Environmental effects of the combustion of fossil fuels
Three major effects

- Thermal pollution
- Chemical and particulate pollution
- Greenhouse gas emissions
Thermal pollution

- Because of thermodynamic limitations, a substantial fraction of the heat from combustion is released to the environment.

- Mechanisms:
  - Large bodies of water
  - Cooling towers
  - Dry heat exchangers

- Consequences:
  - Changes in oxygen level in water
  - Chemical reaction rates affected
  - Seasonal mixing mechanisms
  - Higher humidity / fog near cooling towers
Some examples

- Warm lake near Mount Storm Power station
- Wet cooling towers at Scherer power plant
- Dry cooling towers at Ivanpah solar power plant
Sulphur pollution

Sulphur is a naturally occurring component of fossil fuels, particularly coal, but also present in smaller quantities in some petroleum-based fuels, like diesel.

\[
\begin{align*}
S + O_2 & \rightarrow SO_2 \\
2SO_2 + O_2 & \rightarrow 2SO_3 \\
SO_3 + H_2O & \rightarrow H_2SO_4
\end{align*}
\]
Nitrogen pollution

Nitrogen oxides are formed during high-temperature combustion. The source of nitrogen is the atmosphere.

\[\text{CO} + \text{O}_2 \rightarrow \text{CO}_2 + \text{O}_3\]

\[\text{N}_2 + \text{O}_2 \rightarrow 2\text{NO}\]

\[\text{NO} + \text{O}_3 \rightarrow \text{NO}_2 + \text{O}_2\]

\[\text{NO}_2 + \text{OH} \rightarrow \text{HNO}_3\]

\[\text{NO}_2 \rightarrow \text{NO} + \text{O}\]

\[\text{O} + \text{O}_2 \rightarrow \text{O}_3\]
Coupling of human-natural effects

![Graph showing coupling of human-natural effects](image)
Effects of pollutants - NO$_x$

- Contributes to death and serious respiratory illness (e.g., asthma, chronic bronchitis) due to fine particles and ozone.
- Acidifies surface water, reducing biodiversity and killing fish.
- Damages forests through direct impacts on leaves and needles, and by soil acidification and depletion of soil nutrients.
- Damages forest ecosystems, trees, ornamental plants, and crops through ozone formation.
- Contributes to coastal eutrophication, killing fish and shellfish.
- Contributes to decreased visibility (regional haze).
- Speeds weathering of monuments, buildings, and other stone and metal structures.
Effects of pollutants - $\text{SO}_2$

- Contributes to death and serious respiratory illness (e.g., asthma, chronic bronchitis) due to fine particles.

- Acidifies surface water, reducing biodiversity and killing fish.

- Damages forests through direct impacts on leaves and needles, and by soil acidification and depletion of soil nutrients.

- Contributes to decreased visibility (regional haze).

- Speeds weathering of monuments, buildings, and other stone and metal structures.
Carbon monoxide
Effects of pollutants - Hg

- Humans are effected primarily by eating contaminated fish.
- Human neurological effects can include:
  - impaired motor and cognitive skills, particularly in young children;
  - cardiac, respiratory, and immune system impairments are strongly suspected.
- Loons, mink, otter, and other fish-eating animals also exhibit adverse effects.
Major sources of pollution

**Table 4.1:** Sources of CO released to the atmosphere as a result of fossil fuel use.

<table>
<thead>
<tr>
<th>source</th>
<th>% CO released</th>
</tr>
</thead>
<tbody>
<tr>
<td>vehicles</td>
<td>60</td>
</tr>
<tr>
<td>industrial</td>
<td>10</td>
</tr>
<tr>
<td>waste disposal</td>
<td>8</td>
</tr>
<tr>
<td>agricultural burning</td>
<td>8</td>
</tr>
<tr>
<td>forest fires</td>
<td>8</td>
</tr>
<tr>
<td>other</td>
<td>6</td>
</tr>
</tbody>
</table>

**Table 4.3:** Typical NO\textsubscript{x} emission sources in the United States.

<table>
<thead>
<tr>
<th>source</th>
<th>% NO\textsubscript{x}</th>
</tr>
</thead>
<tbody>
<tr>
<td>vehicles</td>
<td>35</td>
</tr>
<tr>
<td>coal burning</td>
<td>20</td>
</tr>
<tr>
<td>natural gas burning</td>
<td>25</td>
</tr>
<tr>
<td>other</td>
<td>20</td>
</tr>
</tbody>
</table>

**Table 4.4:** Sources of hydrocarbon pollution.

<table>
<thead>
<tr>
<th>source</th>
<th>% HC</th>
</tr>
</thead>
<tbody>
<tr>
<td>vehicles</td>
<td>35</td>
</tr>
<tr>
<td>industrial</td>
<td>20</td>
</tr>
<tr>
<td>natural gas burning</td>
<td>25</td>
</tr>
<tr>
<td>other</td>
<td>20</td>
</tr>
</tbody>
</table>

**Table 4.5:** Sources of SO\textsubscript{2} pollution.

<table>
<thead>
<tr>
<th>source</th>
<th>% SO\textsubscript{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>coal</td>
<td>65</td>
</tr>
<tr>
<td>industrial</td>
<td>25</td>
</tr>
<tr>
<td>other</td>
<td>10</td>
</tr>
</tbody>
</table>
Effects of particulate matter

- Increased premature deaths, primarily in the elderly and those with heart or lung disease
- Aggravation of respiratory and cardiovascular illness, leading to hospitalizations and emergency room visits in children and individuals with heart or lung disease
- Decreased lung function and symptomatic effects such as those associated with acute bronchitis, particularly in children and asthmatics
- New cases of chronic bronchitis
- Increased work loss days, school absences, and emergency room visits
- Changes to lung structure and natural defense mechanisms
## Emissions standards

**Table 4.2: U.S. emission standards for CO, NO\textsubscript{x} and hydrocarbons in grams per mile (grams per km).**

<table>
<thead>
<tr>
<th>Year</th>
<th>CO</th>
<th>NO\textsubscript{x}</th>
<th>HC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960 (precontrol estimate)</td>
<td>84.0 (52.2)</td>
<td>4.1 (2.5)</td>
<td>10.6 (6.58)</td>
</tr>
<tr>
<td>1970</td>
<td>34.0 (21.1)</td>
<td>5.0 (3.1)</td>
<td>4.1 (2.5)</td>
</tr>
<tr>
<td>1975</td>
<td>15.0 (9.3)</td>
<td>3.1 (1.9)</td>
<td>1.5 (0.93)</td>
</tr>
<tr>
<td>1980</td>
<td>7.0 (4.3)</td>
<td>2.0 (1.2)</td>
<td>0.41 (0.25)</td>
</tr>
<tr>
<td>1981</td>
<td>3.4 (2.1)</td>
<td>1.0 (0.62)</td>
<td>0.41 (0.25)</td>
</tr>
<tr>
<td>1983</td>
<td>3.4 (2.1)</td>
<td>1.0 (0.62)</td>
<td>0.41 (0.25)</td>
</tr>
<tr>
<td>1994</td>
<td>3.4 (2.1)</td>
<td>0.4 (0.25)</td>
<td>0.25 (0.16)</td>
</tr>
<tr>
<td>2001</td>
<td>3.4 (2.1)</td>
<td>0.2 (0.12)</td>
<td>0.125 (0.078)</td>
</tr>
<tr>
<td>2004</td>
<td>1.7 (1.1)</td>
<td>0.07 (0.04)</td>
<td>0.09 (0.056)</td>
</tr>
</tbody>
</table>
Nationwide tropospheric ozone map

Counties With Monitors Violating Primary 8-hour Ground-level Ozone Standards
0.060 - 0.070 parts per million

(EPA will not designate areas as nonattainment on these data, but likely on 2008 – 2010 data which are expected to show improved air quality.)

Notes:
1. No monitored counties outside the continental U.S. violate.
2. EPA is proposing to determine compliance with a revised primary ozone standard by rounding the 3-year average to three decimal places.
PM: Gravity separator

Gas with a suspension of particulates from combustor

Buoyant force

Drag force

Gravitational force

To collection bin

Diaphragm valve

Solenoid valve

Compressed air reservoir

Top access

Clean air blow pipe

Inspection port

Polyester felt bag

Access platform

Gas inlet

Hopper

Screw conveyor motor
PM - Cyclonic separator

Cleaned gases to discharge stack

Particle-laden gases

Narrow throat

Water spray to capture particles

Particles trapped in water droplets

Cyclonic spinning action

Slurry collection and treatment
PM - Electrostatic separator

Cylinder walls

Electrons are pulled out of central wire by strong electric force

Oxygen molecule captures electron

Particulate captures molecule and is attracted to positively charged wall of cylinder

Particulates flow up through the cylinder

Mechanism for charging the cylinder and central wire

Electrical insulator

Electrical power supply

Housing

Thermal insulation

Collecting electrodes (plates)

Discharge electrodes (wires)

Access door

Dust handling system

Support

Rapping system

Gas distribution device

Plate and wire support frames
## Technological fixes - NO\textsubscript{x}

<table>
<thead>
<tr>
<th>NO\textsubscript{x} Abatement Method</th>
<th>Techniques Now Available</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Reducing peak temperature</td>
<td>Flue Gas Recirculation (FGR)</td>
<td>50-70%</td>
</tr>
<tr>
<td></td>
<td>Natural Gas Reburning (NGR)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low NO\textsubscript{x} Burners (LNB)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Combustion Optimization</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Burners Out Of Service (BOOS)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Over Fire Air (OFA)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Less Excess Air (LEA)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inject Water or Steam</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduced Air Preheat</td>
<td></td>
</tr>
<tr>
<td>2. Reducing residence time at peak temperature</td>
<td>Air Staging of Combustion</td>
<td>50-70%</td>
</tr>
<tr>
<td></td>
<td>Fuel Staging of Combustion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inject Steam</td>
<td></td>
</tr>
<tr>
<td>3. Chemical reduction of NO\textsubscript{x}</td>
<td>Selective Catalytic Reduction (SCR)</td>
<td>35-90%</td>
</tr>
<tr>
<td></td>
<td>Selective Non-Catalytic Reduction (SNCR)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fuel Reburning (FR)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low NO\textsubscript{x} Burners (LNB)</td>
<td></td>
</tr>
<tr>
<td>4. Oxidation of NO\textsubscript{x} with subsequent absorption</td>
<td>Inject Oxidant</td>
<td>60-80%</td>
</tr>
<tr>
<td></td>
<td>Non-Thermal Plasma Reactor (NTPR)</td>
<td></td>
</tr>
<tr>
<td>5. Removal of nitrogen</td>
<td>Ultra-Low Nitrogen Fuel</td>
<td>No Data</td>
</tr>
<tr>
<td>6. Using a sorbent</td>
<td>Sorbent In Combustion Chambers</td>
<td>60-90%</td>
</tr>
<tr>
<td></td>
<td>Sorbent In Ducts</td>
<td></td>
</tr>
</tbody>
</table>
Technological fixes - SO$_2$

\[
\text{CaCO}_3 + \text{SO}_2 \rightarrow \text{CaSO}_3 + \text{CO}_2
\]

\[
2\text{CaSO}_3 + 2\text{H}_2\text{O} + \text{O}_2 \rightarrow 2\text{CaSO}_4 \cdot \text{H}_2\text{O}
\]
Origins of the EPA

A bad day in LA
Origins of the EPA

- 1969 National Environmental Policy Act (NEPA) declared Congressional intent to "create and maintain conditions under which man and nature can exist in productive harmony," and to "assure for all Americans safe, healthful, productive, esthetically and culturally pleasing surroundings."

- Signing the Act on New Year's Day 1970, Nixon observed that he had "become further convinced that the 1970s absolutely must be the years when America pays its debt to the past by reclaiming the purity of its air, its waters, and our living environment. It is," he said, "literally now or never."
Origins of the EPA

The EPA's role:

- The establishment and enforcement of environmental protection standards consistent with national environmental goals.

- The conduct of research on the adverse effects of pollution and on methods and equipment for controlling it; the gathering of information on pollution; and the use of this information in strengthening environmental protection programs and recommending policy changes.

- Assisting others, through grants, technical assistance and other means, in arresting pollution of the environment.

- Assisting the Council on Environmental Quality in developing and recommending to the President new policies for the protection of the environment.
The acid rain story

- First observed in mid-19th century – forests downwind of industrial areas showed signs of deterioration
- Not considered a serious environmental problem until 1970s, when increased acidity of lakes and streams was detected
- Tropospheric pollutants linked acid rain to distant sources of pollution
- Regional problem – rather than local – meant that federal government must become involved
- Trans-boundary dispute between U.S. and Canada, involving scientific institutions and policymakers, beginning in the late 1970s and ending in 1991 with the Clean Air Act Amendment of 1990
- One of the first instances where scientists became participants in the public debate, resulting in “politicization” of science (and scientists!)
The 1990 CAA Amendments

- **Urban pollution:** Ozone, CO, particulates must comply with standards within a set time (6 to 20 years)
- **Permits:** five-year operating permits for pollution sources must be submitted to EPA within 3 years.
- **Motor vehicles:** cuts in tailpipe emission, improved fuels, clean cars
- **Air Toxics:** Emissions of 189 toxic pollutants, typically carcinogens, mutagens, and reproductive toxins, must be reduced within 10 years
- **Acid Rain:** A two-phase, market-based system to reduce sulfur-dioxide emissions from power plants by more than half. By the year 2000, total annual emissions capped at 8.9 million tons, a reductions of 10 million tons from 1980 levels. Plants will be issued allowances based on fixed emission rates set in the law and on their previous fossil-fuel use. Plants pay penalties if emissions exceed the allowances they hold.
- **Ozone Depletion:** further restrictions (beyond Montreal protocol) on use, emissions, and disposal of chemicals.
Effect of CAA

Reduction in fine particle concentration resulting from CAAA90. Note: US yearly average limit is 15 μg/m$^3$. 
Cost vs. benefit

<table>
<thead>
<tr>
<th>Health Effect Reductions (PM2.5 &amp; Ozone Only)</th>
<th>Pollutant(s)</th>
<th>Year 2010</th>
<th>Year 2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM2.5 Adult Mortality</td>
<td>PM</td>
<td>160,000</td>
<td>230,000</td>
</tr>
<tr>
<td>PM2.5 Infant Mortality</td>
<td>PM</td>
<td>230</td>
<td>280</td>
</tr>
<tr>
<td>Ozone Mortality</td>
<td>Ozone</td>
<td>4,300</td>
<td>7,100</td>
</tr>
<tr>
<td>Chronic Bronchitis</td>
<td>PM</td>
<td>54,000</td>
<td>75,000</td>
</tr>
<tr>
<td>Acute Bronchitis</td>
<td>PM</td>
<td>130,000</td>
<td>180,000</td>
</tr>
<tr>
<td>Acute Myocardial Infarction</td>
<td>PM</td>
<td>130,000</td>
<td>200,000</td>
</tr>
<tr>
<td>Asthma Exacerbiation</td>
<td>PM</td>
<td>1,700,000</td>
<td>2,400,000</td>
</tr>
<tr>
<td>Hospital Admissions</td>
<td>PM, Ozone</td>
<td>86,000</td>
<td>135,000</td>
</tr>
<tr>
<td>Emergency Room Visits</td>
<td>PM, Ozone</td>
<td>86,000</td>
<td>120,000</td>
</tr>
<tr>
<td>Restricted Activity Days</td>
<td>PM, Ozone</td>
<td>84,000,000</td>
<td>110,000,000</td>
</tr>
<tr>
<td>School Loss Days</td>
<td>Ozone</td>
<td>3,200,000</td>
<td>5,400,000</td>
</tr>
<tr>
<td>Lost Work Days</td>
<td>PM</td>
<td>13,000,000</td>
<td>17,000,000</td>
</tr>
</tbody>
</table>

Benefits by Category

- Direct Costs
- Direct Benefits
- Mortality
- Morbidity
- Visibility
- Other
- Other Non-$
Cap and Trade legislation

- Successful example in US in 1990s
  - Lower costs than many predicted
  - Effective in reducing pollution

- Kyoto protocol and EU legislation (largely ineffective)
  - Cap and trade promoted by US
  - EU carbon market introduced in 2005
  - Free emissions permits
  - Generous allowances
  - Biggest polluters got most allowances
  - Carbon offsets

- End result: 2-5% emissions reduction in control period
Carbon tax

- Pollution tax theory dates back to 1930s
- Make fossil fuels more expensive, leading to reduced use
- Price of emissions fixed, not volatile
- Emission reductions uncertain
- Fossil fuels taxed at source or when they cross national boundaries (very simple scheme, unlike C&T), or at the end-use transaction