

A photograph of a coal fire burning in a furnace, with bright orange and yellow flames rising from a dark pile of coal. The image is centered on a red background.

# *Coal Combustion*

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- What is coal? Formation, sources, applications.
- Coal combustion description.
- Coal power plants and air pollution: Mechanisms and control technologies.
- Coal and air pollution in Israel.

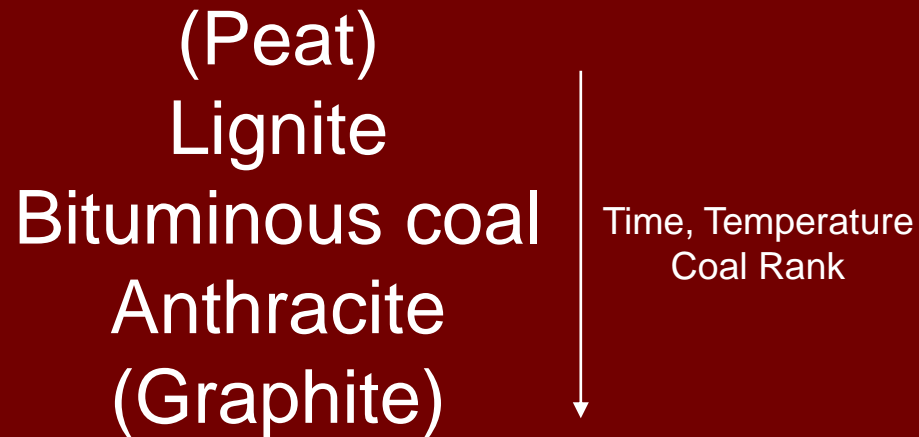


**Eshkol power station  
Haifa**

# Coal – what is it?

Elemental Composition	C	65-95%
	H	2-7%
	O	<25%
	S	<10%
	N	1-2%
Proximate Analysis	Char	20-70%
	Ash	5-15%
	H <sub>2</sub> O	2-20%
	VM	20-45%

- Inhomogeneous organic fuel formed mainly from decomposed plant matter.
- Over 1200 coals have been classified.
- Coalification forms different coal types:

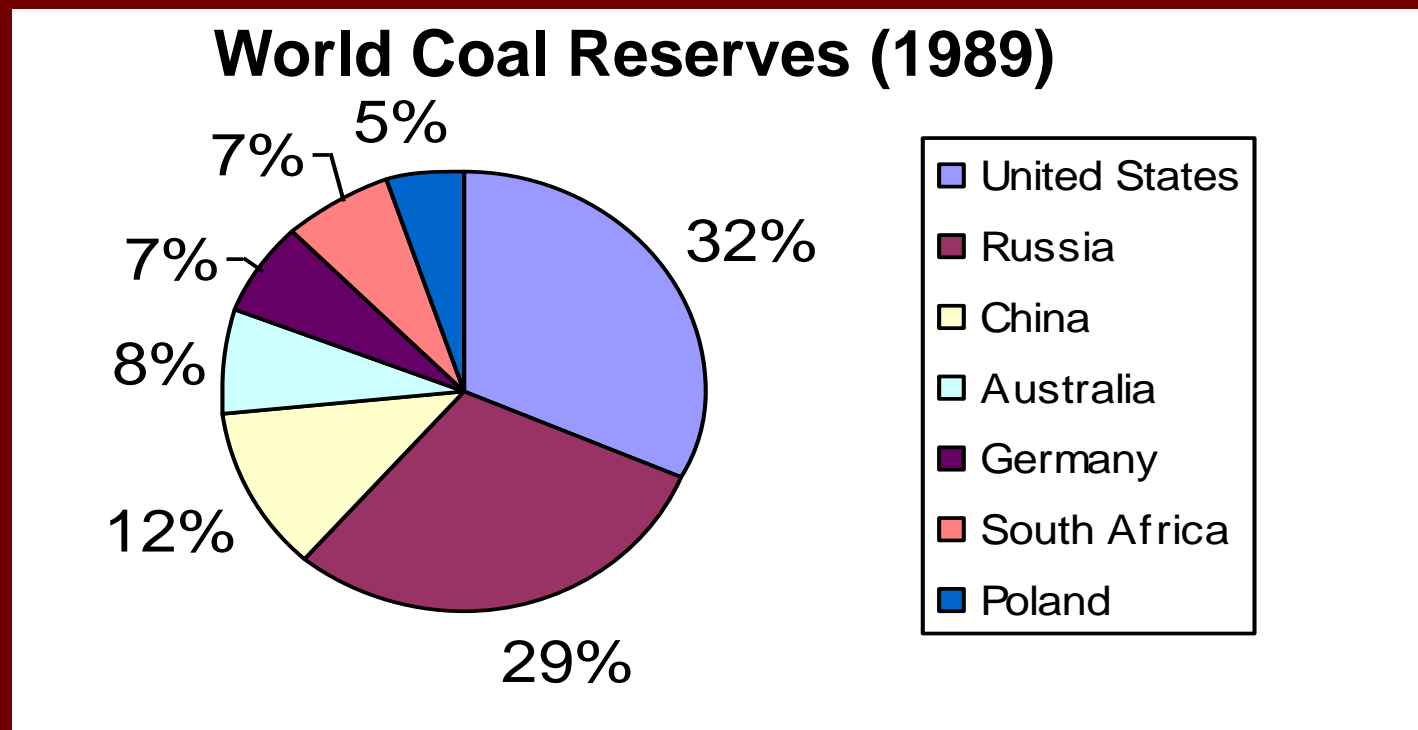


# Coal



# Coal Sources

- Coal is the world's most plentiful fossil fuel.
- Recoverable world coal reserves are estimated at about  $1 \times 10^{12}$  tons.

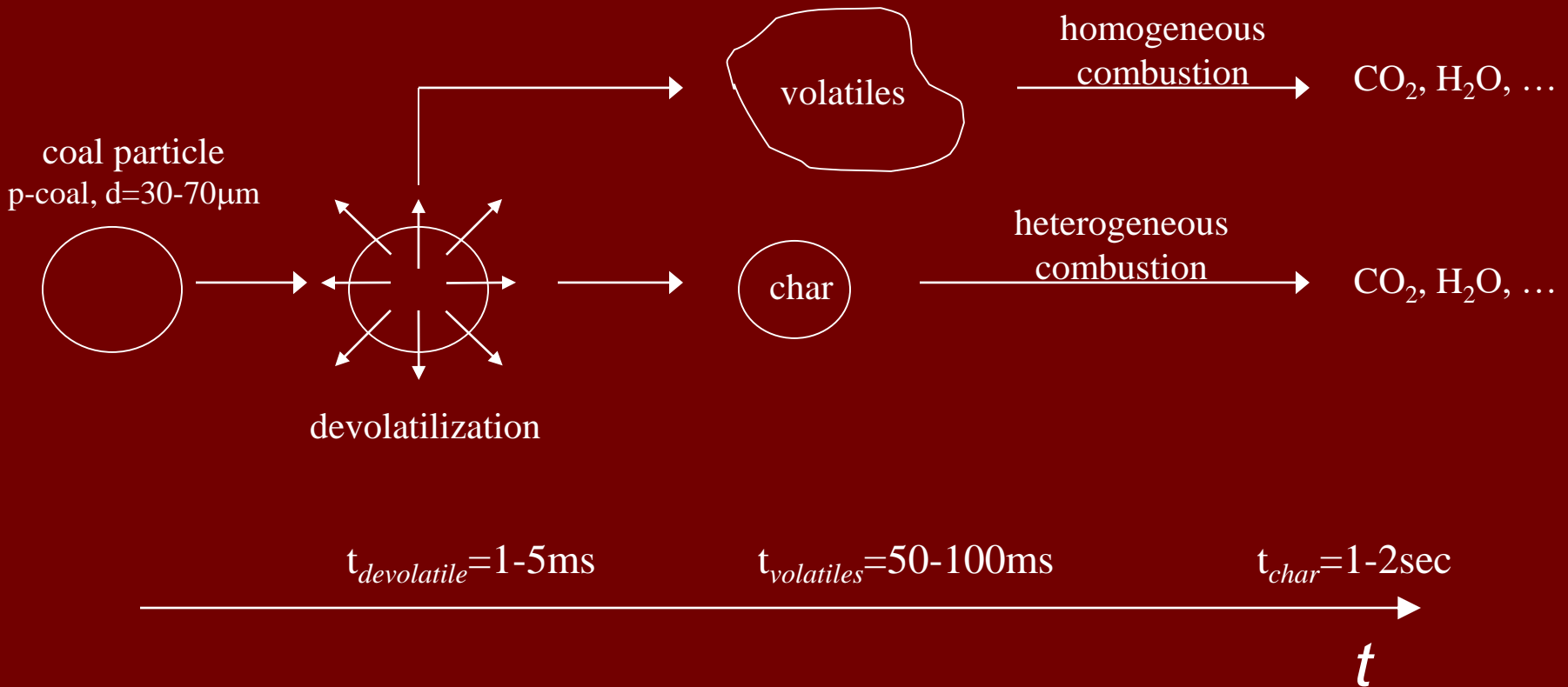


# Coal Applications

- Homes – heat and cooking
- Transportation – steam engines
- Industry – metal works
- Electricity – power plants



# Main Processes in Coal Combustion



# The physical processes influencing pulverized coal combustion

- Turbulent/swirling flow of air and coal.
- Turbulent/convective/molecular diffusion of gaseous reactants and products.
- Convective heat transfer through the gas and between the gas and coal particles.
- Radiative heat transfer between the gas and coal particles and between the coal/air mixture and the furnace walls.

# From *Fumifugium* by John Evelyn (1661)

- on London's air pollution -

"...but so universally mixed with the otherwise wholesome and excellent *Aer*, that her *Inhabitants* breathe nothing but an impure and thick Mist, accompanied by a fuliginous and filthy vapour, which renders them obnoxious to a thousand inconveniences, corrupting the *Lungs*, and disordering the entire habit of their Bodies; so that *Catharrs, Phthisicks, Coughs and Consumptions*, rage more in this one City, than the whole Earth besides. For when in all other places the *Aer* is most Serene and Pure, it is here Ecclipsed with such a Cloud of Sulphure, as the Sun itself, which gives day to all the World besides, is hardly able to penetrate and impart it here; and the weary *Traveller*, at many Miles distance, sooner smells, than sees the City to which he repairs. This is that pernicious Smoake which sullies all her Glory, superinducing a sooty Crust or Fur upon all that it lights, spoyling the moveables, tarnishing the Plate, Gildings and Furniture, and corroding the very Iron-bars and hardest Stones with those piercing and acrimonious Spirits which accompany its Sulphure; and executing more in one year, than exposed to the pure *Aer* of the Country it could effect in some hundreds."

# Coal Combustion Air Pollutants

- $\text{CO}_2$

- CO

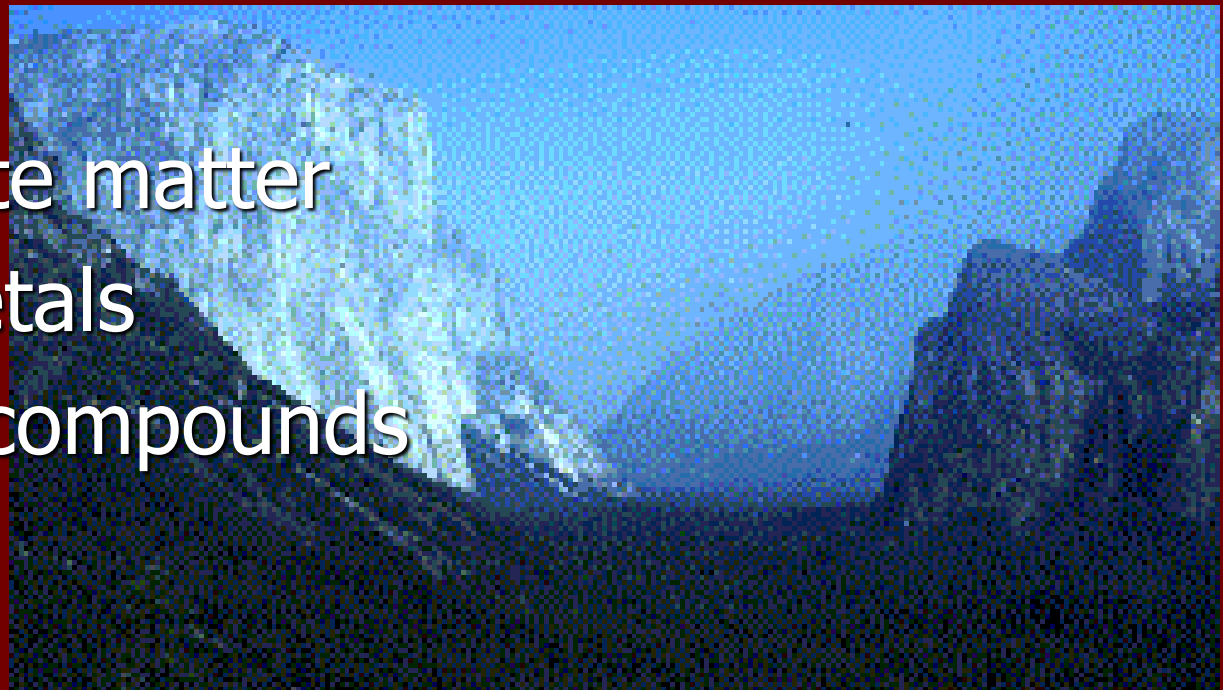
- $\text{NO}_x$

- $\text{SO}_x$

- Particulate matter

- Trace metals

- Organic compounds



# Carbon Dioxide, CO<sub>2</sub>



Almost 99% of C in coal is converted to CO<sub>2</sub>.

In order to lower CO<sub>2</sub> emission levels, coal power plants will have to leave steam-based systems (37% efficiency) and go towards coal gasification technology (60% efficiency).

Meanwhile, CO<sub>2</sub> sequestration is being tested.

# Carbon monoxide, CO



CO is minimized by control of the combustion process (air/fuel ratio, residence time, temperature or turbulence).

# Particulate Matter



```
graph TD; PM[Particulate Matter] --> BA[Bottom Ash]; PM --> FA[Fly Ash];
```

Bottom Ash

Fly Ash

PM composition and emission levels are a complex function of:

1. Coal properties,
2. Boiler firing configuration,
3. Boiler operation,
4. Pollution control equipment.

In PC power plants, since combustion is almost complete, the emitted PM is primarily composed of inorganic ash residues.

# PM controls (AP-42, EPA)

Mainly post combustion methods:

Electrostatic precipitator (ESP)	99% (for $0.1 > d(\mu\text{m}) > 10$ ) <99% (for $0.1 < d(\mu\text{m}) < 10$ )
Fabric filter (or baghouse)	As high as 99.9%
Wet scrubber	95-99%
Cyclone	90-95% ( $d(\mu\text{m}) > 10$ )

# Trace metals

## FORMATION

Concentration of metal in coal, physical and chemical properties of the metal, combustion conditions.



### Class 1

Elements that are approximately equally concentrated in the fly ash and bottom ash (Mn, Be, Co, Cr)

### Class 2

Elements that are enriched in fly ash relative to bottom ash (Ar, Cd, Pb, An)

### Class 3

Elements which are emitted in the gas phase (mainly Hg).

## CONTROL

Control of total particulate matter emissions

Collection of fine particles.

Sorbents ???

# Organic Compounds

Include volatile, semivolatile and condensable organic compounds either present in the coal or formed as a product of incomplete combustion.

Characterized by hydrocarbon class: alkanes, alkenes, aldehydes, alcohols and substituted benzenes.

The main groups of environmental concern are:

- 1) tetrachloro- through octachloro- dioxins and furans.
- 2) Polycyclic organic matter (POM).

Emissions dependent on combustion behavior in the boiler (air/fuel ratio, residence time, temperature or turbulence).

# Sulfur Oxides, SO<sub>x</sub>

# Sulfur in coal (<10%)

## Organic sulfur (40%)

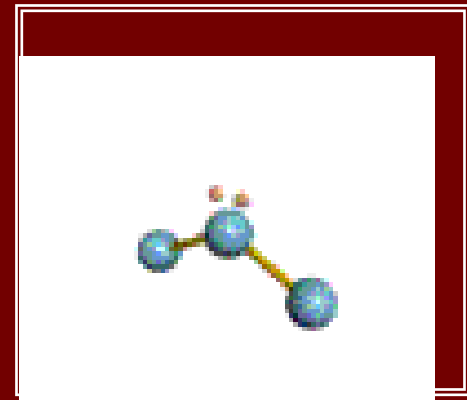
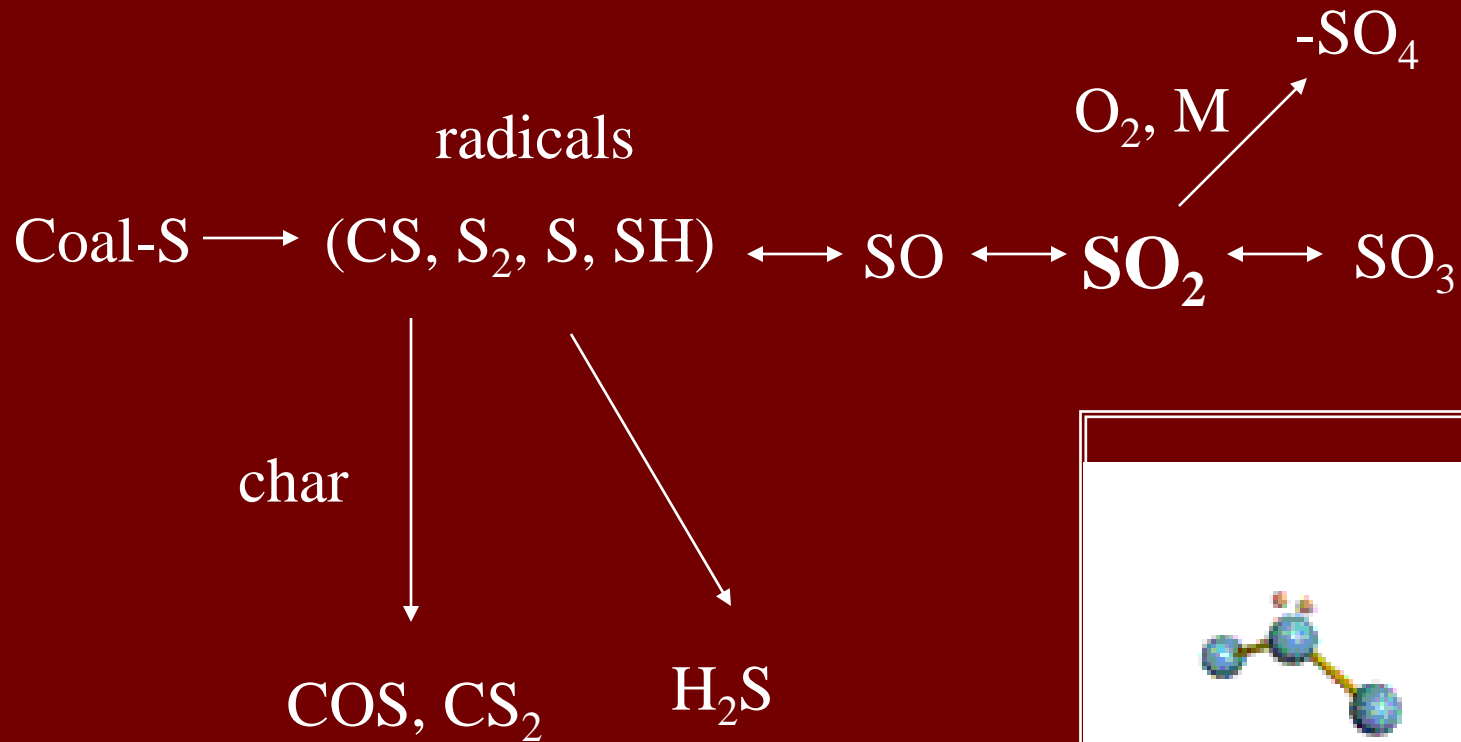
Chemically bonded to the hydrocarbon matrix in the forms of thiophene, thiopyrone, sulfides and thiol.

## Inorganic sulfur (60%)

Imbedded in the coal, as loose pyrite -  $\text{FeS}_2$  or marcasite, and calcium/iron/barium sulfates.

Sources of sulfur in coal: Seawater sulfates,  
Limestone

# SOx Formation

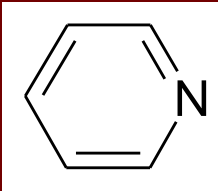
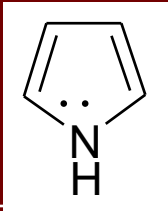
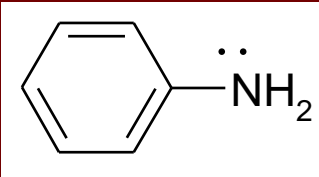


# SO<sub>x</sub> reduction

- Pre combustion removal:
  - Physical cleaning (30-50% removal inorganic sulfur)
  - Chemical and biological cleaning (90% removal organic sulfur)
- Combustion configuration:
  - **No benign sulfur species!**
  - gasification combined-cycle systems (IGCC systems)
- Post-combustion removal:
  - Wet Flue Gas Desulfurization (FGD) (80-98%)
- In situ sulfur capture:
  - Dry Sorbent Injection (DSI) (50%)

# Nitrogen Oxides, NO<sub>x</sub>

# Nitrogen in Coal (1-2%)

Name	Structure	~ Relative amount	Stability
Pyridine <sup>1</sup>		15-40%	More stable
Pyrrole <sup>1</sup>		60%	Less stable
Aromatic amines		6-10%	Stable

<sup>1</sup>Including structures made up of 2-5 fused aromatic rings.

# Main NO Mechanisms

1. Thermal NO
2. Prompt NO
3. Fuel NO: volatiles-NO and char-NO

# Thermal NO

(Zeldovich mechanism)



Strong temperature-dependence:  $>1300\text{-}1500^\circ\text{C}$

Not a major source of NO in coal utility boilers.

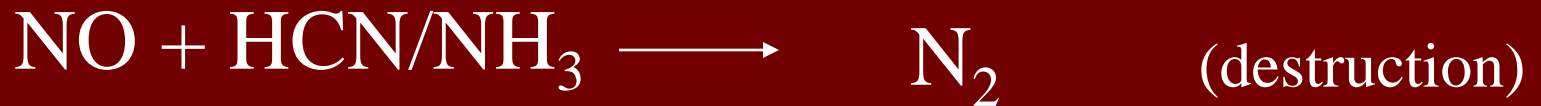
# Prompt NO



Prevalent only in fuel-rich systems.

Not a major source of NO in coal utility boilers.

# Fuel NO (-N in volatiles)



The major source of NO in coal utility boilers (>80%).

# Char NO (-N in the char)



[char-NO = ~25%] < [volatiles-NO = ~75%]

# NO Reduction

## Combustion controls:

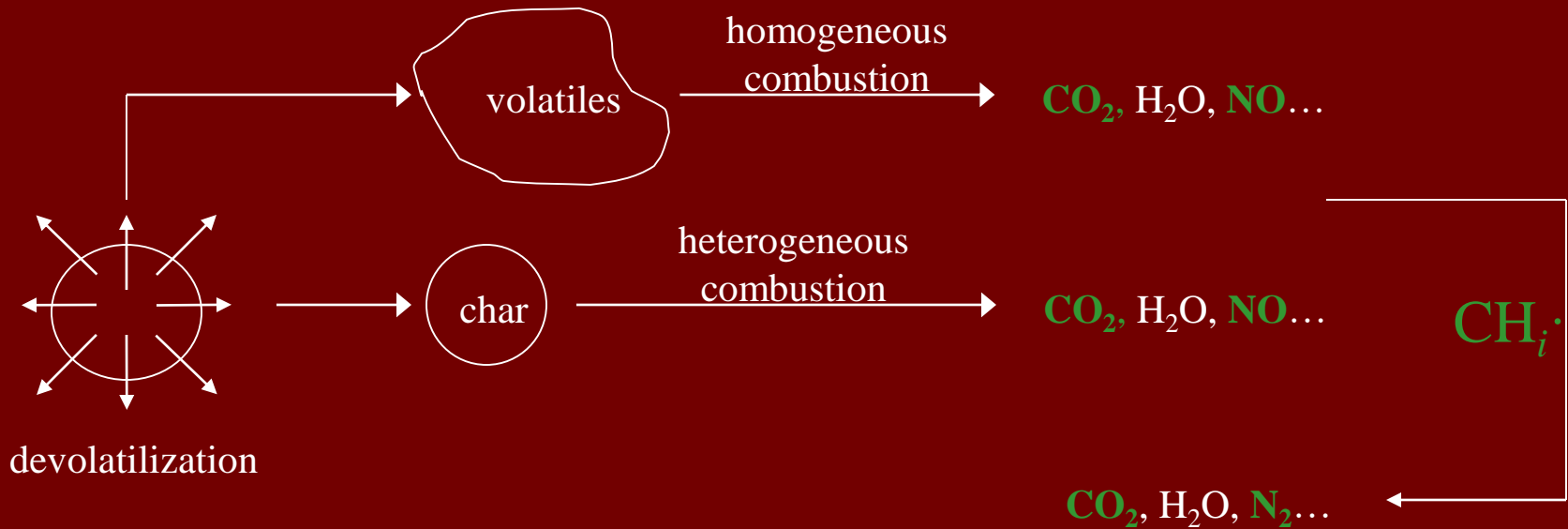
1. Modification of combustion configuration:
  - Reburning
  - Staged Combustion (air/fuel)

## Post combustion controls:

1. Injection of reduction agents in flue gas.
2. Post-combustion denitrification processes.

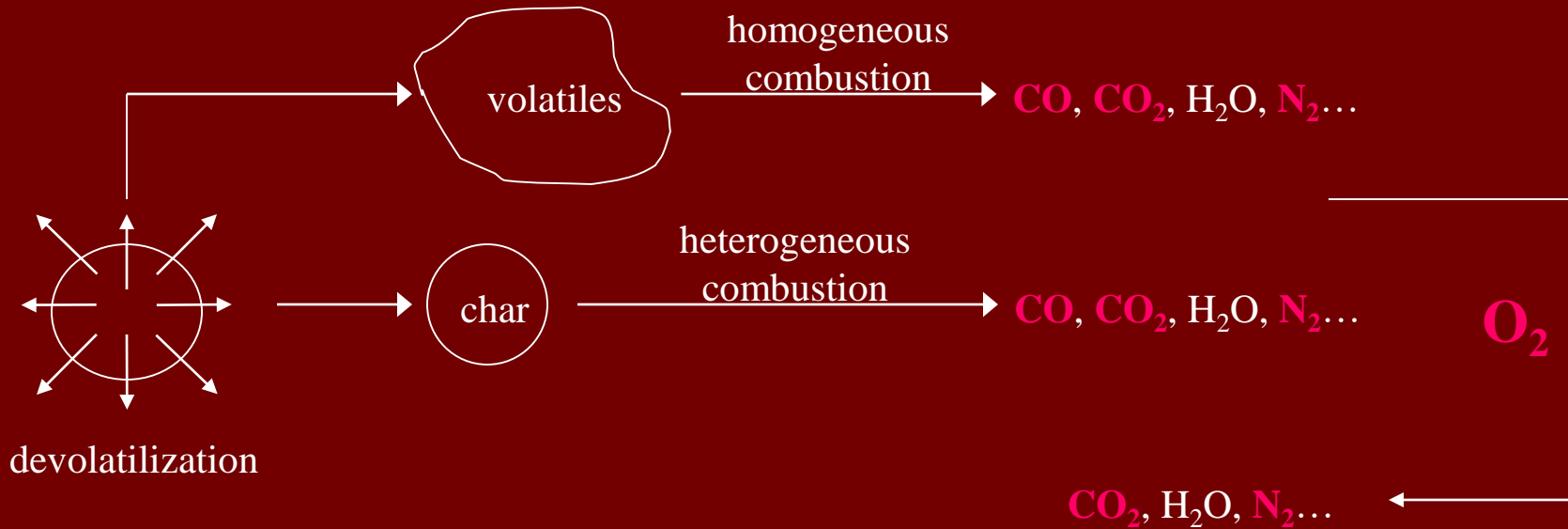
# Reburning

Excess air



# Staged Combustion

**Fuel Rich**



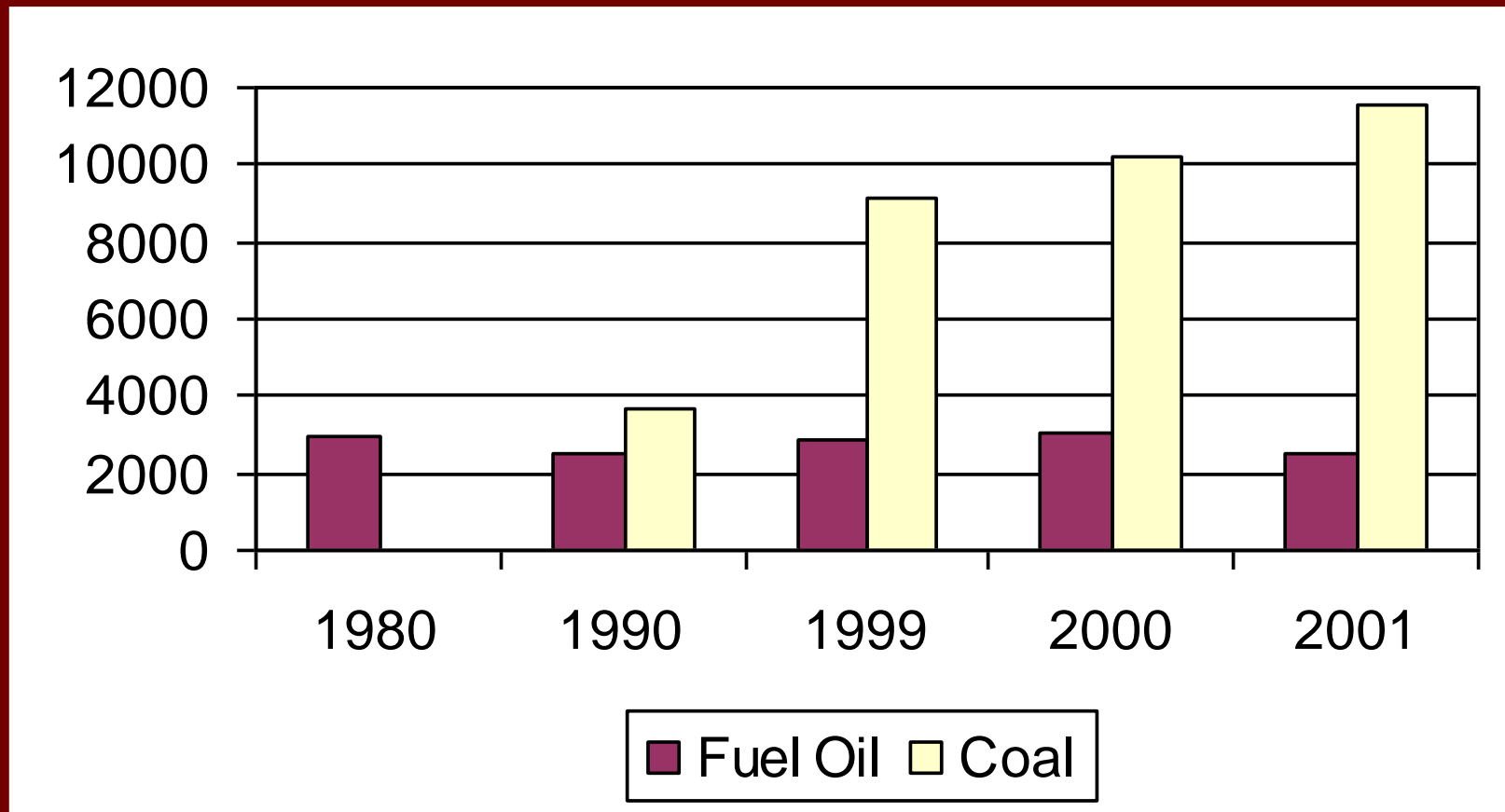
# NOx control options

(from AP-42, EPA)

Control Technique	NO Reduction Potential(%)
Overfire air (OFA)	20-30
Low Nox Burners (LNB)	35-55
LNB + OFA	40-60
Reburn	50-60
SNCR (Selective Non Catalytic Reduction)	30-60
SCR (Selective Catalytic Reduction)	75-85
LNB with SCR	50-80
LNB with OFA and SCR	85-95

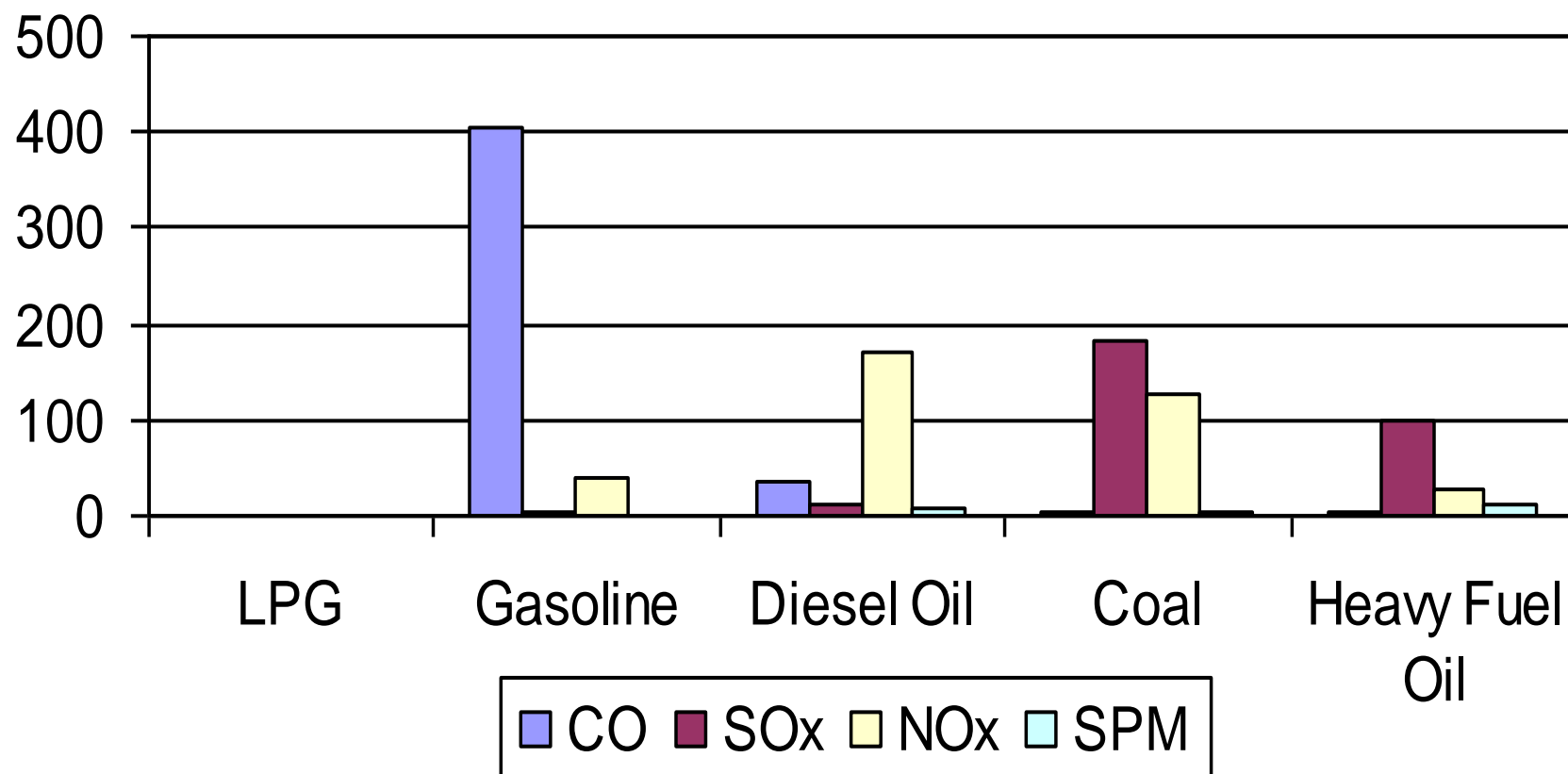
# Fuel Oil and Coal Consumption for Electricity in Israel (1980-2001) (1000 Tons)

Source: Israeli CBS, 2001



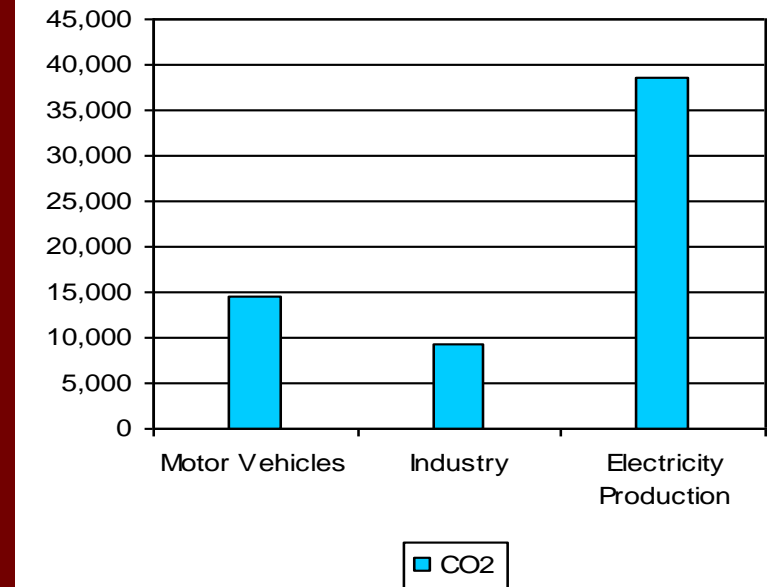
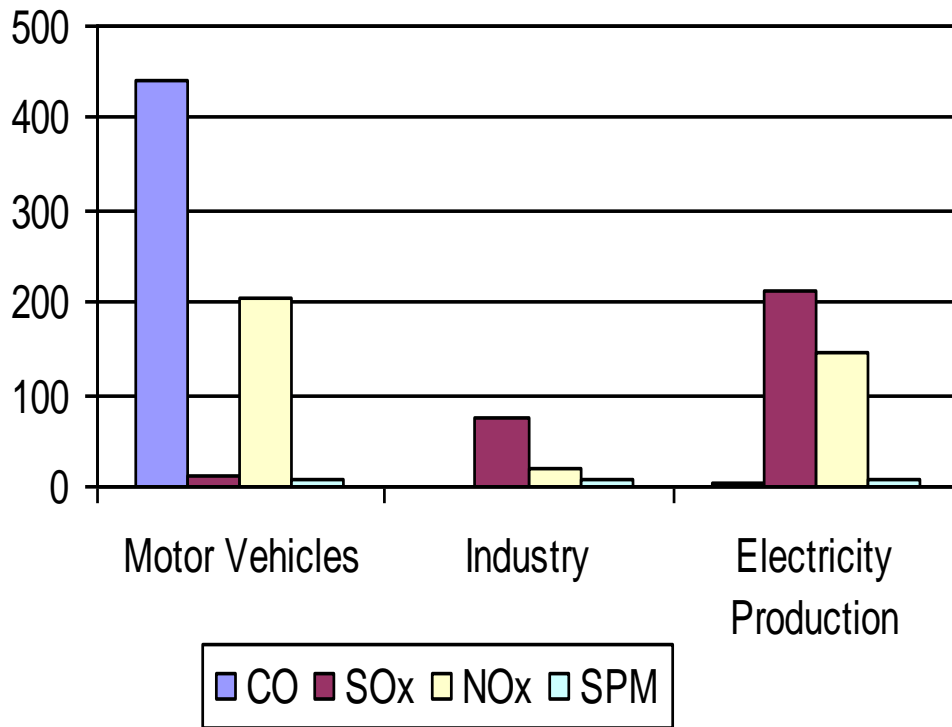
# Fuel Combustion Emissions in Israel by Fuel, 2002 (1000 Tons)

Source: Israeli Central Bureau Statistics (CBS), 2002



# Fuel Combustion Emissions in Israel by Sector, 2002 (1000 Tons)

Source: Israeli CBS, 2002



- 1) Coal combustion in Israel has **tripled** since 1990. Almost all of coal use is for electricity production.
- 2) Coal combustion emissions in Israel:
  - 71% of total SO<sub>2</sub> emissions.
  - 62% of total CO<sub>2</sub> emissions.
  - 39% of total NO<sub>x</sub> emissions.
  - 38% of total SPM emissions.
  - 1% of total CO emissions.

# References

- Compilation of Air Pollutant Emission Factors, AP-42, Fifth Edition, Volume I: *Stationary Point and Area Sources* (<http://www.epa.gov/ttn/chief/ap42/ch01/>).
- “Fundamentals of coal combustion: for clean and efficient use”, edited by L. Douglas Smoot, Elsevier Science Publishers, 1993.
- Israel Central Bureau of Statistics, Shanton 54, 2003 (<http://www.cbs.gov.il>).