

### The Impact Equation

(Mihelcic & Zimmerman, pages 180, 182)

... where scientists and engineers fit in the picture

In a series of papers in 1970-74, Paul Ehrlich and John Holdren proposed the following equation to estimate the overall impact of our economic activities on the environment:

$$I = P \times A \times T$$

Impact

Population  
(# people)

Affluence  
(# units of technology per person)

Technology  
(impact per unit of technology)

This equation has since been known as the "IPAT" equation, or also the "Master Equation".

When written as a single product, the IPAT equation is somewhat misleading because the most affluent people (ex. Americans) are not necessarily those using the dirtiest technologies (ex. Former Soviet block countries) or those having the highest population (ex. Chinese).

Thus, I propose that we split the IPAT equation in the sum of three terms, each corresponding to a region of the globe:

$$I = P_1 A_1 T_1 + P_2 A_2 T_2 + P_3 A_3 T_3$$

"First World"  
Highly developed nations  
(USA, Canada, Europe,  
Japan, Southeast Asia)

"Second World"  
Transition nations  
(BRIC: Brazil, Russia,  
India & China; Mexico)

"Third World"  
Poor nations

"First World": Relatively clean technologies and stable population; problem is affluence ( $A_1$ )

"Second World": Moderate affluence but dirty technologies ( $T_2$ ) and, for some, population ( $P_2$ )

"Third World": Very little affluence, some dirty technology ( $T_3$ ) and, for some, high population ( $P_3$ ).

## A variation of the IPAT equation

Because energy consumption leads to all kinds of environmental impacts, both upstream (depletion of non-renewable energy sources & oil spills) and downstream (air pollution and greenhouse gases), it can serve as a good measure of the "Impact".

*Environmental impact of energy use*

=

*Environmental impact per unit of energy*

(This combines the renewability and cleanliness factors. On one side, one should consider that petroleum reserves are being depleted and, on the other side, elements such as oil spills, air pollution and greenhouse gas emissions. Reduction lies in adopting the following forms of energy: solar, wind, hydro-electric and biomass-derived fuels.)

X

*Number of energy units used per unit of economic activity*

(This is the energy-efficiency factor. It has improved, with a 60% reduction from 1958 to 1990.)

X

*Number of units of economic activity per person*

(This is the affluence factor. If everyone in the world were to adopt a standard of living equal to that in the United States, this factor would increase by a factor 5.)

X

*Number of people*

(This is the population factor. It is expected to double on earth before it levels off.)

Or, in a way reminiscent of the ecological footprint analysis:

$$I = P \times A \times T$$

total acreage used    # of people    amount of activity per person    acres used per activity

The obvious question is: Does the total acreage used exceed to size of the Earth?

If it does, the set of activities is unsustainable, and one needs to reduce one or several of the factors:

- $P$  → population issues
- $A$  → decrease of consumerism
- $T$  → change to less impacting activities

Another variation of the IPAT equation

As for the affluence factor, one can take the Gross Domestic Product (GDP) of the nation.

Thus, the IPAT equation can also be formulated as

$$I = P \times A \times T$$

The diagram shows the equation  $I = P \times A \times T$ . Arrows point from the following labels to the variables:
 

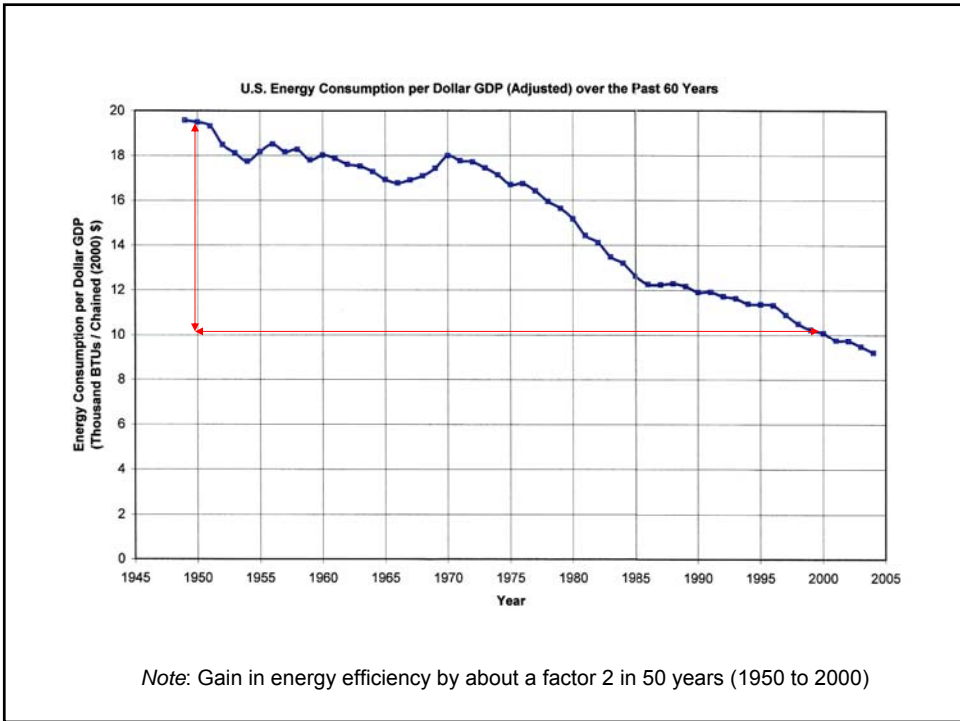
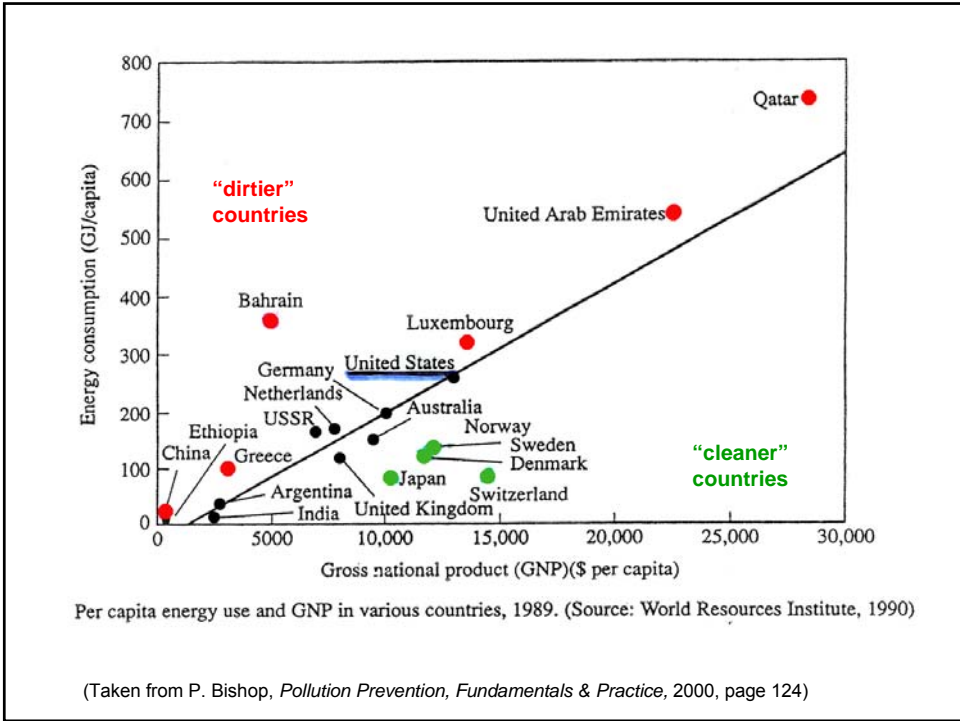
- $I$ : energy consumption
- $P$ : # of people
- $A$ : \$ of GDP per person
- $T$ : energy consumed per \$ of economic activity

 A bracket is drawn under the variables  $P$  and  $A$ , with the label "GDP of the nation" centered below it.

From this follows that reduction in environmental impact can be enacted in part by increased energy efficiency.

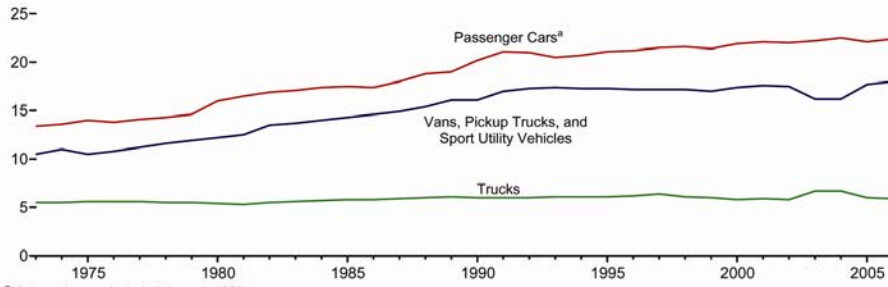
Country	Population (in million)	GDP (in \$ billion)	GDP per capita
Somalia	9.926	5.896	\$600
Ethiopia	90.874	84.02	\$1,000
Haiti	9.720	11.18	\$1,200
Nigeria	155.216	369.8	\$2,400
India	1,189.17	4,046	\$3,400
China	1,336.72	9,872	\$7,400
Brazil	203.430	2,194	\$10,900
Mexico	113.724	1,560	\$13,800
Russia	138.740	2,229	\$15,900
Turkey	78.786	958.3	\$12,300
Slovenia	2.000	56.81	\$28,400
Italy	61,017	1,782	\$30,700
France	65,103	2,160	\$33,300
Germany	81.472	2,960	\$35,900
Canada	34.031	1,335	\$39,600
USA	313.232	14,720	\$47,400

(Source:  
CIA World Factbook 2011  
2010 numbers)



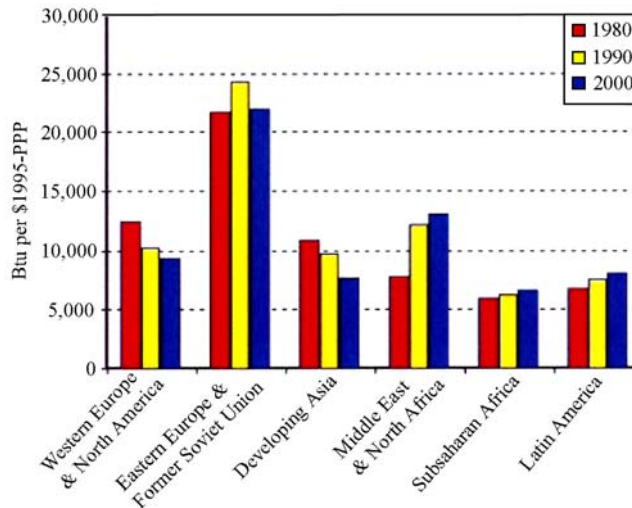
### Energy Intensity in Transportation (in USA)

**Motor Vehicle Fuel Rates, 1973-2006**  
(Miles per Gallon)



<sup>a</sup>Motorcycles are included through 1989.  
Web Page: <http://www.eia.doe.gov/emeu/mer/overview.html>.  
Source: Table 1.8.

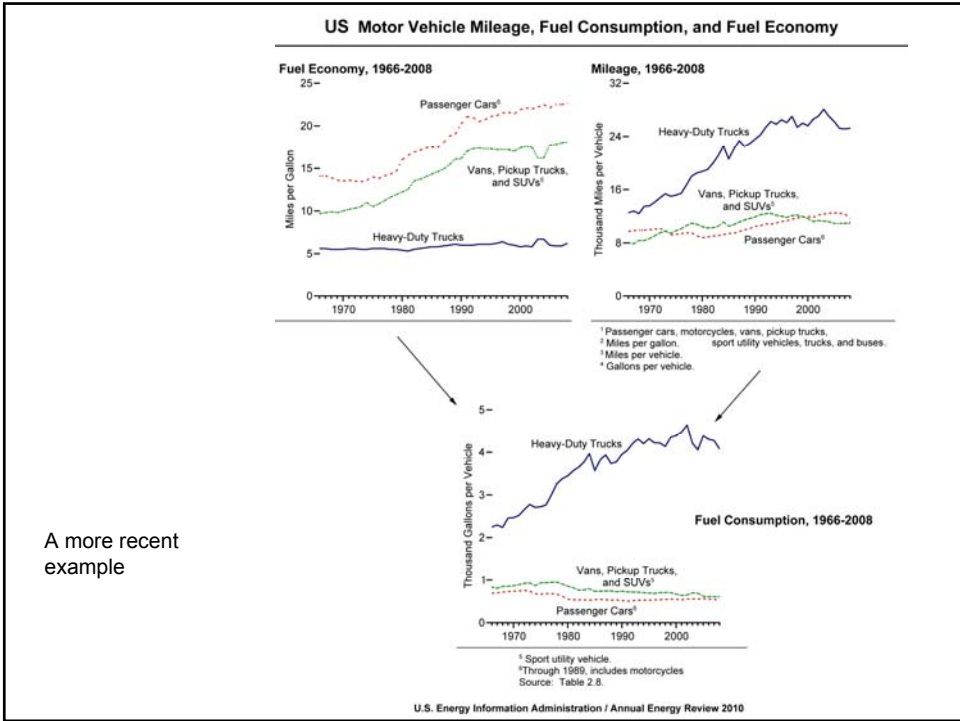
### Regional Energy Intensity Trends



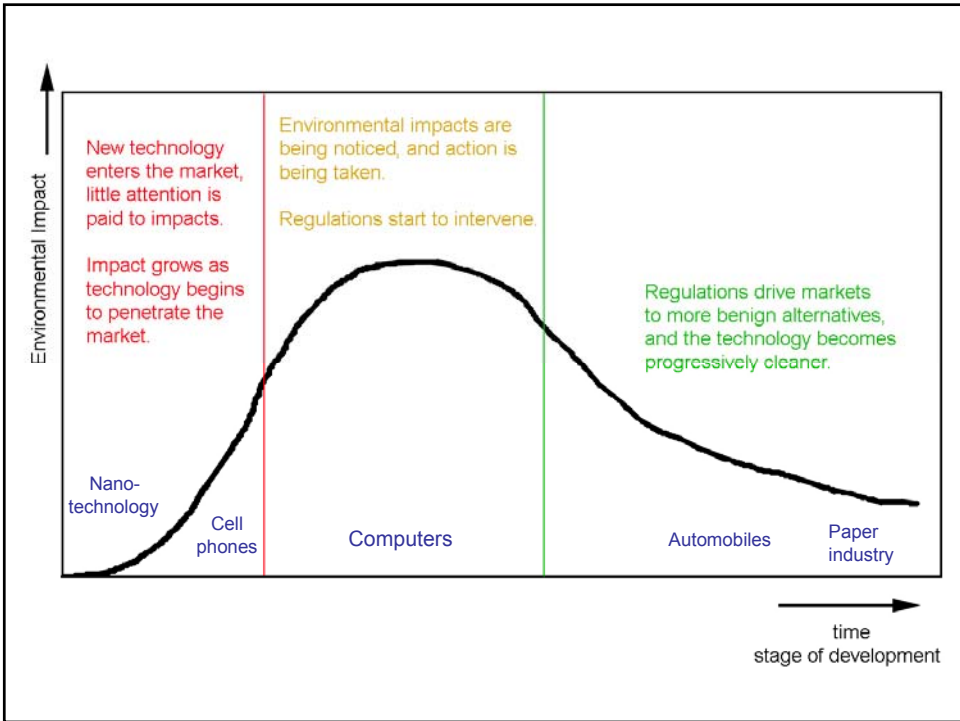
(Source: N. Wilson *World Energy Use and carbon Dioxide Emissions, 1980-2001*, US DoE, May 2004)

Note: Btu = British Thermal Unit  
= energy needed to raise the temperature of one pound of water by one degree Fahrenheit



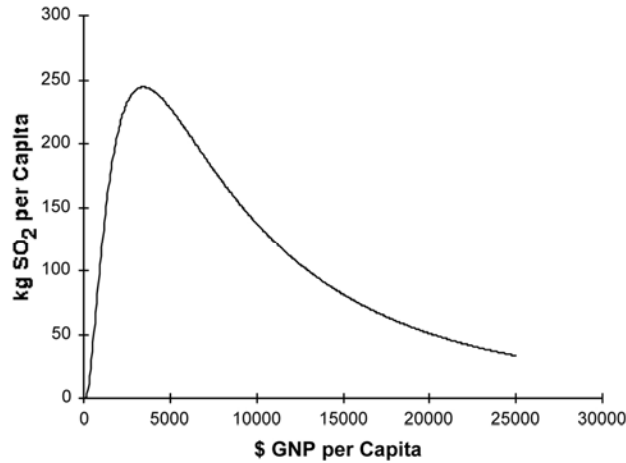


A more recent example



An example

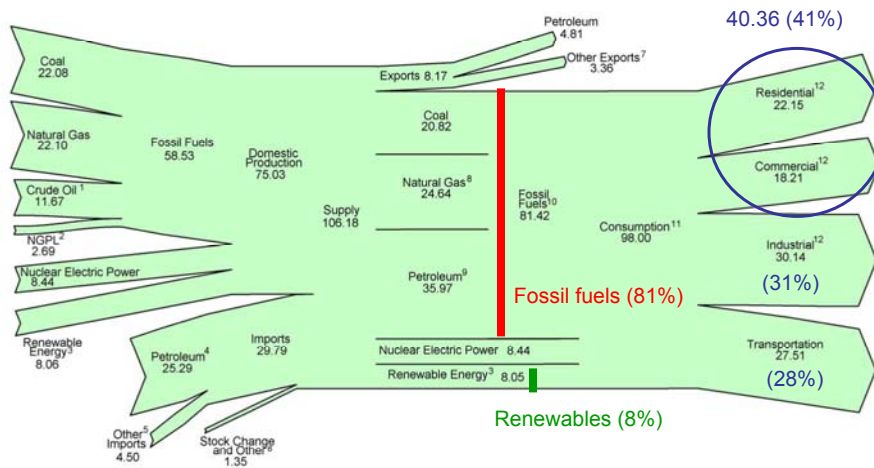
### Environmental Kuznets Curve for Sulfur Emissions



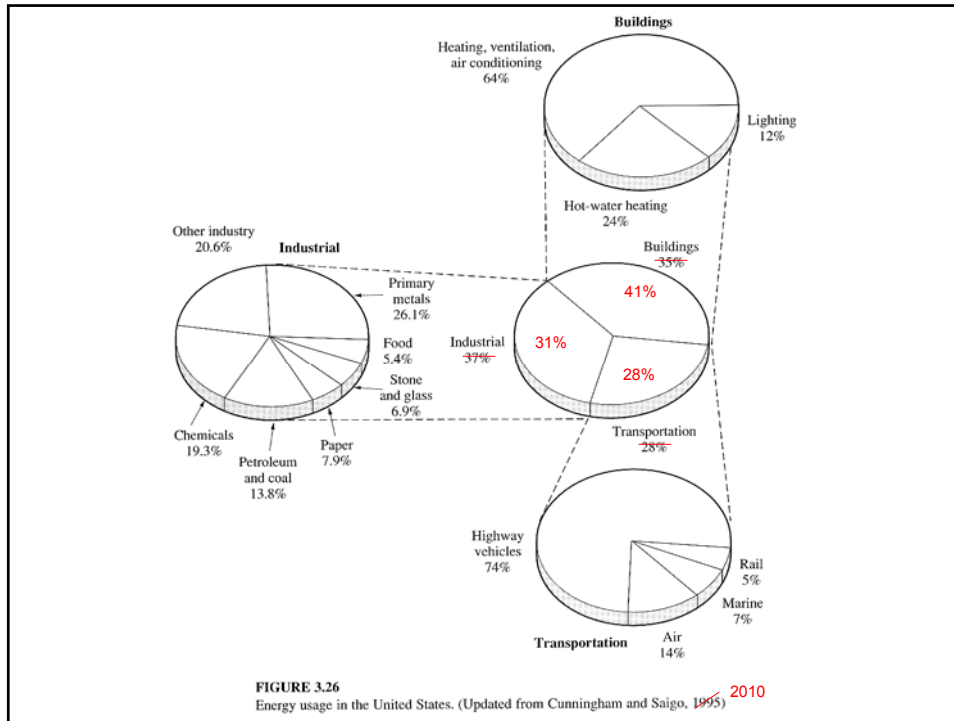
Source: Panayotou (1993), Stern *et al.* (1996).

This figure extracted from "The Environmental Kuznets curve" by David I. Stern (RPI, June 2003)  
[http://www.ecoeco.org/publica/encyc\\_entries/Stern.pdf](http://www.ecoeco.org/publica/encyc_entries/Stern.pdf)

### US Energy Flow, 2010 (Quadrillion Btu) (in 10<sup>15</sup> BTUs per year)



<sup>1</sup> Includes lease condensate.  
<sup>2</sup> Natural gas plant liquids.  
<sup>3</sup> Conventional hydroelectric power, biomass, geothermal, solar/photovoltaic, and wind.  
<sup>4</sup> Crude oil and petroleum products. Includes imports into the Strategic Petroleum Reserve.  
<sup>5</sup> Natural gas, coal, coal coke, biofuels, and electricity.  
<sup>6</sup> Adjustments, losses, and unaccounted for.  
<sup>7</sup> Coal, natural gas, coal coke, electricity, and biofuels.  
<sup>8</sup> Natural gas only; excludes supplemental gaseous fuels.  
<sup>9</sup> Petroleum products, including natural gas plant liquids, and crude oil burned as fuel.  
<sup>10</sup> Includes 0.01 quadrillion Btu of coal coke net exports.  
<sup>11</sup> Includes 0.09 quadrillion Btu of electricity net imports.  
<sup>12</sup> Total energy consumption, which is the sum of primary energy consumption, electricity retail sales, and electrical system energy losses. Losses are allocated to the end-use sectors in proportion to each sector's share of total electricity retail sales. See Note, "Electrical Systems Energy Losses," at end of Section 2.  
 Notes: • Data are preliminary. • Values are derived from source data prior to rounding for publication. • Totals may not equal sum of components due to independent rounding.  
 Sources: Tables 1.1, 1.2, 1.3, 1.4, and 2.1a.



## Renewable Energy Technologies

This is a non-comprehensive list of "alternative" energy technologies

### Hydroelectricity

Dam → water pressure → turbine → electricity

### Solar technologies

Passive solar design (sunbeam → low-temperature heat)

Solar thermal (parabolic mirrors to focus sunbeam → steam in tower → electricity)

Photovoltaic cells (direct conversion sunbeam → electricity)

### Wind technology

Wind turbines (wind → electricity, or compressed air for later conversion in electricity)

### Geothermal power generation

Use of permanent temperature difference on earth between surface and depth  
→ thermodynamic engine (such as heat pump)

### Biomass

Organic material → natural oils (biodiesel)

→ sugars → alcohol (= fuel)

→ cellulosic matter → sugars → alcohol (= fuel)

### Resource recovery

Incineration of solid waste → heat/steam → heating or electricity

Used vegetable oil → fuel for transportation

Methane emissions from municipal landfills → capture → fuel

### Energy from the ocean

Wave/tidal energy, current energy, geothermal energy

## Renewable Energy Possibilities

### Solar

$1.2 \times 10^5$  TW on Earth's surface  
36,000 TW on land (world)  
2,200 TW on land (US)

### Wind

2-4 TW extractable

### Tide/Ocean Currents

2 TW gross

### Geothermal

9.7 TW gross (world)  
0.6 TW gross (US)  
(small fraction technically feasible)



### Biomass

5-7 TW gross  
(world)  
0.29% efficiency for  
all cultivatable land  
not used for food

### Hydroelectric

4.6 TW gross (world)  
1.6 TW technically feasible  
0.6 TW installed capacity  
0.33 gross (US)

(Source: George Crabtree, Materials Science Division, Argonne National Laboratory, 2005)