

## Clean Coal Technology: Options and Tradeoffs

Stu Dalton ([sdalton@epri.com](mailto:sdalton@epri.com))

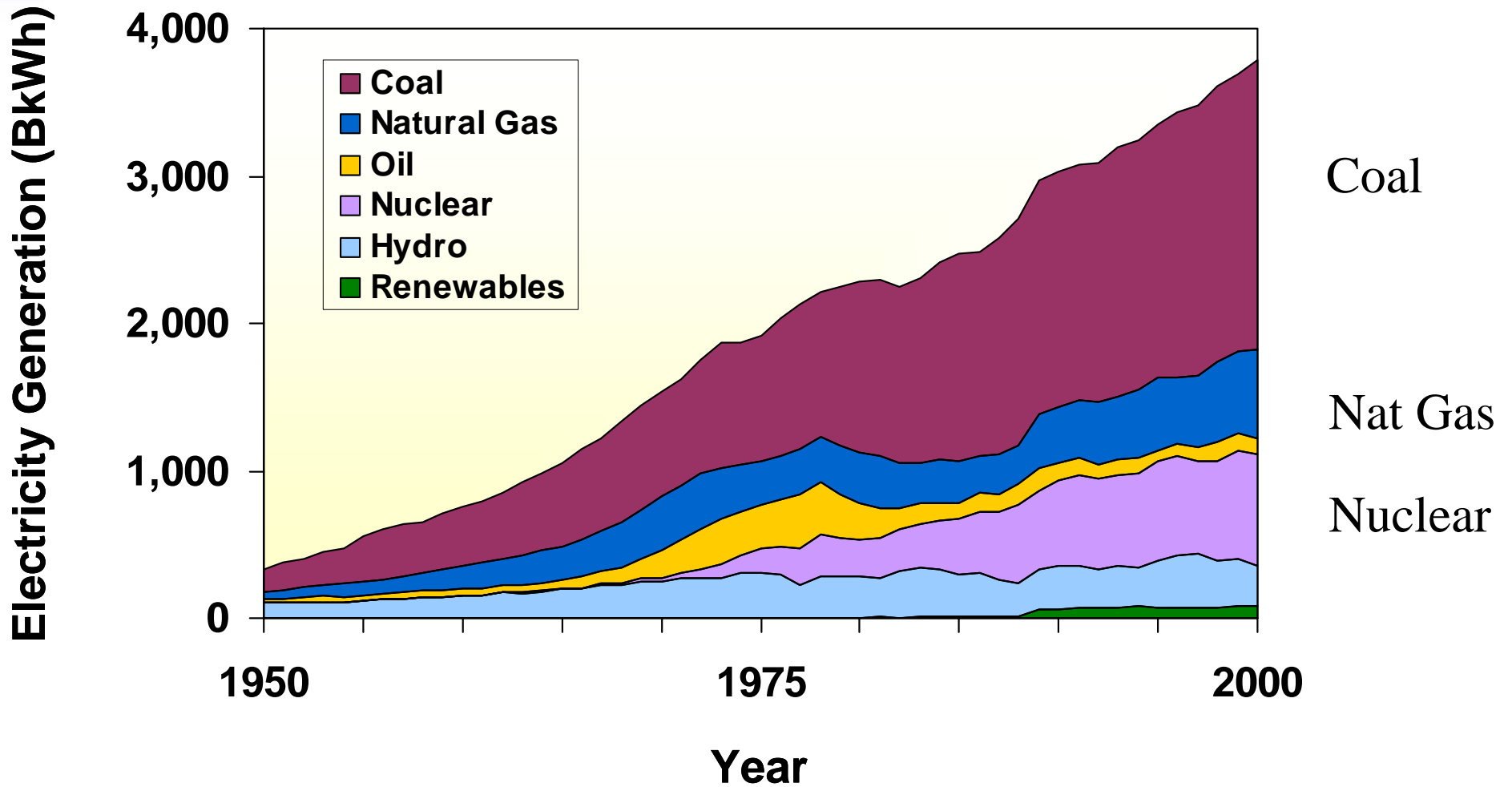
Director, Generation

Electric Power Research Institute

**December 2, 2005**

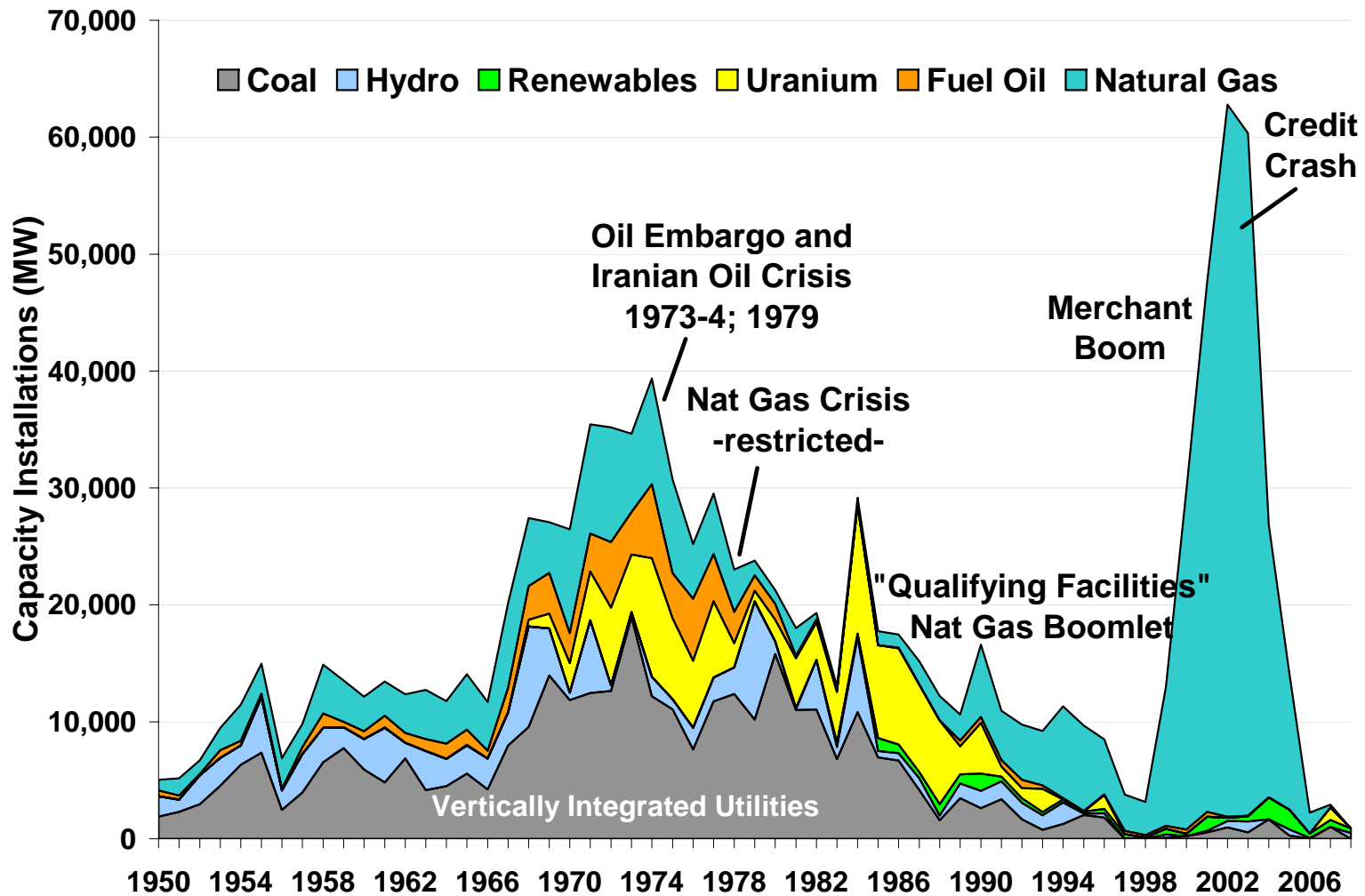


# U.S. Generation by Fuel



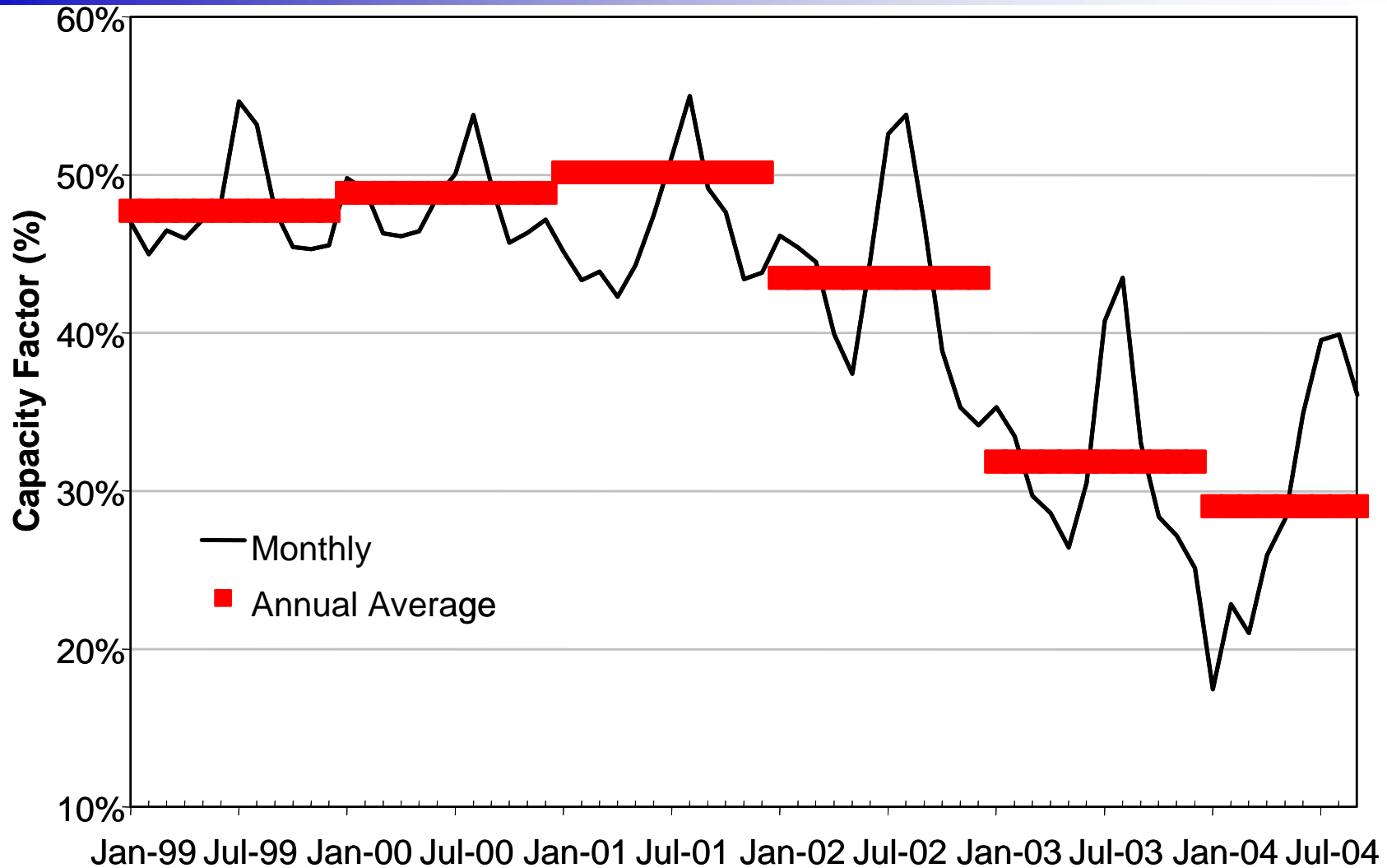
Source: DOE/EIA

# Generation Capacity Additions



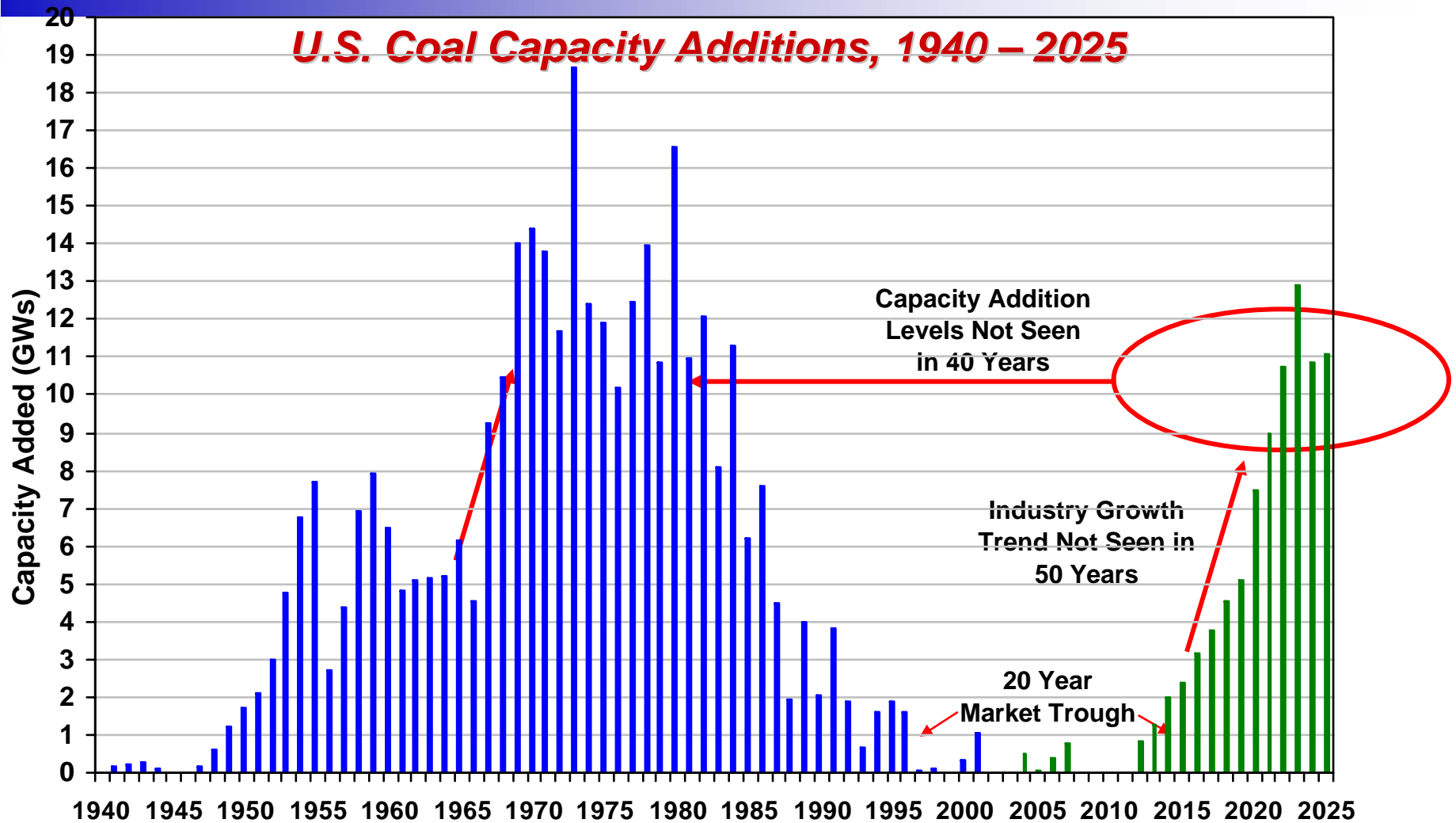
By permission: Global Energy Decisions and the Global Energy Reference Case March 2004; adapted from Oct-04 *Public Utilities Fortnightly*.

# Gas Generation Usage with Rising Prices



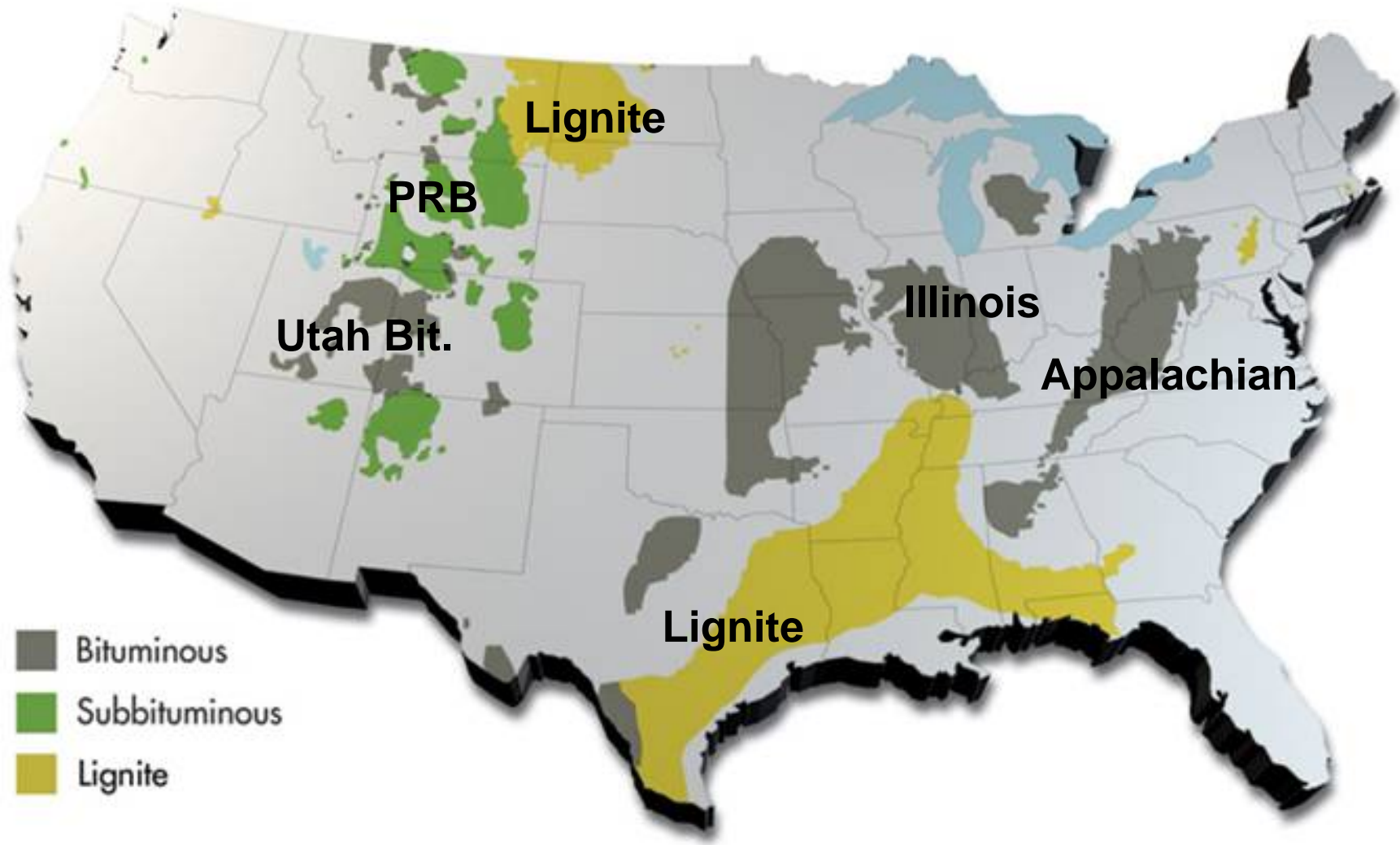
Source EPRI newsletter Understanding Power & Fuel Markets

# U.S. Forecasts Largest Coal Generation Capacity Installation in 40 Years



Source: U.S. Department of Energy NETL & Annual Energy Outlook 2005.

# U.S. Coal Types and Basins



# Typical U.S. Coal Analyses (Coal Properties Differ Markedly)

	Pittsburgh	Illinois	Wyoming	Texas
	#8	#6	PRB	Lignite
<b>Ultimate Analysis</b>				
<b>Moisture</b>	<b>5.2</b>	<b>12.2</b>	<b>30.24</b>	<b>33.03</b>
<b>Carbon</b>	<b>73.8</b>	<b>61.0</b>	<b>48.18</b>	<b>35.04</b>
<b>Hydrogen</b>	<b>4.9</b>	<b>4.25</b>	<b>3.31</b>	<b>2.68</b>
<b>Nitrogen</b>	<b>1.4</b>	<b>1.25</b>	<b>0.70</b>	<b>0.77</b>
<b>Chlorine</b>	<b>0.07</b>	<b>0.07</b>	<b>0.01</b>	<b>0.09</b>
<b>Sulfur</b>	<b>2.13</b>	<b>3.28</b>	<b>0.37</b>	<b>1.16</b>
<b>Oxygen</b>	<b>5.4</b>	<b>6.95</b>	<b>11.87</b>	<b>11.31</b>
<b>Ash</b>	<b>7.1</b>	<b>11.0</b>	<b>5.32</b>	<b>15.92</b>
<b>Higher Heating Value as received (Btu/lb)</b>	<b>13,260</b>	<b>10,982</b>	<b>8,340</b>	<b>6,010</b>

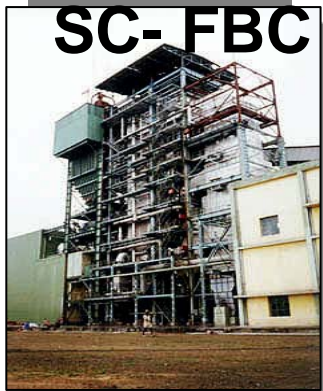
# Types of Coal Generation

- **Pulverized coal (PC):** Finely ground coal is burned to make steam and then flue gases are cleaned up; there are more than 1000 such “conventional coal” plants in the U.S.
- **Very high-temperature versions of PC** employ supercritical (SC) steam, and even higher are ultra-supercritical (USC)
- **Circulating fluidized-bed combustion (CFBC or FBC):** Larger coal pieces are “fluidized” by combustion air and entrained with a “sorbent” such as limestone to remove  $\text{SO}_2$
- **Gasification** of coal involves reaction with oxygen and heat/steam to produce a “synthesis gas” containing CO, hydrogen, and methane. The gas is cleaned and then burned in gas turbine with the exhaust heat used to make steam; such plants are “integrated gasification combined cycle” (IGCC).

## What Is “Clean Coal?”

- Even modern conventional coal plants are much cleaner than prior designs, but most people refer to designs meeting very stringent emission regulations as “clean coal”
- Coal-based IGCC plants have very low SO<sub>2</sub>, NO<sub>x</sub> and mercury emissions and are almost as clean as natural gas plants
- DOE, EPRI, and the Coal Utilization Research Council have defined clean coal plant performance and emission goals for 2010 and 2020 (see Roadmap at [www.coal.org](http://www.coal.org))

# Regional U.S. Coal Differences Favor Multiple Advanced Coal Options



- **IGCC with slurry feed economics are best with “high-rank” bituminous coals or low-rank (PRB) coal plus petroleum coke (today's economics do not favor IGCC, but it has lower emissions)**
- **New IGCC designs may be better for low-rank coal and may be cheaper, but these designs are still developmental**
- **Waste coals and biomass may be best in fluidized-bed combustion (FBC) units, but supercritical steam conditions are unproven**
- **Most U.S. plans are for new “conventional” pulverized coal due to lower fuel costs; in Europe and Japan, where fuel costs are high, ultra-supercritical (USC) designs are favored**

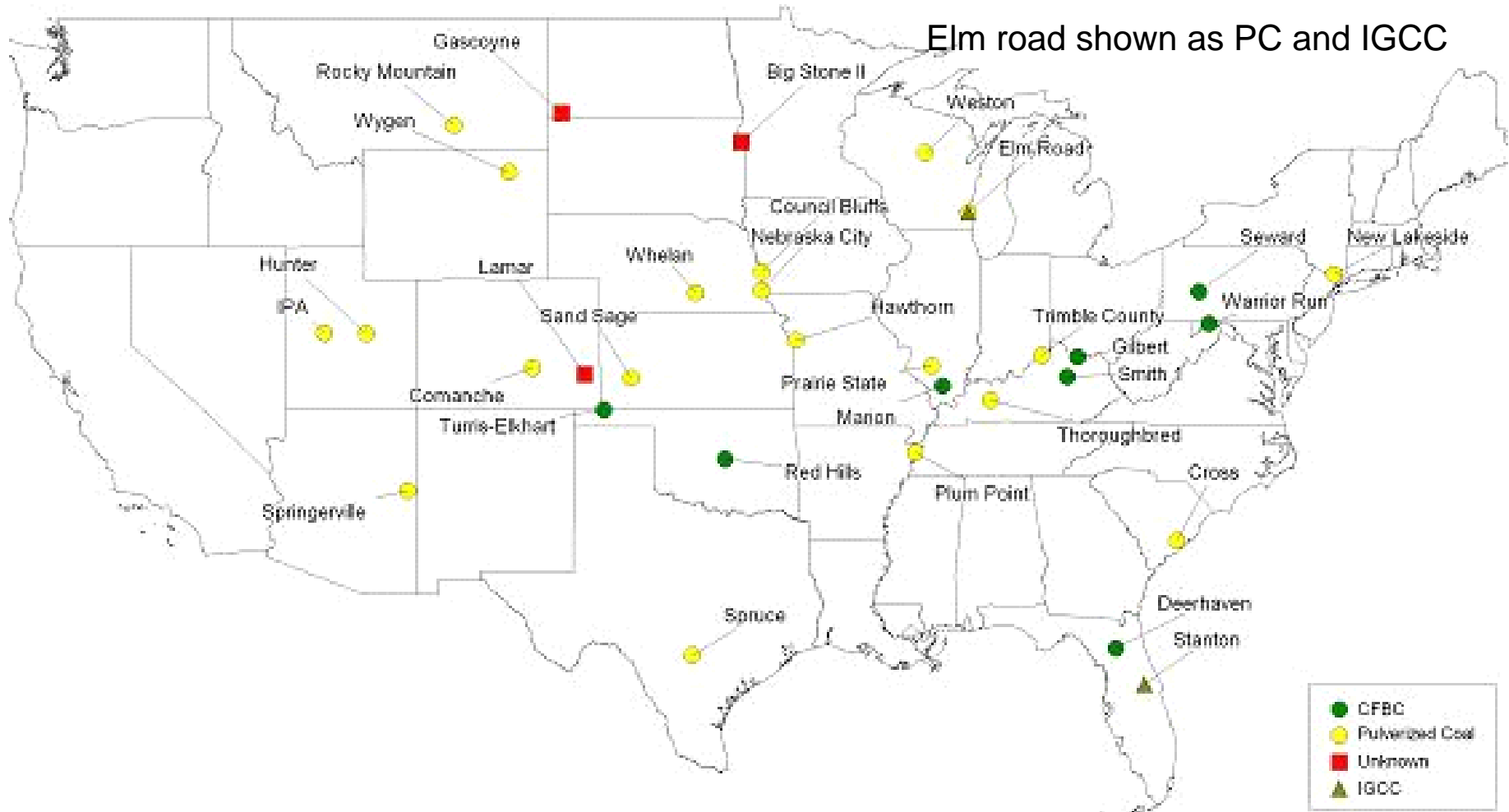
# Do Either Gasification or Conventional Coal Inherently Remove CO<sub>2</sub>?

- **No** – both IGCC and a modern pulverized coal unit emit roughly 0.8 ton of CO<sub>2</sub> per MWh, roughly twice that of a modern gas-fired combined cycle
- However, because gas is roughly four times or more the cost of coal and because much of the cost of electricity is fuel cost, gas fueled generation is more expensive to run
- The important question is how much cost and energy does it take to add equipment to remove CO<sub>2</sub> from either system (PC or IGCC) and then store it underground
- It is easier to remove CO<sub>2</sub> from a gasifier before it is burned due to fundamental physics and chemistry - the synthetic gas from coal is much higher pressure and the concentration of CO<sub>2</sub> can be higher

# Potential Coal 2005–2012

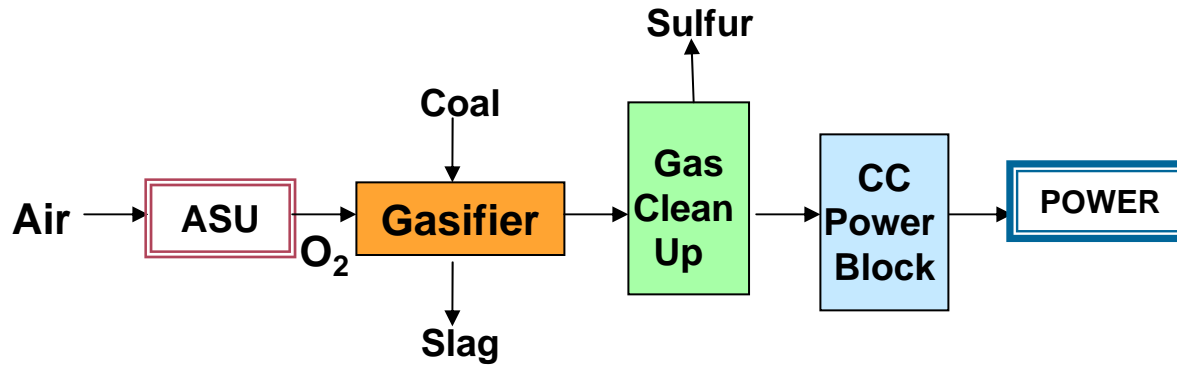
Note this is potential as of Spring 2005  
changes occur on list continually

Elm road shown as PC and IGCC

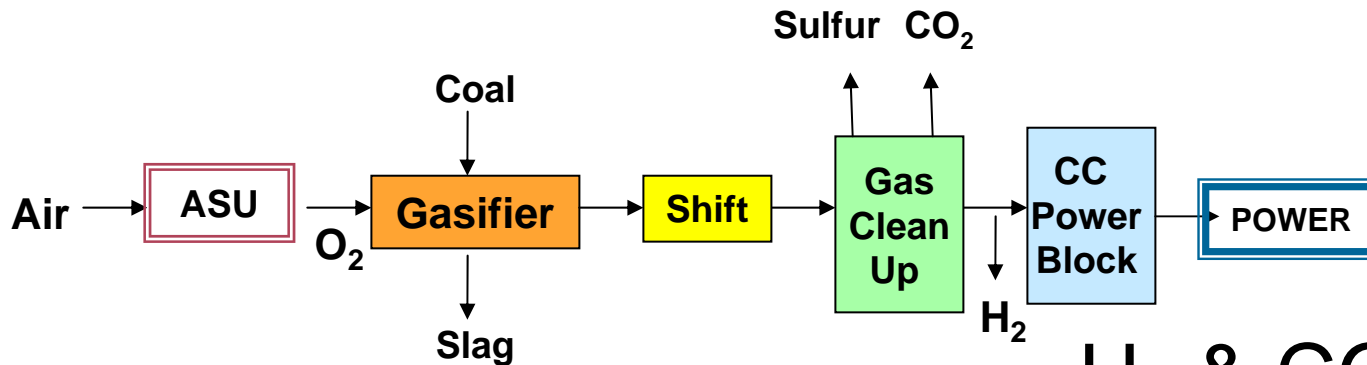


Ref.: EPRI P67 Newsletter on New Power Plants, March-April 2005

# IGCC with and without CO<sub>2</sub> Removal



IGCC



H<sub>2</sub> & CO<sub>2</sub>  
(e.g., FutureGen)

# Today's Existing Coal-Based IGCC Plants



**Puertollano (Spain)**



**Wabash (Indiana)**



**Polk (Florida)**



**Buggenum (Netherlands)**

# IGCC Environmental Control

- Sulfur can be removed from syngas at >99.5%
- NO<sub>x</sub> emissions are controlled in the CT combustion but with N<sub>2</sub> dilution ; Selective Catalytic Reduction addition is possible
- Particulates are removed from the syngas by filters and water wash prior to combustion, so emissions are negligible
- Current IGCC design studies with SCR plan ~3 ppmv each of SO<sub>x</sub> and NO<sub>x</sub> with some cost penalty
- Mercury can be removed from syngas at >90% by absorption in a special activated carbon bed
- By-product slag is vitreous and inert and often salable
- Water use is ~ 70% of a conventional coal plant
- CO<sub>2</sub> under pressure takes less energy to remove than from PC flue gas at atmospheric pressure (Gas volume is <1% of flue gas from same MW-size PC)

# IGCC Status, Markets, and Vendors

- 4 single-train coal-based IGCC 250–300 MW (+ 2 others)
- Main needs are capital cost reduction and availability improvement; federal Energy Bill contains incentives
- AEP, Energy Northwest and Cinergy plan ~600 MW plants. Several others are in development including co-production (ammonia, synthetic natural gas, liquid fuels)
- Technology needs improvement for low-rank coals (the predominant type in the West) and some new designs have been recently proposed
- Worldwide market for IGCC based on petroleum residuals supplying power, steam, and hydrogen to refineries. 8 IGCC plants operating on petroleum residuals (including two multi-train 550 MW plants in Italy). Potential for refinery replacement H<sub>2</sub> co-product?
- Vendor teams (for coal and pet coke): GE/Bechtel, ConocoPhillips/Fluor, Shell/Uhde/Black & Veatch. Possibly others in development (Southern/KBR, Future Energy?)

# EPRI Economic Estimates for IGCC & PC Plants without CO<sub>2</sub> Capture—500 MW with Low-Rank Coals (estimates from 2002–03 – estimates currently being updated)

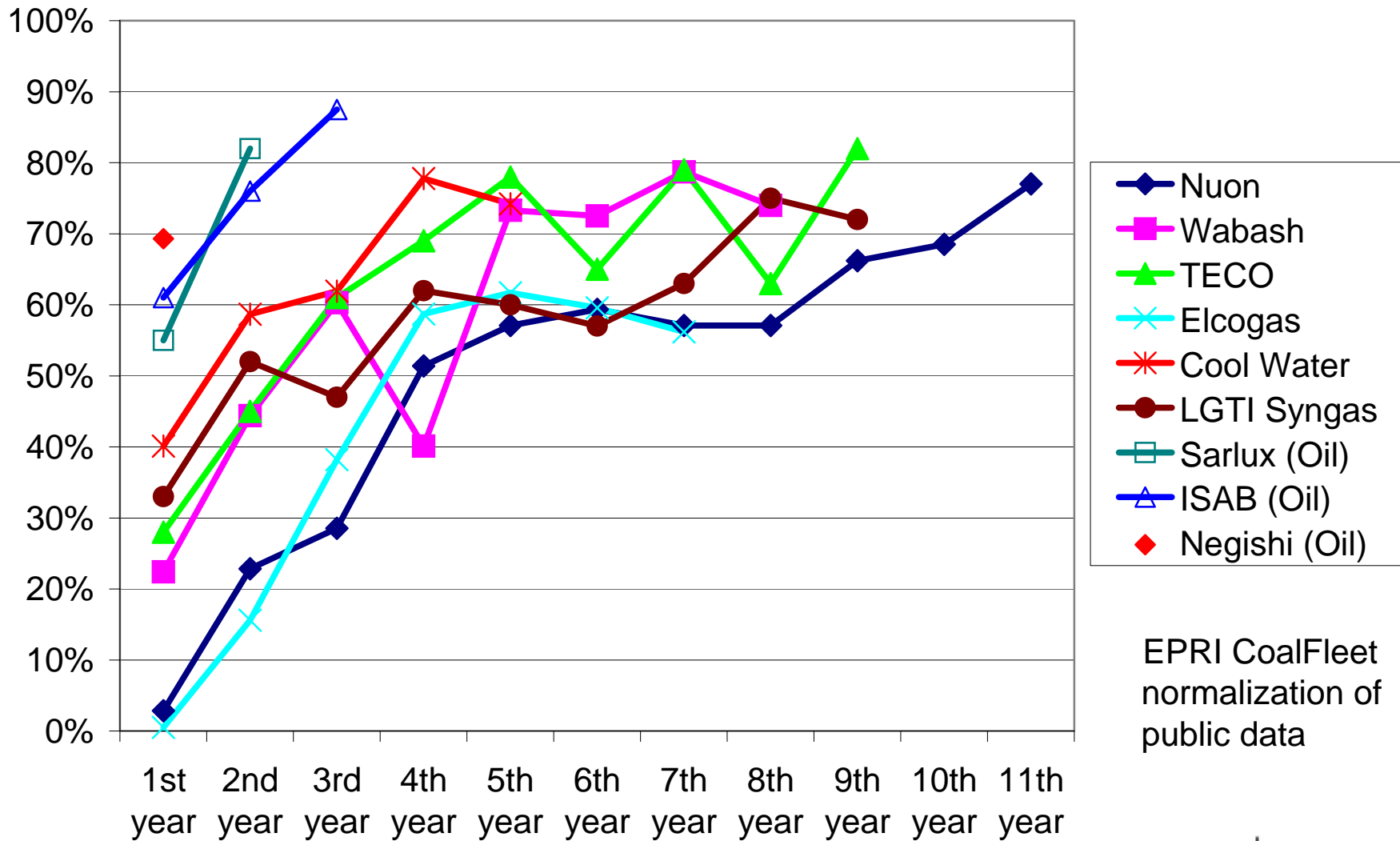
Technology	IGCC E Gas	IGCC Shell No Spare/ Spare	PC Sub	IGCC E Gas	PC Sub
Coal	Wyo. PRB	Wyo. PRB	Wyo. PRB	Lignite	Lignite
TPC \$/kW	1640	1480/1690	1330	1830	1340
Coal Cost \$/MBtu HHV	1.0	1.0	1.0	0.5	0.5
COE \$/MWh at 80% Capacity Factor	54	48/54	44	55	43

# Reliability of IGCC and Pulverized Coal Plants

- Today's statistics are that IGCC is some 5-7 % less reliable than pulverized coal plants.
- Projections and implications of new designs are that this gap will close, but it is a concern for those planning new plants
- The latest NERC GADS data (for years 2000-2004 operation) shows average PC equivalent availability was 84.9%.
- For PCs in the 200 - 299 MW size range (same as most of the IGCCs which are operating) it was 85.5%.
- See next slide – the commercial data for the first generation IGCC plants after a number of years is mostly less than 80%

# IGCC Availability History

(excludes operation on back-up fuel)



EPRI CoalFleet  
normalization of  
public data

# Heat Rate with Different Fuels

(CoP Paper - 2005 Gasification Technologies Conference 10/05)

	Petroleum coke	Pittsburgh #8	Illinois #6	Wyoming PRB
Coal				
Coal short tons/day	4300	4637	5852	8200
Oxygen short tons/day	3670	3670	4220	4700
Slurry Dry solids Wt%	66	66	63	53
Cold gas efficiency%	82	82	79	76
Net Power MW	620	631	637	646
Heat Rate Btu/kWh HHV basis (eff. %)	8300 (41.1)	8300 (41.1)	8675 (39.4)	8890 (38.4)
Overnight EPC \$/kW	1280-1570	1270-1550	1330-1620	1380-1680

Paper available at [www.gasification.org](http://www.gasification.org) case shown no SCR

# CoP E-Gas Effect of Elevation on IGCC Cost and Performance (PRB Coal)

(CoP Paper - 2005 Gasification Technologies Conference 10/05)

<b>Location/Elevation</b>	Midwest / 500ft	Wyoming Mine / Mouth / 5000ft
<b>Cooling</b>	Cooling Tower	Air Cooling
<b>Heat Rate Btu/kWh HHV</b>	8996	9075
<b>Coal tpd AR</b>	8341	7259
<b>Net Power MW</b>	644.3	555.9
<b>TPC \$ Millions</b>	935-1131	868-1051
<b>Nominal TPC \$/kW (-5%/+15%)</b>	1527	1644
<b>Annual O&amp;M \$ Millions</b>	37	39

Case shown with SCR

## PRB and Lignite – other suppliers

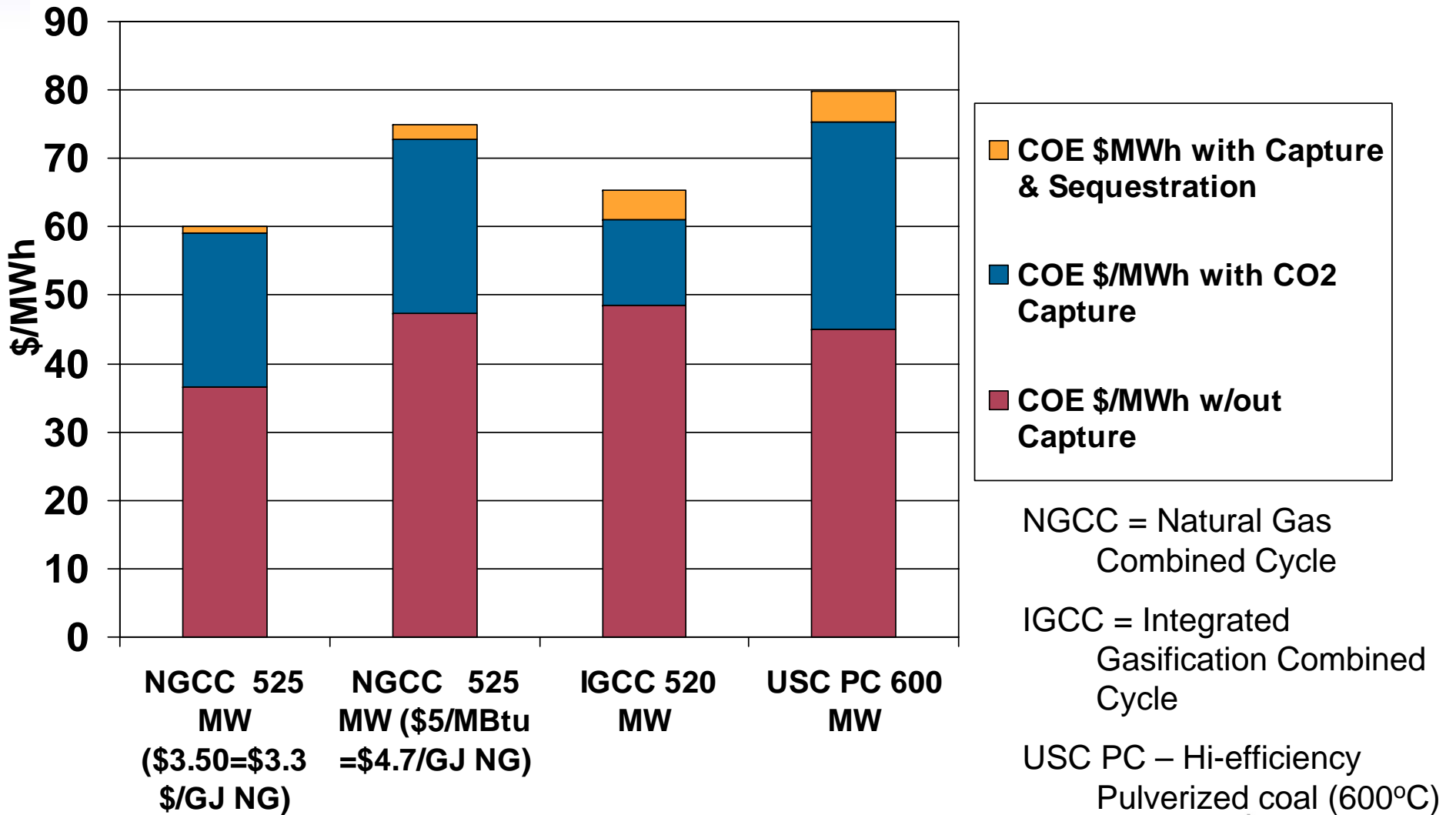
- Shell are representing 8200 (41.6%) HR for PRB and about 8000-8100 for Pittsburgh #8 but higher for Illinois #6 at 8500 (40.2%)-8600 (39.7%). EPRI does not have independent estimates as yet for Shell.
- We do not have information for lignite.
- Shell normally requires coal drying prior to the process efficiency calculation
- EPRI's CoalFleet for Tomorrow work is looking at lignite designs by Shell, and KBR.
- GE and Conoco Philips are not actively bidding lignite to our knowledge and both are developing "standard" packages for PRB

# What About CO<sub>2</sub>?

- Higher efficiency designs inherently produce less CO<sub>2</sub> per kWh
- Neither IGCC nor pulverized coal inherently captures CO<sub>2</sub>
- US and world efforts are aimed at developing better options for high efficiency generation and understanding how to economically capture and safely store CO<sub>2</sub>



# Costs of Electricity from New Fossil Fuel Power Plants with CO<sub>2</sub> Capture and Sequestration (Bituminous Coal, 2003 EPRI study)

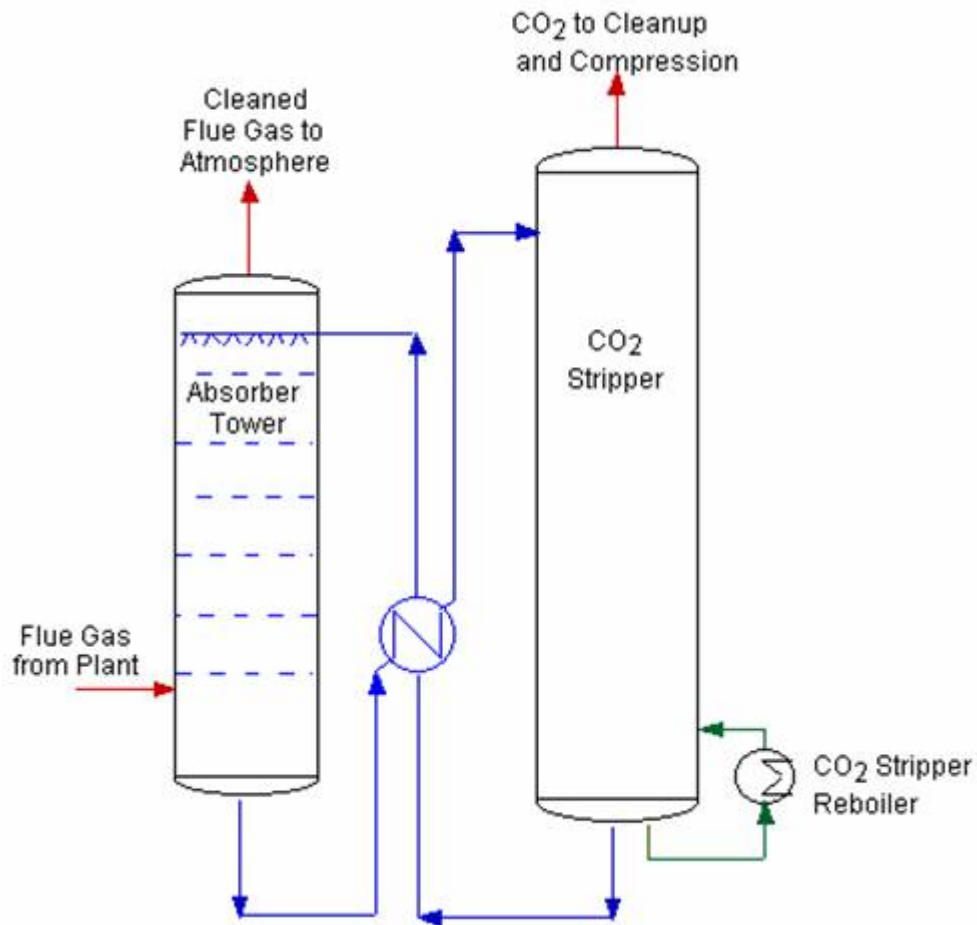


# What is CO<sub>2</sub> Capture and Storage?

## Four Basic Steps

1. **Capture** -either in flue gas at atmospheric pressure and 3-15% CO<sub>2</sub> or from high pressure, concentrated IGCC syngas
2. **Compress** and dehydrate the gas
3. **Transport** – usually at > 100 bar (critical point is 73 bar so it is a liquid). Long pipelines do exist > 2MTPY as individual pipelines and > 30 MTPY total
4. **Store - Inject underground** in a suitable geologic formation (e.g., saline aquifer, oil, coal and gas strata, basalt)

# CO<sub>2</sub> Capture by Chemical Absorption (Post-Combustion)



- Amine type processes are commercially available (Fluor, Kerr McGee, MHI) and have been demonstrated at 300 mt/day CO<sub>2</sub> (500 MW PC produces ~10,000 mt/day CO<sub>2</sub>)
- Requires extensive flue gas pretreatment
  - » Essentially no NO<sub>x</sub> or SO<sub>2</sub>
- Large reboiler steam requirement
  - » Large reduction in net output
  - » Make-up power source for retrofit of existing plant?
- Looking at options for reduced steam consumption

# IGCC—Pre-Engineering for CO<sub>2</sub> Capture

- Converting an IGCC plant to capture CO<sub>2</sub> will take less energy and equipment than a pulverized coal plant, but it is not trivial—it is **not** just “pre-engineering to leave space”
- Gasifiers and Air Separation Units would have to be oversized to match later CO<sub>2</sub> removal (more syngas is needed)
- More moisture is needed to “shift” CO in syngas to CO<sub>2</sub>, so different gasifier designs (e.g., quench) may be favored
- Pure hydrogen turbines have not been run at large scale
- Newest “FB” class turbines have not run commercially on syngas, and earlier GE gas turbines have a mismatch on torque limits—new blading may be needed on “FA” turbines, firing temperature derates?
- New burners may be needed as lean pre-mixed low-NO<sub>x</sub> burners are not suitable for H<sub>2</sub>; N<sub>2</sub> would need to be injected
- EPRI estimates from 2003 Parsons study—it may cost \$30/kW to save \$50/kW later, and the present value may not be there
- More work is needed

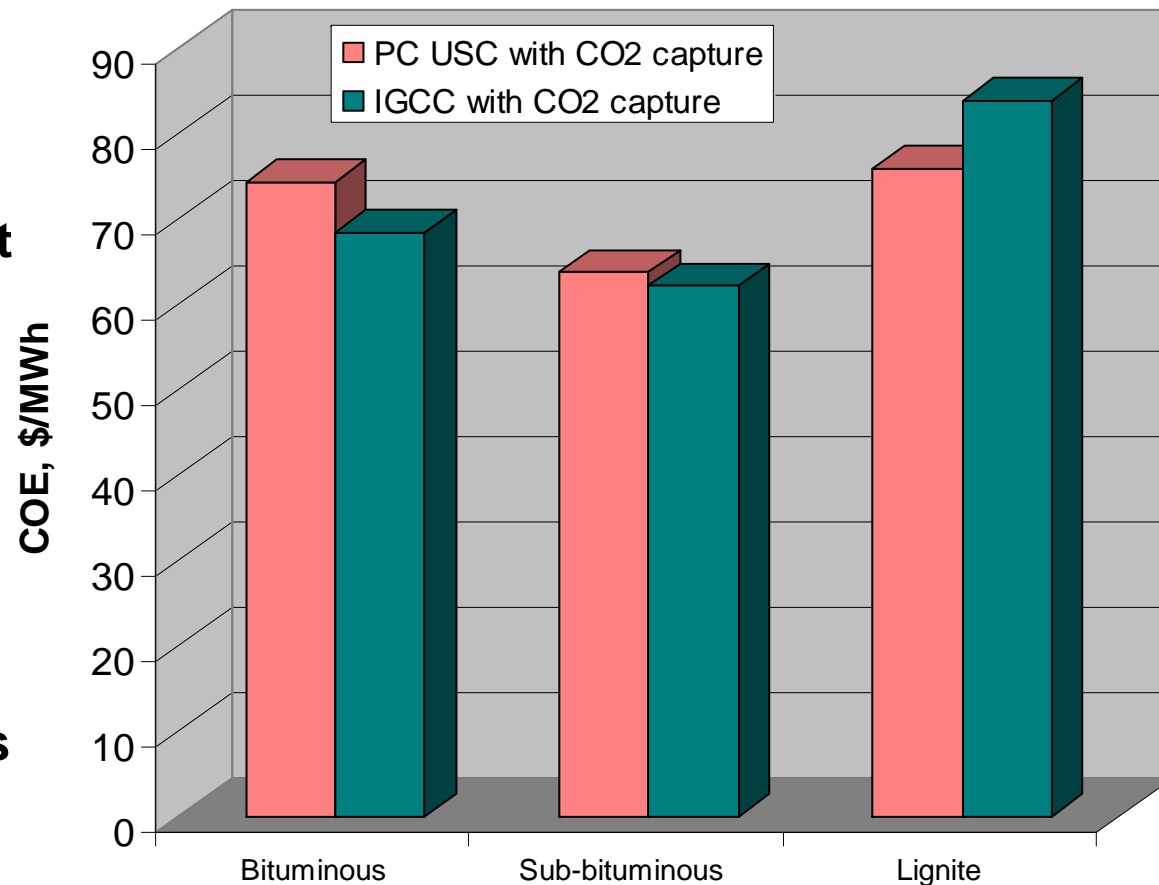
# Processes for CO<sub>2</sub> Capture

- Current post-combustion process: MEA (amine) scrubbing — absorption plus thermal stripping using high amounts of energy
- Future improvements for post-combustion: DOE has major programs (EPRI developing pilot efforts)
  - Improved solvents with lower energy use
  - Novel processes (enzyme, mineralization, ammonia, carbonates)
  - Novel contacting equipment (membranes, pressure swing, etc.)
  - Improved design of processes and integration
- Alternatives
  - Oxy-fuel (make almost pure CO<sub>2</sub>; dry and compress)
  - Gasification plus water-shift and separation of CO<sub>2</sub>

# Fuel Impact on PC vs. IGCC Cost of Electricity: Canadian Study Results (first set of data)

Source  
Canadian Clean  
Power Coalition

- **PC: Higher cost than IGCC except for lignite**
- **Suggests that fuel choice may have an impact on technology selection**
- **Suppliers addressing the issue**
- **Canadian studies ongoing re-analysis**

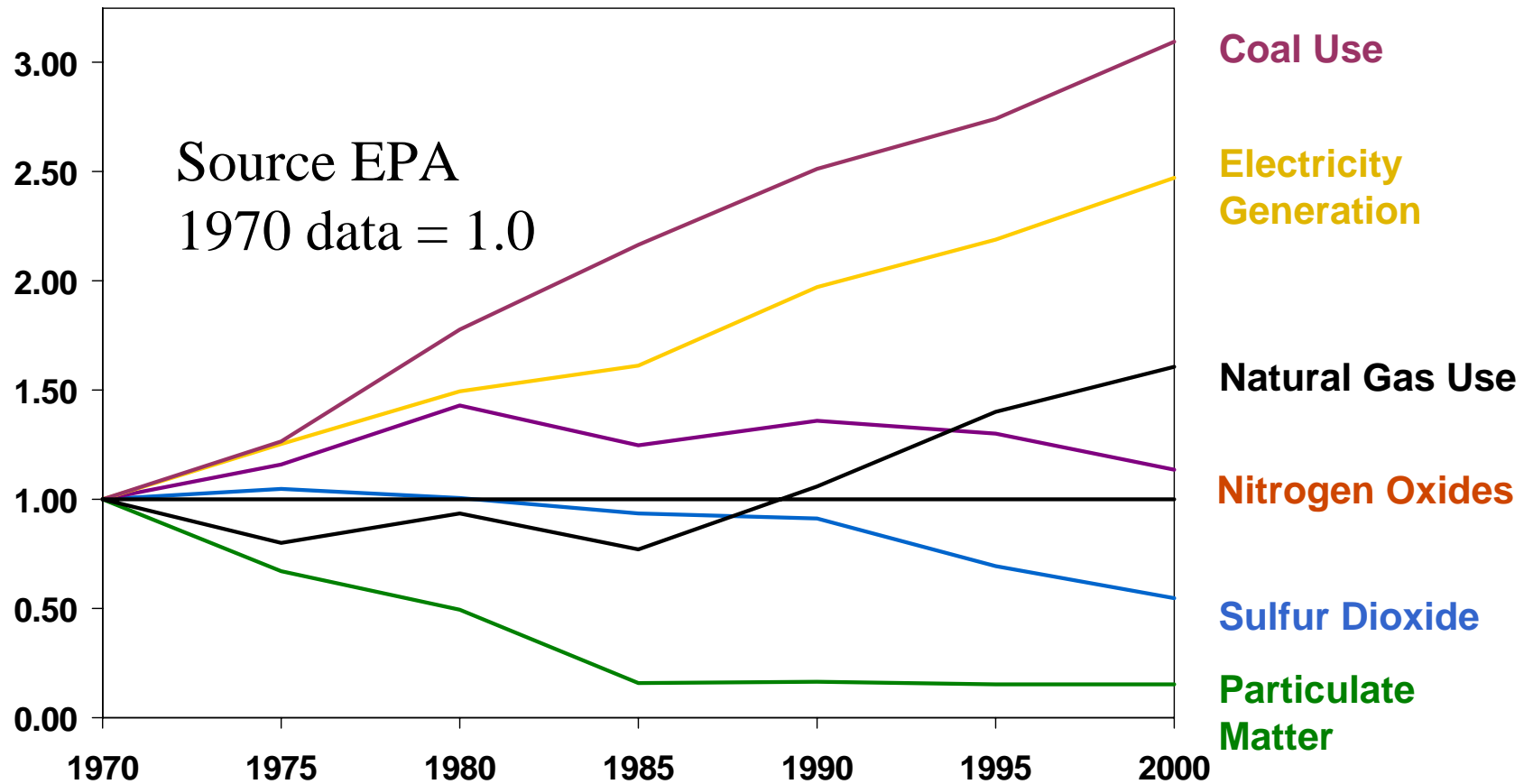


See also Paper - <http://uregina.ca/ghgt7/PDF/papers/nonpeer/068.pdf>

Note: Coal Cost—Bit=\$1.92/MBtu, SB=\$0.48/MBtu, L=\$0.845/MBtu; 90% Cap Factor;

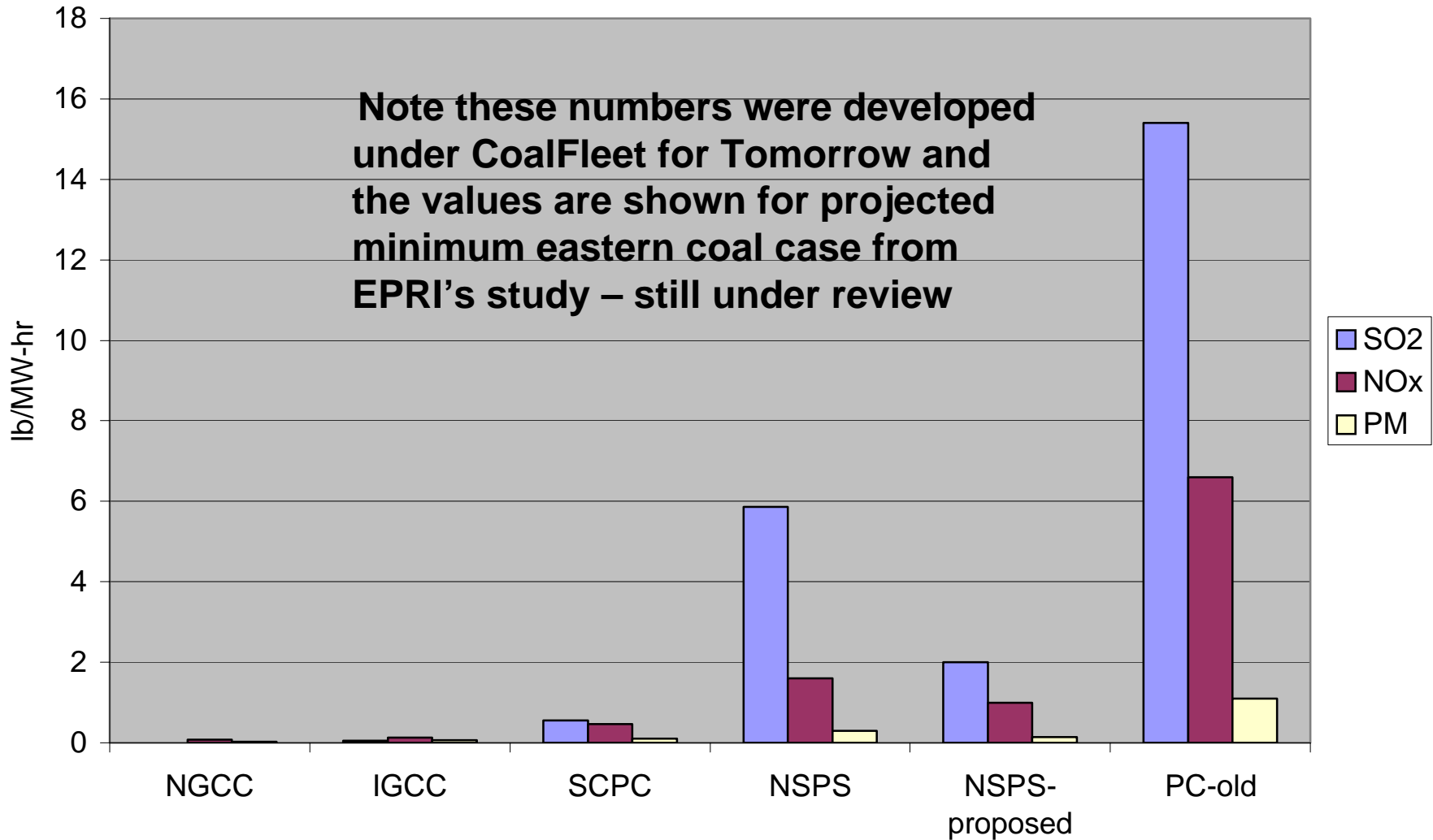
CO2 removal—IGCC 86-89%, PC 95%

# U.S. Electric Generation, Fuel Use, and Emission Trends



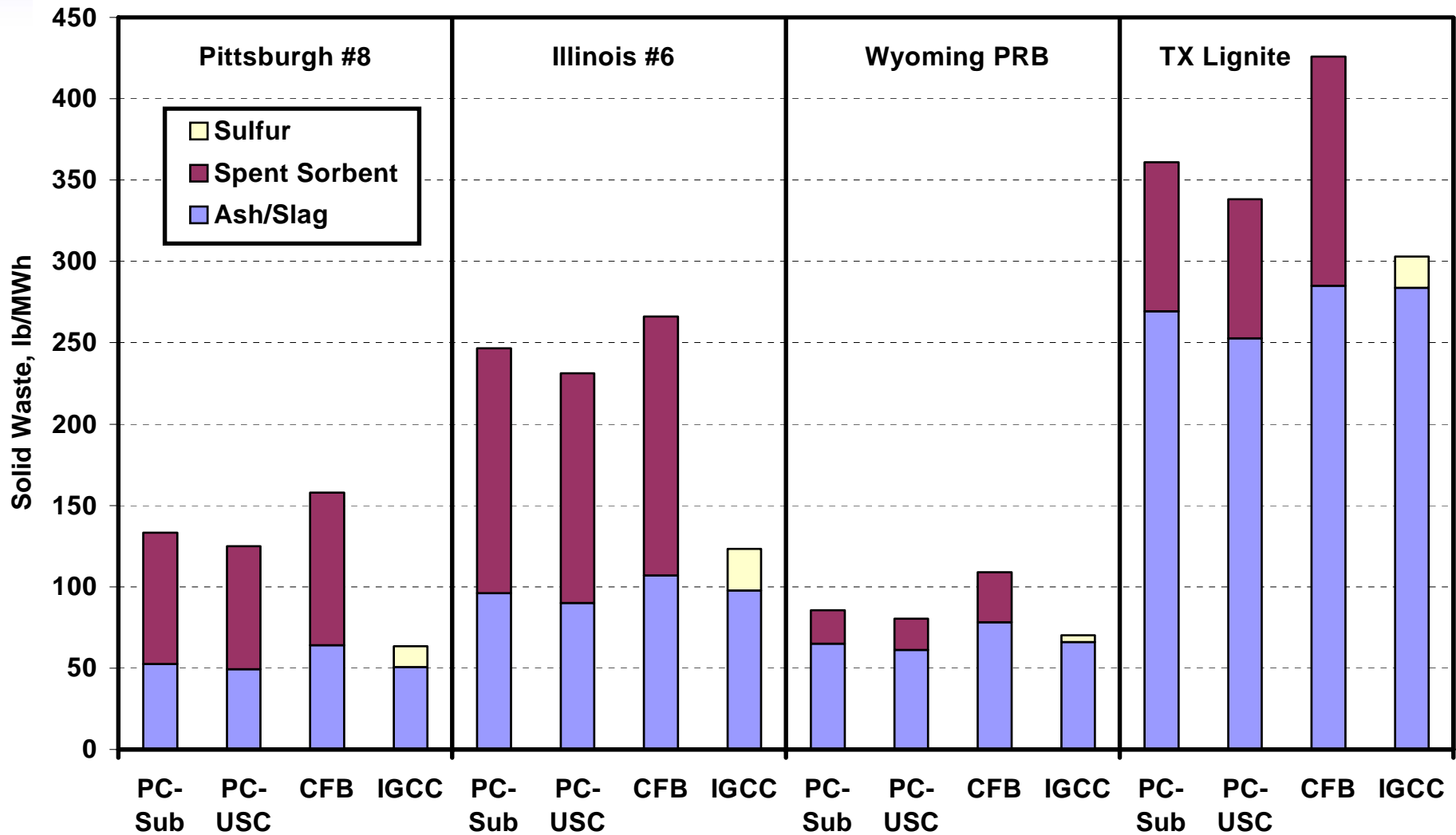
EPA, National Air Quality and Emissions Trends Report, 1999 (March 2001)  
DOE, EIA Annual Energy Review

# Emissions Comparison with Older Coal Plants and Federal Standards

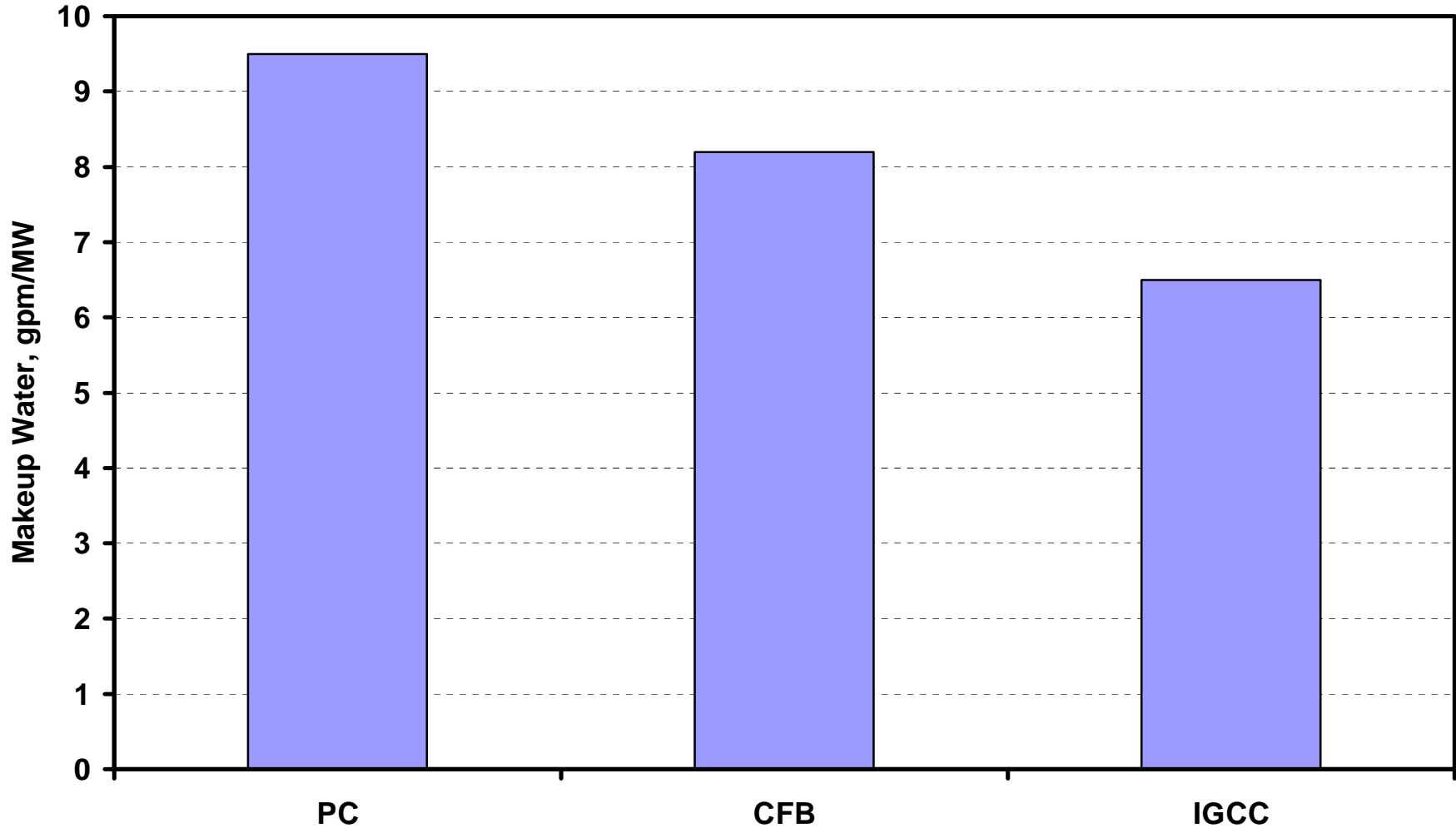


# Solid Waste Comparison

(Based on nominal 500 MW plant size)

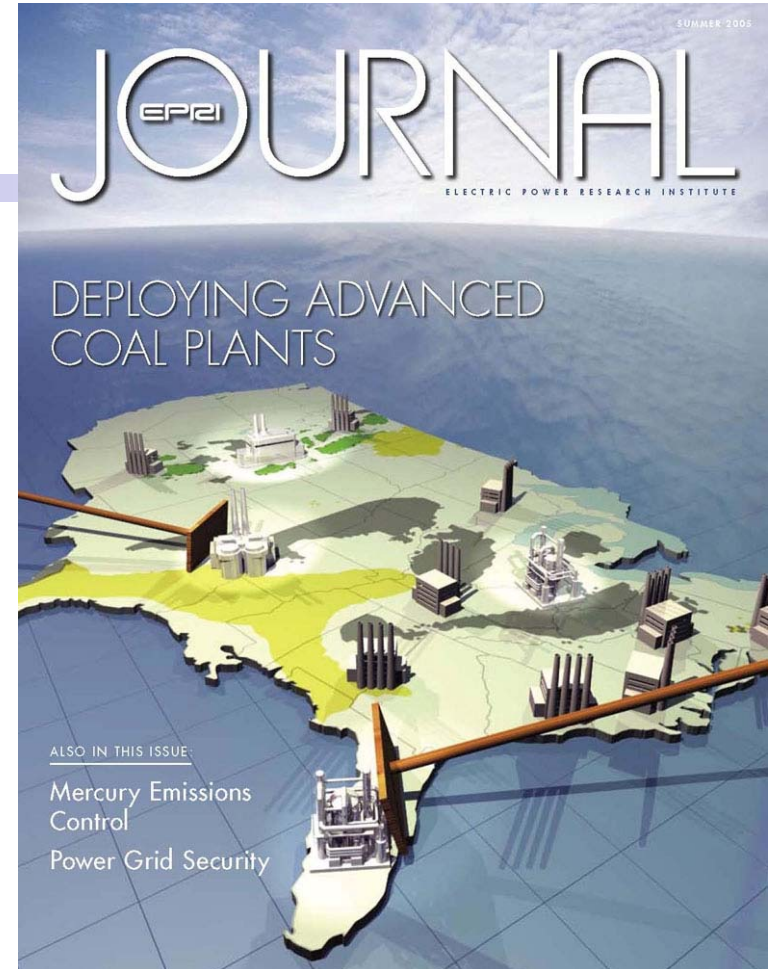


# Makeup Water Comparison



# CoalFleet for Tomorrow an EPRI Program

- An Industry Initiative to Accelerate the Deployment of Advanced Coal-Based Power Plants
- Billion Dollar Plus Investments in an Emission-Limited World
- Risks and questions
  - Is it reliable?
  - What designs are best?
  - How can it be licensed?
  - How much will the new technology cost?
  - How can it be financed?
  - How can it be made CO<sub>2</sub> capture ready?

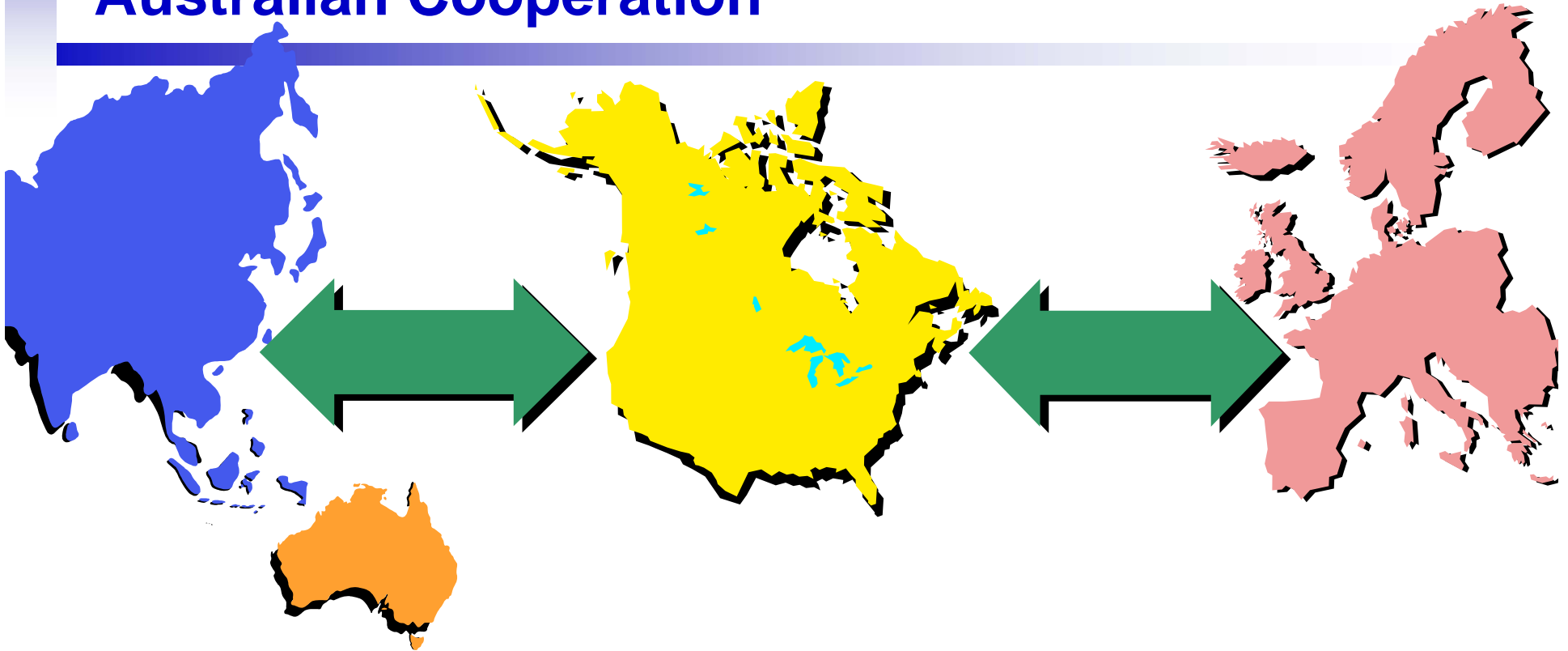


**Summer 2005 EPRI  
Journal article  
available at  
[www.EPRI.COM](http://www.EPRI.COM)**

# CoalFleet Roster (Nov 11, 2005)

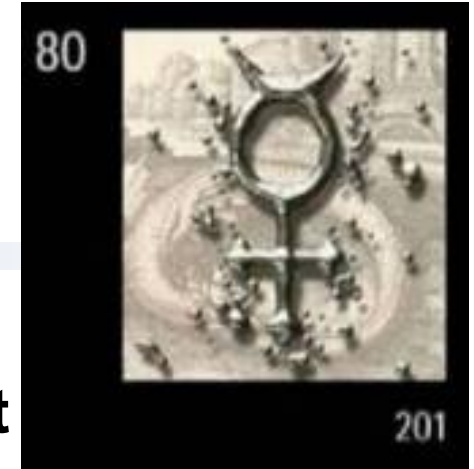
- AES
- Alstom Power
- Ameren
- American Electric Power
- Associated Electric
- Austin Energy
- Babcock & Wilcox
- Bechtel Corp
- Black & Veatch
- Calpine
- Cinergy
- City Public Service, San Antonio
- ConocoPhillips Technology
- CSX Corporation
- Doosan Heavy Industries
- Duke Energy
- Dynegy
- E.ON AG
- E.ON UK
- First Energy
- Fluor Corporation
- GE Energy
- Great River Energy
- Hitachi
- KBR
- LG&E Energy
- Minnesota Power
- Mitsubishi Heavy Industries
- New York Power Authority
- PacifiCorp
- Portland General Electric
- Progress Energy
- Public Service Co. New Mexico
- Salt River Project
- Seminole Electric
- Shell
- Siemens
- Southern California Edison
- Southern Company
- Stanwell Corporation
- Tri-State G&T
- TVA
- TXU
- U.S. DOE
- Wisconsin Public Service

# CoalFleet Encourages US, European, Asian and Australian Cooperation



- VGB-led consortium developing and deploying materials and designs for USC plants (Emax)
- Australian consortium (Stanwell, et al.) developing an IGCC demonstration project with CO<sub>2</sub> capture

# What About Mercury Controls?



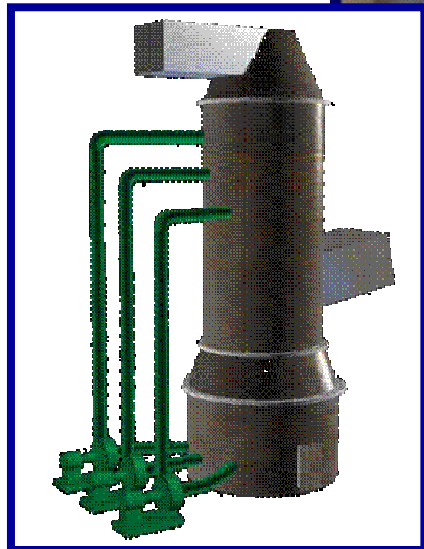
- **Mercury should be able to be controlled cost effectively with IGCC via adding a special carbon-bed filter based on commercial gasification experience**
- **There is are very large research , development and demonstration programs ongoing on the control of conventional combustion with dozens of field tests**
- **We Energy TOXECON™ demonstration under construction**
- **Additional information is available in the EPRI Journal – Summer edition 2005 available at [www.epri.com](http://www.epri.com)**

# Mercury Control Technology Overview for Pulverized Coal



- **Major advances, but questions remain**
  - **Promising results with**
    - SCR/FGD co-benefits (E. Bit)
    - ECO® (E. Bit, so far); an emerging option for plants scheduled for SCR/FGD
    - Newer sorbents
  - **Key technical questions**
    - Sustainable reductions
    - Extrapolation of ~30 tests to U.S. boiler population
    - Long-term impacts on plant operation
    - Cost-effective solutions for small/old plants
- **When “commercially available?”**
  - **Depends on consistency of DOE field test results (2004 – 2009)**
    - Do they replicate among similar plants?
    - Can we predict/prevent the “surprises”?

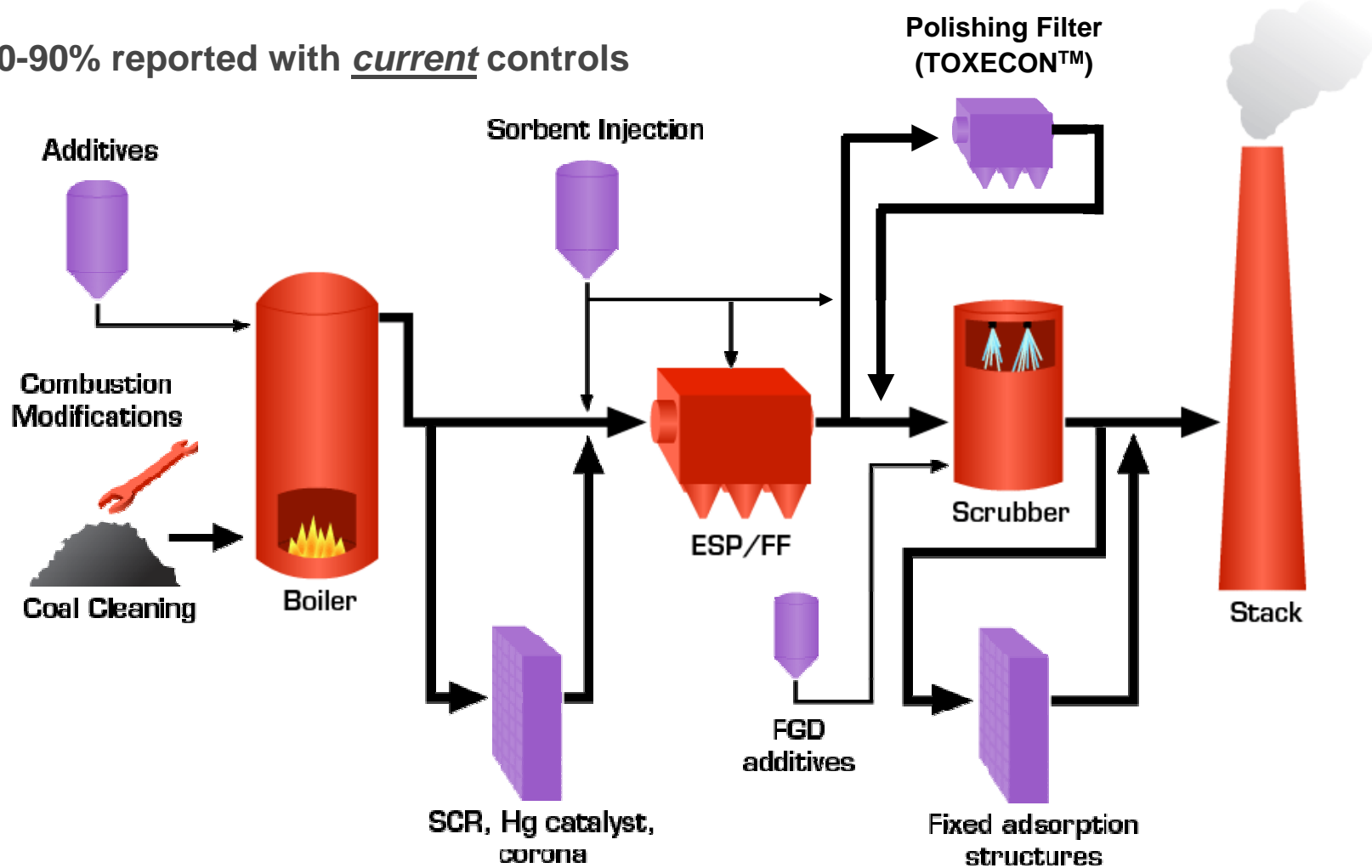
# Industry/DOE/EPRI Investing Heavily in Development & Demonstration – 2005 Tests



- **> 20 sites**
  - **Many with DOE, some just EPRI + member**
- **All coal types, some blends**
- **Wide range of plant configurations**
- **Many different mercury controls**
- **EPRI provides integrated analysis – “What does it all mean for you?”**

# Power Plant Mercury Control Options

10-90% reported with current controls

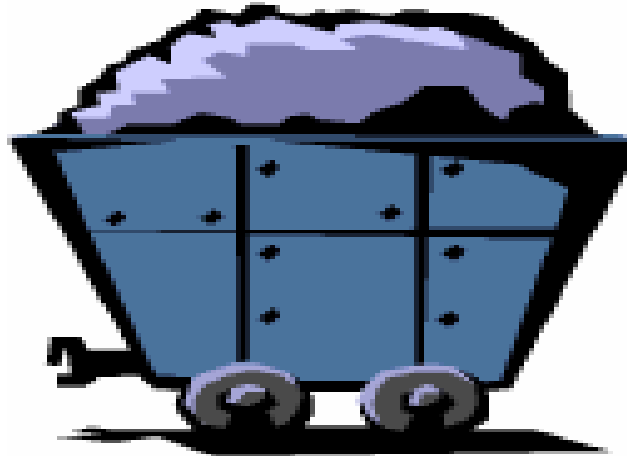


# Summary – Mercury Control Status



- **There's hope**
  - SCR/FGD co-benefits > 80% seem plausible for E. Bit; is there a ppm floor?
  - Chemically-treated sorbents seem to provide high removals with western fuels
  - Will have substantial data base by early/mid-07
- **There are also major uncertainties**
  - Sustainable reductions under normal plant dispatch and operations (no specialized test crews)
  - Validity of extrapolation from a few sites of several coal/device configurations to diverse fleet
  - Long-term impacts on plant operation, secondary emissions, ash
  - **“Commercial availability” – i.e., when can Hg controls first be procured with confidence – depends on consistency of ongoing field tests + some long-term experience**

# *Questions?*



# Background Slides for Combustion Options

- Un-presented PowerPoint slides follow

# “Cleaning” a Pulverized Coal Plant



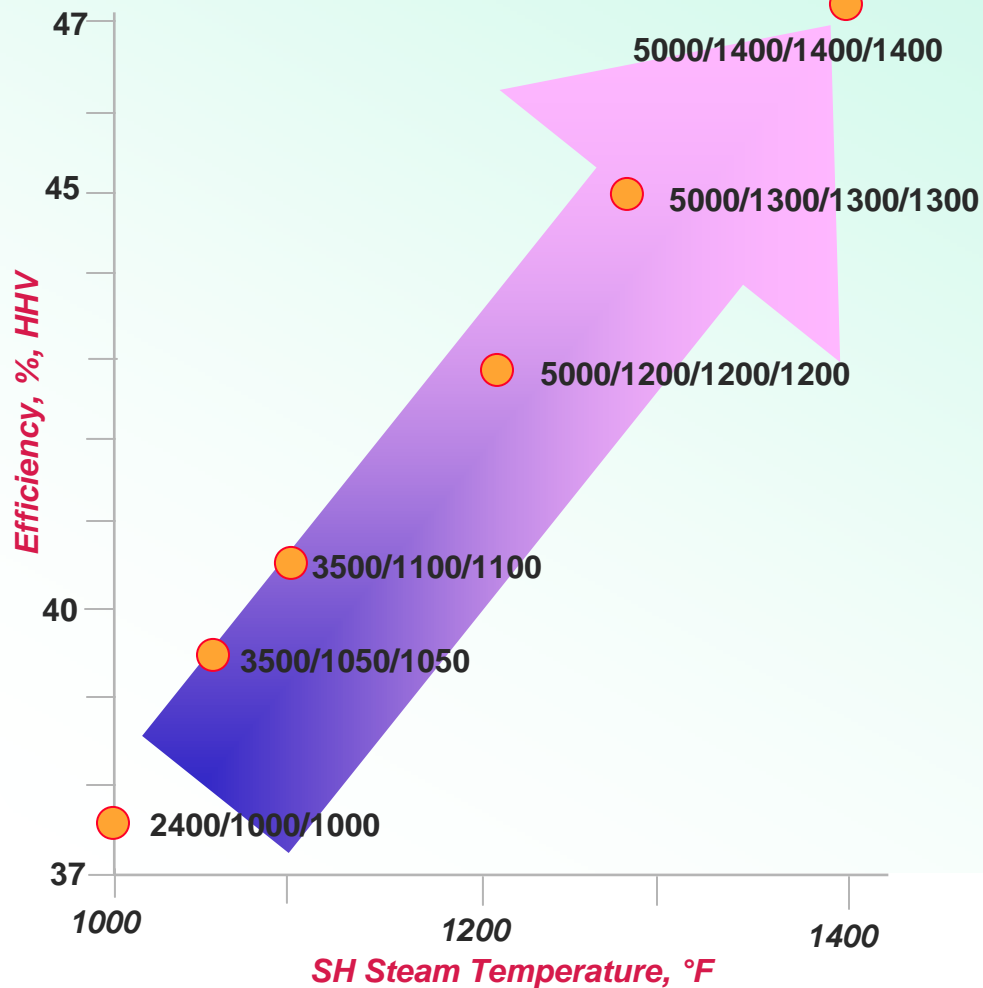
Fuel (low S)    Burners (Low NO<sub>x</sub>)    Catalyst for NO<sub>x</sub>    Precipitator (Particulate)    Scrubber (SO<sub>2</sub>)

- Fuel selection is critical for sulfur and other contaminants
- Burners on new units emit less NO<sub>x</sub> via controlling fuel air mixing and temperature
- Billions being invested on selective catalytic reduction (SCR...NO<sub>x</sub> + NH<sub>3</sub> going to N<sub>2</sub> + H<sub>2</sub>O)—very low NO<sub>x</sub> possible from combustion and SCR
- High-efficiency (>99.5%) electrostatic precipitators (ESP) or fabric filters (baghouses) remove dust (fly ash)
- Flue gas desulfurization (scrubbers) react limestone with SO<sub>2</sub> giving gypsum; new designs offer >95% removal, 99% is possible

# Subcritical vs. Supercritical and Ultra-Supercritical Coal

- These are all terms for variations of boilers that make steam to run a steam turbine
- Supercritical steam is above the supercritical point of water (3208 psi). Ultra-supercritical is jargon for higher efficiency steam above  $\sim 1050^{\circ}\text{F}$
- Hundreds of supercritical boilers exist, most are larger units
- In the U.S., low fuel price has made the boiler choice less uniform; in China, Japan, and Europe, supercritical and ultrasupercritical designs dominate new units
- Newest units are  $>40\%$  efficient and have low emissions vs. fleet average of  $\sim 32\%$  for existing coal

# Ultrasupercritical PC Plants



- **European and Japanese USC PC Experience Base**

- 600°C (1112°F) high availability, good load following
- Baseline S-O-A for a new coal-fired plant

- **In Development:**

- European Advanced 700°C PC (1292°F)
- *DOE EIO/EPRI 760°C (1400°F) boiler materials program*

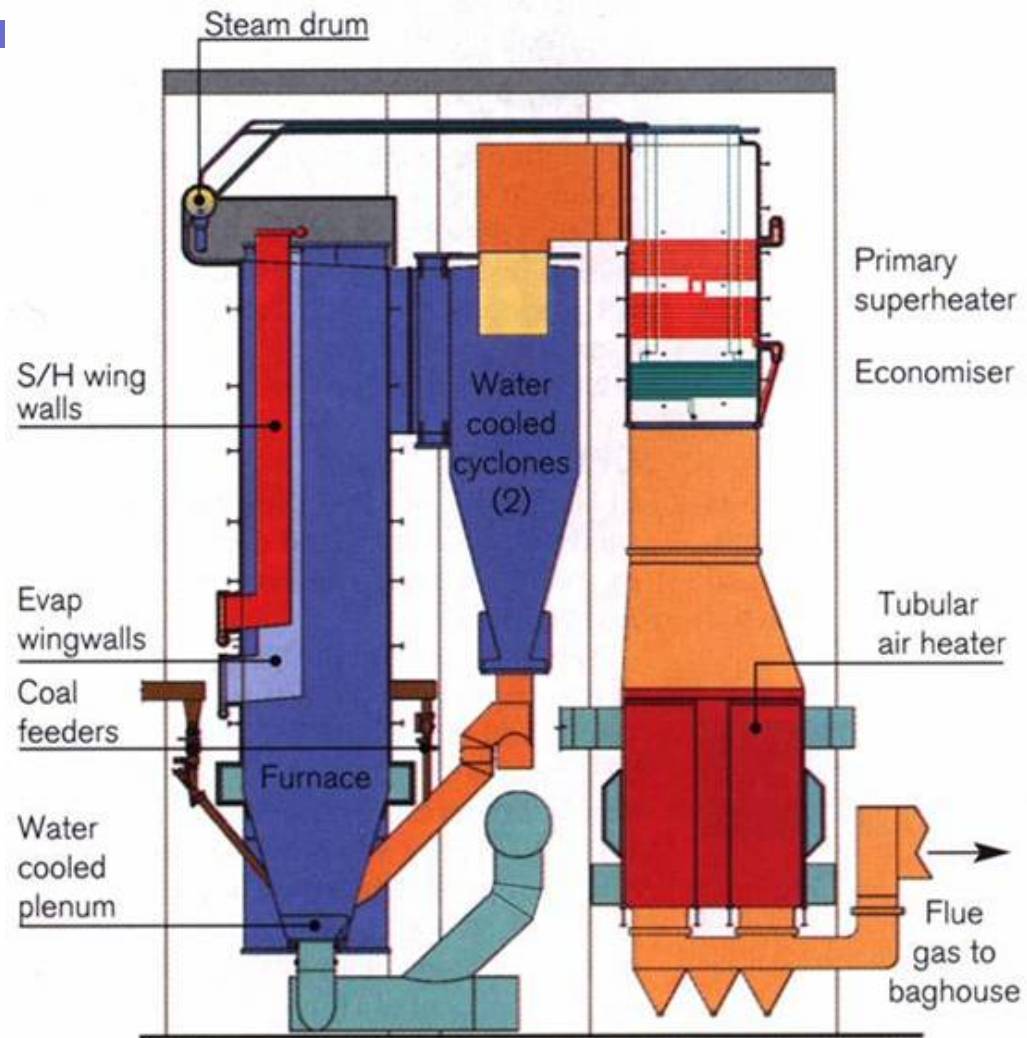
# PC Plants Status, Markets, and Vendors

- 310 GW in U.S.; mostly built 25–50 years ago. Majority are subcritical, but there are 150 supercritical plants at steam temperatures  $<1050^{\circ}\text{F}$  and up to 1300 MW in size.
- For new U.S. PC plants, subcritical or modest supercritical designs are being selected
- Uncertainty and concern about potential regulation of  $\text{CO}_2$
- Main vendors in U.S. (and worldwide) are Babcock & Wilcox, Alstom, Foster Wheeler, Hitachi, Babcock Hitachi, Mitsubishi, IHI, and Mitsui Babcock

# Atmospheric Fluidized-Bed Combustion (AFBC): Comparison to PC

- Combustion occurs at 1600°F, well below the 2500°F of a PC boiler
  - Reduced inherent NO<sub>x</sub>
  - Less ash deposition and fouling
  - In-situ SO<sub>2</sub> capture with limestone
  - Able to handle a wider range of fuels
  - Fuel size up to ½ inch
- Many similarities to PC boiler
  - Water-wall construction, convection pass, air heaters, baghouse/ESP, ash handling equipment

# Circulating AFBC Installed at Marion, Illinois



115 MW net – Photo Source Alstom

# FBC Plant Status, Markets, and Vendors

- Circulating FBC dominates. Currently most look at a maximum size of 300 MW and subcritical steam. First 440-MW supercritical unit ordered for Poland.
- ~10 GW installed in U.S. - Market niche for poor quality and variable quality coals, petroleum coke, and biomass/“opportunity fuels”
- Pressurized FBC developed up to 350 MW in Japan, but does not compete with 1-GW PC plants. Future commercial application unlikely in EPRI’s view
- Main vendors: Alstom (U.S., Europe), Foster Wheeler (U.S., Finland), Kvaerner (U.S., Finland), and Lurgi (Germany)