How Clean Is Clean, At What Cost, and When?

Committee Workshop on
Clean Coal Technology Status and Potential Issues
for California Energy Policy:
2005 Integrated Energy Policy Report (IEPR)
California Energy Commission
Sacramento, CA
August 17, 2005

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Supported by

Carnegie Mellon University
Climate Decision Making Center
http://cdmc.epp.cmu.edu/
NSF SES-034578

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Outline

- Pollutants and control technologies
  - Solid waste
  - Particulate matter (PM)
  - Sulfur dioxide (SO_2)
  - Nitrogen oxides (NO_X)
  - Mercury (Hg)
  - Carbon dioxide (CO_2)
- Costs
- Innovation and policy

Key points

- Affordable, coal-fired electricity can be compatible with environmental protection, as long as suitable policies are in place.

- Technological innovation and adoption for environmental protection requires public policy.

- Public policies exist for all pollutants except carbon dioxide.

Solid Waste

- Coal combustion products (CCP) can sometimes be marketed
  - Europe: >90%
  - U.S. ~1/3, both ash and gypsum

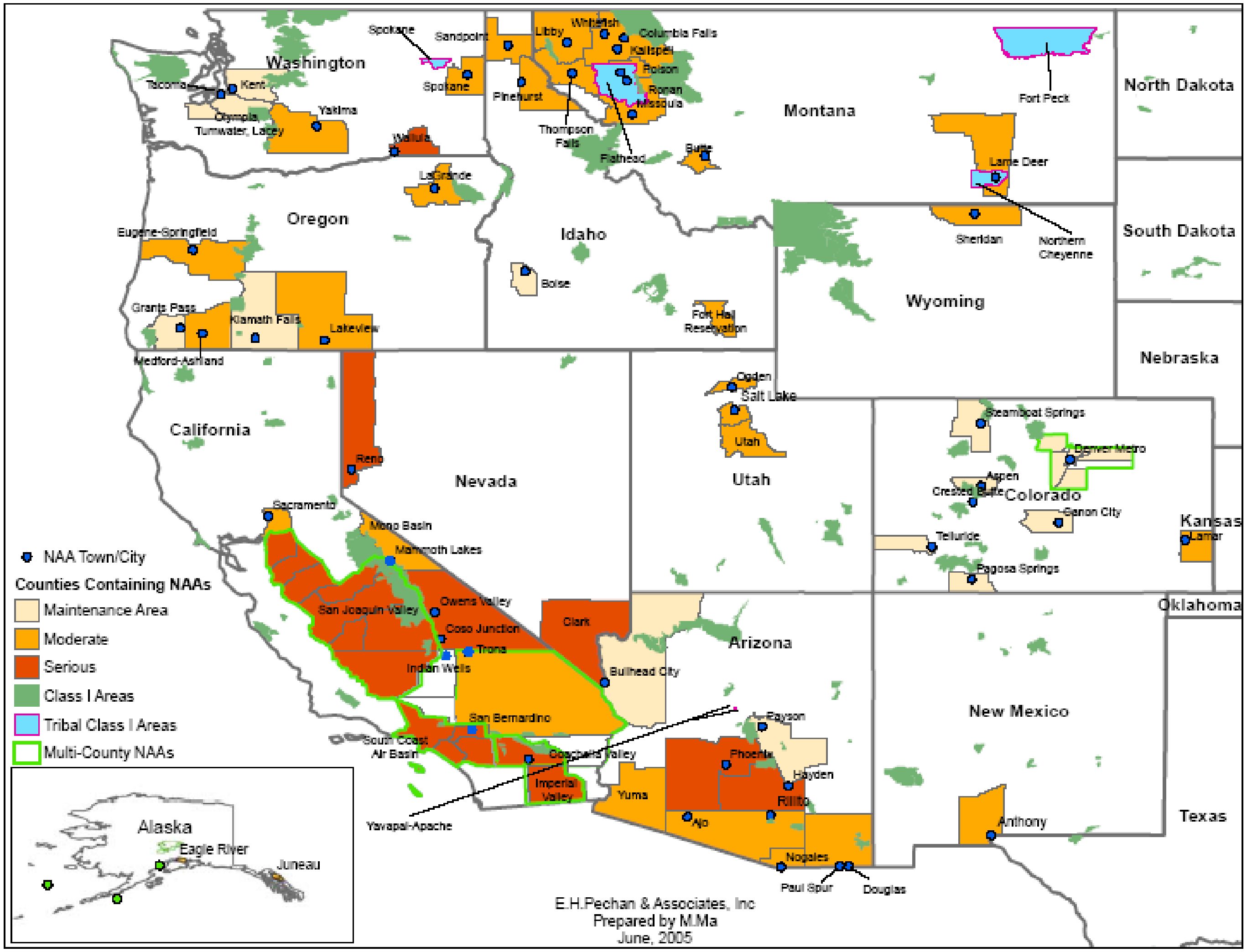
- Ammonia from air pollution control technologies can make CCP unsalable and difficult to handle

- Surface disposal of solid waste is somewhat expensive, but not significantly constrained

Smoke and coarse particles (PM10)

- Why we care:
  - Health
  - Visibility
- How big a problem:
  - moderate (?)

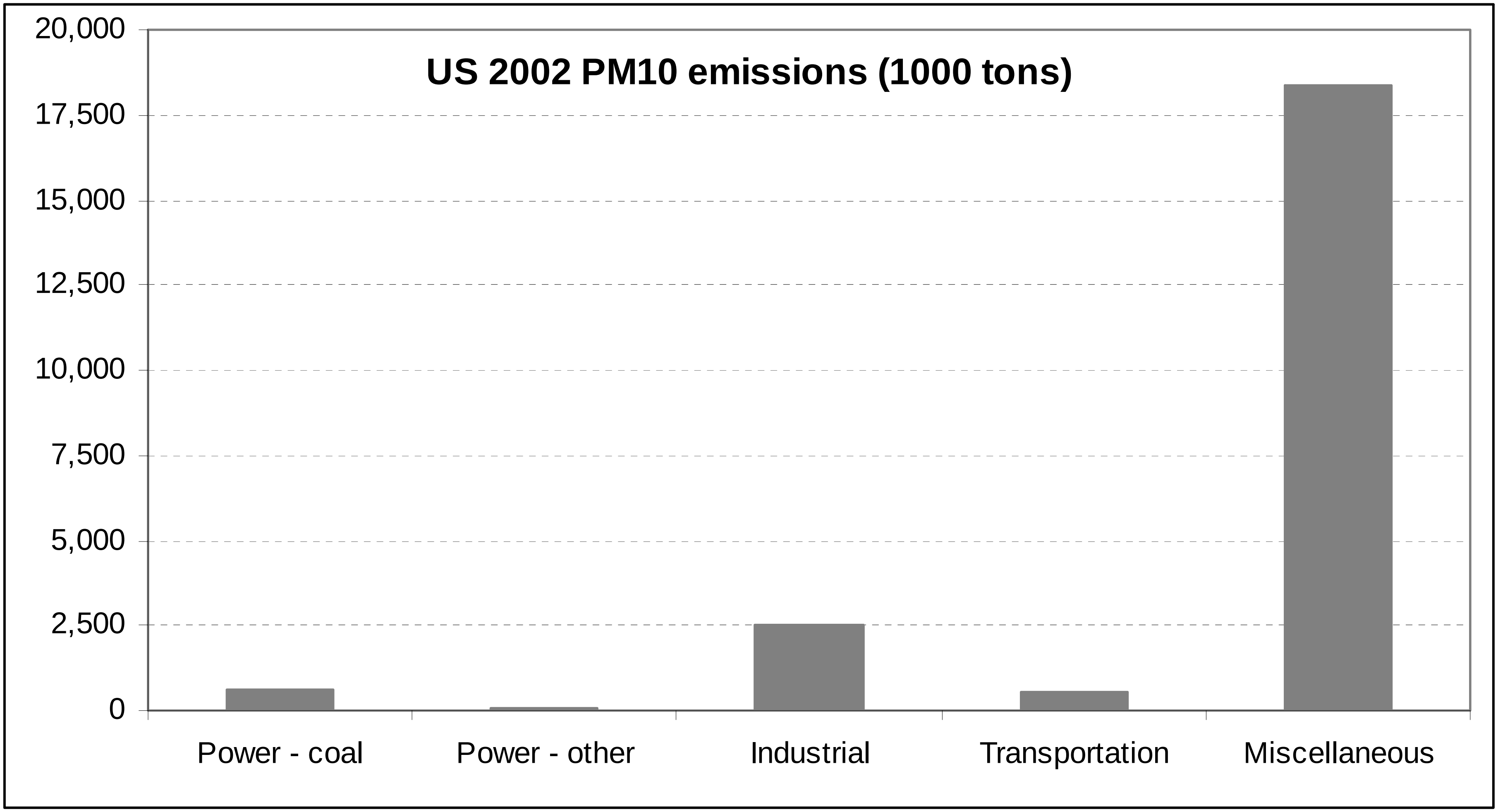
WRAP PM10 non-attainment and maintenance areas



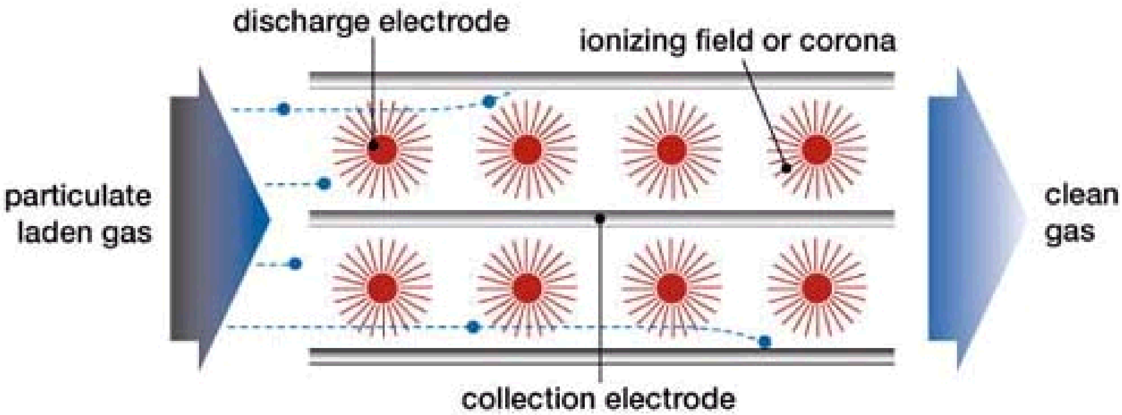
Source: Western Regional Air Partnership (2005a)

PM10 – Role of coal plants

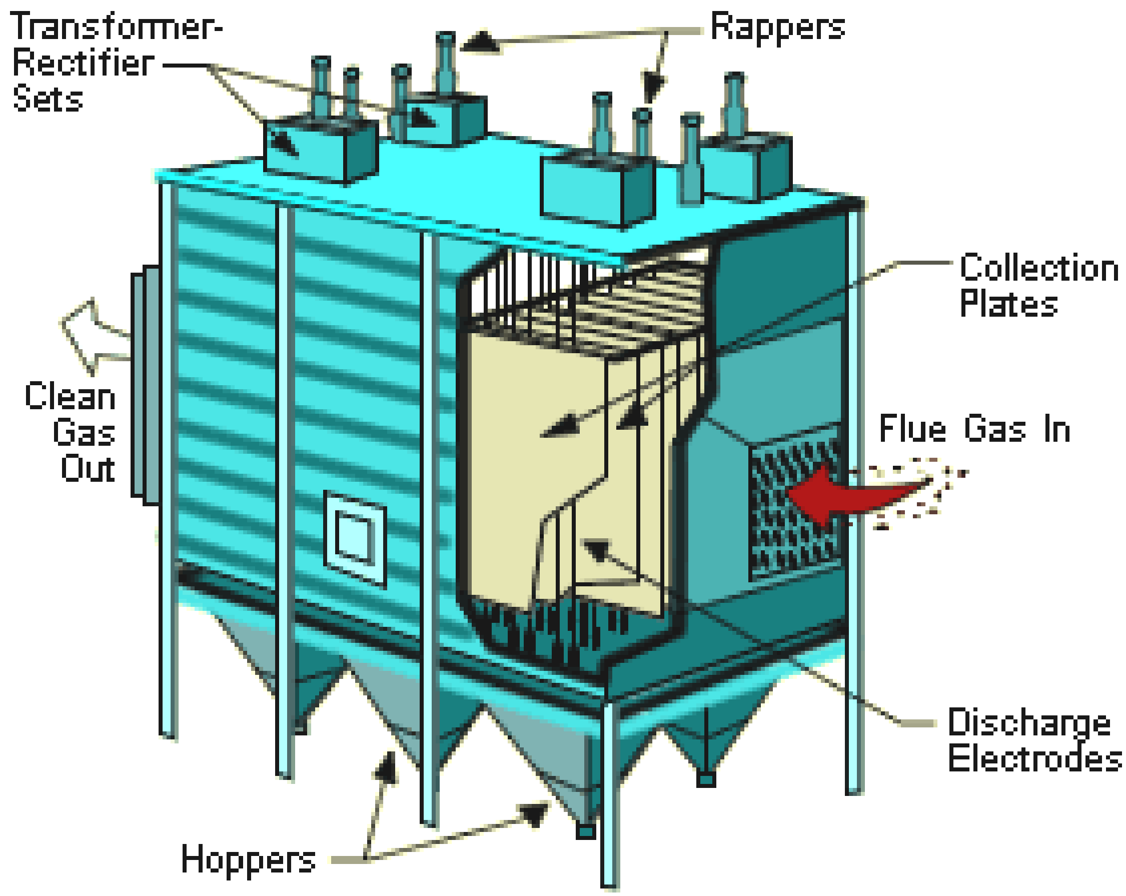
- >99% of PM10 emissions are captured at the power plant



Source: EPA (2005)

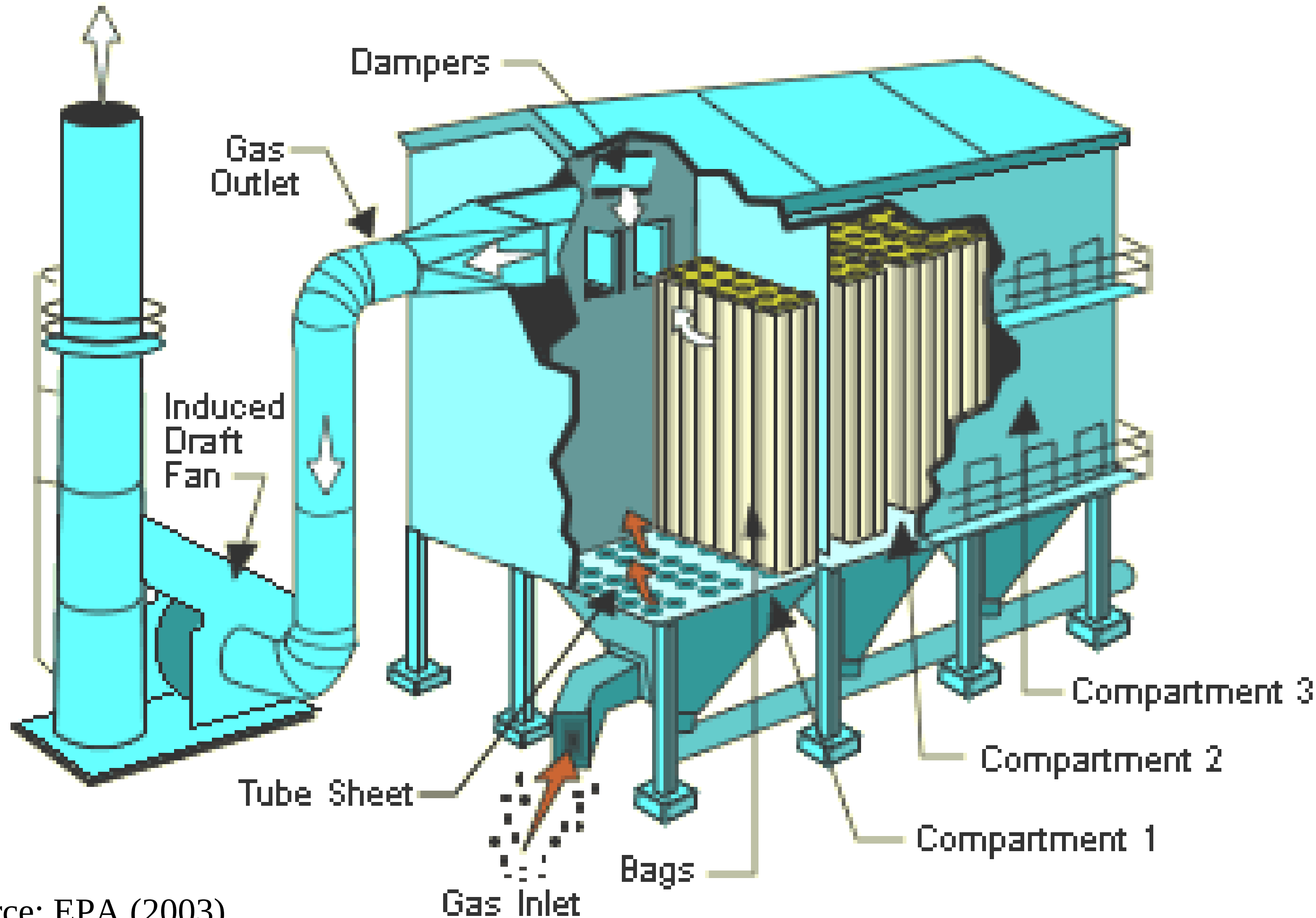


PM Control – Electrostatic Precipitators



Source: EPA (2003)

PM Control – Fabric Filter



Source: EPA (2003)

One key difference

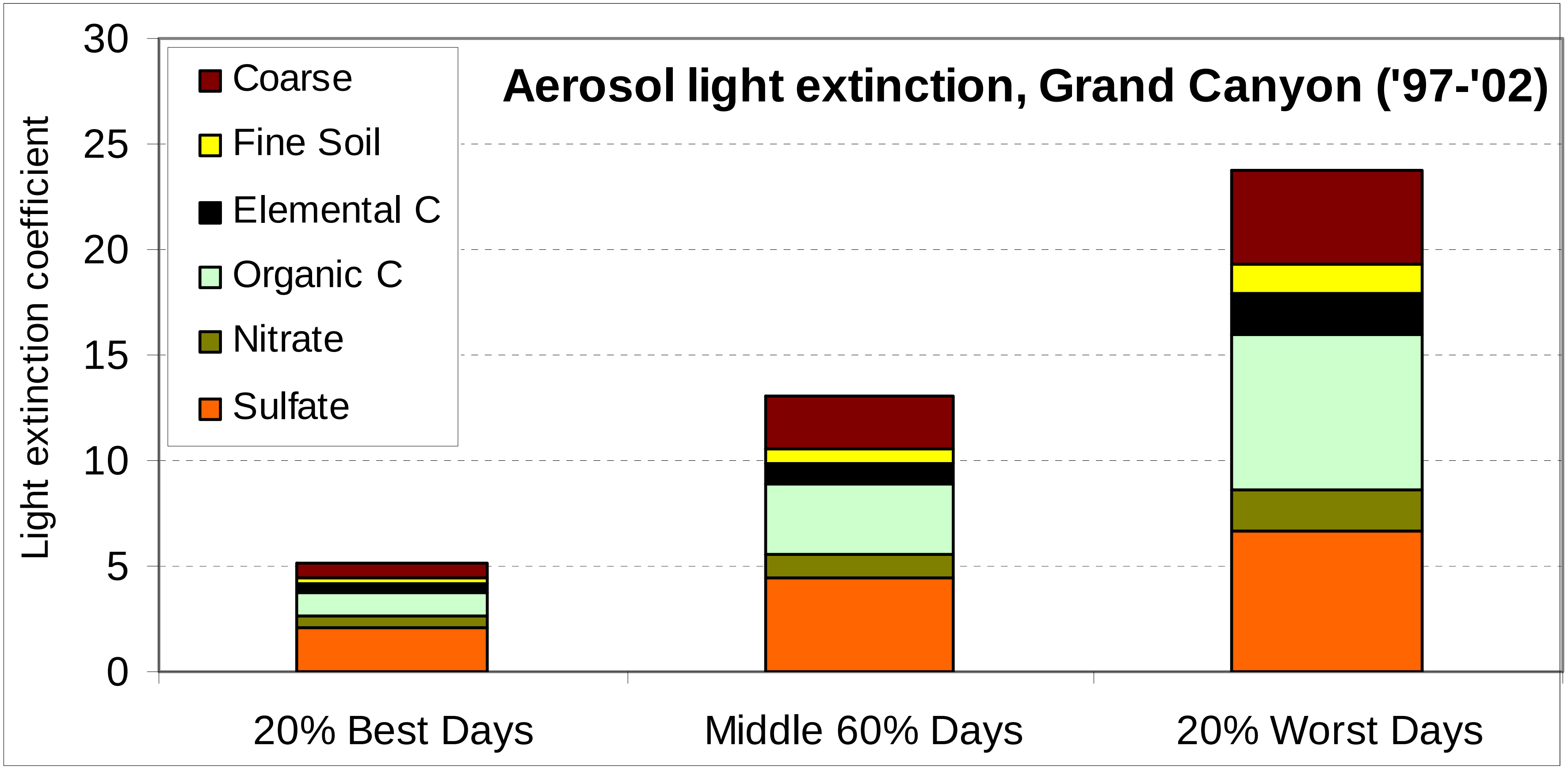
- Electrostatic Precipitator
  - Poor contact between particles and exhaust gas

- Fabric Filters
  - Repeated contact between particles and exhaust gas

- We will see why this matters shortly

SO_2 Environmental Effects

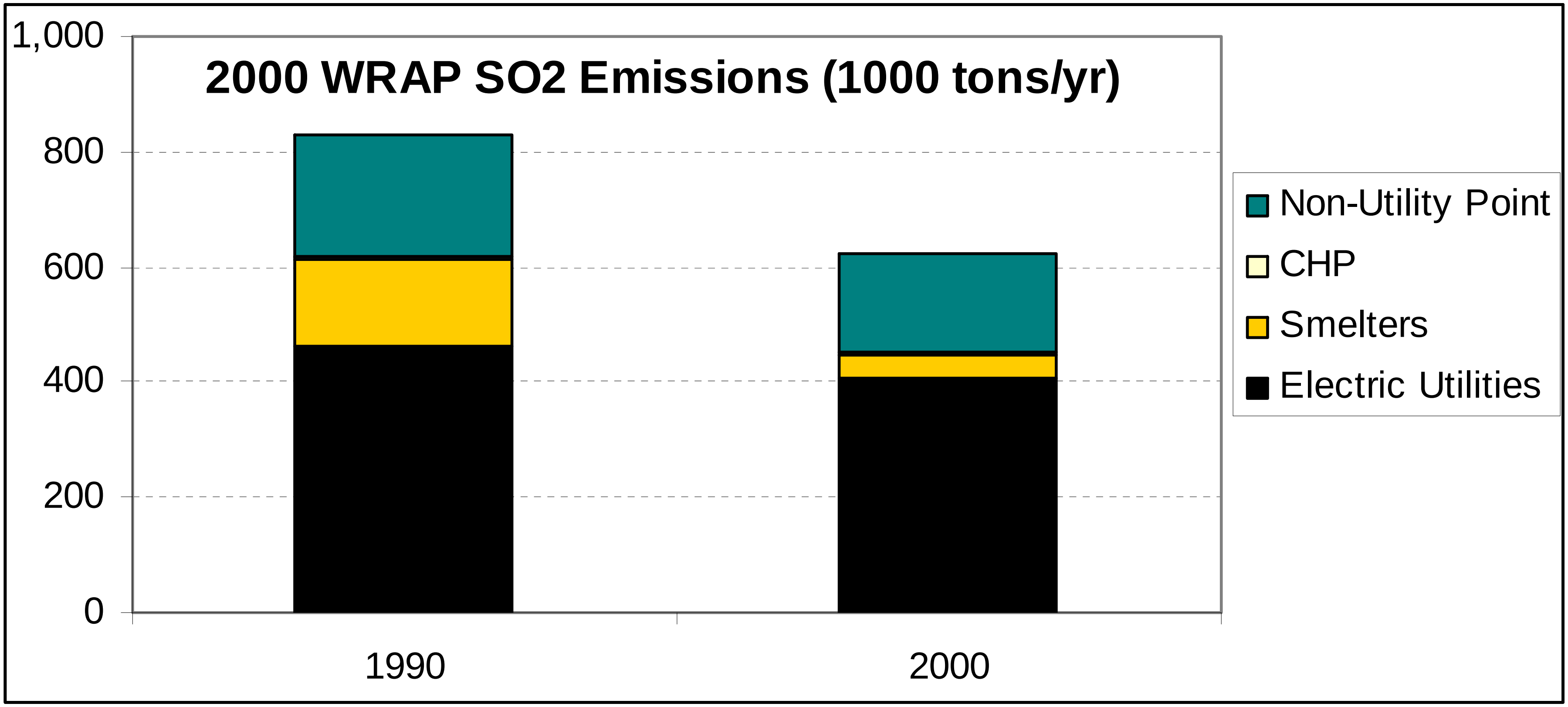
- Why we care: health, acidification, haze, global warming
- How big a problem?



Source: Causes of Haze Assessment (2005)

SO_2 – Role of coal plants

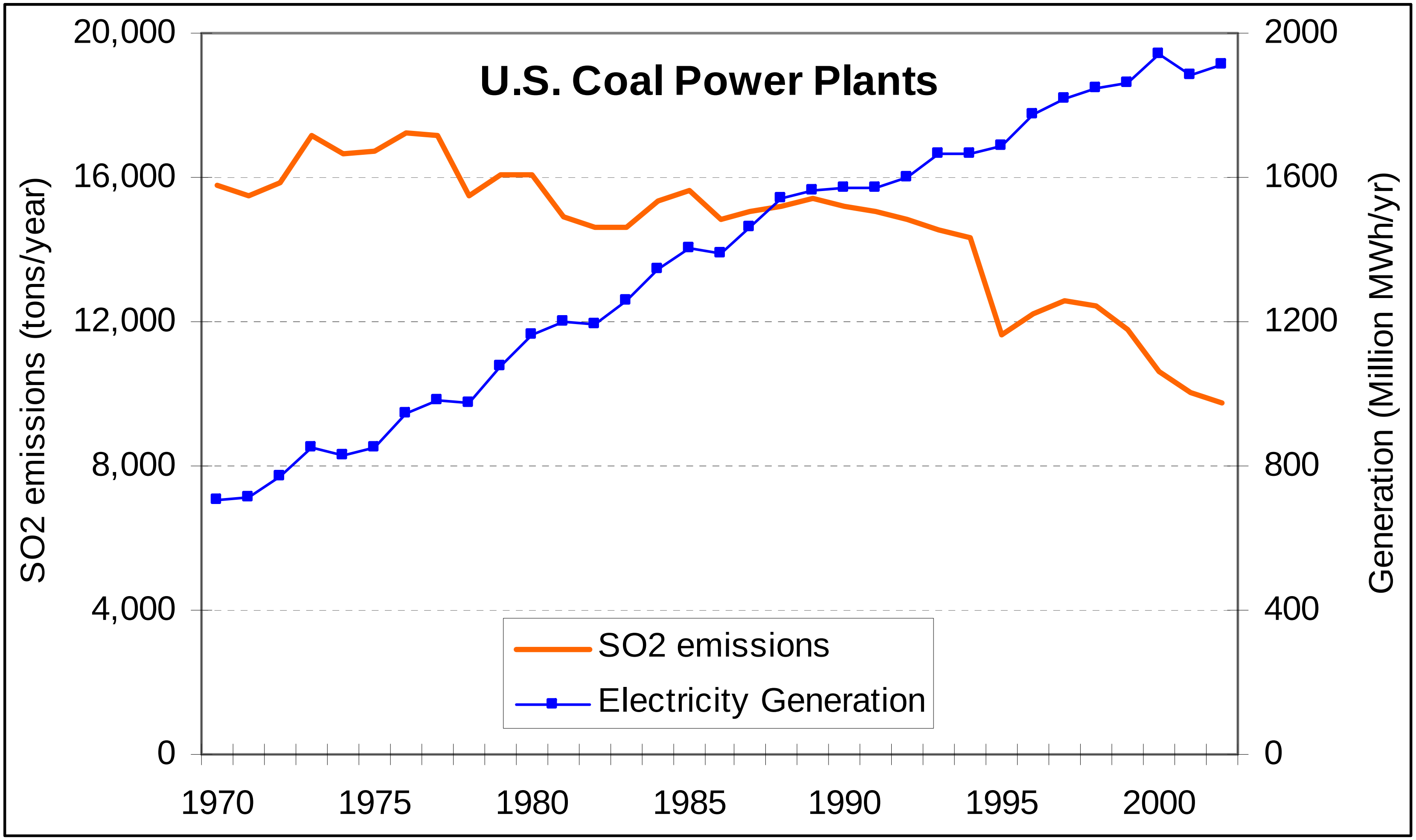
- How much do coal power plants contribute to SO_2 emissions?
  - Globally electric power plants emit >1/3 of all anthropogenic SO_2
  - Regionally, it's twice that:



Source: WRAP (2005c)

SO_2 - Experience

- What is the experience of controlling SO2 from coal power plants?
  - 75% reduction in <u>emissions rate</u> since 1970



Source: EPA *National Emission Inventory* and EIA *Annual Energy Review*

SO_2 - Technologies

- Most of the emission reductions due to lower emission rates at existing units, *not* replacement of older, dirty units with new, clean technologies.
- Fuel switching to low-sulfur western coal was important, especially in the beginning of the acid rain program.
  - Rail deregulation
  - Boiler technology

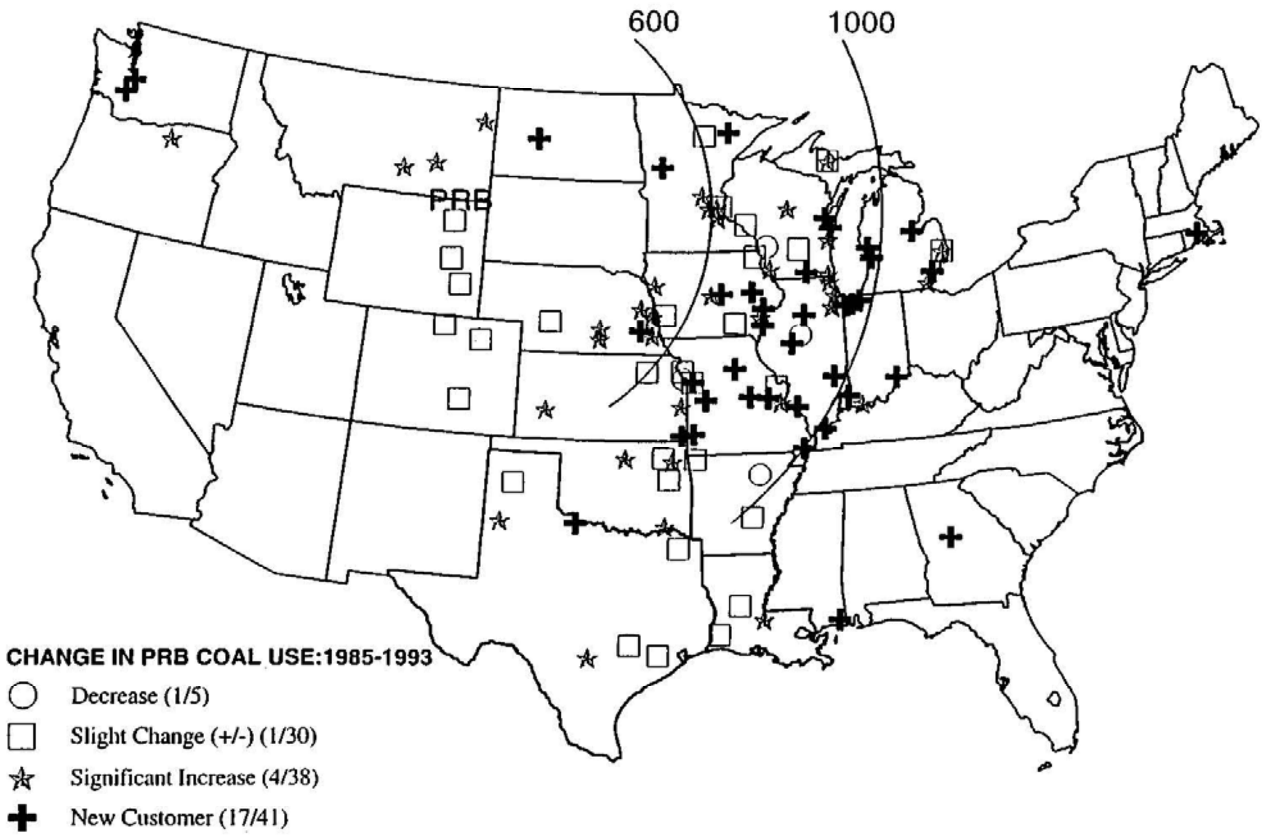


FIG. 1. Power plants burning PRB coal: 1985–1993.

Source: Ellerman and Montero (1998)

SO_2 - Technologies

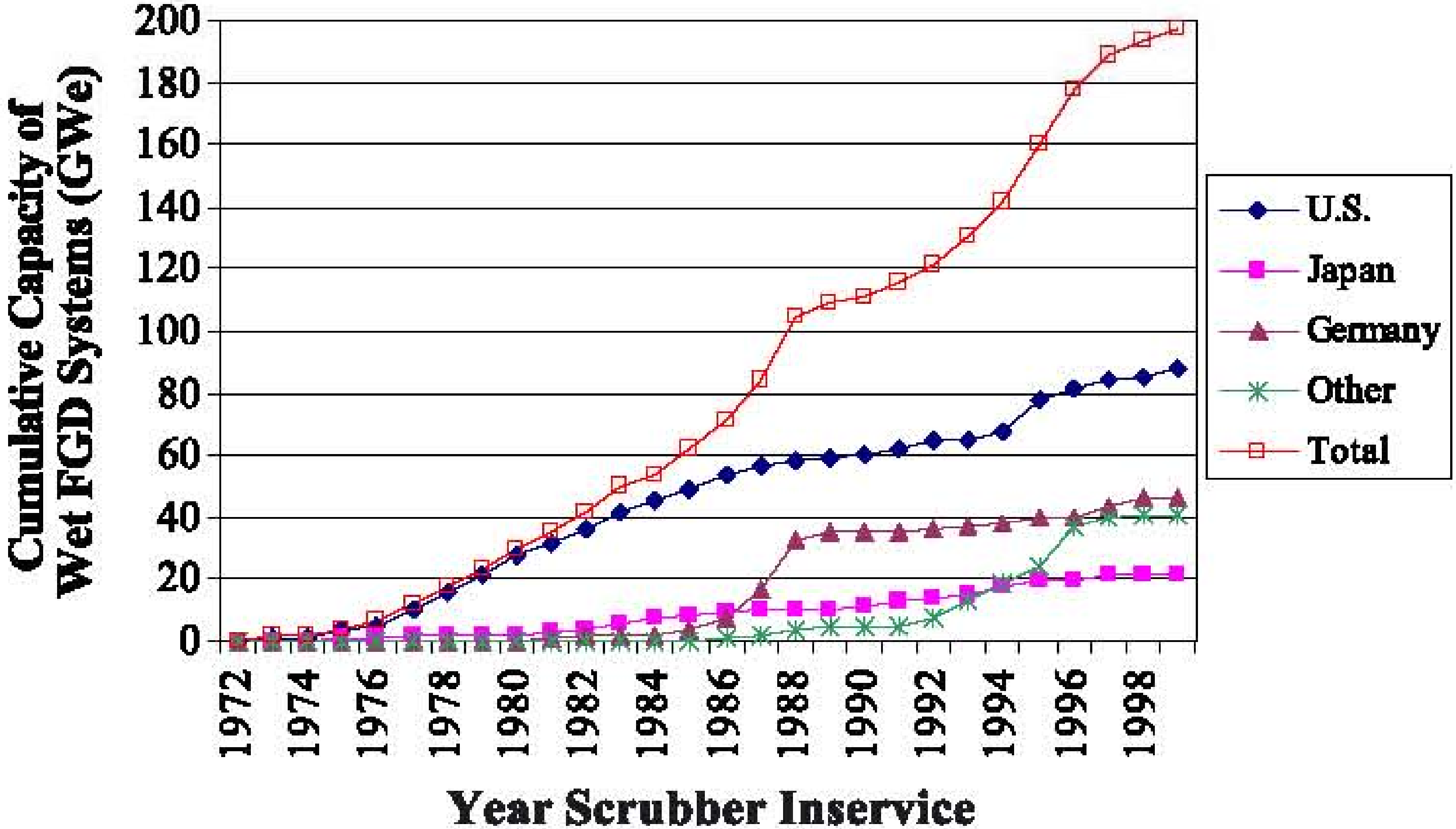
- Increasing use of limestone scrubber to reduce SO_2 emissions

SO_2 + $CaCO_3$ + 1/2O_2 + 2H_2O -> CaSO4.2H_2O + CO_2

SO_2 scrubber for a 150MW unit at Cherokee Station in Denver

SO2 Scrubbers – Installed Capacity

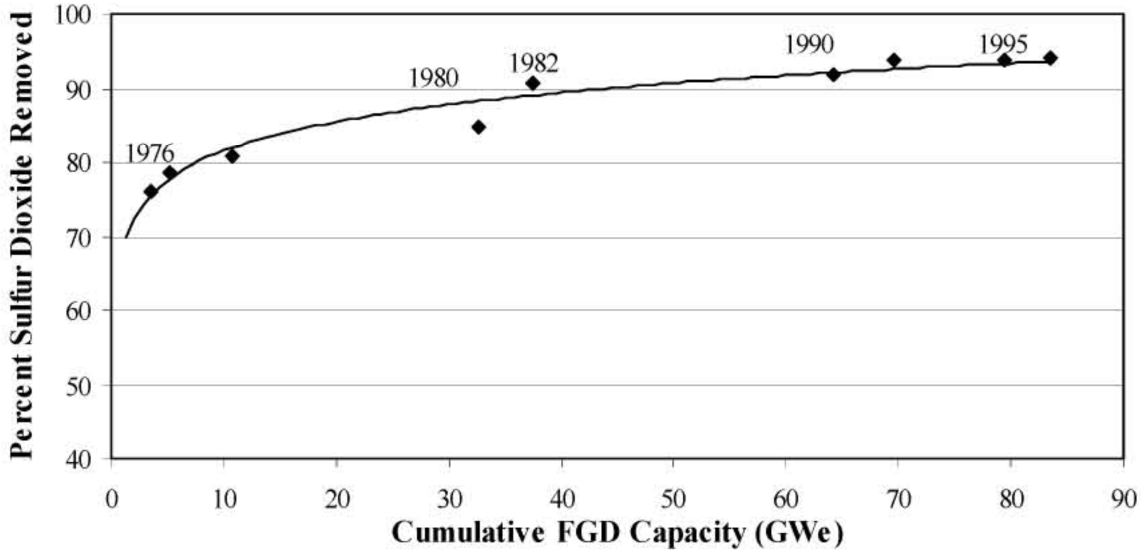
- Steady increase in capacity



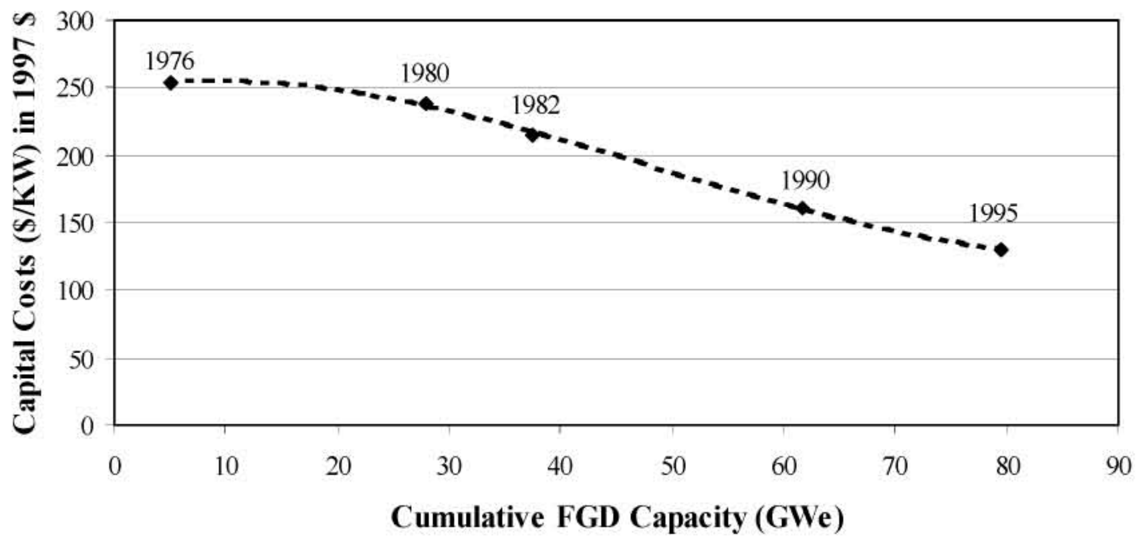
Source: Taylor et al. (2005)

SO_2 Scrubbers – Induced Innovation

Improvements in SO2 removal efficiency as a function of installed US FGD capacity



Reductions in scrubber capital costs as a function of installed US FGD capacity



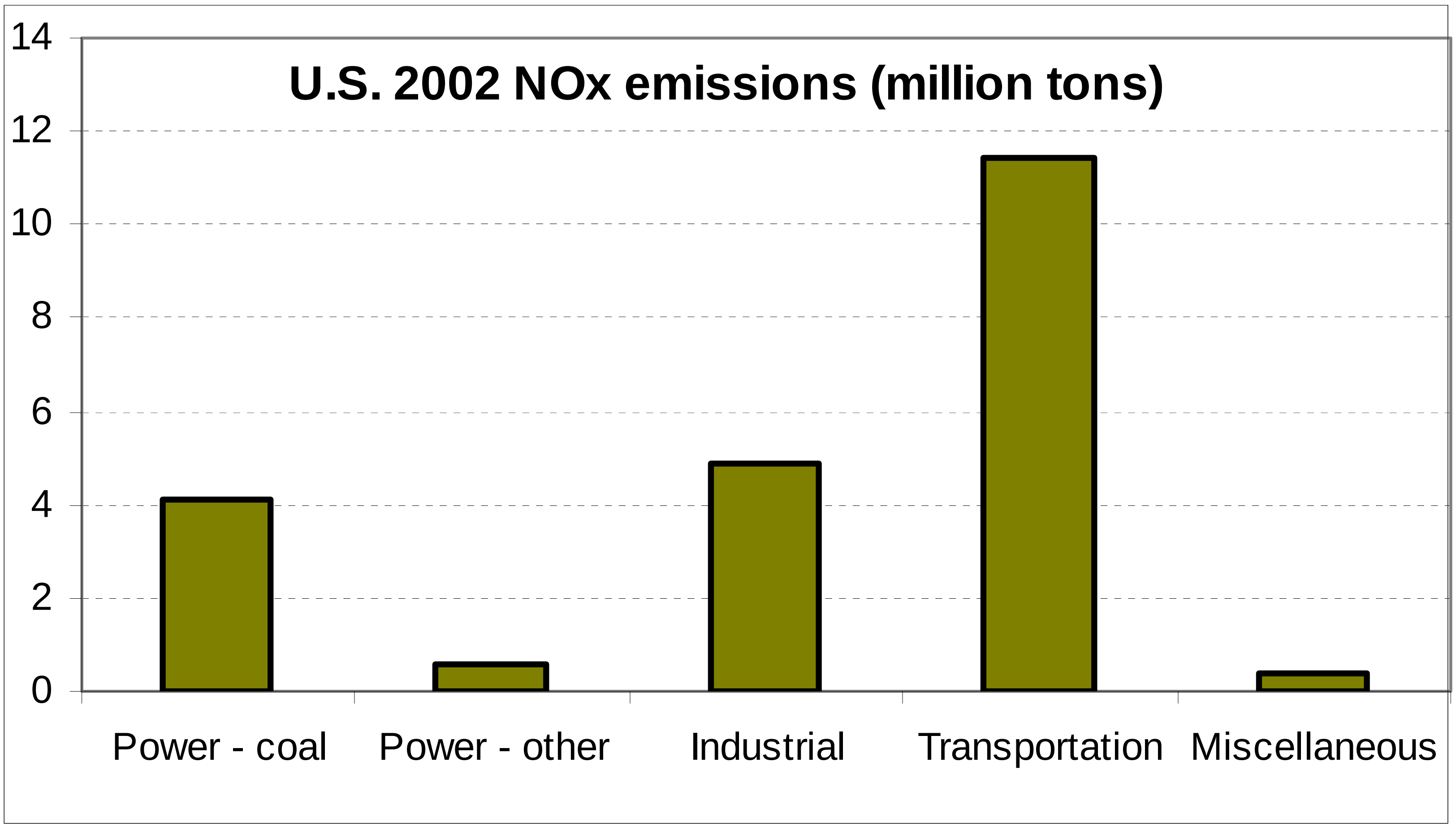
Source: Taylor et al. (2005)

Induced Innovation

- Innovation is costly and entails risk
  - Firms are typically compensated by increased market share or higher revenues for new products
- The environment is a public good or externality – that is, it is <u>not</u> part of the purchasing decisions of consumers.
  - Usual compensation mechanisms for innovation don’t work
- Therefore, government must play a role
  - Patent protection, direct R&D expenditures, and demonstration projects play a role
  - Regulation that require new technologies serves a vital function
    - Emphasis on cost control
    - Creates operating experience – learning by doing
    - Post-adoption innovation
  - Uncertainty weakens policy drivers of innovation

NO_X – Role of coal power plants

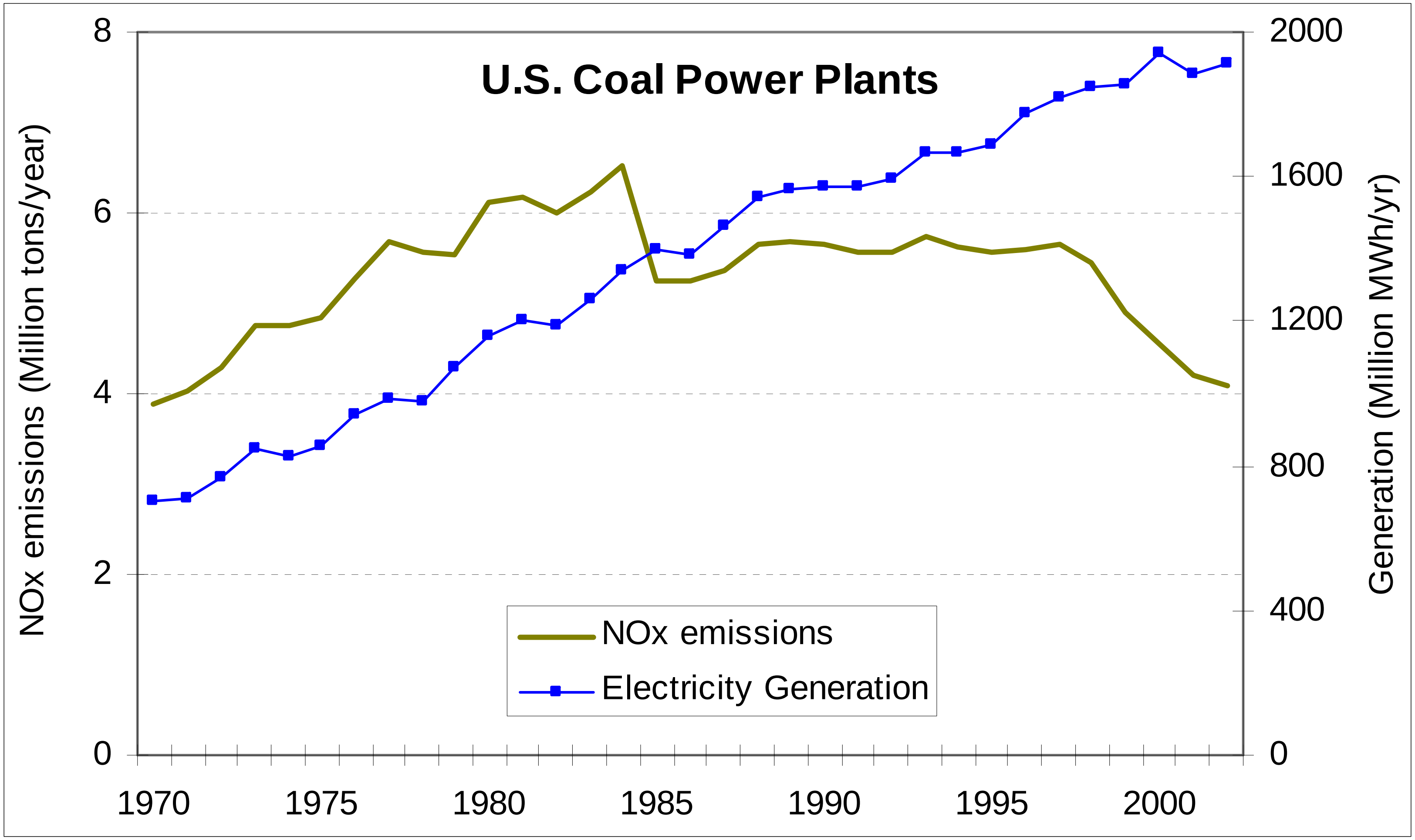
- Why we care: smog (ozone), acidification, fine particles, haze
- How big a problem: coal power plants ~1/5 of U.S. emissions.



Source: EPA (2005)

NO_X - Experience

- What is the experience of controlling NO_X from coal power plants?
  - >50% reduction in emissions rate since 1970



Source: EPA (2005) and EIA (2005)

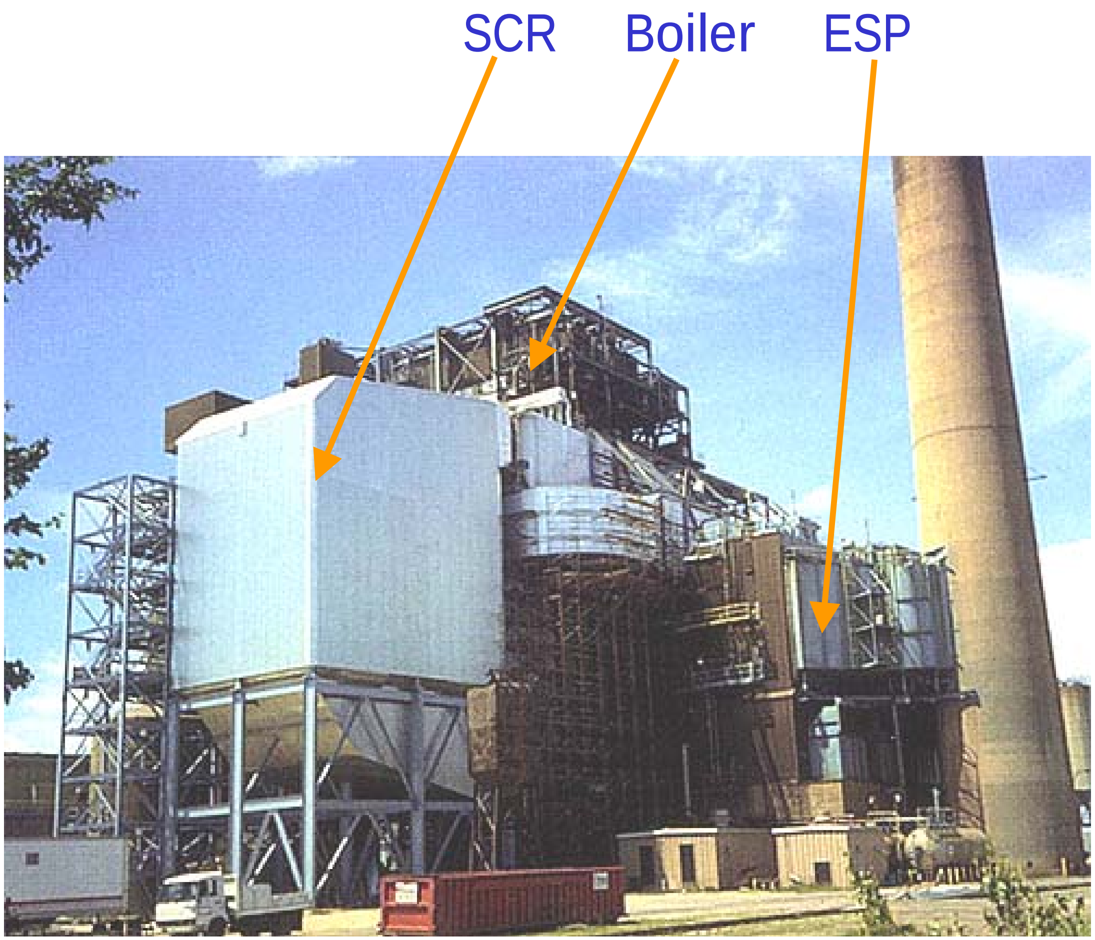
NO_X Control Technologies

- Combustion control
  - Low-NOX burners
  - Overfire Air
  - Reburn
  - Other

- Post-combustion control
  - Selective Non-Catalytic Reduction (SNCR)
  - Selective Catalytic Reduction (SCR)

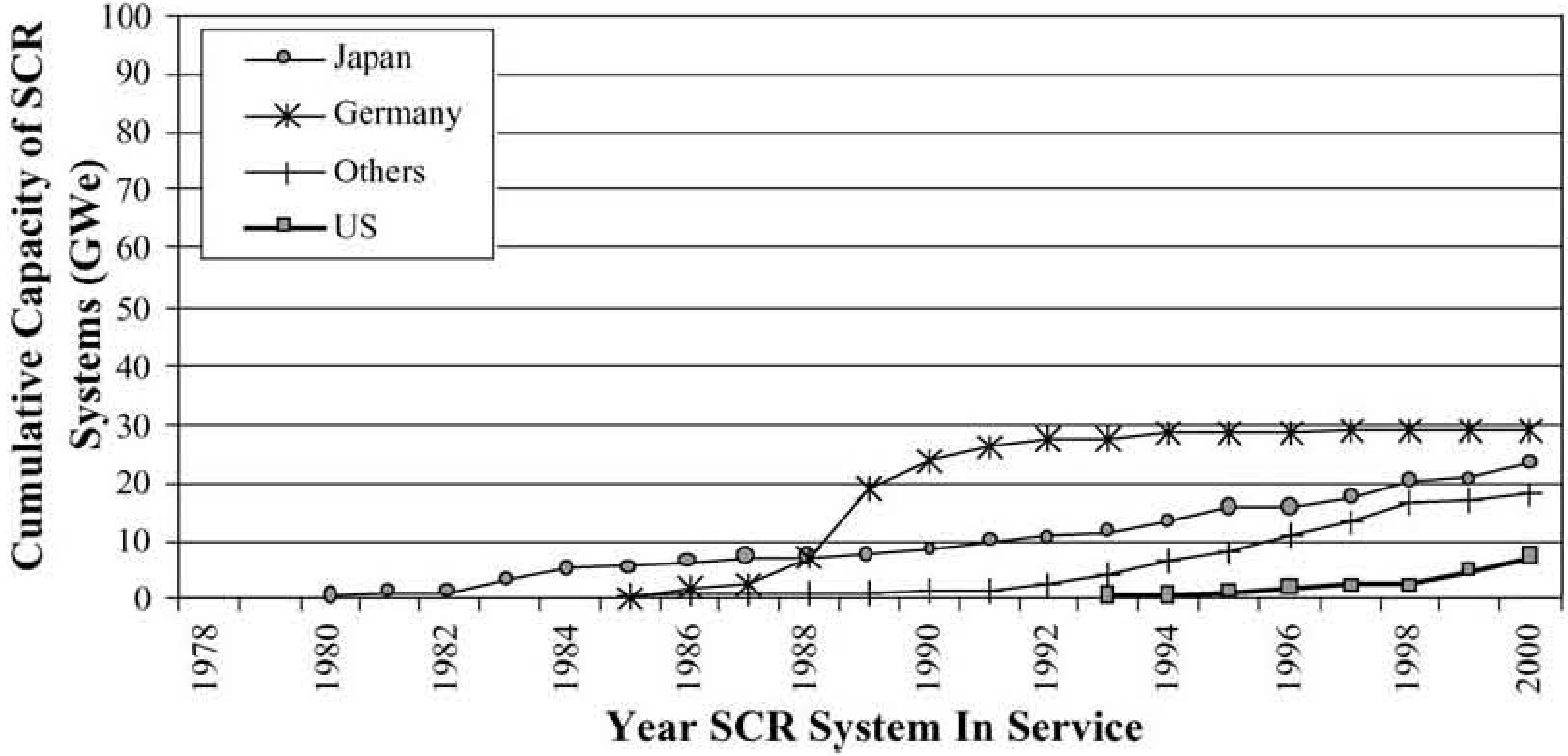
$$aNO_x + bNH_4 + cO_2 \underset{(catalyst)}{\rightarrow} dN_2 + eH_2O$$

Merrimack Station, NH



SCR – Installed capacity

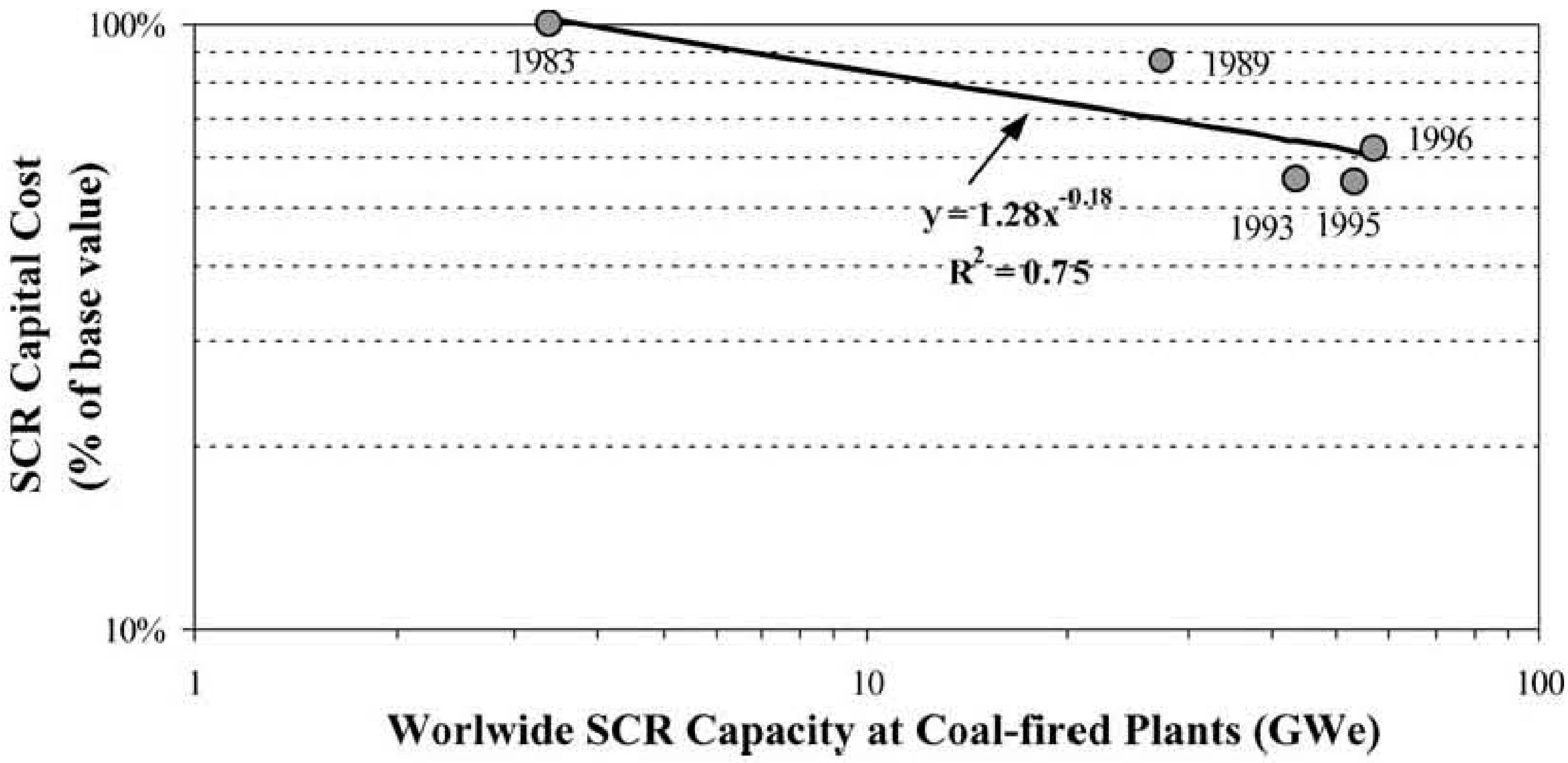
- Early installations outside of U.S.



Source: Rubin et al (2004)

SCR – Induced Innovation

- Reductions in capital cost for a standardized plant size and configuration



Source: Rubin et al (2004)

Mercury (Hg)

- Why we care: health impacts
- How big a problem:
  - Global Hg emissions from the coal power plants are ~½ of all anthropogenic and >¾ of natural flows.
  - Hemispheric, bio-accumulating pollutant
- Coal power plants
  - ~40% of U.S. emissions, only major source without controls
  - ~75 tons enter coal plants each year
  - ~27 tons is left in ash and scrubber sludge

Hg control challenge

- Remaining 48 tons elemental mercury (Hg°) leaves coal plant stacks as a very dilute gas

- Hg° is not very reactive

- Main strategies
  - Reduce Hg in coal
  - Oxidize and capture: e.g. HgCl
  - Collection on particle surfaces

Hg control technologies

1. Fuel switching/management
   - Monitor and avoid high-Hg coal production
   - Rationalize coal shipments for Hg control (ship higher-Hg coal to plants with higher capture rates)

2. Improved PM controls
   - Add a fabric filter stage to ESPs

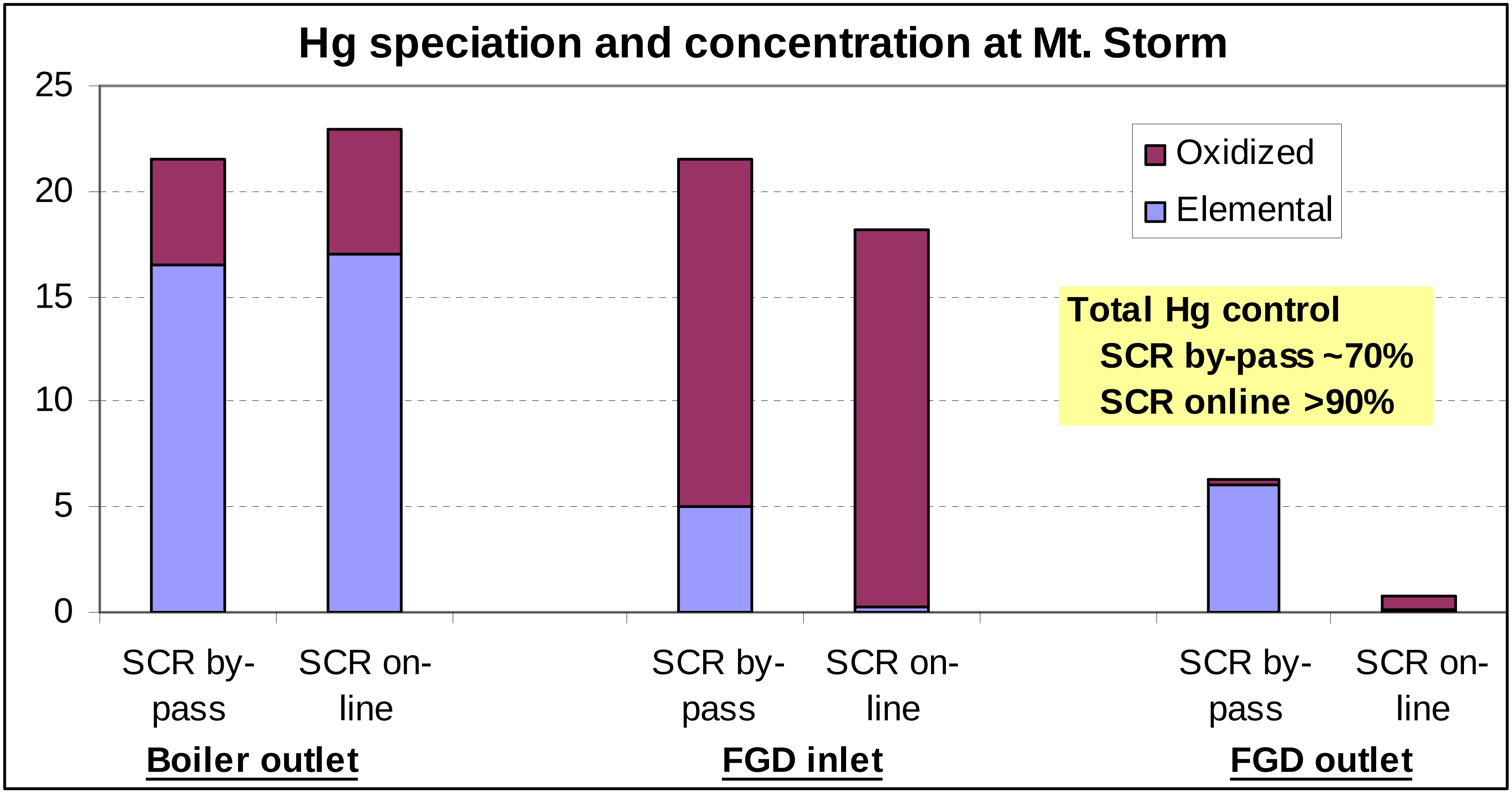
	Percent Hg captured	
PM controls	Bituminous	Sub-Bituminous
Cold-side ESP	46%	16%
Hot-side ESP	12%	13%
Fabric Filter	83%	72%

Source: ICR

Hg control strategies (continued)

3. Utilize existing/new SO_2 scrubbers to oxidize Hg° and capture

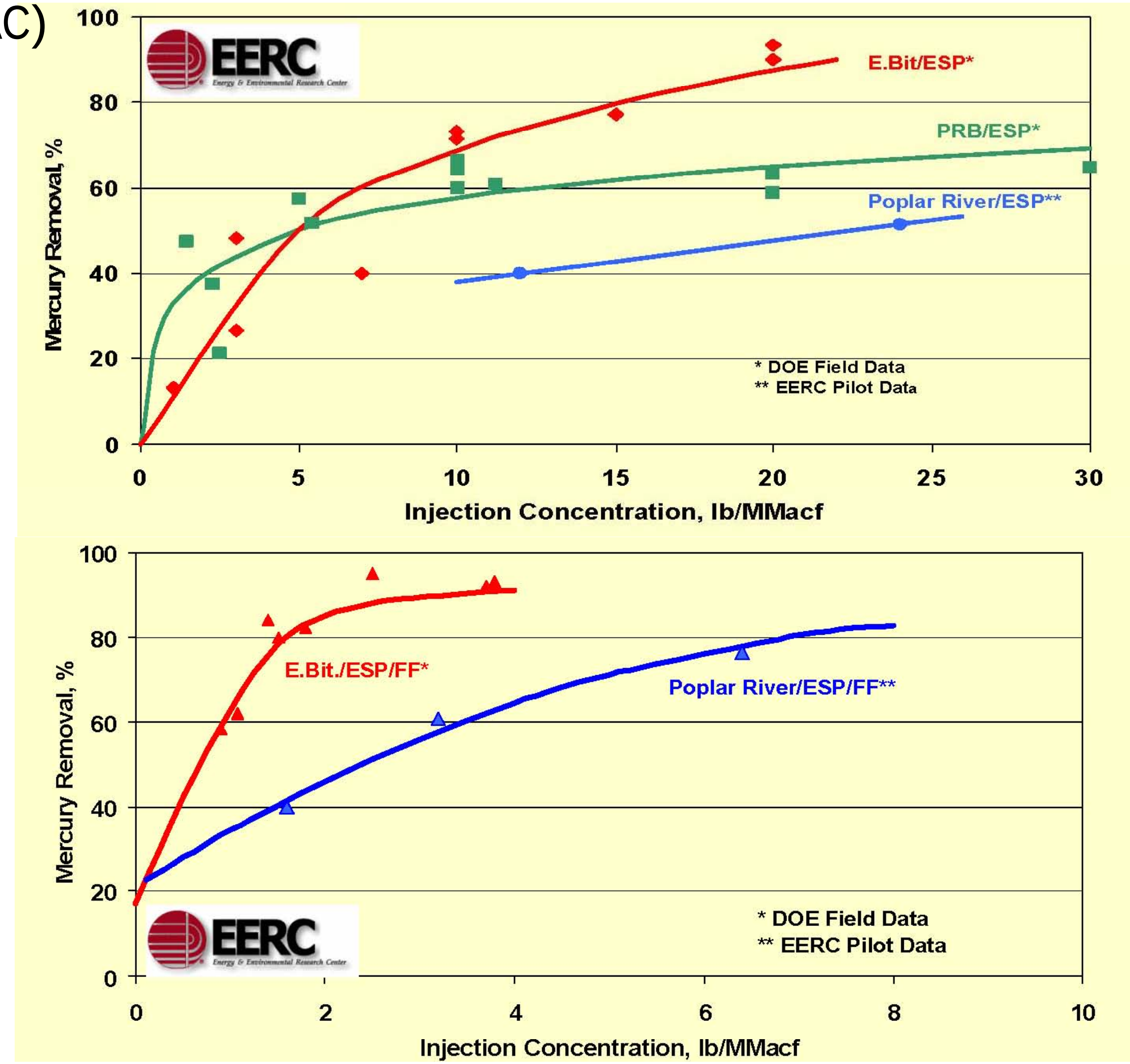
(sometimes called co-benefits)



Source: Renninger (2004)

Hg control strategies (continued)

4. Add sorbent injection to flue gas treatment system
   – Activated carbon (AC)
   – Add oxidizers

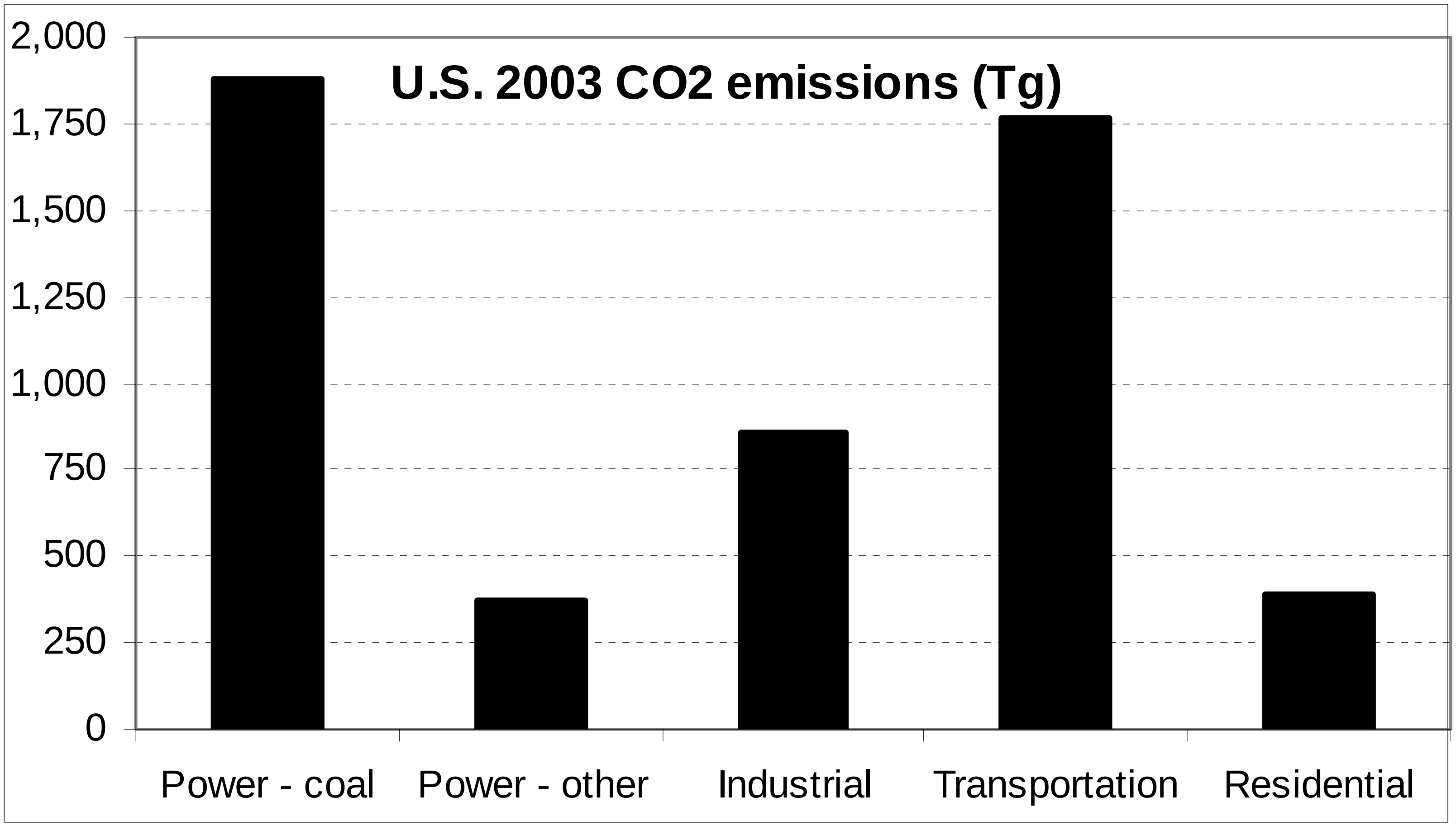


AC injection with ESP (top) and FF (bottom). Note change in horizontal scale.

Source: Smith et al. (2005)

CO_2

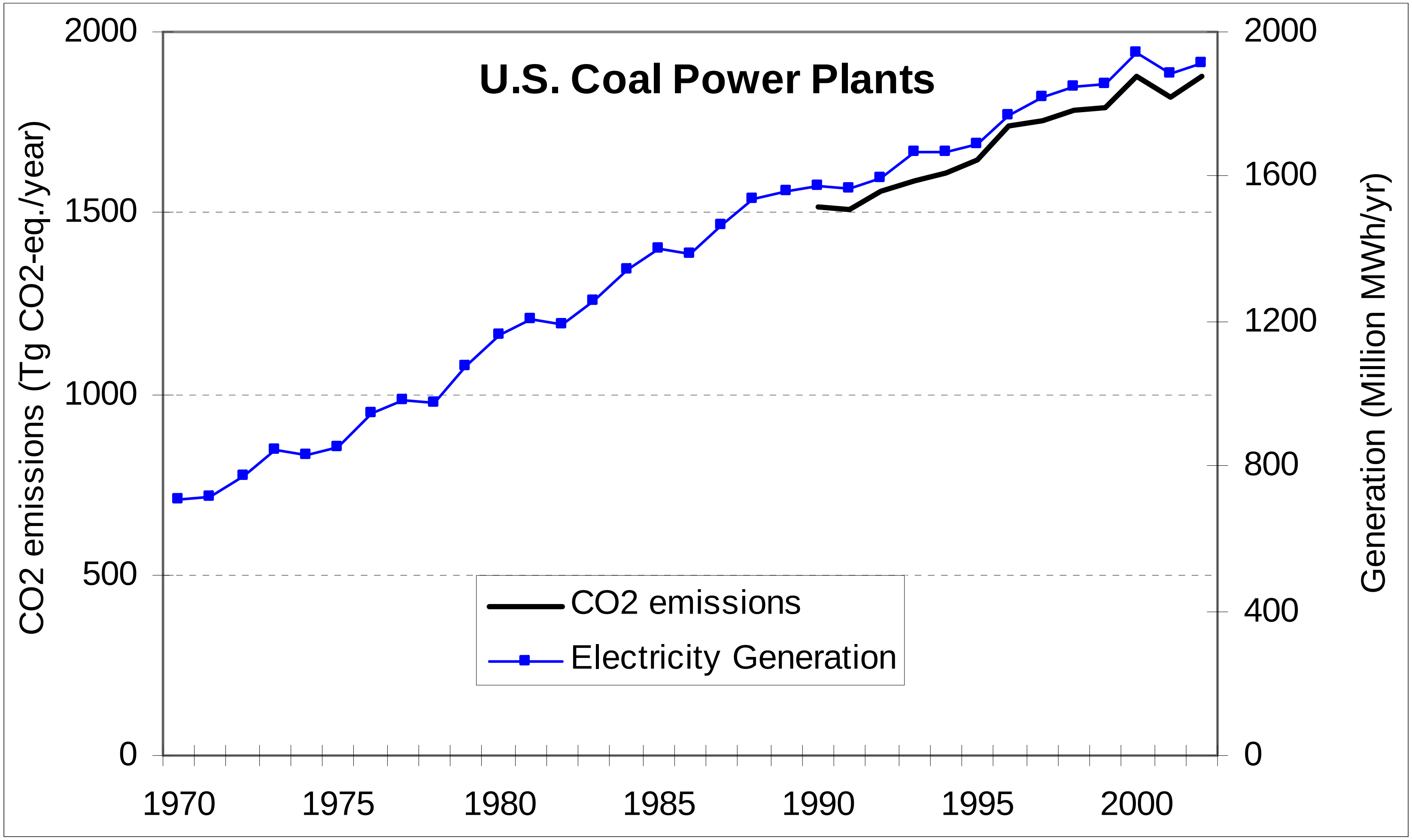
- Why we care: climate change
- How big a problem: Globally electric power plants emit >1/4 of all anthropogenic emissions.



Source: EPA (2005)

CO_2 – No experience in control

- A tougher problem, CO_2 is the desired product from carbon combustion, not a contaminant (SO_2, Hg) or byproduct (NO_X)



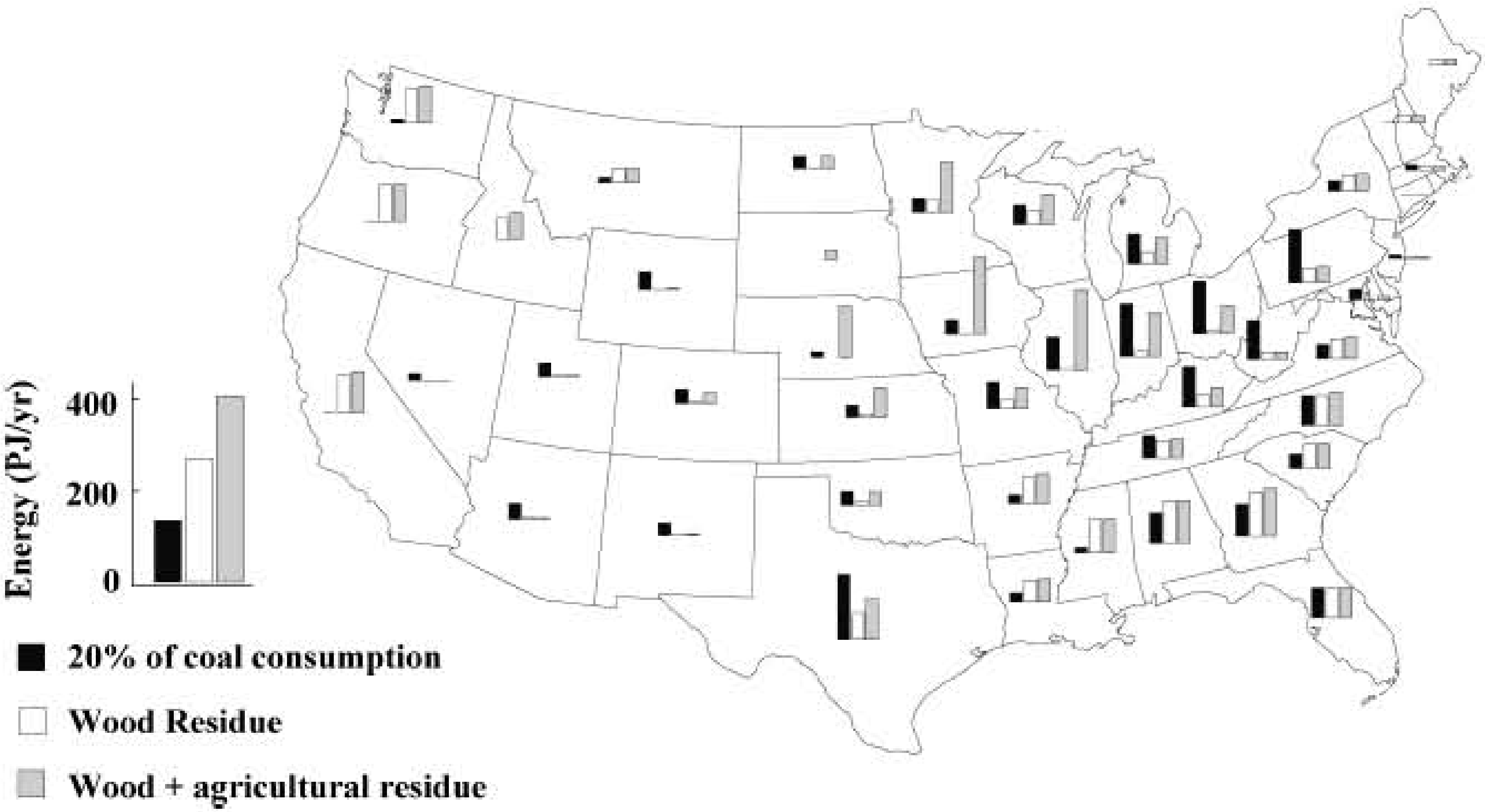
Source: EPA (2005) and EIA (2005)

CO_2 Control Technologies

- Fuel switching – irrelevant for plants defined by fuel
- Biomass co-firing – Like fuel switching, only less so.
- Carbon Capture and Storage (CCS)

CO_2 – Biomass cofiring

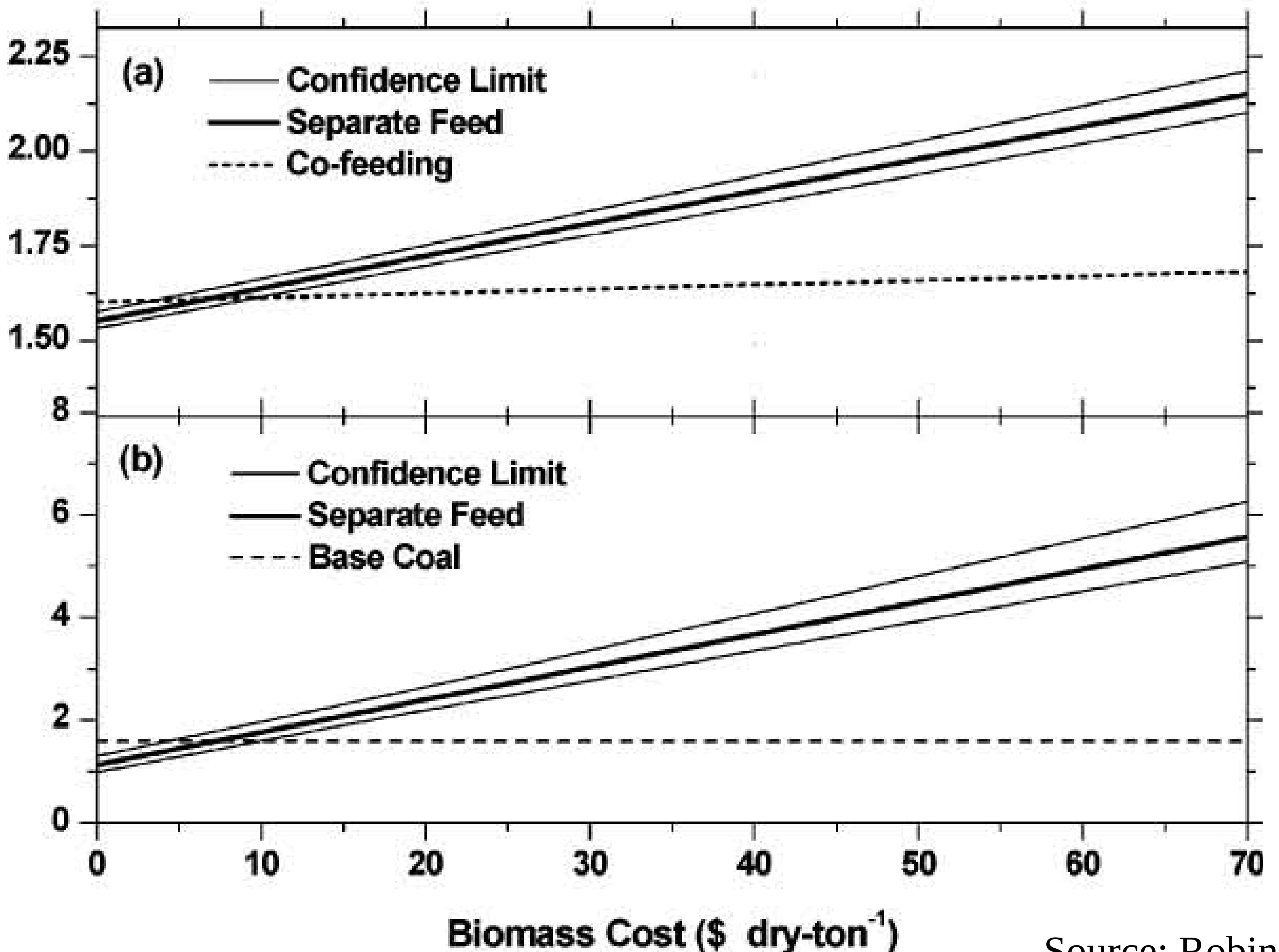
- Numerous demonstrations have shown technical feasibility
- Non-trivial resource base



Source: Robinson et al. (2003)

CO_2 – Biomass cofiring

- Can be implemented quickly and in large scale in existing boilers
- Moderate costs

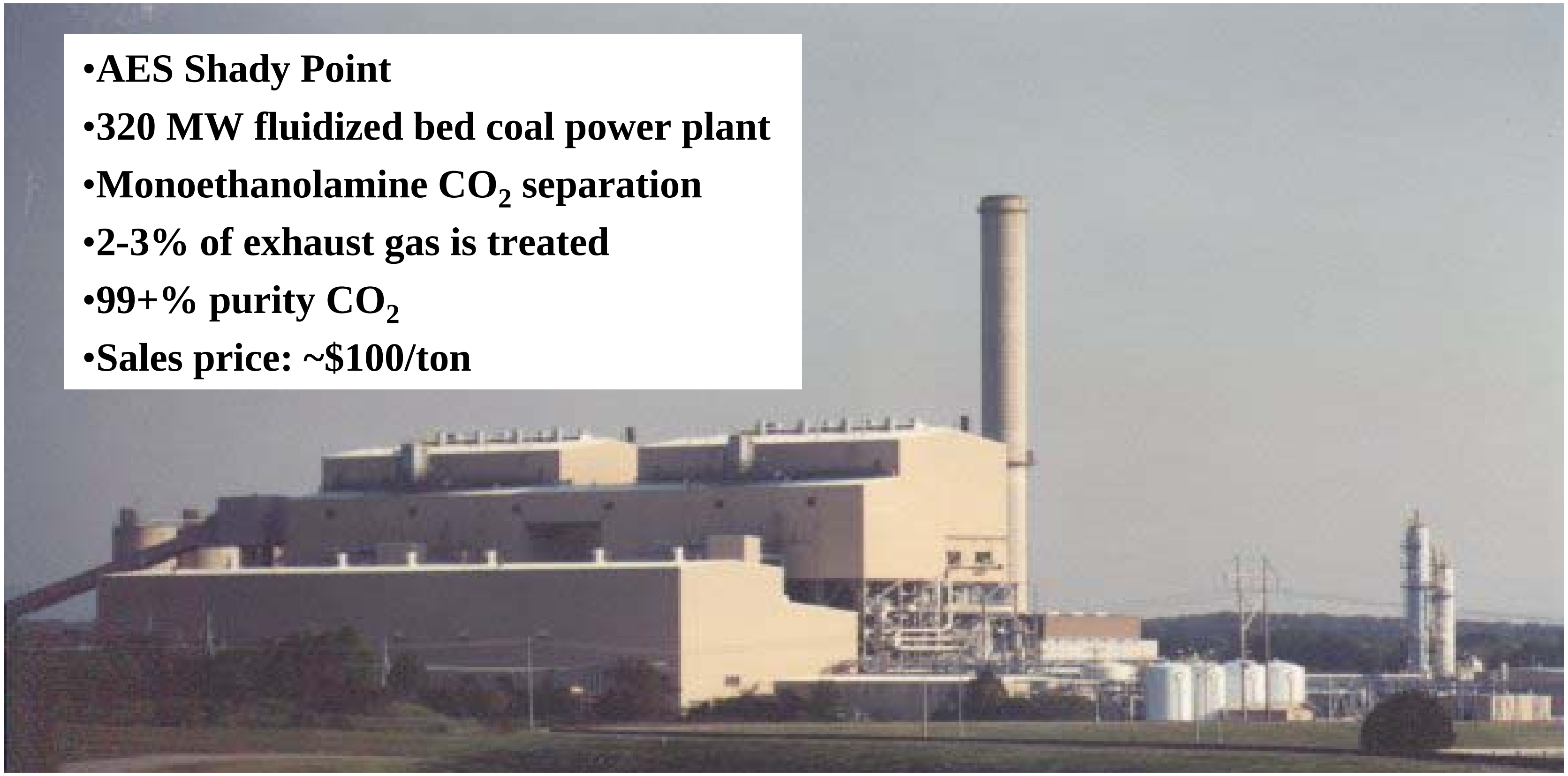


Cost of electricity (¢/kWh) as a function of biomass price for a) overall plant, and, b) biomass energy only.

Source: Robinson et al. (2003)

Carbon Capture Technologies

- Flue gas separation
  - Post-combustion
  - CO_2 is 3% to 15% of exhaust gas
  - ~15 commercial facilities worldwide
  - CO_2 is removed from exhaust gases with a solvent (MEA)

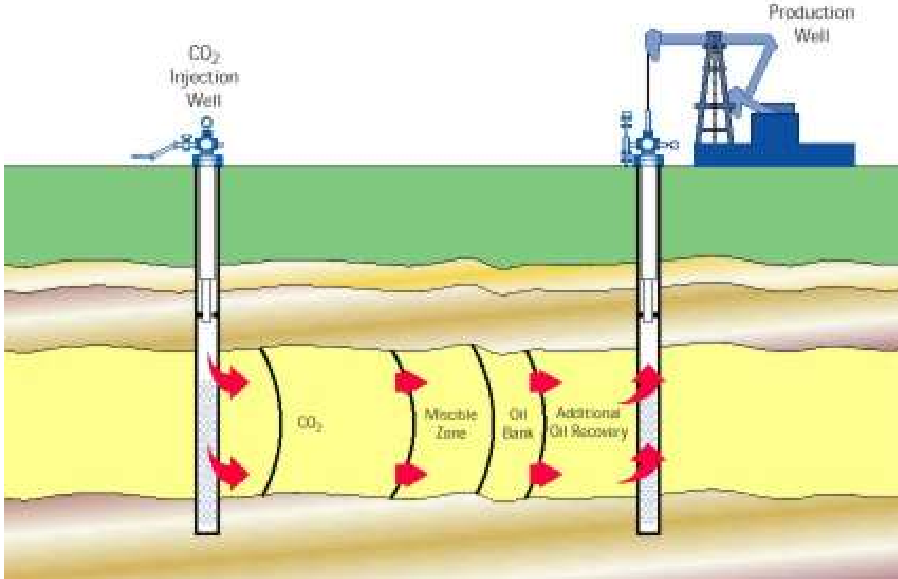


Carbon Capture Technologies

- Flue gas separation
  - Post-combustion
  - CO_2 is 3% to 15% of exhaust gas
  - ~15 commercial facilities worldwide
  - CO_2 is removed from exhaust gases by a solvent (MEA)
- Oxyfuel combustion
  - Cryogenic production of oxygen
  - Exhaust gas is is easily separable CO_2 and water vapor
  - Air Separation Unit (ASU) can consume 15% of power output
- Precombustion capture
  - Removed from synthesis gas by solvent (methanol or ethelyne glycol)
  - Many commercial facilities for CO_2 or hydrogen production
  - Can be readily integrated with IGCC
  - Cannot be retrofit to coal boilers

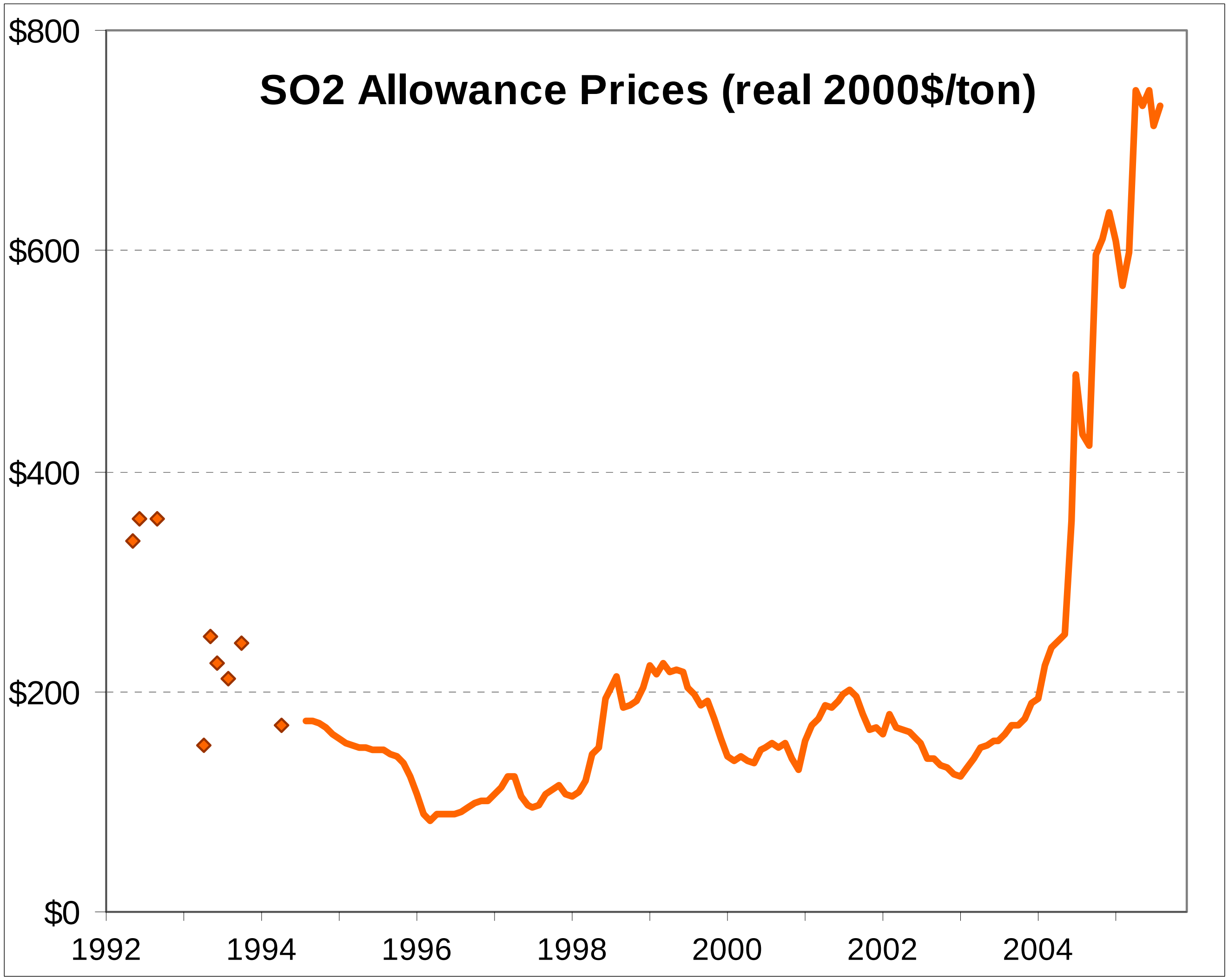
Existence Proof

- Great Plains synfuel plant
- Weyburn oilfield
- 5,000 ton/day of CO_2



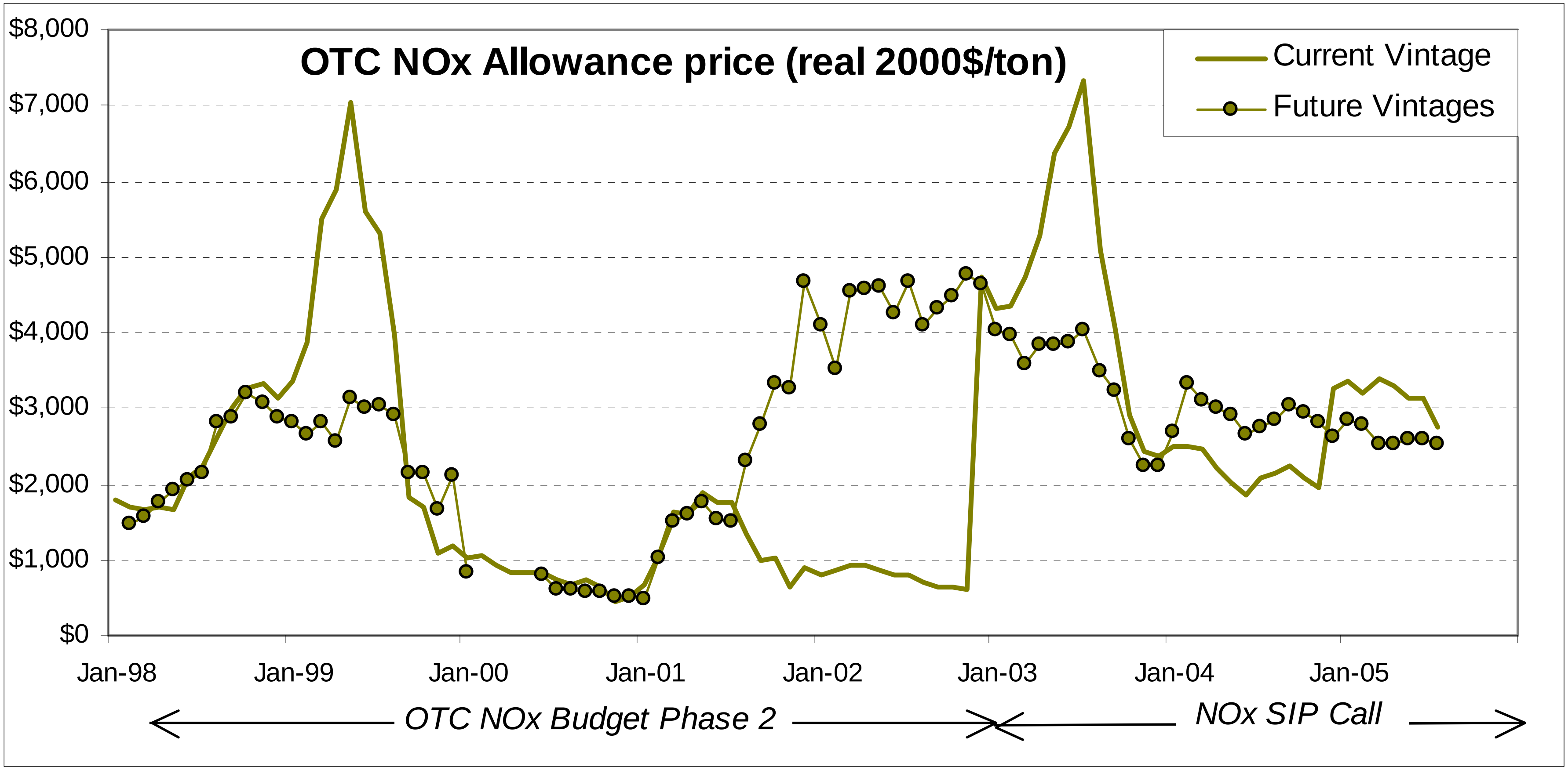
Costs – Allowances

- SO_2 allowances
  - Current 2005-7: $840-$860 (nominal)



Costs - Allowances

- NO_x allowances (Eastern U.S.)
  - Current 2005-7: $2400-$2600 (nominal)

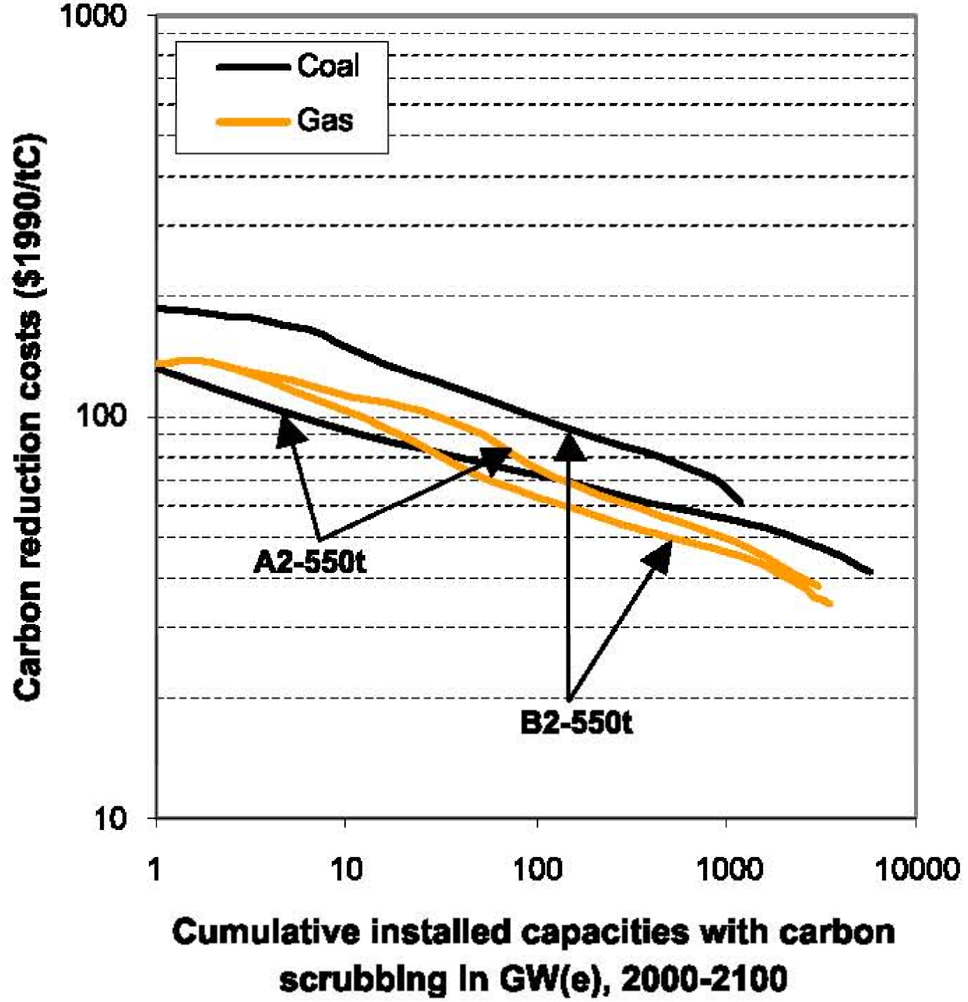


Costs - Projections

- U.S. Energy Information Agency (2001)
  - Jeffords-Lieberman Bill
  - 2020 reductions: SO_2 –75%; NO_X –65%; Hg –90%; CO_2 –39%
  - Reference: average COE increases from $61 to $81 per MWh
  - Advanced Technology: increase is to $67 per MWh (65% smaller)
- Tellus Institute (2004)
  - California/Oregon/Washington GHG emissions in 2020 reduced to 26% below business as usual (mostly efficiency improvements)
  - Less than a 1% rise in electricity supply costs
- WRAP (2005)
  - "SCR on BART Yes" option: $731 to $3,182 per ton NO_X, on average
  - "Scenario 3": $440 per ton, on average
  - A few tenths of a dollar per MWh to a few dollars

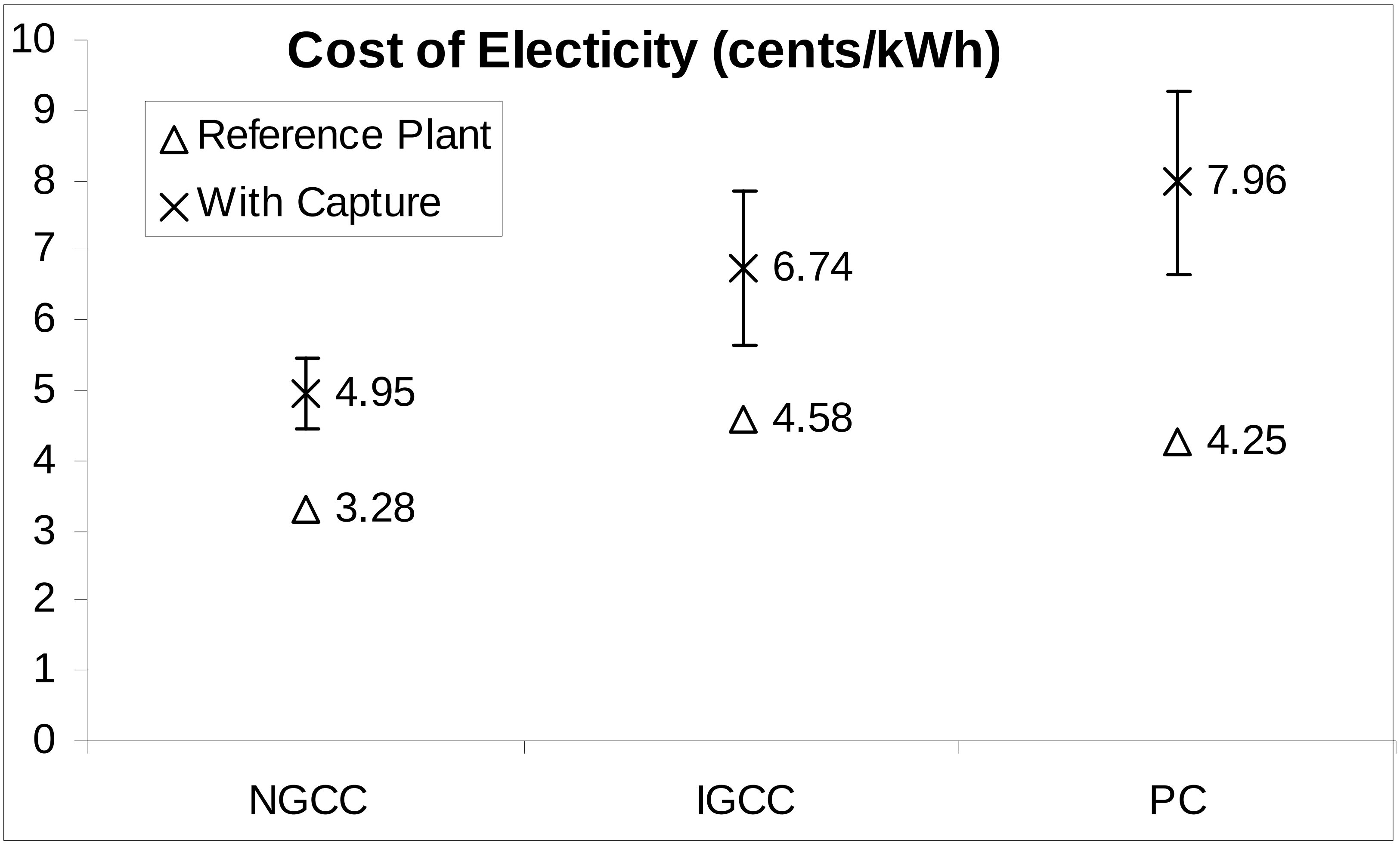
Costs – The Importance of Induced Innovation

- Riahi, Rubin et al (2004)
  - *Without* learning carbon capture increases COE from 32 to 72 $/MWh
  - *With* learning the increase is only to 42 $/MWh (75% smaller)



Costs – The PC-IGCC Conundrum

- COE is lower for PC without CCS, but higher *with*



Source: Herzog 2004

The challenge of integration

- Coal power plants as gigantic “chemistry experiments”
  - Processes interact,
    - Ammonium bisulphate (NH_4HSO_4)
  - Processes are challenging to maintain in balance
    - Ammonia slip – air quality and ash handling/sales

- Adequate space is often an issue

- Sequential regulations make integration especially challenging

- Example: General Gavin plant in Ohio

Gen. Gavin Power Plant – Original 1974 Schematic

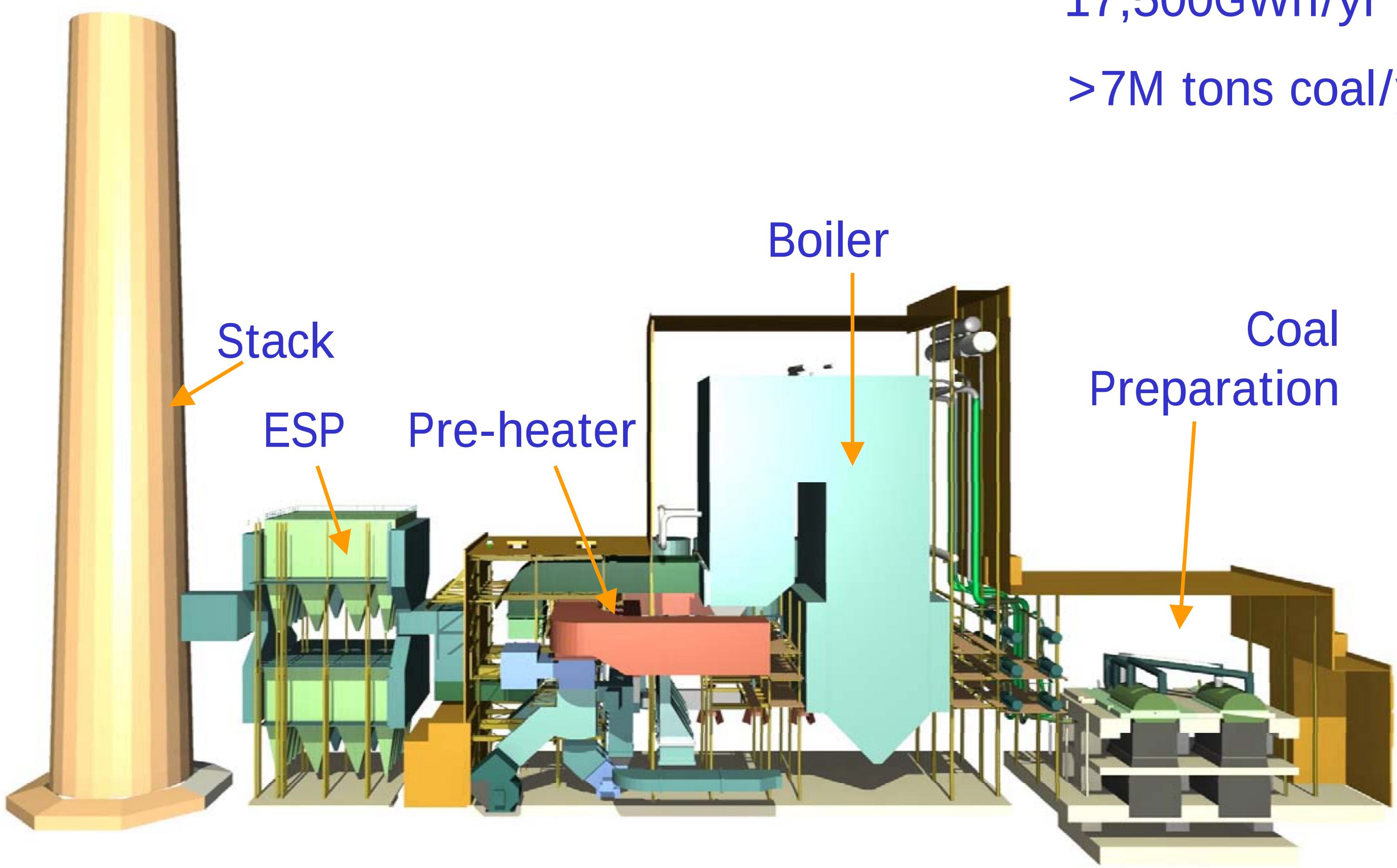
$1.7Billion (1999$)

Met NSR requirements

2x 1300 MW units

17,500GWh/yr

>7M tons coal/yr.



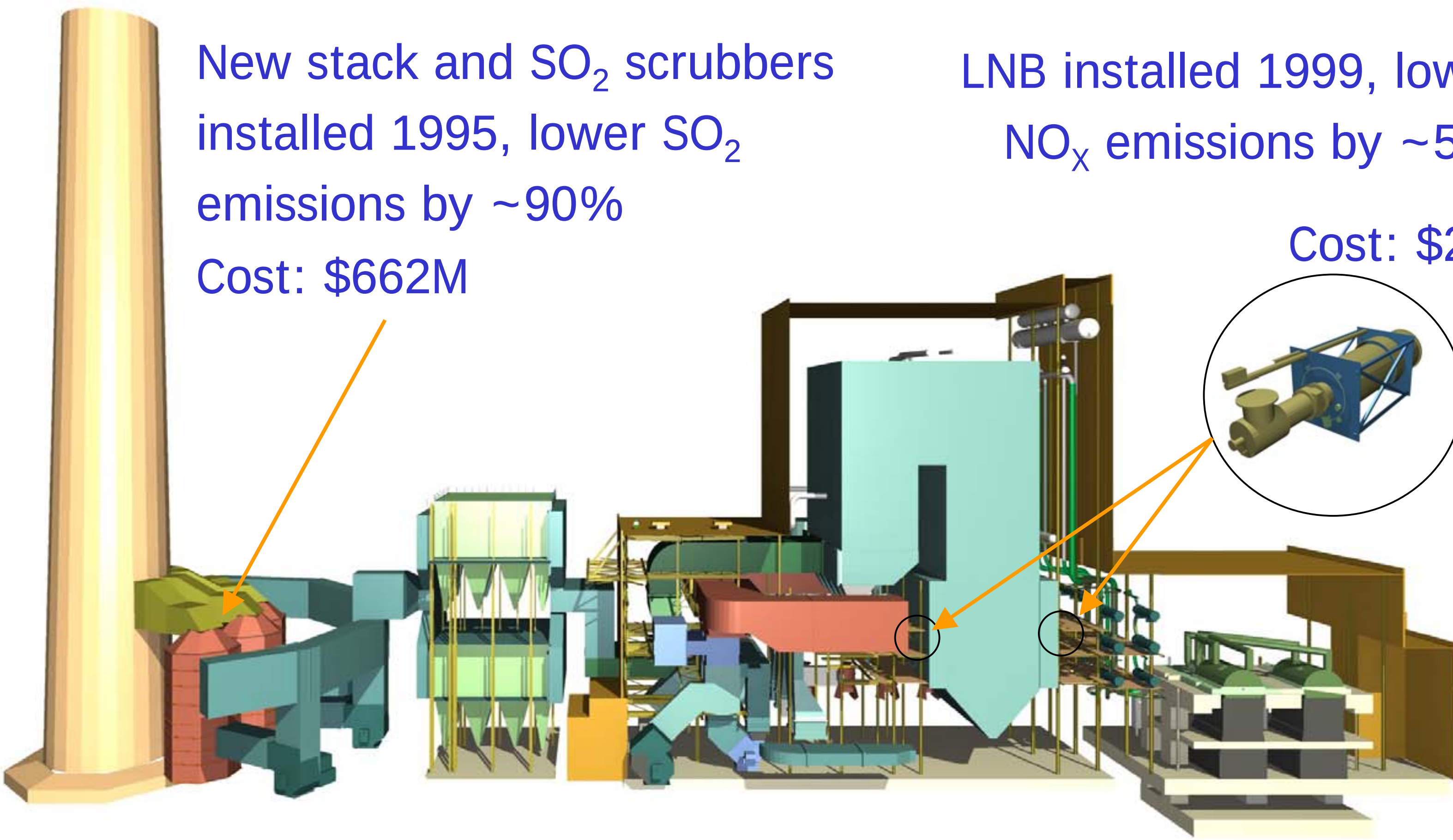
Gavin – 1990 Clean Air Act Compliance

New stack and SO_2 scrubbers installed 1995, lower SO_2 emissions by ~90%

Cost: $662M

LNB installed 1999, lowers NO_X emissions by ~50%

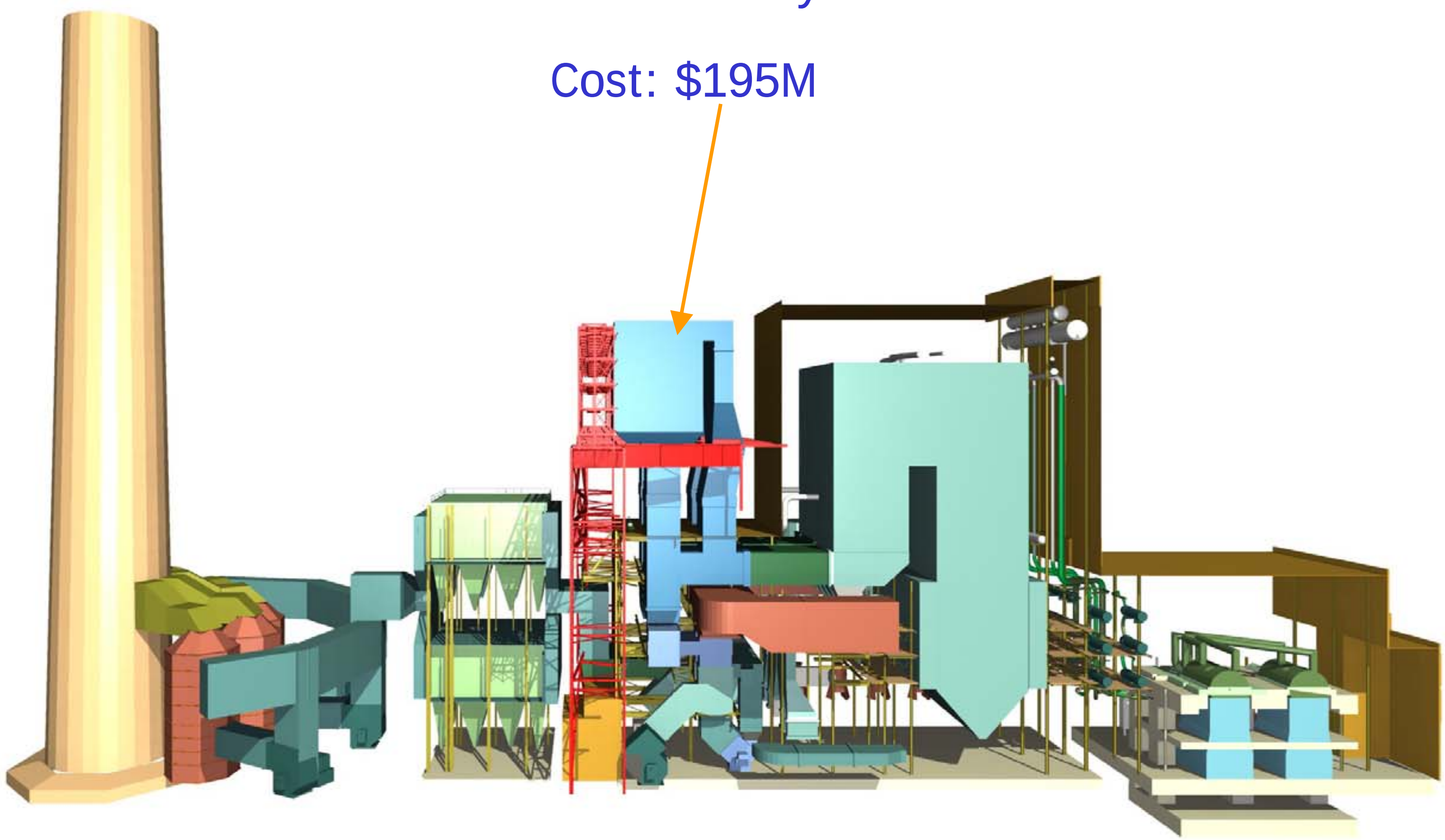
Cost: $27M

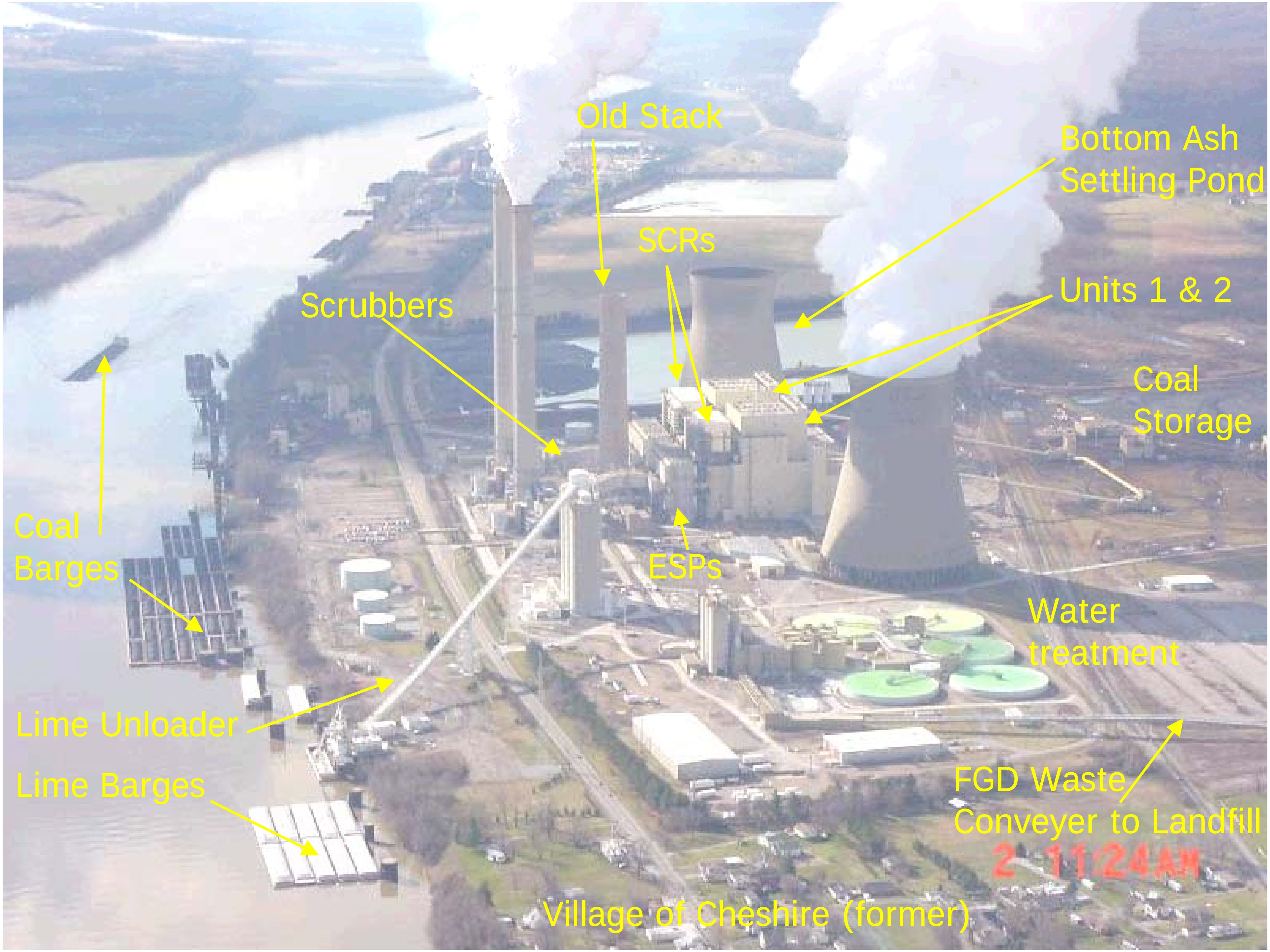


Gavin – NO_X SIP Call

SCR installed 2001, lower SO2 emissions by ~90%

Cost: $195M




Old Stack
Bottom Ash
Settling Pond
SCRs
Units 1 & 2
Scrubbers
Coal
Storage
Coal
Barges
ESPs
Water
treatment
Lime Unloader
Lime Barges
FGD Waste
Conveyer to Landfill
2 11:24AM
Village of Cheshire (former)

Innovation and Policy

- Environmental technologies **require** policy drivers
  - Environment is a public good, which has no market by definition
- New Source Review (NSR) -
  - New source performance standards (NSPS)
- Clean Air Interstate Rule (CAIR) -
  - ~2/3 reduction in both SO_2 and NO_X emissions
  - 29 Eastern States – only an indirect effect on California
- Clean Air Mercury Rule
  - New source performance standards (NSPS)
  - Cap-and-Trade: 15 tons/yr. by 2018 (70% reduction)
- Regional Haze Rule/Best Available Retrofit Technology (BART)
  - Will determine SO_2 and NO_X control requirements in the West
  - Western states currently developing plans through WRAP

A role for California policy?

- PM10
  - Little to do
- SO_2 and NO_X
  - California is already participating through WRAP
  - Difficult to influence market-based regulatory mechanisms
- Hg
  - New federal rule
  - Difficult to influence market-based regulatory mechanisms
- CO_2
  - The intent of Executive Order 3-05 seems clear: take action to prevent California from suffering from climate change
  - Opportunity to influence large investments in new coal power plants
  - Empirical evidence from prior examples – R&D and demonstration projects are not enough.

Summary

- How clean?
  - Coal power plants can meet solid waste and air quality goals

- At what cost?
  - Non-zero but it won't break the bank (see prior slides for a variety of opinions)

- When?
  - PM, SO_2, and NO_X control technologies are available now.
  - Mercury technologies are under active development.
  - Several CO2 control technologies are possible, some are deployable at very moderate costs

The challenge

1. Some people view the existing policy drivers as inadequate
   - Regional Haze/BART and Mercury rules
   - Not really a technology issue
2. In my view, the real challenge is the development of CO_2 mitigation technologies across the entire energy sector.
   - Will current and imminent investments in new power plants be for “capture ready” designs (IGCC) or brand-new “legacy” (PC) plants?
   - What government will provide the policy drivers needed to develop CO_2 mitigation technologies?
   - When will CO_2 mitigation technologies be cheap enough so they are politically acceptable and can be implemented widely?
   - These are interdependent questions – leadership is needed to begin to drive CO_2 control costs down so that preventing climate change becomes affordable.


Thank you for your attention.

References 1

- Western Regional Air Partnership (2005a) Evaluation of PM10 SIPs and Their Applicability to Visibility Control in Western Class I Areas. www.wrapair.org
- U.S. EPA (2003) Basic Concepts in Environmental Sciences. www.epa.gov/eogapti1/home/index.htm
- Causes of Haze Assessment. www.coha.dri.edu
- Ellerman, A.D. and J.P. Montero (1998) The declining trend in sulfur dioxide emissions: Implications for allowance prices. Journal of Environmental Economics and Management. 36(**1**): 26-45.
- Taylor, M.R. et al. (2005) Control of SO2 emissions from power plants. Technological Forecasting and Social Change. 72(6): 697-718
- Taylor, M.R. et al. (2003) Effect of Government Actions on Technological Innovation for SO2 Control. Environmental Science & Technology. 37(20): 4527-4534
- Rubin, E.S. et al (2004) Learning curves for environmental technology and their importance for climate change. Energy 29: 1551-1559.
- Robinson, A.L. et al (2003) Assessment of Potential Carbon Dioxide Reductions Due to Biomass-Coal Cofiring in the the U.S. Environmental Science & Technology 37(22):5081-9
- Herzog, H. (2004) Carbon Capture and Storage from Fossil Fuel Use. In Encyclopedia of Energy. Cleveland, C. Executive Editor. Elsevier. Pp. 277-287

References 2

- Western Regional Air Partnership (2005b) Analysis of Combustion Controls for Reducing NOX emissions from coal-fired EGU's in the WRAP region. www.wrapair.org
- U.S. Energy Information Agency (2001) Analysis of Strategies for Reducing Multiple Emissions from Electric Power Plants with Advanced Technologies. SR/OIAF/2001-05
- Riahi, K., Rubin, E. S. et al (2004) Technological Learning for Carbon Capture and Sequestration Technologies. Energy Economics 26: 539-564.
- Tellus Institute (2004) Turning the Corner on Global Warming Emissions. San Francisco: The Energy Foundation. 44 pp.
- Energy Information Agency (2005) Annual Energy Review 2003. Washington: U.S. Department of Energy
- U.S. EPA (2005) National Emission Trends. Washington.
- Western Regional Air Partnership (2005c) Year 2000 Point Source SO2 Emissions Analysis. www.wrapair.org
- Smith D. et al (2005) Sorbent Injection for Mercury Control at Saskatchewan Power. At Electric Utilities Environment Conference. Tucson, AZ. January 25.
- Renninger S. (2004) Effects of SCR Catalyst on Speciation and Removal of Mercury within a Forced-Oxidized Limestone Scrubber. At MegaSymposium.