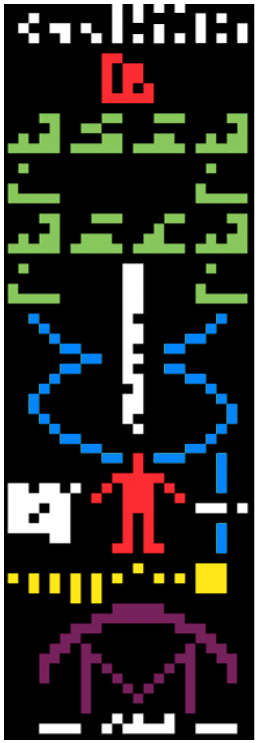
Manufacturing & Sustainability

Timothy Gutowski, MIT

Objectives of this talk

1. Part 1
   - What is Sustainability?
2. Part 2
   - What is Manufacturing?

Is there intelligent life in the universe?



Green Bank
West Virginia
Meeting
1961
Searching for
Intelligent life
in the universe
(SETI)

Walter Sullivan, We are not alone, 1964

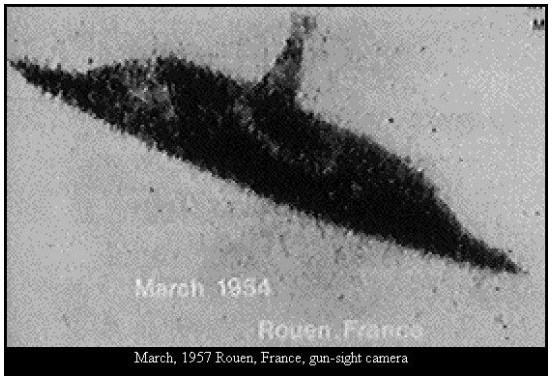
SEARCHING FOR INTERSTELLAR COMMUNICATIONS

By GIUSEPPE COCCONI* and PHILIP MORRISON†
Cornell University, Ithaca, New York

NO theories yet exist which enable a reliable estimate of the probabilities of (1) planet formation ; (2) origin of life ; (3) evolution of societies possessing advanced scientific capabilities. In the absence of such theories, our environment suggests that stars of the main sequence with a lifetime of many billions of years can possess planets, that of a small set of such planets two (Earth and very probably Mars) support life, that life on one such planet includes a society recently capable of considerable scientific investigation. The lifetime of such societies is not known ; but it seems unwarranted to deny that among such societies some might maintain themselves for times very long compared to the time

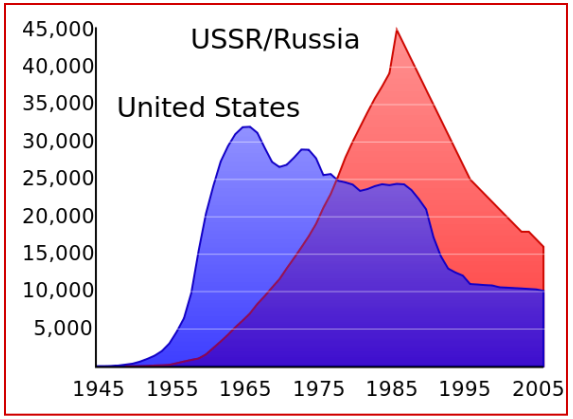
To the beings of such a society, our Sun must appear as a likely site for the evolution of a new society. It is highly probable that for a long time they will have been expecting the development of science near the Sun. We shall assume that long ago they established a channel of communication that would one day become known to us, and that they look forward patiently to the answering signals from the Sun which would make known to them that a new society has entered the community of intelligence. What sort of a channel would it be ?

The Optimum Channel



March, 1957 Rouen, France, gun-sight camera

UFO's



Nuclear Warheads

Is There Intelligent Life on Earth?

$$N = R_* f_p n_e f_l f_i f_e \cdot L$$

N = number of civilizations in the galaxy that are currently capable of communicating with other solar systems

R_* = The rate at which stars were being formed in the galaxy during the period when the solar system itself was born

f_p = The fraction of stars with planets

n_e = The number of planets per solar system, with an environment suitable for life

f_l = The fraction of suitable planets on which life actually appears

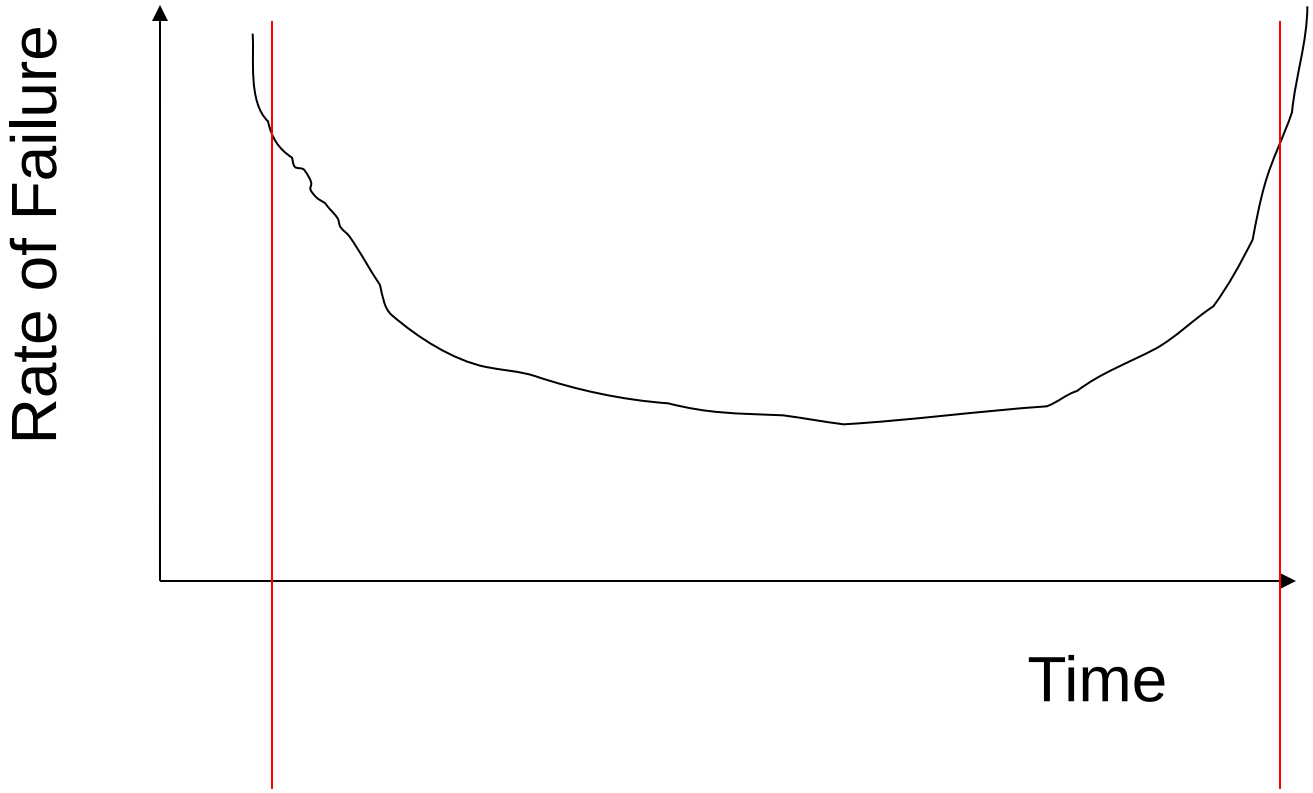
f_i = The fraction of life-bearing planets on which intelligence emerges

f_e = The fraction of intelligent societies that develop the ability and desire to communicate with other worlds.

L = Longevity of each civilization in the communicative state.

Frank Drake's equation

Bathtub Curve for "L"



Bathtub Curve for "L"

Thomas Malthus, late 1700's

Starvation,

Nuclear destruction,
Climate change,
Sustainability

Rate of Failure

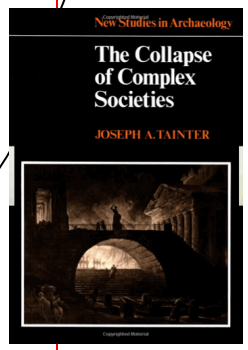
Time

<1000 years

>100 million years

Slogging our way to 100 million years

Fred Hoyle, 1960's collapse of complex organizations,



Joseph Tainter, 1988

Hope that extraterrestials could help

Rate of Failure

Time

<1000 years

>100 million years

Key Points from SETI* debate

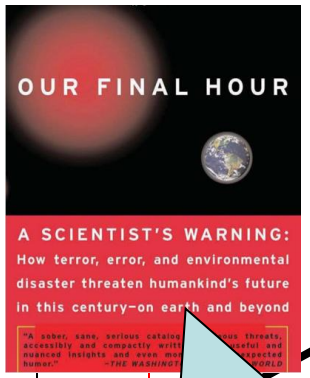
- We seem to know very little about ourselves
- Manifest as optimists & pessimists
- Threats and solutions somewhat a function of the times
- Theme of collapse & rebirth

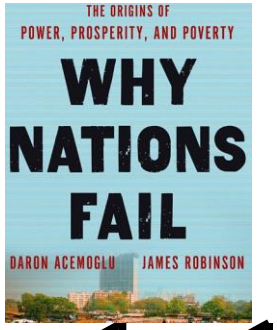
*Search for extraterrestrial intelligence (SETI)

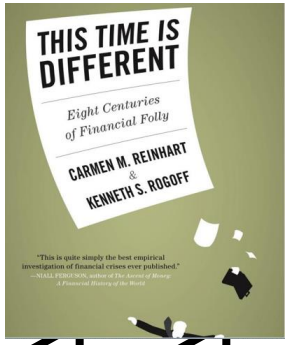
The Debate goes on…

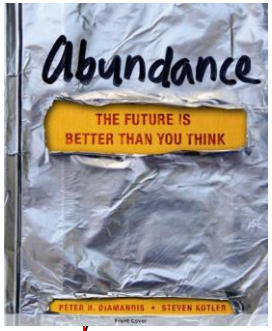
The Debate goes on…

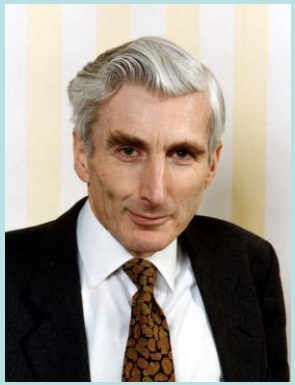
Rate of Failure









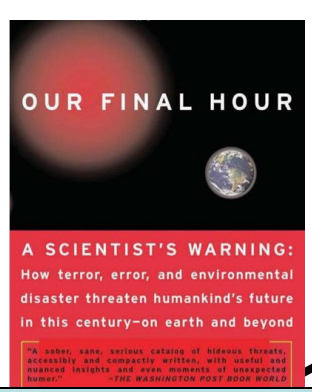


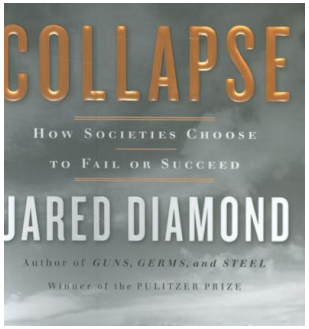
Martin Rees FRS, says- We're toast: terror, error, and environmental disaster

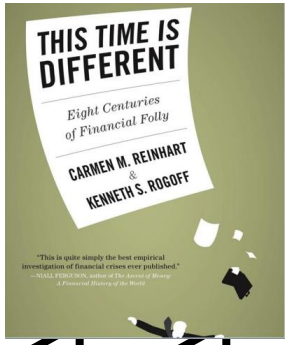
>100 million years

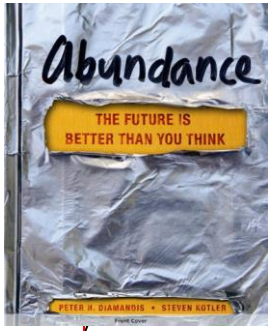
The Debate goes on…

In the middle…





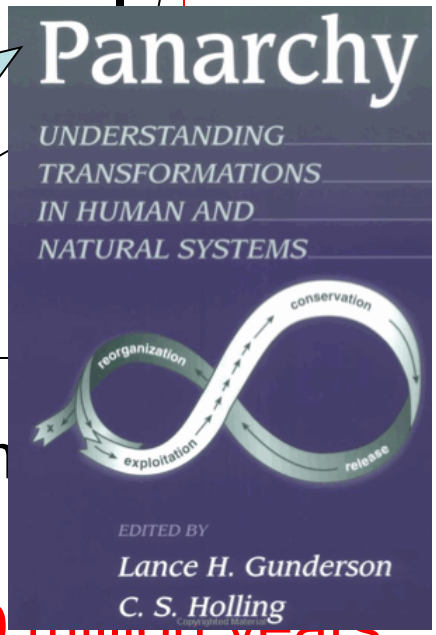




Rate of Failure

Eco-system Ecologists

Holling and Gunderson,
We see a pattern here…

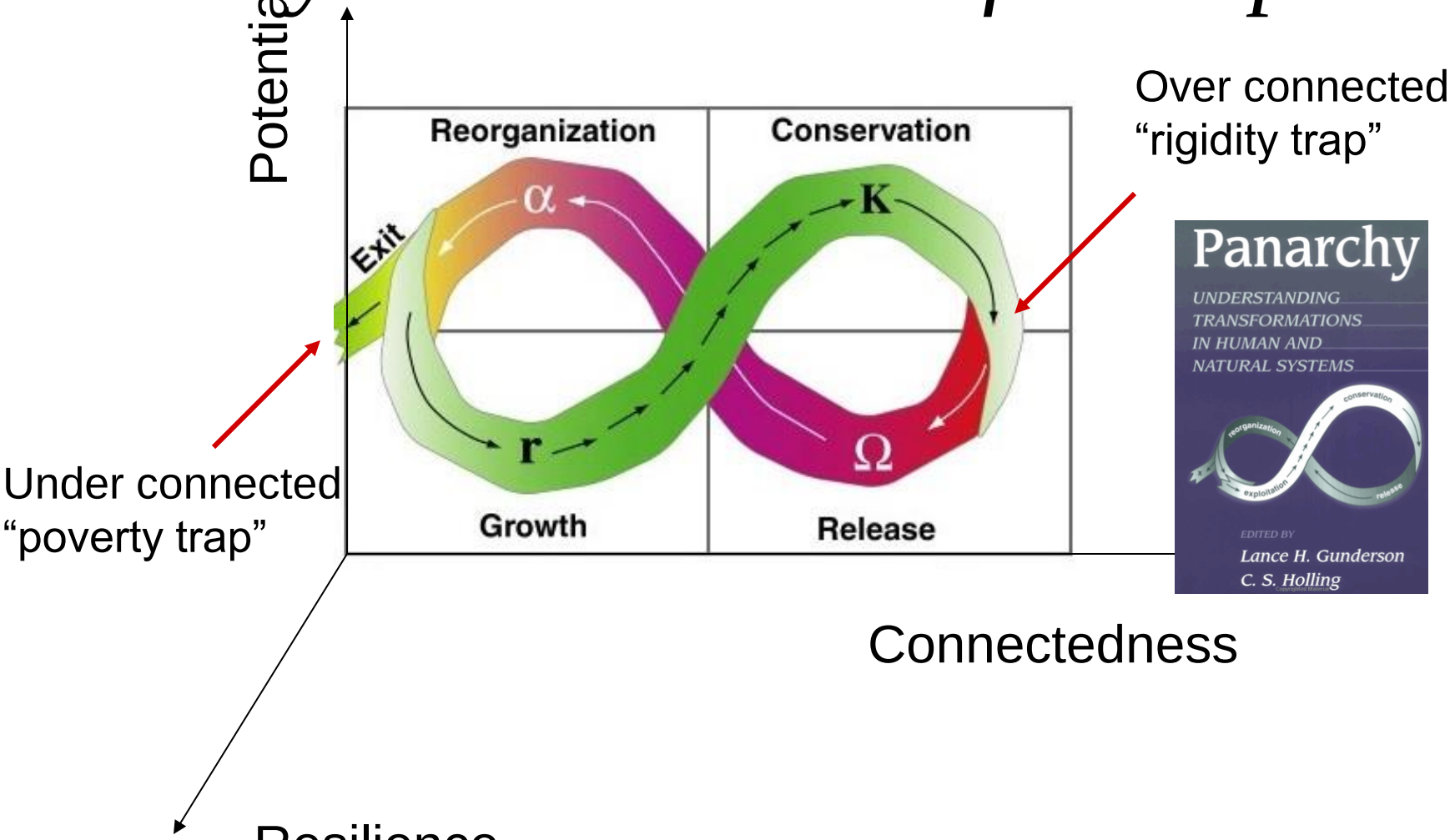


Tim

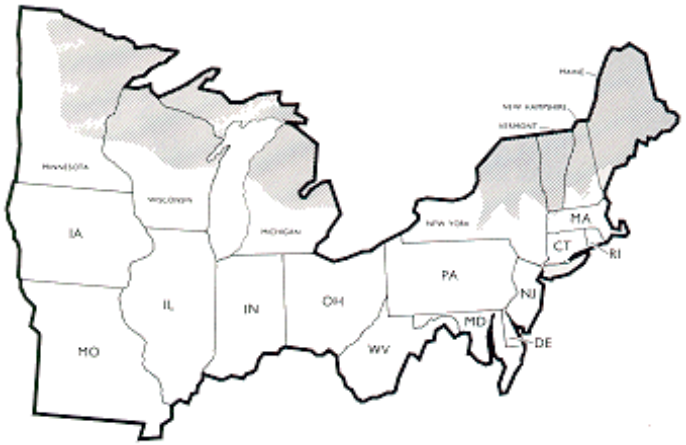
<1000 years

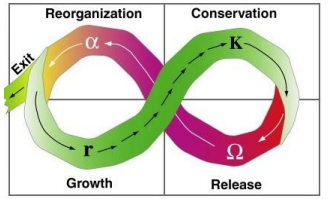
>100 million years

Eco-Systems Patterns of Collapse



Budworm & NE Forests



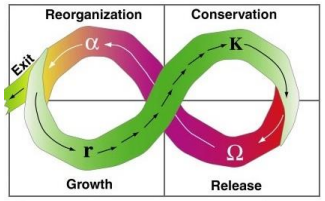


In mature forests the foliage
interferes with the birds hunt for the budworms
resulting in the devastation of the spruce forest
…and the budworms

Key points from Panarchy

- Patterns of collapse and recovery in complex eco-systems
- Nature is not in “steady state”
- Possible similarities in human systems
- What role foresight?

Foresight: Sustainable Development



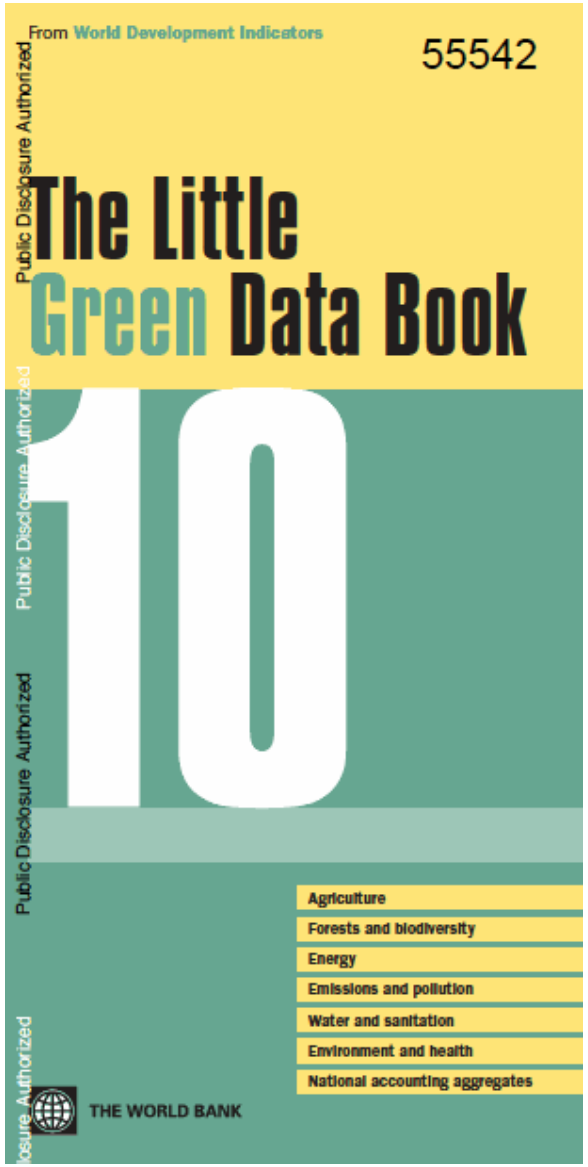
"...development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Dr. Gro Harlem Brundtland
former PM of Norway,
chairwomen of UN commission
"Our Common Future

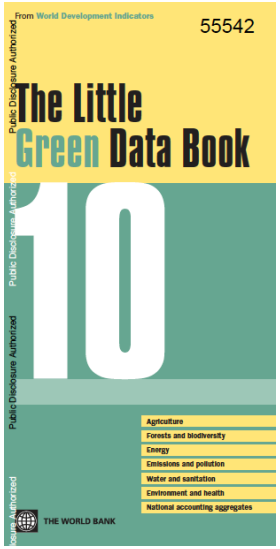
UN, "Brundtland Report" 1987

In the middle

The World Bank's Aggregate Measures



1. Manufactured Capital
2. Human Capital
3. Natural Capital
   - Energy depletion
   - Minerals depletion
   - Net forest depletion
   - CO_2 damage
   - Particulate emissions



World Accounts

National accounting aggregates

Gross savings (% of GNI)	20.9
Consumption of fixed capital (% of GNI)	13.0
Education expenditure (% of GNI)	4.2
Energy depletion (% of GNI)	3.9
Mineral depletion (% of GNI)	0.5
Net forest depletion (% of GNI)	0.0
CO_2 damage (% of GNI)	0.4
Particulate emissions damage (% of GNI)	0.2
Adjusted net savings (% of GNI)	7.2

2 2010 The Little Green Data Book

National accounting aggregates—savings, depletion and degradation

Gross savings (% of GNI)	18.3
Consumption of fixed capital (% of GNI)	13.1
Education expenditure (% of GNI)	4.2
Energy depletion (% of GNI)	2.0
Mineral depletion (% of GNI)	0.3
Net forest depletion (% of GNI)	0.0
CO_2 damage (% of GNI)	0.4
Particulate emissions damage (% of GNI)	0.2
Adjusted net savings (% of GNI)	6.4

2 2011 The Little Green Data Book

Journal of Economic Perspectives—Volume 18, Number 3—Summer 2004—Pages 147–172

Are We Consuming Too Much?

Kenneth Arrow, Partha Dasgupta,
Lawrence Goulder, Gretchen Daily, Paul Ehrlich,
Geoffrey Heal, Simon Levin, Karl-Göran Mäler,
Stephen Schneider, David Starrett and
Brian Walker

Sustainability Criterion

$$d\frac{V(t)}{dt} \geq 0$$

Genuine Investment relative to population must be non-negative.

Genuine investment is the change in society's productive base, including 1) manufactured capital, 2) human capital 3) natural capital and 4) institutions

Table 2

Growth R[illegible] Genuine Wealth

World bank

Arrow et al

Country	(1) Genuine Investment as Percent of GDP	(2) Growth Rate of Unadjusted Genuine Wealth	(3) Population Growth Rate	(4) Growth Rate of Per Capita Genuine Wealth—before TFP Adjustment	(5) TFP Growth Rate	(6) Growth Rate of Per Capita Genuine Wealth—after TFP Adjustment	(7) Growth Rate of per capita GDP
Bangladesh	7.14	1.07	2.16	−1.09	0.81	0.30	1.88
India	9.47	1.42	1.99	−0.57	0.64	0.54	2.96
Nepal	13.31	2.00	2.24	−0.24	0.51	0.63	1.86
Pakistan	8.75	1.31	2.66	−1.35	1.13	0.59	2.21
China	22.72	3.41	1.35	2.06	3.64	8.33	7.77
Sub-Saharan Africa	−2.09	−0.31	2.74	−3.05	0.28	−2.58	−0.01
Middle East/ North Africa	−7.09	−1.06	2.37	−3.43	−0.23	−3.82	0.74
United Kingdom	7.38	1.48	0.18	1.30	0.58	2.29	2.19
United States	8.94	1.79	1.07	0.72	0.02	0.75	1.99

Note: These calculations employ the following parameters: output-capital ratio, poor countries/regions 0.15; output-capital ratio, rich countries 0.20; α (share of human and reproducible capital in output) 0.58.

Data for genuine investment, population growth, and GDP growth derive from the World Bank (2003). The genuine investment percentages of GDP derive from data over the time-intervals indicated in Table 1. The population growth rate is the average rate over the period 1970–2000.

The estimate for China's total factor productivity (TFP) growth is from Collins and Bosworth (1996). For all other countries or regions, the estimates are from Klenow and Rodriguez-Clare (1997).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Nature's role in sustaining economic development

Partha Dasgupta

Phil. Trans. R. Soc. B 2010 **365**, 5-11
doi: 10.1098/rstb.2009.0231

Table 1. The progress of poor nations. Adapted from Arrow *et al.* (2004).

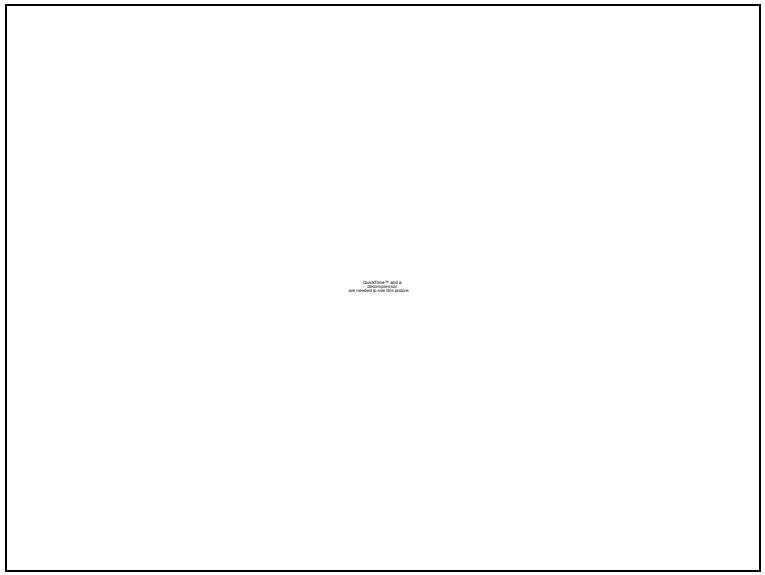
	% annual growth rate 1970–2000				
country/ region	wealth	population per head	wealth per head	GDP per head	ΔHDI[a]
sub-Saharan Africa	−0.1	2.7	−2.8	−0.1	+
Bangladesh	1.4	2.2	−0.8	1.9	+
India	1.6	2.0	−0.4	3.0	+
Nepal	1.8	2.2	−0.4	1.9	+
Pakistan	1.3	2.7	−1.4	2.2	+
China	5.9	1.4	4.5	7.8	+

[a]Change in HDI between 1970 and 2000.

Close your eyes and imagine a sustainable world

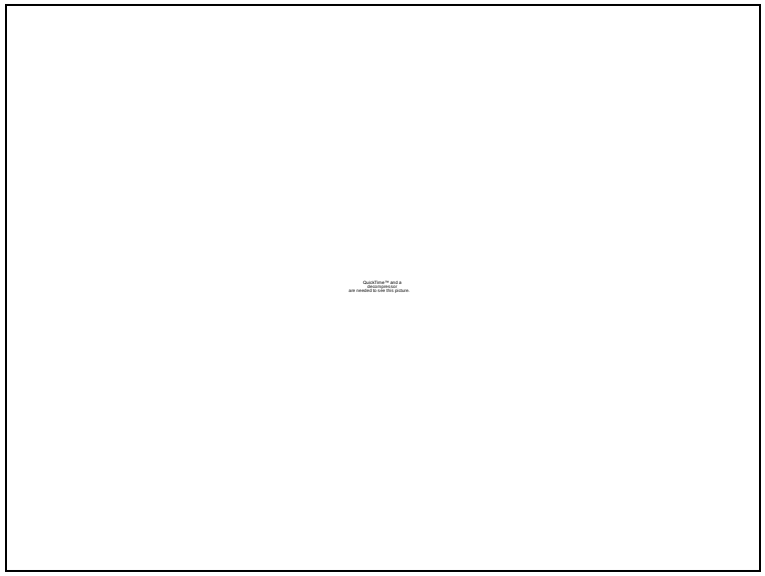
What does it look like?

What does it look like?



This?

What does it look like?



This?

Or this?

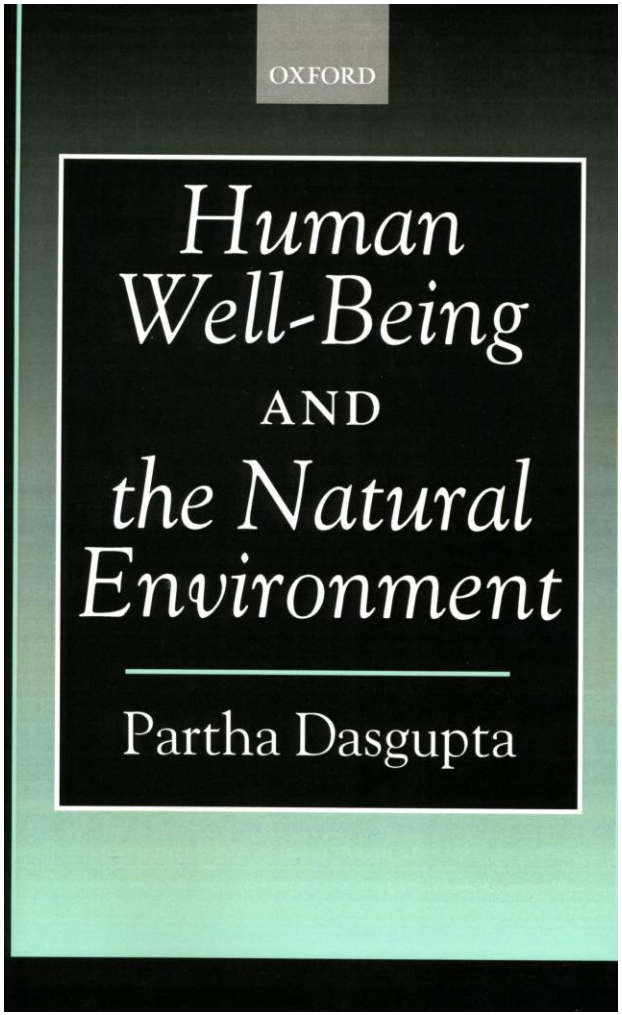
Issues with the economist's view

- Weak sustainability
- substitutability
- discount rate
- prices for eco-system services

Economics Summary

- The Right Question: can technology substitute for nature?
- Theory better than most alternatives
- Prices lacking
- Ultimately: The Maintenance of a Resource Base

One more thing,



- Sustainability metrics
- Differentiates between current and inter-temporal human well-being

Measuring human well-being

Constituents of well-being:	Determinants of well-being:	Determinants of inter-temporal Well-being:
•Health •Happiness •Freedom	•Food •Clothing •Potable water •Shelter •Access to knowledge and information •Resources for security	• Mfg capital • Human Capital • Natural Capital • Institutions

Evaluate other indices

- *Human Development Index*
  - Life expectancy at birth
  - GNP/cap
  - Adult literacy
- *Eco-Efficiency*
  - Good and Services
  - Impact or Resources Used

Evaluate other indices

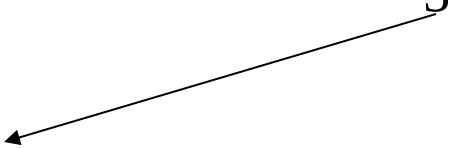
- *Human Development Index*
  - Life expectancy at birth - current
  - GNP/cap - current questionable
  - Adult literacy - current and inter-temporal
- *Eco-Efficiency*
  - Good and Services - current
  - Impact or Resources Used- inter-temporal

What do the physical scientists say?

1. Climate change
2. Ocean acidification
3. Ozone depletion
4. Nitrogen cycle
5. Global freshwater
6. Land use change
7. Species extinction
8. Atmospheric aerosol loading
9. Chemical pollution

*Planetary Boundaries**

Range of uncertainty
350 to 450 ppm



QuickTime™ and a
decompressor
are needed to see this picture.

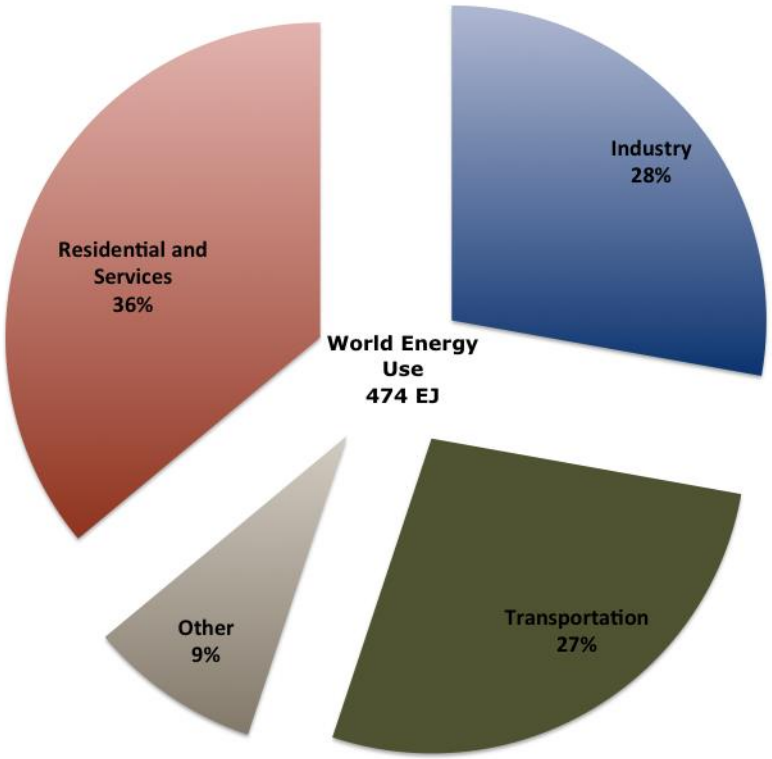
*Rockstrom, J., W. Steffen, K. Noone, A. Persson, F. S. Chapin, III, E. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. Schellnhuber, B. Nykvist, C. A. De Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sorlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J. Foley. 2009. Planetary boundaries:exploring the safe operating space for humanity. *Ecology and Society* **14**(2): 32.

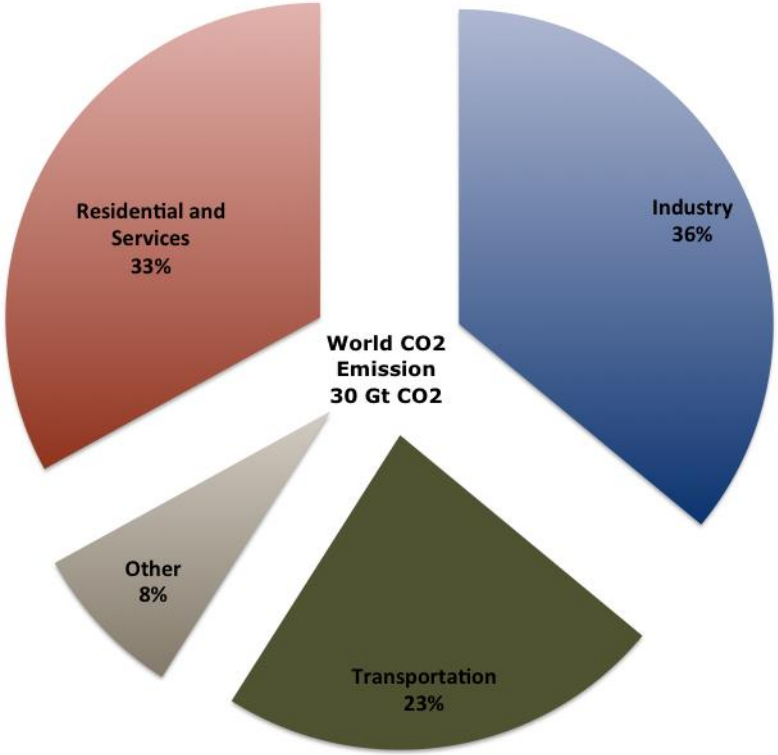
Part 2

Address Climate change

Focus on energy & carbon used in manufacturing, with constraints on other issues

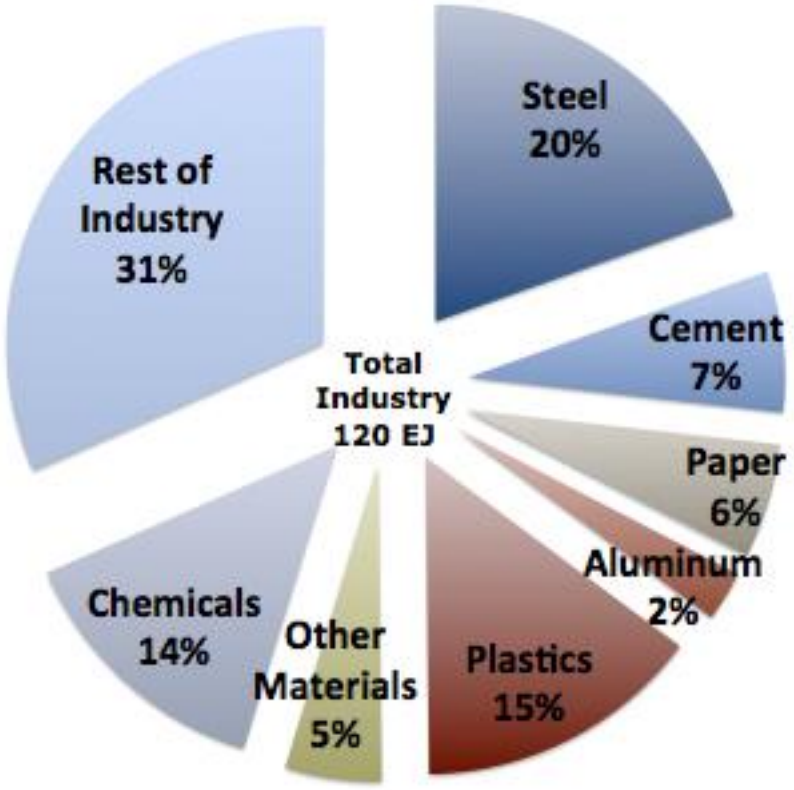
World Energy and Carbon



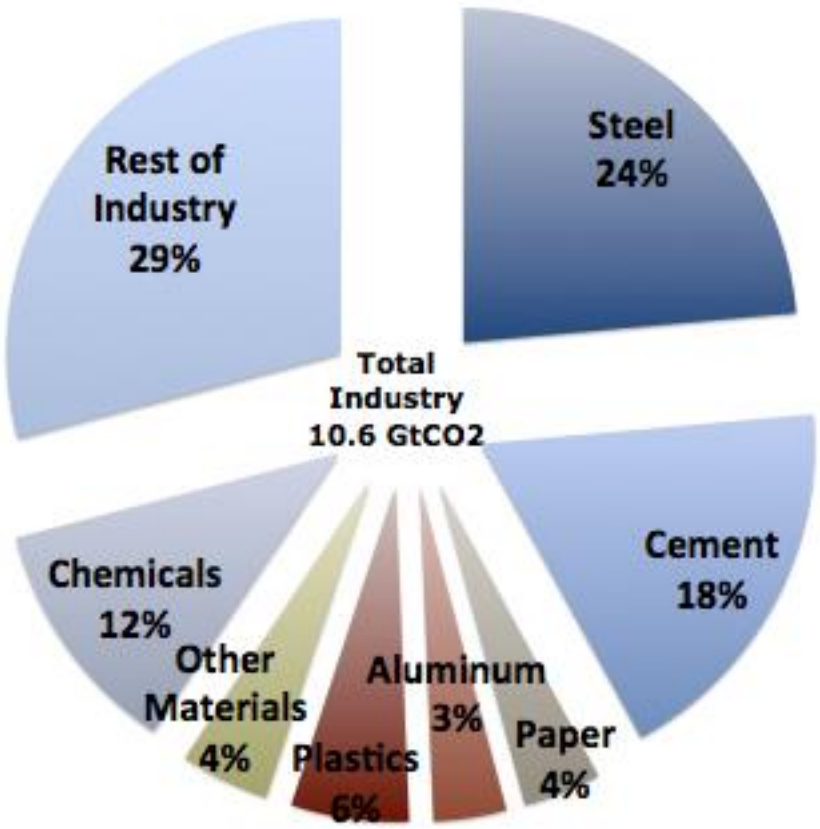


IEA 2010

The Role of Materials in Manufacturing



Final Energy



Carbon Dioxide

Strategies to improve the materials sector

$$C = Q \cdot \frac{E}{Q} \cdot \frac{C}{E}$$

carbon

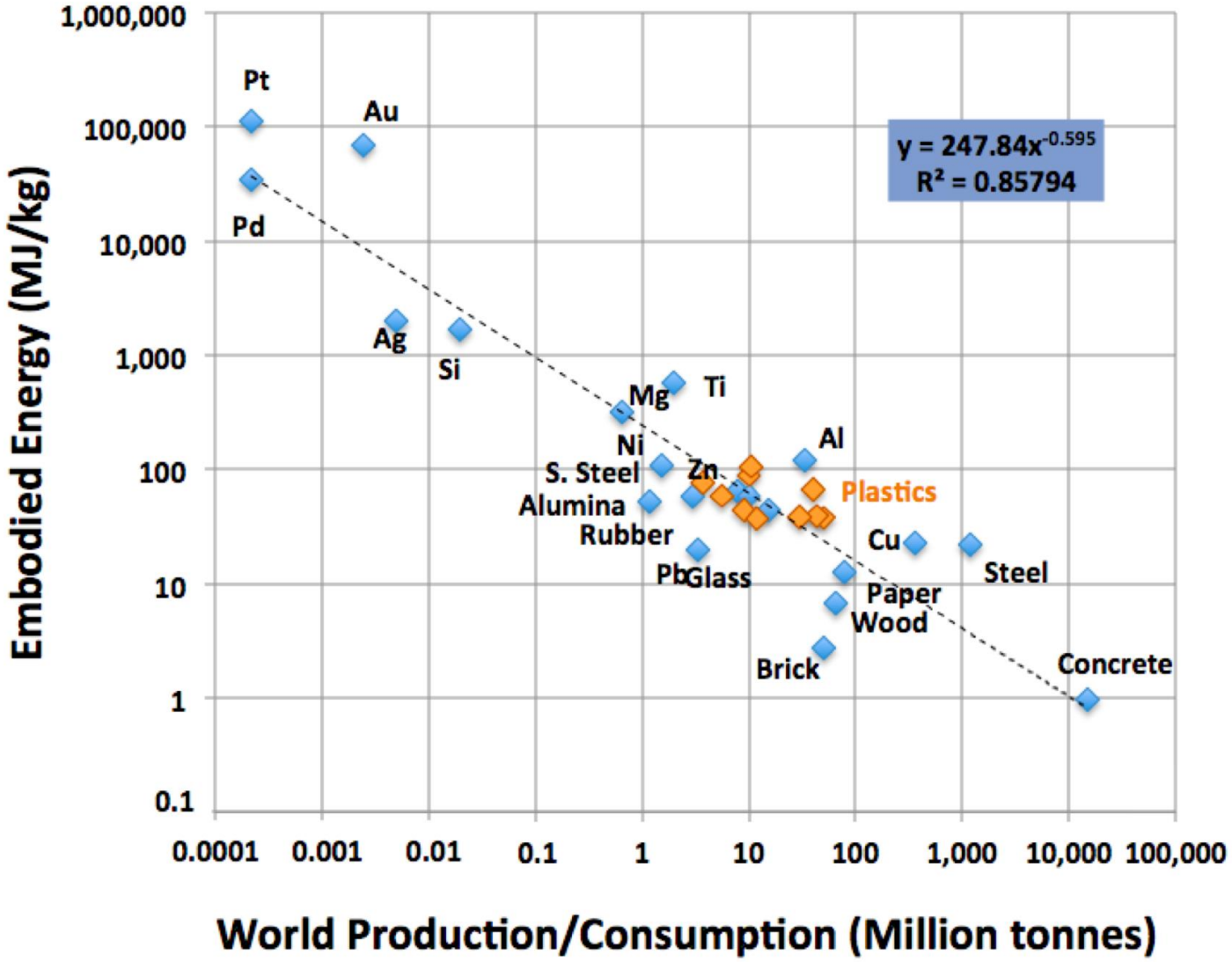
demand

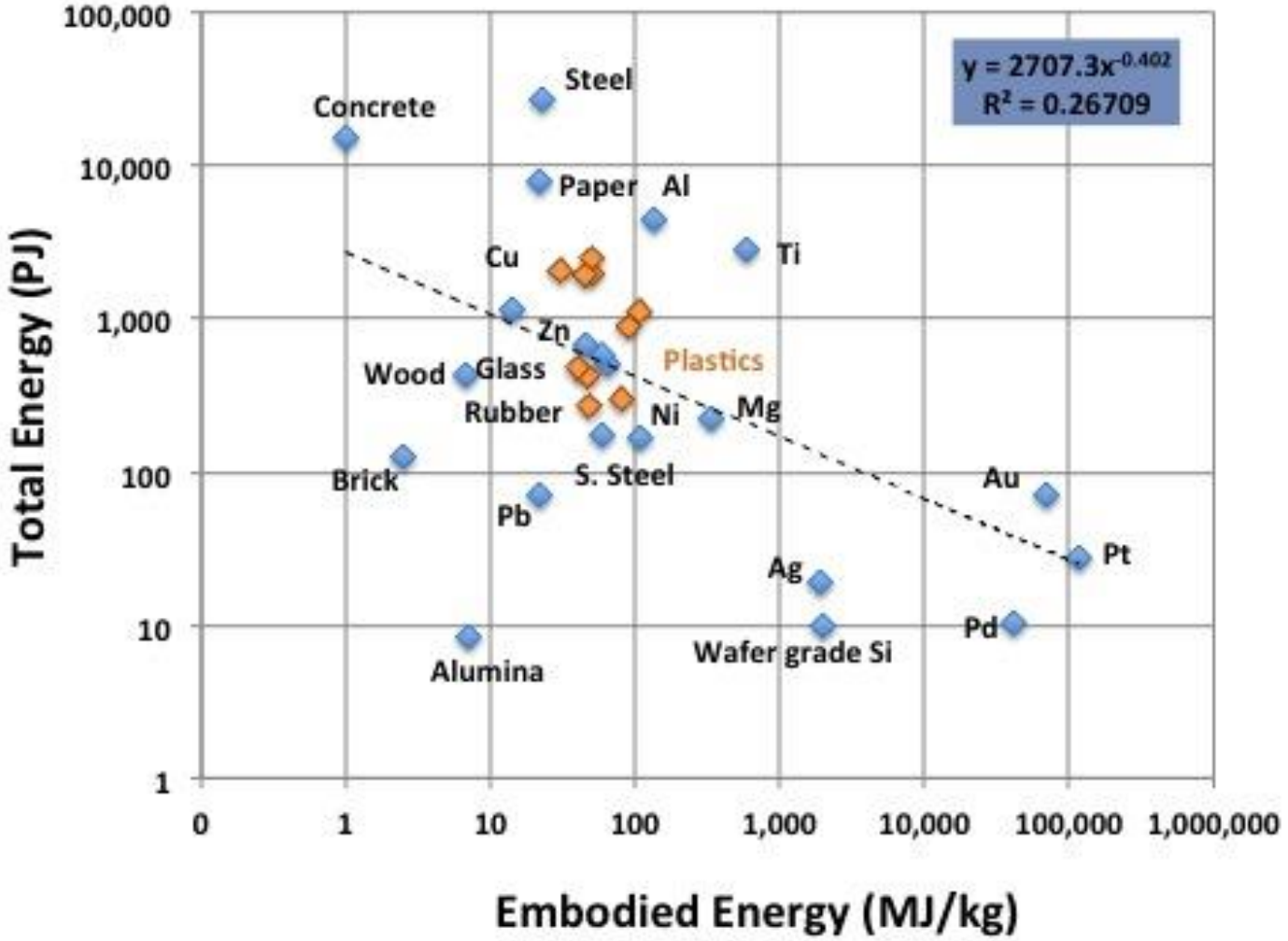
efficiency & recycling

carbon intensity of energy

Strategies to improve the materials sector

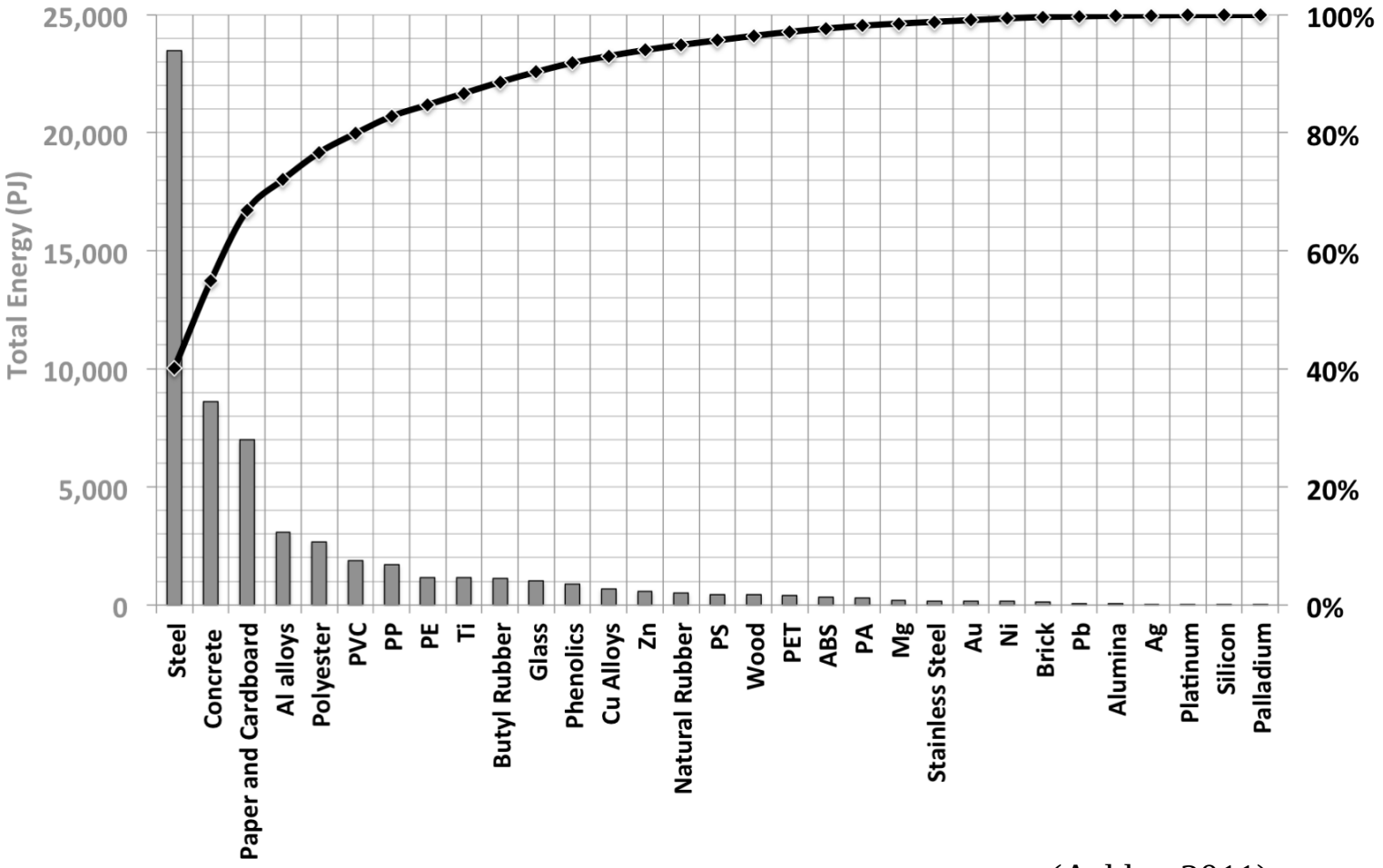
1. Internal - efficiency
2. Recycling - products
3. Demand
4. Energy supply - renewables
5. Carbon sequestration


Embodied Energy (MJ/kg)
1,000,000
100,000
10,000
1,000
100
10
1
0.1
0.0001
0.001
0.01
0.1
1
10
100
1,000
10,000
100,000
World Production/Consumption (Million tonnes)
y = 247.84x^-0.595
R² = 0.85794
Pt
Au
Pd
Ag
Si
Mg
Ti
Ni
S. Steel
Zn
Alumina
Rubber
Pb
Glass
Al
Plastics
Cu
Steel
Paper
Wood
Brick
Concrete



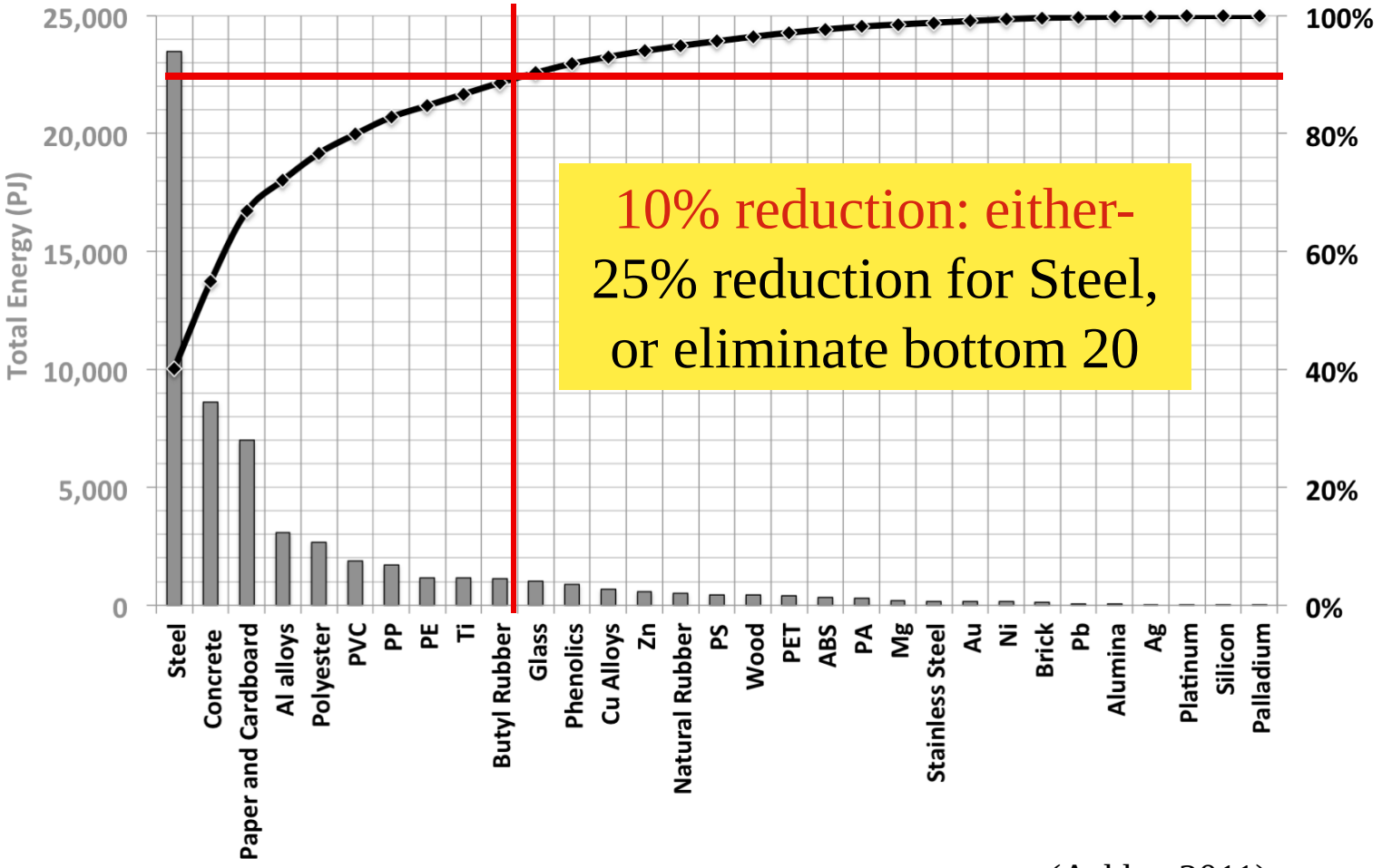
Data taken from Ashby 2009

Steel dominates



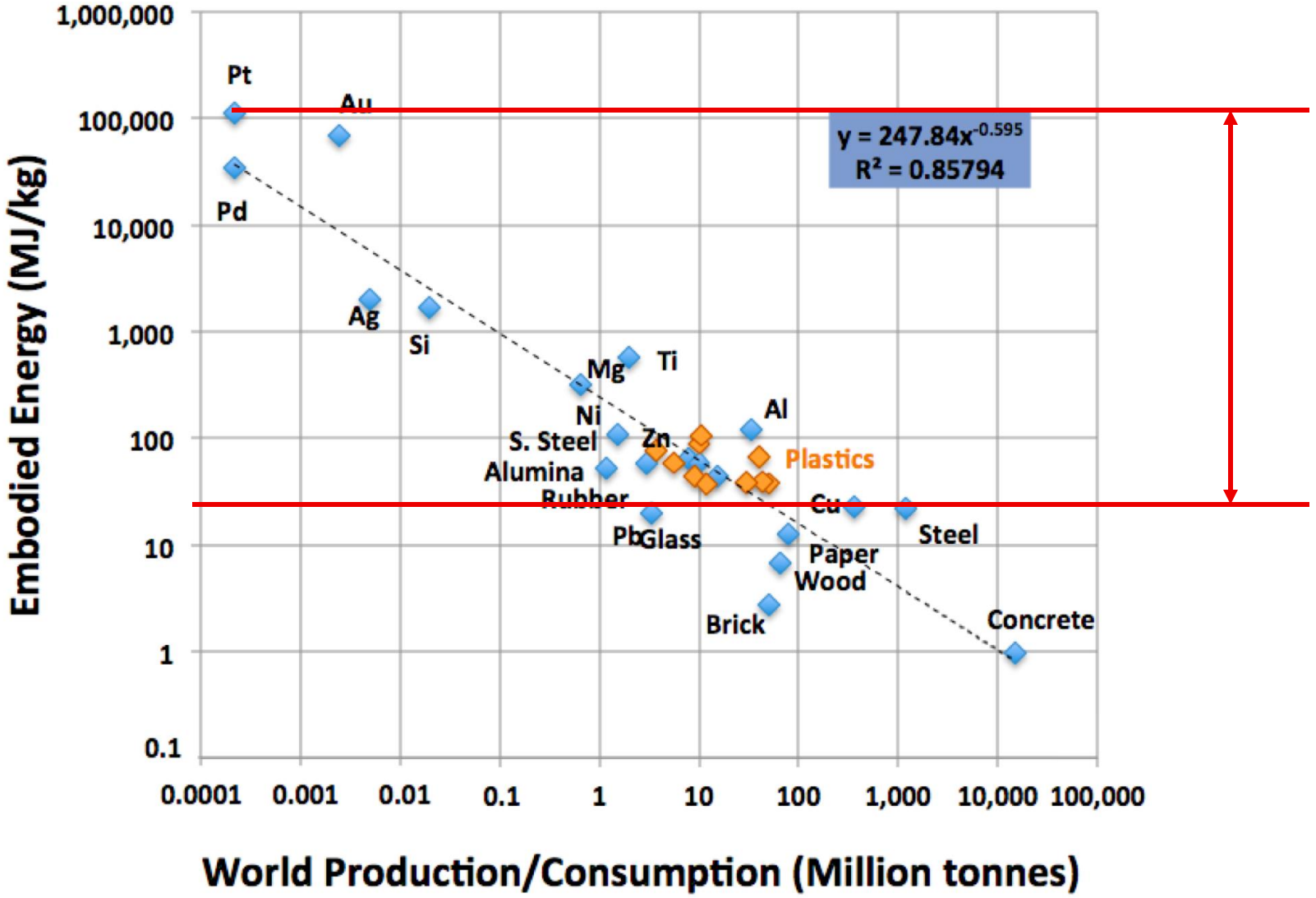
(Ashby, 2011)

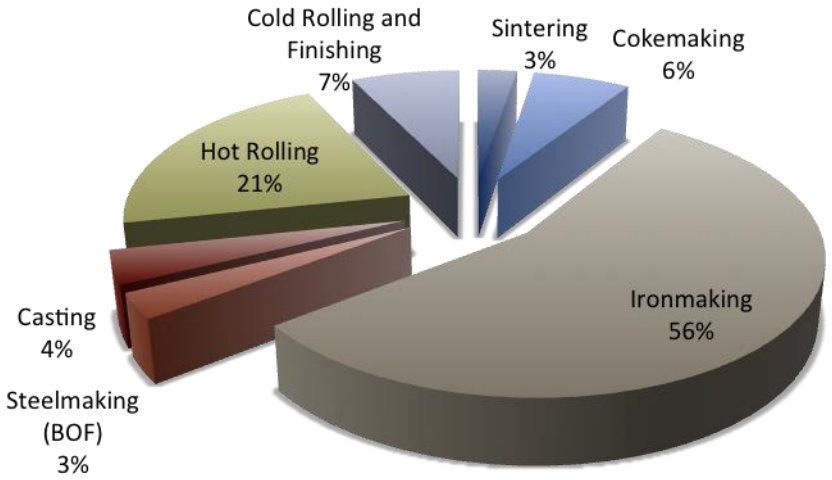
Steel dominates



(Ashby, 2011)

1 kg of Pt = 5 tonnes of steel in terms of energy saved





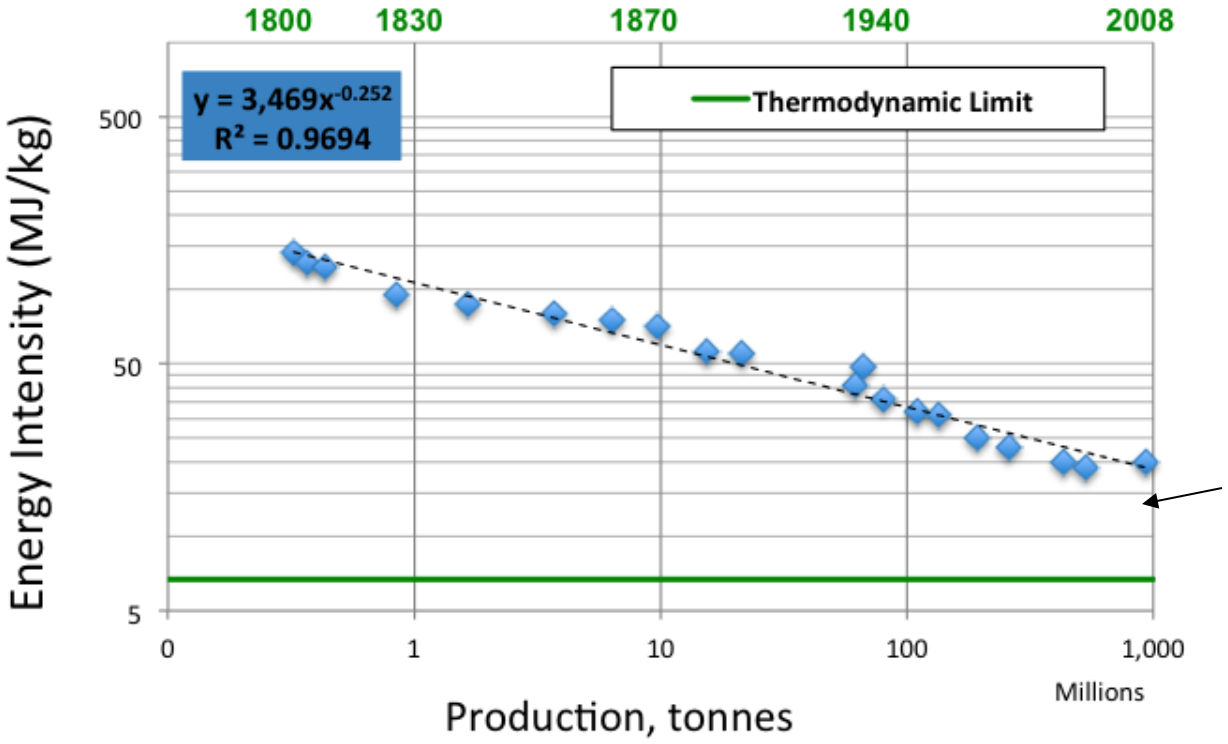
$Fe_2O_3 \rightarrow 2Fe + 1.5O_2$

Minimum exergy 6.65 MJ/kg of Fe

$2Fe_2O_3 + 3.76C + 0.76O_2 \rightarrow 4Fe + 3.76\ CO_2$

Minimum carbon 6.9 MJ/kg of Fe

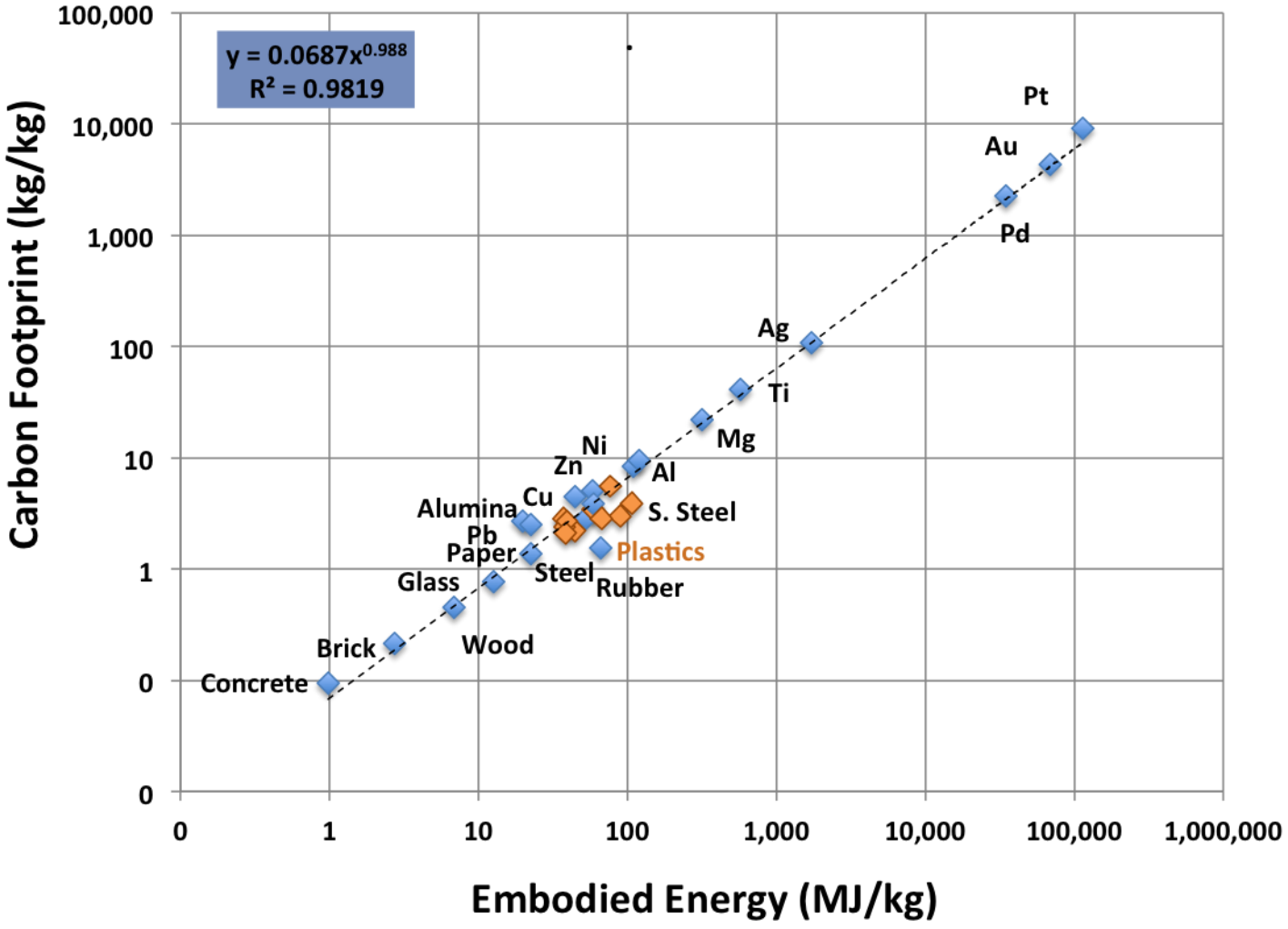
Pig Iron



Kyushu Oita:
14.5 MJ/kg
Inland Steel #7:
14.0 MJ/kg

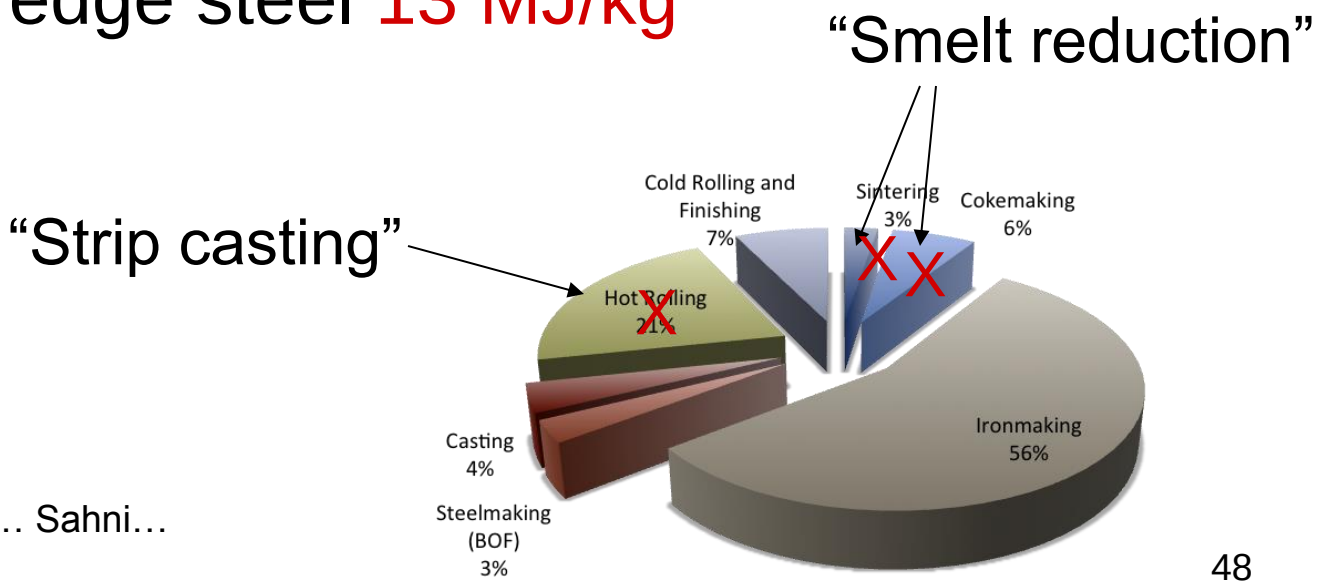
$\eta \approx 0.5$

Carbon (CO_2) and energy are highly correlated



Improvement Potential for iron/steel

- Cutting edge improvement:
  - Current steel 25 MJ/kg →
  - BAT steel 19 MJ/kg →
  - Cutting edge steel 13 MJ/kg

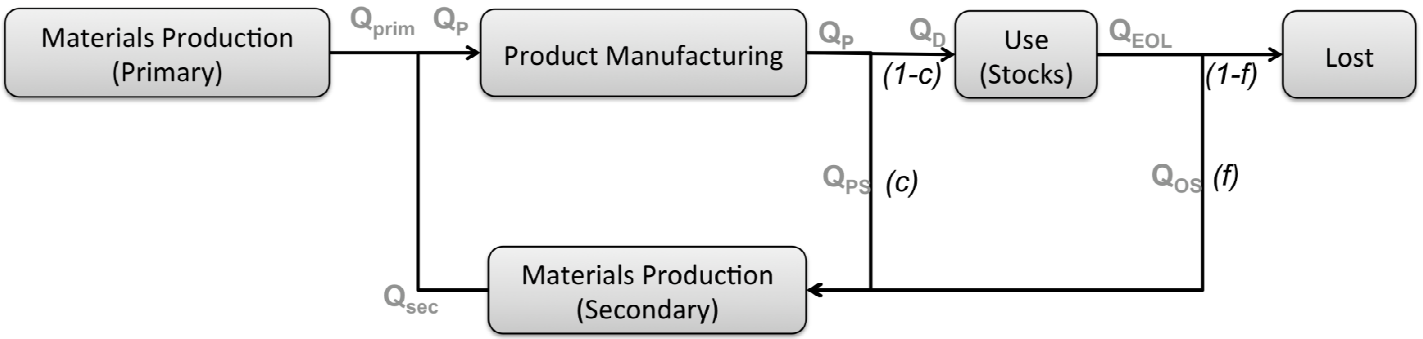


Refs: de Beer…, Allwood,… Sahni…

Current Steel Recycling

$$r = Q_{sec}/Q_p \qquad r = c + f \cdot \frac{Q_{EOL}}{Q_p}$$

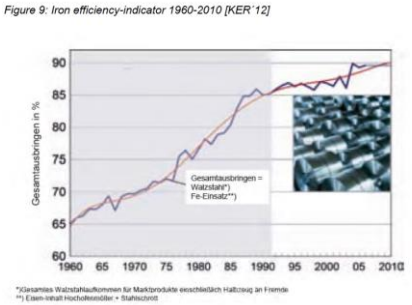
$$r \approx 0.3 \text{ to } 0.4$$



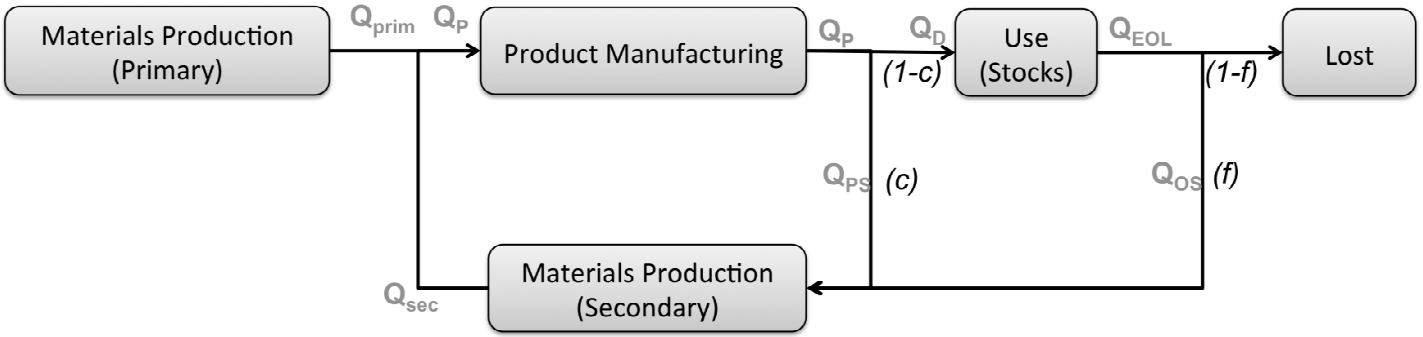
Steel Recycling alternatives

$$r = c + f \cdot \frac{Q_{EOL}}{Q_p}$$

German Best Practice w/o sheet forming trim



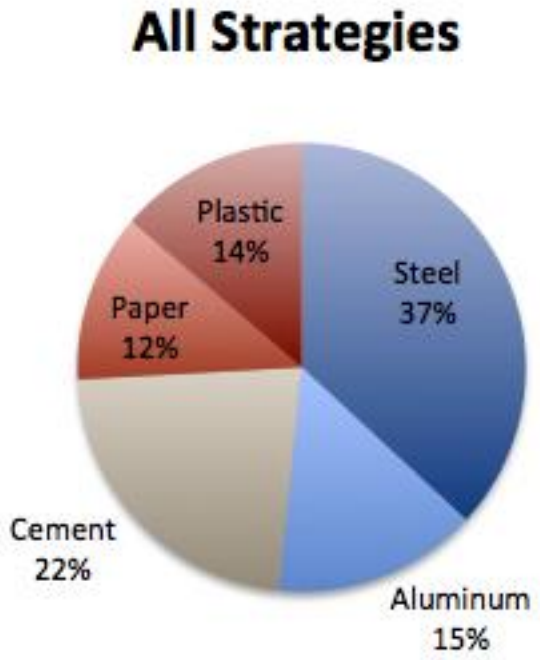
Today: r = 0.15 + 0.7 x $(1.03)^{-35}$ = 0.4



Future: r =0.05 + 0.9 x $(1.015)^{-45}$ = 0.51

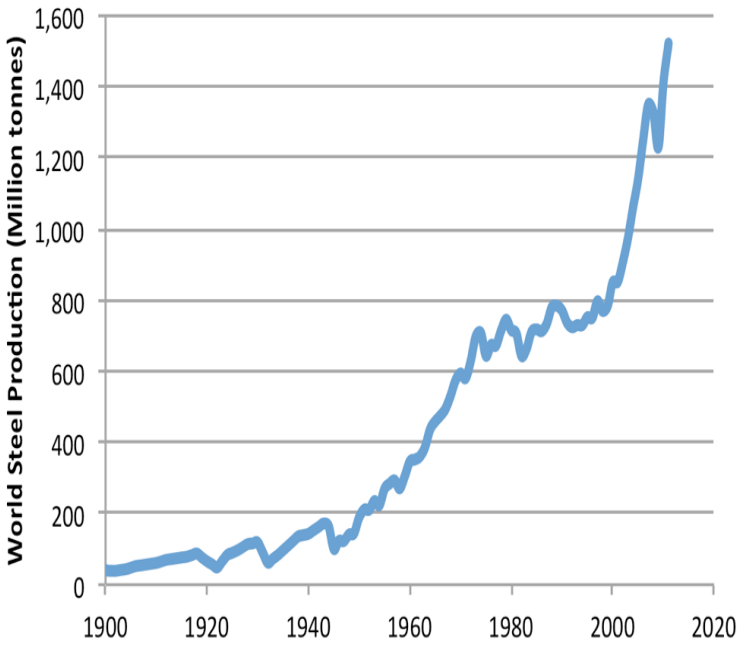
Summary - Energy Reduction Potential without growth - 5 materials

Average to BAT	20%
BAT to cutting edge	37%
Aggressive recycling	44%
Improved recycling	50-56%



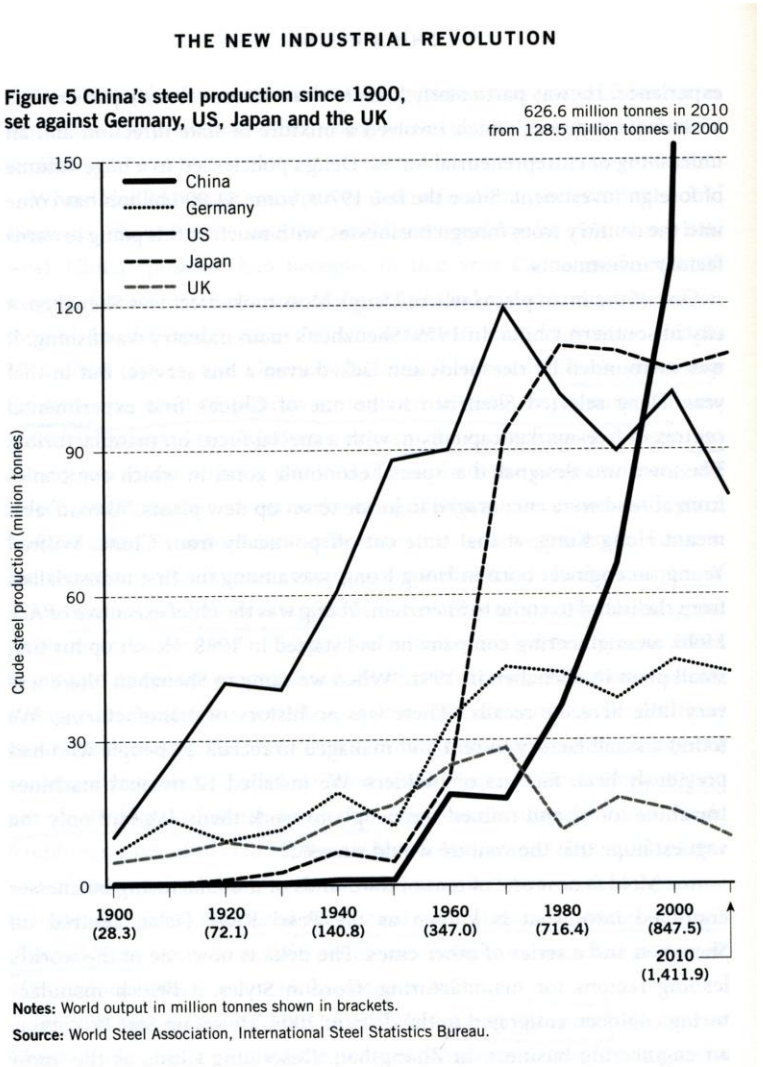
Ref. Gutowski, Sahni, et al 2013

Demand for Steel

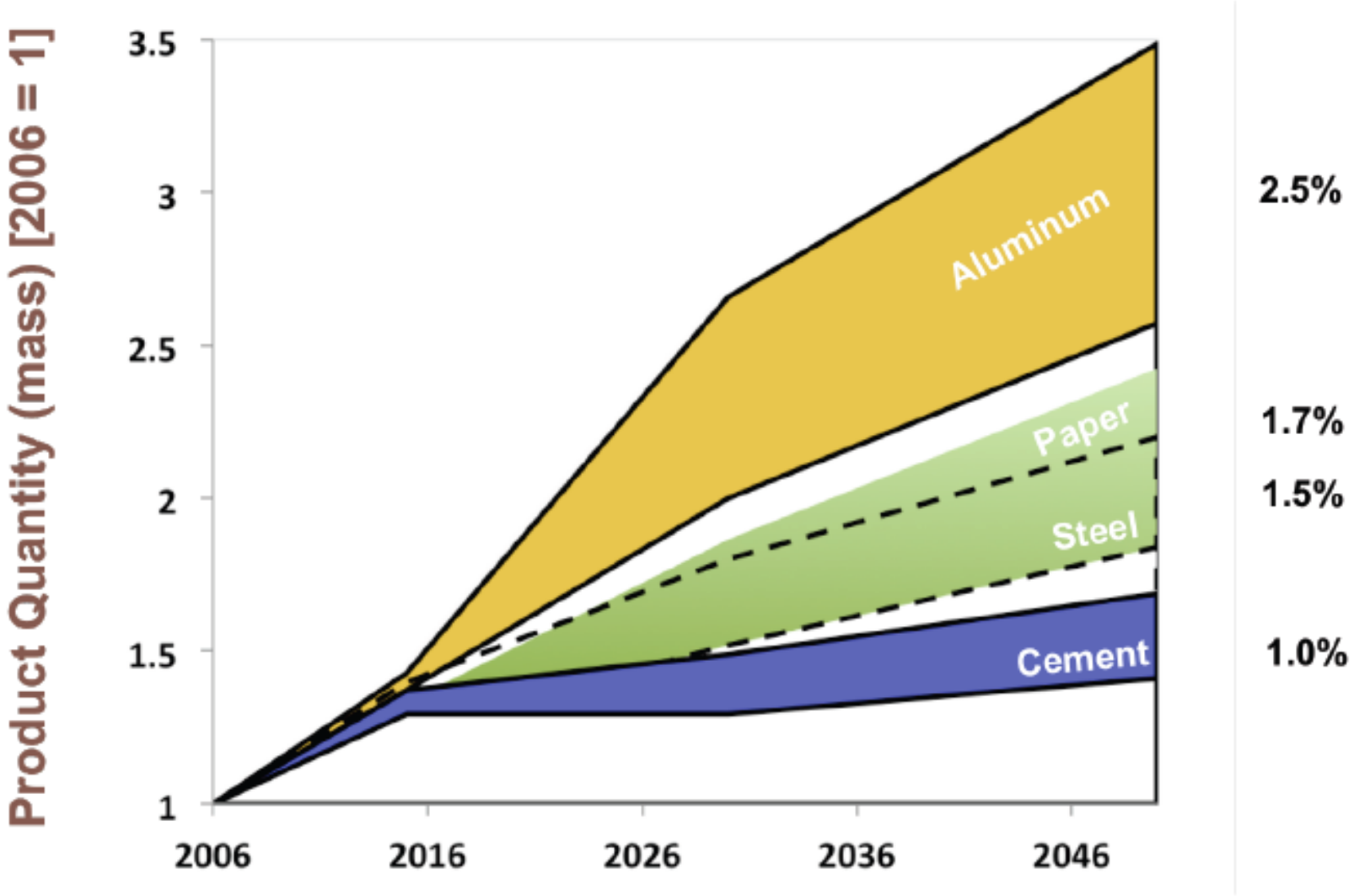


World Steel Production 1900-2010

World Steel Association

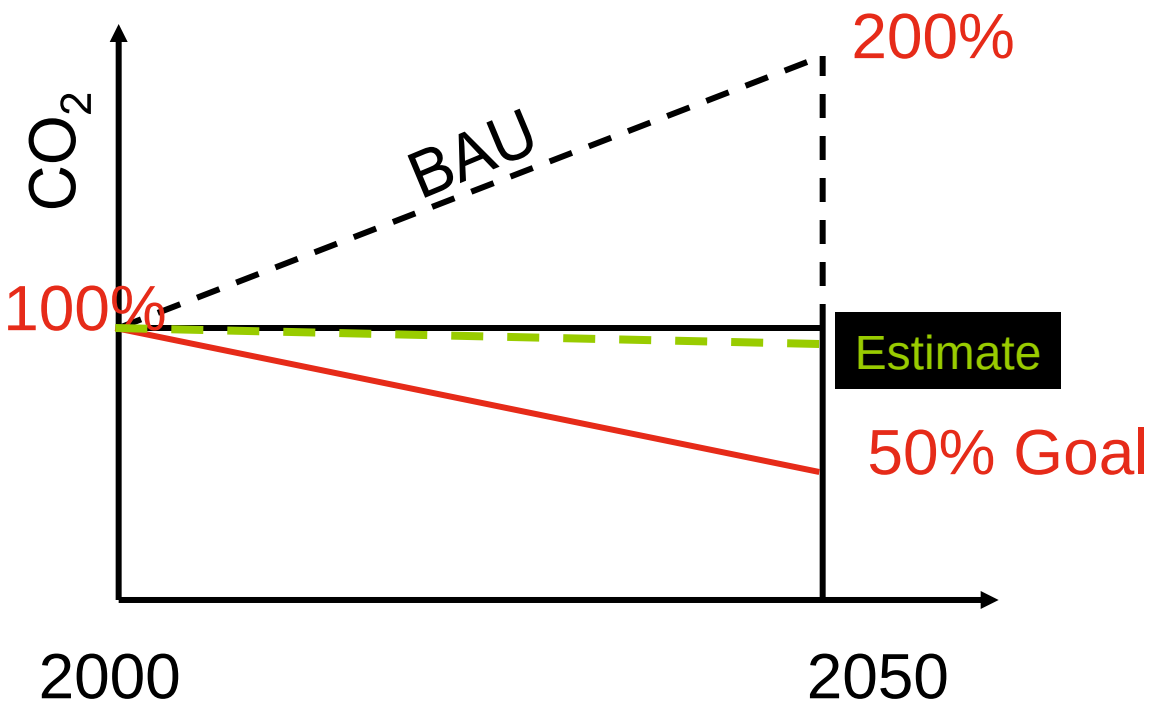


Peter Marsh, 2012



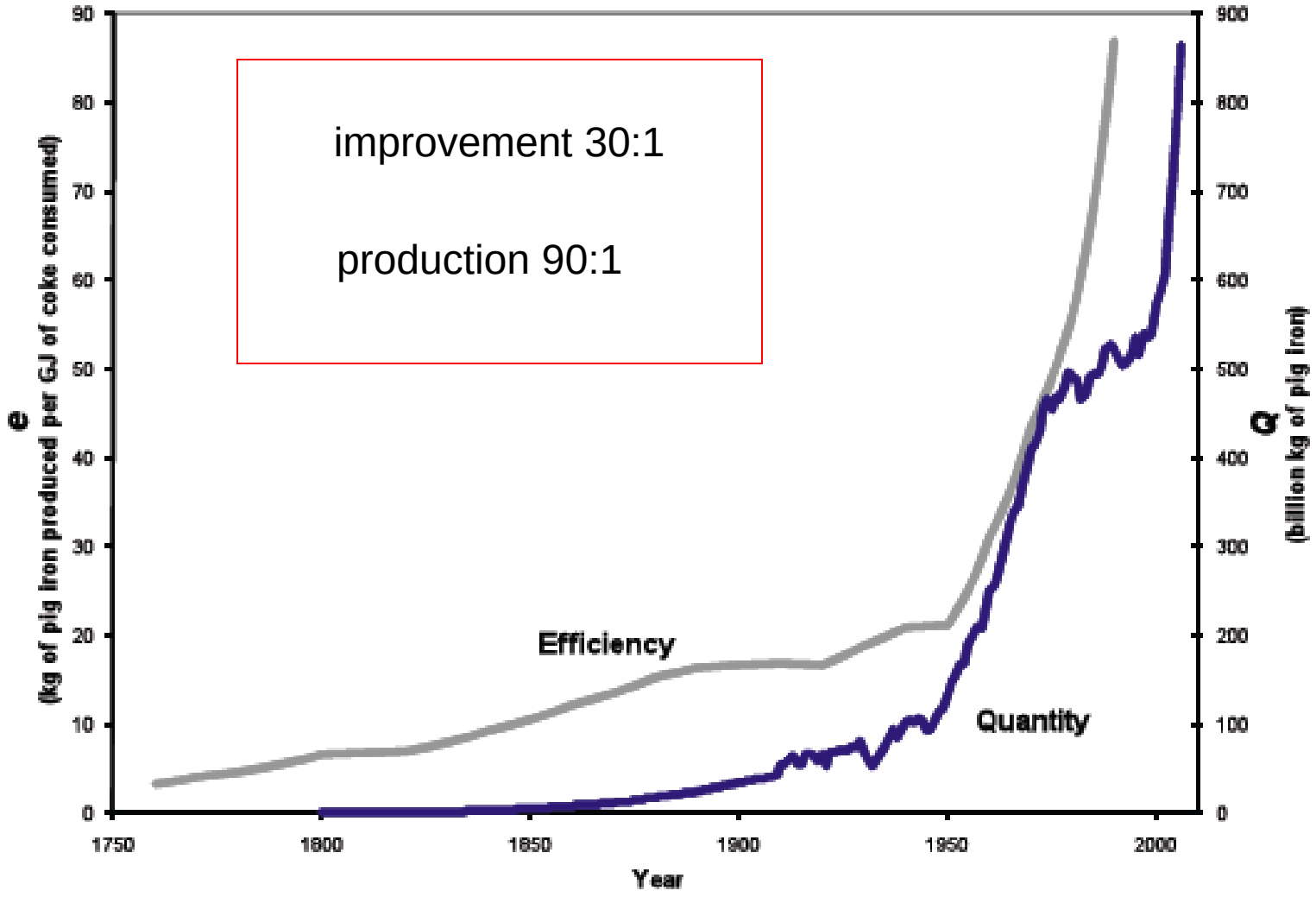
IEA materials forecasts (plastics similar to paper)

We have to try harder



Estimate relative to the IPCC target of 50% absolute reduction

Historically growth outpaces efficiency



Primary Materials Summary

- Dominate Mfg sector
- Significant improvement potential still,
  ~ 50%
- But with 2X demand $\rightarrow$ ~ breakeven in absolute energy use
- Limits on recycling due to growth

Mat'ls Fuels & electrification

- Iron/steel - coke, EAF recycle
- Paper/cardboard - biomass
- Plastics -petroleum
- Cement - anything that burns
- Aluminum - electricity (> 50% hydro-electric)

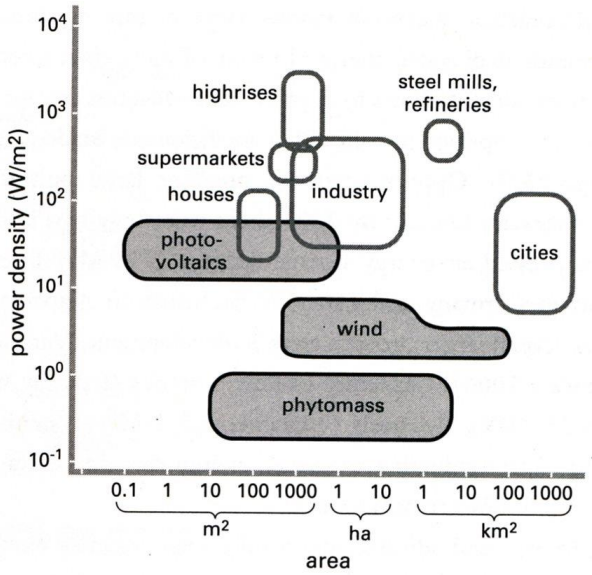
Mat'ls Fuels & electrification

- Iron/steel - coke, EAF recycle
- Paper/cardboard - biomass
- Plastics -petroleum
- Cement - anything that burns
- Aluminum - electricity (> 50% hydro-electric)

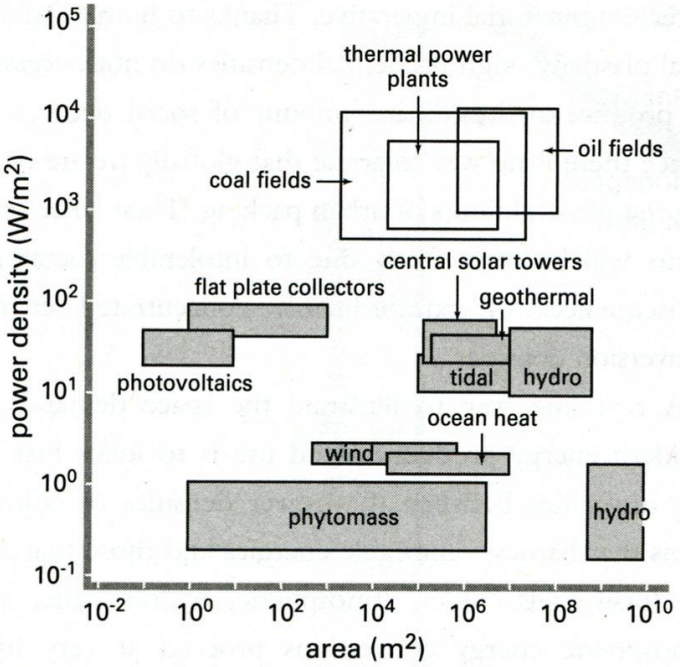
Steel from Trees?

- Back of the envelope charcoal calculation…
- Carbon reduction requires 3.76 mol C per 4 mol Fe (reduction + energy), 1:5
- NPP for tropical forests ≈ 1 kg C /m^2/yr
- Large blast furnace 5Mt/yr $\rightarrow$1000km^2

Power/ land density



13.8 Mismatch of typical power densities of renewable energy conversions and common energy uses in modern societies.



11.2 Power densities of fossil fuel extraction compared to power densities of renewable energy conversions.

Ref: Vaclav Smil, "Energy in Nature and Society: MIT Press 2008

Electro-chemical steel reduction

Ref Allwood,Cullen 2012

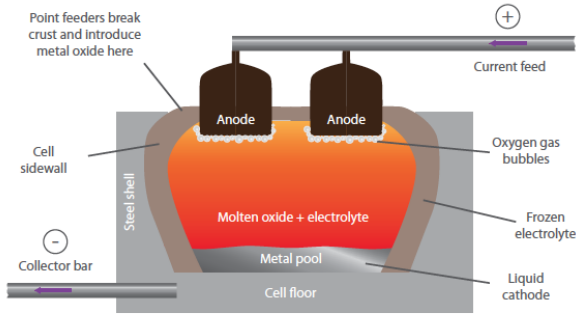


Figure 9.3—**Schematic of iron ore pyroelectrolysis**

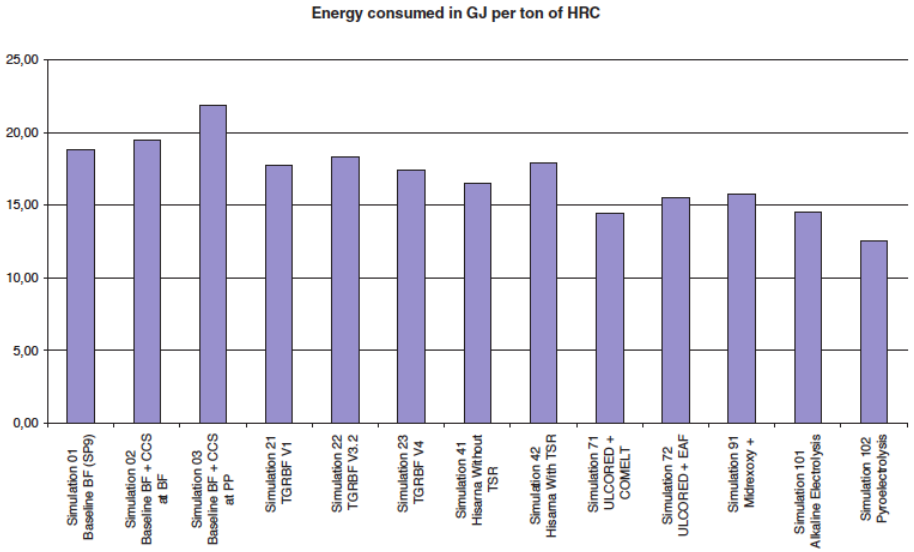


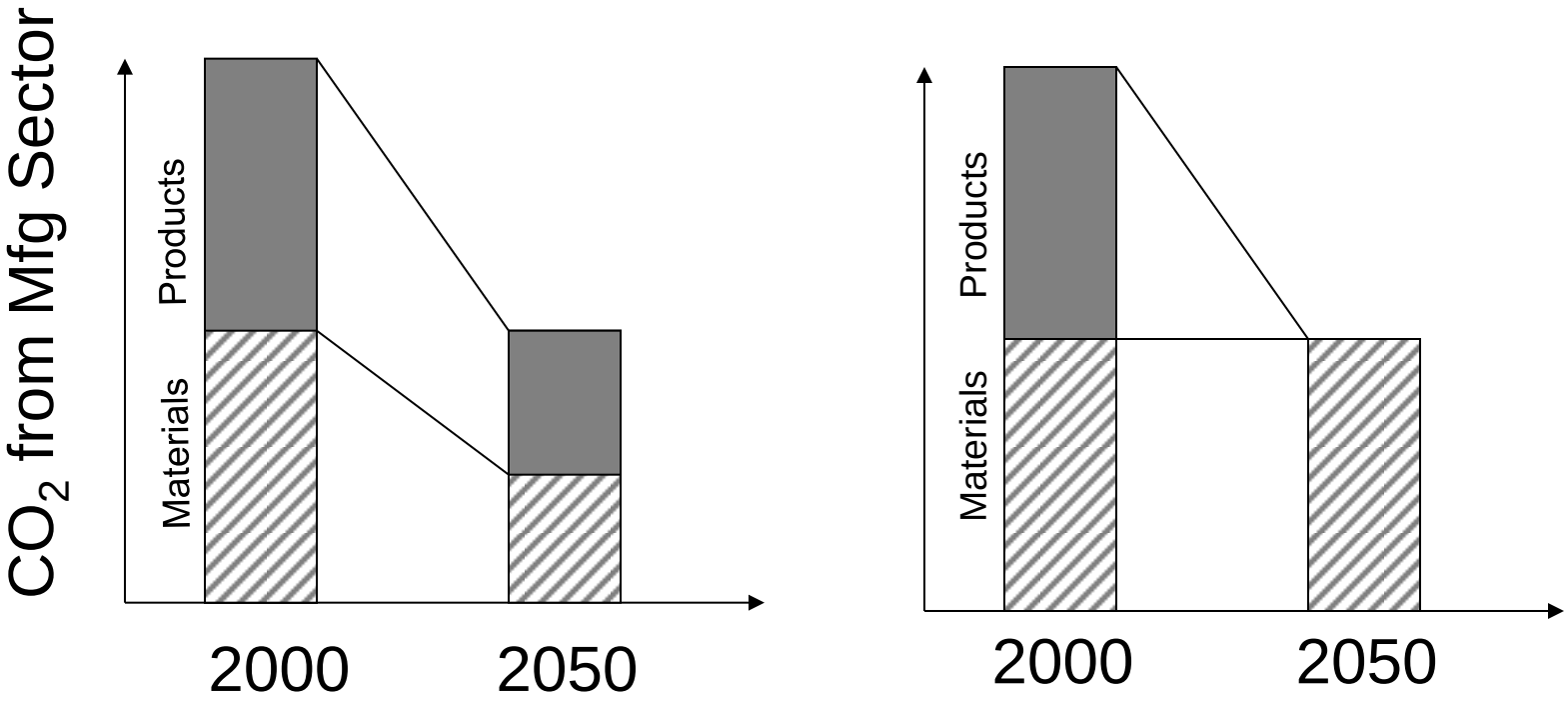
Fig. 7 - Energy consumption of the ULCOS routes – Y4 estimates

Ref Birat et al 2009

What's left?

- Material efficiency
- Materials substitution
- Carbon sequestration
- Product Manufacturing
- Transportation and Buildings

The Manufacturing Sector

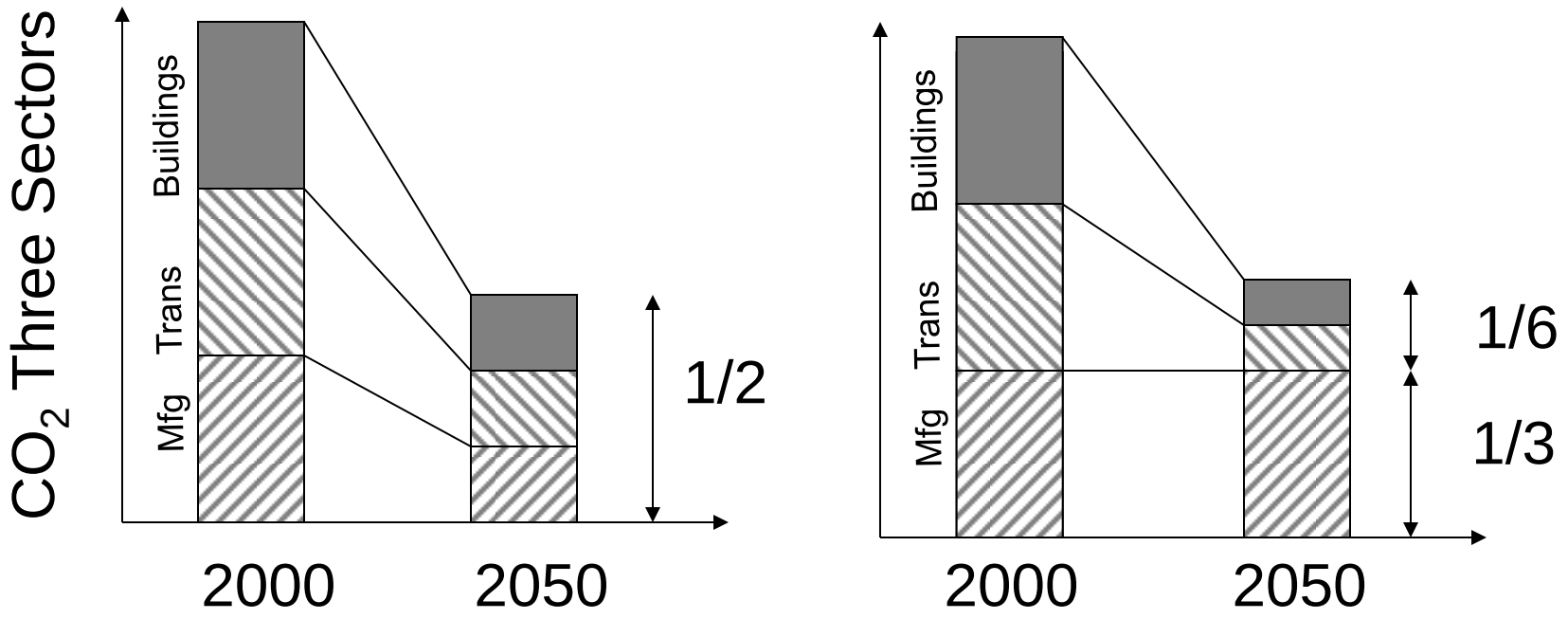


Two ways to reduce CO_2 emission by half

This raises some questions

- How constrained are other sectors?
  - Transportation
  - Buildings
  - Energy Supply
- How much future demand will there be?

Manufacturing, Transportation and Buildings



Two ways to reduce CO_2 emission by half


Thank You,
for more of this,
take:2.83 in the Spring