The impact Equation
… 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:

$$I = P_1 \boxed{A_1} T_1 + P_2 A_2 \boxed{T_2} + \boxed{P_3} A_3 T_3$$

"**First World**"
Highly developed nations
(USA, Canada, Europe, Japan, SE 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 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 oils 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, undergoing 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 become 5 times larger.)

X

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

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 be read as

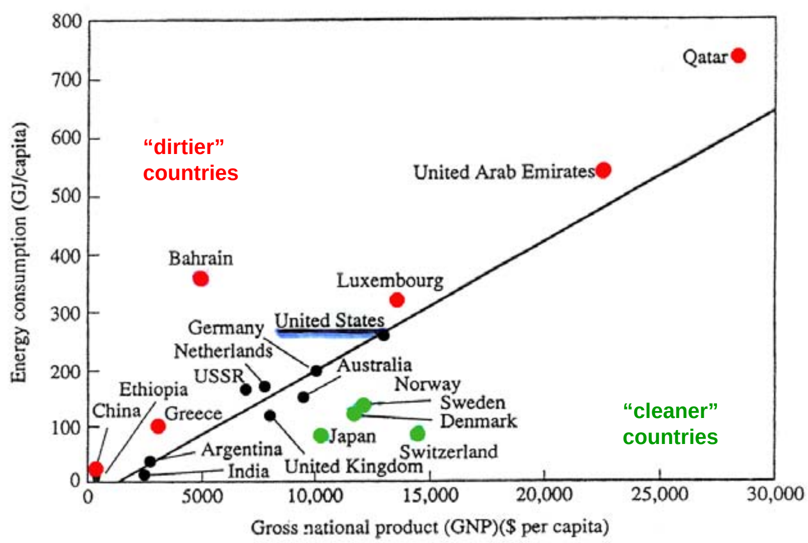
$$I = P \times A \times T$$

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

From this follows that the reduction in environmental impact

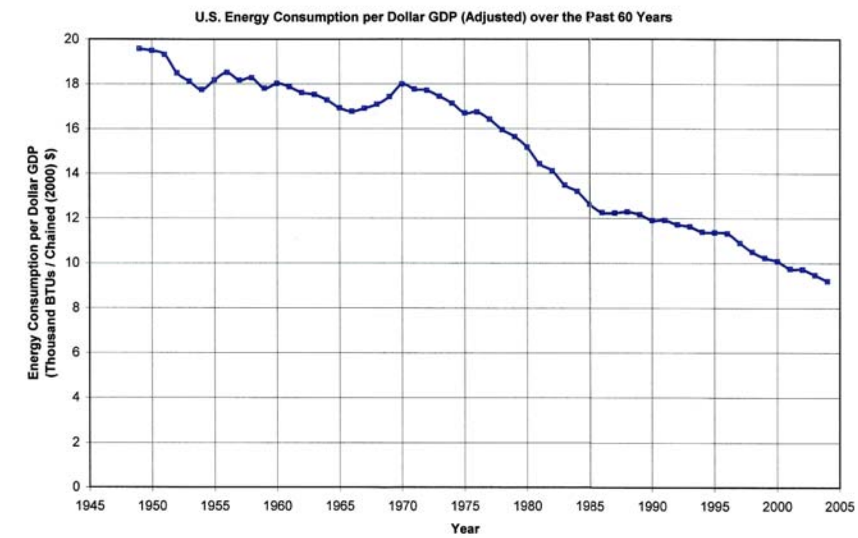
Country	Population (in million)	GDP (in $ billion)	GDP per capita
Somalia	9.926	5.896	$600
Ethiopia	90.874	84.02	$1,000
Haiti	9.720	11.18	$1,200
Nigeria	155.216	369.8	$2,400
India	1,189.17	4,046	$3,400
China	1,336.72	9,872	$7,400
Brazil	203.430	2,194	$10,900
Mexico	113.724	1,560	$13,800
Russia	138.740	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)

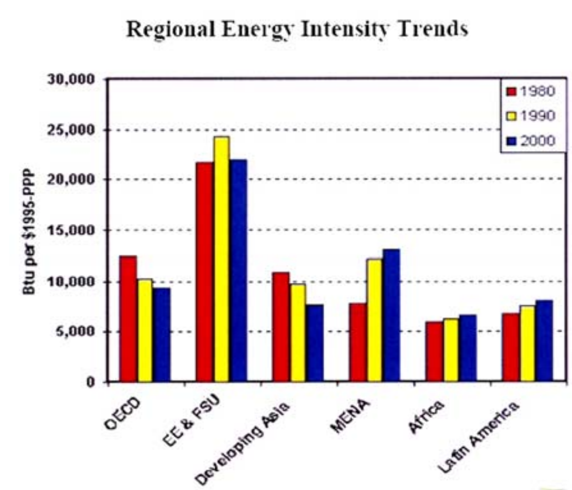


Per capita energy use and GNP in various countries, 1989. (Source: World Resources Institute, 1990)

(Taken from P. Bishop, *Pollution Prevention, Fundamentals & Practice,* 2000, page 124)

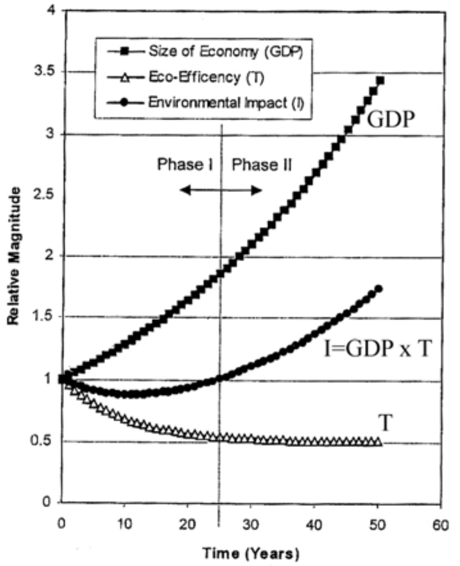


Note: Gain in energy efficiency by a factor 2 in 50 years (1950 to 2000)



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

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

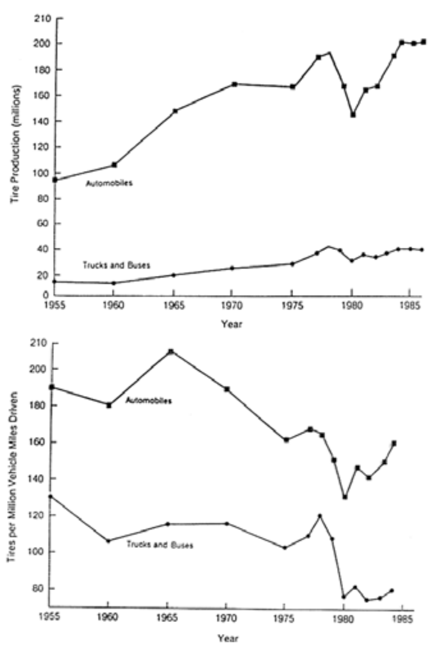


There is a limit to how clean technology (T) can be but no apparent limit to wealth (GDP).

The result is an eventual increase of impact (I).

Fig. 5. Predicted changes in total environmental impact (I) according to Eq. (8) assuming a GDP growth rate of 2.5% per year and a maximum improvement in eco-efficiency (T) by a factor of two within the next 25 years (From Huesemann, 2003)

A clear example: Rubber tires

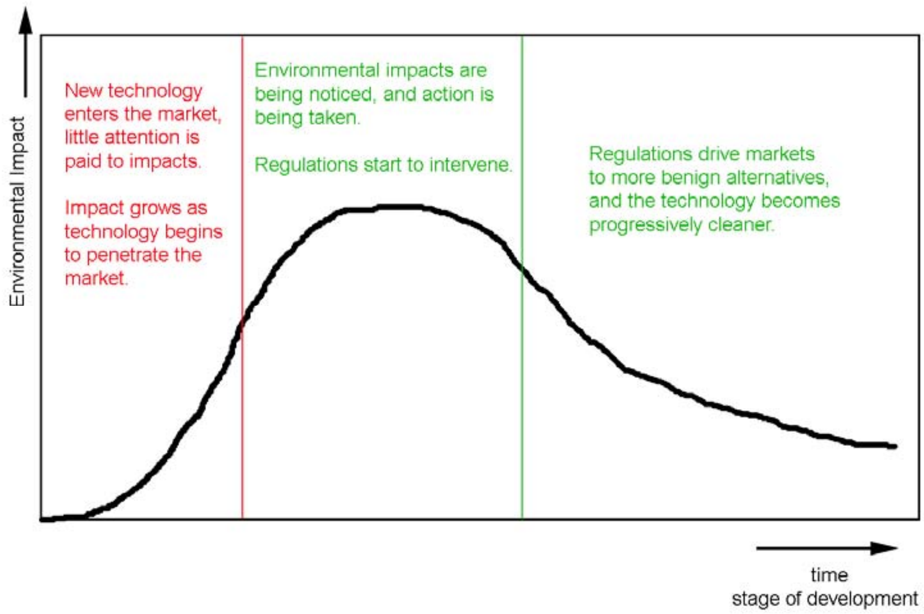


- On one hand, we make better, smarter materials
- This allows us to use less or use the same longer
- But, on the other hand, there are more of us
- And, each one of us consumes more.

The total amount used of a material =

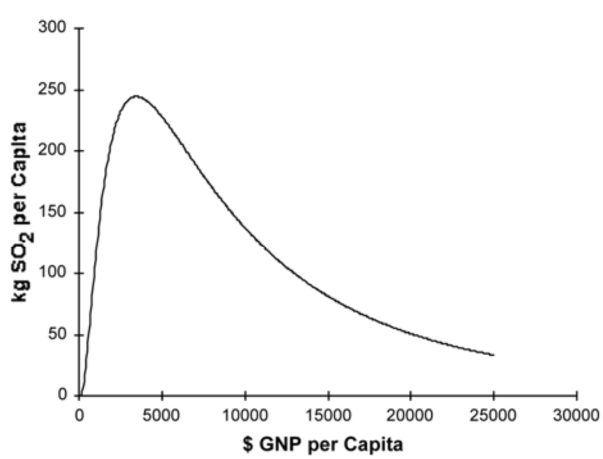
Amount per product x Number of products

↓ ↑



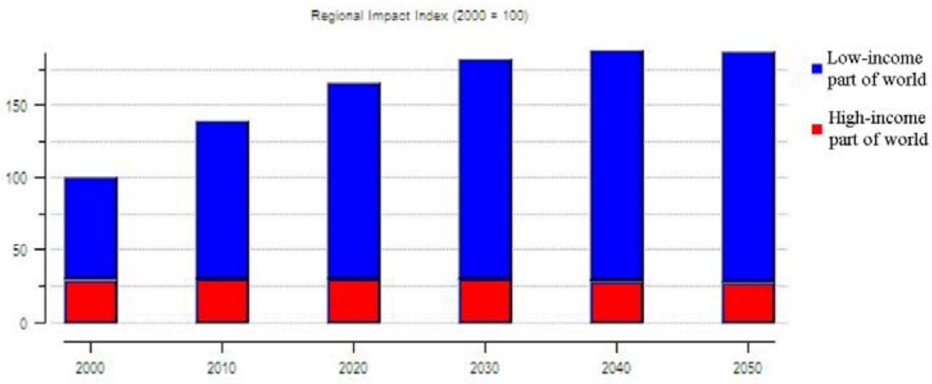
An example

Environmental Kuznets Curve for Sulfur Emissions



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

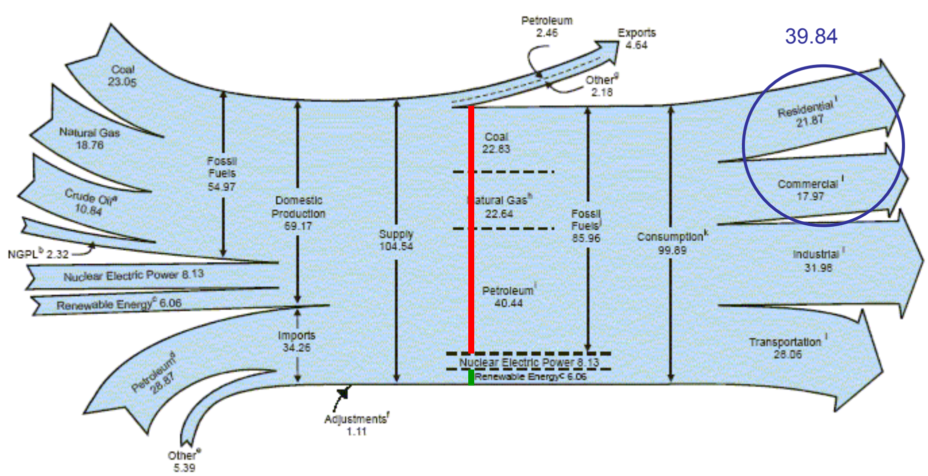
This figure extracted from "The Environmental Kuznets curve" by David I. Stern (RPI, June 2003)
(http://www.ecoeco.org/publica/encyc_entries/Stern.pdf)



Environmental impact by region.

(from Eric Kemp-Benedict "Traveling along the environmental Kuznets curve" IPAT-S, a script language for sustainability scenarios, 30 November 2003)

Energy issues



Energy flow in the United States in 2005, in 10^{15} BTUs/year
(*Source*: U.S. Department of Energy)

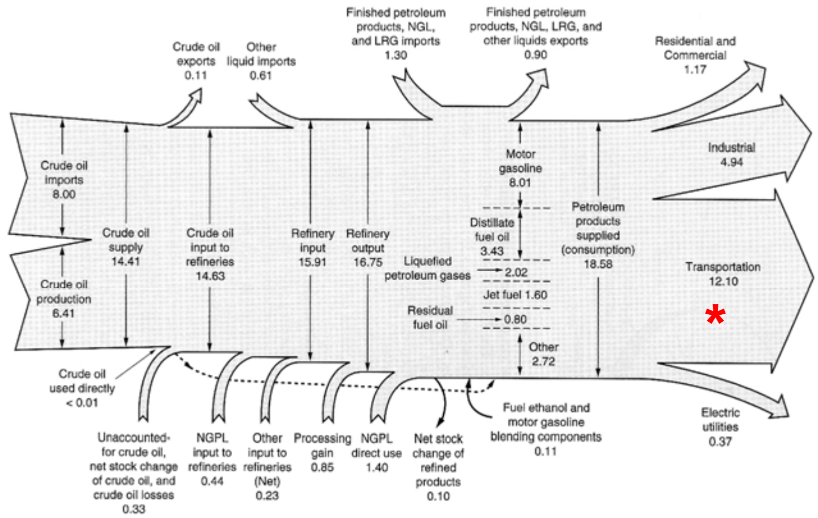


FIGURE 3.30
Petroleum flow in the United States, 1997 (million barrels per day). (Source: U.S. Department of Energy, 1998)

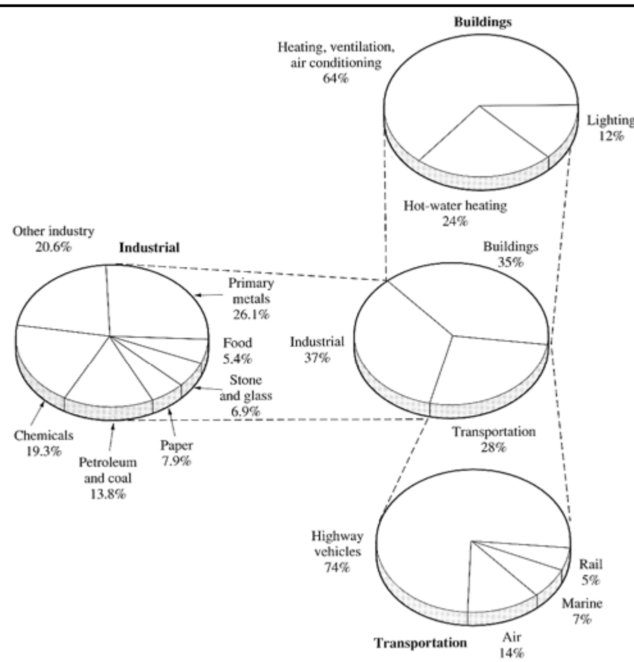


FIGURE 3.26
Energy usage in the United States. (Updated from Cunningham and Saigo, 1995)

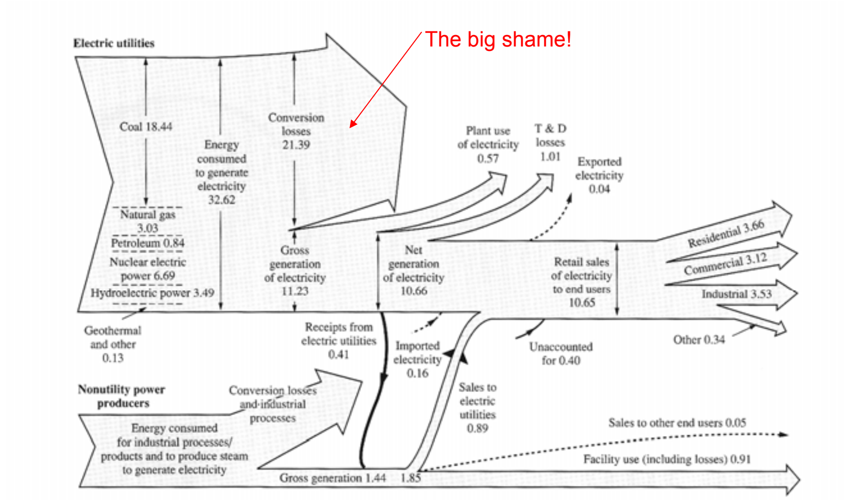


FIGURE 3.33
Electricity flow in the United States, 1997. (Source: U.S. Department of Energy, 1998)

(in 10^{15} Btu per year)

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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)

Geothermal power generation
use of permanent temperature difference on earth
→ thermodynamic engine (on land or at sea)

Biomass
Organic material → natural oils (biodiesel)
→ sugars → alcohol (= fuel)

Resource recovery
Incineration of solid waste → heat/steam → heating or electricity
Methane emissions from municipal landfills → capture → fuel

Energy from the ocean
Wave energy, tidal energy, geothermal energy

Renewable Energy Possibilities

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

Wind
2-4 TW extractable

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

Tide/Ocean Currents
2 TW gross

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

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

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