The “IPAT” Equation

References

Ehrlich, P.R. and J.P. Holdren, 1972. Critique: One Dimensional Ecology. *Bulletin of the Atomic Scientists* 28(5): 16, 18-27.

Commoner, Barry. “The Environmental Cost of Economic Growth.” in Population, Resources and the Environment. Washington, DC: Government Printing Office Pp. 339-63, 1972.

Disaggregating the Problem

$$\text{Impact} = \text{Population} \times \frac{\text{Goods \& Services}}{\text{Person}} \times \frac{\text{Impact}}{\text{Goods \& Services}}$$

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

The IPAT equation is a mathematical identity that shows that the underlying environmental problems are related to “scale”. Growth in Population and Affluence have exceeded improvements in Technology. Furthermore the terms in the equation are highly coupled!

for infinitesimals

$$\frac{\Delta I}{I} = \frac{\Delta P}{P} + \frac{\Delta A}{A} + \frac{\Delta T}{T}$$

Technology

Population Growth

Affluence = GWP per captia

Population Dynamics

$R_{IN} \longrightarrow \boxed{P_0} \longrightarrow R_{OUT}$

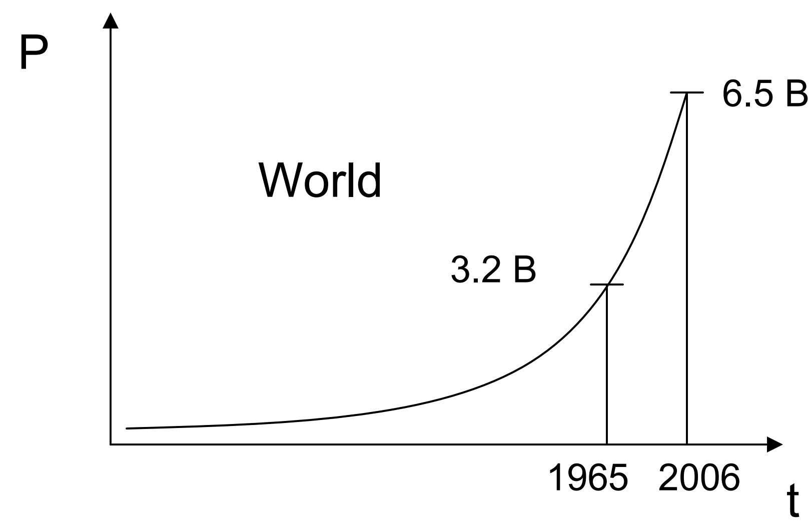
$$\Delta R = [birth - death] + [immigration - emigration]$$

$$\frac{dP}{dt} = \Delta R \cdot P \qquad \frac{dP}{P} = \Delta R \cdot dt \qquad \boxed{P = P_o e^{\Delta R \cdot t}}$$

in the discrete form…

$$P = P_o (1 + i)^n$$

Currently $i \approx 1\%$



We are adding 70-80 M people/yr

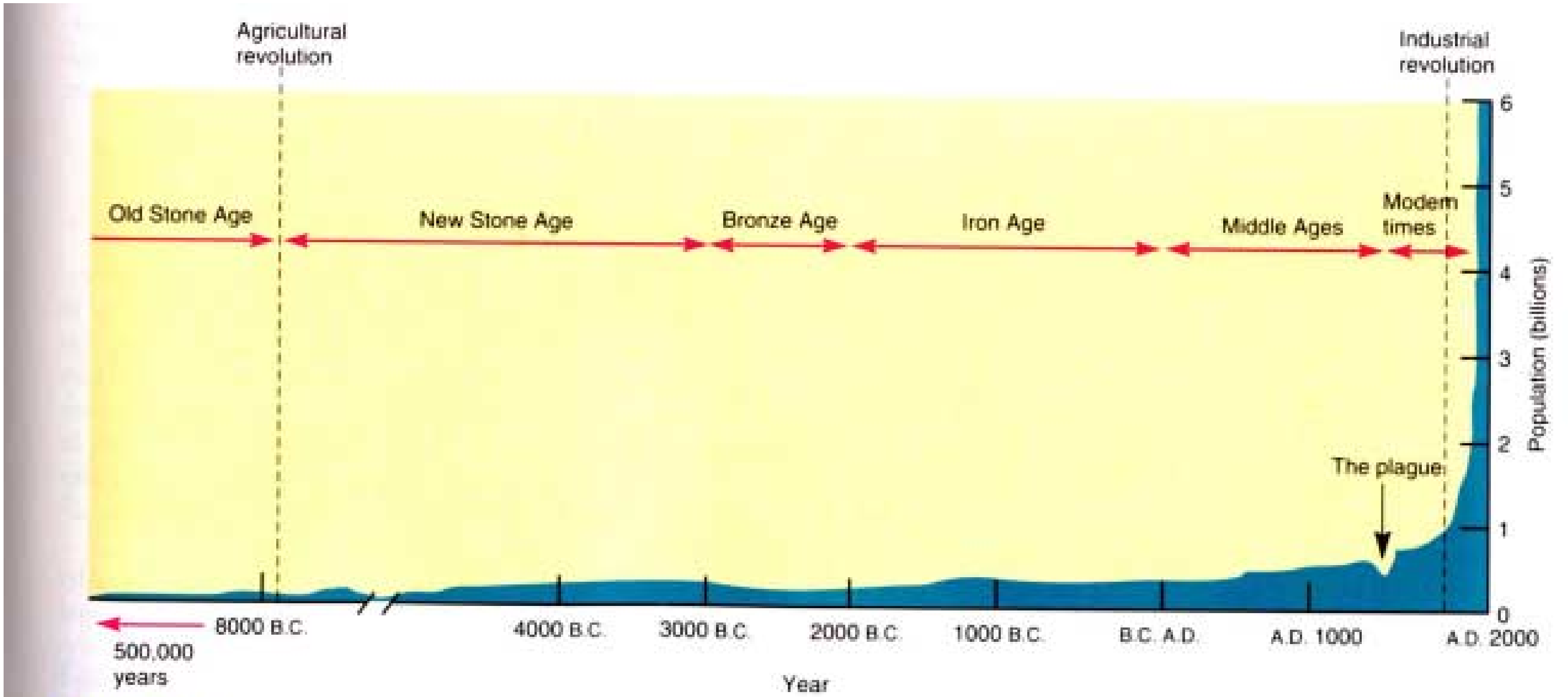


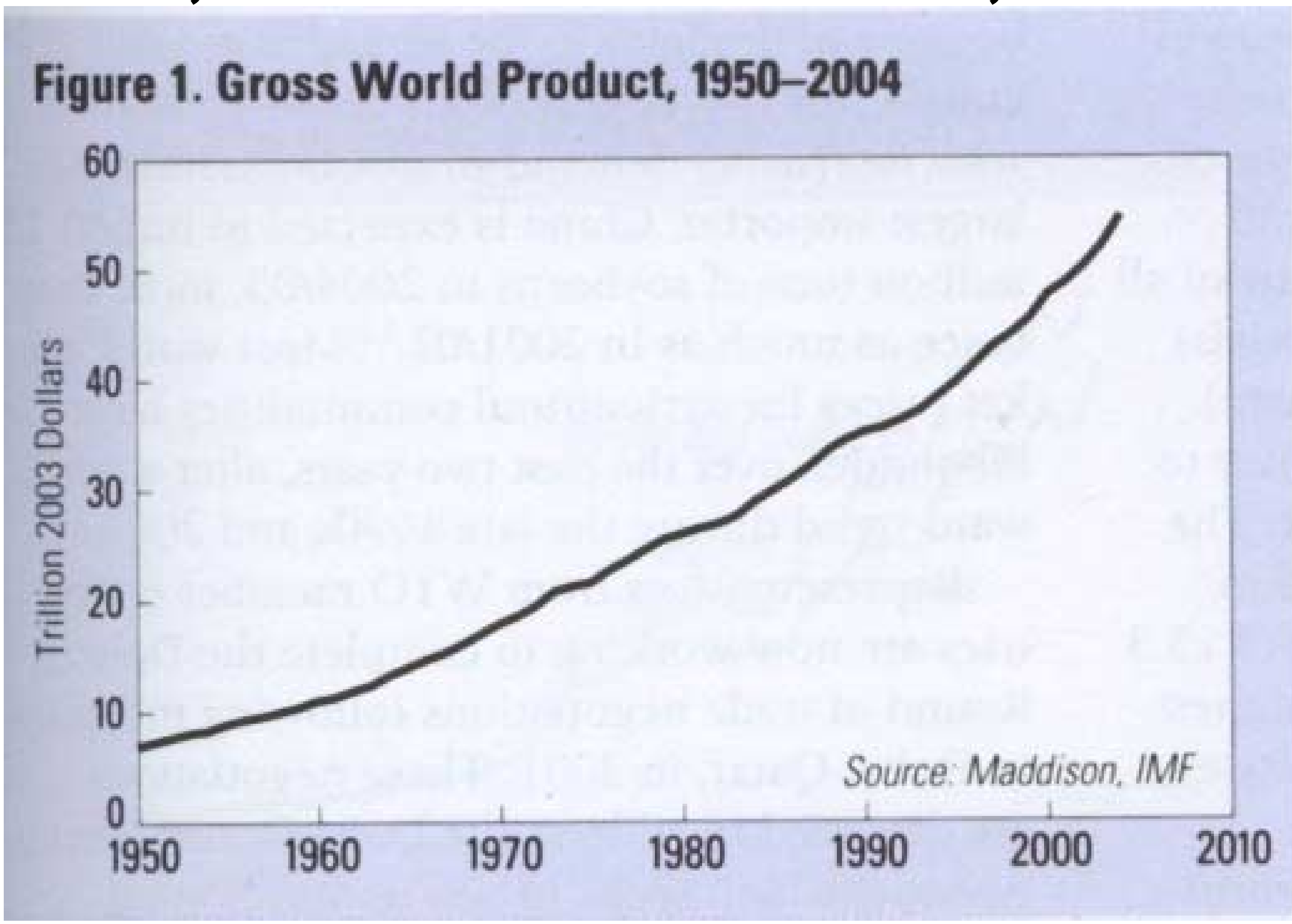
Figure 7.3 Human population levels through history. Since about A.D. 1000, our population curve has assumed a J shape. Are we on the upward slope of a population overshoot? Will we be able to adjust our population growth to an S curve? Or can we just continue the present trend indefinitely?

Add one Germany or 2X Canada each year

Affluence and GDP, GWP

- GDP = Gross Domestic Product
- GWP = Gross World Product
- GWP = market value of all goods and services produced for a year

GWP, i ≈ 5% for 2004, 2005



Over the last several decades the growth in GWP has been less, more like 3%

To improve, we want…

$$\frac{\Delta I}{I} = \frac{\Delta P}{P} + \frac{\Delta A}{A} + \frac{\Delta T}{T} < 0$$

"technology"

Based on global estimates…

$$1\% + 4\% - 5\% = 0$$

We must improve our environmental performance on goods and services by 5% a year just to stay even.

“IPAT “ examples

1. Automobiles and gasoline
2. pig iron and energy
3. global carbon

1. Gasoline Used in Automobiles

What are the factors that influence the amount of gasoline we burn in automobiles?

$$\text{gasoline} = \text{number of cars} \times \frac{\text{miles driven}}{\text{car}} \times \frac{\text{gasoline}}{\text{mile}}$$

Impact "I"

population "P"

$\frac{\text{service provided}}{\text{car}}$ "A"

technology "T"

2. Energy used to make pig iron

$$\text{Energy} = \text{number of factories} \times \frac{\text{pig iron}}{\text{factory}} \times \frac{\text{energy}}{\text{pig iron}}$$

$$\text{Energy} = \text{pig iron produced} \times \frac{\text{energy}}{\text{pig iron}}$$

Again the energy used per ton pig iron produced depends upon the technology used.

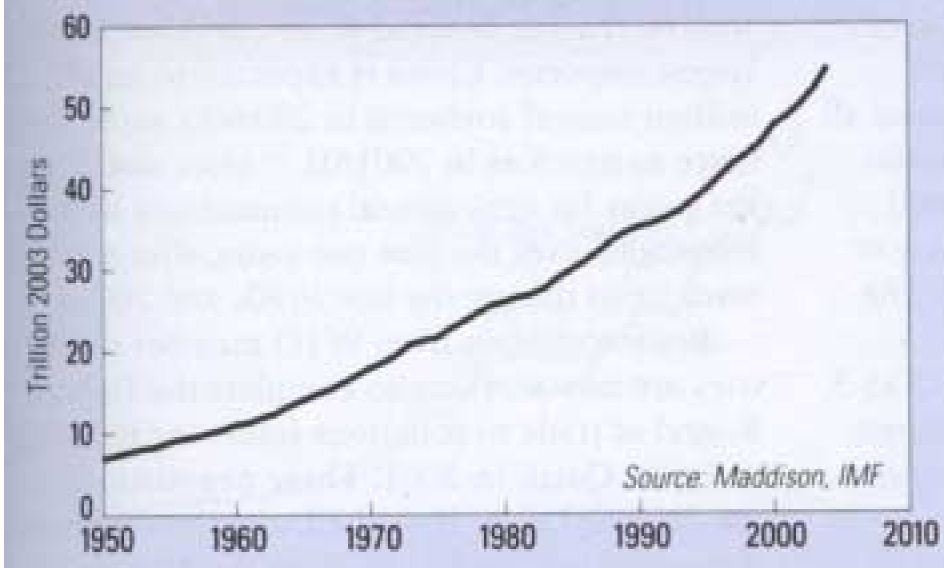
3. Carbon emissions

$$\text{Carbon} = \text{Population} \times \frac{\text{GWP}}{\text{Pop}} \times \frac{\text{Energy}}{\text{GWP}} \times \frac{\mathit{Carbon}}{\mathit{Energy}}$$

$$\frac{\Delta\text{Carbon}}{\text{Carbon}} = \quad +1\% \qquad +2\% \quad -1.25\% \quad -0.25\% \quad = \quad +1.5\%$$

These are *rough* averages over the last 3 decades,
data taken or calculated from Pacala & Socolow, Science 2004

Figure 1. Gross World Product, 1950–2004



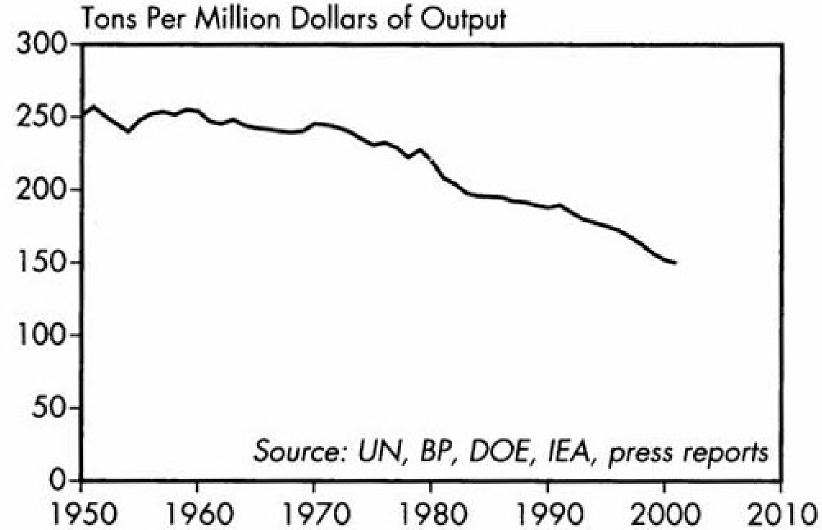
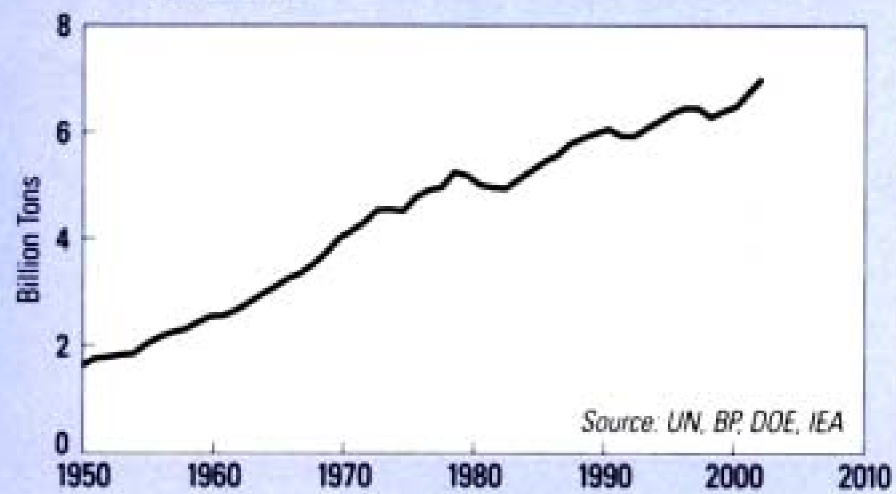
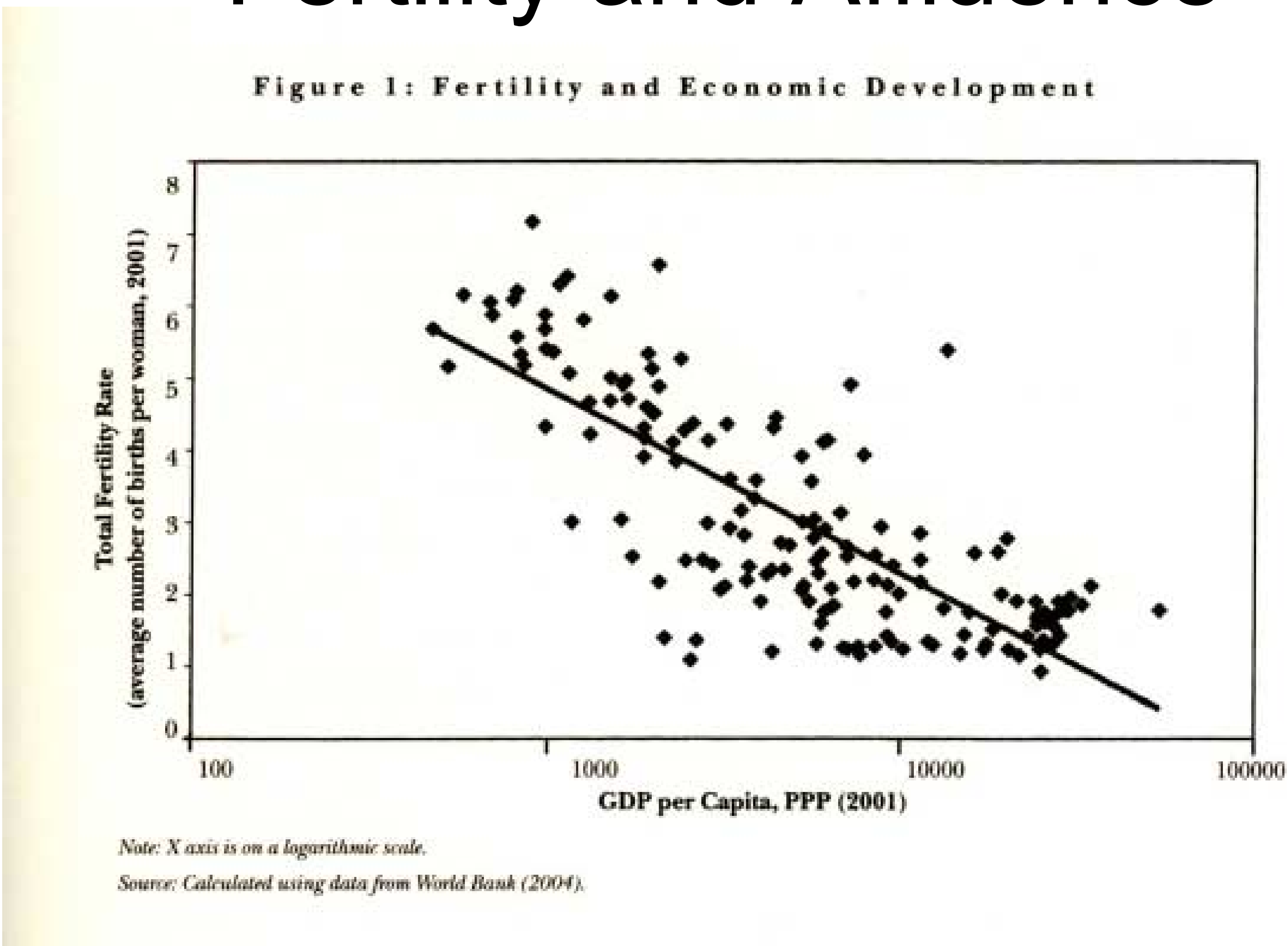


Figure 2: Carbon Intensity of the World Economy, 1950–2001

Figure 3. Carbon Emissions from Fossil Fuel Burning, 1950–2003



Fertility and Affluence



see www.Harvard.edu

Affluence and Energy are correlated

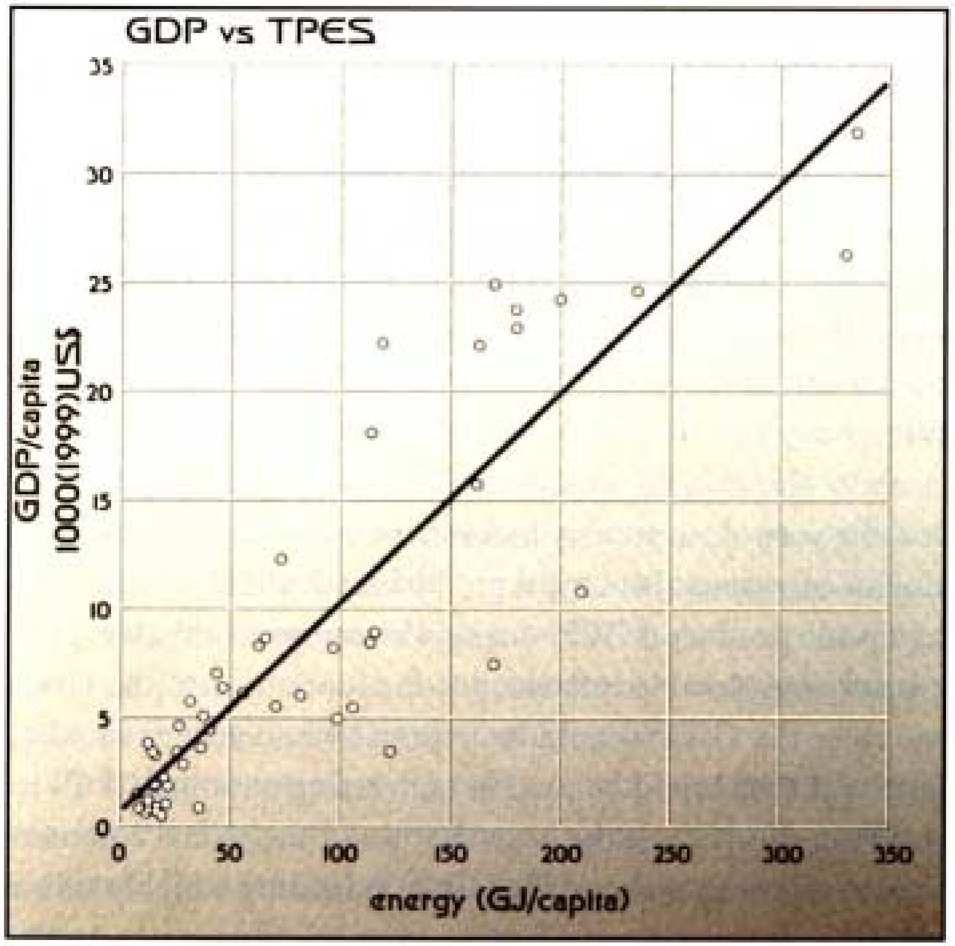


Figure 2.1
A high correlation between TPES and GDP, with both values expressed as per capita averages for the year 2000. Values calculated from data in BP (2001) and UNDP (2001).

From Smil

From a Production point of view

$$\text{Impact} = \text{Production} \times \frac{\text{Impact}}{\text{Production}}$$

Energy Used Production (P) or Consumption 1/efficiency (e)

$$I = P \times \frac{1}{e}$$

Differentiating

$$\frac{dI}{dt} = \frac{1}{e}\frac{dP}{dt} - \frac{P}{e^2}\frac{de}{dt} \leq 0$$

Normalizing, and taking yearly increments, you are an environmentally benign producer when...

$$\frac{\Delta e}{e} \geq \frac{\Delta P}{P}$$

The Gold Standard

Note that "e" and "P" are coupled!

- $e = f\,(P)$ *Increased production leads to increased efficiency through learning effects and economies of scale*

- $P = f\,(e)$ *Increased efficiency can lead to reduced prices and increased demand. The phenomenon is called the "rebound effect"*