NATIONAL ENERGY TECHNOLOGY LABORATORY

Environmental Issues 101 for Coal-Fired Power Plants

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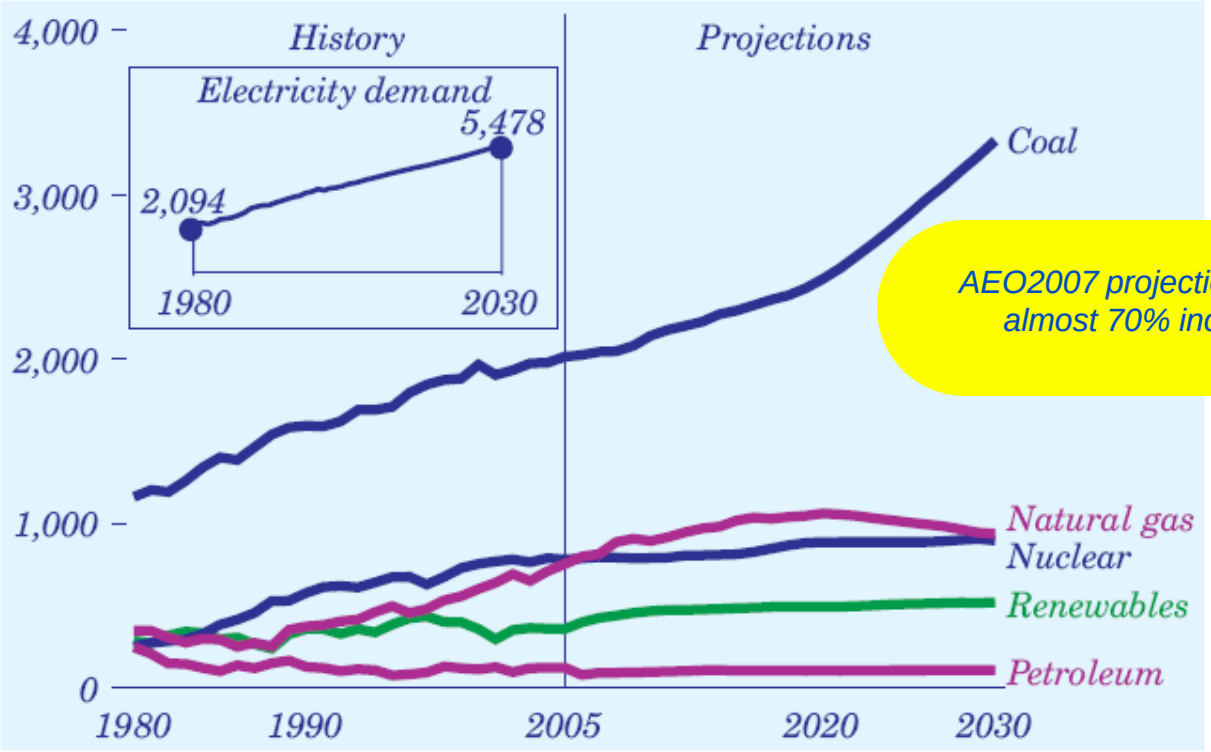
Environmental Issues 101
Presentation Outline

- **Coal combustion and resultant air pollutants**
- **Air pollution control devices**
- **Air emission regulatory requirements**
- **Supplemental Information**
  - Solid waste issues
  - Water issues

U.S. Electricity Generation by Fuel Type
(billion kilowatt-hours)

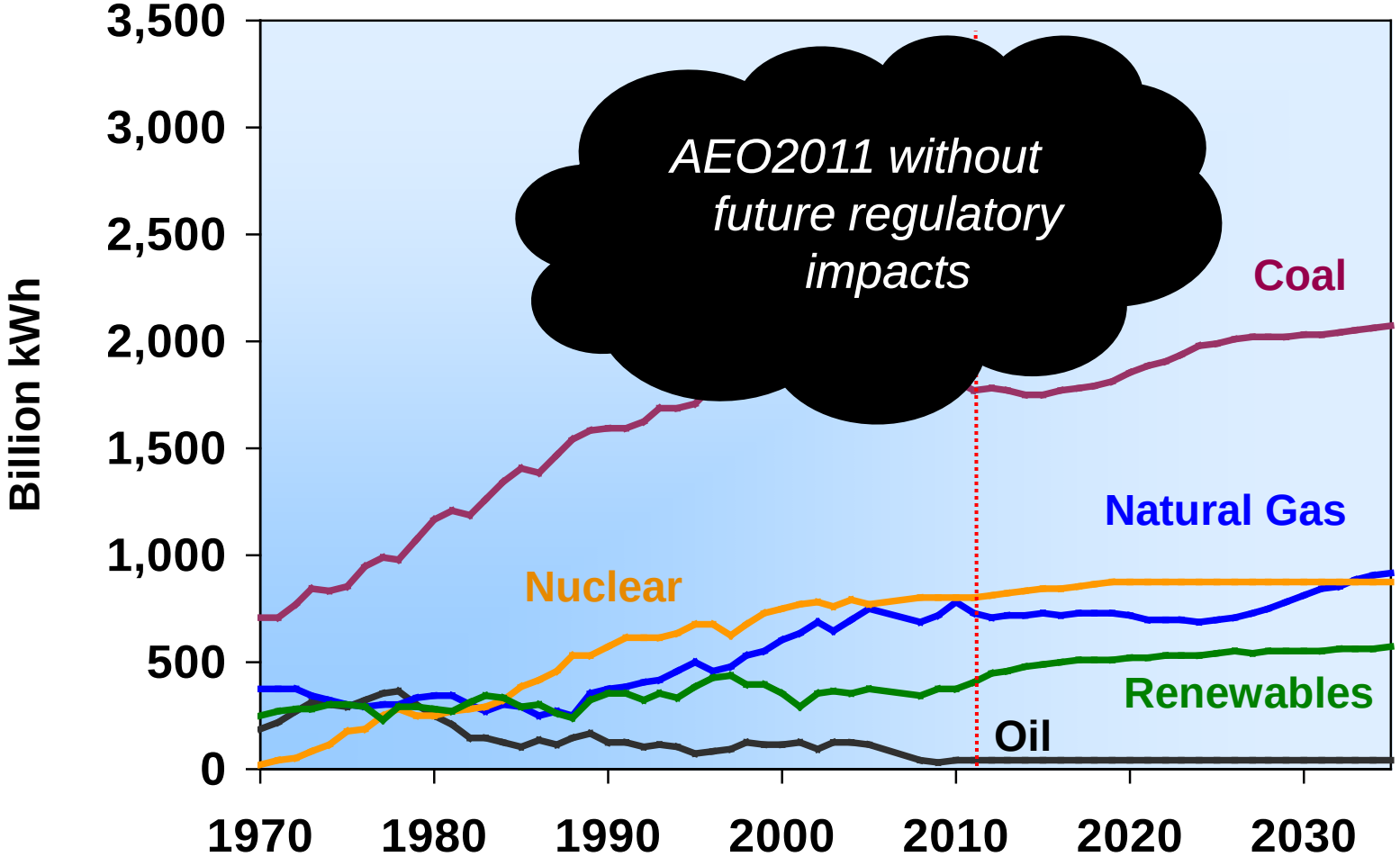


AEO2007 projections show almost 70% increase

Coal is used to produce about 50% of U.S. electricity

Source: Annual Energy Outlook 2007

Coal's Share of Power Generation Projected to Decrease



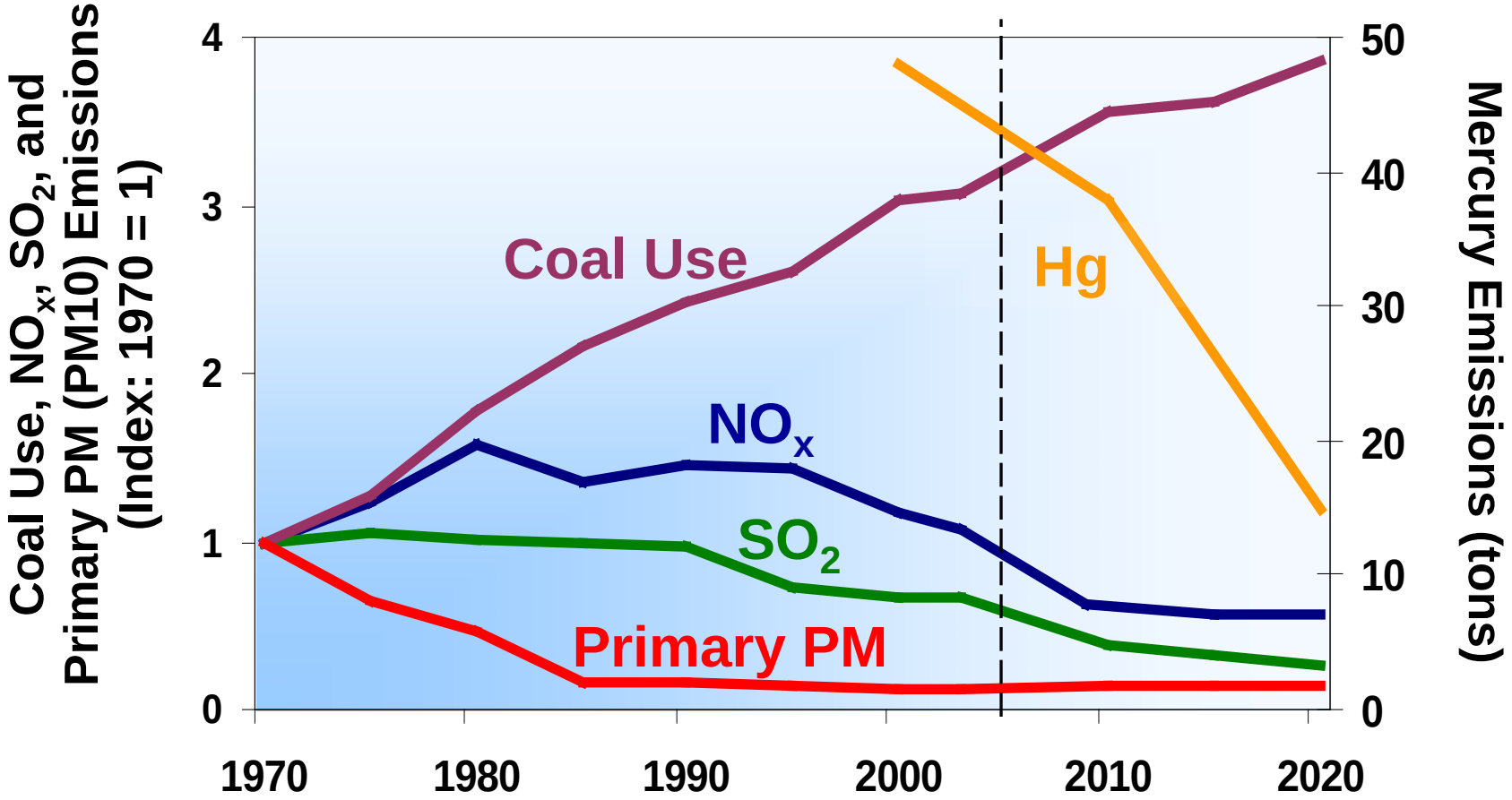
Annual Energy Outlook 2011 Reference Case

Air Emissions from Burning Coal

- **Nitrogen oxides (NOx)**
- **Sulfur dioxide (SO_2)**
- **Particulate matter (PM)**
- **Hazardous air pollutants (HAP)**
  - Mercury (Hg)
  - Hydrogen Chloride (HCl)
- **Carbon dioxide (CO_2)**

Concern with human health and environmental impacts

Annual U.S. Air Emission Trends and Projections

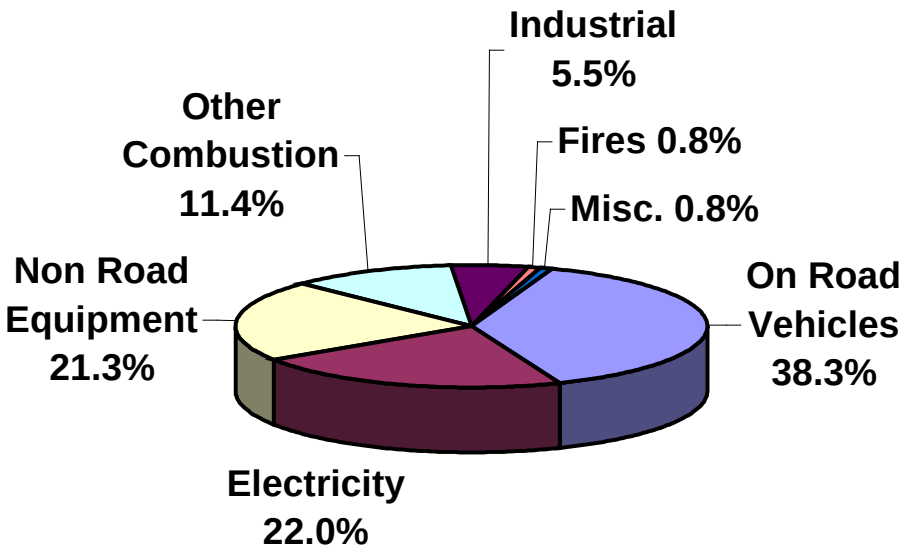


Historical data (1970–2000): Coal consumption and electricity generation per DOE EIA, AER 2005
NO_x, SO_2, and filterable PM10 per EPA Air Trends Report: http://www.epa.gov/air/airtrends/econ-emissions.html
Projected data (2003–2020): Coal consumption and electricity generation per DOE EIA, AEO 2005
NO_x and SO_2 per EPA projections under CAIR: http://www.epa.gov/interstateairquality/charts.html
Mercury per EPA Clean Air Mercury Rule
Filterable PM10 per coal consumption projections

What about NOx?

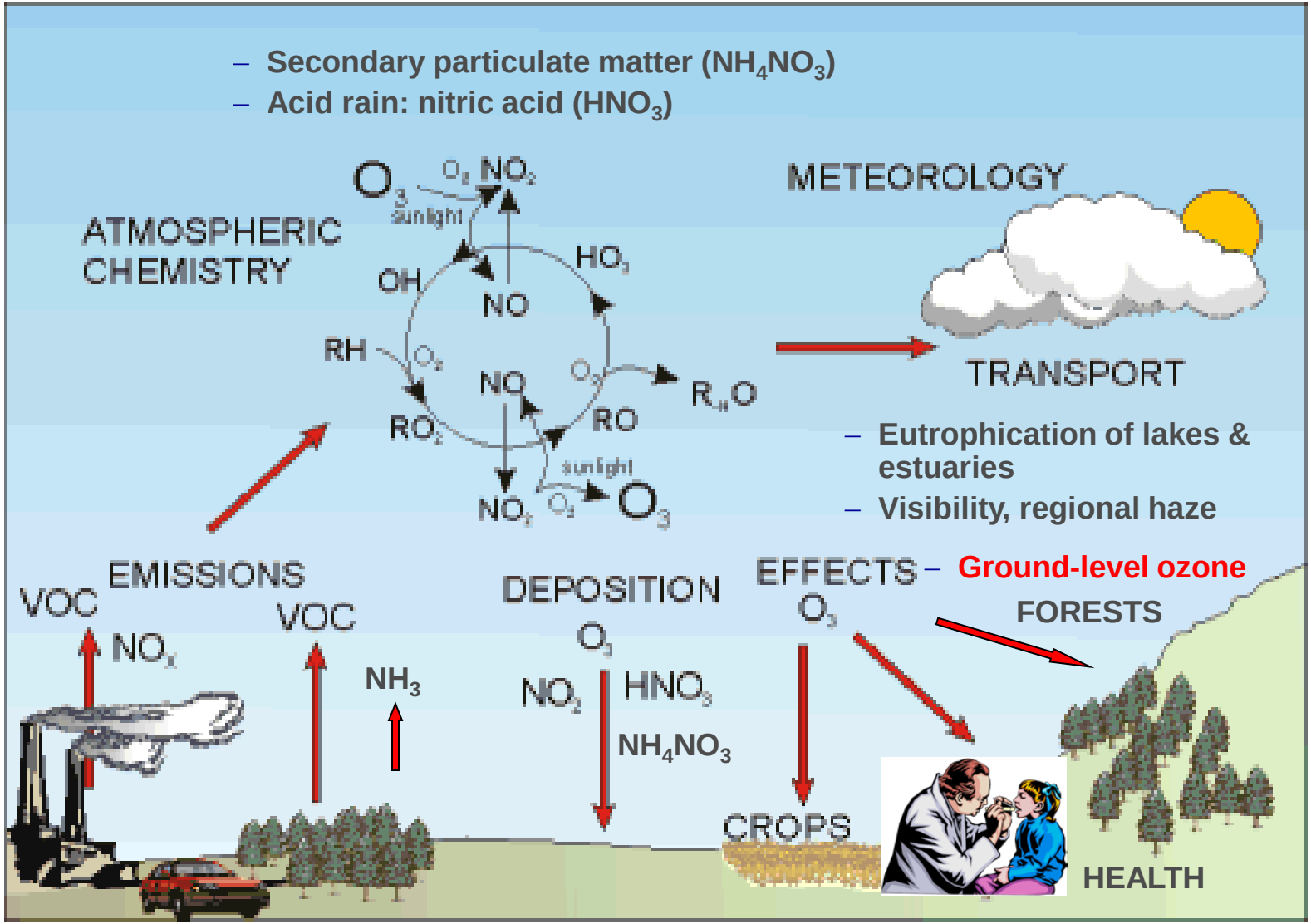
- **What's NOx?**
  - **Nitric oxide (NO)**
  - **Nitrogen dioxide (NO_2)**
  - Nitrous oxide (N_2O)

U.S. NOx Emissions, 2002



- **NOx Formation in Coal Boilers**
  - Thermal NOx: reaction of nitrogen in the combustion air with excess oxygen at elevated temperatures
  - Fuel NOx: oxidation of nitrogen that is chemically bound in the coal

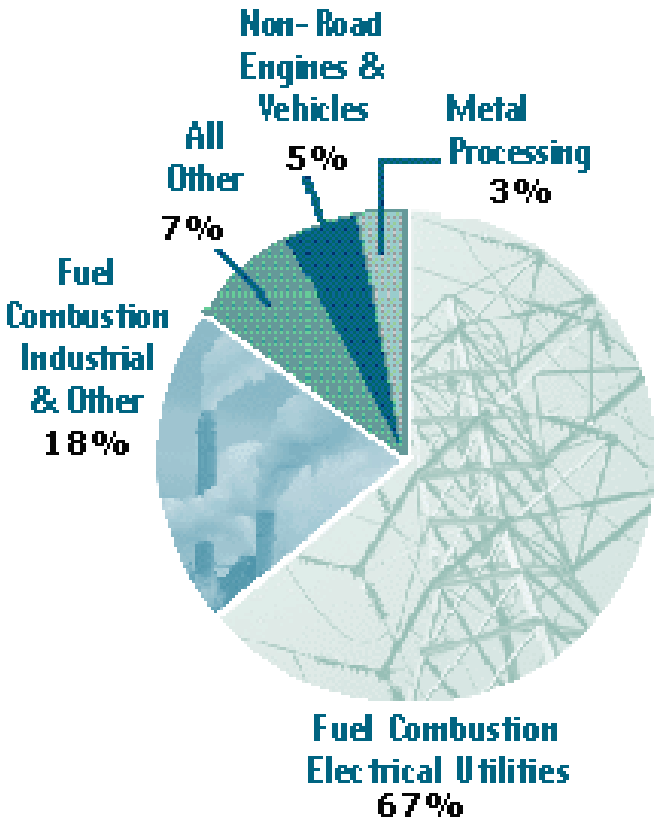
NOx: Health and Environmental Impacts



What about SO_2?

- **How is SO_2 formed in the furnace?**
  - Sulfur (S) + oxygen (O_2) → sulfur dioxide (SO_2)

- **Health and environmental impacts**
  - Direct respiratory effects
  - Acid rain: sulfuric acid (H_2SO_4)
  - <u>Greatest Concern:</u> Secondary Particulate Matter ($NH_4HSO_4$and $(NH_4)_2SO_4$)
  - Visibility, regional haze



Stack SO_3/H_2SO_4 Emissions

Photo courtesy of URS Corp.

- **What's the problem?**
  - **Opacity violation "blue plume" caused by sulfuric acid mist**
  - **"Fallout" affects local community, destroys public relations**
  - **Affects plants equipped with wet FGD & SCR**
  - **Goal: Limit SO_3 to 5-10 ppm**

What about PM?

- **What's particulate matter (PM)?**

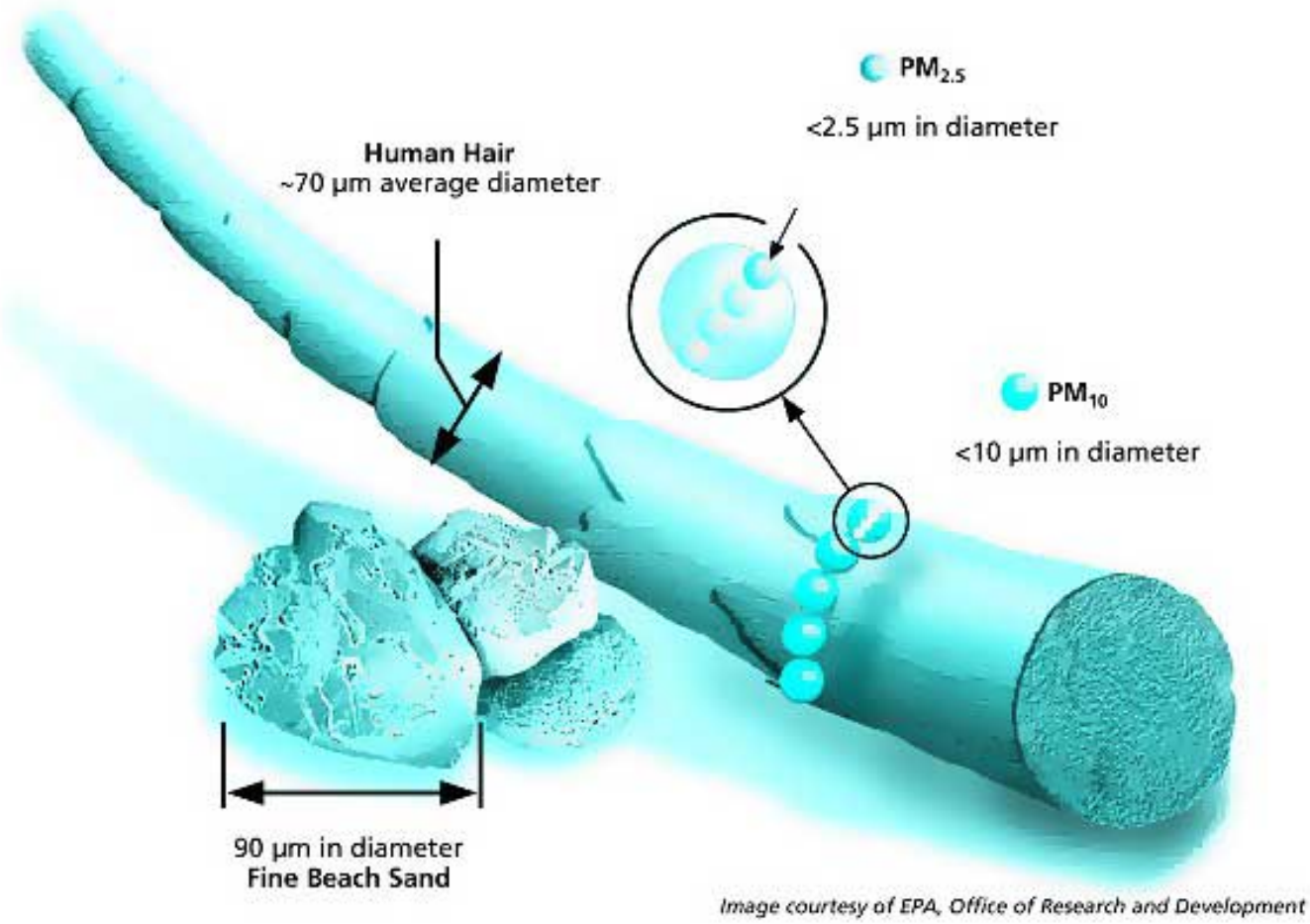
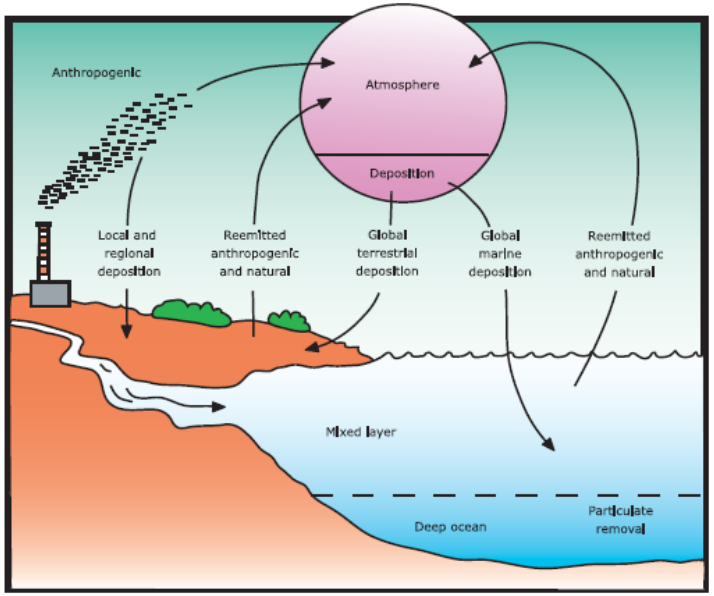


Image courtesy of EPA, Office of Research and Development

What about Mercury?

- **What happens to mercury emissions from a power plant?**
  - Wet deposition (rain)
  - Dry deposition
  - Converts to methyl mercury in water bodies
  - Methylmercury bioaccumulates in fish and shellfish

- **Health and environmental impacts**
  - MeHg is a powerful neurotoxin
  - Human exposure from consumption of fish and shellfish
  - Exposure at high levels can harm the brain, heart, kidneys, lungs, and immune system

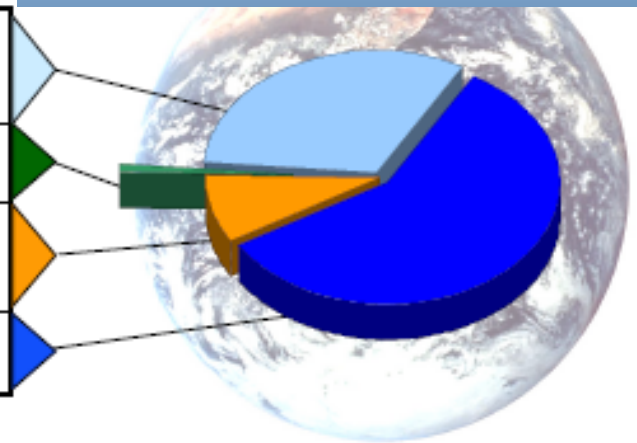


Mercury is a global pollutant

It is estimated that U.S. coal-fired power plants emit approximately 1% of annual global mercury emissions

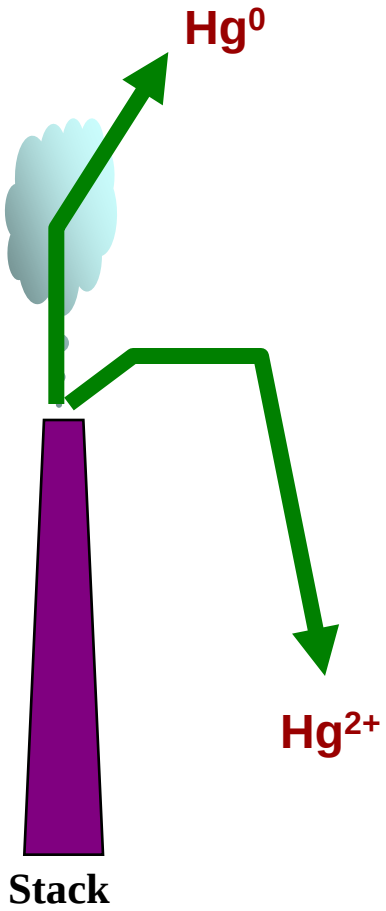
Emissions from Natural Sources (Volcanoes, Forest Fires, etc.)	1540 tons
U.S. Coal-Fired Power Plants	48 tons
Re-Emission of Prior Anthropogenic Emissions	440 tons
New Anthropogenic Emissions*	2820 tons

*Note: Does not include U.S. Coal-Fired Power Plant Emissions



Forms of Mercury in Coal Plant Emissions

- **Elemental (Hg^0)**
  - Insoluble in water; atmospheric lifetime ~ 1 yr+
- **Oxidized (Hg^{2+})**
  - a.k.a. Reactive Gaseous Mercury (RGM)
  - Very soluble; atmospheric lifetime < 1 day – few weeks
  - Can be deposited close to sources (bad)
  - Easier to remove via in-plant control technologies (good)
- **Particulate-bound (Hg_p)**
  - Easily removed via particulate control devices
  - Very small % of Hg emissions

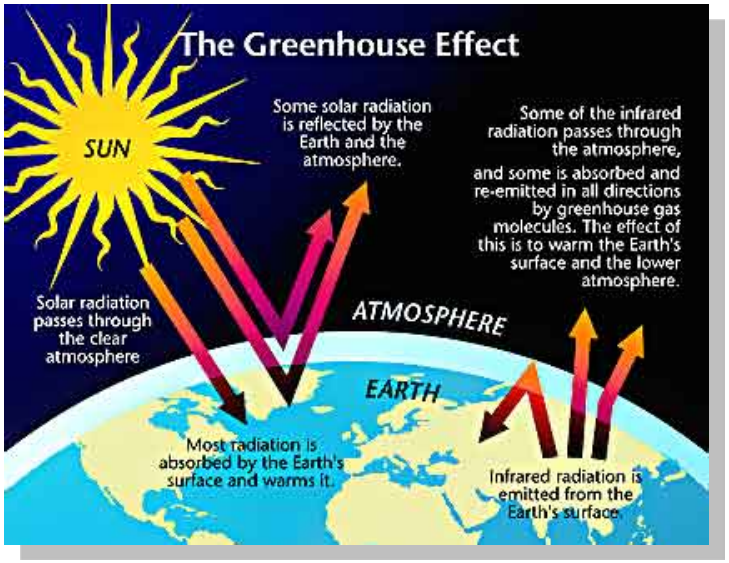


The form of Mercury is key to its deposition and control!

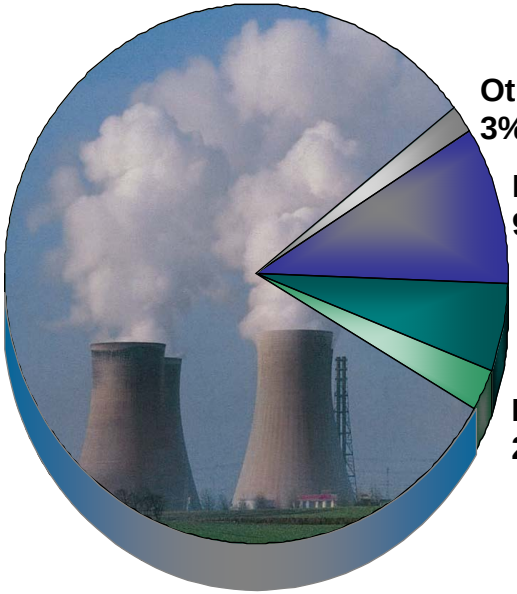
What about CO_2?

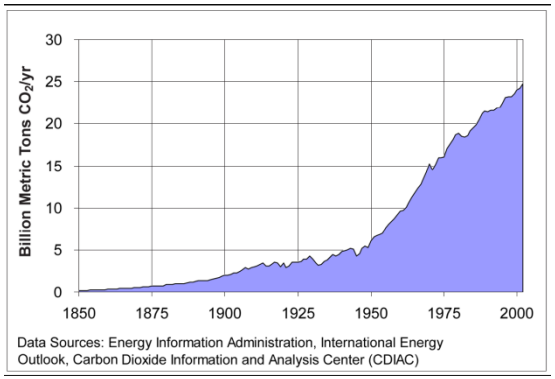
Gases that trap heat in the atmosphere are called greenhouse gases

- Carbon dioxide (CO_2)
- Methane (CH_4)
- Nitrous oxide (N_2O)
- Fluorinated gases



United States Greenhouse Gas Emissions
(Equivalent Global Warming Basis)





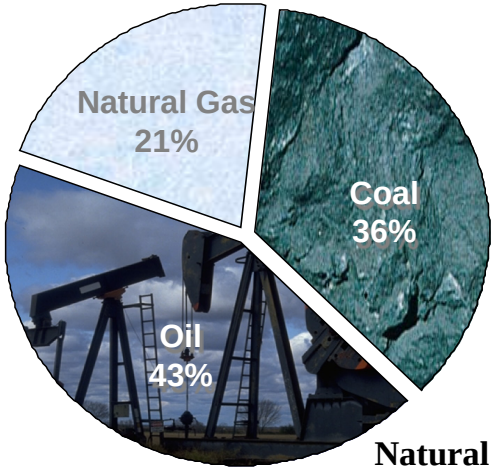
Worldwide CO_2 Emissions from Fossil Fuel Combustion and Cement Manufacture

"EIA Emissions of Greenhouse Gases in the U.S.: 2000"

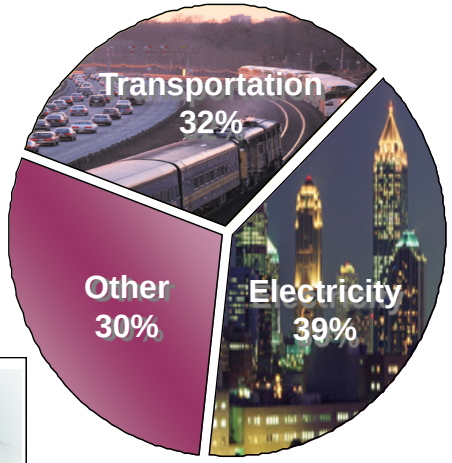
Anthropogenic CO_2 Emissions

All Fossil Fuels & Energy Sectors Contribute to U.S. CO_2 Emissions

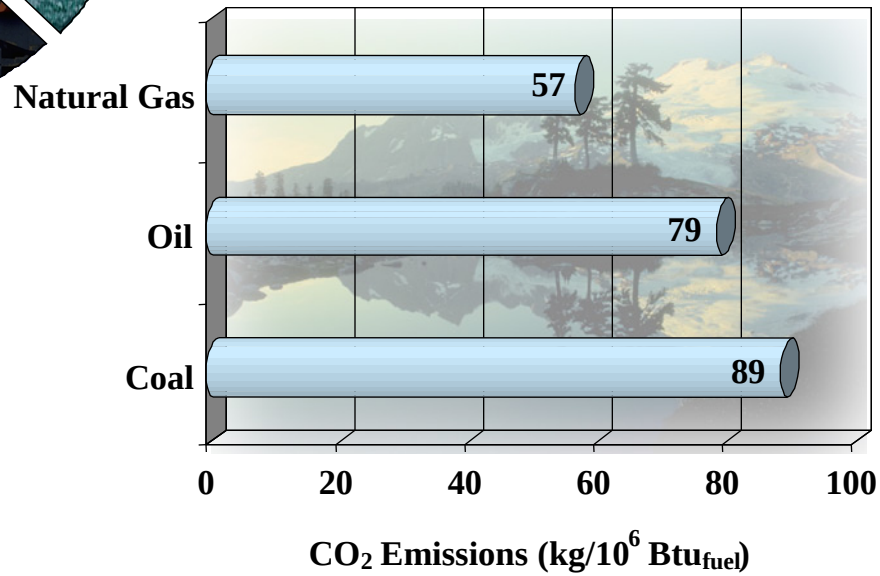
36% Emissions From Coal



39% Emissions From Electricity



CO_2 Intensity

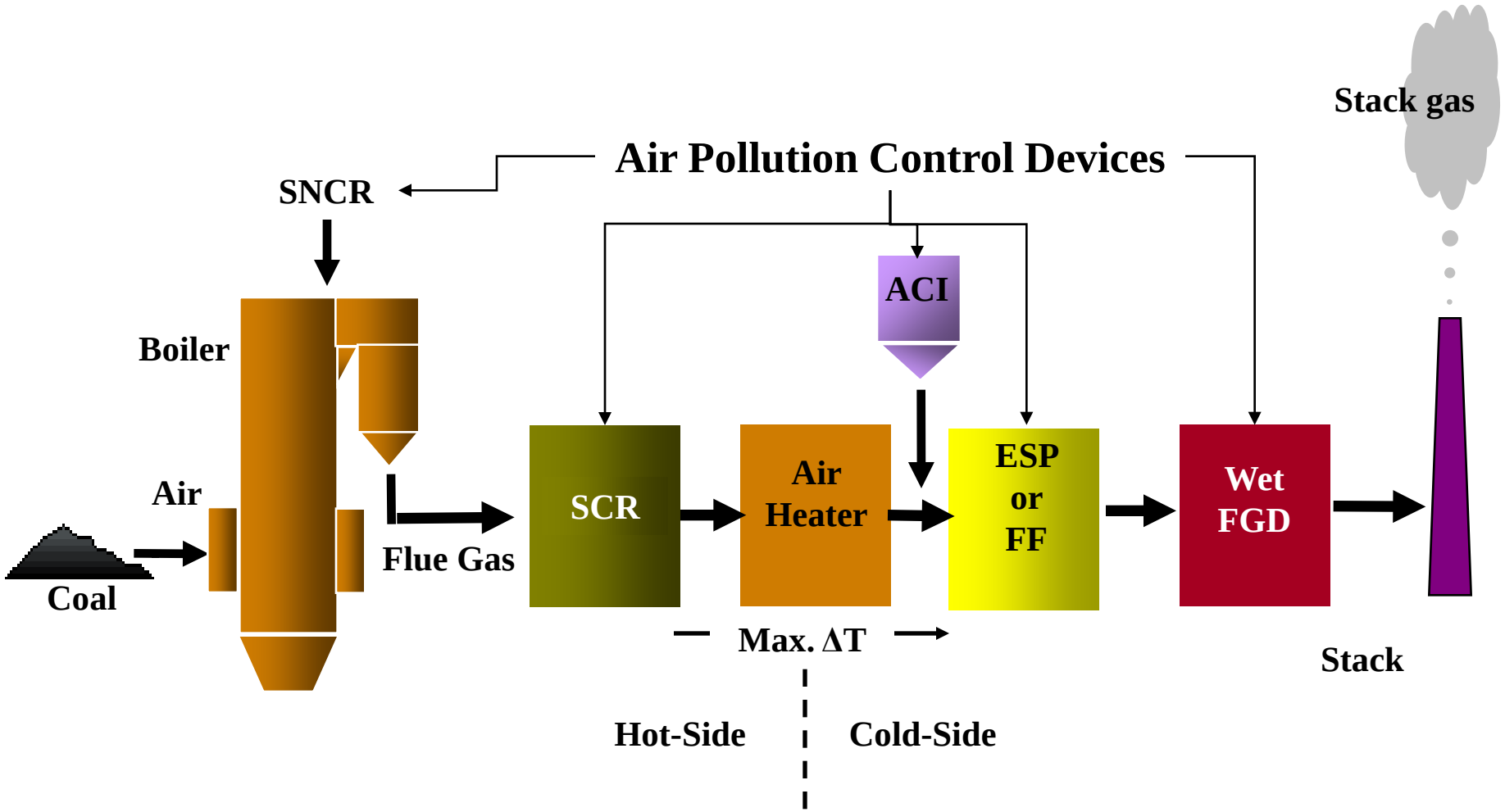


AEO2004

Environmental Issues 101
Presentation Outline

- **Coal combustion and resultant air pollutants**
- **Air pollution control devices**
- **Environmental regulatory requirements**
- **Supplemental Information**
  - Solid waste issues
  - Water issues

Coal-Fired Power Plant Flue Gas "Treatment Train"



NOx Control Technologies

In-Furnace Combustion Control

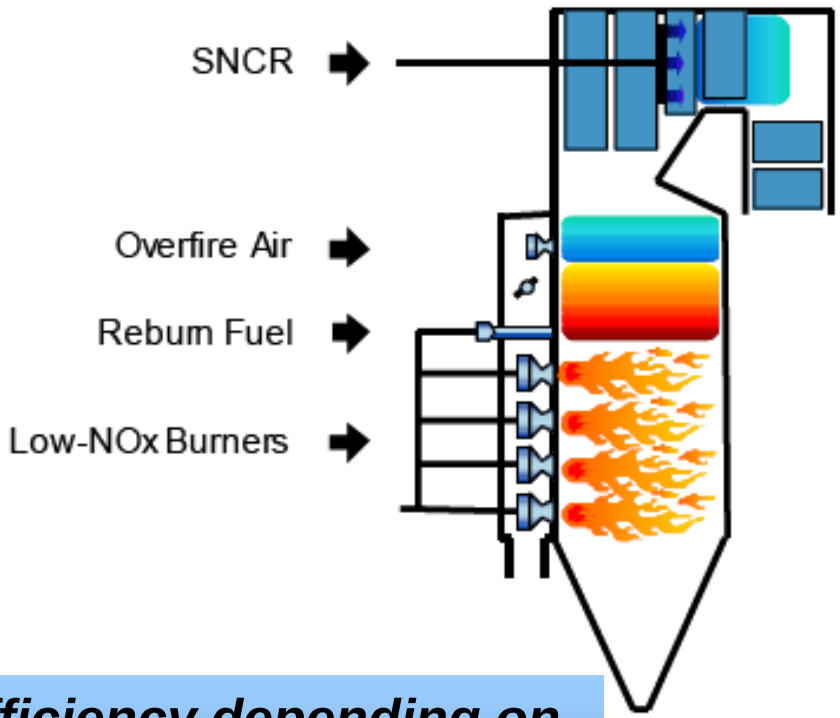
Principles of Control

- **Time**
- **Temperature**
- **Turbulence**

Technologies

- **Low NOx Burners (LNB)**
- **Overfire Air (OFA)**
- **Reburn**
- **Flue Gas Recirculation**

NOx Control Technologies

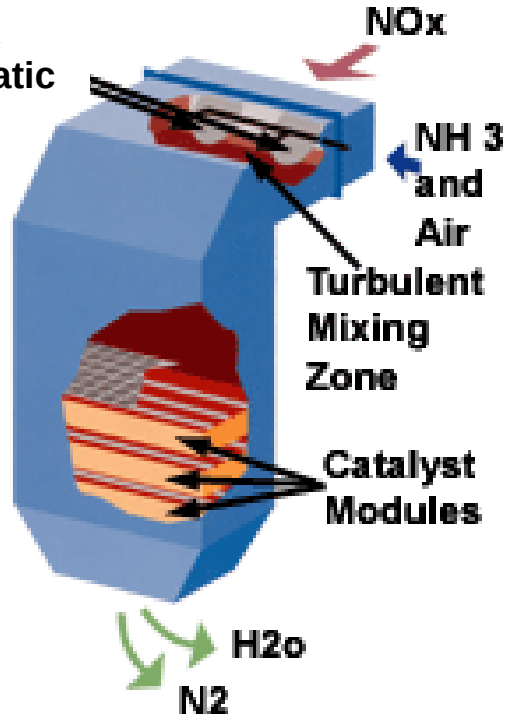


10 to 50% control efficiency depending on technology and type of boiler

NOx Control Technologies

Post-Combustion Control

SCR Schematic



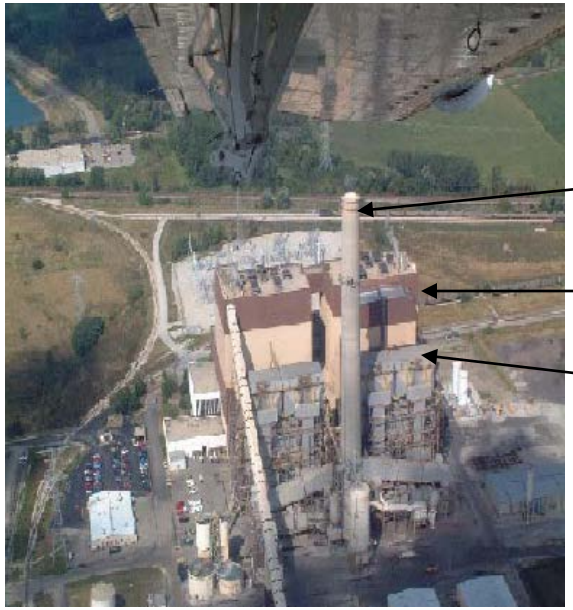
Control efficiency
SNCR: 30 to 50%
SCR: 80 to 90%

Principles of Control

- **NOx + Ammonia → Nitrogen + Water**

Technologies

- **Selective Non-Catalytic Reduction (SNCR)**
  - Most effective @ 900° – 1100° C
- **Selective Catalytic Reduction (SCR)**
  - Optimum @ 300° – 400° C



Particulate Matter Control Technologies

Principles of Control

- **Similar to household forced-air heating system – electronic air cleaner and air filter**

Technologies

- **Dry Electrostatic Precipitator (ESP)**
  - Used at > 70% of existing plants
    - Cold-side (> 60%)
    - Hot-side (~10%)
- **Fabric Filter**
  - More versatile & efficient than ESP
  - Higher O&M costs (bag replacement)
- **Wet Scrubber**
  - Older technology; less efficient
- **Wet Electrostatic Precipitator**
  - Very expensive; only a few in use

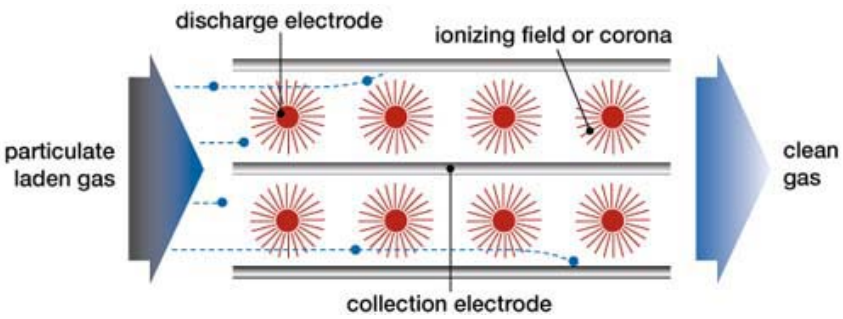
Dry Electrostatic Precipitator

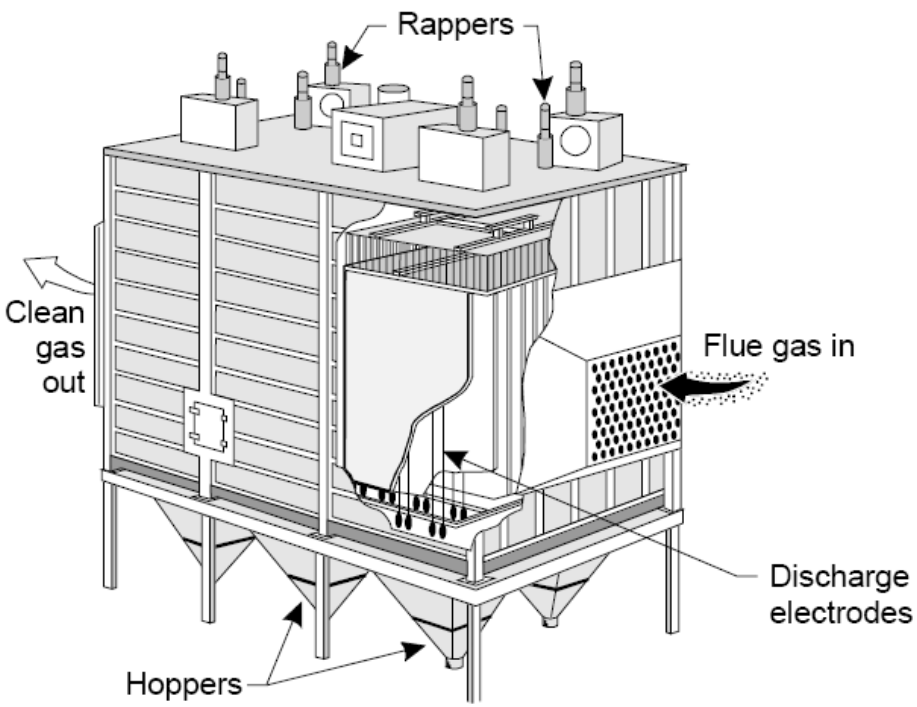
>99.5% control efficiency

Electrostatic Precipitator - Principle of Control

- **High voltage electrode imparts electrostatic charge on the ash particles**
- **Charged particles are attracted to and deposited on plates**

Top View of ESP Schematic Diagram

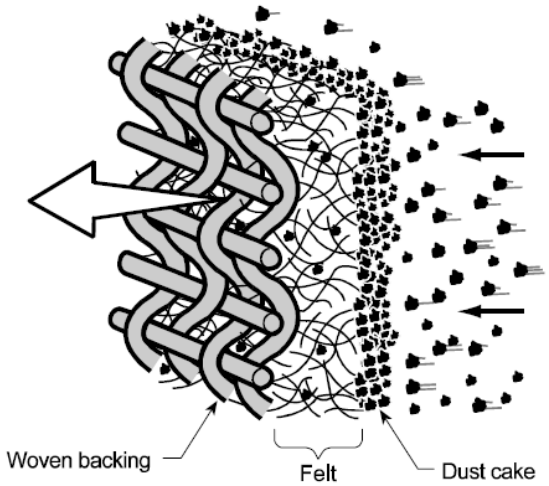


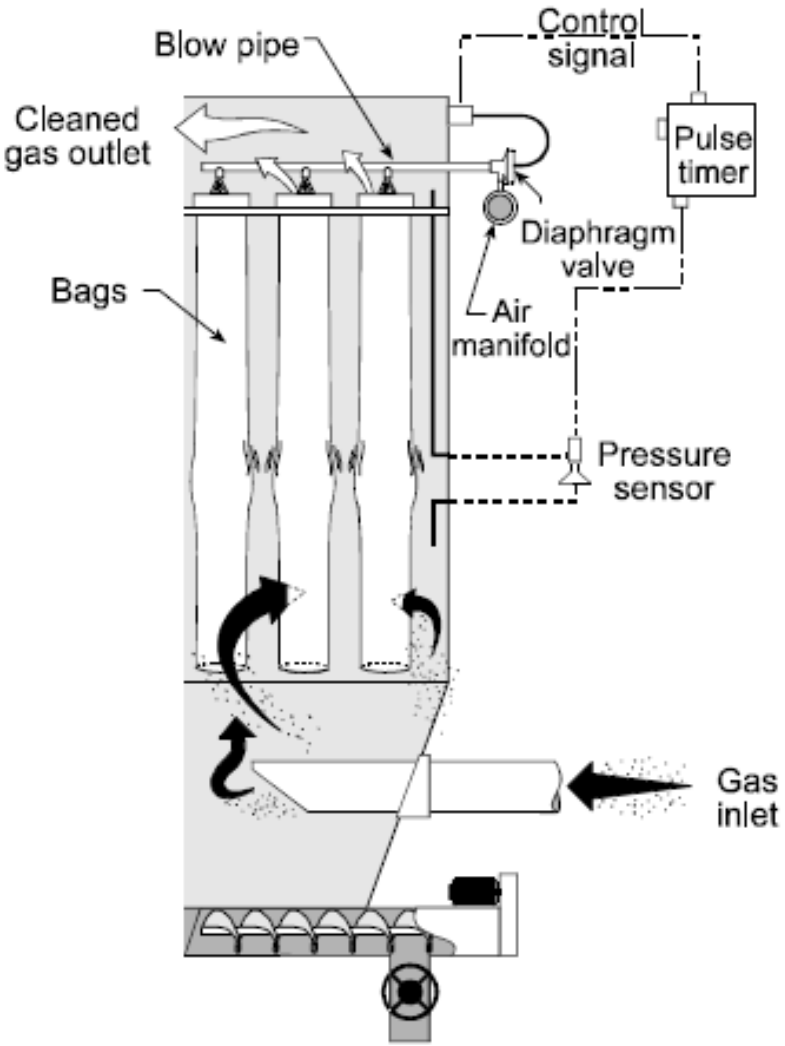


- **Rappers used to dislodge ash from collecting plates**
- **Ash is collected in hoppers and removed**

Fabric Filter - Principle of Control

- **Flue gas flows through filter bags where ash particles collect on the filter medium**
- **Filter bags are periodically cleaned**
  - Pulse-jet of air
  - Reverse gas flow
- **Ash is collected in hoppers and removed**





Pulse-Jet Fabric Filter Baghouse

SO_2 Control Technologies

Principles of Control

- **Acid + Base → Salt**
  - Acid: SO_2 + water → sulfuric acid
  - Base: lime or limestone
  - Salt: calcium sulfite or calcium sulfate (gypsum)

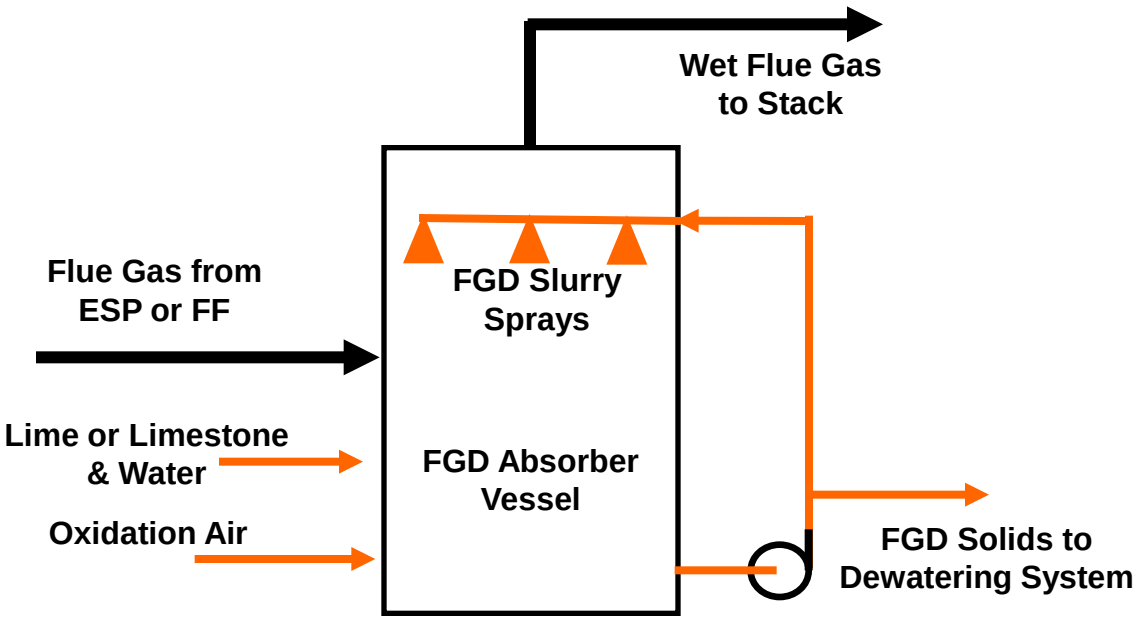
Technologies

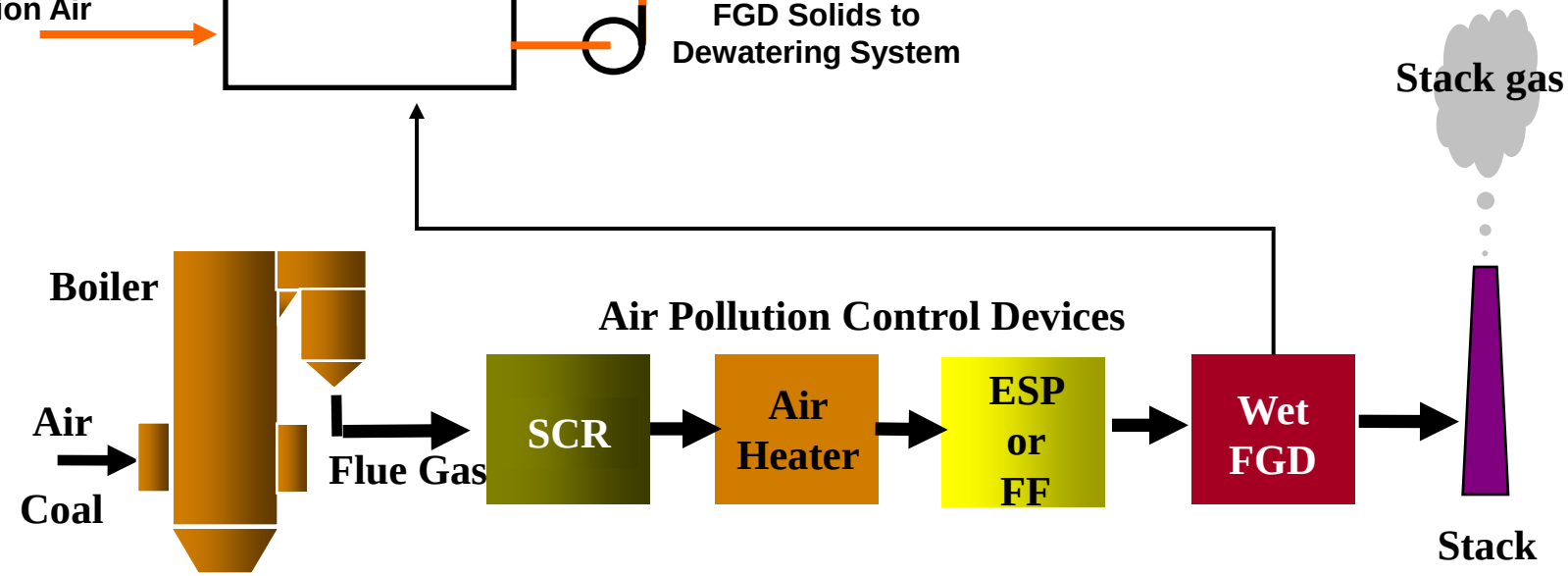
- **Wet Flue Gas Desulfurization (Wet FGD)**
  - Lime; Magnesium-enhanced lime
  - Limestone

- **Dry Flue Gas Desulfurization (Dry FGD)**
  - Hydrated Lime
  - Just enough water to distribute spray across flue gas stream (water evaporates)

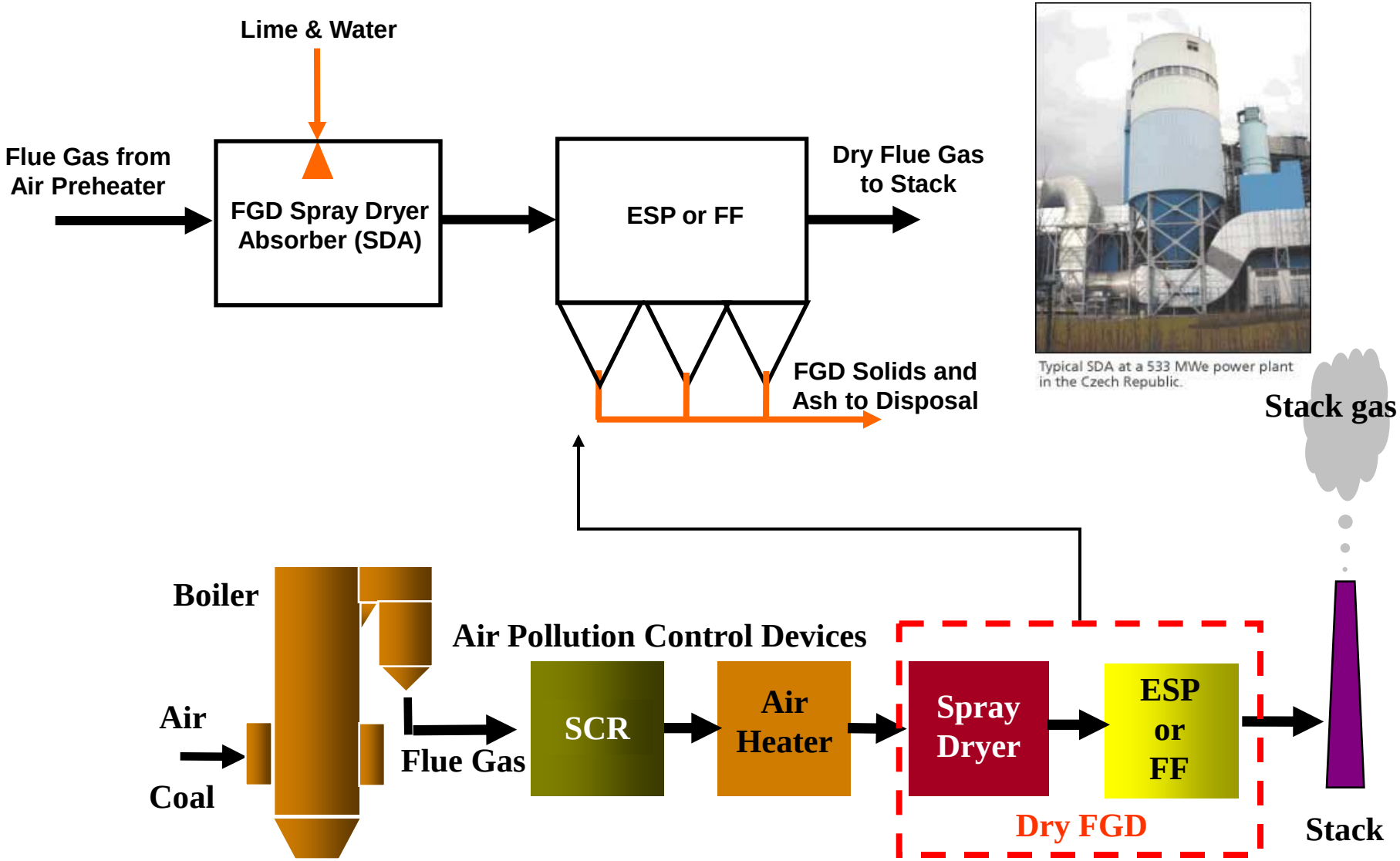
90 - 95% control efficiency

Wet FGD Process Schematic





Dry FGD Process Schematic



Mercury Control Technologies

Principles of Control

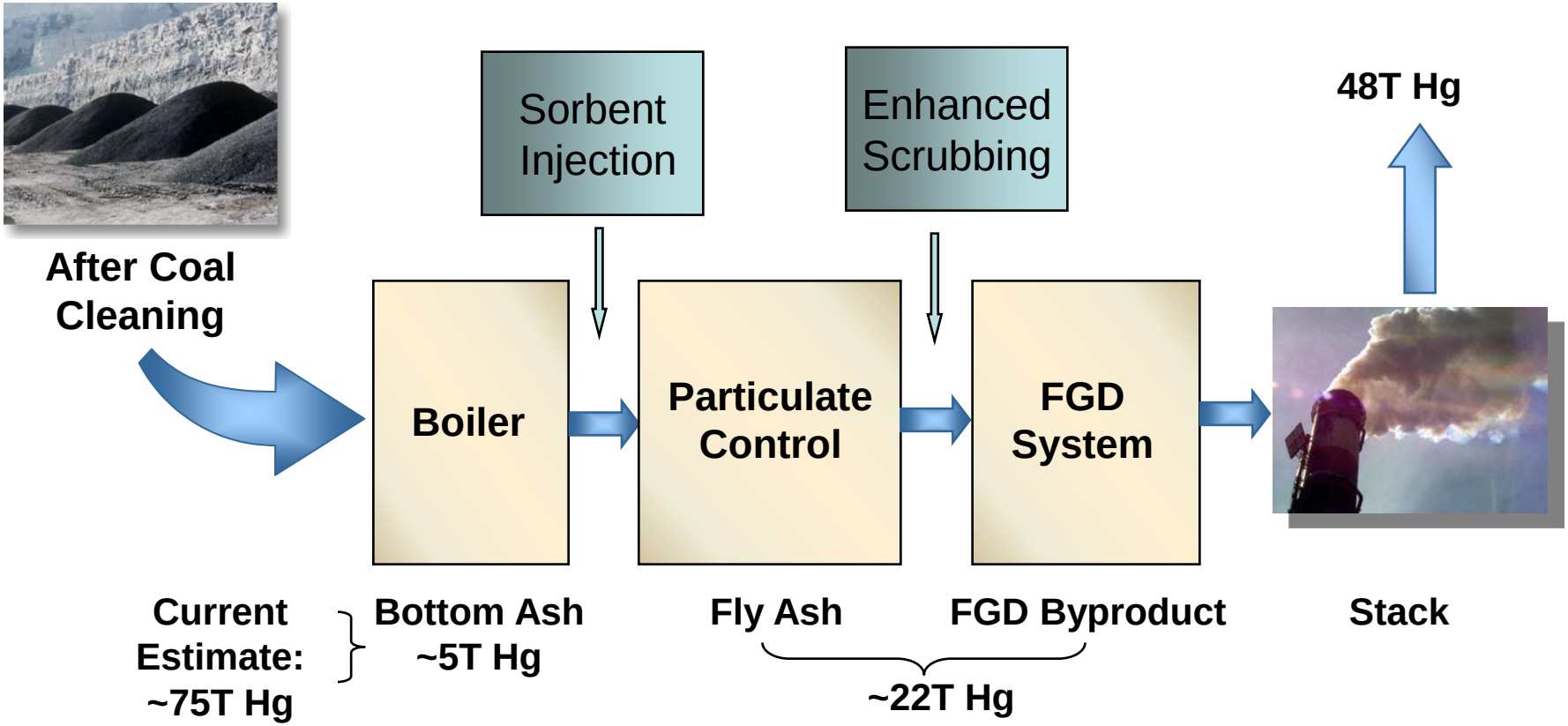
- **Co-benefit Hg capture**
  - Hg oxidation across SCR
  - Hg capture via PM control device
  - Hg capture via wet FGD
- **Hg+ adsorbent**

Technologies

- **Sorbent injection**
  - Activated carbon injection (ACI)
  - Halogenated ACI
  - Other sorbents
- **Enhanced Wet FGD**
  - Hg oxidation additives

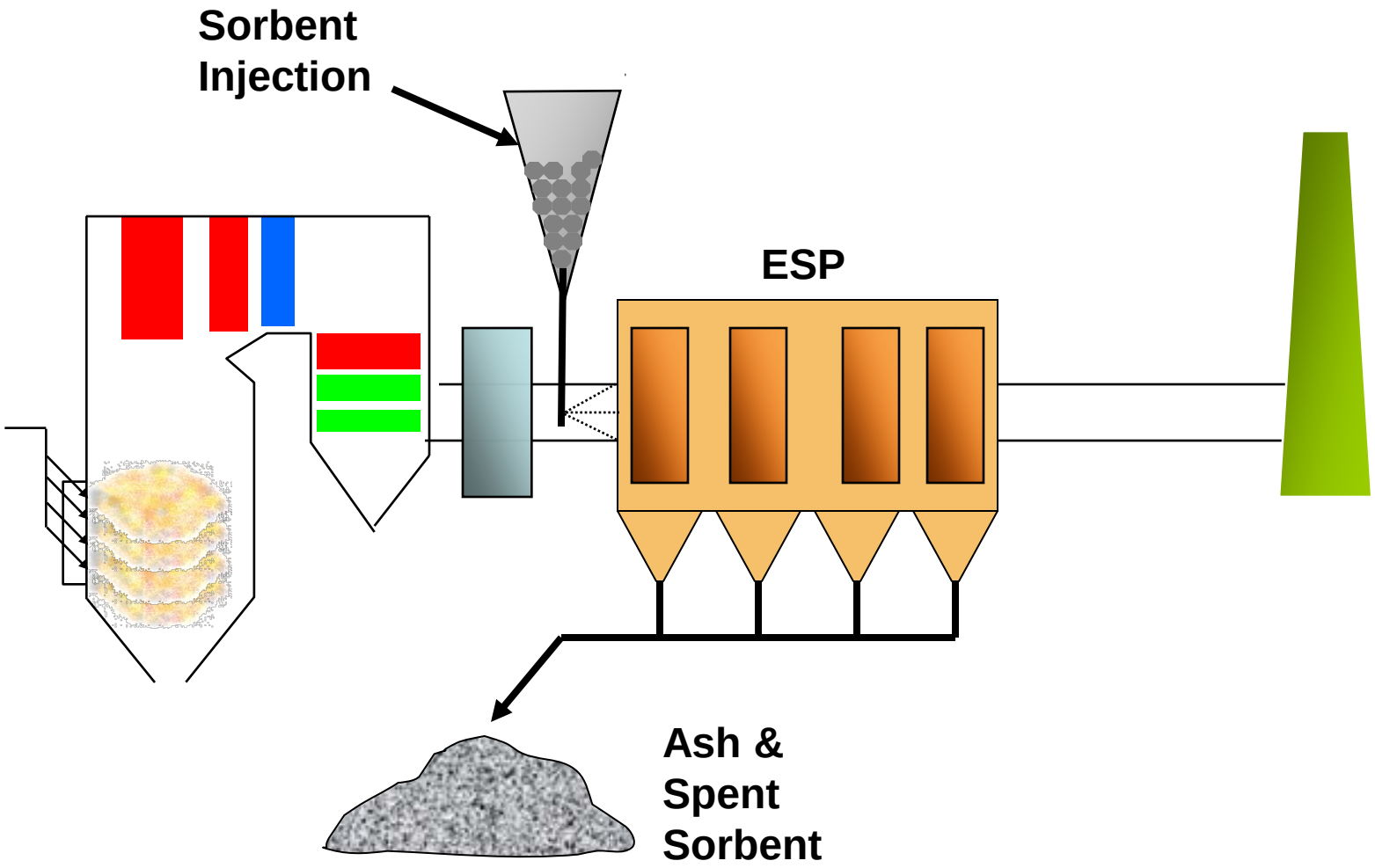
50 to +90% control efficiency depending on technology and coal rank

Mercury Partitioning in Coal Power Plants

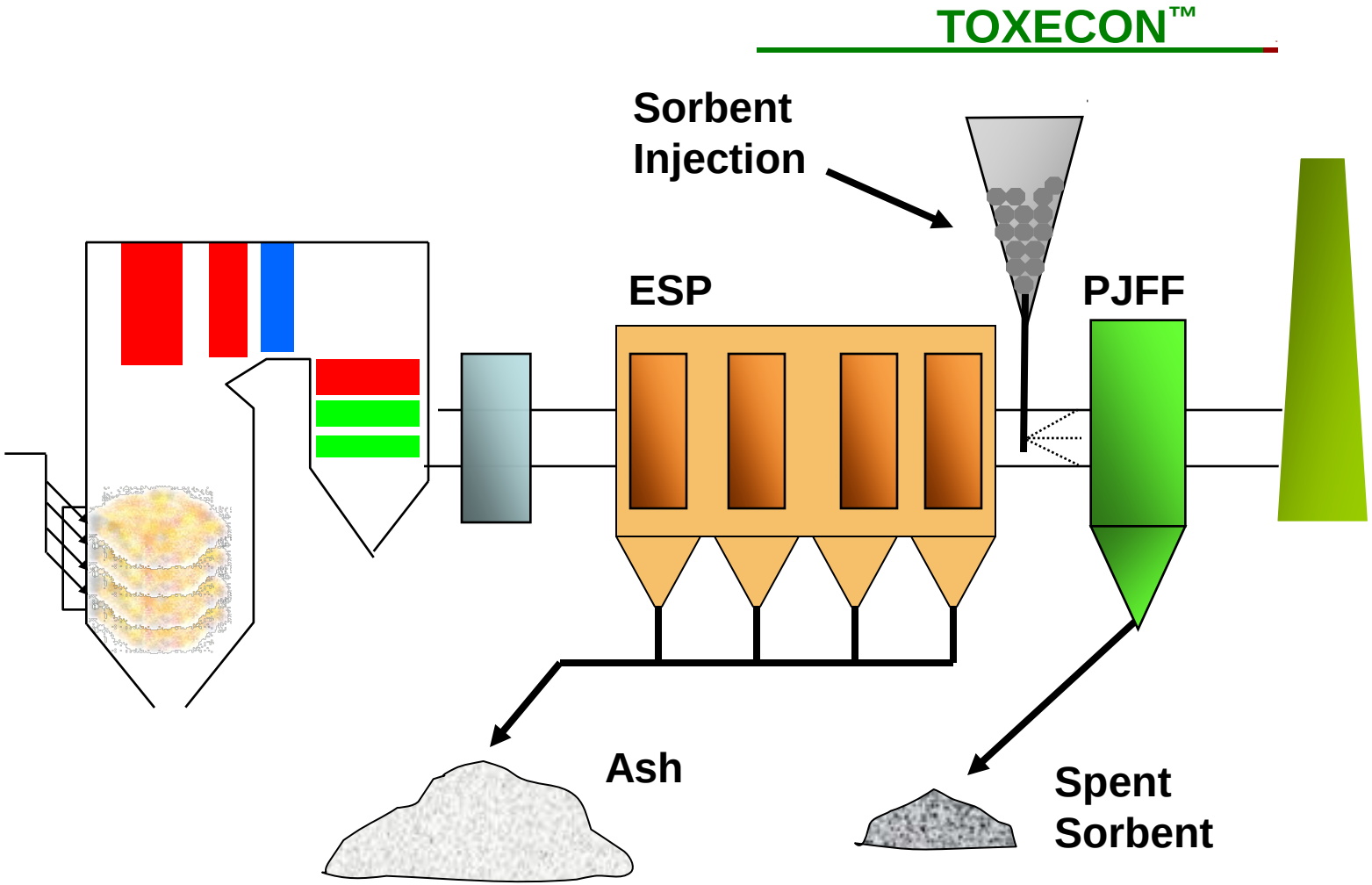


50 to +90% control efficiency depending on technology and coal rank

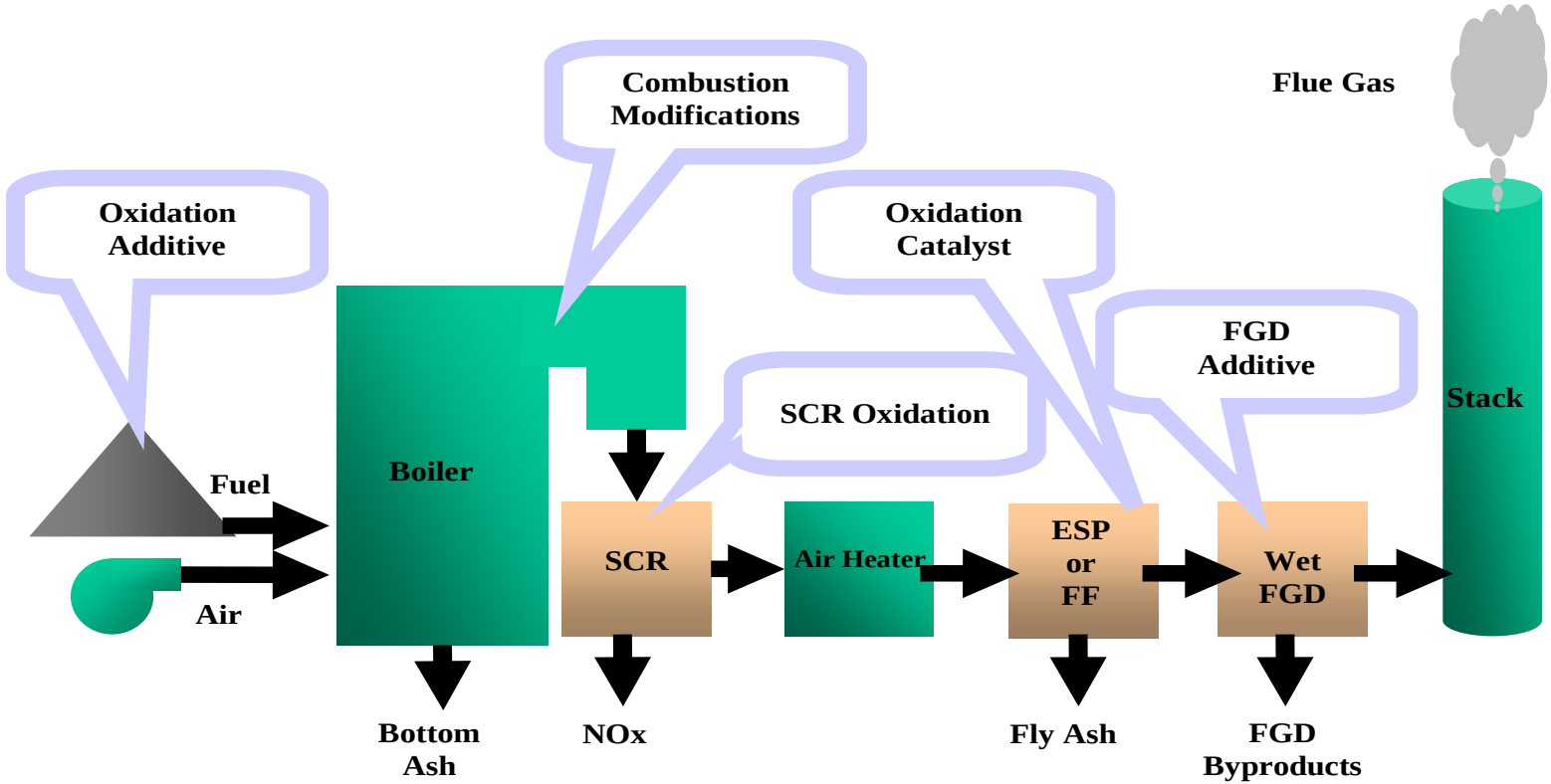
Sorbent Injection Configuration



TOXECON™ Configuration

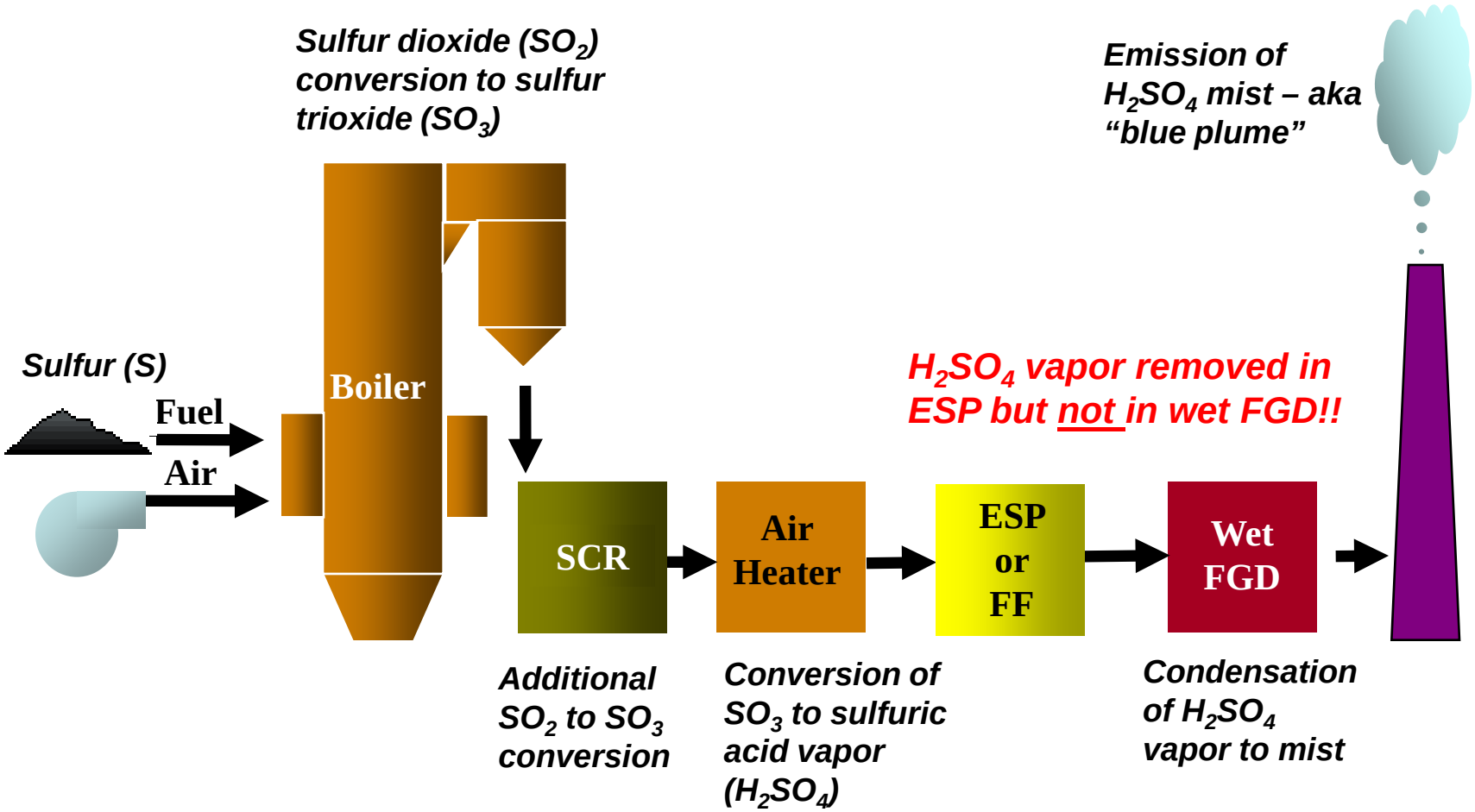


Enhancing Mercury Removal with FGD

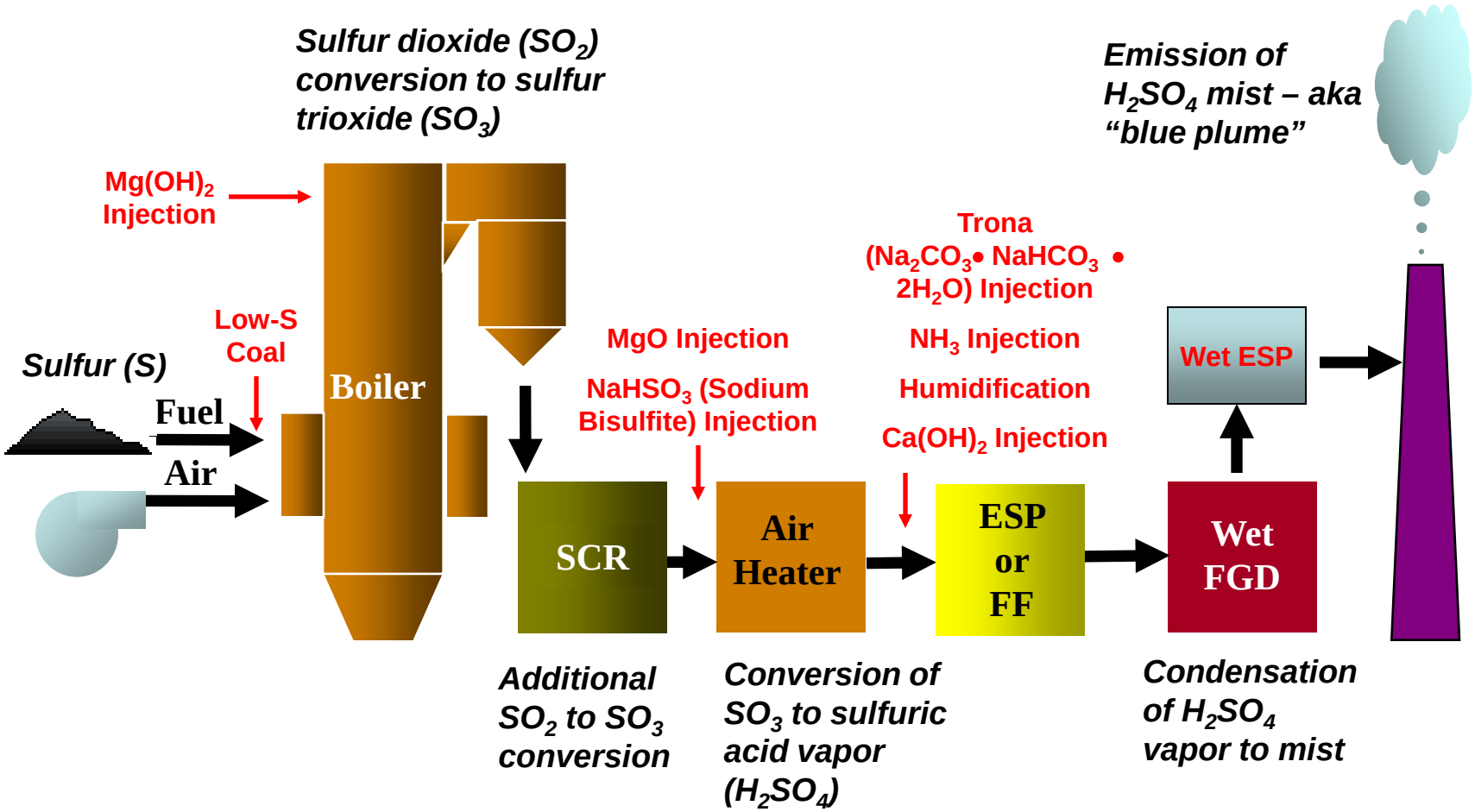


- ***Oxidized mercury (Hg^{2+}) is removed across wet FGD systems***
- ***Multiple possibilities for enhancing mercury oxidation***
- ***Ensure that captured mercury is not re-emitted from FGD***

Formation of SO_3/H_2SO_4 Emissions from a Coal-Fired Power Plant



SO_3/H_2SO_4 Emissions Control Options



Summary - Air Pollution Control Devices on U.S. Coal-Fired Power Plants

	MW	No. Units	% Total MW	% Total Units
PM Controls				
Cold-side ESP	228,958	767	74%	59%
Hot-side ESP	32,453	121	10%	9%
Fabric Filter	32,187	164	10%	13%
Wet Scrubber	6,290	17	2%	1%
Cyclone	718	7	0%	1%
Not Specified	9,108	220	3%	17%
Total PM	309,714	1,296	100%	100%
SO2 Controls				
Wet Scrubber	129,445	289	42%	22%
Dry Scrubber	15,176	51	5%	4%
Reagent injection	5,828	75	2%	6%
Total SO2	150,450	415	49%	32%
Post-Combustion NOx Controls				
SCR	100,099	199	32%	15%
SNCR	18,358	100	6%	8%
Total NOx	118,457	299	38%	23%
Total Coal	**309,714**	**1,296**		

All plants have PM Controls

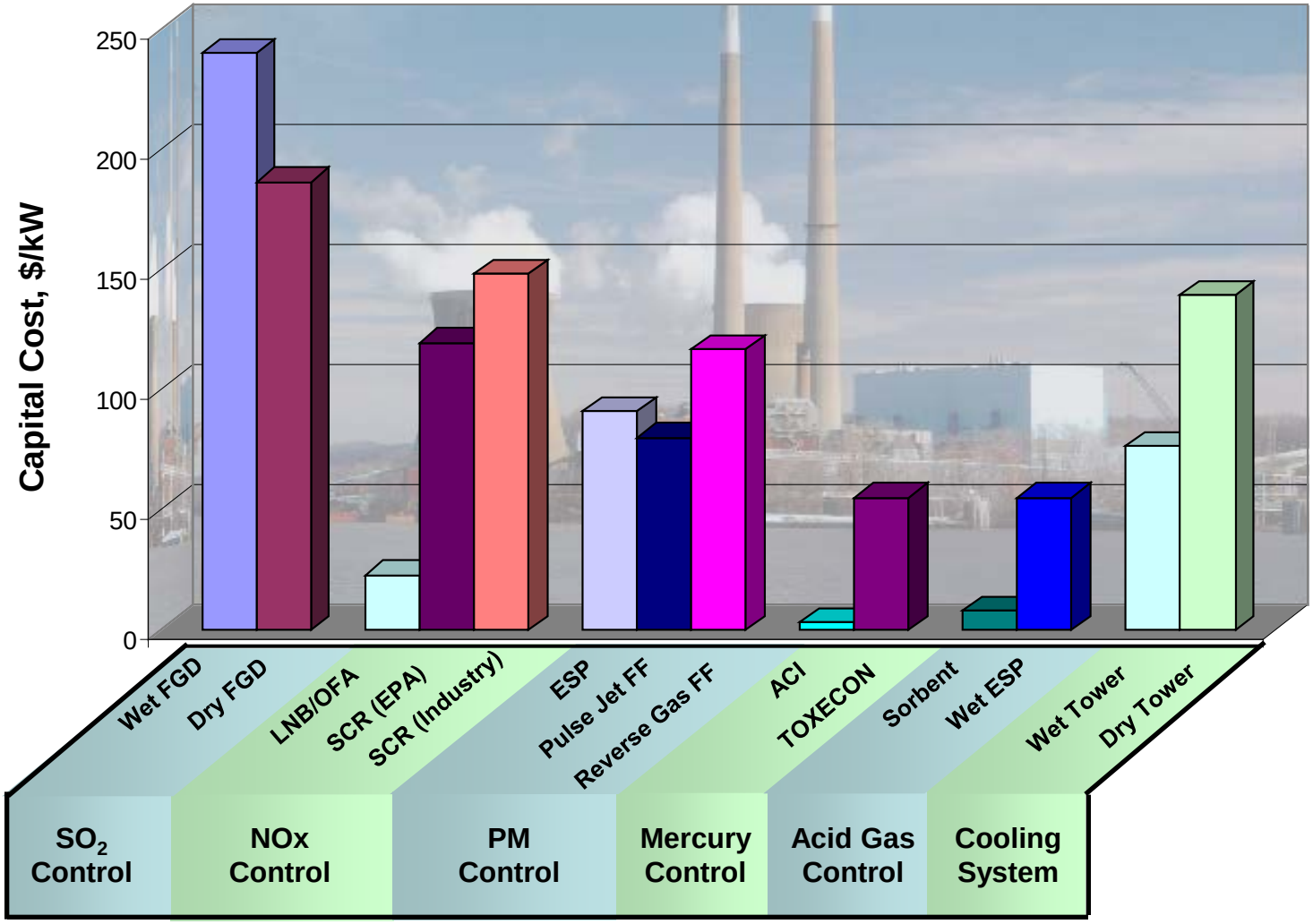
~50% of capacity has SO_2 controls

~40% of capacity has SCR or SNCR

>70% of capacity has Low-NOx burners (ASME, 2005)

Source: EPA's National Electrical Energy Data System for 2006 (NEEDS 2006)

Estimated Capital Cost for Environmental Controls



Estimated costs for reference 500-MW coal-fired power plant – 2005$.

Technological Carbon Management Options

Pathways for Reducing GHGs -CO_2

Reduce Carbon Intensity

- Renewables
- Nuclear
- Fuel Switching

Improve Efficiency

- Demand Side
- Supply Side

Sequester Carbon

- Enhance Natural Sinks
- Capture & Store

All options needed to:

- Affordably meet energy demand
- Address environmental objectives

What is Carbon Sequestration?

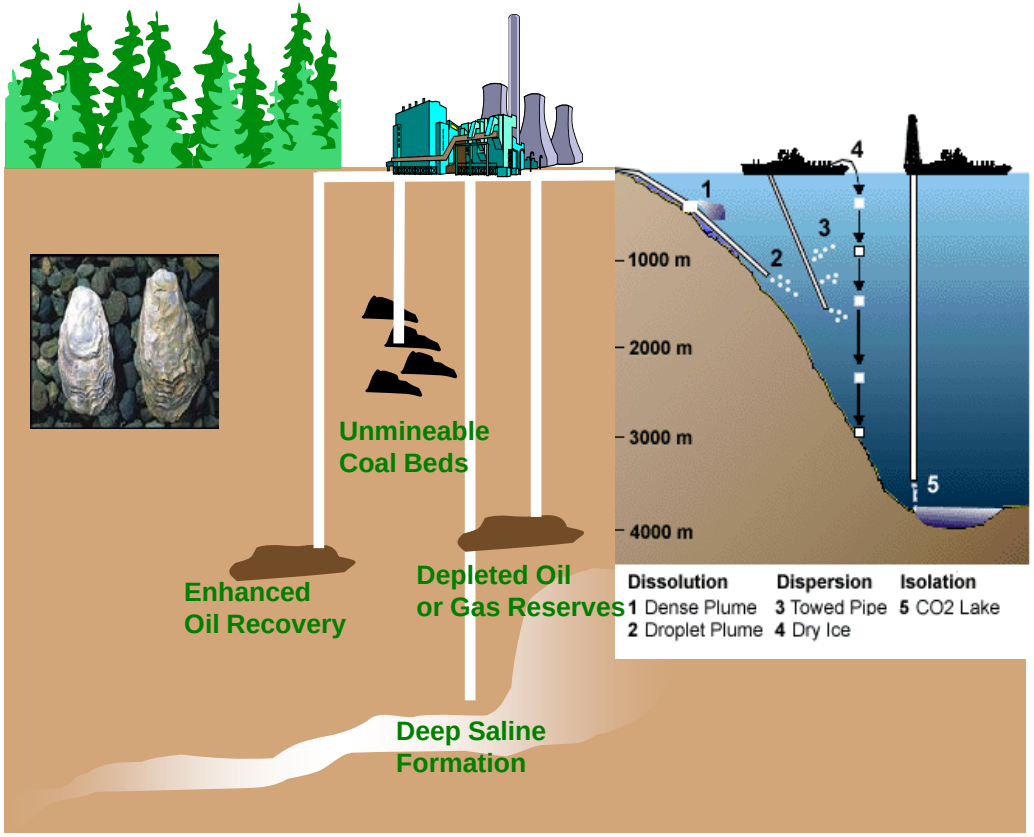
Capture and storage of CO_2 and other Greenhouse Gases that would otherwise be emitted to the atmosphere

Capture can occur:

- at the point of emission
- when absorbed from air

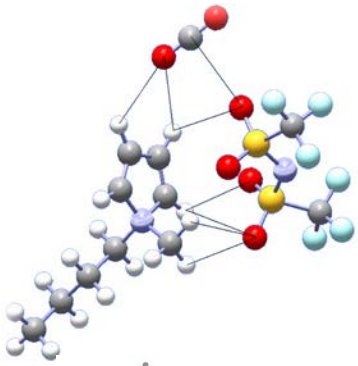
Storage locations include:

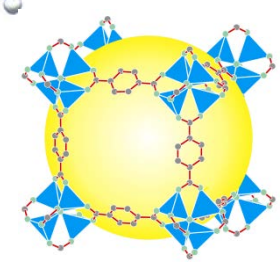
- underground reservoirs
- converted to solid materials
- trees, grasses, soils, or algae
- dissolved in deep oceans

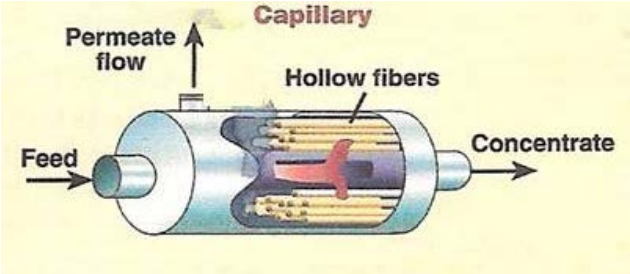


CO_2 Capture Technologies

1) Solvents
2) Sorbents
3) Membranes
4) Oxy-combustion
5) Chemical looping
6) Compression

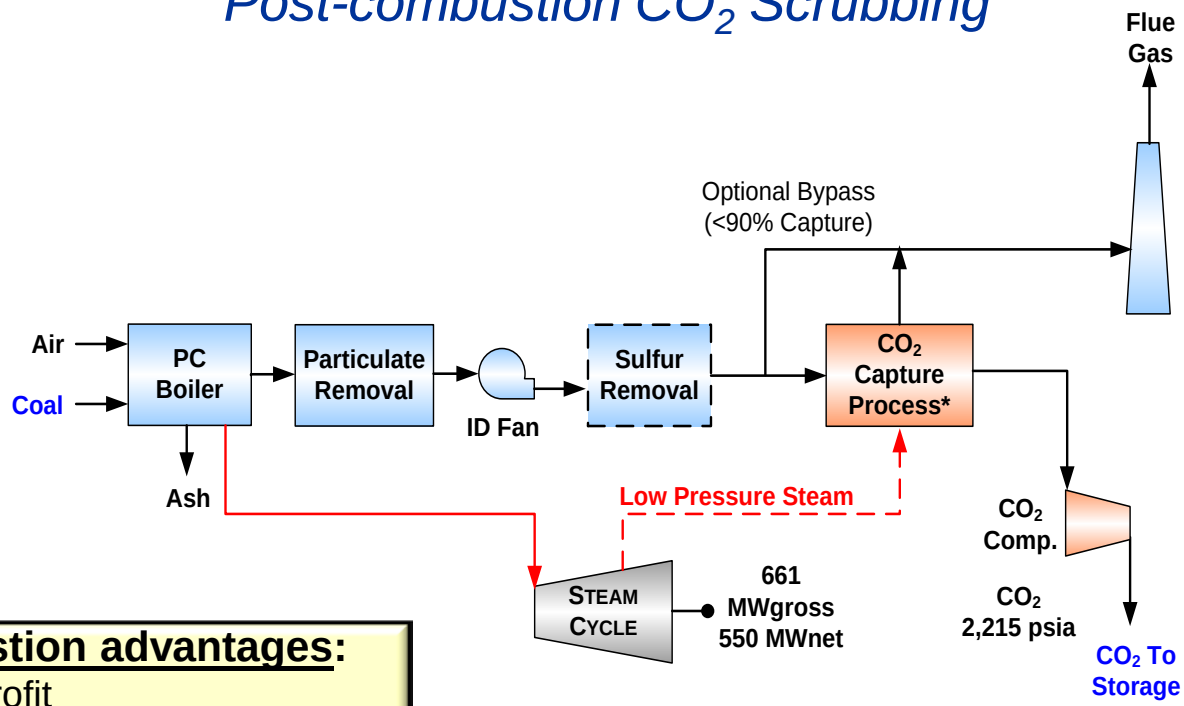






Pulverized Coal Power Plant System

Post-combustion CO_2 Scrubbing



Post-combustion advantages:

- Back-end retrofit
- Slip-stream (0 to 90% capture)

Amine scrubbing advantages:

- Proven technology (Petroleum refining, NG purification)
- Chemical solvent → High loadings at low CO_2 partial pressure
- Relatively cheap chemical ($2-3/lb)

Key Challenges:

- Dilute flue gas (12-15 volume %)
- 2-3 MM acfm for a 500-600 MWe plant
- ~50% currently scrubbed for SOx/NOx
- Increased cooling requirements

Two-step separation process requiring 5 energy inputs:

Energy = Q (sensible) + Q (reaction) + Q (stripping) + W (Process) + W (Comp.)

ALL must be reduced in order to significantly reduce Capture COE impact!

Deployment Barriers for CO_2 Capture On New and Existing Coal Plants Today

1. **Scale-up**
   - Current Post Combustion capture ~200 TPD
   - 550 MWe power plant produces 13,000 TPD
2. **Energy Penalty**
   - 20% to 30% less power output
3. **Cost**
   - Increase Cost of Electricity by 80%
   - Adds Capital Cost by $1,500 - $2,000/KW
4. **Regulatory framework**
   - Transport — pipeline network
   - Storage
5. **Economies of Scale**
   - Land, power, water use, transportation, process components, …

Environmental Issues 101
Presentation Outline

- **Coal combustion and resultant air pollutants**
- **Air pollution control devices**
- **Environmental regulatory requirements**
- **Supplemental Information**
  - Solid waste issues
  - Water issues

History of the Clean Air Act

1955
- *Air Pollution Control Act* funded air pollution research

1963
- First *Clean Air Act* authorized a national program to address air pollution related environmental problems

1967
- *Air Quality Act* authorized enforcement procedures for air pollution problems

1970
- *Clean Air Act* authorized National Ambient Air Quality Standards, requirements for State Implementation Plans, New Source Performance Standards (new and modified stationary sources), National Emission Standards for Hazardous Air Pollutants, and control of motor vehicle emissions.
- Increased enforcement authority

1971
- EPA was established to implement *Clean Air Act of 1970*

1977
- Amendments regulate high emitting older industrial facilities exempted by the *Clean Air Act of 1970*

1990
- Amendments expand National Ambient Air Quality Standards, establish a program to phase out ozone layer depleting chemicals, establish a program to control 189 toxic pollutants, and further increase enforcement authority

Source: US EPA, 2010. History of the Clean Air Act. http://www.epa.gov/air/caa/caa_history.html (Accessed June 10, 2011).

1990 Clean Air Act Amendments

- ***Title I – National Ambient Air Quality Standards (NAAQS)***
- ***Title III – Hazardous Air Pollutants***
  - Addressed air toxic emissions from coal-fired power plants
  - Primary issue: Mercury
- ***Title IV – Acid Deposition Control***
  - NOx emissions control
    - Two phase implementation – 1996 and 2000
    - Boiler-type specific NOx emission rates – 0.40 to 0.86 lb/MMBtu
  - SO_2 emissions control via cap-and-trade program
    - Two phase implementation – 1995 and 2000
    - National emissions cap equivalent to 2.5 lb/MMBtu in 1995 and 1.2 lb/MMBtu in 2000
  - Required installation of stack continuous emission monitors
- ***Title V – Operating Permits***
  - Considerable authority given to states & localities

Compliance Options Under a Cap-and-Trade Program

- **Power plant must possess one allowance for each ton of emissions**
- **EPA and/or States allocate allowances to individual plants**
- **Three main compliance options:**
  - Install expensive, high-performance controls to “over-comply;” sell unused allowances to pay for controls
  - No controls or low-cost “moderate” controls; buy additional allowances
  - Curtail operations or shut down plant
- **Some plants must over comply or shut down to generate a supply of allowances for sale in the market**

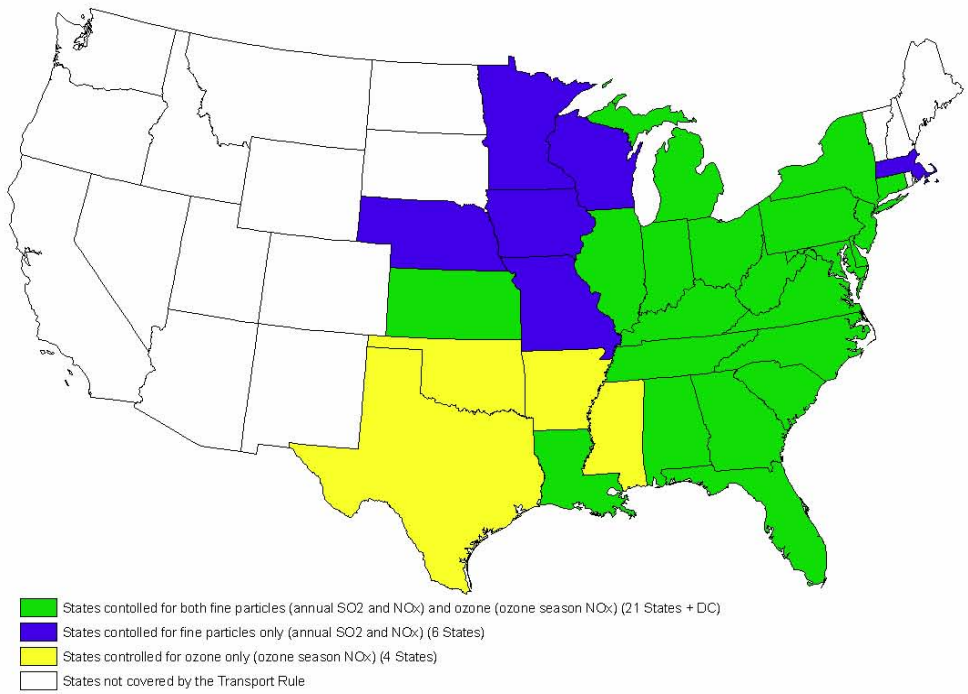
Proposed Transport Rule

Background

- *CAIR remanded back to EPA in December 2008*
  - *CAIR requirements remain in effect*
- *Transport Rule proposed by EPA on July 6, 2010 to replace CAIR*
- *Final Transport Rule expected in 2011*

Framework

- *Reduce interstate transport of SO_2 and NOx emissions*
- *Two phases (2012 & 2014)*
- *By 2014:*
  - *71% reduction in SO_2*
  - *52% reduction in NOx (based on 2005 levels)*



Utility MACT Rule

MACT Rule proposed on May 3, 2011
Currently under 90-day public review to replace CAMR (vacated Feb. 2008)
Final MACT Rule expected November 2011

- MACT floors based on top 12% best-performing units
- Includes start-up, shutdown & malfunctions
- Total PM a surrogate for non-Hg metallic HAPs (As, Cd, Cr, Mn, Ni, Pb)
- HCl a surrogate for acid gas HAPs (HF, HCN)
- Three-year window to comply with MACT standards

Subcategory	Unit Type	Total Particulate Matter	Hydrogen Chloride	Mercury
Units designed for coal ≥ 8,300 Btu/lb	Existing	0.03 lb/MMBtu (0.3 lb/MWh)	0.002 lb/MMBtu (0.02 lb/MWh)	1.2 lb/Tbtu (0.013 lb/GWh)
	New	0.05 lb/MWh	0.3 lb/GWh	0.0002 lb/GWh
Units designed for coal < 8,300 Btu/lb	Existing	0.03 lb/MMBtu (0.3 lb/MWh)	0.002 lb/MMBtu (0.02 lb/MWh)	4.0 lb/Tbtu* (0.04 lb/GWh)*
	New	0.05 lb/MWh	0.3 lb/GWh	0.04 lb/GWh
IGCC	Existing	0.05 lb/MMBtu (0.3 lb/MWh)	0.0005 lb/MMBtu (0.003 lb/MWh)	3.0 lb/Tbtu (0.02 lb/GWh)
	New	0.050 lb/MWh*	0.30 lb/GWh*	0.0002 lb/GWh*

* Beyond-the-floor standards

Regional Haze Rule

- **Goal to improve visibility in national parks and wilderness areas to pristine conditions within 60 years**

- **On October 5, 2006, EPA finalized requirements for an emissions trading program that provides states and tribes with a process to show that an emissions trading program may be used as an alternative to applying Best Available Retrofit Technology Requirements (BART) to improve visibility in specially protected areas.**

Great Smoky Mountains National Park

… on a clear day

… on a hazy day

New Source Performance Standards (NSPS)

- **Sets a specific numerical level of control for PM, SO_2, and NOx for all new, reconstructed, and modified sources of air pollution**

- **Level varies based on plant build date**
  - after August 17, 1971
  - after September 28, 1978
  - after February 28, 2005

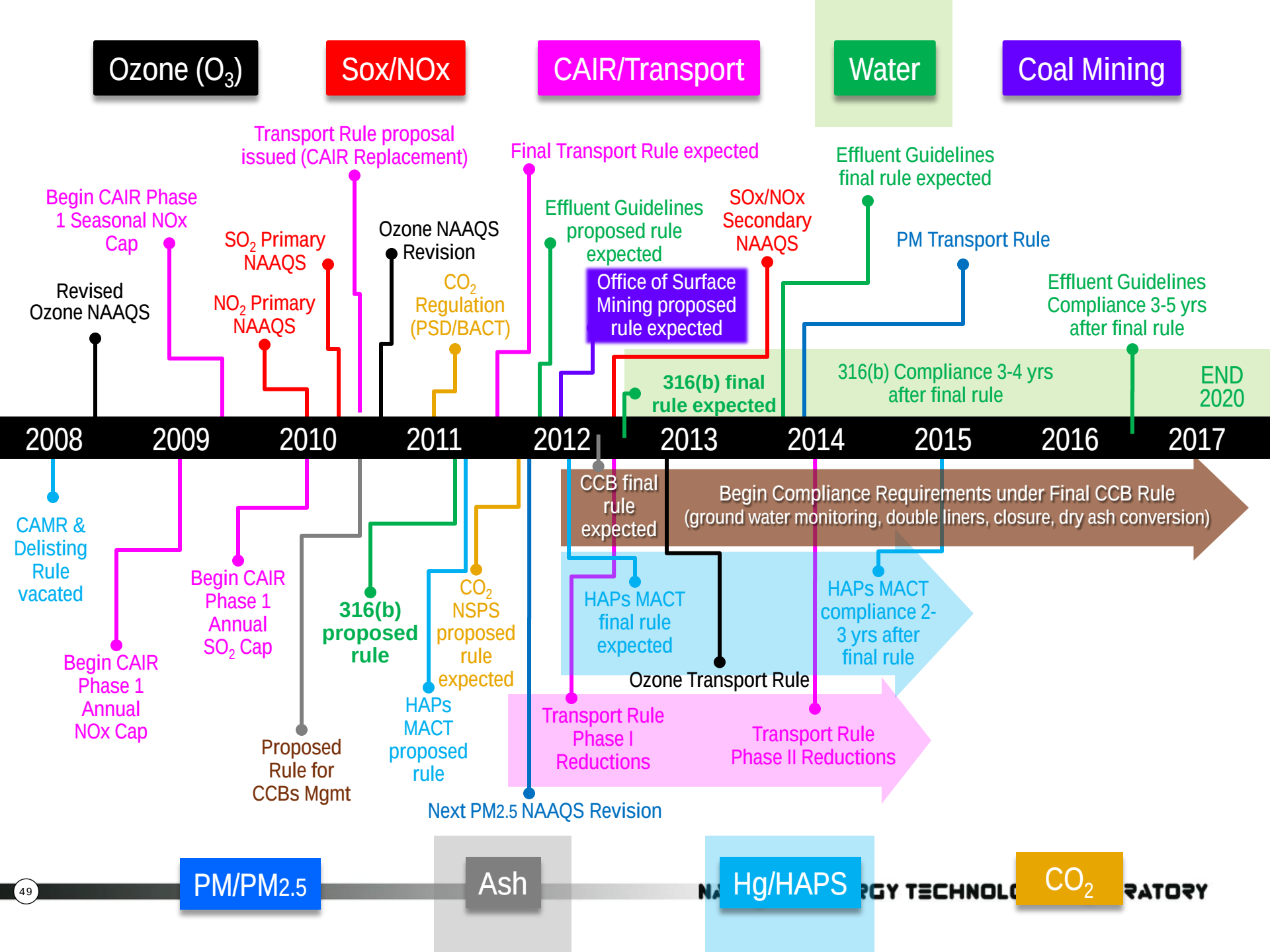
Greenhouse Gas (GHG) NSPS

Overview

- Genesis is “Endangerment Finding” on December 5, 2009
- Thresholds re-defined through the “Tailoring Rule” issued June 3, 2010
- GHG BACT guidance published November 17, 2010
- GHG NSPS framework evolves from lawsuit settlements on December 23, 2010
  - Proposed rule due September 30, 2011 (due date was originally July 26, 2011)
  - Deadline for final standards remains May 26, 2012

Framework Speculation

- NGCC base case
- Efficiency standards for existing units
- Cap-and-Trade
- Averaging across units at single site


Ozone (O_3)
Sox/NOx
CAIR/Transport
Water
Coal Mining
Transport Rule proposal issued (CAIR Replacement)
Final Transport Rule expected
Effluent Guidelines final rule expected
Begin CAIR Phase 1 Seasonal NOx Cap
SO_2 Primary NAAQS
Ozone NAAQS Revision
Effluent Guidelines proposed rule expected
SOx/NOx Secondary NAAQS
PM Transport Rule
Revised Ozone NAAQS
NO_2 Primary NAAQS
CO_2 Regulation (PSD/BACT)
Office of Surface Mining proposed rule expected
Effluent Guidelines Compliance 3-5 yrs after final rule
316(b) final rule expected
316(b) Compliance 3-4 yrs after final rule
END 2020
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
CCB final rule expected
Begin Compliance Requirements under Final CCB Rule (ground water monitoring, double liners, closure, dry ash conversion)
CAMR & Delisting Rule vacated
Begin CAIR Phase 1 Annual SO2 Cap
Begin CAIR Phase 1 Annual NOx Cap
316(b) proposed rule
CO_2 NSPS proposed rule expected
HAPs MACT final rule expected
HAPs MACT compliance 2-3 yrs after final rule
Ozone Transport Rule
Proposed Rule for CCBs Mgmt
HAPs MACT proposed rule
Transport Rule Phase I Reductions
Transport Rule Phase II Reductions
Next PM2.5 NAAQS Revision
PM/PM2.5
Ash
Hg/HAPS
CO_2

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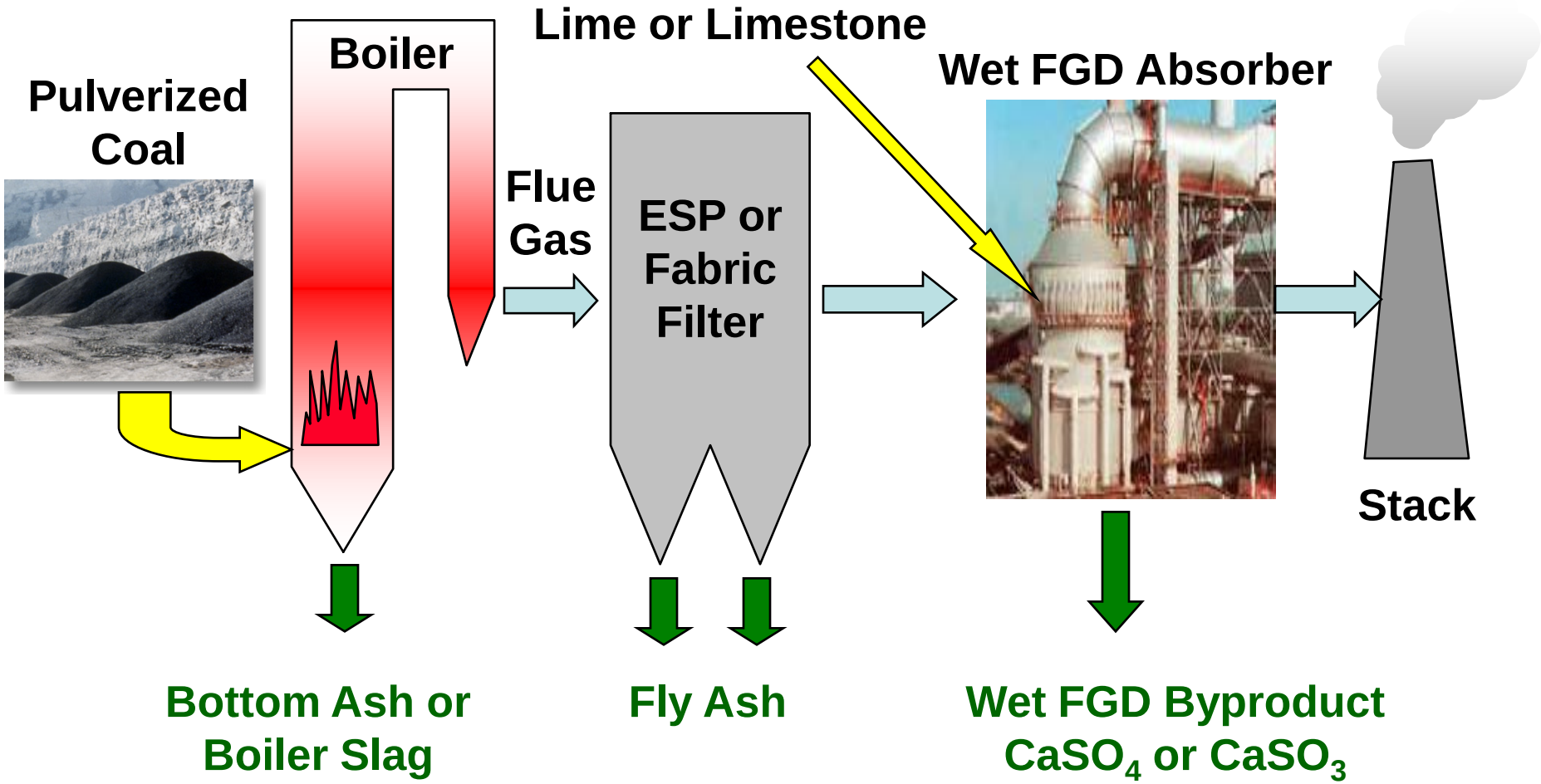
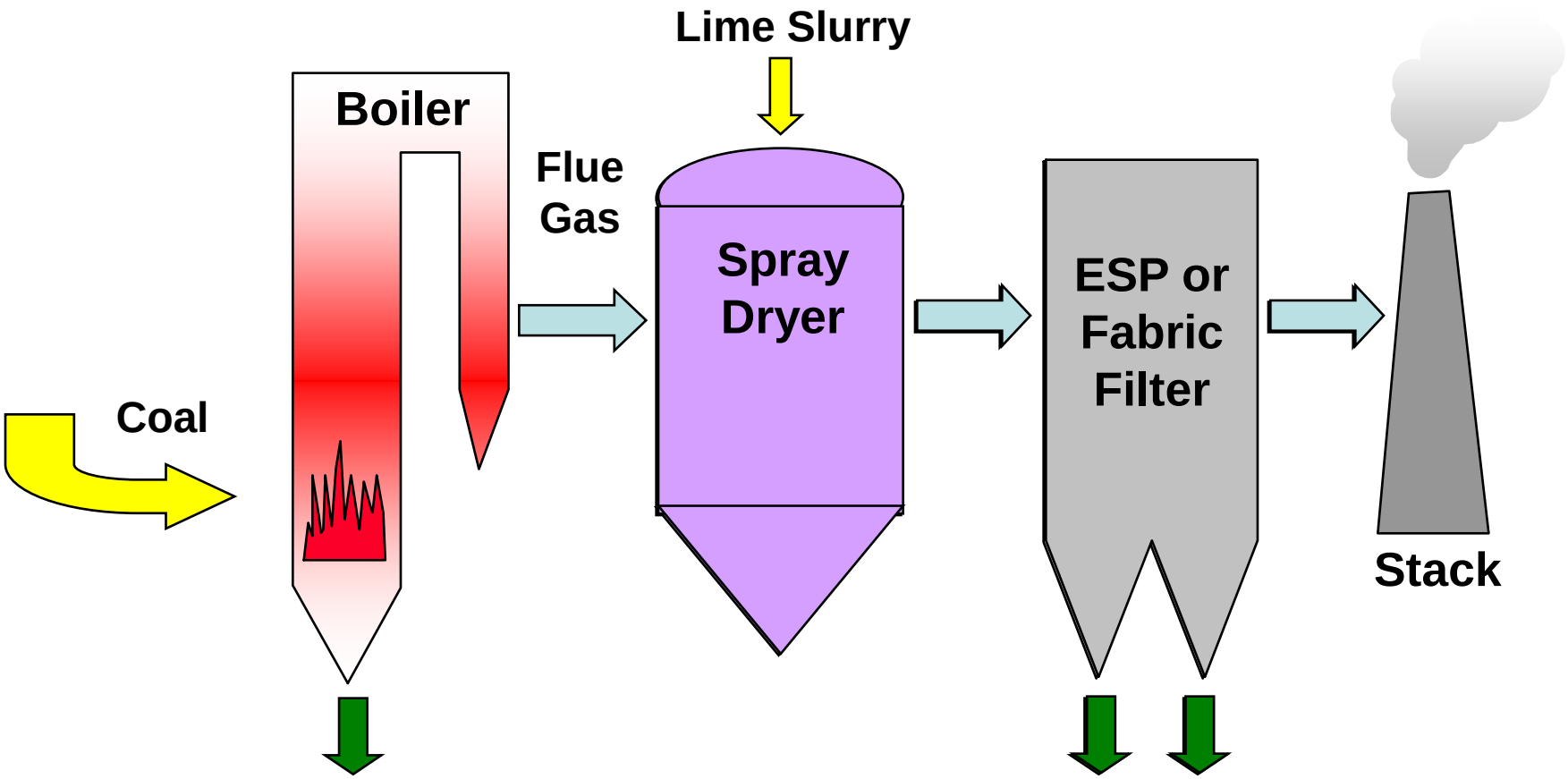
DOE Terminology: CUBs

- **Coal Utilization By-products**
  - Includes Fly ash, Bottom ash, Boiler slag, FGD solids
  - Other acronyms: CCBs, CCPs, CCW, FFCW, CCR ...
- **Utilization includes:**
  - Combustion
  - Gasification & Hybrid systems
- **By-products because:**
  - $ from electricity sales >> $ from CUB sales
  - Become "Products" when sold or beneficially used
  - Become "Wastes" when sent to a permanent disposal site
    - Can still become "products" after disposal

Coal Combustion produces separate streams of fly ash, bottom ash, and FGD byproducts



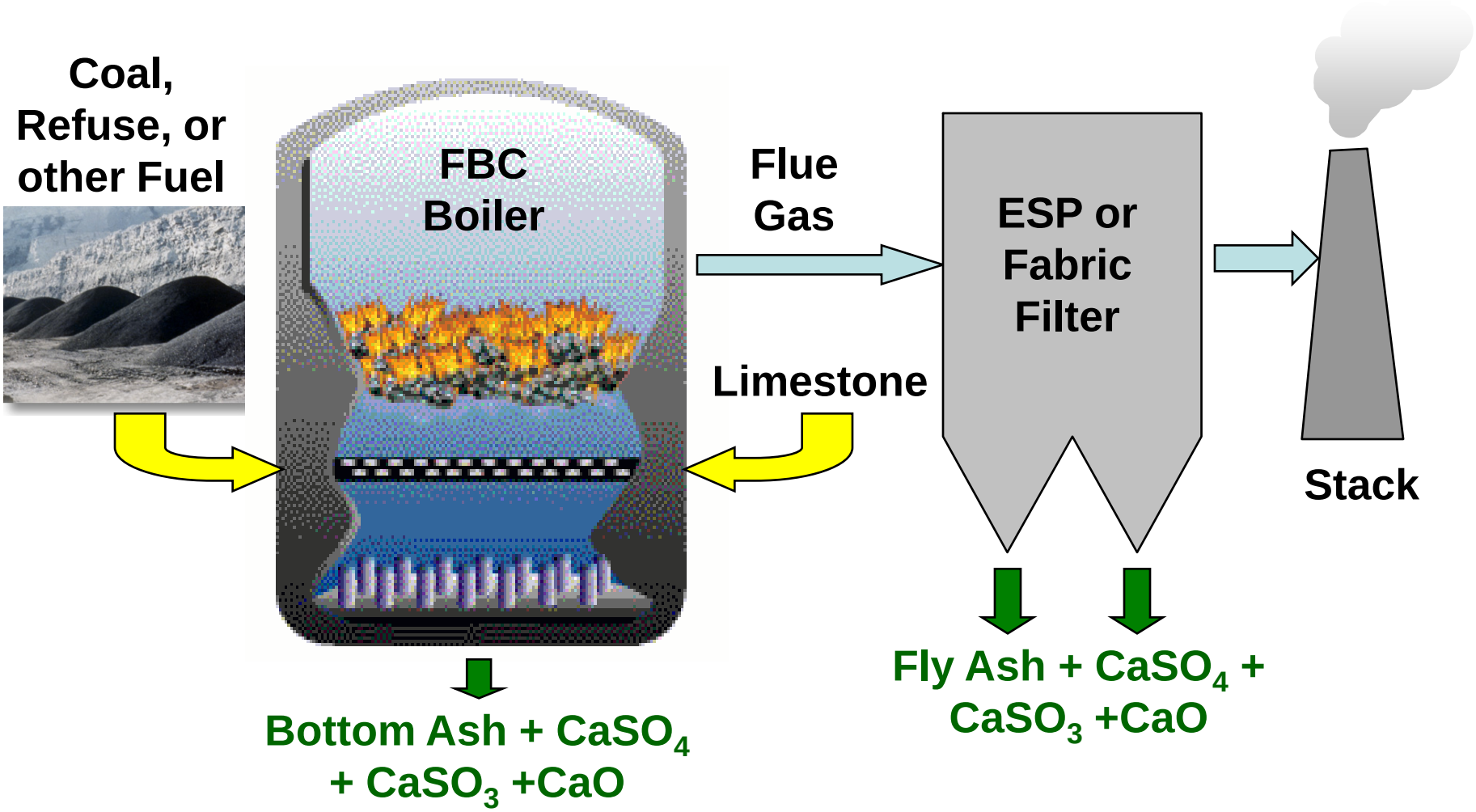
Dry FGD produces bottom ash and <u>inseparable mix</u> of fly ash and FGD byproducts



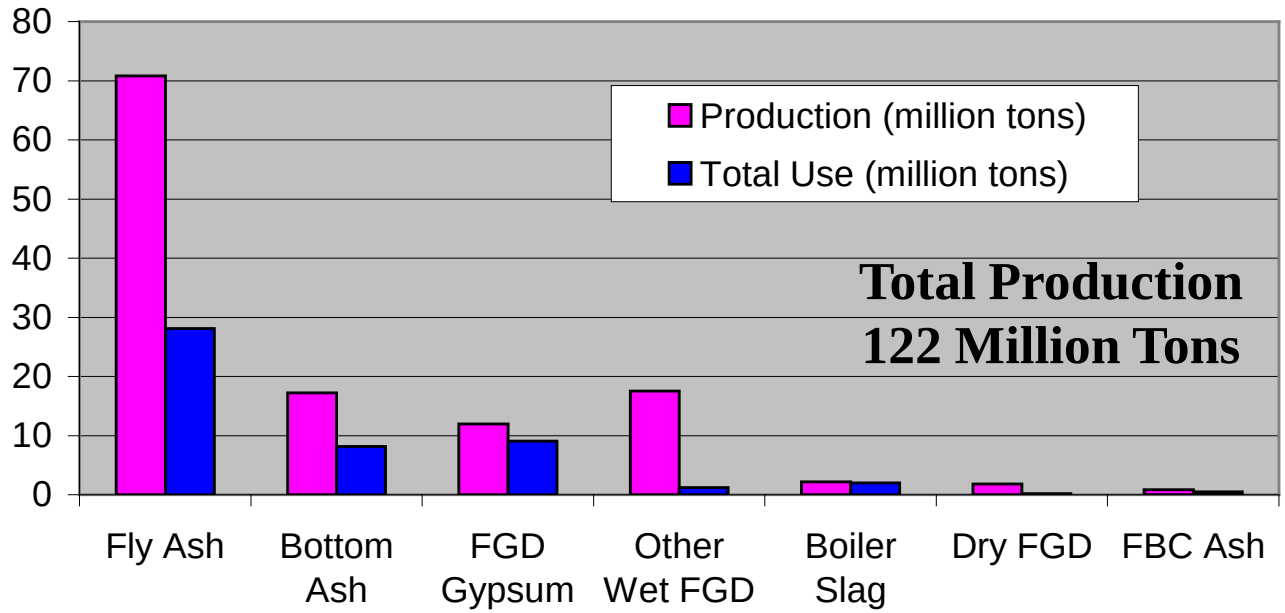
Bottom Ash or Boiler Slag

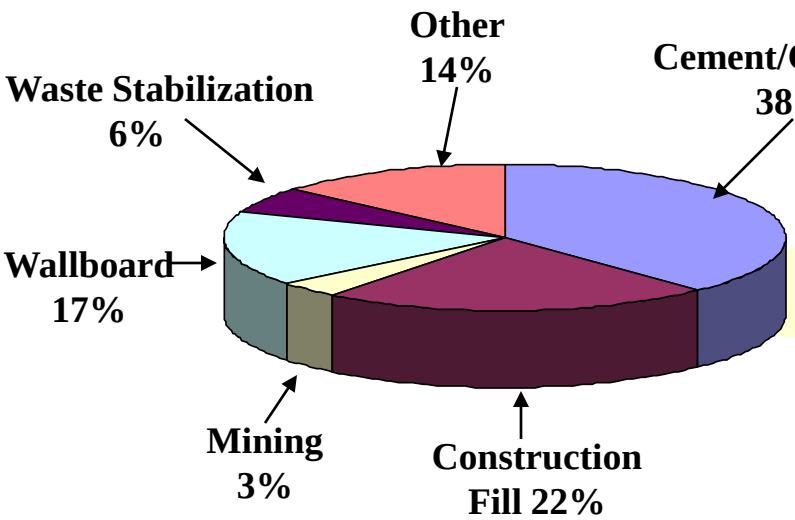
Dry FGD Byproduct = Fly Ash + $CaSO_3$ + $CaSO_4$ + $Ca(OH)_2$

FBC - Mix of FGD Byproducts with Bottom Ash and Fly Ash



Current CUB Production and Utilization





Utilization
49 Million Tons
(40% of Production)

Source: American Coal Ash Association, *2004 Coal Combustion Product Production and Use Survey*.

Multiple Benefits of Using Fly Ash to Replace Cement in Concrete

- *Performance*
  - Enhance physical and chemical characteristics, e.g., increased strength, improved workability
- *Environmental*
  - Reduced greenhouse gas emissions
  - Reduced land disposal requirements
- *Economic*
  - Plant avoids fly ash disposal costs
  - Plant receives revenue from sale of by-products
  - Tax incentives
  - Less expensive than cement to end-user

Key Challenges to Increased CUB Use

- **Additional FGD = increased volume of FGD byproducts**

- **More low-NOx burners and SCR = more unburned carbon and NH_3 in fly ash**

- **Hg control**
  - ACI = carbon in fly ash = unusable for concrete
  - Increased scrutiny & negative perception due to transfer of Hg from flue gas to fly ash and scrubber solids

Regulation of CUB Disposal and Utilization

- **Disposal is regulated under the Resource Conservation and Recovery Act (RCRA)**
  - Classified as "Special Wastes" since 1970s (Bevill Exemption)
  - Regulated solely by States pending EPA action
- **EPA's May 2000 regulatory determination**
  - Excluded from Subtitle C (hazardous waste) regulation
  - EPA to develop regulations under Subtitle D for CUB disposal and mine placement applications
- **Current Regulatory Status – Two options under consideration after ash impoundment rupture at TVA's Kingston Plant (Dec 2010)**
  - Non-hazardous under RCRA Subtitle D
    - Liners on new wet storage ponds to prevent slurry leaching
    - Liners on existing ponds or closure within five years
  - Hazardous under RCRA Subtitle C
    - Wet storage pond phase-out
    - New dry landfill requirements

Annual costs could exceed $20 billion

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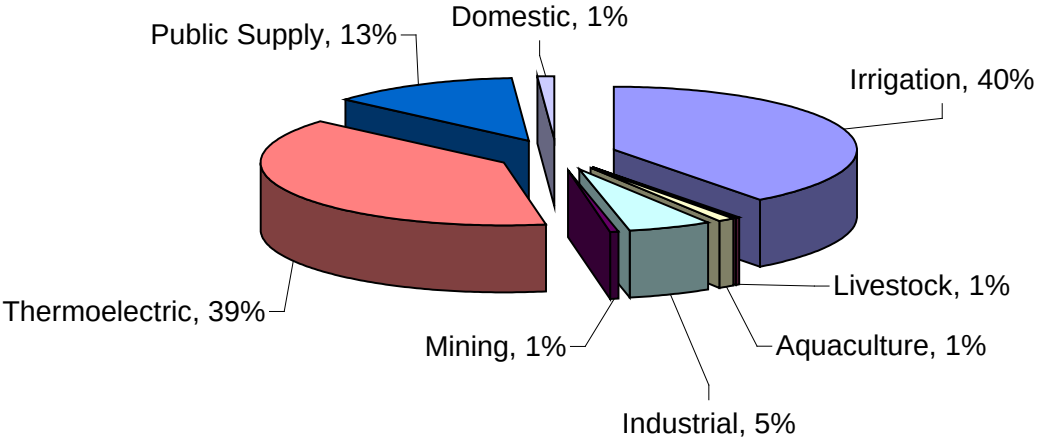
Water Usage for a Coal-Fired Plant

- **Major process water needs**
  - Cooling water
  - Boiler make-up
  - FGD system make-up

- **Major process water discharges**
  - Cooling water
  - Boiler wastewater
  - FGD wastewater
  - Ash impoundment discharge
  - Coal pile runoff

The Issues: Competing Freshwater Uses

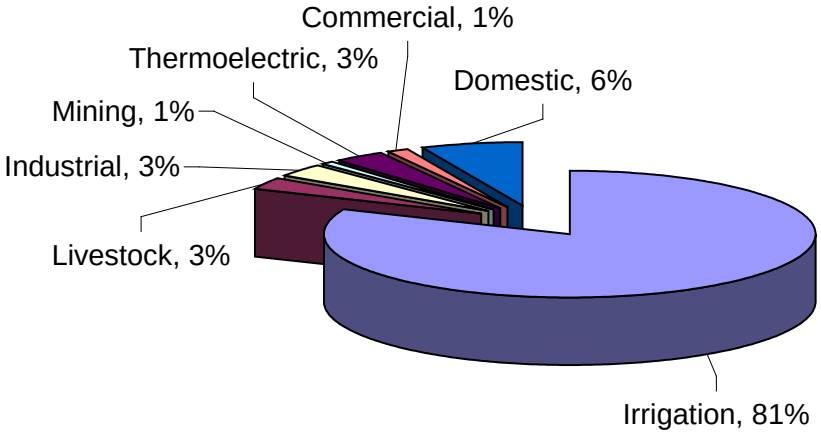
U.S. Freshwater Withdrawal (2000)



2000 thermoelectric water requirements:

- **Withdrawal: ~ 136 BGD**
- **Consumption: ~ 3 BGD**

U.S. Freshwater Consumption (1995)



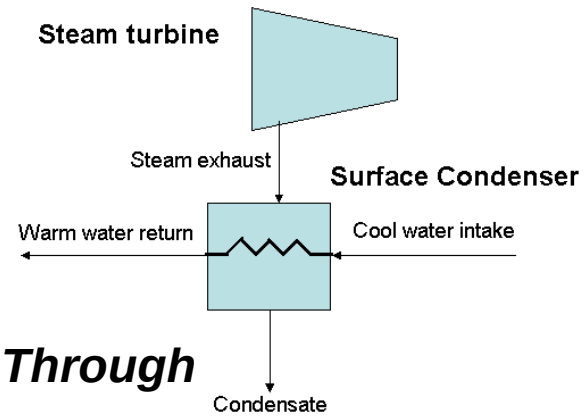
Terminology

- **Withdrawal: used but returned to the source**
- **Consumption: used and not returned to the source**

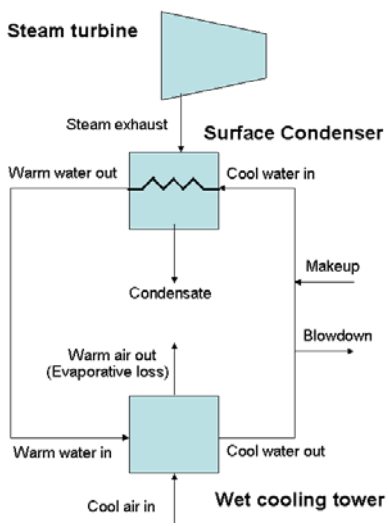
Sources: USGS, Estimated Use of Water in the United States in 2000, USGS Circular 1268, March 2004
USGS, Estimated Use of Water in the United States in 1995, USGS Circular 1200, 1998

Wet Cooling Systems

- **High water withdrawal:**
  - **20,000 to 50,000 gal/hr per MW**
- **Low water consumption:**
  - **~ 300 gal/hr/MW**



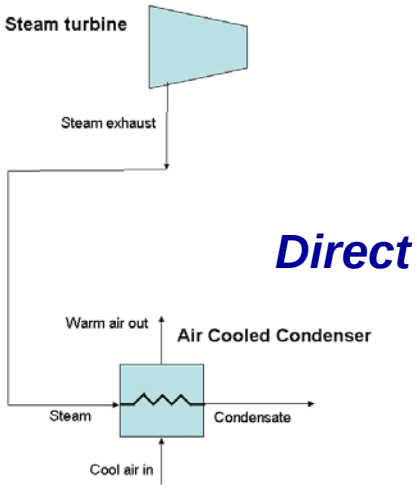
Once-Through



Recirculating

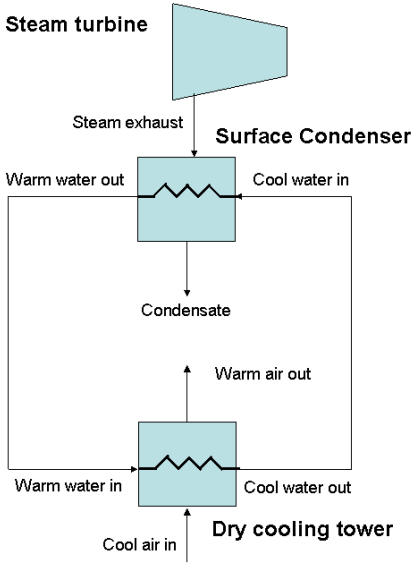
- **Low water withdrawal:**
  - **500 to 600 gal/hr per MW**
- **High water consumption:**
  - **480 gal/hr/MW**

Dry Cooling Systems



Direct

- **Minimal water withdrawal**
- **Minimal water consumption**
- **High capital cost**
- **Output penalty with high ambient air temperature**

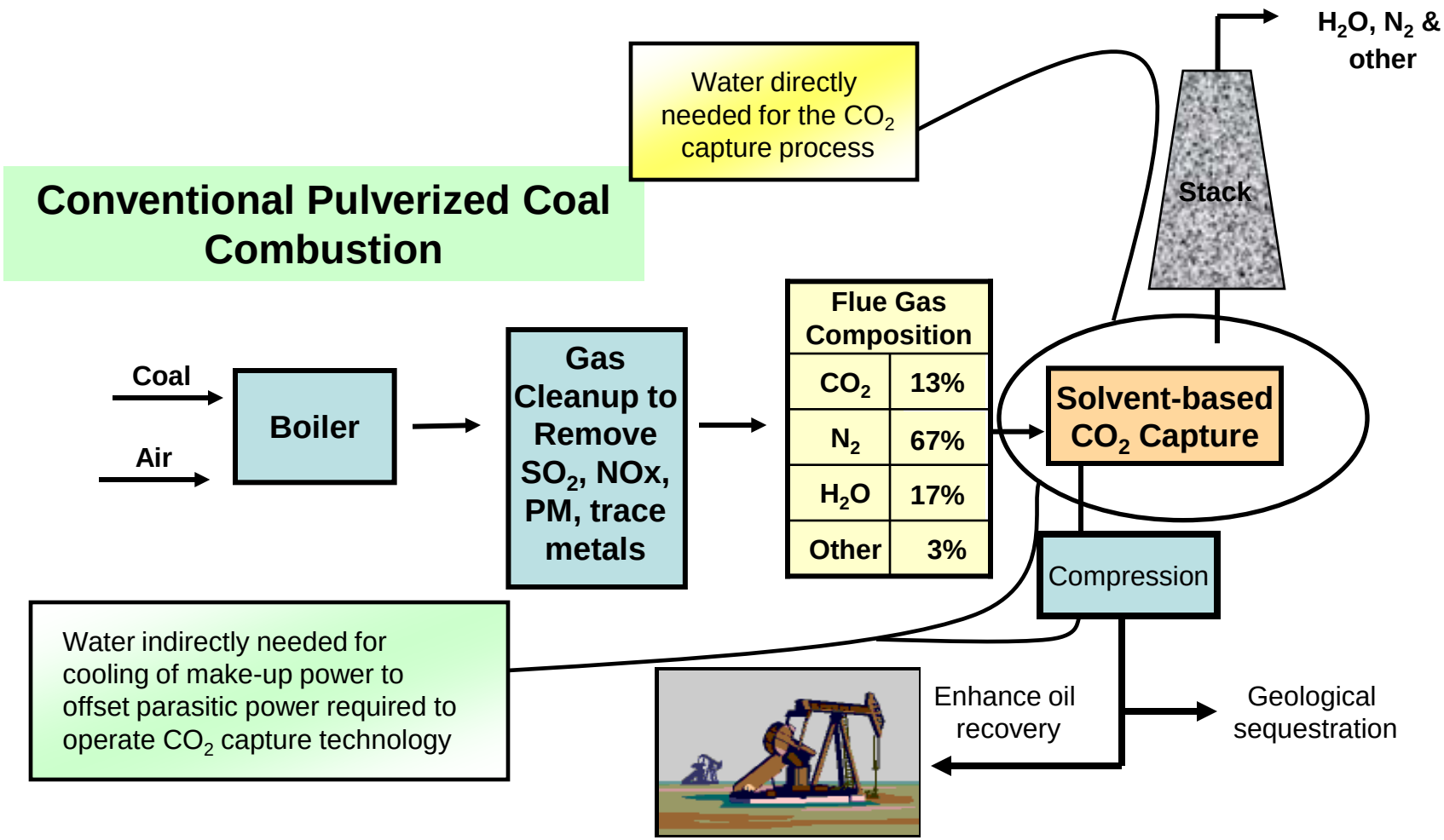


Indirect

Water Quality Related Issues

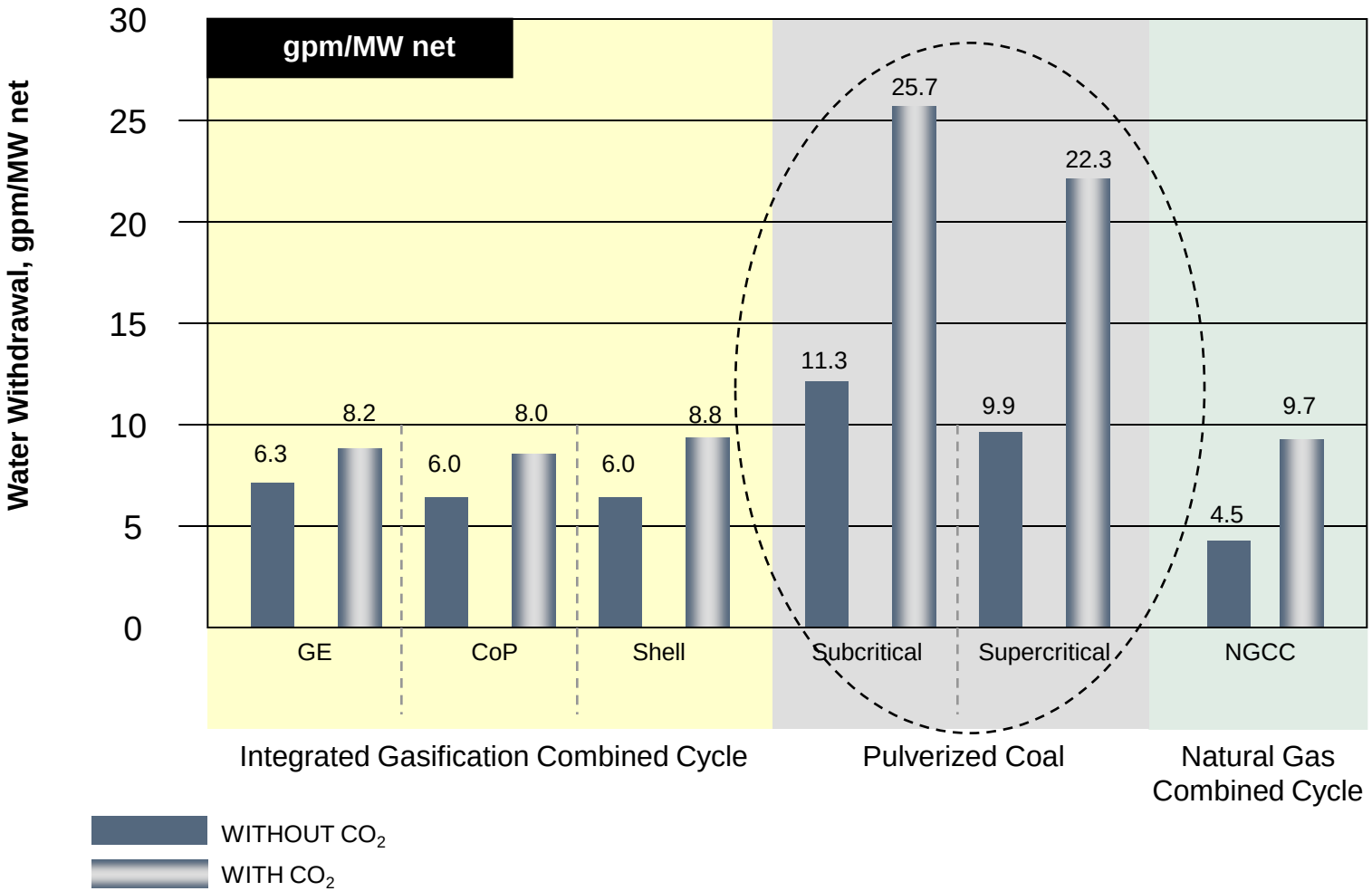
- **Impingement & entrainment of aquatic organisms at cooling water intake (CWA Section 316b)**
- **Thermal pollution at cooling water discharge**
- **Chemical pollutants in water discharges**
  - Hg, Se, As, nitrates from ash ponds
- **Acid drainage from coal pile runoff**

Water and CO_2 Capture



Source: NETL "2007 Pulverized Coal Oxyfuel Combustion Power Plants" August 2007 Final Report.

Potential Impact of CO_2 Capture on Power Plant Water Withdrawal Requirements



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

Visit Office of Fossil Energy & NETL Websites

http://fossil.energy.gov/

http://www.netl.doe.gov