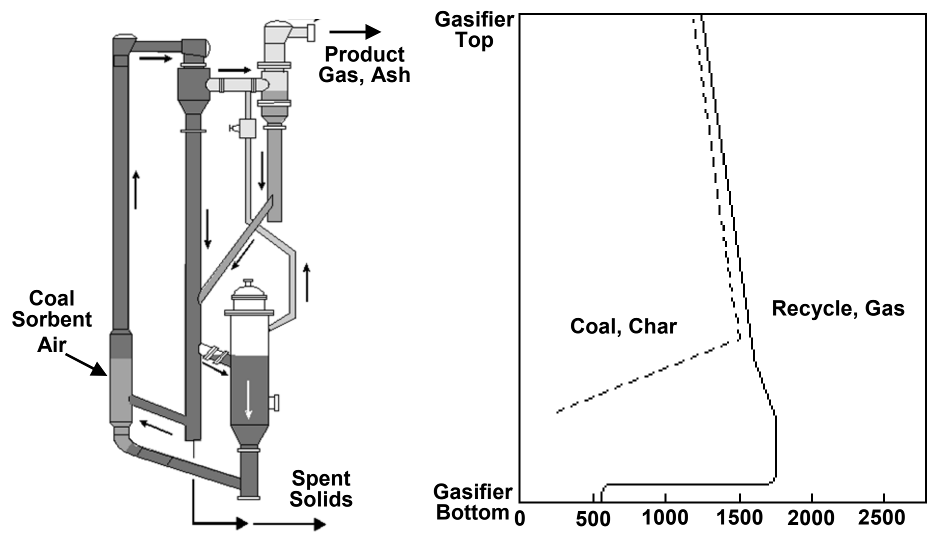
Entrained Flow



Fluidized Bed



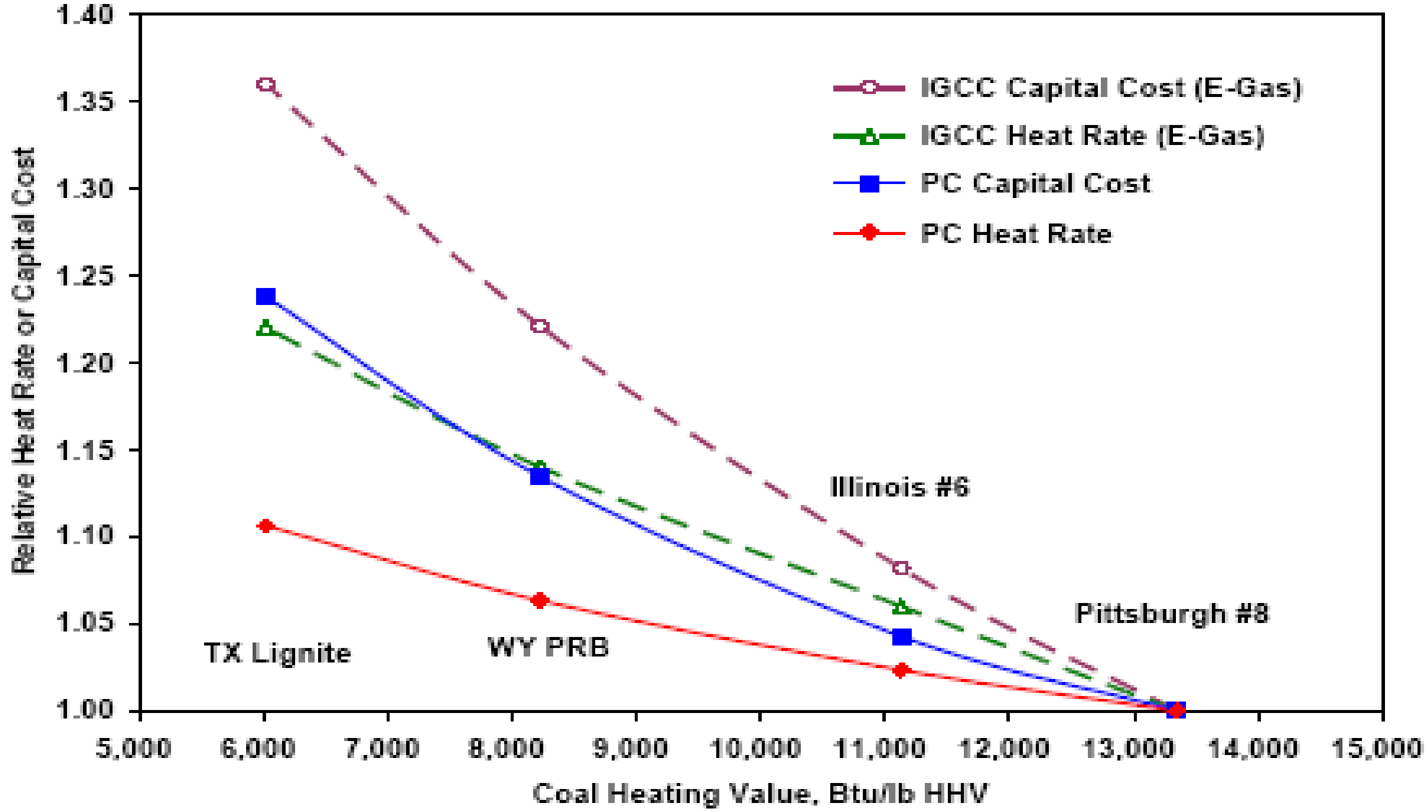
Transport



Comparison of Gasifier Characteristics

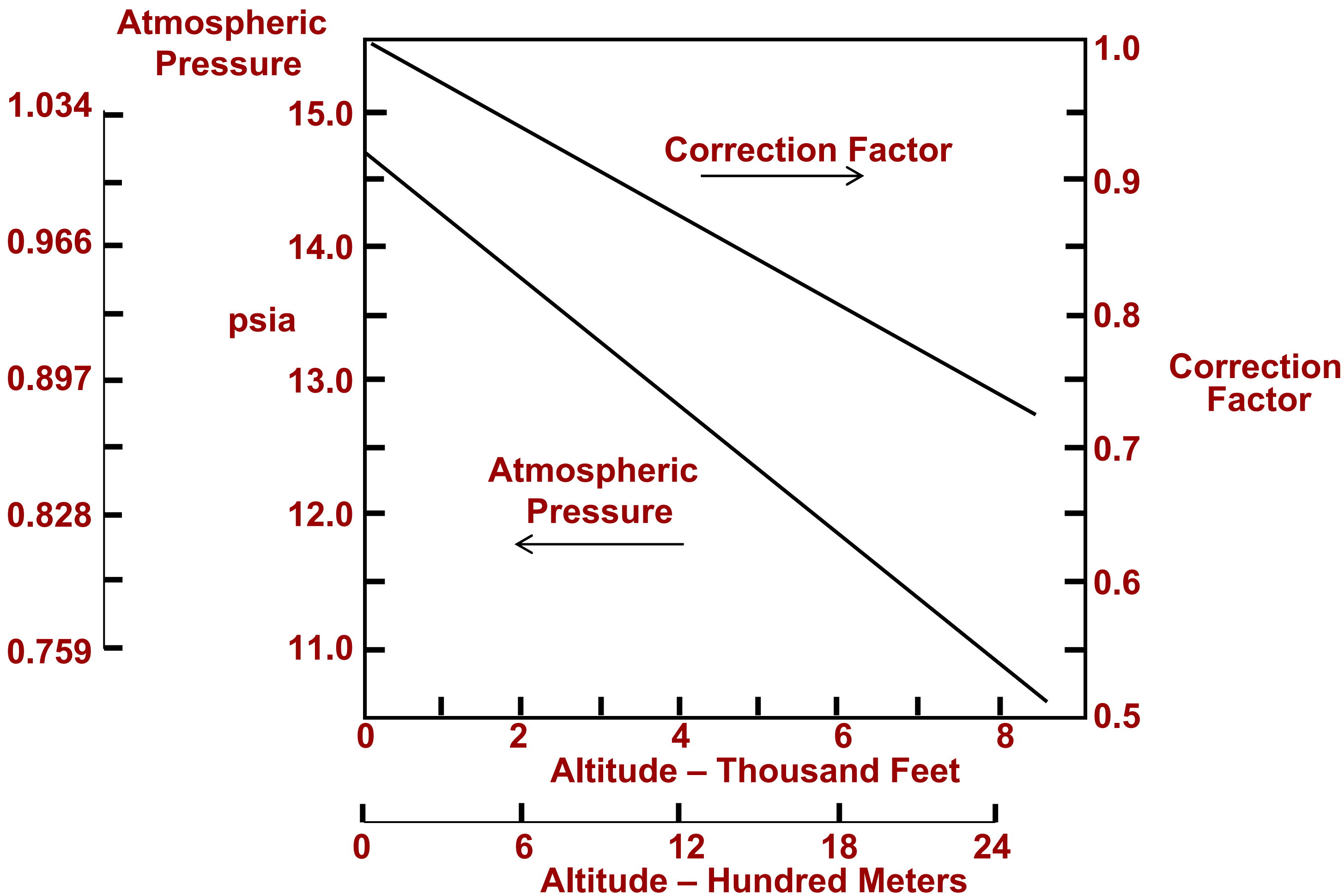
	Moving Bed		Fluidized Bed		Entrained Flow	Transport Flow
Ash Condition	Dry	Slagging	Dry	Agglomerate	Slagging	Dry
Coal Feed	~ 2 in	~ 2 in	~ 1/4 in	~ 1/4 in	~ 100 Mesh	~1/16in
Fines	Limited	Better than dry ash	Good	Better	Unlimited	Better
Coal Rank	Low	High	Low	Any	Any	Any
Gas Temp. (°F)	800-1,200	800-1,200	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



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

Effect of Altitude on Performance



Courtesy: General Electric

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
H_2	**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	—
CH_4	1.5	0.1	0.0	0.3	8.2	6.9	0.2	5.1	0.5	0.1	0.1	93.9
CO_2	9.3	13.3	17.1	30.0	14.0	2.8	5.6	1.6	17.9	15.8	17.8	14.5
N_2 + 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
H_2O	22.7	0.3	0.4	—	—	—	39.8	—	0.1	0.4	0.1	0.9
LHV[a]												
Btu/ft^3	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/M^3	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	—
H_2/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_2O	Steam	H_2O/N_2	N_2/H_2O	n/a
Equivalent LHV[b]												
Btu/ft^3	**150.0**	**118.0**	**113[c]**	**198.0**	—	**200.0**	—	[c]	**116.0**	**150.0**	**115.3**	**134.6**
kJ/M^3	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

Source: D. Todd GE - 2002

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 - 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

PROJECT- LOCATION	*COD**	*OUTPUT (MWe)*	*FEEDSTOCK - PRODUCTS*
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
Total Operating IGCC Output (MW)		*4100*	

** COD: Commercial Operation Date*

IGCCs are using a variety of feedstocks

Based on: Gas Turbine World, Jan – Feb 2007

IGCC Technology in Early Commercialization

U.S. Coal-Fueled Plants

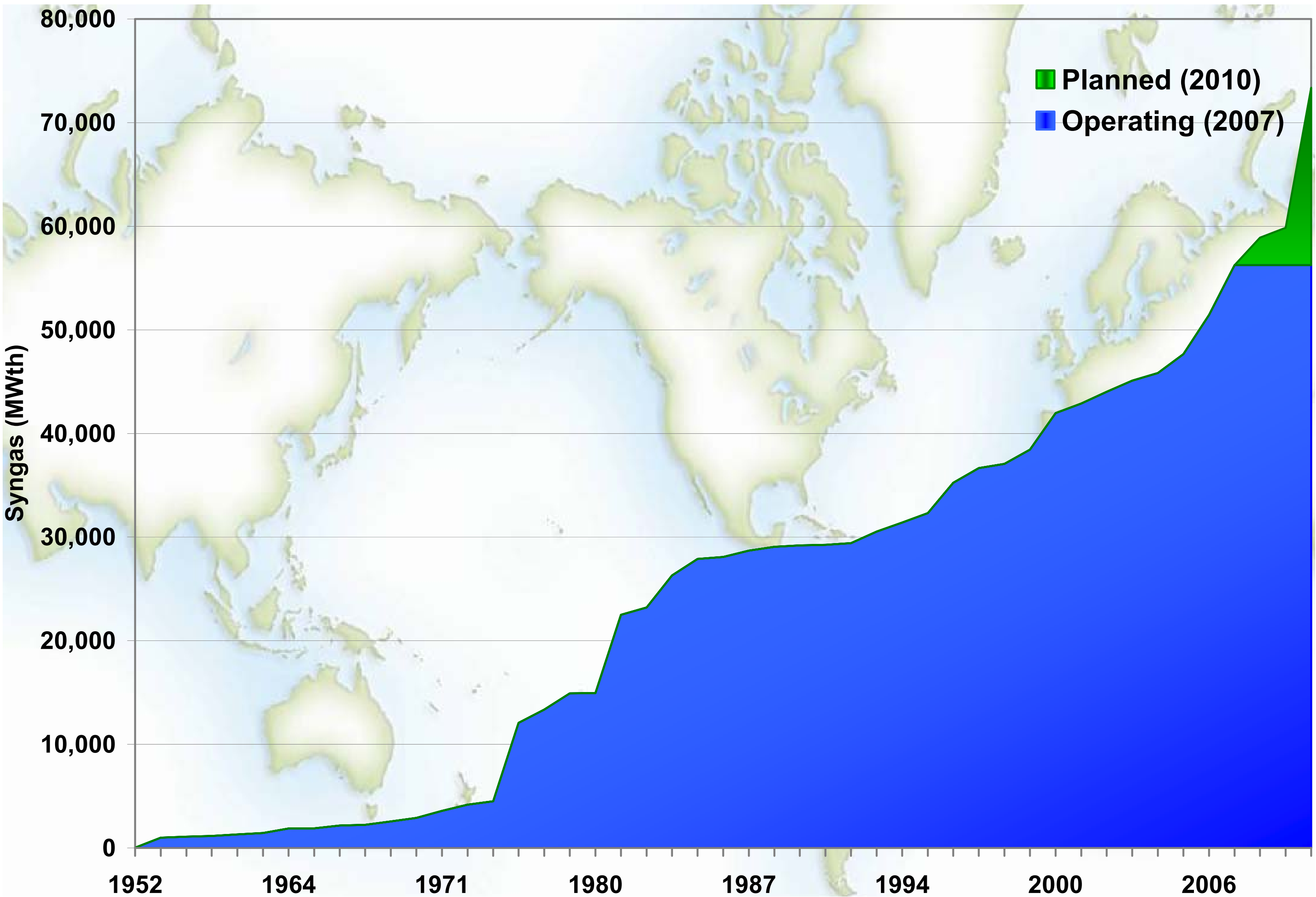
- **Wabash River**
  - 1996 Powerplant of the Year Award*
  - Achieved 77% availability **
- **Tampa Electric**
  - 1997 Powerplant of the Year Award*
  - First dispatch power generator
  - Achieved 90% availability **

Nation's first commercial-scale IGCC plants, each achieving
> 97% sulfur removal
$\geq$ 90% NO_x reduction

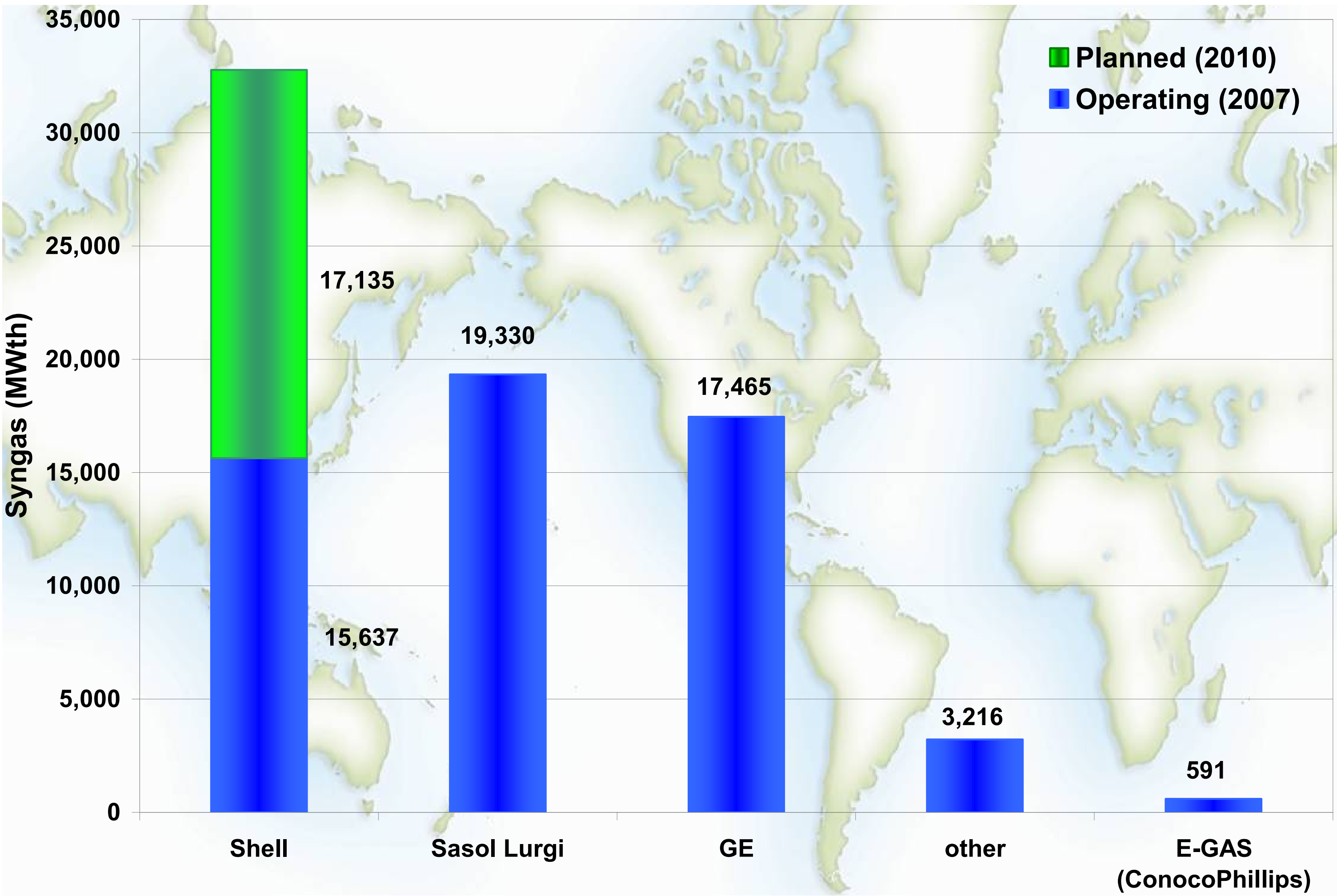
Power Magazine* * Gasification Power Block*

Worldwide Gasification Capacity and Planned Growth

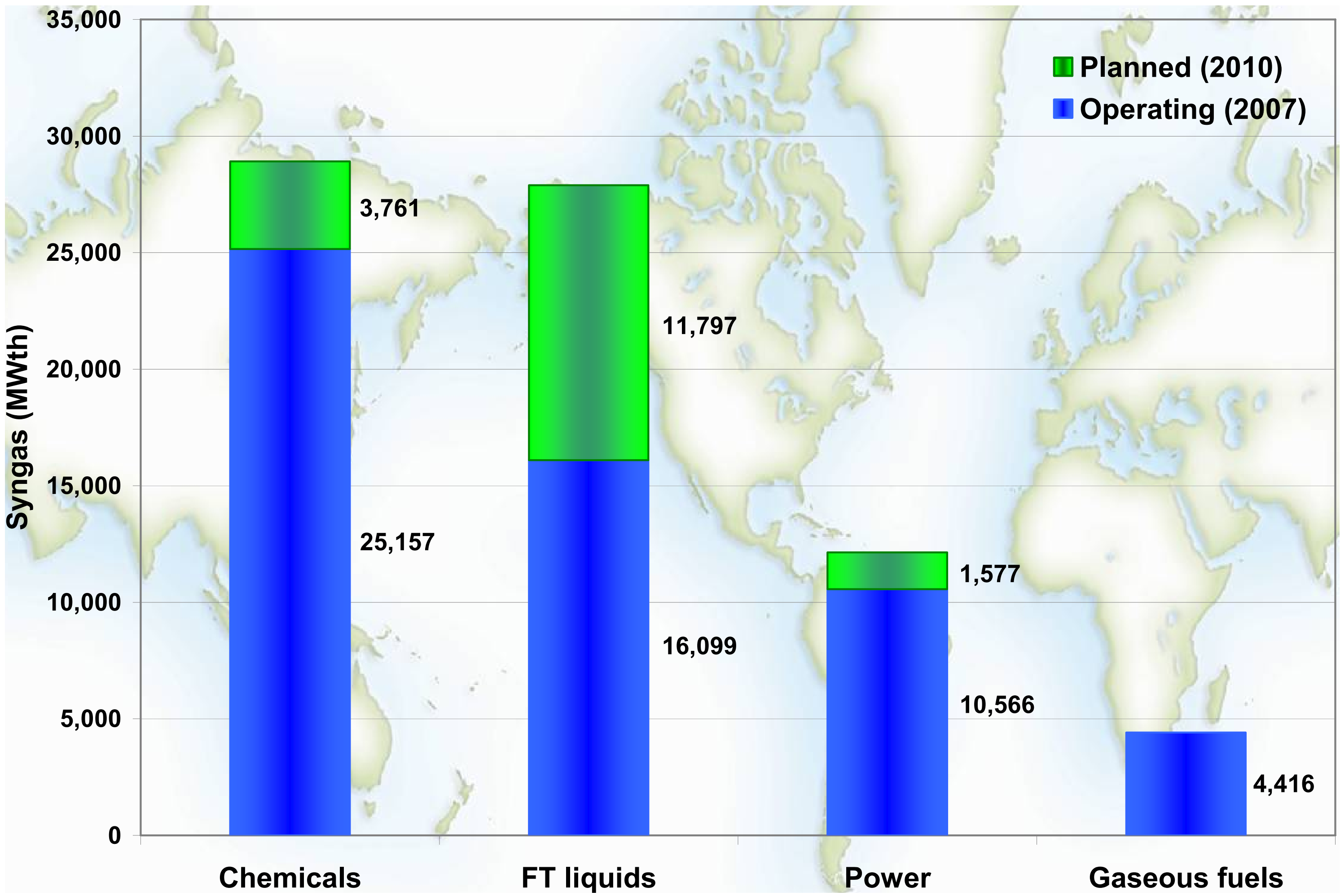
Cumulative by Year



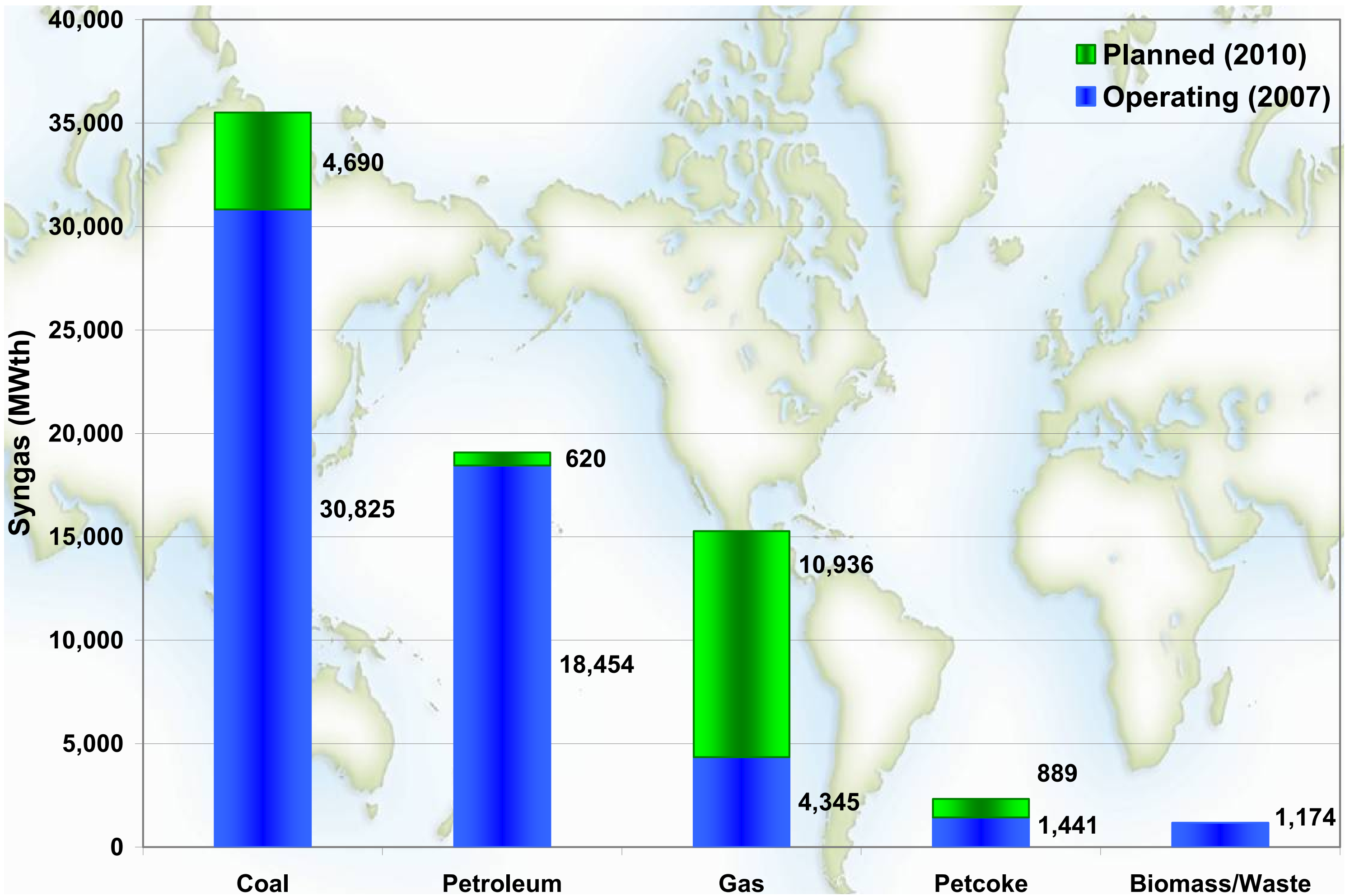
Worldwide Gasification Capacity and Planned Growth
by Technology



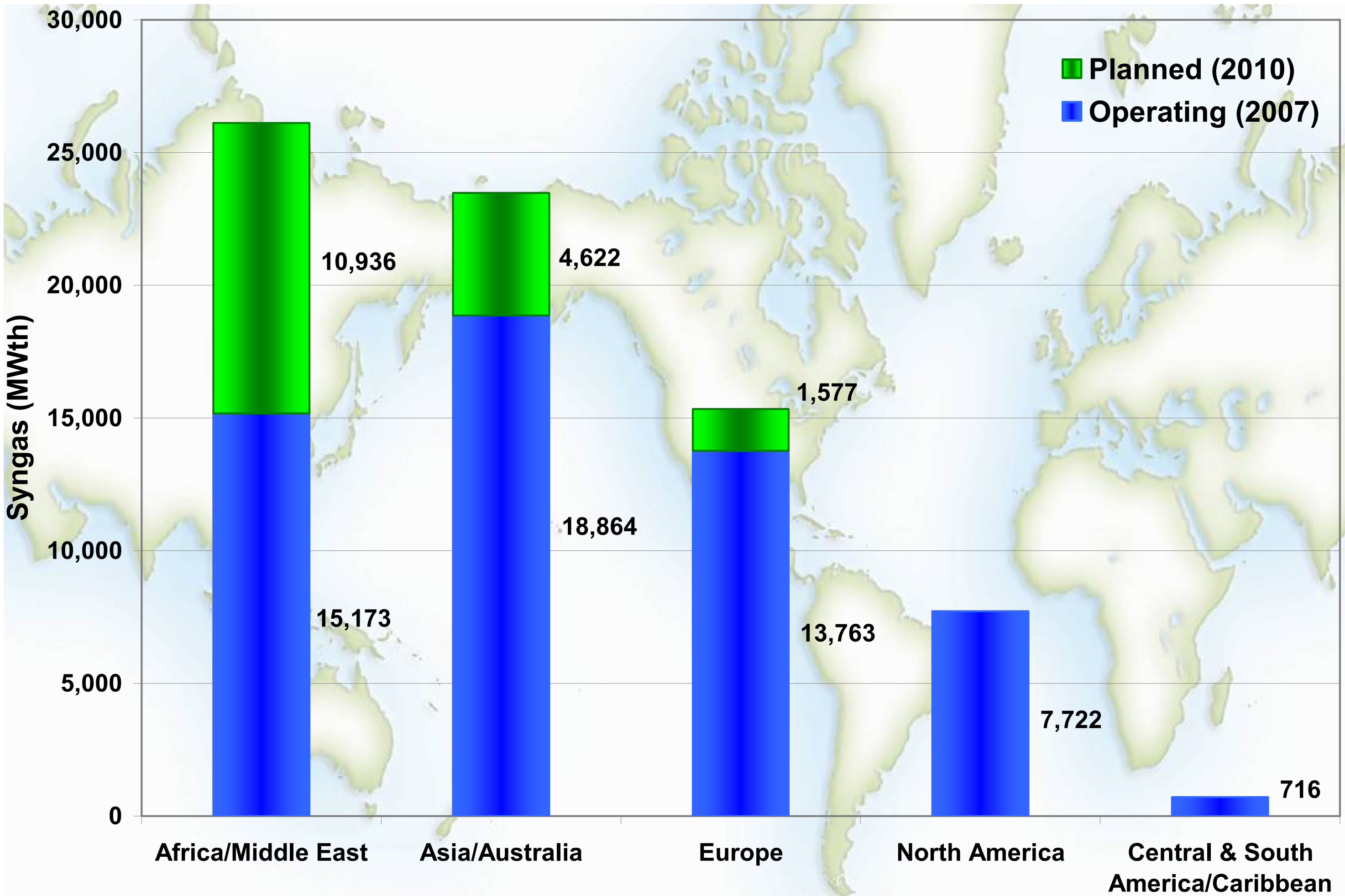
Worldwide Gasification Capacity and Planned Growth
by Product



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**

http://www.gasification.org/Docs/Penwell%202005/PowerGen%202005_Amick_r1.pdf

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.

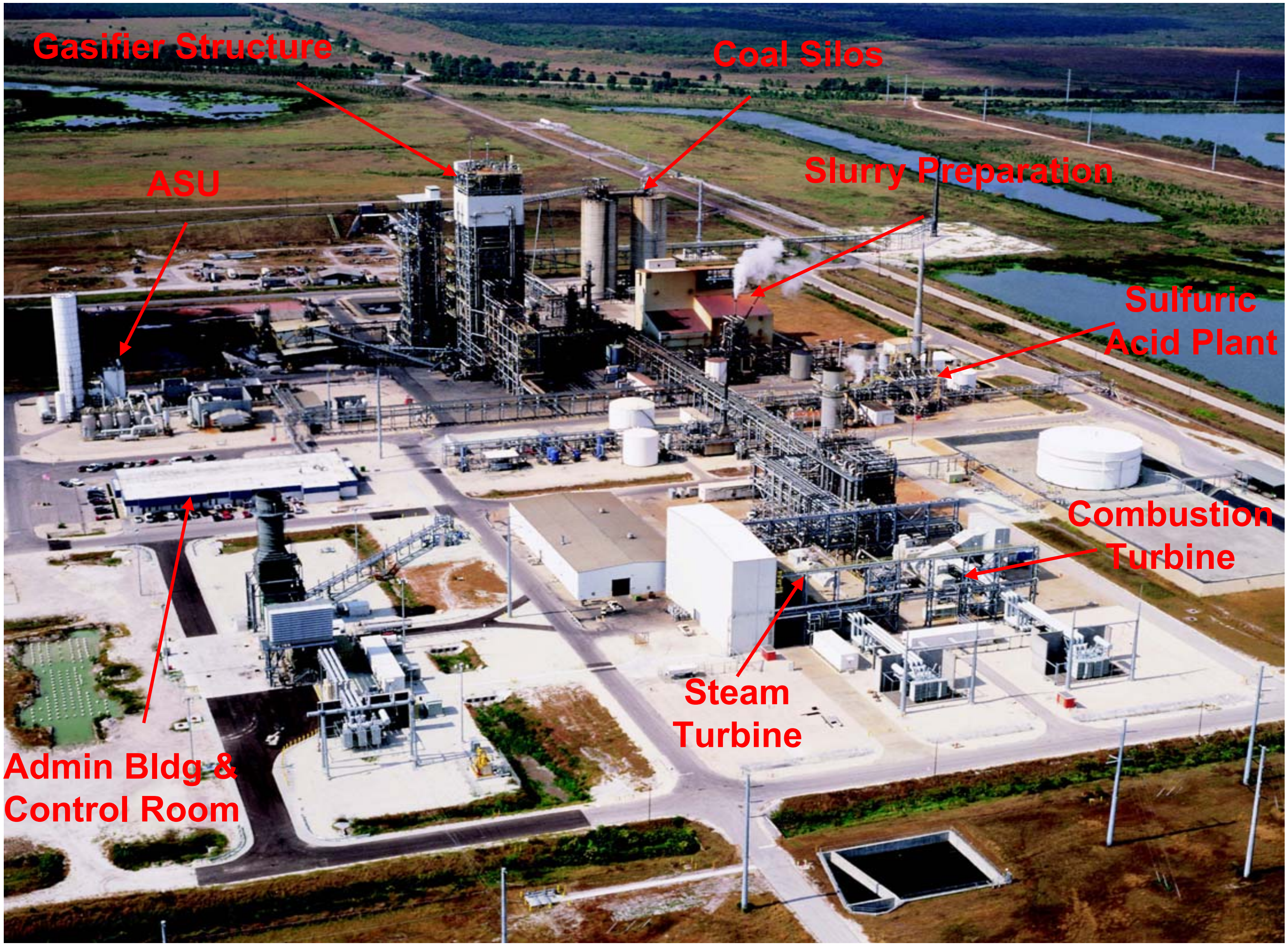
Mulberry, FL

- **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**

Courtesy: Tampa Electric Co.

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

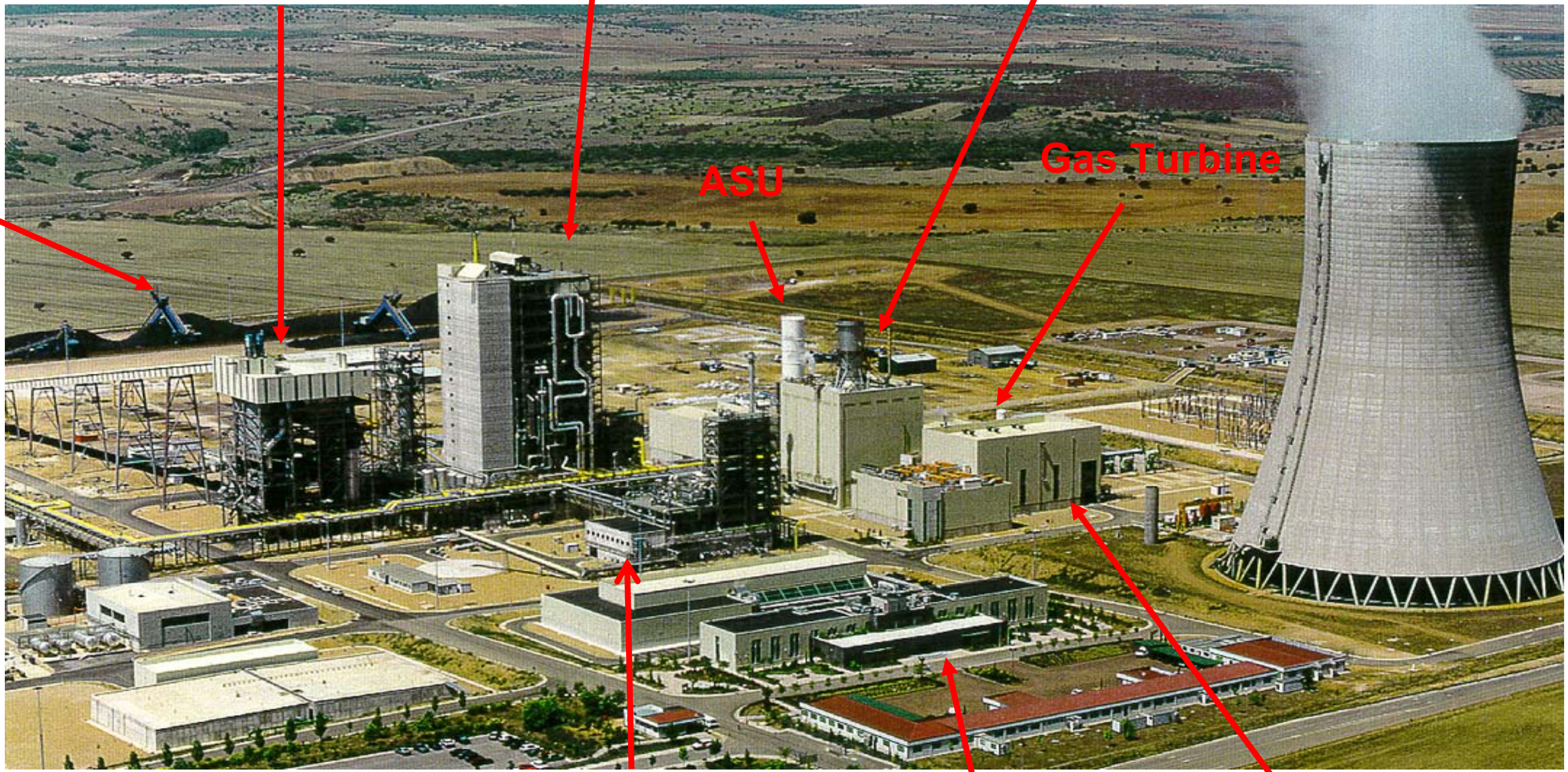
- **Power generation**

	ISO	at site
– Combustion turbine:	200 MW	182.3 MWe
– Steam turbine:		135.4 MWe
– Internal load:		- 35.0 MWe
– **Net output:**	300 MW	282.7 MWe

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

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

ELCOGAS Plant Aerial Photo



Nuon IGCC Plant
Buggenum, The Netherlands

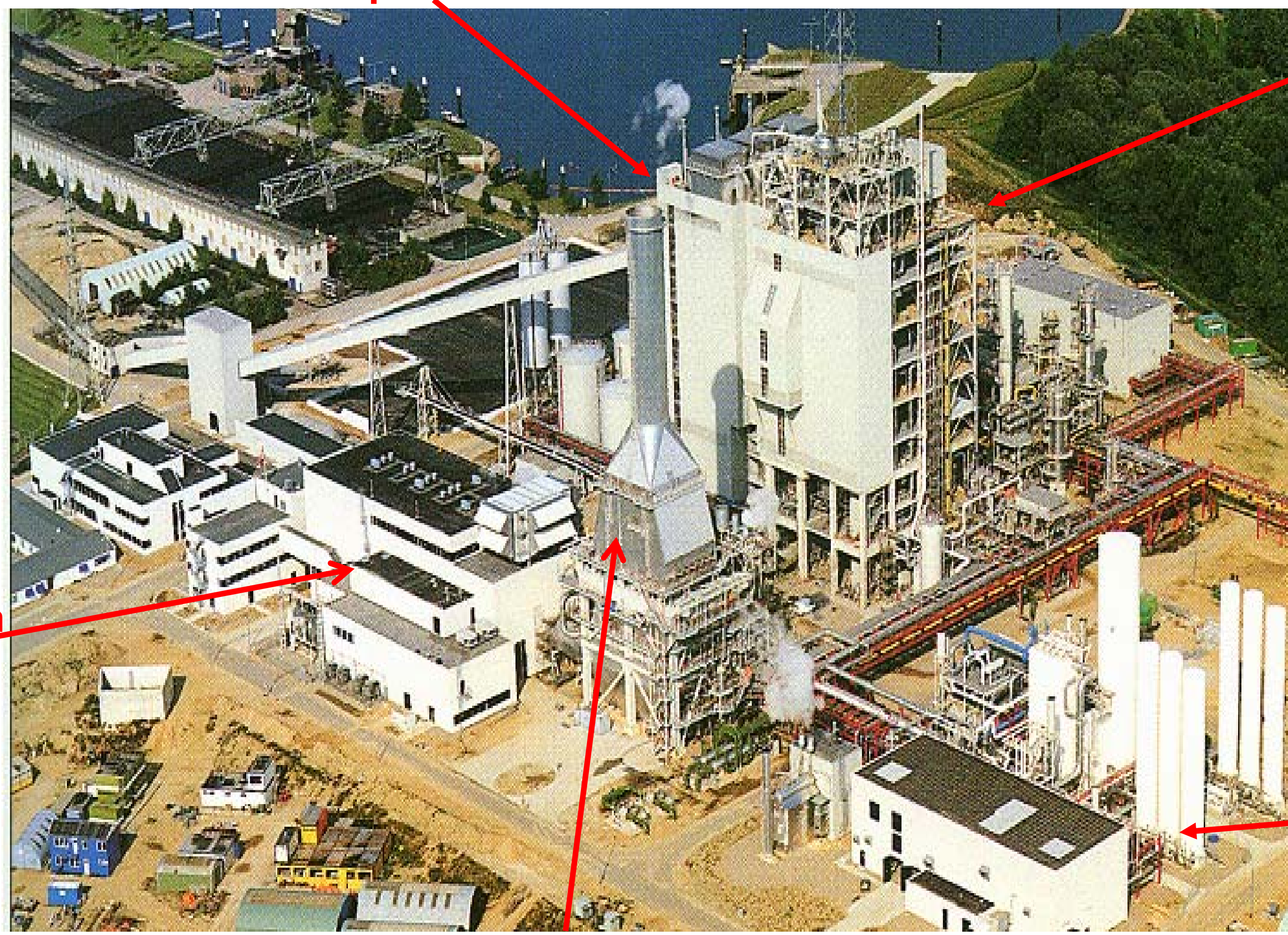
- **Shell Gasification**
  - offered jointly with Krupp Uhde
- **Gas turbine: Siemens V94.2**
- **2,000 tons/day feedstock**
  - bituminous coal
  - biomass
- **Plant startup 1993**
- ***Only large-scale biomass installation in operation today***

Buggenum IGCC Plant

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

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

Nuon Plant Aerial Photo



Note: Sulfur Removal & Recovery (out of view)

Courtesy: Nuon

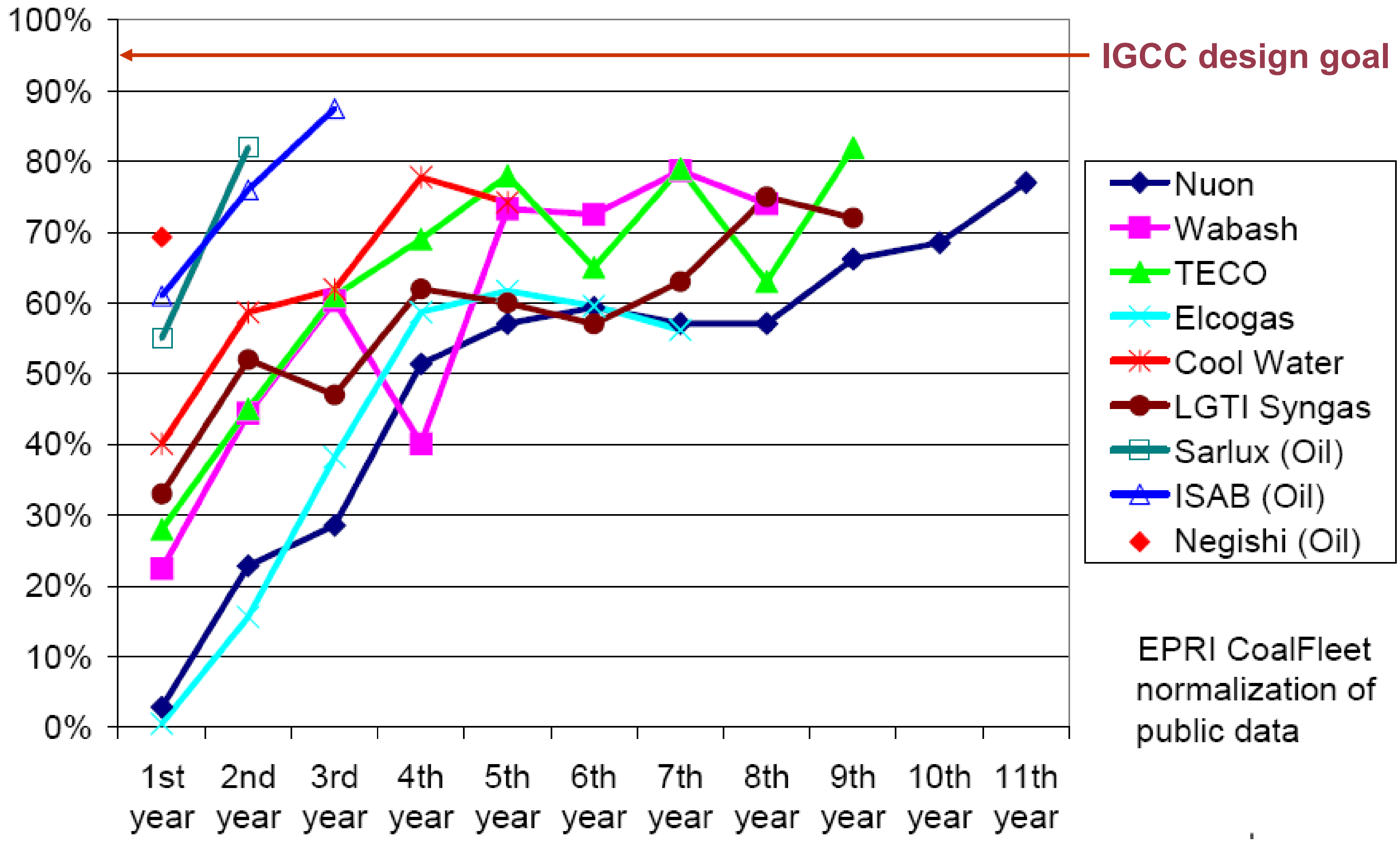
Valero Refinery
Delaware City, Delaware

- **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



Source: EPRI

Dakota Gasification Company

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 CO_2 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

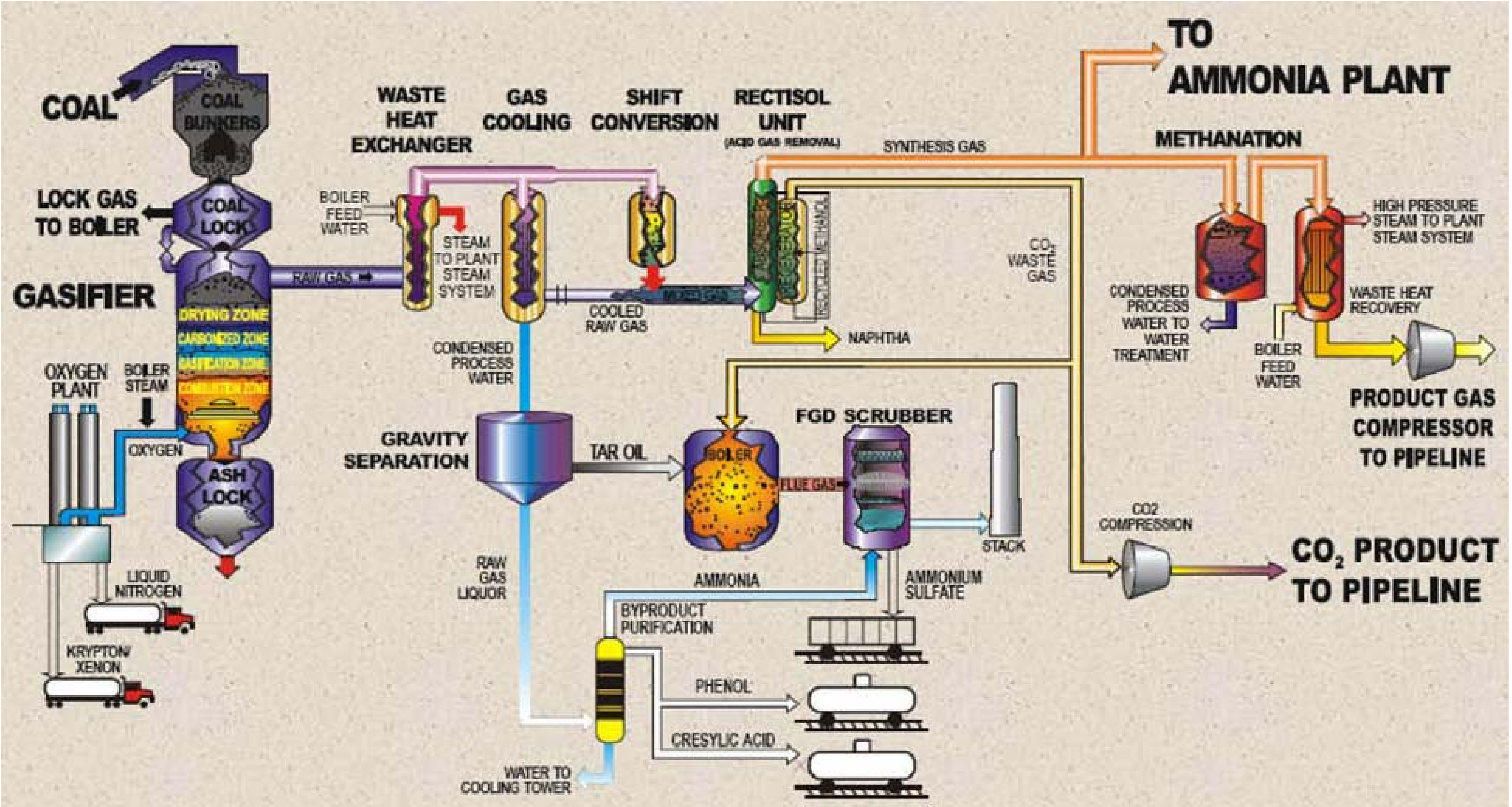
CO_2 is captured, pressurized, and piped 205 miles to Saskatchewan and sold for use in enhanced oil recovery (EOR) by EnCana and Apache Canada

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.

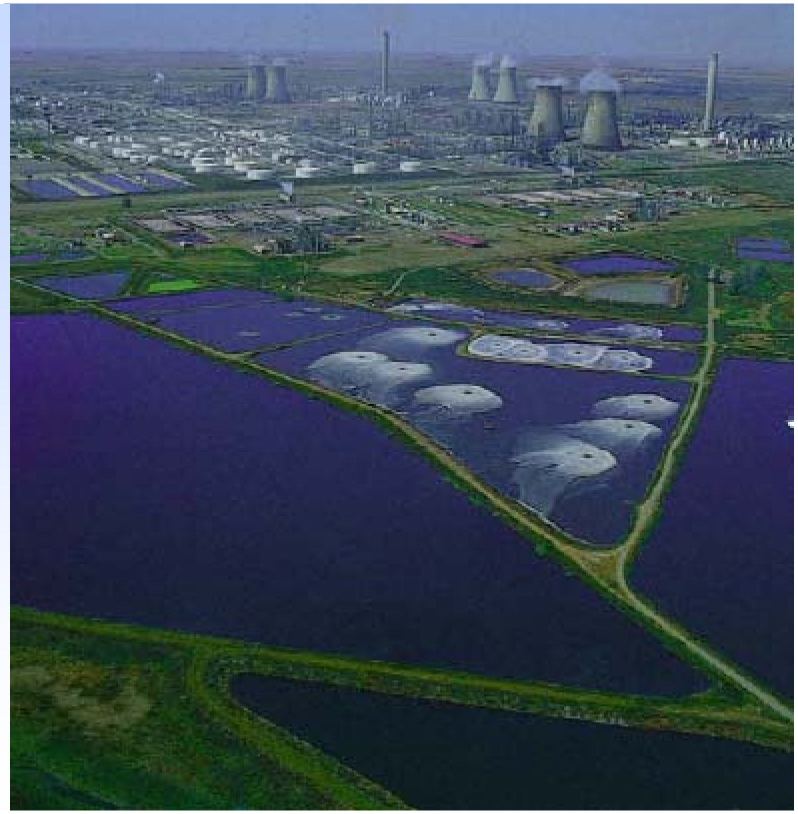
Eastman Chemical Company

Kingsport, Tennessee

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*

Photo: John Sichinga

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

Photo: Courtesy Sasol

Coffeyville Resources Nitrogen Fertilizers

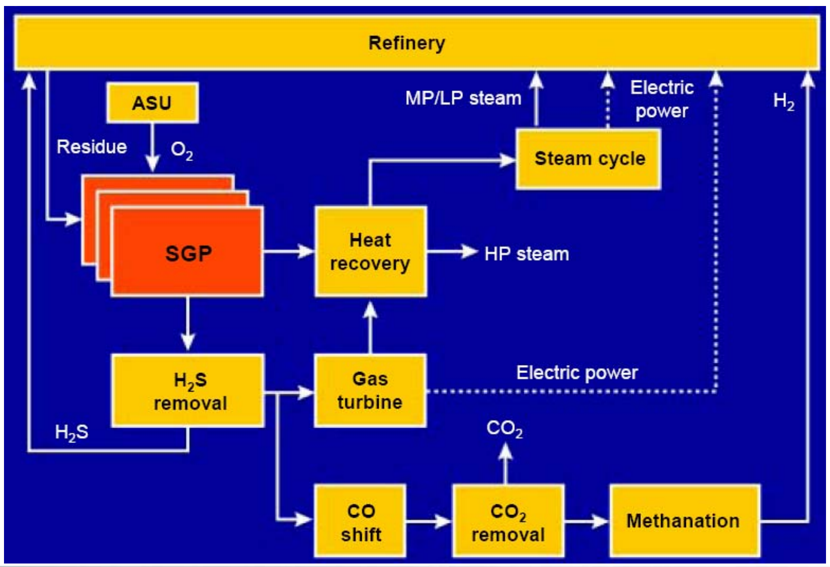
Coffeyville, Kansas

- **Plant converted from natural gas to petcoke to reduce costs by adding GE Energy gasifier**
- **Produces syngas with CO and H_2**
- **Syngas shifted to CO_2 and H_2**
- **CO_2 removed, leaving concentrated H_2 stream**
- **H_2 used to make ammonia for fertilizer**
- **326,663 short tons ammonia in 2007**

Technology suitable for Carbon Capture

Pernis Refinery IGCC/Hydrogen Project

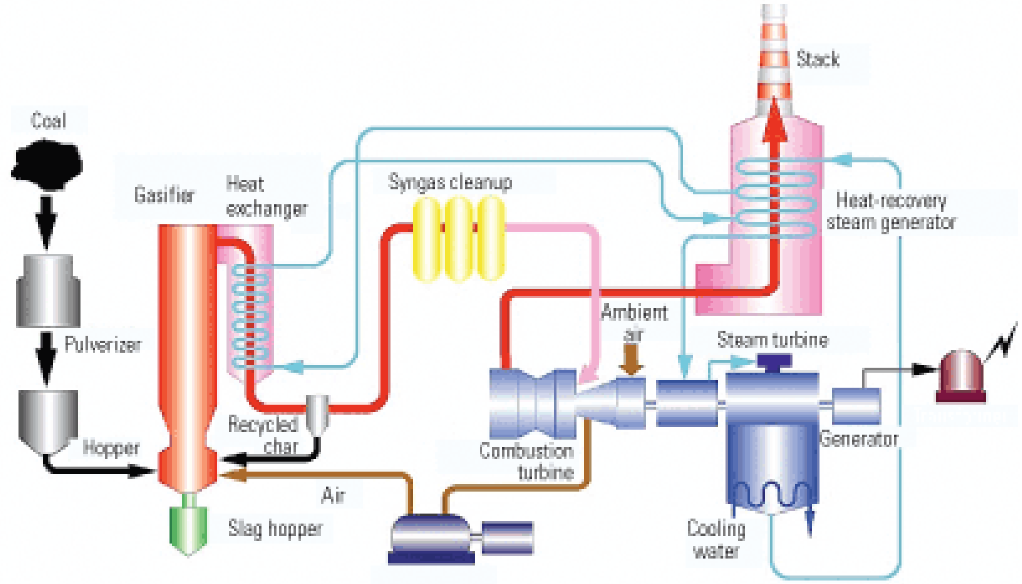
- Major $2.2 billion refinery renovation
- Completed May 1997
- Gasifies 1,656 mt/d visbreaker residue
- Produces 118 MMscf/d H_2
- 3 Shell Gasifiers
- Rectisol process for gas cleanup
- 2 General Electric 6B turbines



Clean Coal Power R&D IGCC Demonstration Plant

Nakoso, Japan

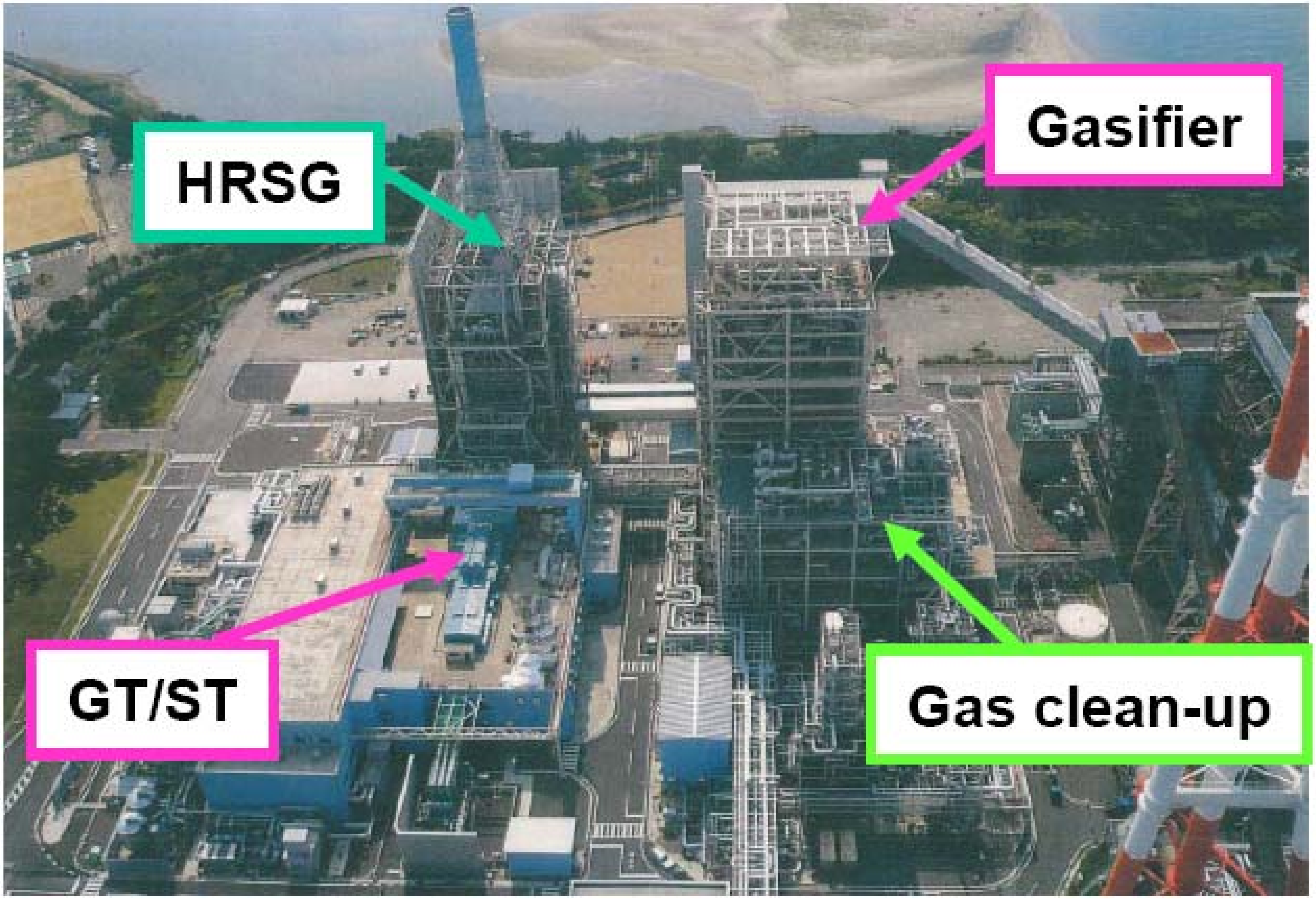
- **Mitsubishi Gasifier**
  - 250 MWe
  - Air-blown
  - Entrained flow
  - Dry coal feed
- **1,700 tons/day coal**
  - Suited to wide range of coals
- **Water wall structure**
- **Gas clean-up MDEA chemical absorption**
- **Plant startup**
  - September 2007



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

Clean Coal Power R&D IGCC Demonstration Plant

Aerial Photo



WMPI Coal-to-Clean Fuels & Power Project

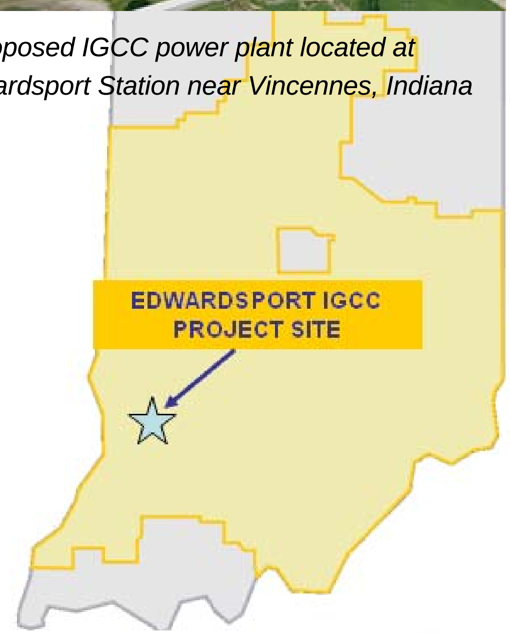
Gilberton, PA

- 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)

Emission	*NSPS*	*NSPS on Gasifier Input Basis (calculated)*
NO_x	1.0 lb/MWh*	0.143 lb/MMBtu
SO_2	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

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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

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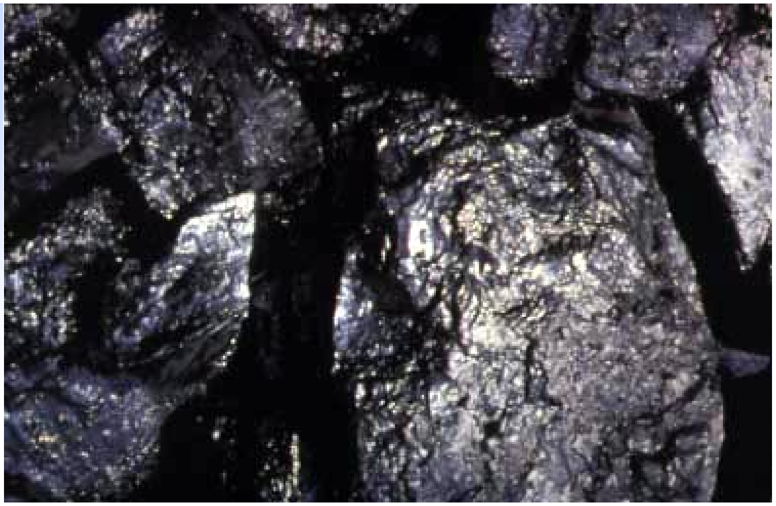
Potential Feedstocks

- **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

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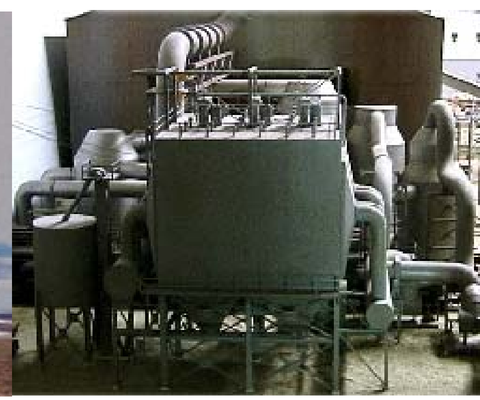
Air Emissions

- **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

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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

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What About SCR for IGCC?

- **Technical issues**
  - The <u>fuel</u> is syngas, not natural gas as in NGCC
  - Ammonium sulfate/bisulfate deposit in the HRSG, causing corrosion and plugging, requiring numerous washdowns
  - No <u>coal-based</u> 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

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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

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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

EPA United States Environmental Protection Agency

EPA-430/R-06/006
July 2006

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

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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

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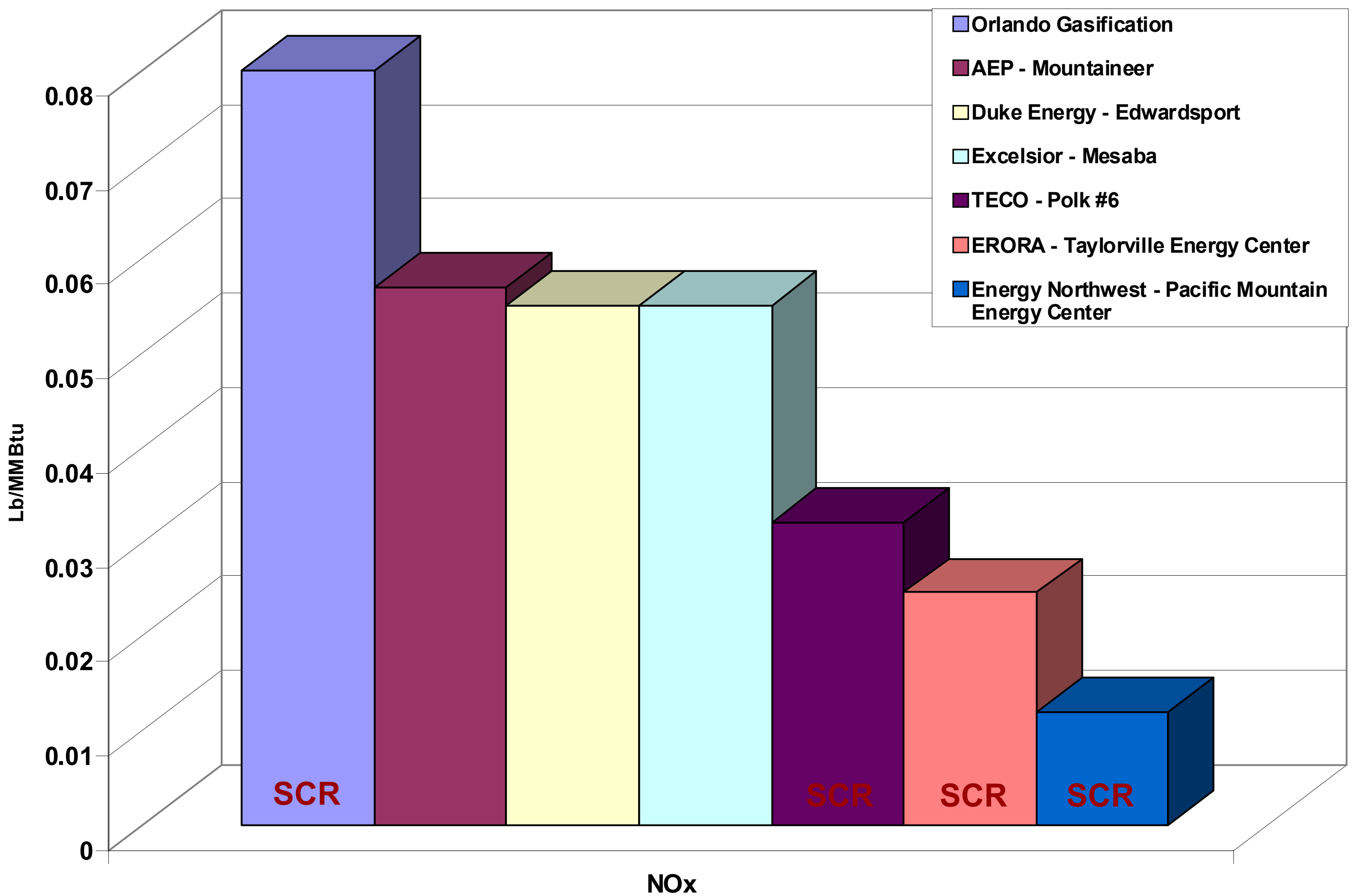
NOx Emission Rate Comparisons

Gasifier Heat Input Basis



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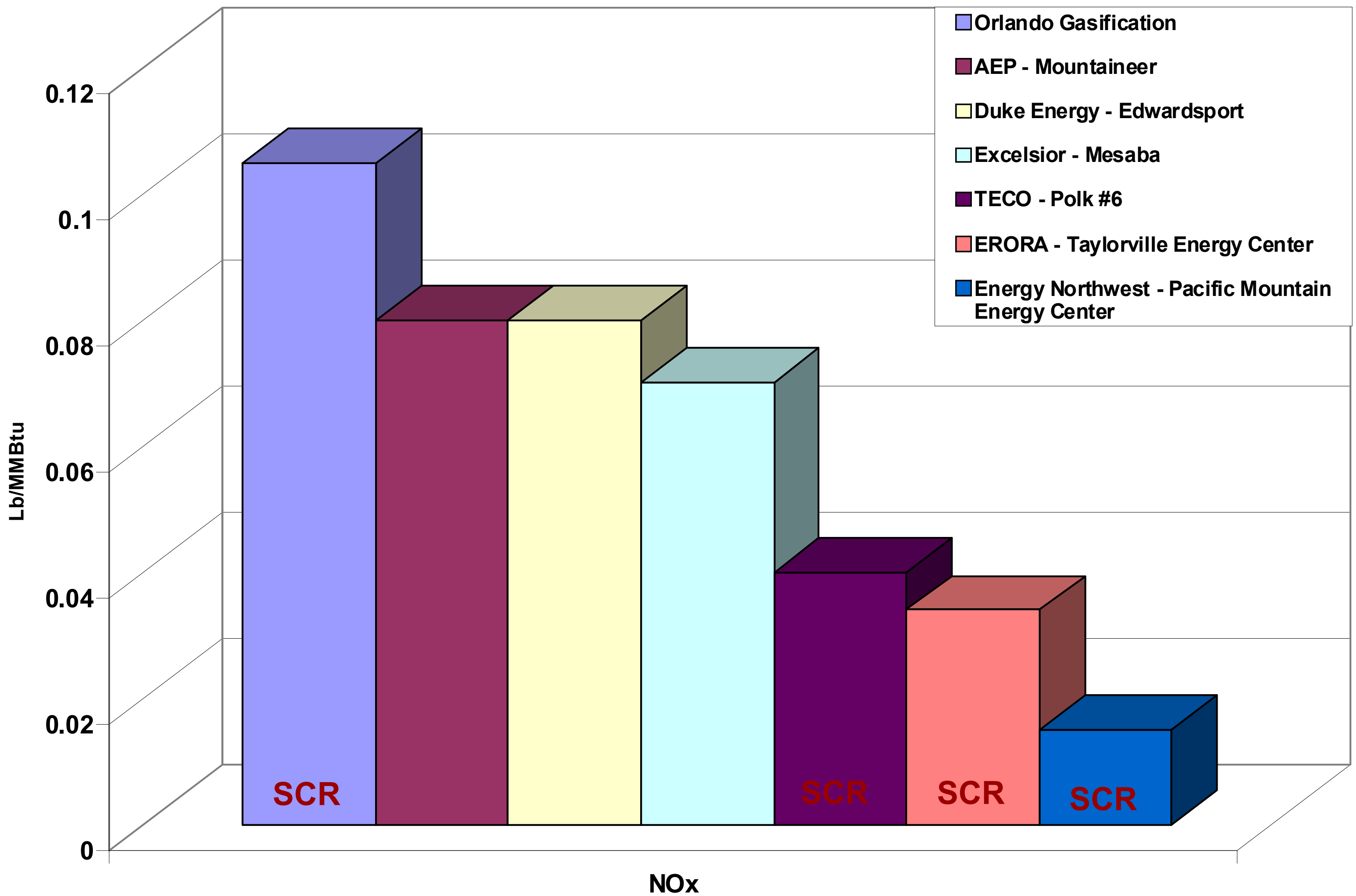
NOx Emission Rate Comparisons

Gas Turbine Heat Input Basis



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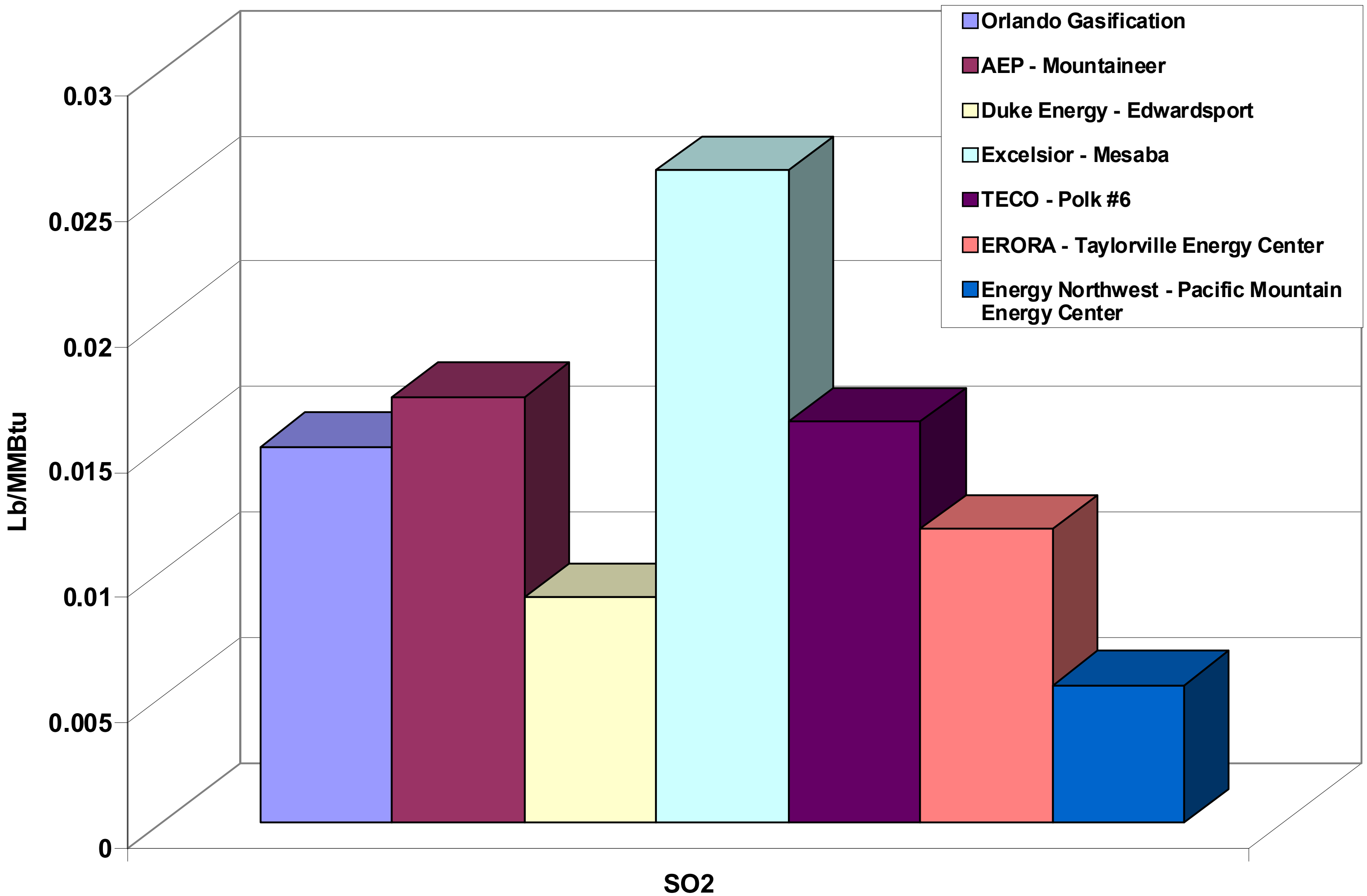
SO_2 Emission Rate Comparisons

Gasifier Heat Input Basis



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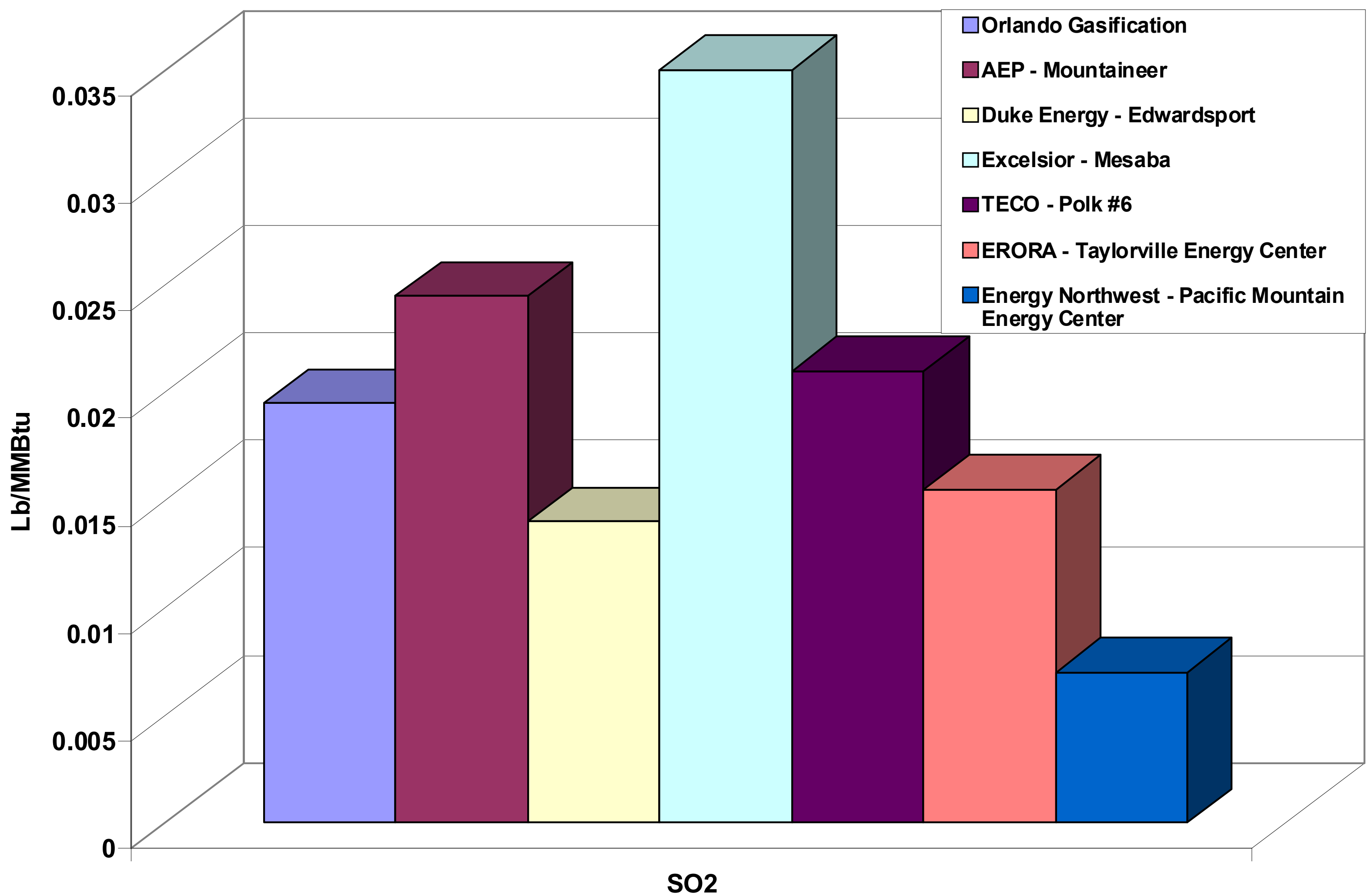
SO_2 Emission Rate Comparisons

Gas Turbine Heat Input Basis



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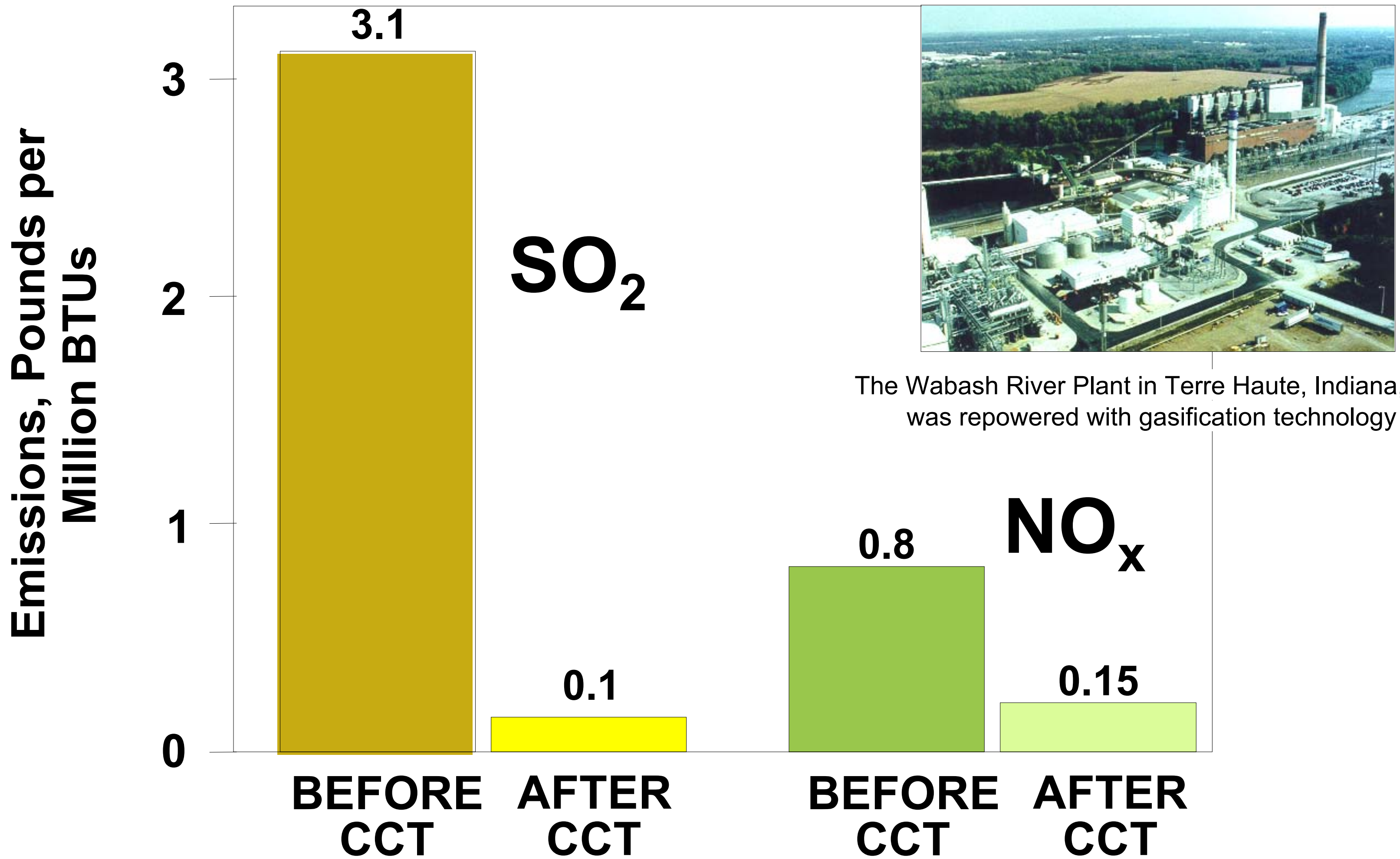
Wabash River Clean Coal Project

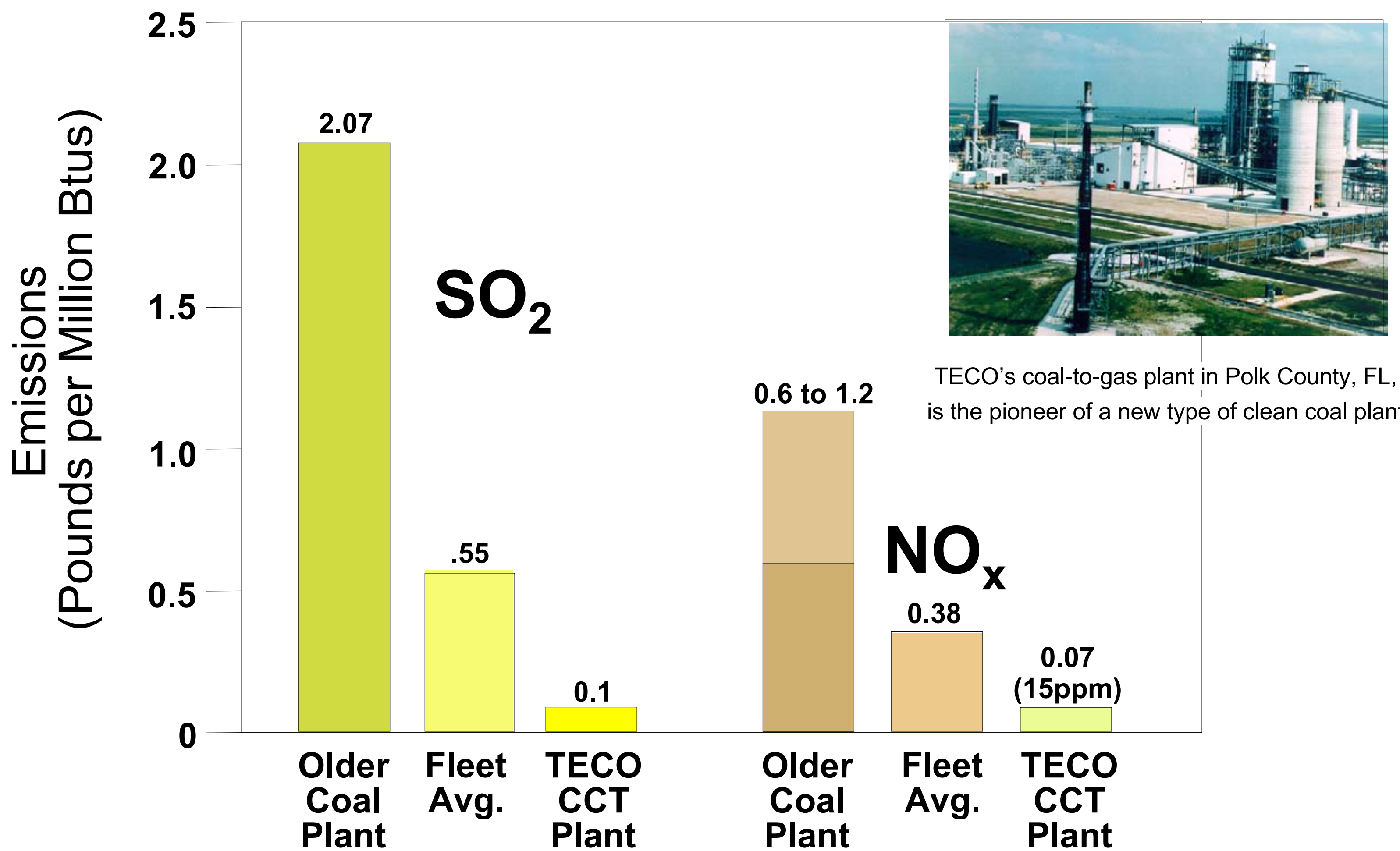
A Case Study for Cleaner Air



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



TECO's coal-to-gas plant in Polk County, FL, is the pioneer of a new type of clean coal plant.

NATIONAL ENERGY TECHNOLOGY LABORATORY

Proposed U.S. Gasification Plants - *IGCC*

Project	*State*	*Feedstock*	*MWe*	*MFG.*	*Capture*	*In Service*
Edwardsport IGCC Project	Indiana	coal	630	GE	study	2012
Taylorville Energy Center	Illinois	coal	630	GE	NO	2012
Cash Creek Generation*	Kentucky	coal	720	GE	EOR	2012
Carson Hydrogen Power Project	California	petcoke	500	GE	4 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	
Luminant IGCC Commercial Demonstration Project	Texas	coal	630		YES	
Luminant IGCC Commercial Demonstration Project	Texas	coal	630		YES	
On Hold						
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	
**also SNG project*						

Proposed U.S. Gasification Plants – *CTL & Chemicals*

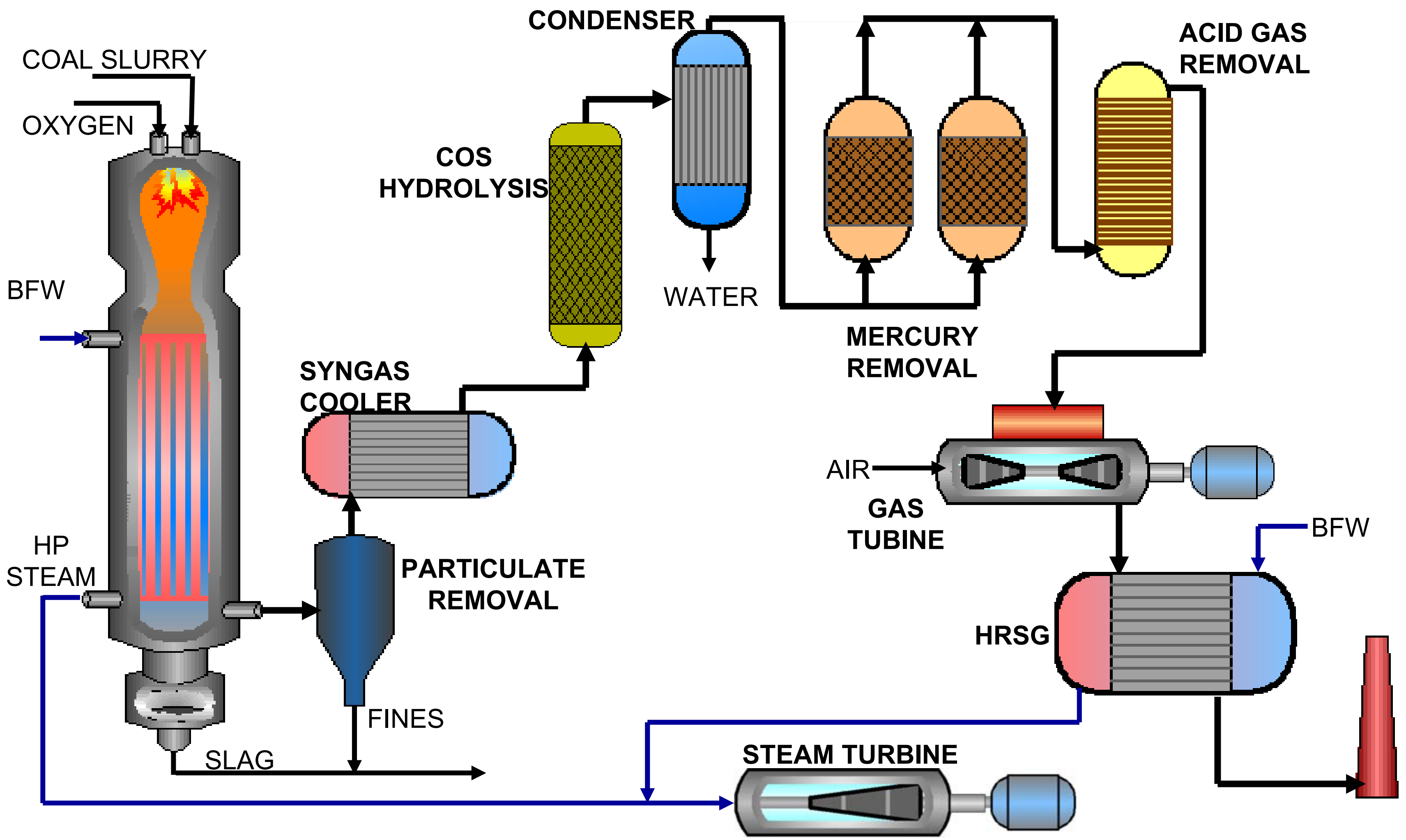
Project	*State*	*Feed stock*	*Product*	*Capacity*	*Unts*	*MFG*	*Capture*	*In Service*
WMPI Coal-to-Clean Fuels & Power Project	Pennsylvania	waste coal	ultra-clean transportation fuels	5,000	BPD	Shell	NO	
Illinois Clean Fuels project	Illinois	coal	ultra-clean transportation fuels	400	Mgal/Y		YES	2012
Natchez Strategic Fuels and Chemicals Complex	Mississippi	coal	ultra-clean transportation fuels	1,600	BPD		YES	2011
Medicine Bow Fuel & Power LLC	Wyoming	coal	MTG	20,000	BPD	GE		2013
Malmstrom AFB CTL project	Montana	coal	jet fuels	25,000	BPD		EOR	
American Lignite Energy	North Dakota	coal	ultra-clean transportation fuels	32,000	BPD			
Power County Advanced Energy Center	Idaho	coal	fertilizer	3,100	TPD	E-Gas		2011
Ohio River Clean Fuels, LLC	Ohio	coal	jet fuels	23,000	BPD	Shell	85%	
Kentucky CTL project	Kentucky	coal	ultra-clean transportation fuels	30,000	BPD			2010
Eastman Texas Gasification Project	Texas	petcoke	chemicals	>450	Mgal/Y	GE	EOR	2011
Faustina Hydrogen Products LLC	Louisiana	petcoke	chemicals	4,600	TPD		EOR	2010
On Hold								
Rentech Energy Midwest Facility	Illinois	coal	ultra-clean transportation fuels					
Twin River Energy Center	Maine	coal	clean diesel fuel	9,000	BPD			

Proposed U.S. Gasification Plants - *SNG*

Project	*State*	*Feedstock*	*Capacity*	*Unts*	*MFG*	*Capture*	*In Service*
Kentucky Syngas	Kentucky	coal	50-70	BSCF/year	E-Gas	READY	
Hunton Energy Freeport Plant (Lockwood)	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
On Hold							
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	
**also power project*							

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

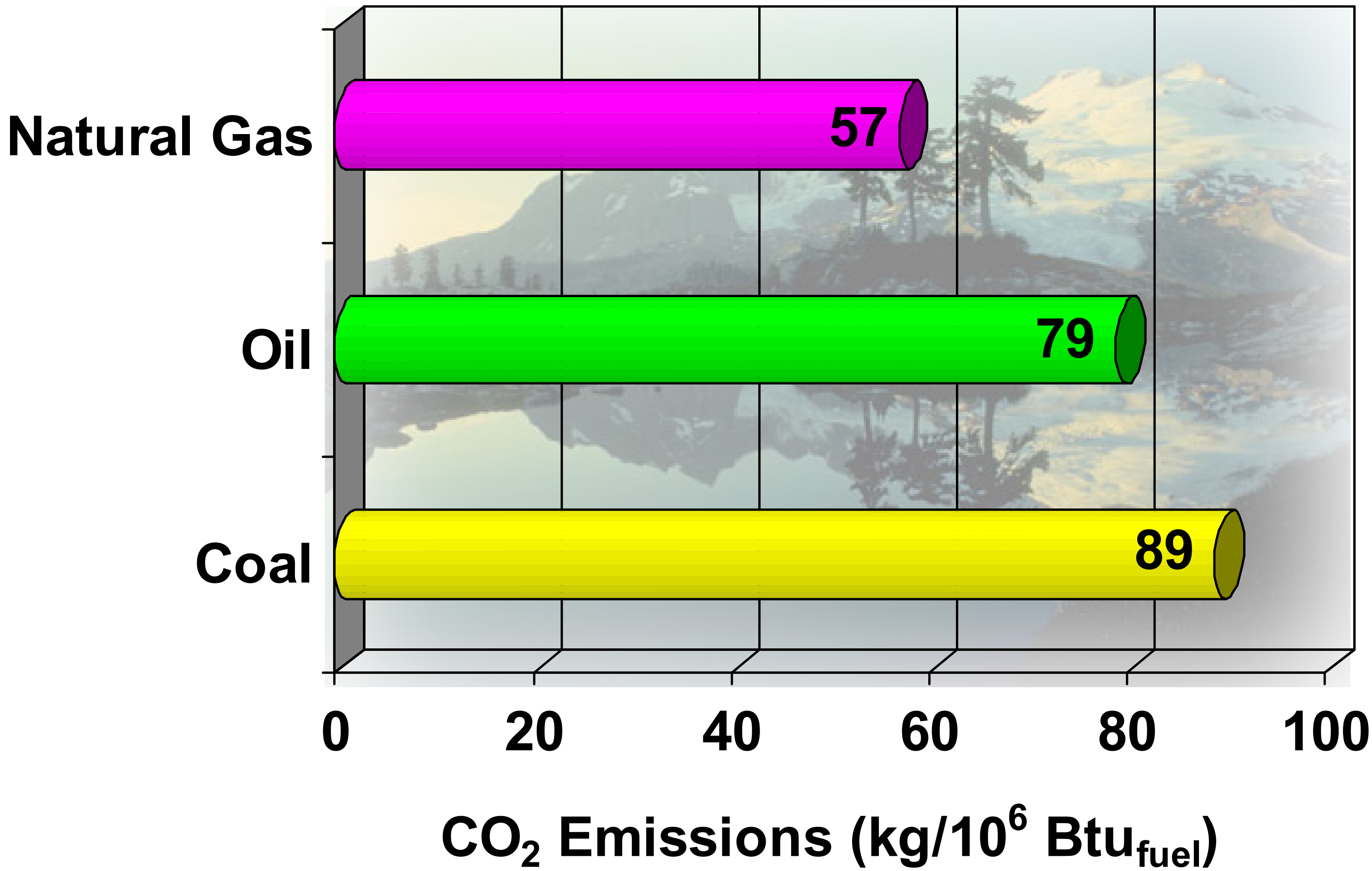
*Estimates for IGCC plant based on the 640 MWe nominal plants used in NETL's "Cost and Performance Baseline for Fossil Energy Power Plants" study**

* http://www.netl.doe.gov/energy-analyses/pubs/Bituminous%20Baseline_Final%20Report.pdf

Gasifier Slag

- **Very similar to slag from coal-fired boilers**
- **It is <u>not</u> 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 <u>mineral processing waste</u>**
- **Mineral processing wastes, as listed in 40 CFR 261.4(b)(7) include:**
  - “Gasifier ash from coal gasification”

Fossil Fuel CO_2 Emissions



Source: NETL Combustion Calculations - HHV Basis

Uncontrolled CO_2 Emissions –
Comparison of Fossil-Fired Power Generation Technologies

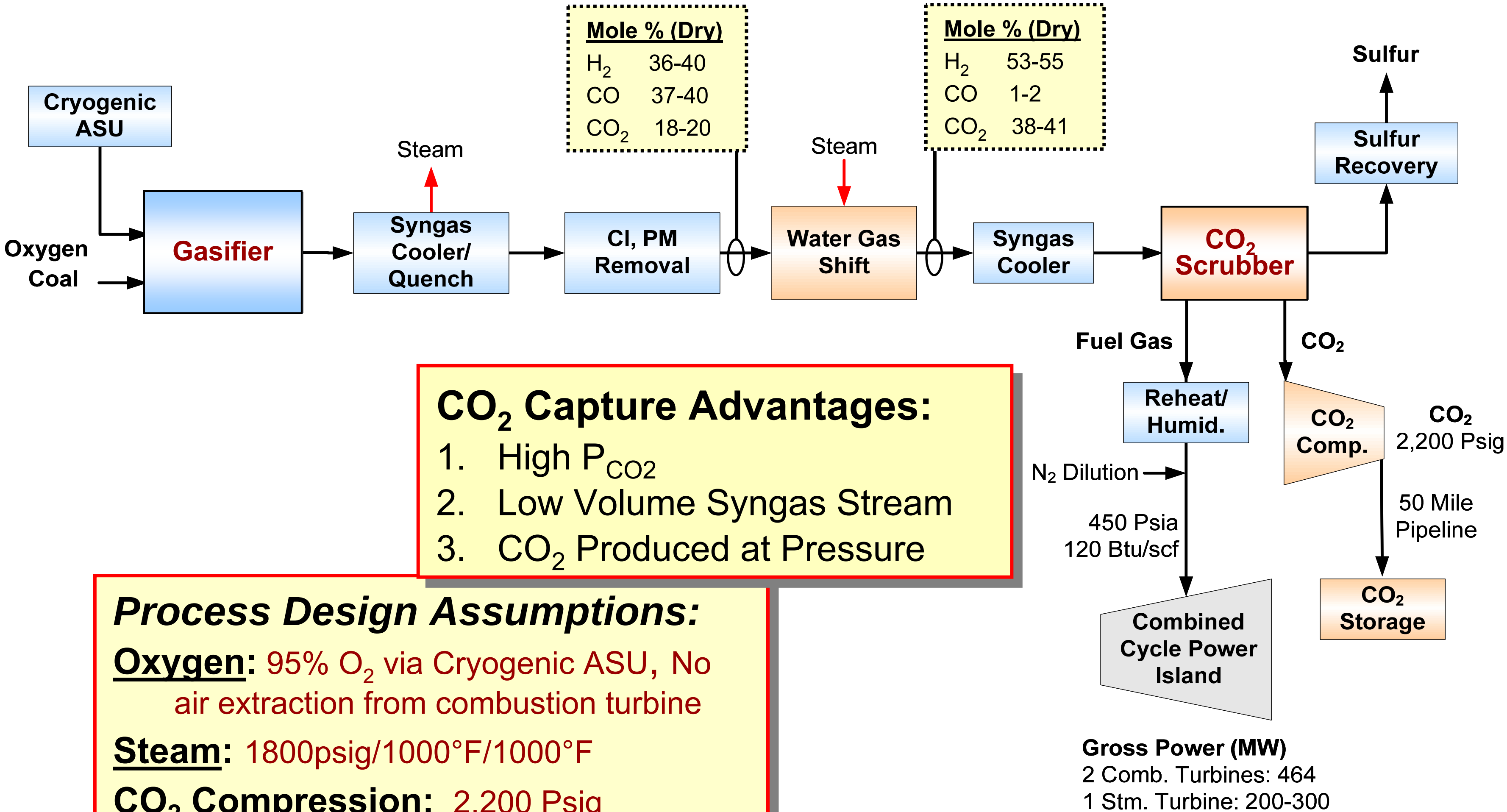
Power Generation Technology	*Heat Rate, Btu/kWh*	*CO_2 Emission, lb/kWh*
Conventional Pulverized Coal-Fired with FGD	**9,800**	**2.00**
Pressurized Fluidized Bed Combustion	**8,700**	**1.81**
Integrated Gasification Combined Cycle (IGCC)	**8,700**	**1.74**
Natural Gas Combustion Turbine (Simple Cycle)	**11,000**	**1.27**
Advanced Gasification-Fuel Cell	**6,000**	**1.20**
Natural Gas Combined Cycle (NGCC)	**7,500**	**0.86**

Volume of CO_2 Produced

- 1 million metric tons of liquid CO_2:
  - 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 CO_2 per year
  - Under an EIA reference case scenario cumulative CO_2 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 CO_2 Scrubbing



CO_2 Capture Advantages:

1. High P_{CO2}
2. Low Volume Syngas Stream
3. CO_2 Produced at Pressure

Process Design Assumptions:

Oxygen: 95% O_2 via Cryogenic ASU, No air extraction from combustion turbine

Steam: 1800psig/1000°F/1000°F

CO_2 Compression: 2,200 Psig

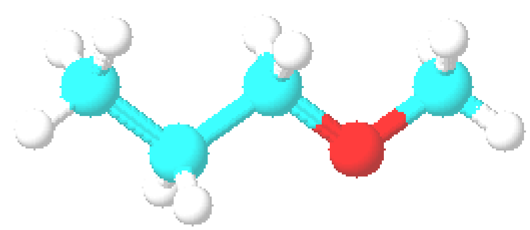
CO_2 Capture via Selexol Scrubbing

Advantages

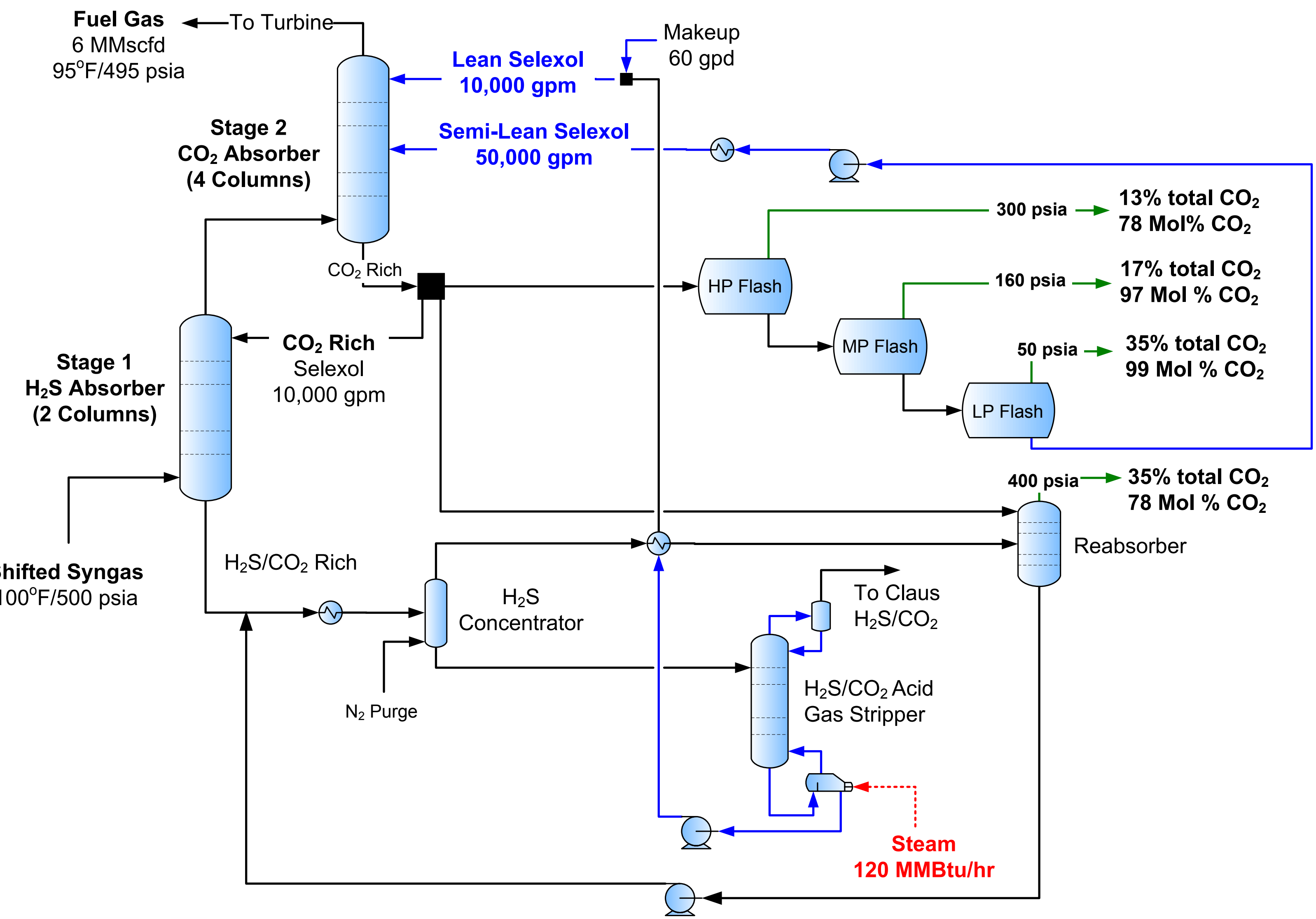
- Physical Liquid Sorbent → High loadings at high CO_2 partial pressure
- Highly selective for H_2S and CO_2 → No need for separate sulfur capture system
- No heat of reaction (ΔH_{rxn}), small heat of solution
- Chemically and thermally stable, low vapor pressure
- 30+ years of commercial operation (55 worldwide plants)

Disadvantages

- Requires Gas Cooling (to ~100°F)
- CO_2 regeneration by flashing



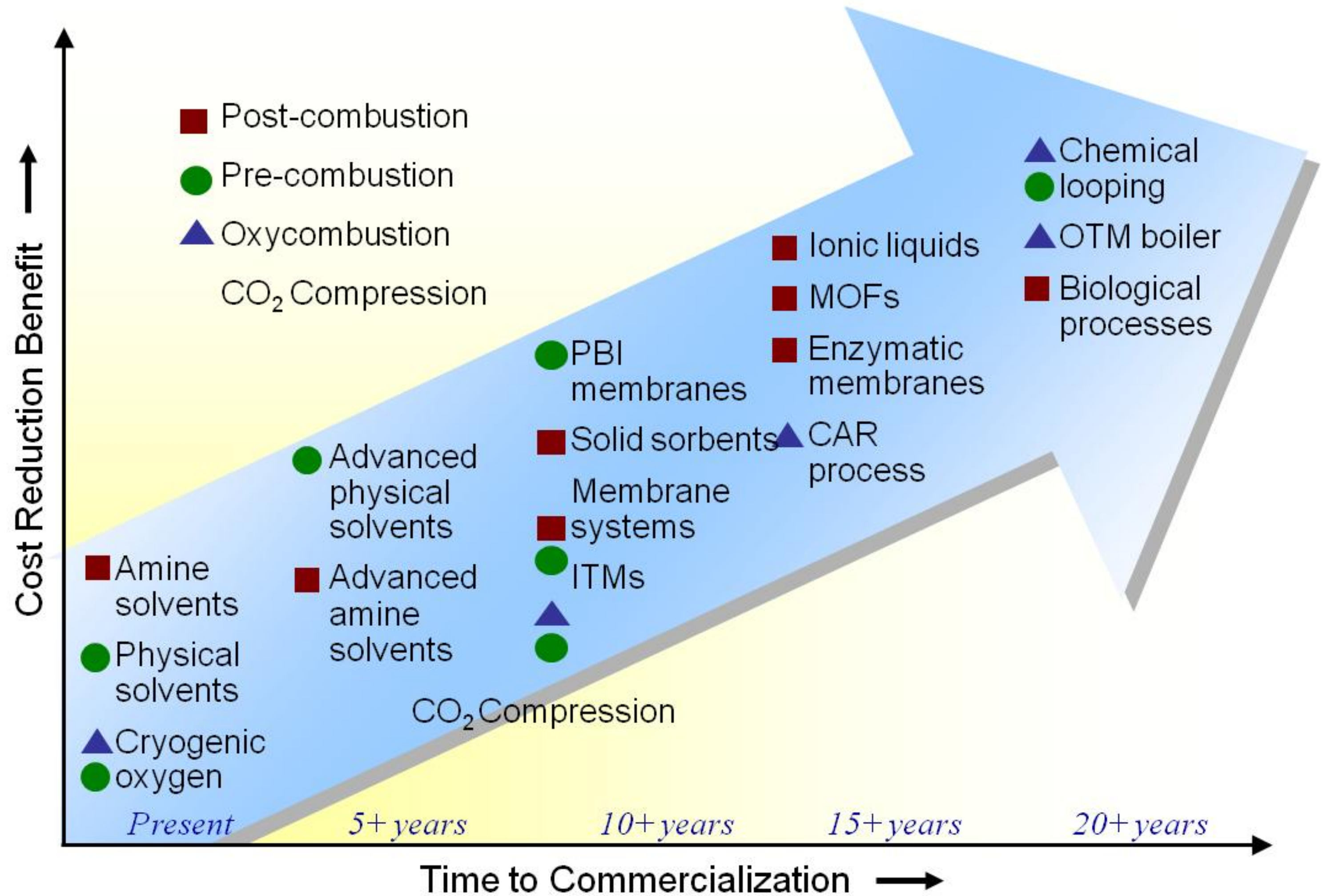
Selexol™ Scrubbing



CO_2 Capture via Rectisol Scrubbing

- **Based on low-temperature (refrigerated methanol)**
- **Capable of deep total sulfur removal as well as CO_2 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 CO_2 removal but no published cost studies**

Technology Advances for Carbon Capture



Sample CO_2 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*
CO_2 (mole%)	> 95%	> 96%	> 96%	> 95%		> 95%	> 95%
N_2 (ppmv)	< 40,000	< 300	< 6,000	< 40,000	< 20,000	< 40,000	< 40,000
CH_4 (ppmv)	< 50,000	< 7,000	< 20,000	< 50,000	< 10,000	< 50,000	< 50,000
H_2S (ppmv)	< 1,061	< 9,000	< 20,000	< 200	< 100 (ppmv)	< 200	< 1,500
O_2 (ppmv)	< 7.5	< 50	< 100	< 10	< 2 (ppmv)	< 100	< 10
H_2O (ppmv)	< 641	< 20	< 2	< 480	< -5C DP at 300 psia	< -40C DP	< 28lb/MMCF

Source: GE Energy

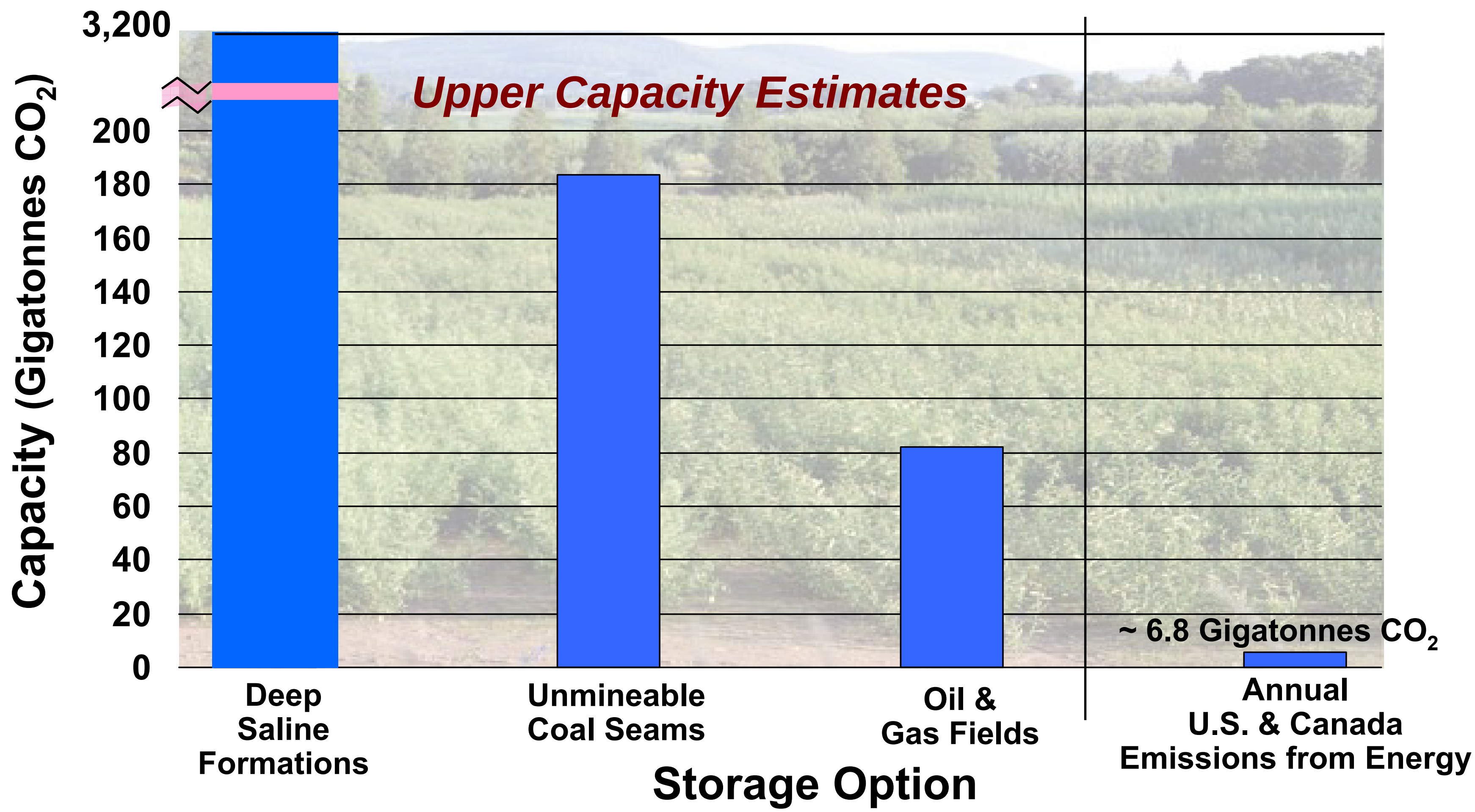
Comparison of CO_2 Storage Options

Characteristics	*EOR*	*Saline Aquifers*	*Depleted Oil & Gas Reserviors*	*Coal Beds*
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 CO_2 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 capactiy needs to be quantified	Significant technical uncertainty

From a presentation given by Norm Shilling, General Electric Co, entitled, "IGCC: Its Role in Solving the Carbon Puzzle"

North America Geologic Storage Capacity

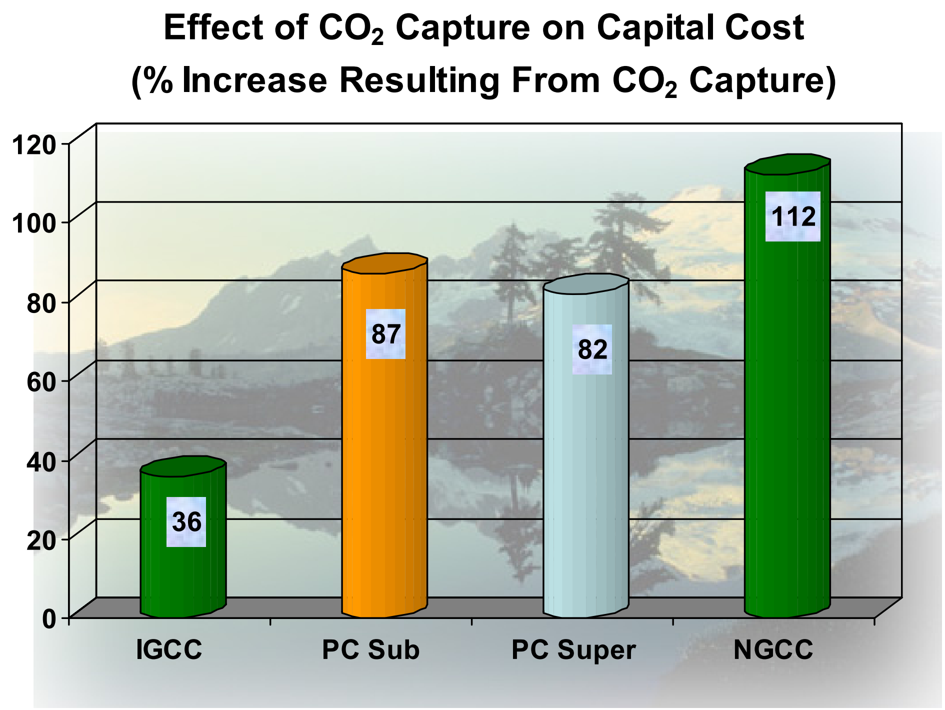
(> 500 Year Potential Storage Capacity for U.S. & Canada)

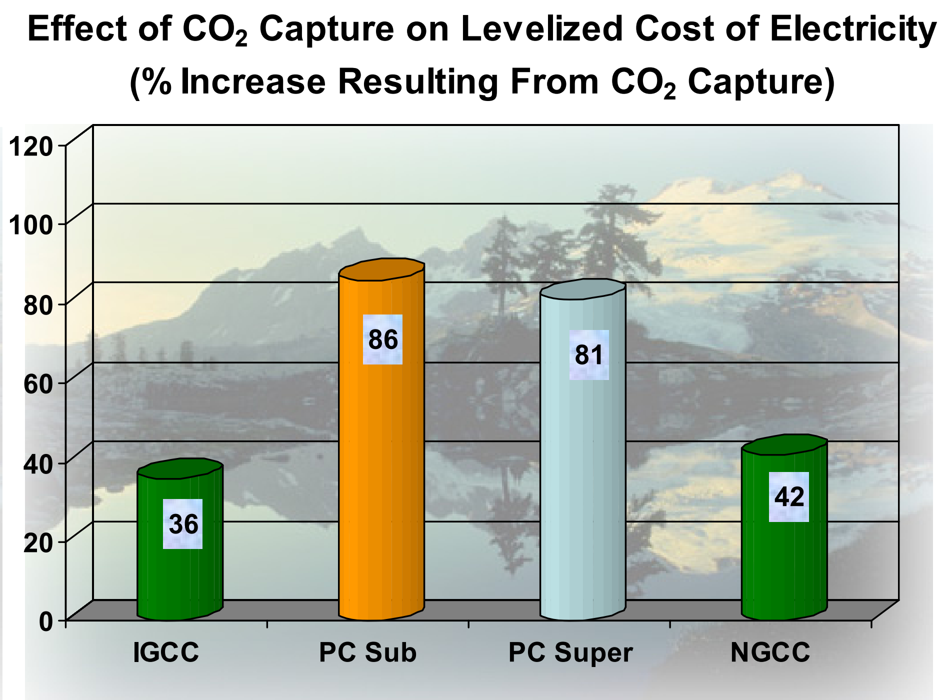


Capacity data source: Carbon Sequestration Atlas of the United States and Canada, DOE-NETL, Feb 2007

Emissions data source: EIA, "International Carbon Dioxide Emissions and Carbon Intensity" extrapolated to mid-2007

Impact of CO_2 Capture





January 2007 Dollars, 85% Capacity Factor,

16.4% (no capture) 17.5% (capture) Capital Charge Factor,

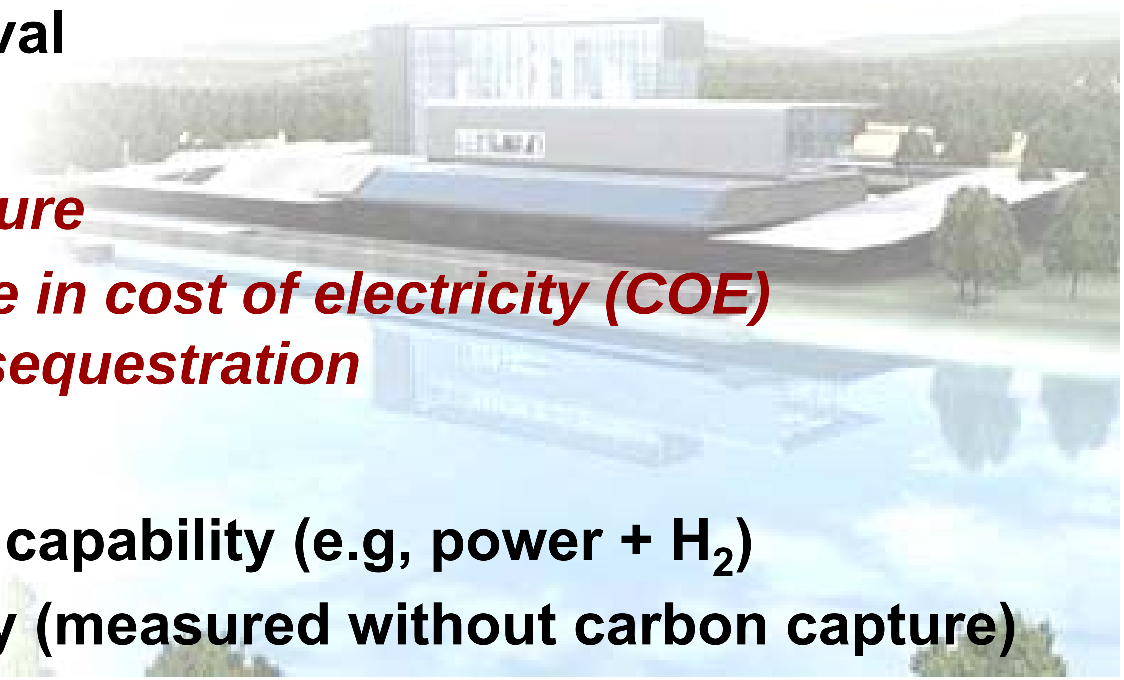
Coal cost $1.80/106Btu, Natural Gas cost $6.75/106Btu

Source: NETL Baseline study: Cost and Performance Baseline for Fossil Energy Power Plants study, Volume 1: Bituminous Coal and Natural Gas to Electricity (May 2007)

DOE Gasification Program Overview

Advanced Power Systems Goal

- **2010:**
  - **45-50% Efficiency (HHV)**
  - **99% SO_2 removal**
  - **NOx< 0.01 lb/MM Btu**
  - **90% Hg removal**
- **2012:**
  - ***90% CO_2 capture***
  - ***<10% increase in cost of electricity (COE) with carbon sequestration***
- **2015:**
  - **Multi-product capability (e.g, power + H_2)**
  - **60% efficiency (measured without carbon capture)**



Advanced Power Systems Program

2012 Goal

Complete R&D to integrate this technology with CO_2 separation, capture, and sequestration into a “near-zero” emission configuration that can provide electricity with less than 10 percent increase in cost.

Near- Zero	
SO_2	>99% removal
H_2S	50 ppbw
NH_3	10 ppm
HCl	10 ppb
Hg	5 ppbw (>90% removal)
As	5 ppbw (>90% removal)
Se	0.2 ppm
Cd	30 ppb
CO_2	>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 (NOx, SOx, Hg, As, Cd, Se, PM)

Reduction of CO_2 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
- CO_2 capture & sequestration

Targets

By 2010
- Efficiency 45-50% (HHV)
- Capital $1000/kW*

By 2012
- Increase COE < 10% w/CO_2 capture

By 2015**
- Efficiency 50-60% (HHV)
- Capital $900/kW*

*Cost in 2002$
**Targets for Plants w/o Carbon Capture

Major Technology Issues

Oxygen Membrane

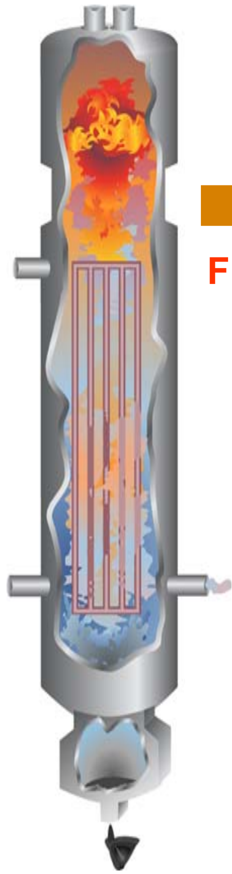
Oxygen

Durability of the Membrane
Integration with Overall Process

Low-rank Coal

Coal

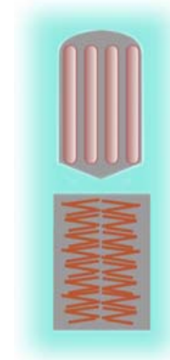
Injector Reliability
Single Train Availability
Durability of Refractory Material
Durability and Accuracy of Monitoring Devices
Alternative Feedstocks
Feed System Reliability
Heat Removal
Temperature Measurement & Control



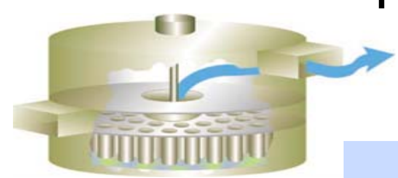
Gasification

Fuel Gas

Gas Cleaning



Cost-Effective Multi-Contaminant Control to Ultra-Clean Specifications
Moderate Temperatures (S, NH_3, Cl)
Hg, As, Se, Cd Removal at Elevated Temperatures
Integrated Specifications with Downstream Process Requirements
Integration with NOx Reduction Processes
Process Intensification



Hydrogen

CO_2

Water-Gas Shift
$H_2 – CO_2$ Gas Separation

Durability of the Membrane
Low Flux
Contaminant Sensitivity
Heat Removal

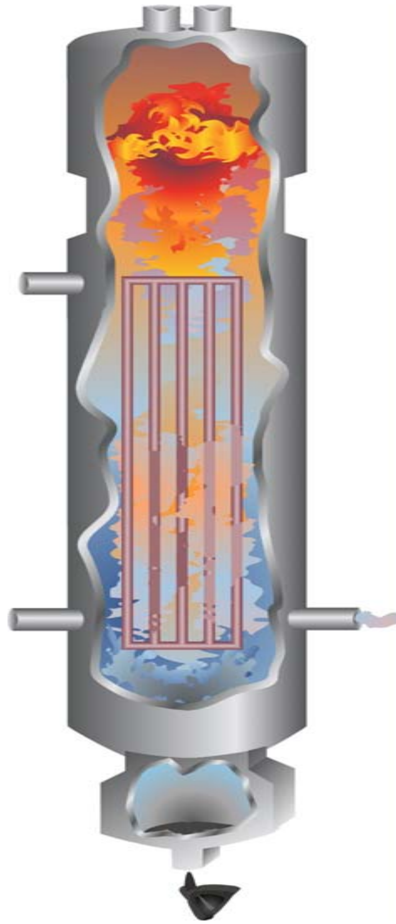
Gasification R&D Program
Power Systems Development Facility (PSDF)
Wilsonville, AL

- 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

Alstom
Hybrid combustion-gasification using high temp chemical and thermal looping
- Solids transfer media
- Multiple reactors for oxidation, reduction, carbonation, and calcination of calcium compounds



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

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

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 & H_2 membranes

Hybrid Combustion-Gasification Chemical Looping Coal Power Technology Development

Objective:

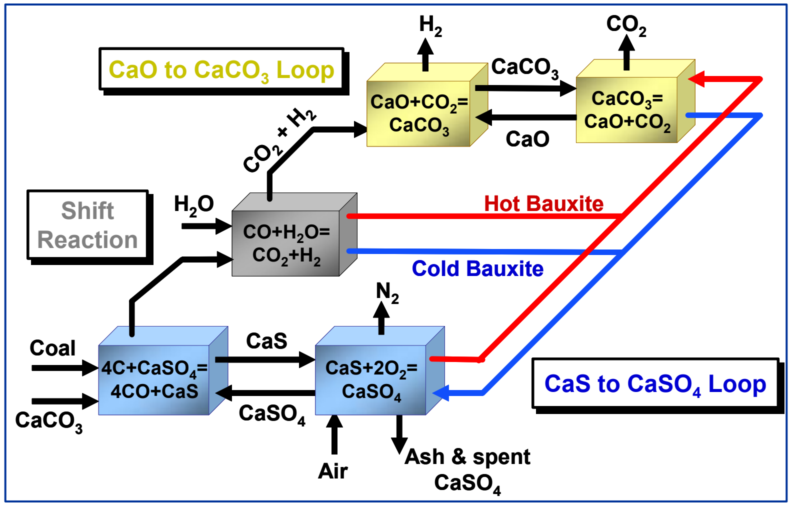
Develop a system to produce concentrated streams of H_2 and CO_2 without the need for costly and energy intensive cryogenic oxygen production

Accomplishments:

- Successfully demonstrated syngas production from coal with $CaS/CaSO_4$ loop
- Successfully demonstrated CO_2 capture and H_2 production from coal with $CaO/CaCO_3$ loop

Future Work:

- Design, construct and operate a prototype chemical looping plant



Advanced Chemical Looping Process

ALSTOM Power, Inc.

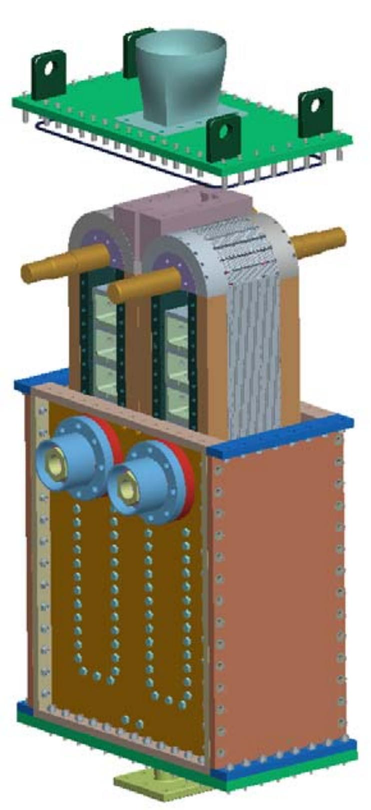
High Pressure Solids Pump

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

Pratt Whitney Rocketdyne



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

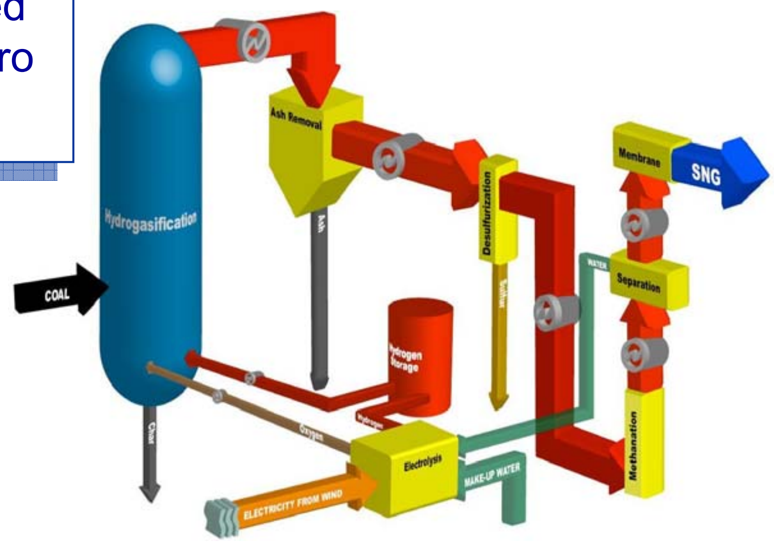
Coal Feed Pump Favorable   Coal Feed Pump Less Favorable

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



Proposed APS Advanced Hydrogasification Process

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 $g/m^2/d$, peak - 174 $g/m^2/d$)

> Twice growth rate reported in the literature

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

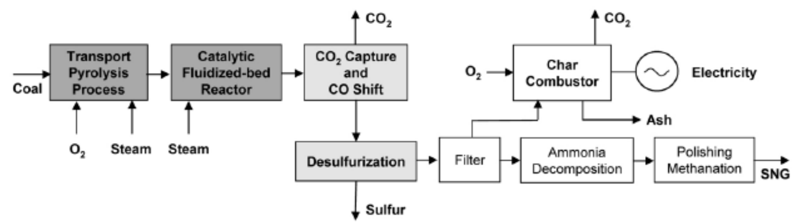
via Catalytic Coal Gasification

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 CO_2 sorbent for >90% CO_2 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



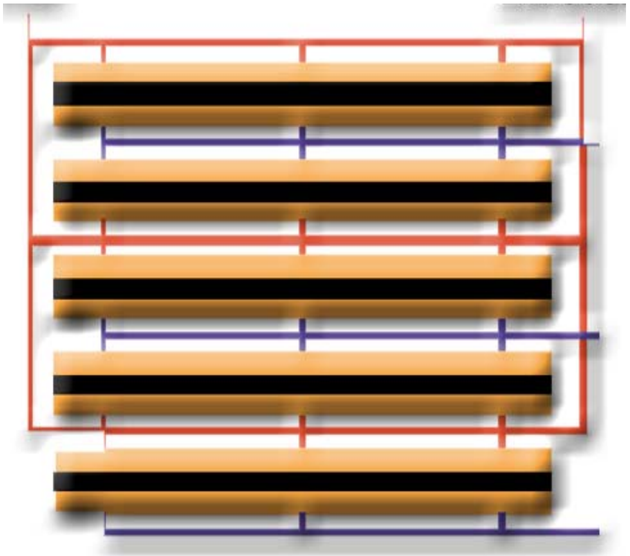
Proposed Process for the Co-Production of SNG and Electricity via Catalytic Coal Gasification

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

Advanced Gas Separation



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

Eltron Research
- CoorsTek
- NORAM Engineering & Constructors
- Praxair

Developing materials to separate hydrogen from syngas

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"

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

(ITM capacity: 4,550 sTPD oxygen)

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

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

Photos: Air Products and Chemicals, Inc. 2006

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

Co-Production of Electricity and Hydrogen

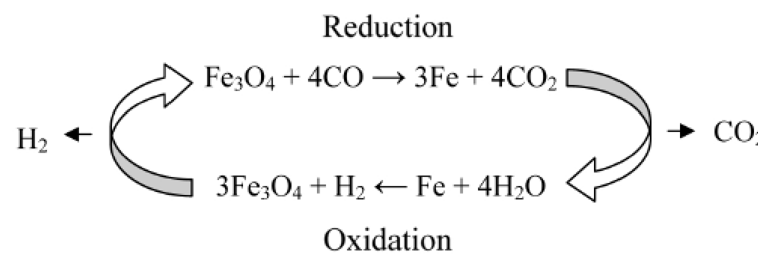
Using a Novel Iron-Based Catalyst

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:

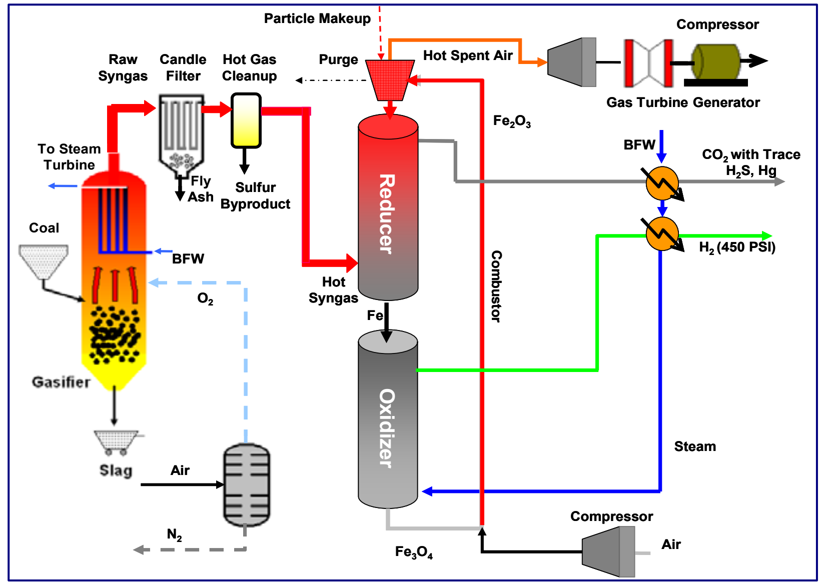
Enable co-production of high purity hydrogen and electricity from an IGCC at an economic level

Enhanced Hydrogen Production

Integrated with CO_2 Separation

Goal:
Develop a process that produces a pure hydrogen stream and a concentrated CO_2 stream in two separate reactors — avoiding additional CO_2 separation cost

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

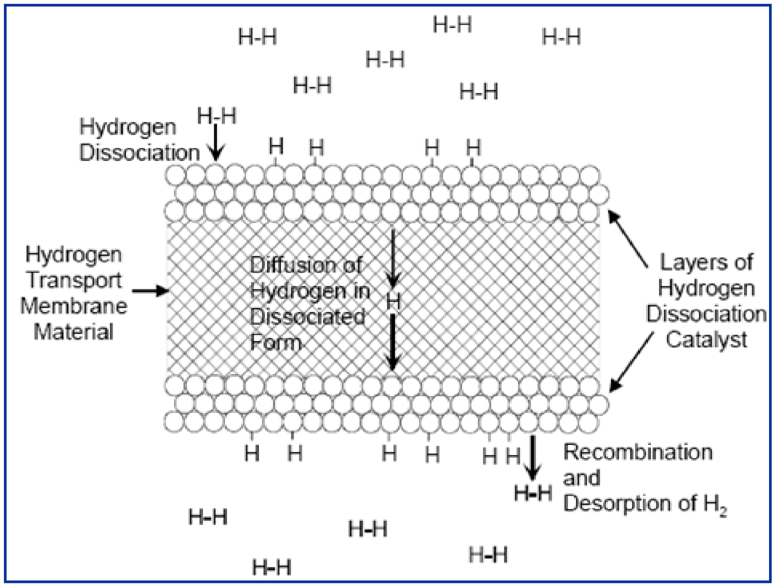


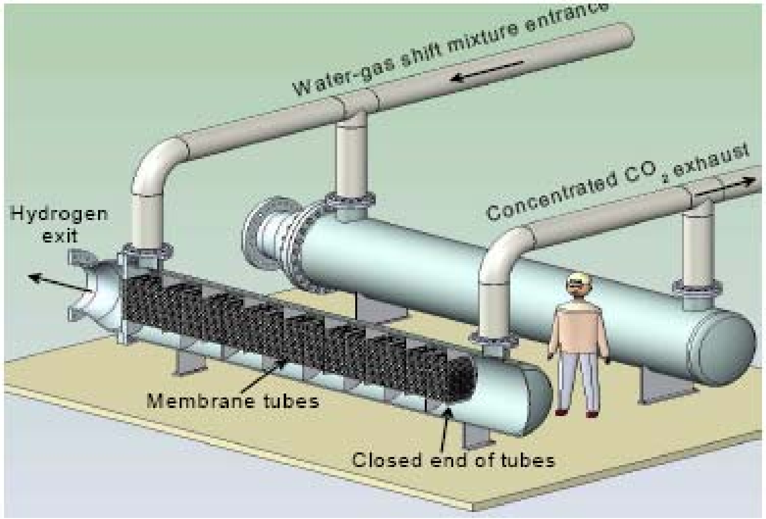
Simplified schematic of the Syngas Chemical Looping Process for H_2 production from coal

Ohio State University

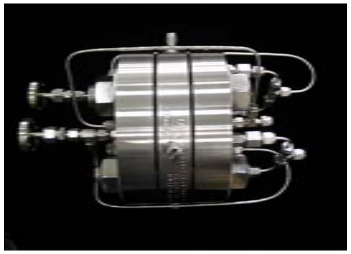
ELTRON Hydrogen Membrane

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





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



- **Status**
  – Seeking development partner
  – Current testing at 1.5 lb/d
  – Scale-up to 220 lb/d - 2010

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

Progress Towards DOE-FE Targets

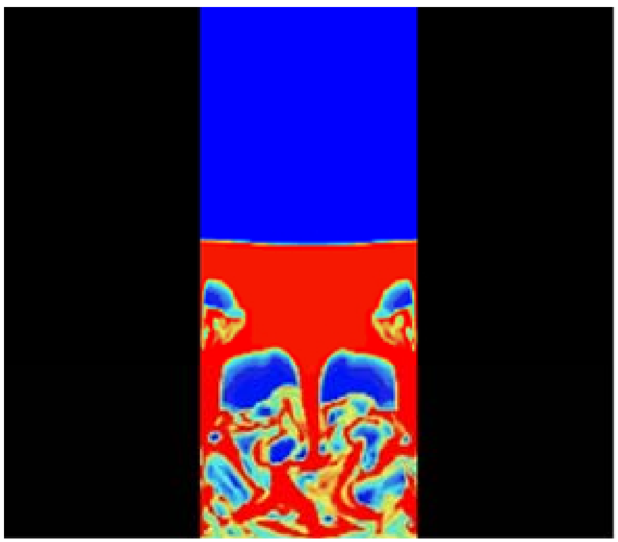
Performance Criteria	*2005 Target*	*2010 Target*	*2015 Target*	*Current Eltron Membrane*
Flux (sccm/cm^2/100 psi ΔP)	**50**	**100**	**150**	160
Operating Temperature (°C)	**400-700**	**300-600**	**250-500**	**300-400**
S Tolerance (ppmv)	**N/A**	**2**	**20**	20 (early)
System Cost ($/ft^2)	**1000**	**500**	**<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



Hydrodynamics in the Bubbling Fluidized Oxidation Reactor

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

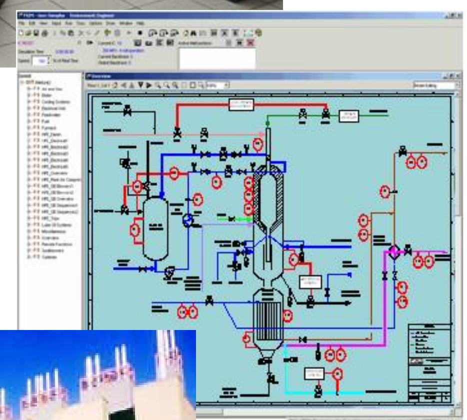
NETL
Office of Research and Development
Computational Fluid Dynamics (CFD) modeling of advanced gasifiers

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



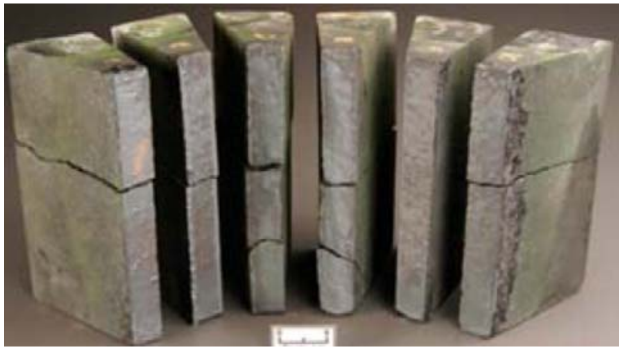
WVU's NRCCE

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

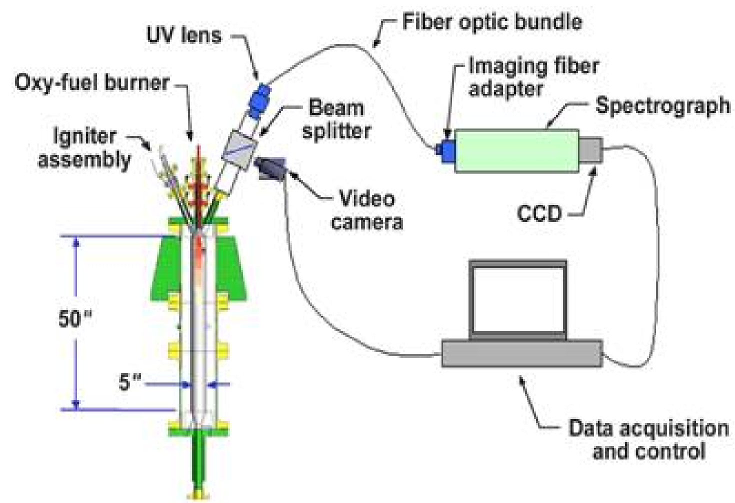
Gas Technology Institute

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:

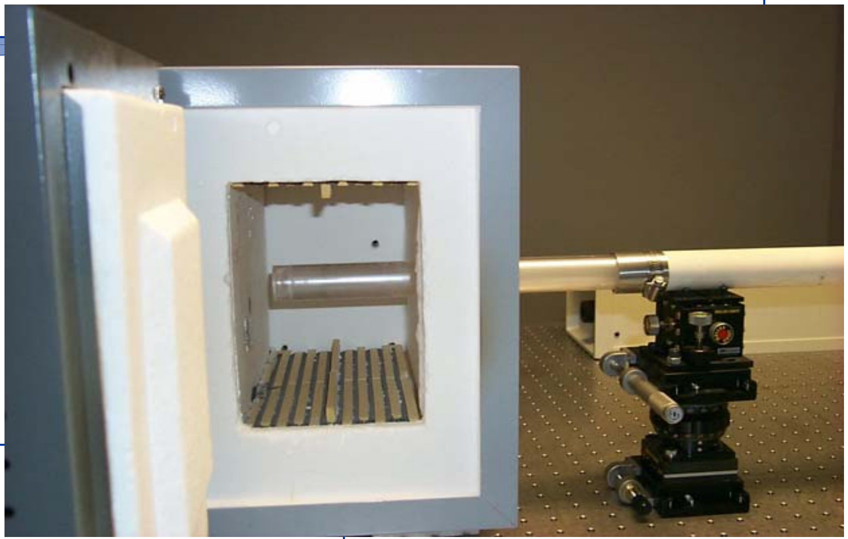
Field demonstration tests at the Wabash River gasifier (2009)

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

Transport Desulfurization Modeling

Office of Research and Development

Objective:

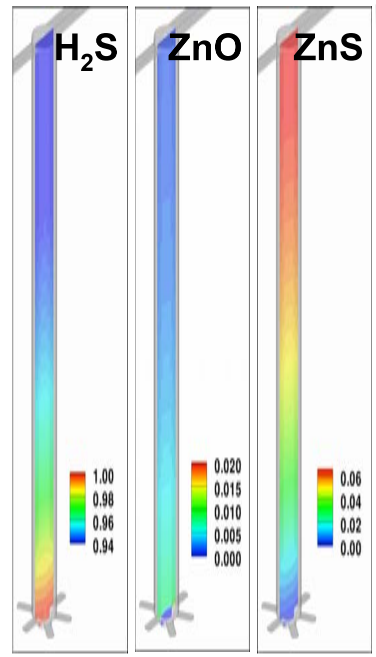
- Model sorbent-based sulfur capture systems
  - For absorption and regeneration

Status:

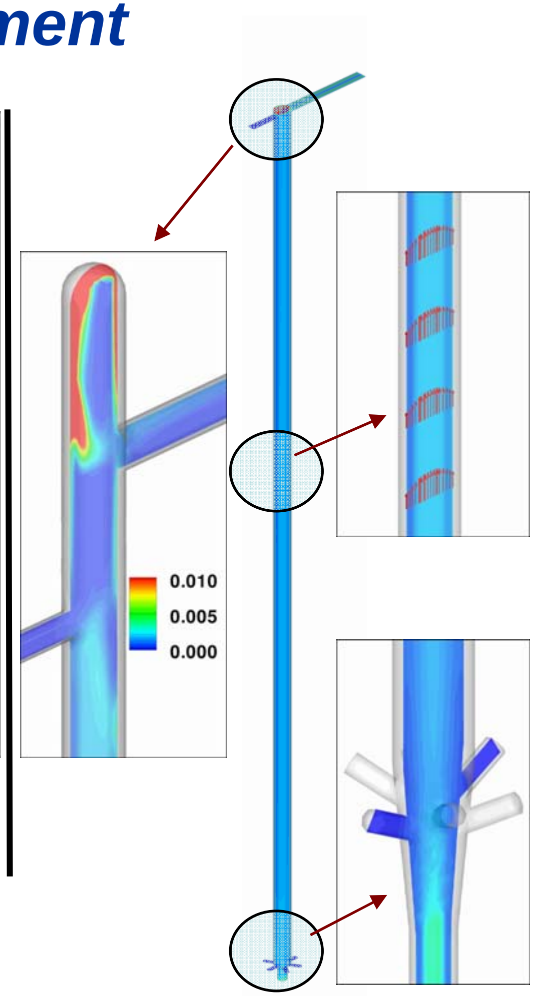
- Developed absorption model;
  - Applied to NETL transport reactor experiments
- Identified several candidate reaction models for regeneration

Future Work:

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



Mole Fractions



Solid Volume Fraction

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 H_2S, COS, NH_3, 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 H_2S, NH_3, and HCl and heavy metals (Hg, As, Se, Cd) in single process reactor - - Includes high pressure conversion of H_2S 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^{o}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^{o}F

Prototype test system for field evaluations at PDSF

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

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 H_2S 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 NH_3, 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 *LTGC + SELEXOL + CLAUS + SCOT*	IGCC RTI Case *RTI WGCU/DSRP*
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

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

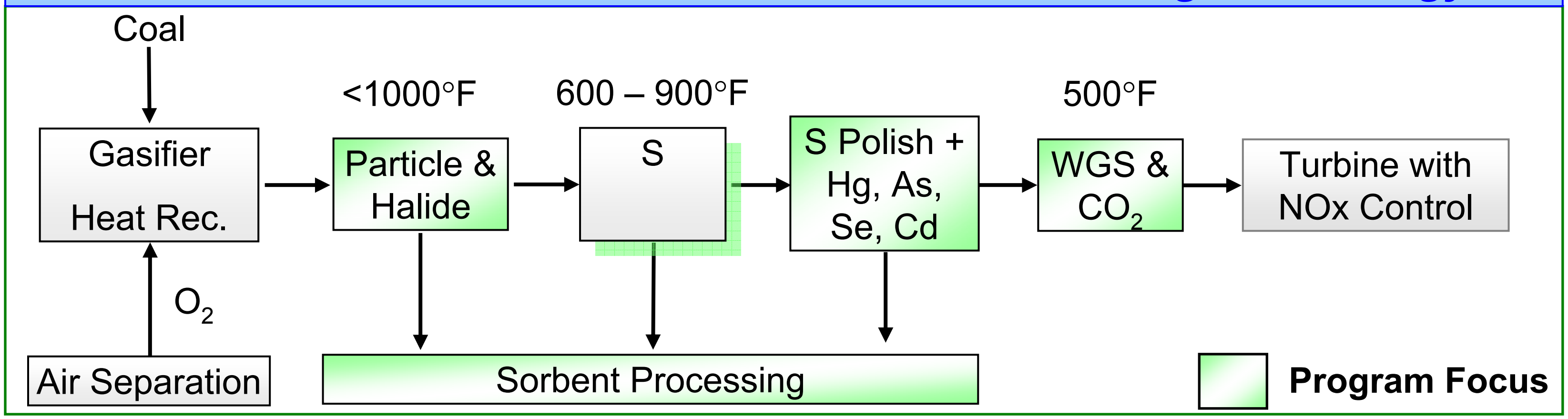
Next:
- Test removal of Hg, As, and Se at ≥ 400°F and ≥ 600 psi

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
- CO_2 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 H_2S Using Regenerative Sorbents in Fixed-Bed or Moving-Bed Systems
- CO_2 Capture Using Magnesium-Based Sorbents in Fluid-Bed or Moving-Bed Systems
- CO_2 Capture Using Solvent (Fluorinated Hydrocarbons or Ionic Liquids) in Absorber-Stripper System
- CO_2 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

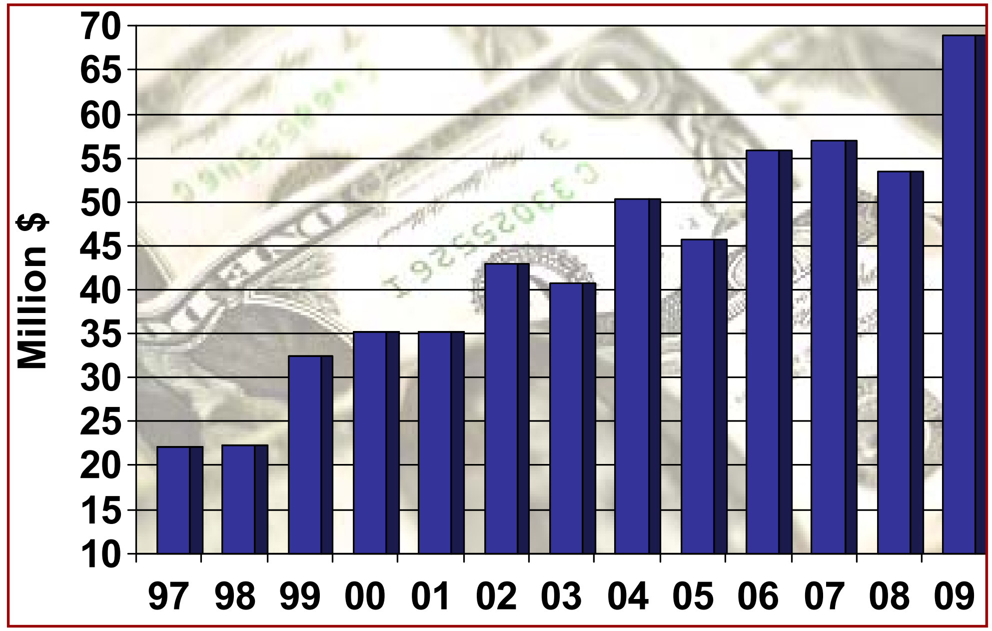
February 2008 | *Office of Chief Financial Officer* | *Volume 7*

FY08 Gasification Technology Program

27 Projects

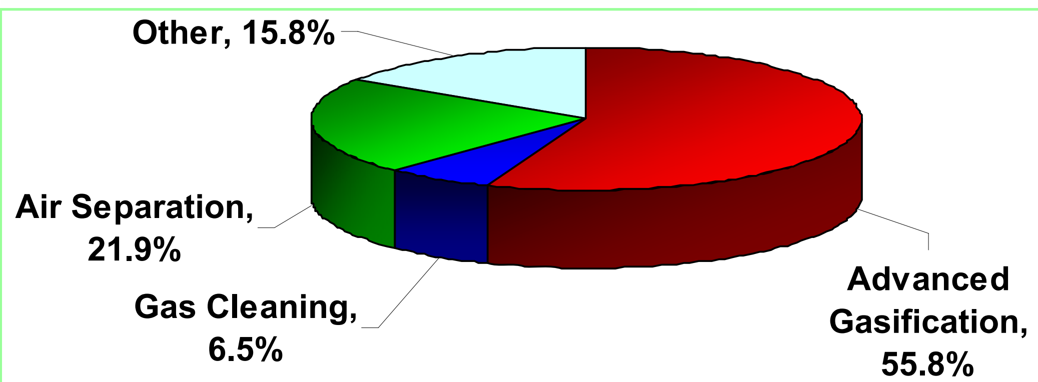
Organizations

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

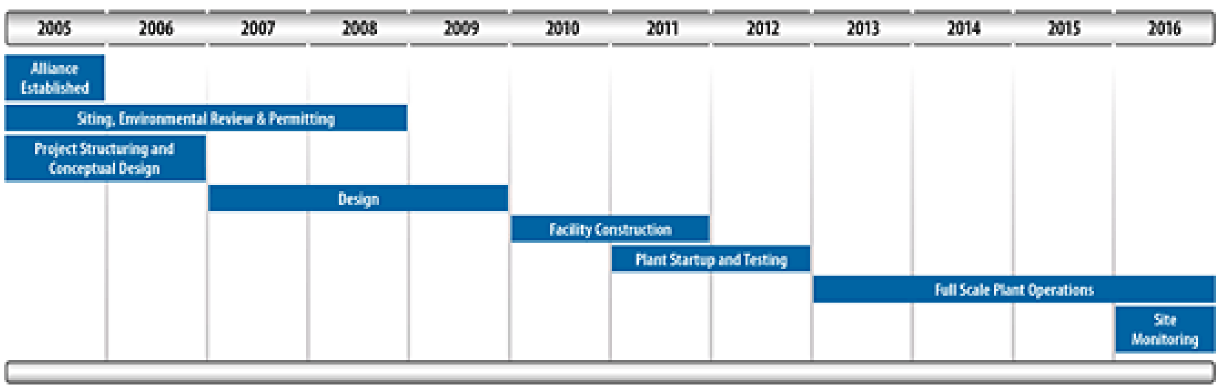


Annual Budget

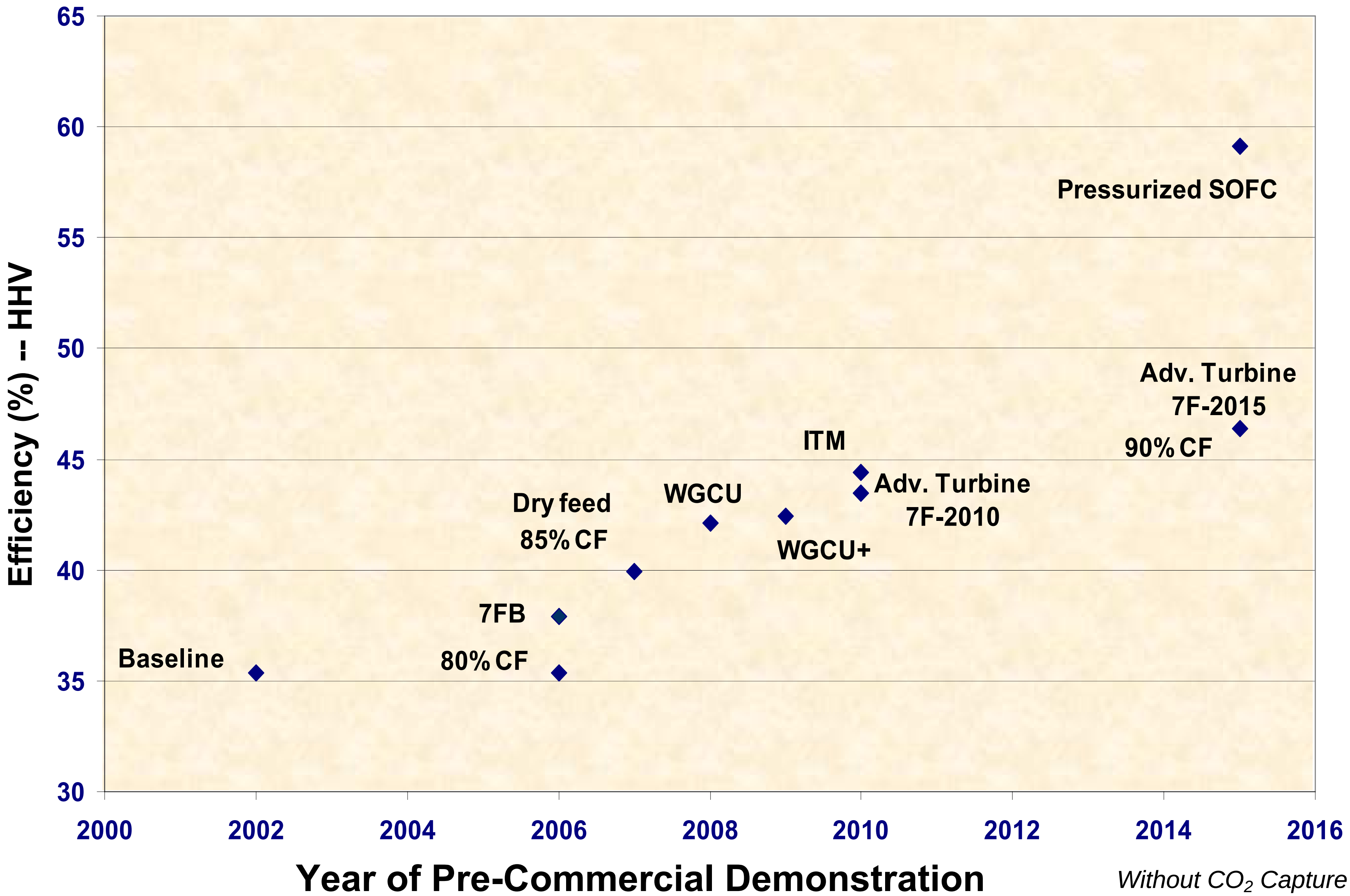
FY08 Budget Allocation



Technology Roadmap Timeline

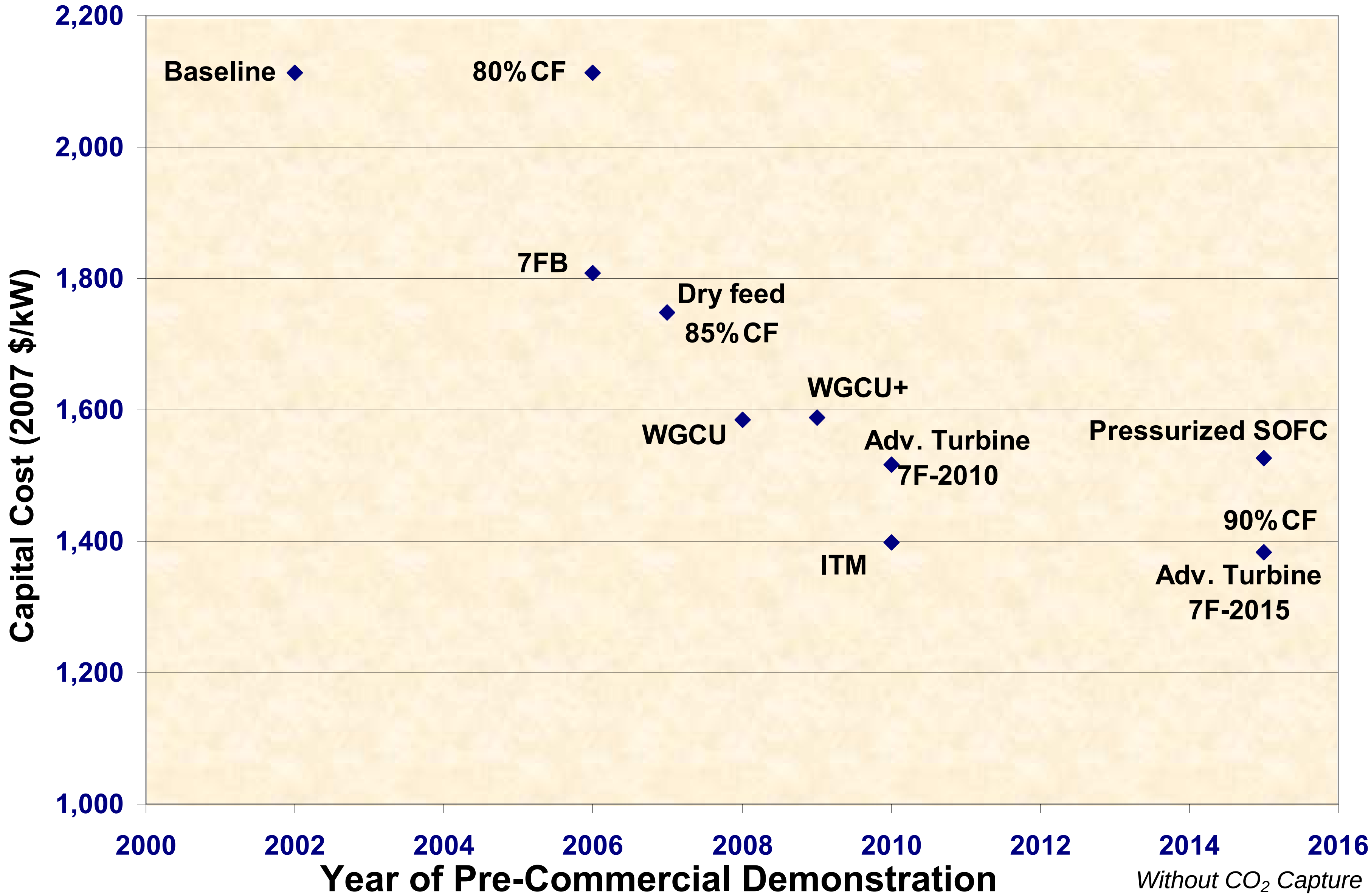


Efficiency Timeline



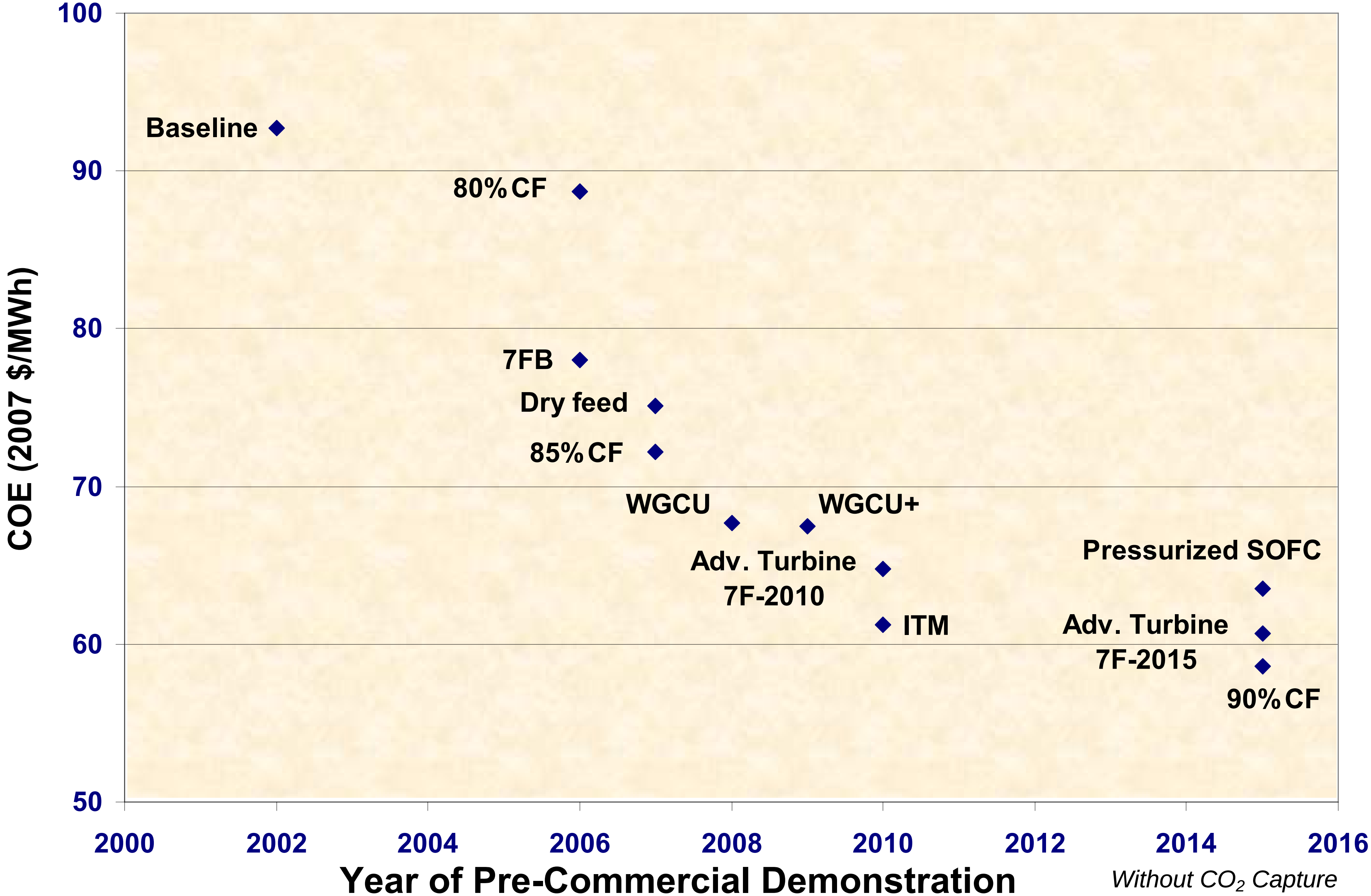
Without CO_2 Capture

Capital Cost Timeline



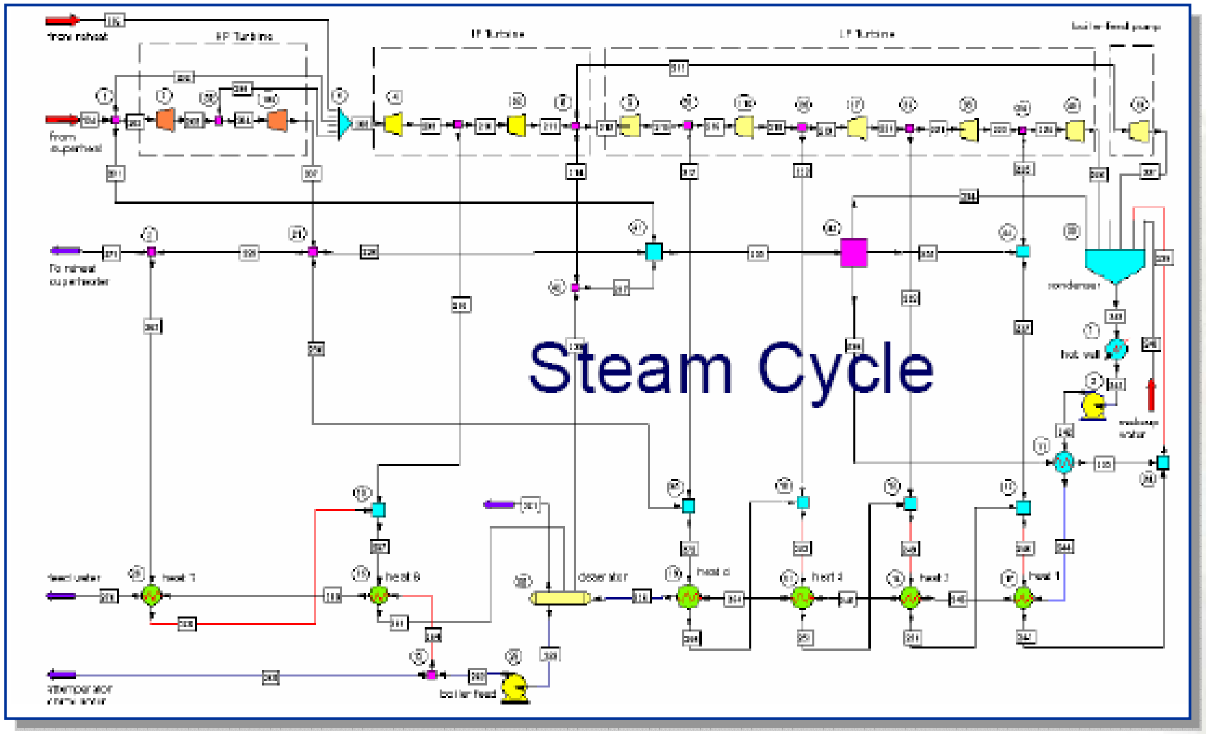
Without CO_2 Capture

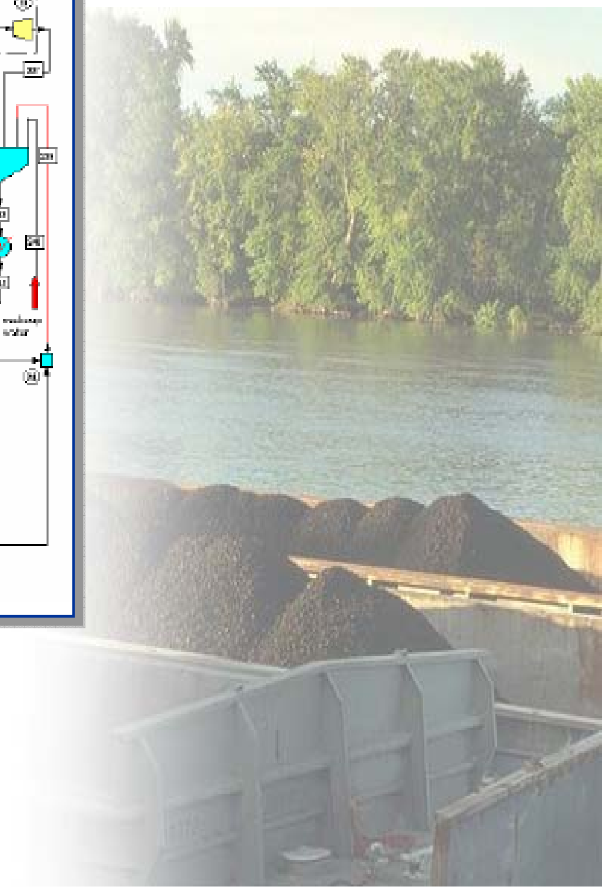
COE Timeline



Without CO_2 Capture

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) 1800/1000/1000 (CO_2 capture cases)	F Class	GE	Selexol / - / Claus	
				Selexol / Selexol / Claus	90%
			CoP E-Gas	MDEA / - / Claus	
				Selexol / Selexol / Claus	88%[1]
			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] CO_2 capture is limited to 88% by syngas CH_4 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
NOx	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

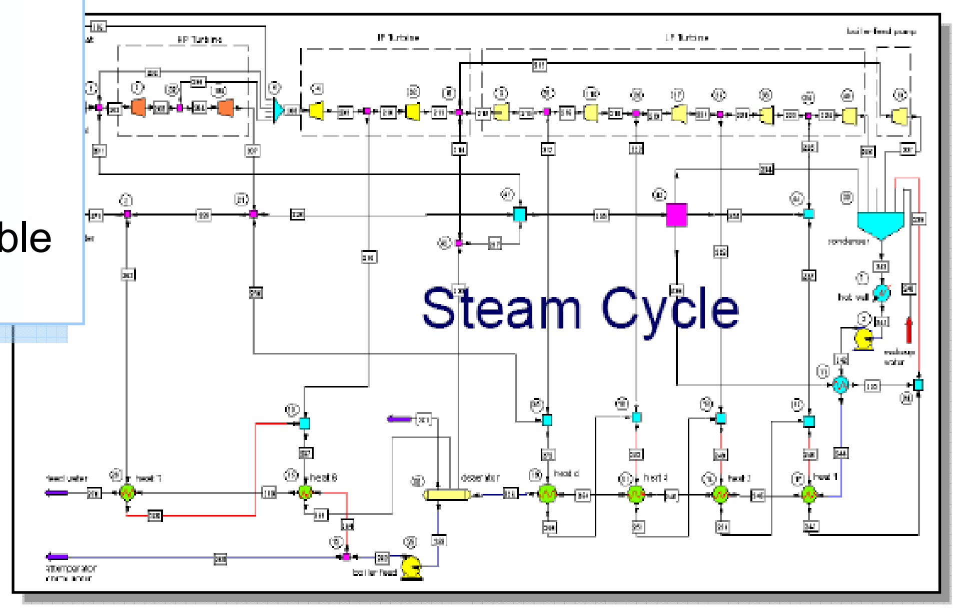
Technical Approach

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

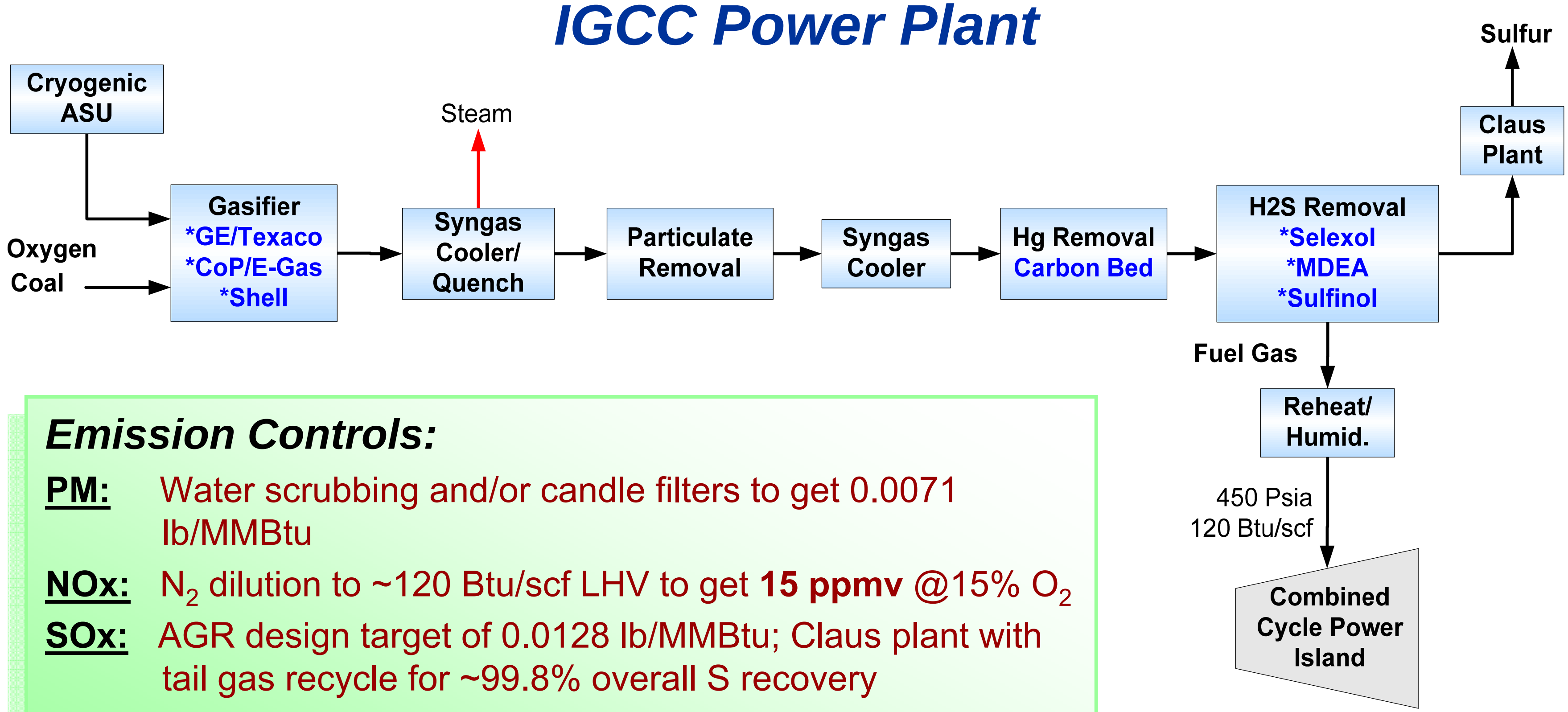
- **Capacity Factor = Availability**
  - IGCC capacity factor = 80% w/ no spare gasifier
  - PC and NGCC capacity factor = 85%
- **GE gasifier operated in radiant/quench mode**
- **Shell gasifier with CO_2 capture used water injection for cooling (instead of syngas recycle)**
- **Nitrogen dilution was 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 CO_2 capture cases, CO_2 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**
- **CO_2 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

NOx: N_2 dilution to ~120 Btu/scf LHV to get **15 ppmv** @15% O_2

SOx: 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

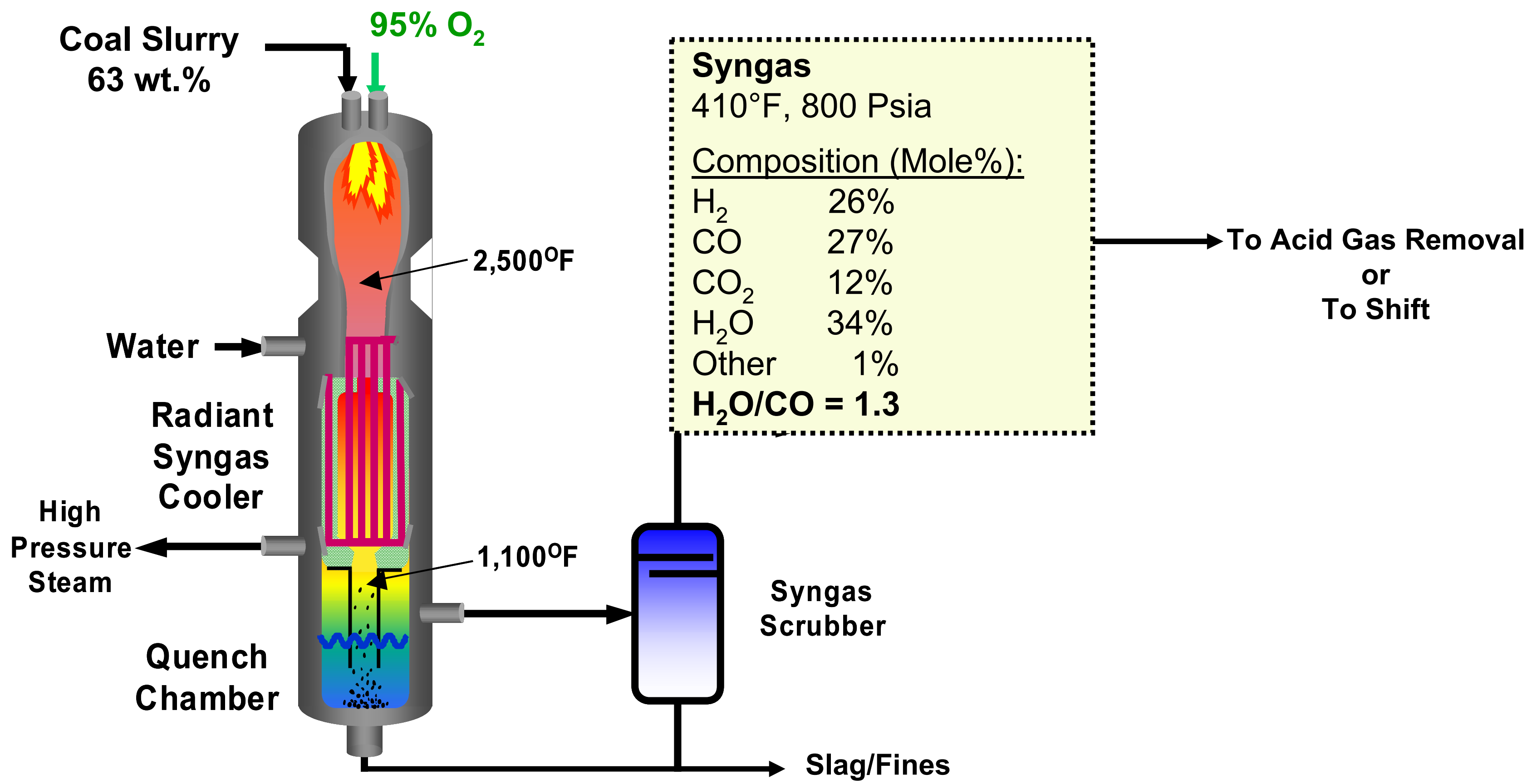
Advanced F-Class CC Turbine: 232 MWe

Steam Conditions:

1800 psig/1050°F/1050°F (non-CO_2 capture cases)

1800 psig/1000°F/1000°F (CO_2 capture cases)

GE Energy Radiant



Syngas
410°F, 800 Psia

Composition (Mole%):

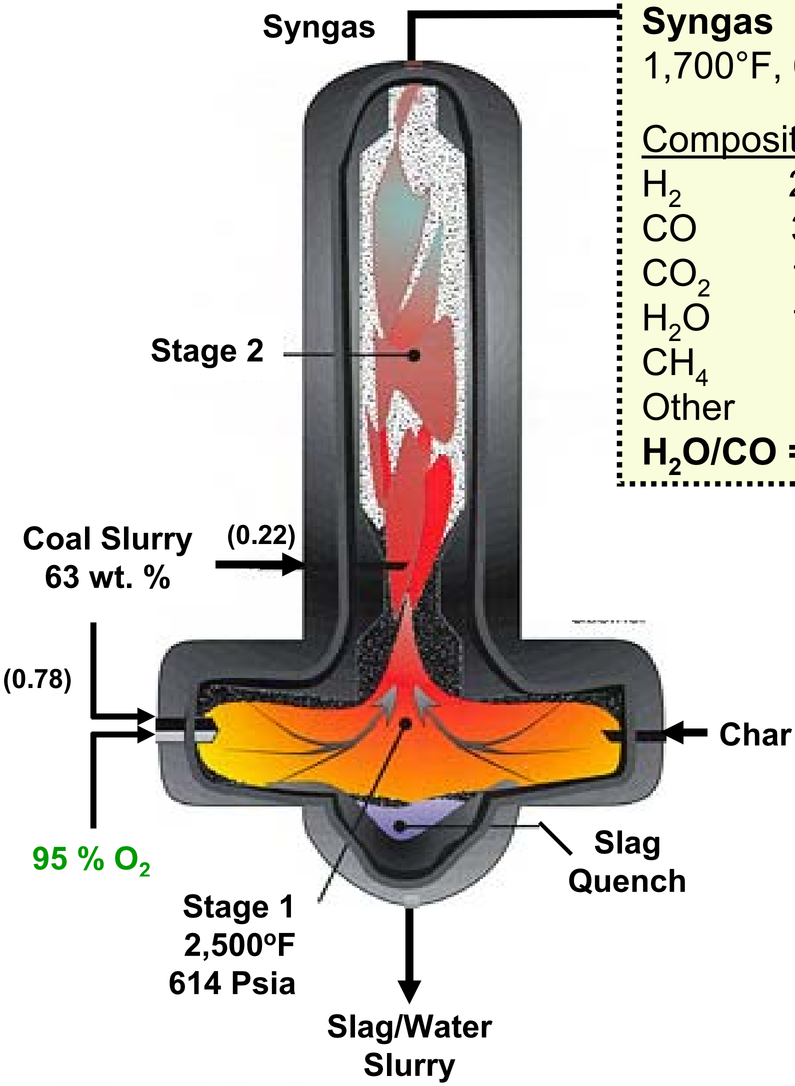
H_2	26%
CO	27%
CO_2	12%
H_2O	34%
Other	1%

H_2O/CO = 1.3

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™



Syngas
1,700°F, 614 psia

Composition (Mole%):

H_2	26%
CO	37%
CO_2	14%
H_2O	15%
CH_4	4%
Other	4%

H_2O/CO = 0.4

To Fire-tube boiler

To Acid Gas Removal or To Shift

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

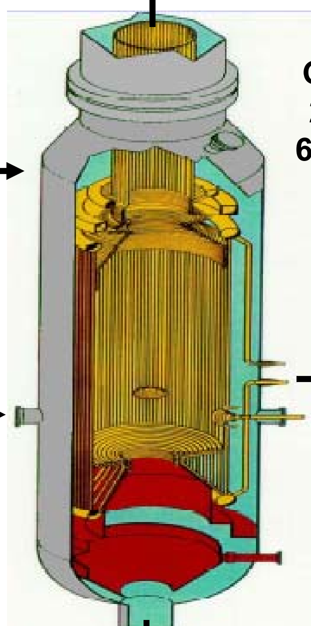
Note: All gasification performance data estimated by the project team to be representative of an E-Gas gasifier

Shell Gasification

HP Steam

Convective Cooler Soot Quench & Scrubber

Syngas Quench[2]



Gasifier 2,700°F 615 psia

HP Steam

95% O_2

Dry Coal

Slag

650°F

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. CO_2 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_2O	4%
Other	8%

H_2O/CO = 0.1

To Acid Gas Removal or To Shift

Source: "The Shell Gasification Process", Uhde, ThyssenKrupp Technologies

IGCC Performance Results

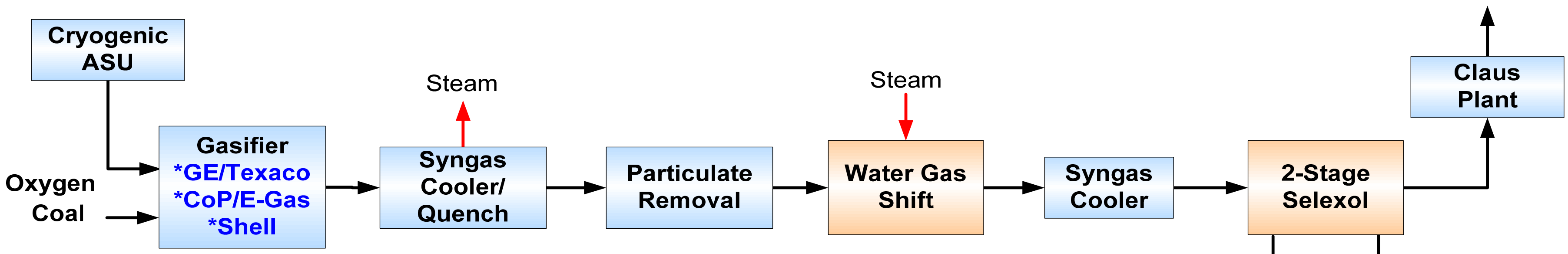
No CO_2 Capture

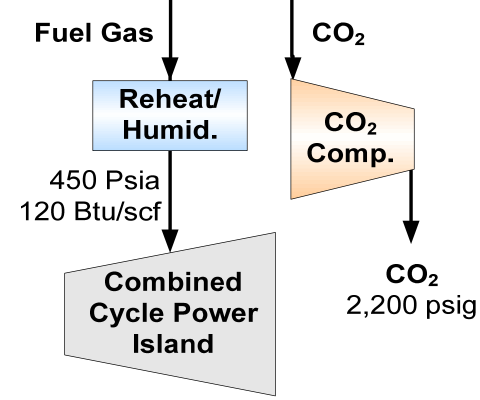
	GE Energy	E-Gas	Shell
Gross Power (MW)	**770**	**742**	**748**
Auxiliary Power (MW)			
Base Plant Load	23	25	21
Air Separation Unit	103	91	90
Gas Cleanup	4	3	1
Total Aux. Power (MW)	130	119	112
Net Power (MW)	640	623	636
Heat Rate (Btu/kWh)	8,922	8,681	8,306
Efficiency (HHV)	**38.2**	**39.3**	**41.1**

IGCC Power Plant With CO_2 Capture

Current Technology

IGCC Power Plant with CO_2 Scrubbing





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

Emission Controls:

PM: Water scrubbing and/or candle filters to get 0.007 lb/MMBtu

NOx: N_2 dilution to ~120 Btu/scf LHV to get **15 ppmv** @15% O_2

SOx: Selexol AGR removal of sulfur to < **28 ppmv** H_2S 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

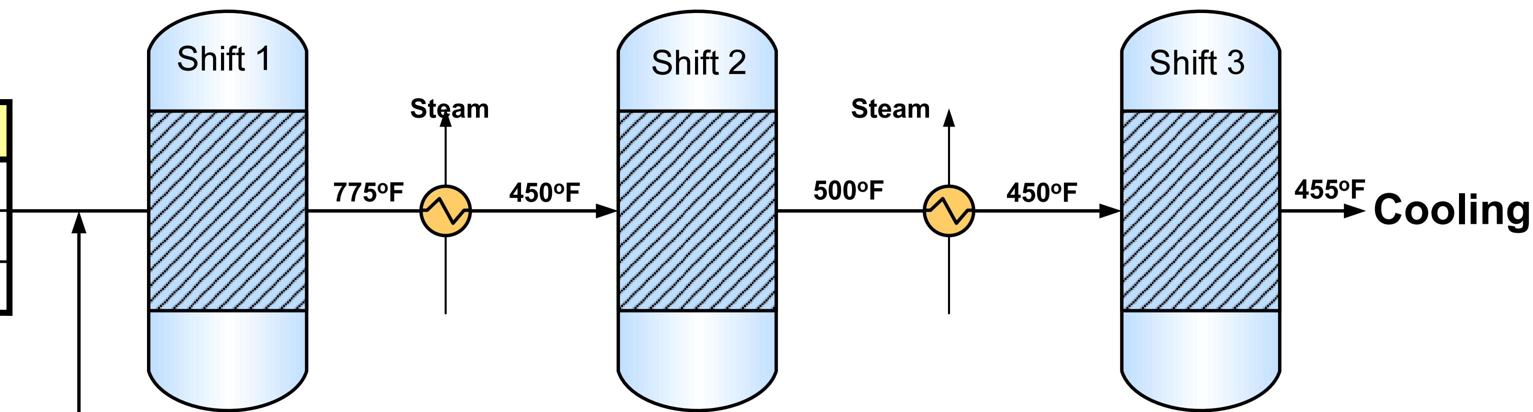
Water-Gas Shift Reactor System

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 ΔP = ~30 psia

H_2O/CO Ratio[1]	
GE	1.3
E-Gas	0.4
Shell	1.5

[1] Prior to shift steam addition



	Relative HP* Steam Flow	Steam Turbine Output (MW)
GE	1.0	275
E-Gas	2.4	230
Shell	0.9	230

*High Pressure Steam

$$H_2O + CO \longleftrightarrow CO_2 + H_2$$

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 Penalty[1]	-	5.7

Steam for Selexol

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

Includes H_2S/CO_2 Removal in Selexol Solvent

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

IGCC Performance Results

	GE Energy		E-Gas		Shell	
CO_2 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 Penalty[1]	**-**	**5.7**	**-**	**7.6**	**-**	**9.1**

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

IGCC Key Points

IGCC

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

IGCC with CO_2 Capture

- CO_2 capture reduces efficiency by 6-9 percentage points
- 5-7 percentage points higher than PC with CO_2 capture
- 11-12 percentage points lower than NGCC with CO_2 capture

R&D can increase competitiveness and reduce costs

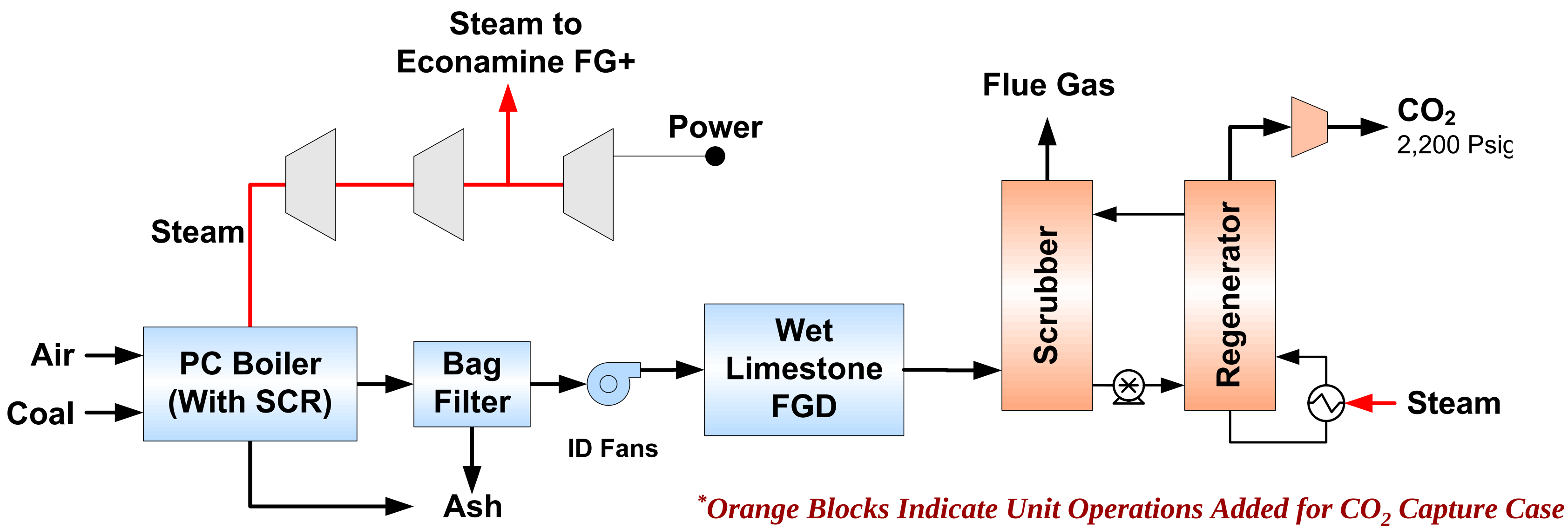
- Reduced ASU cost (membranes)
- Warm gas cleaning for sulfur removal
- Improved gasifier performance
  - carbon conversion, throughput, RAM
- Advanced carbon sorbents and solvents
- High-temperature membranes for shift and CO_2 separation
- Co-sequestration

Comparison to PC and NGCC

Current State-of-the-Art

Current Technology

*Pulverized Coal Power Plant**



**Orange Blocks Indicate Unit Operations Added for CO_2 Capture Case*

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

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

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

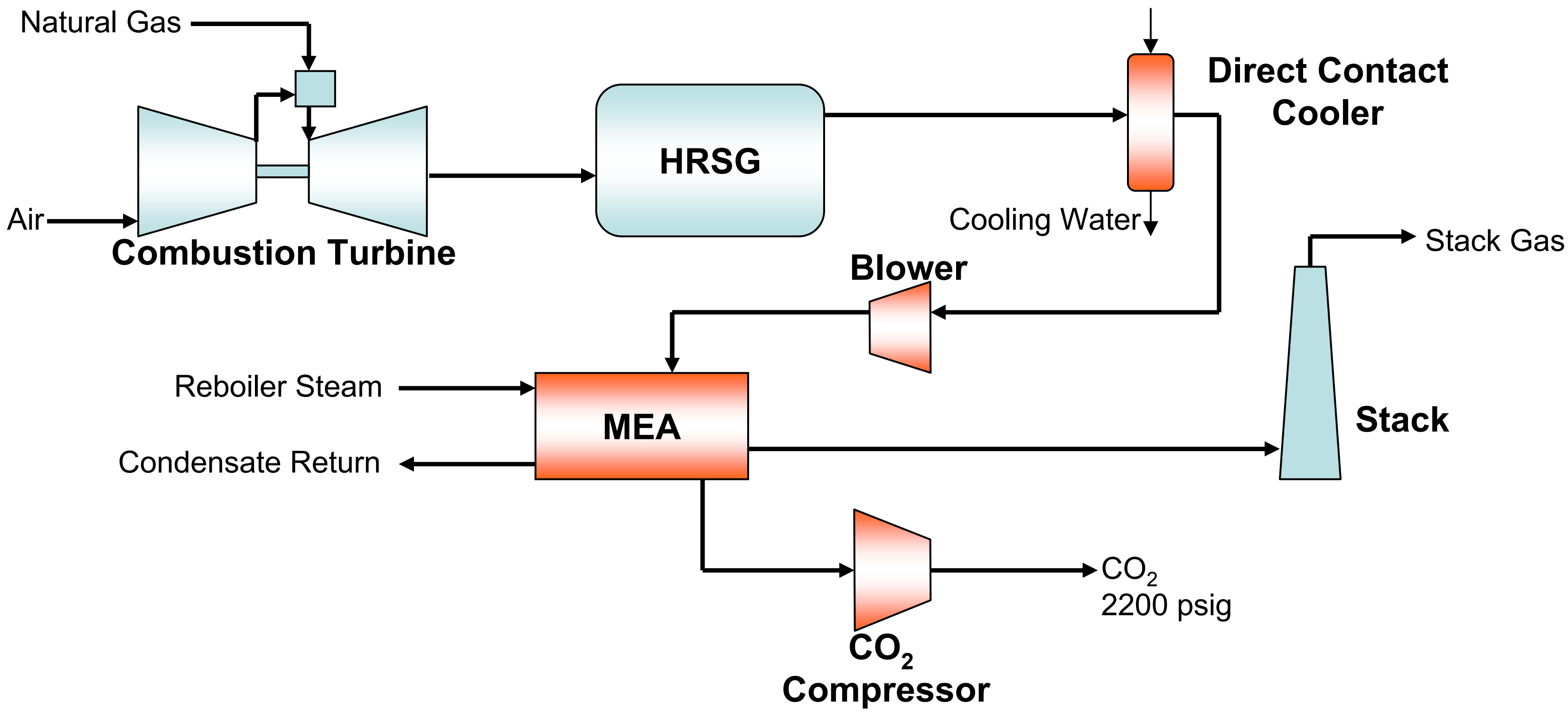
Mercury Control: Co-benefit capture ~90% removal

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 CO_2 Capture Case

NOx Control: LNB + SCR to maintain 2.5 ppmvd @ 15% O_2

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

PC and NGCC Performance Results

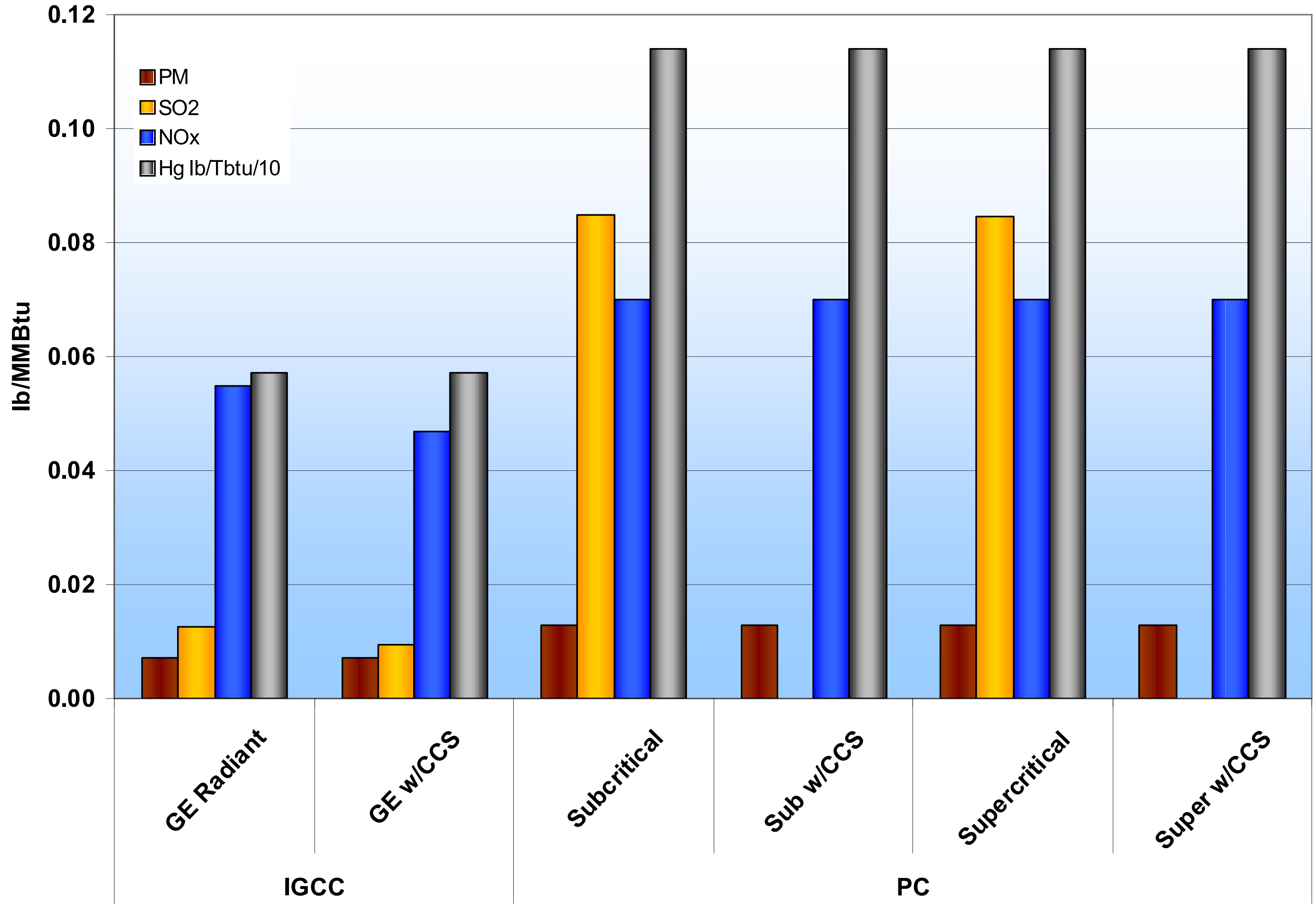
	Subcritical		Supercritical		NGCC	
CO_2 Capture	**NO**	**YES**	**NO**	**YES**	**NO**	**YES**
Gross Power (MW)	**583**	**680**	**580**	**663**	**570**	**520**
Base Plant Load	29	48	26	43	10	13
Gas Cleanup/CO_2 Capture	4	30	4	27	0	10
CO_2 Compression	-	52	-	47	0	15
Total Aux. Power (MW)	**33**	**130**	**30**	**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 Penalty[1]	**-**	**11.9**	**-**	**11.9**	**-**	**7.1**

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

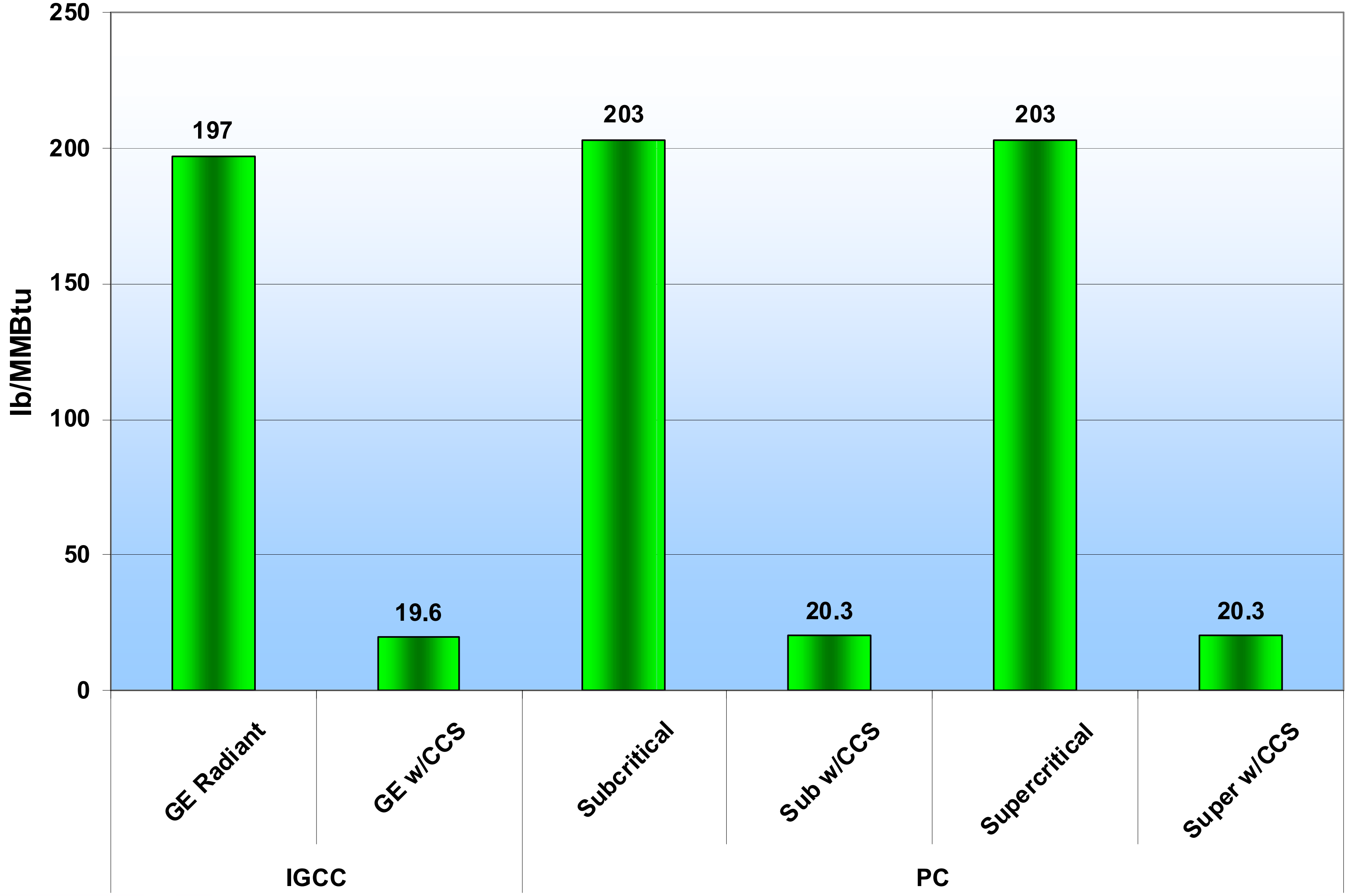
Environmental Performance Comparison

IGCC, PC and NGCC

Criteria Pollutant Emissions for All Cases



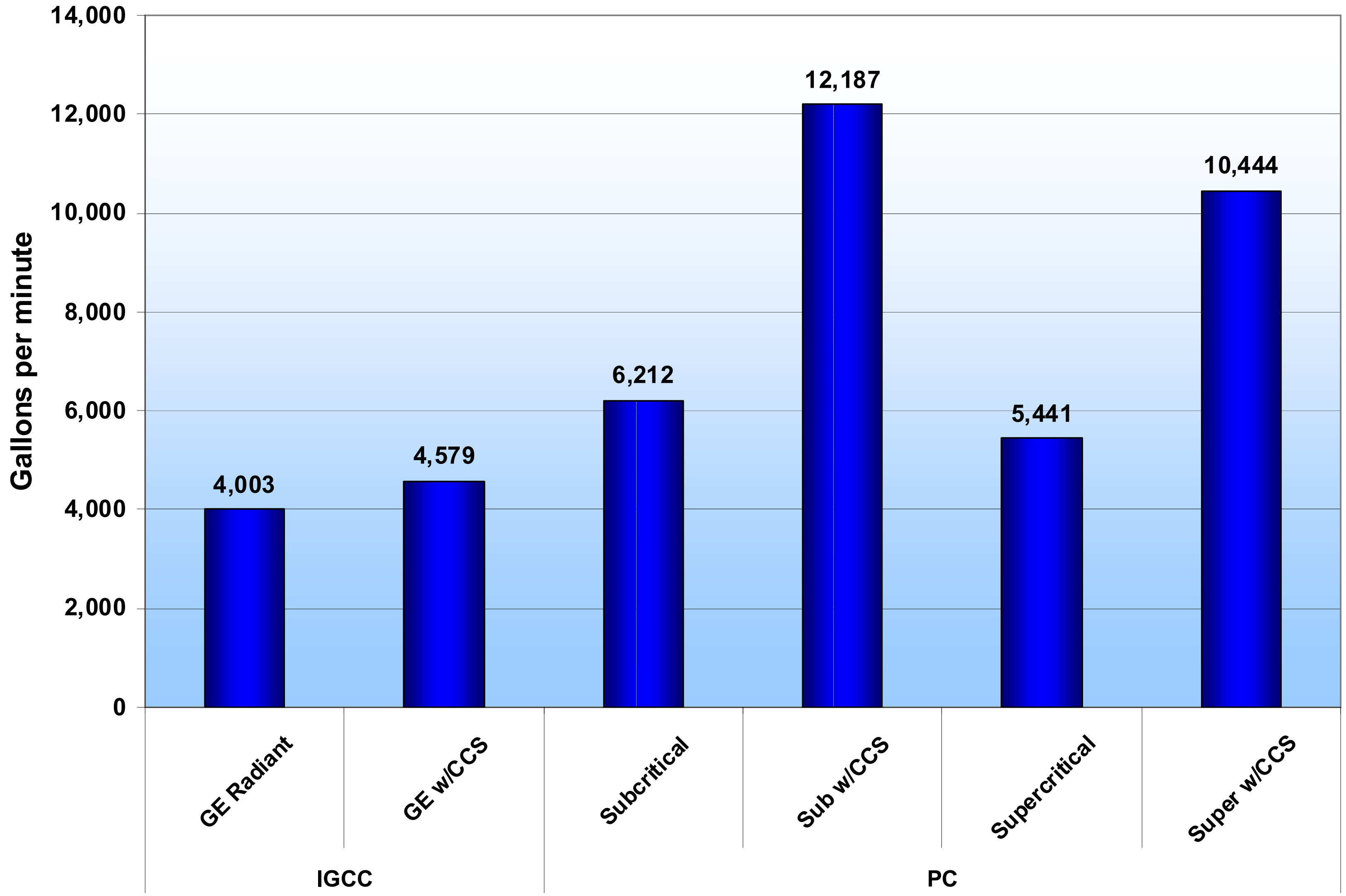
CO_2 Emissions for All Cases



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 CO_2 capture)	**17.5**
Low Risk	
(PC/NGCC without CO_2 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 CO_2 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 COE[2] (¢/kWh)	**7.80**	**7.52**	**8.05**

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

[2]January 2007 Dollars, 80% Capacity Factor, 17.5% Capital Charge Factor, Coal cost $1.80/10^6$Btu

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)	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
CO_2 TS&M COE (¢/kWh)	0.00	0.39	0.00	0.41	0.00	0.41
Total COE[2] (¢/kWh)	**7.80**	**10.29**	**7.53**	**10.57**	**8.05**	**11.04**
Increase in COE (%)	**-**	**32**	**-**	**40**	**-**	**37**
$/tonne CO_2 Avoided	-	35	-	45	-	46

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

[2]January 2007 Dollars, 80% Capacity Factor, 17.5% Capital Charge Factor, Coal cost $1.80/10^{6}Btu

PC and NGCC Economic Results

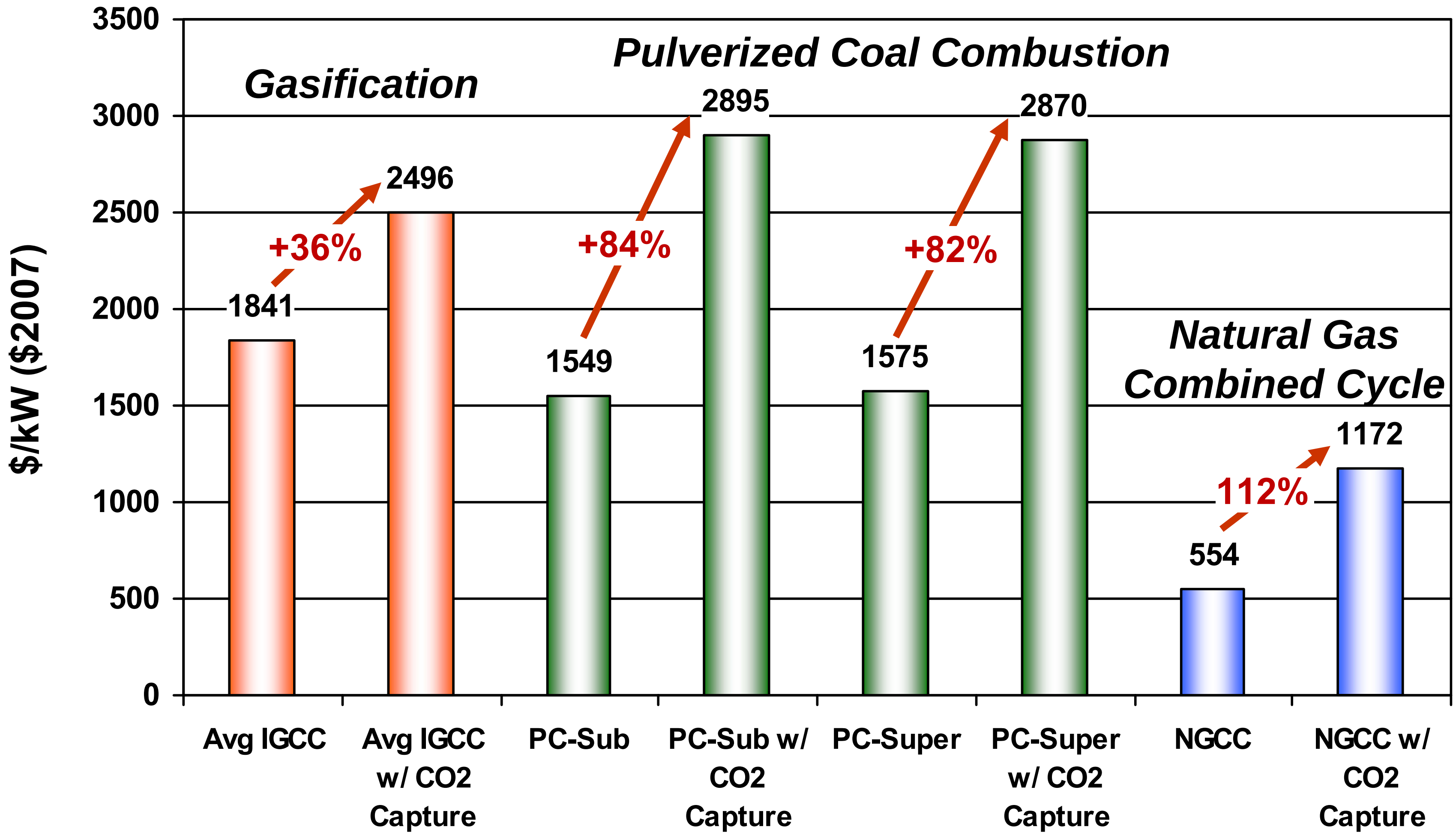
	Subcritical		Supercritical		NGCC	
CO_2 Capture	**NO**	**YES**	**NO**	**YES**	**NO**	**YES**
Plant Cost ($/kWe)[1]						
Base Plant	1,302	1,689	1,345	1,729	554	676
Gas Cleanup (SOx/NOx)	246	323	229	302	-	-
CO_2 Capture	-	792	-	752	-	441
CO_2 Compression	-	89	-	85	-	52
Total Plant Cost ($/kWe)	**1,549**	**2,895**	**1,575**	**2,870**	**554**	**1,172**
Capital COE (¢/kWh)	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
CO_2 TS&M COE (¢/kWh)	0.00	0.43	0.00	0.39	0.00	0.29
Total COE[2] (¢/kWh)	**6.40**	**11.88**	**6.33**	**11.48**	**6.84**	**9.74**
Increase in COE (%)	**-**	**85**	**-**	**81**	**-**	**43**
$/tonne CO_2 Avoided	-	75	-	75	-	91

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

[2]January 2007 Dollars, 85% Capacity Factor, 16.4% (no capture) 17.5% (capture) Capital Charge Factor, Coal cost $1.80/10^{6}Btu, Natural Gas cost $6.75/10^{6}Btu

Capturing CO_2 with Today's Technology is Expensive

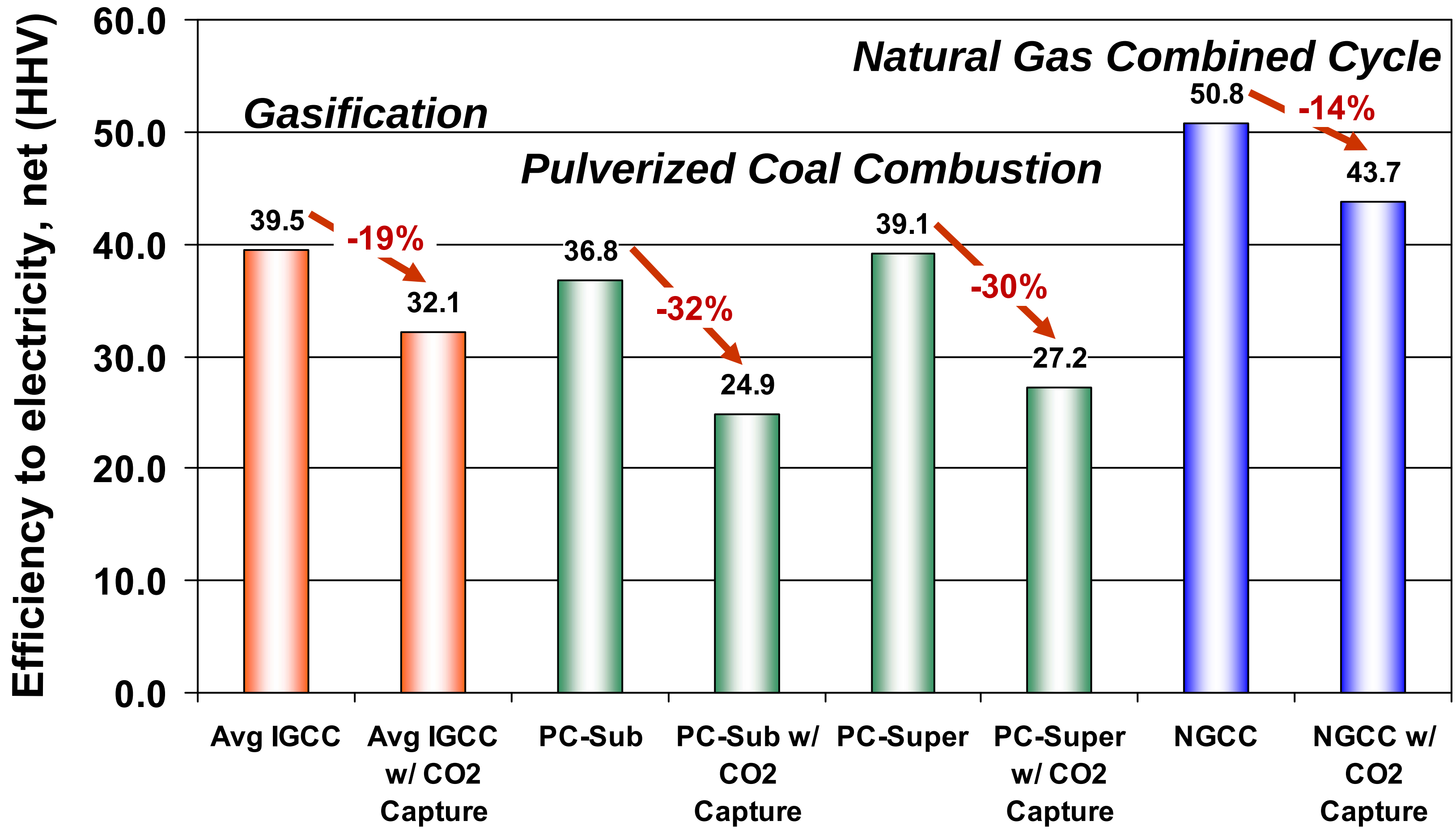
Total Plant Cost Comparison



Total Plant Capital Cost includes contingencies and engineering fees

DOE/NETL Report: "Cost and Performance Baseline for Fossil Energy Plants", May 2007

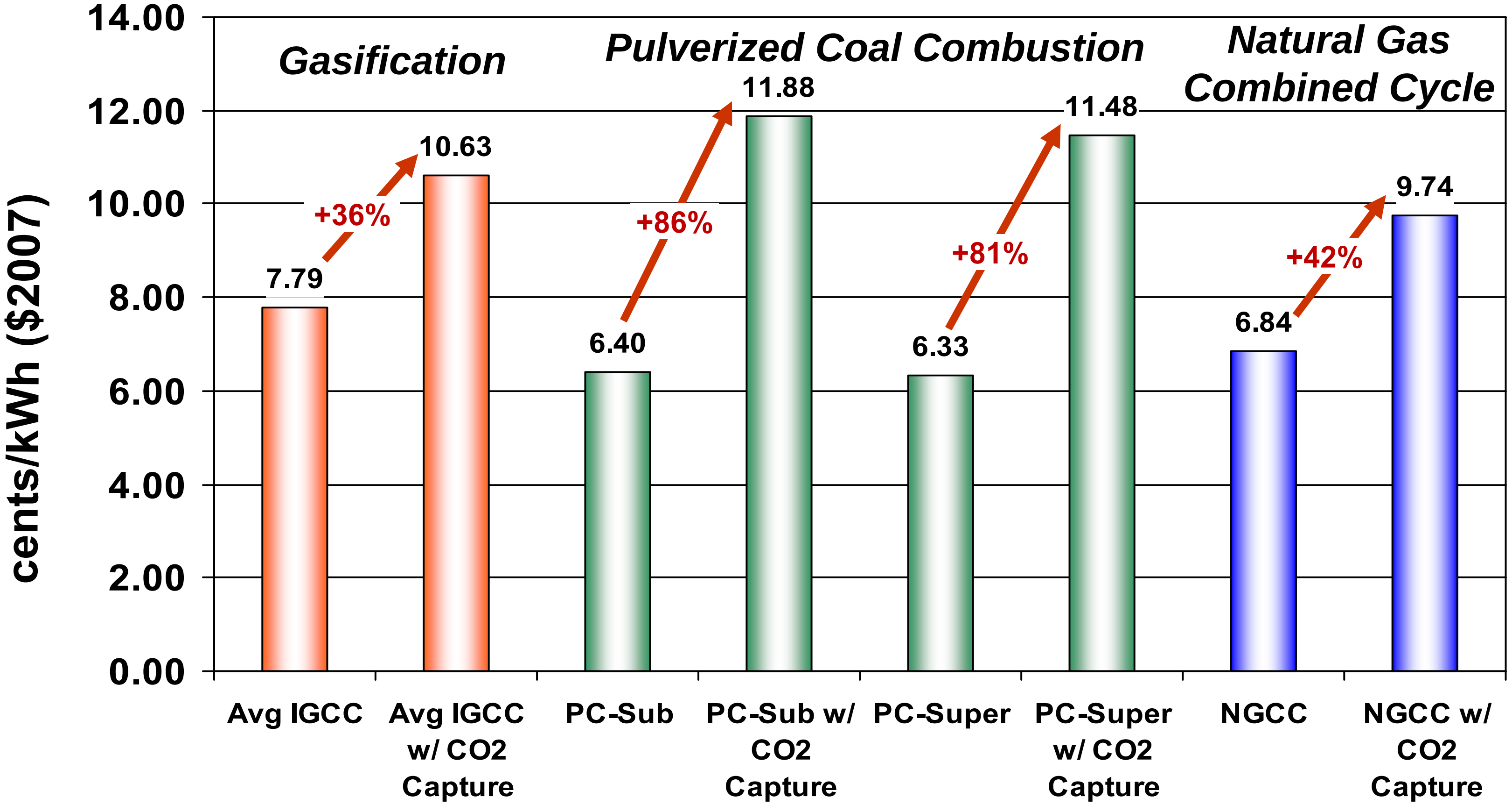
Capturing CO_2 with Today's Technology
Significantly Reduces Plant Efficiency



DOE/NETL Report: "Cost and Performance Baseline for Fossil Energy Plants", May 2007

Capturing CO_2 with Today's Technology is Expensive

Cost of Electricity Comparison



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… 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 CO_2 capture**
- **Ultra-clean Liquids from Coal -- Early Source of Hydrogen**

Visit NETL Gasification Website

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