Environmental Impact of Fuel Cells

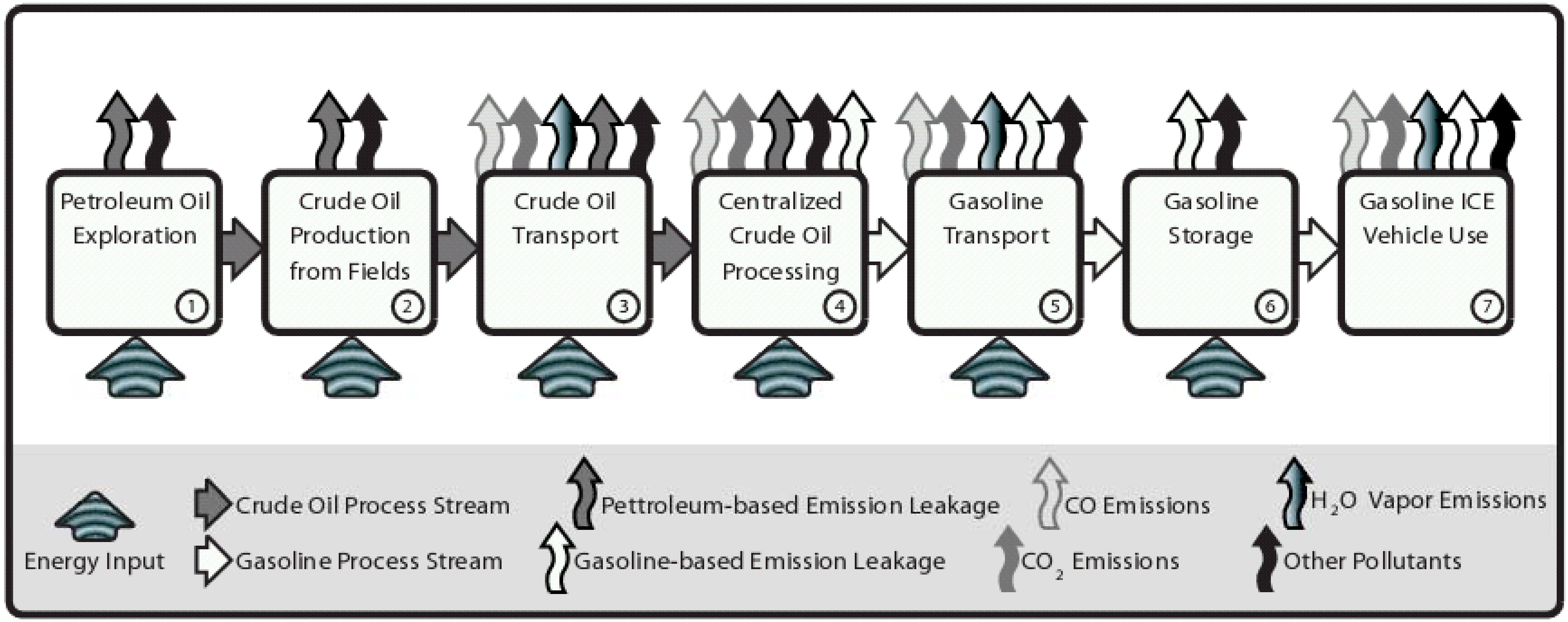
PCA (Process Chain Analysis)

1. Analyze the relevant energy and material inputs and outputs associated with the change in energy technology along the entire supply chain. The supply chain begins with raw material extraction, continues on to processing, then to production and end use, and finally to waste management. Within this chain, it is important to focus on the most energy and emission-intensive processes, the "process bottlenecks." [54]

2. Quantify the environmental impacts associated with these energy and material changes, and

3. Rate the proposed change in energy technology against other scenarios.

PCA (Process Chain Analysis)



PCA of Gasoline ICE

PCA Methodology

1. *Research and develop an understanding of the supply chain* from raw material production to end use.

2. *Sketch a supply chain* showing important processes and primary mass and energy flows. Examples of processes include chemical and energy conversion, production and transport of fuels, and fuel storage; mass flows include the flow of raw materials, fuels, waste products, and emissions; energy flows include the use of electric power, additional chemical energy consumed in a process, and work done on a process.

3. *Identify the "bottleneck" processes*, which consume the largest amounts of energy or which produce the largest quantities of harmful emissions (or both).

4. *Analyze the energy and mass flows in the supply chain using a control volume analysis and the principles of conservation of mass and energy.*

PCA Methodology

5. Having analyzed the individual processes within the supply chain, *evaluate the entire supply chain as a single control volume*. Aggregate net energy and emission flows for the chain.

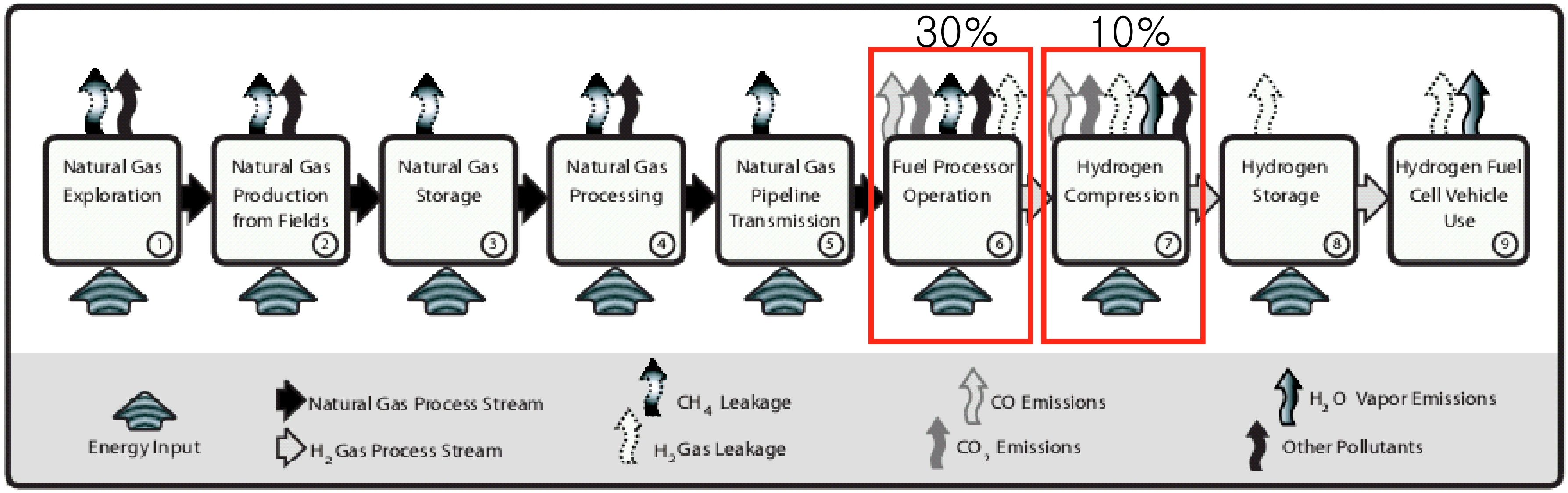
6. *Quantify the environmental impacts of these net flows*, for example, in terms of human health impacts, external costs, and potential for global warming. We will discuss definitions of these terms and methods for conducting this analysis in subsequent sections.

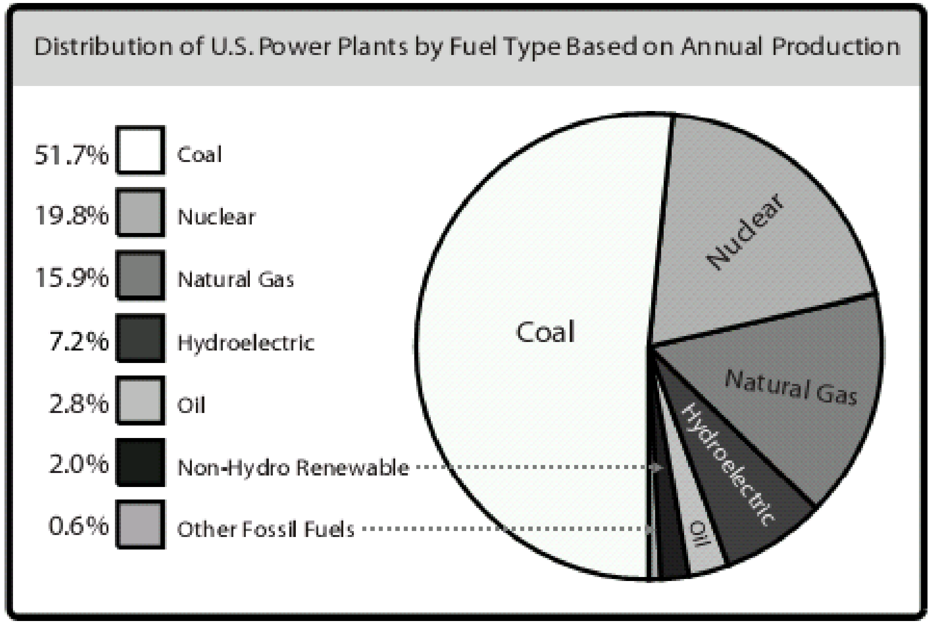
7. *Compare the net change in energy flows, emissions, and environmental impacts of one supply chain with another.*

8. *Rate the environmental performance* of each supply chain against the others.

9. *Repeat analysis* for an expanded, more detailed number of processes in the supply chain.

Fuel Cell PCA



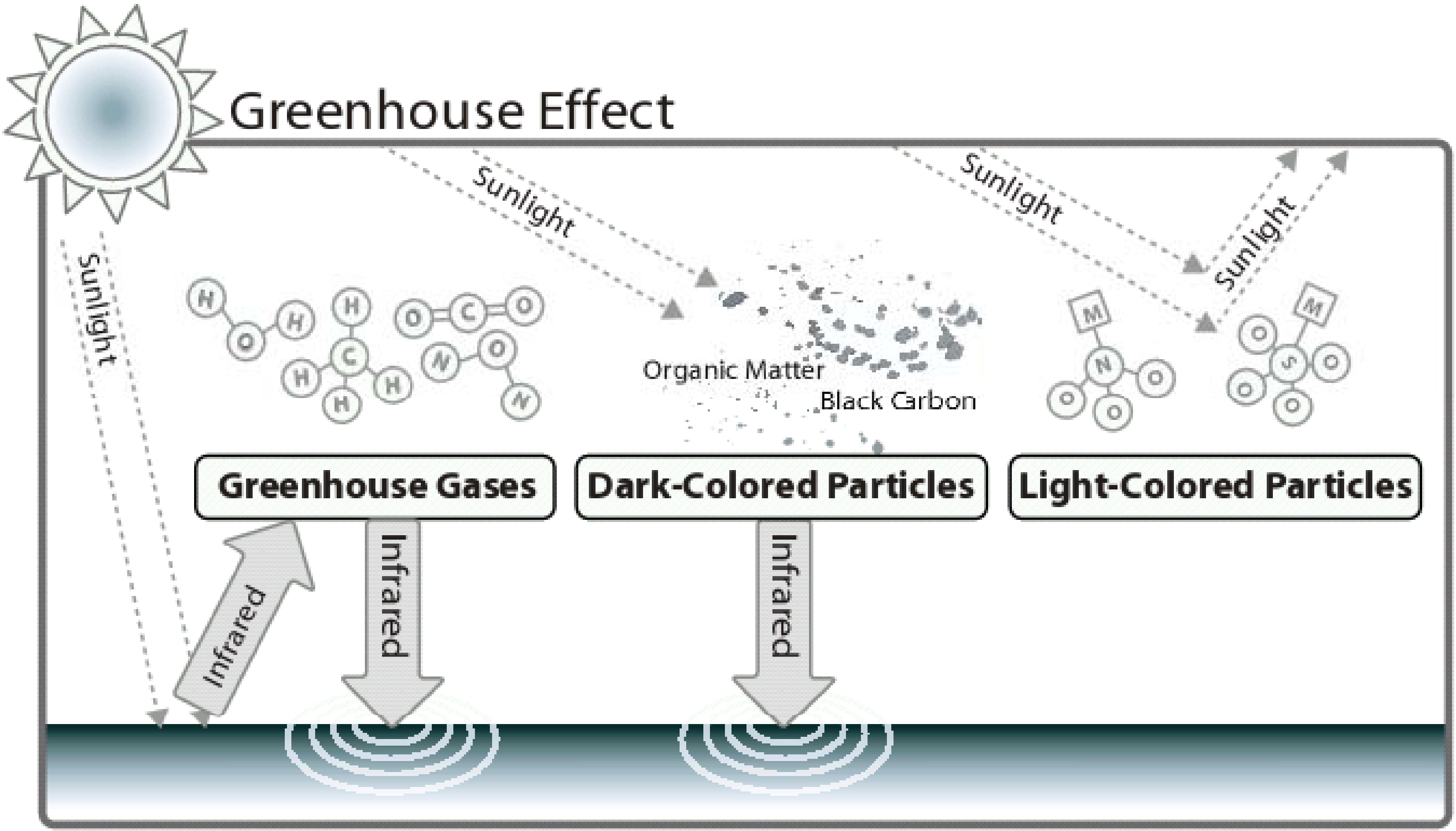


Fuel Cell PCA

Hydrogen Generator Emission Factors			Electricity Plant Emission Factors			
Emission	Natural Gas Steam Reformer	Coal Gasification	Natural Gas Combustion combined cycle gas turbine, low NOx		Coal Combustion coal boiler, steam turbine, low NOx	
	kg emission /kg natural gas fuel	kg emission /kg coal fuel	g emission /kWh electricity	kg emission /kg natural gas fuel	g emission /kWh electricity	kg emission /kg coal fuel
CO_2	2.6	2.37	390	2.5	850	2.4
CH_4	0.000048	unknown	1.5	0.010	3.0	0.0084
Particulate Matter	negligible	0	0.074	0.00047	0.20	0.00056
SO_2	negligible	0.000762	0.27	0.0017	1.0	0.0028
NO_x as NO_2	0.000046	0.000108	0.70	0.0045	2.0	0.0056
CO	0.0000033	0.00734	0.33	0.0021	0.12	0.00035
VOC	0.00000066	0	0.016	0.00010	0.013	0.000038

Table 11.1: Emission factors for two types of hydrogen generators: 1) a natural gas steam reformer and 2) a coal gasification plant; and for two types of electricity generators: 1) a natural gas turbine power plant and 2) a coal combustion power plant.

Global Warming: Green House Effect



Evidence of Global Warming

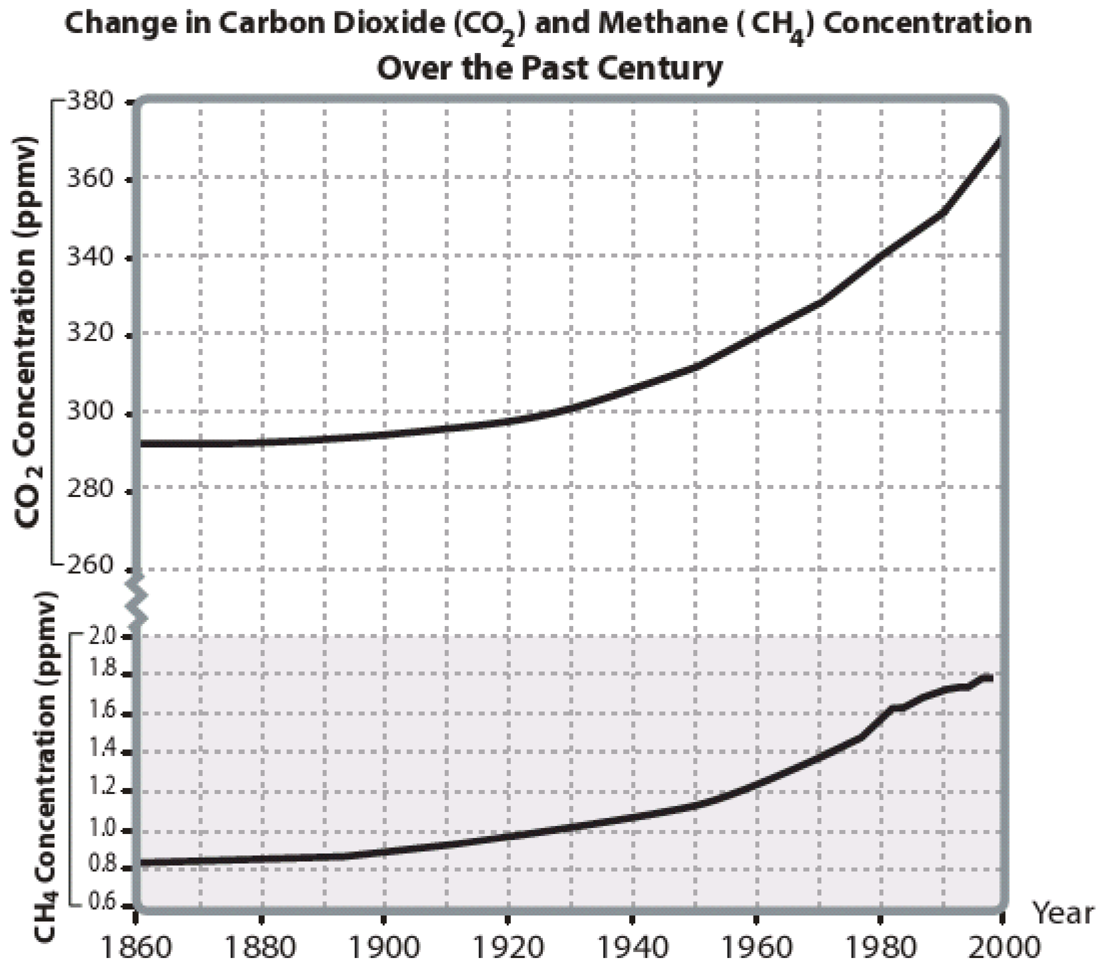


Figure 11.6: Since the 1860s, the concentrations of the primary greenhouse gases – CO_2 and CH_4 – in the lower atmosphere have increased by 30% and 143%, respectively.

Evidence of Global Warming

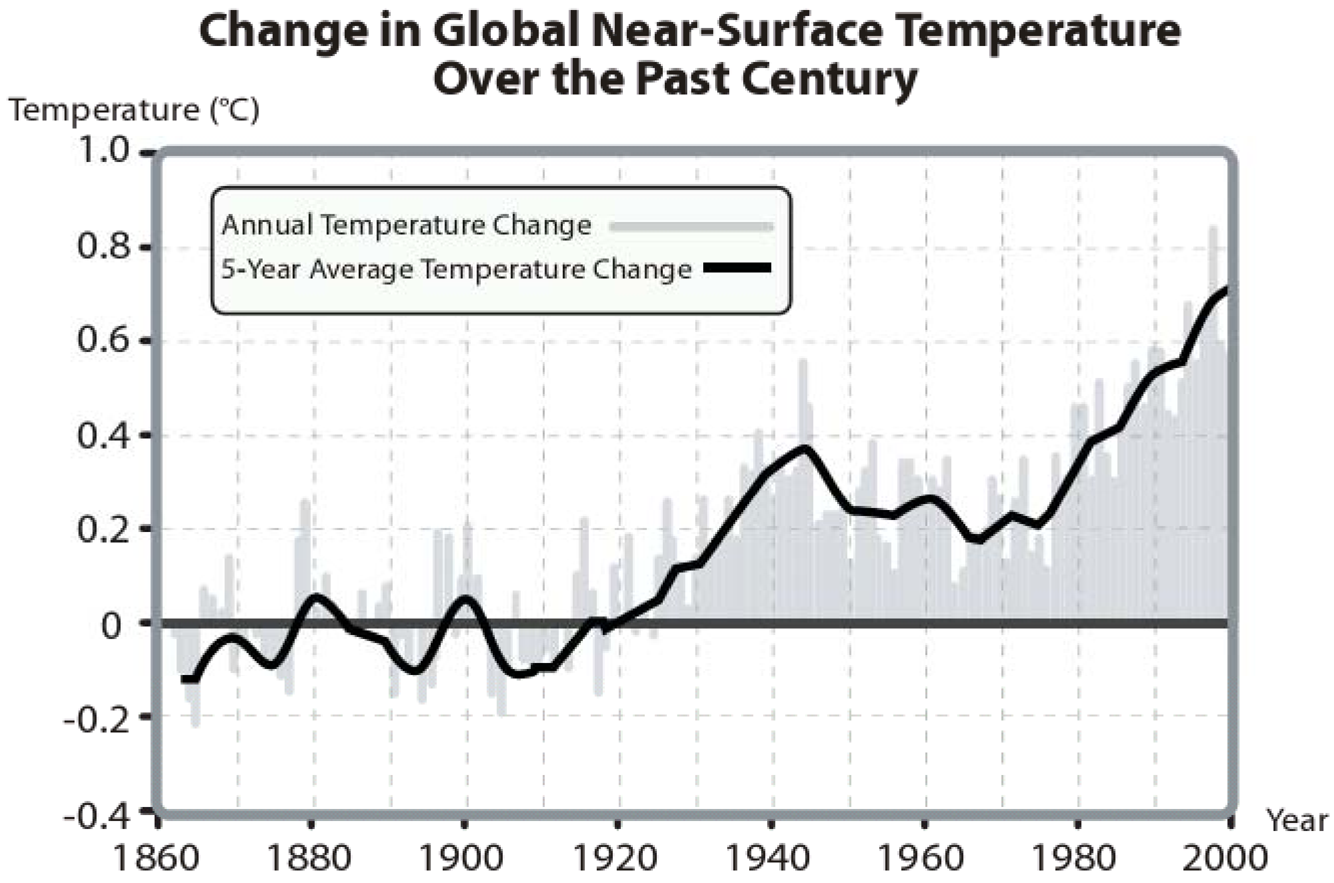


Figure 11.7: Since the 1860s, the Earth's near surface temperature has increased by $0.6°C$ on average.

CO_2 Equivalent Effect

$$
\begin{aligned}
&CO_{2\ equivalent} \\
&= m_{CO_2} + 23m_{CH_4} + 296m_{N_2O} + \alpha(m_{OM,2.5} + m_{BC,2.5}) \\
&\quad - \beta[m_{SULF,2.5} + m_{NIT,2.5} + 0.40m_{SO_X} + 0.10m_{NO_X} + 0.05m_{VOC}]
\end{aligned}
$$

α: 95~191
β: 19~39
OM: Sub 2.5um organic matter
BC: Black carbon
SULF: Sulfates
NIT: Nitrates
SOx: Sulfer oxide
NOx: Nitrogen oxide
VOC: Volatile organic compound

Cost of Global Warming

1. An increase in sea level, resulting in flooding of some low-lying areas,
2. An intensification of the hydrological cycle, resulting in both more drying and more flooding due to an increase in extreme precipitation events.
3. Shifts in regions with arable land and changes in agricultural regions, and
4. Damage to ecosystems.

\$0.026~0.067/kg of $CO_{2\ equivalent}$ (2004)

Air Pollution by Emission

1. ozone (O_3),
2. carbon monoxide (CO),
3. nitrogen oxides (NO_x),
4. particulate matter (PM),
5. sulfur oxides (SO_x), and
6. volatile organic compounds (VOC).

$$H_2 + OH \rightarrow H_2O + H$$

$$H + O_2 + M \rightarrow HO_2 + M$$

$$NO + HO_2 \rightarrow NO_2 + OH$$

$$NO_2 + h\nu \rightarrow NO + O$$

$$O + O_2 + M \rightarrow O_3 + M$$

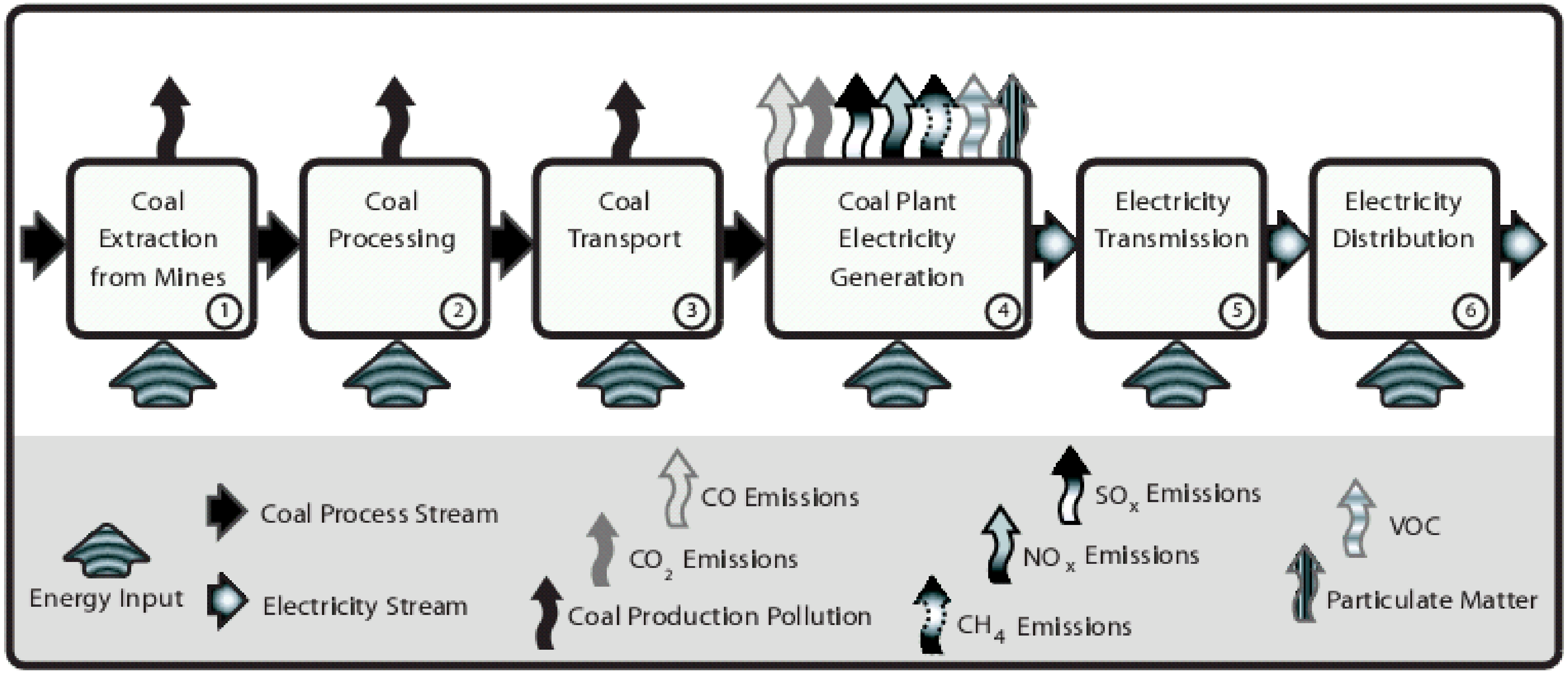
Air Pollution Effect on Health

Health Effects of Air Pollution					Example	
Emission	Ambient Pollutant	Health Effect	Health Effect Factor (Thousands of Cases/ Tonne Ambient Pollutant)		Change in Health Effects (Thousands of Cases) with A Fleet Change from Conventional to Fuel Cell	
			Low	High	Low	High
CO	CO	Headache	1.22	1.45	-7.53E+04	-8.95E+04
		Hospitalisation	0.0000572	0.000164	-3.54	-10.2
		Mortality	0.00000357	0.0000107	-0.221	-0.663
NO_x	NO_2	Sore throat	11.5	11.6	-8.68E+04	-8.81E+04
		Excess phlegm	5.26	5.34	-3.98E+04	-4.04E+04
		Eye irritation	4.73	4.81	-3.58E+04	-3.64E+04
VOC + NO_x	O_3	Asthma attacks	0.0811	0.255	-1.01E+03	-3.19E+03
		Eye irritation	0.752	0.830	-9.40E+03	-1.04E+04
		Lower respiratory illness	1.08	1.80	-1.35E+04	-2.25E+04
		Upper resipiratory illness	0.328	0.548	-4.10E+03	-6.85E+03
		Any symptom or condition (ARD2)	0	6.13	0	-7.67E+04
PM_{10}, SO_2, NO_x, VOC	PM_{10}	Asthma attacks	0.147	0.155	-188	-199
		Respiratory Restricted Activity Days (RRAD)	4.33	5.87	-5,566	-7,540
		Chronic illness	0.00190	0.00454	-2	-6
		Mortality	0.00391	0.00669	-5	-9

Health Costs of Air Pollution

Health Costs of Air Pollution				Example	
Emission	Ambient Pollutant	Health Cost of Air Pollution ($2004/tonne of emission)		Change in Health Costs due to Air Pollution ($2004) with A Fleet Change from Conventional to Fuel Cell	
		Low	**High**	**Low**	**High**
CO	CO	12.7	114	-7.87E+08	-7.08E+09
NO_x	Nitrate-PM_{10}	1.30E+03	2.11E+04	-9.83E+09	-1.60E+11
	NO_2	191	929	-1.45E+09	-7.03E+09
$PM_{2.5}$	$PM_{2.5}$	1.33E+04	2.03E+05	-2.22E+09	-3.39E+10
$PM_{2.5}$ - PM_{10}	$PM_{2.5}$ - PM_{10}	8.52E+03	2.25E+04	-4.38E+08	-1.16E+09
SO_x	Sulphate-PM_{10}	8.78E+03	8.33E+04	-2.39E+09	-2.27E+10
VOC	Organic-PM_{10}	127	1.46E+03	-6.27E+08	-7.21E+09
VOC + NO_x	O_3	12.7	140	-1.59E+08	-1.75E+09
Total				-1.79E+10	-2.40E+11

Example Scenario 1

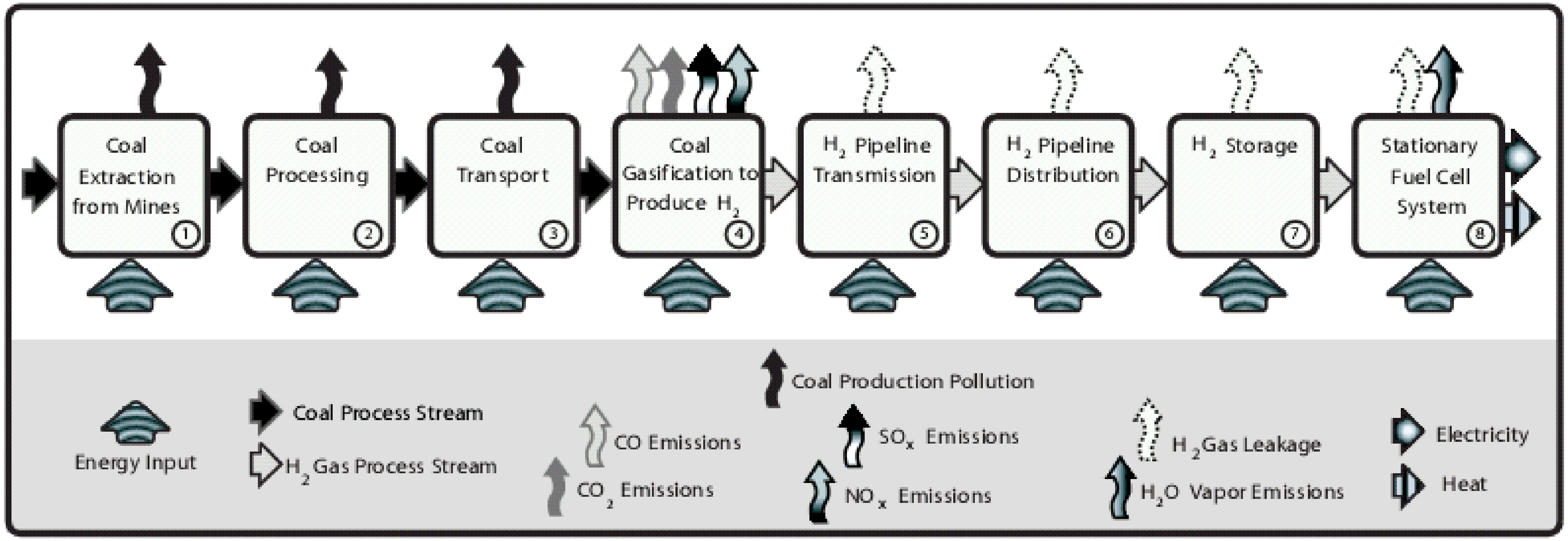


Electricity production from coal

Efficiency=26%

With heat recovery = 26%+0%=25%

Example Scenario 2



Electricity production from coal via fuel cell

Efficiency = 25%

With heat recovery = 25%+10% = 35%