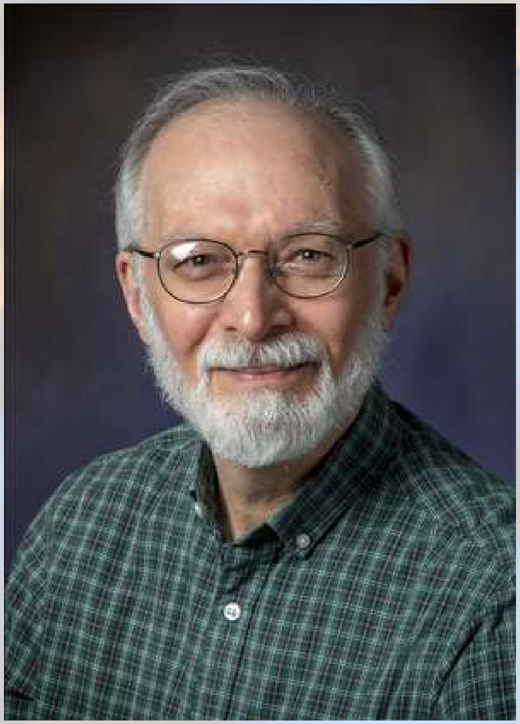
Evaluating Sustainability
Prof. John Abelson

Department of Materials Science and Engineering



Professor Abelson received his BS from Yale University in 1979, was a researcher at the Solar Energy Research Institute (1979-81) and the Ecole Polytechnique, Paris (1981-82), received his PhD from Stanford in 1987, then joined the Department of Materials Science and Engineering at UIUC. He is a Fellow of the American Vacuum Society.

Professor Abelson's research career began with a focus on thin-film photovoltaic materials and devices. In recent years, he has developed new methods of thin-film growth by chemical vapor deposition.

Professor Abelson co-founded the Energy and Sustainability Engineering (EaSE) initiative at UIUC, including the MEng–Energy Systems program.

He created and has taught courses *Materials for Sustainability* (MSE 489) and *Theory of EaSE* (ENG 571).

Evaluating Sustainability : Goals, Life Cycle Assessment, Tradeoffs

John Abelson

Materials Science and Engineering

Energy and Sustainability Engineering

Perspective

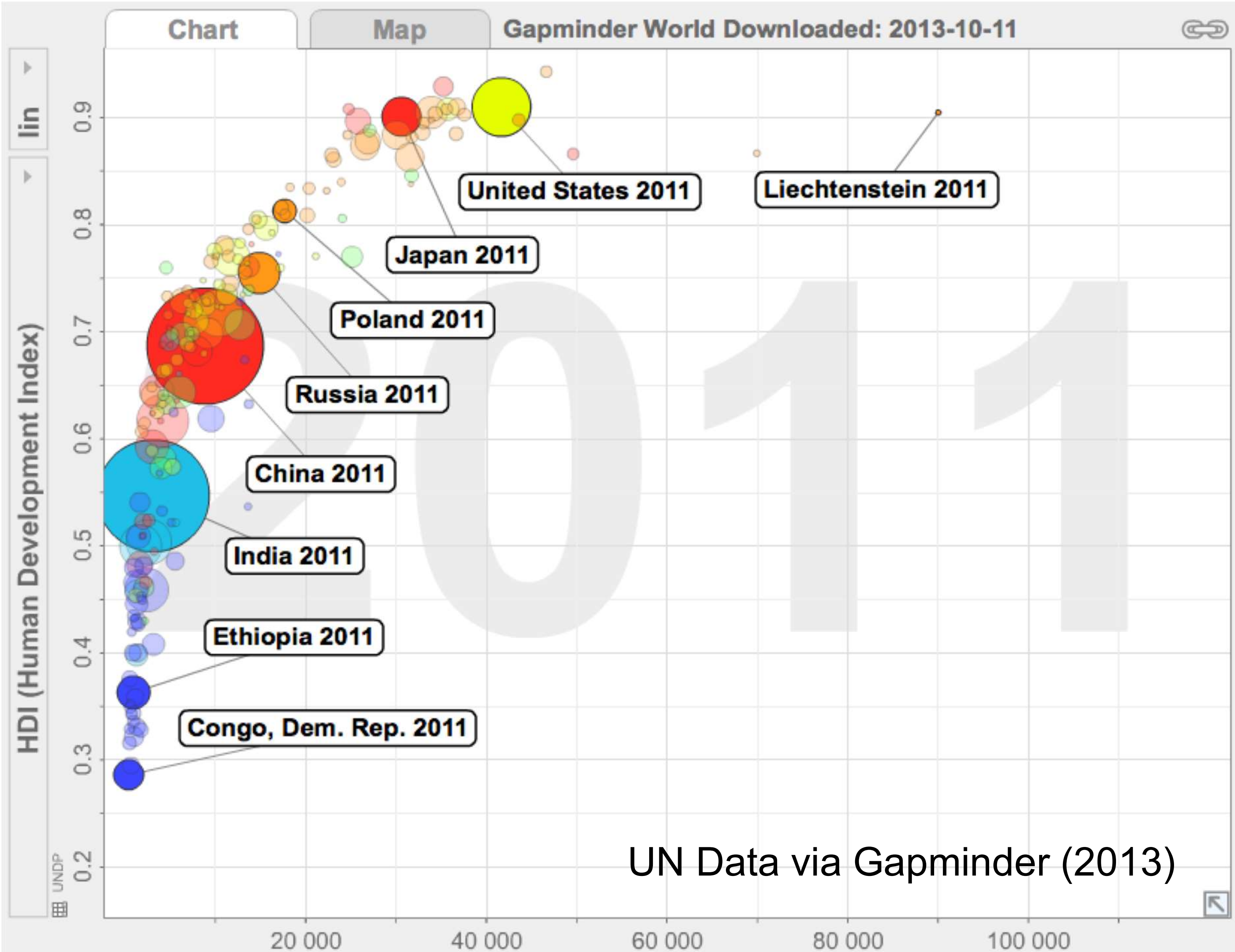
"Our greatest fear should not be of failure but of succeeding at things that don't really matter"

– Francis Chan

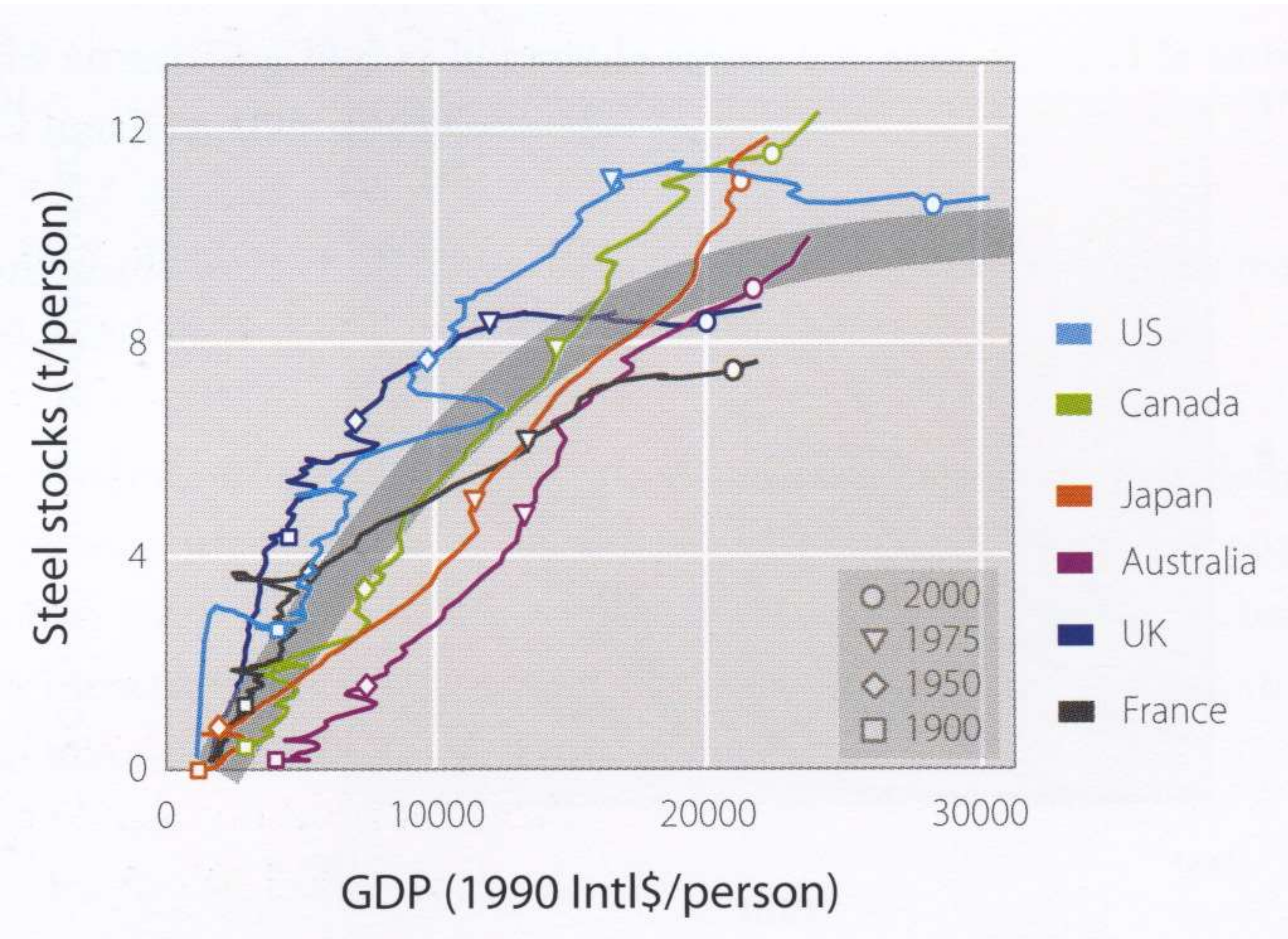
UN Sustainable Development Goals

https://www.un.org/sustainabledevelopment/sustainable-development-goals

Human Development Index (HDI) vs. Income per Capita



Materials : Steel Stocks vs. Economic Development



J M Allwood & J M Cullen, Sustainable Materials (2012)

Country	Steel (tonne / p)
Argentina	4.1
Australia	9.8
Bangladesh	0.1
Brazil	3.1
Canada	12.1
China	2.2
Congo, DRC	0.1
Egypt	1.1
Ethiopia	0.1
France	7.5
Germany	9.0
India	0.4
Indonesia	0.3
Japan	13.6
Mexico	4.8
Nigeria	0.1
Pakistan	0.1
Philippines	0.1
Russia	4.6
South Africa	3.0
South Korea	7.9
Spain	8.7
Thailand	2.2
Turkey	4.2
United Kingdom	8.5
United States	10.5
Vietnam	0.1
World	**2.7**

Sustainability Problem (in part)

By 2100, world population rises to ≈ 11 B people

Affluence rises (~ 1 B people rise to the middle class)

Housing, transport, infrastructure are built using gigatons of materials (huge energy inputs to mine and process)

Consumption of fossil energy and CO2 emissions rise

Overall human well-being increases !

…While we also want to stabilize atmospheric CO2 and ensure resources for the future…

Different Goals Imply Different Actions

Minimize :

- *Energy use*
- *CO2 emission*
- *Resource depletion*
- *Environmental impact*
- *Investment cost*

Maximize :

- *Ability to recycle*
- *Job creation*
- *Convenience*
- *Personal image*
- *Profit*

Problem Definition Makes Tradeoffs Apparent

All proposals for sustainable development need :

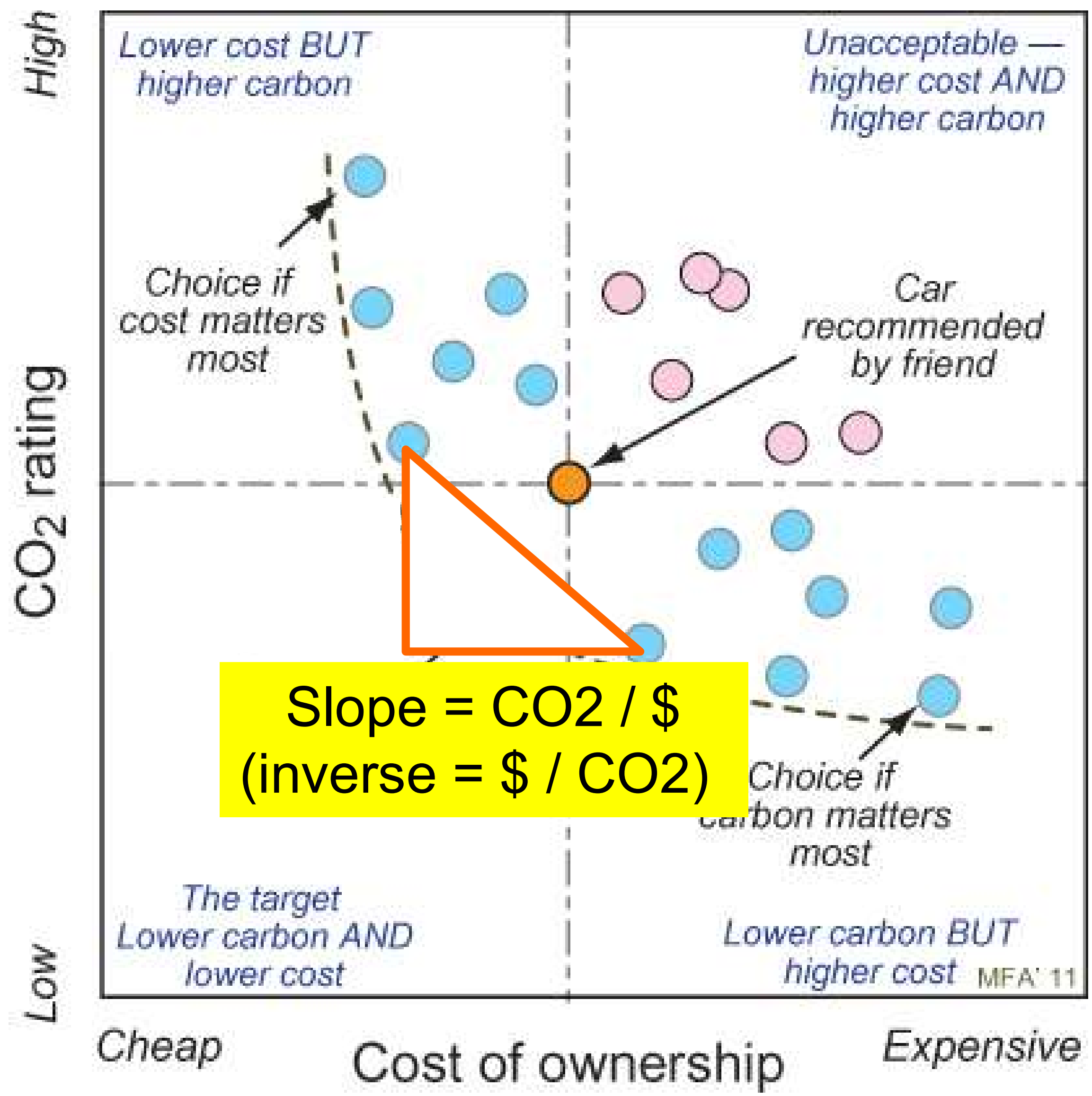
- problem definition : goals? possible approaches?
- objectives : what must be maximized or minimized?
- constraints : what conditions must be met?
- life cycle assessment : all costs? net benefits?
- optimization methods : how to value tradeoffs?
- boundaries : what factors have not been included?

All proposals involve economics :

- capital cost
- return on investment
- economies of scale and the learning curve
- who owns? who pays?

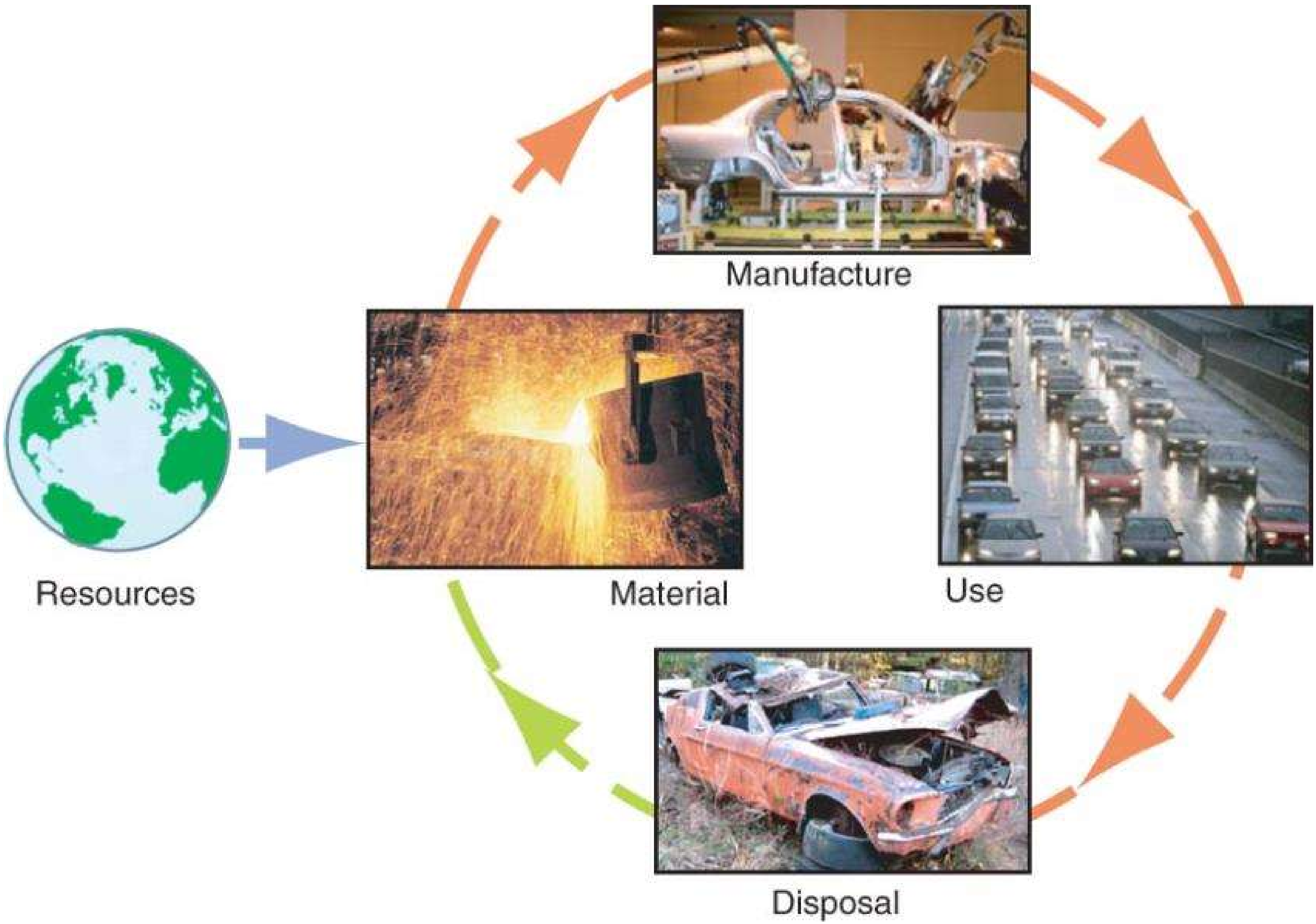
Tradeoffs on a ‘Pareto Surface’

Example : Automobile CO2 vs. Cost

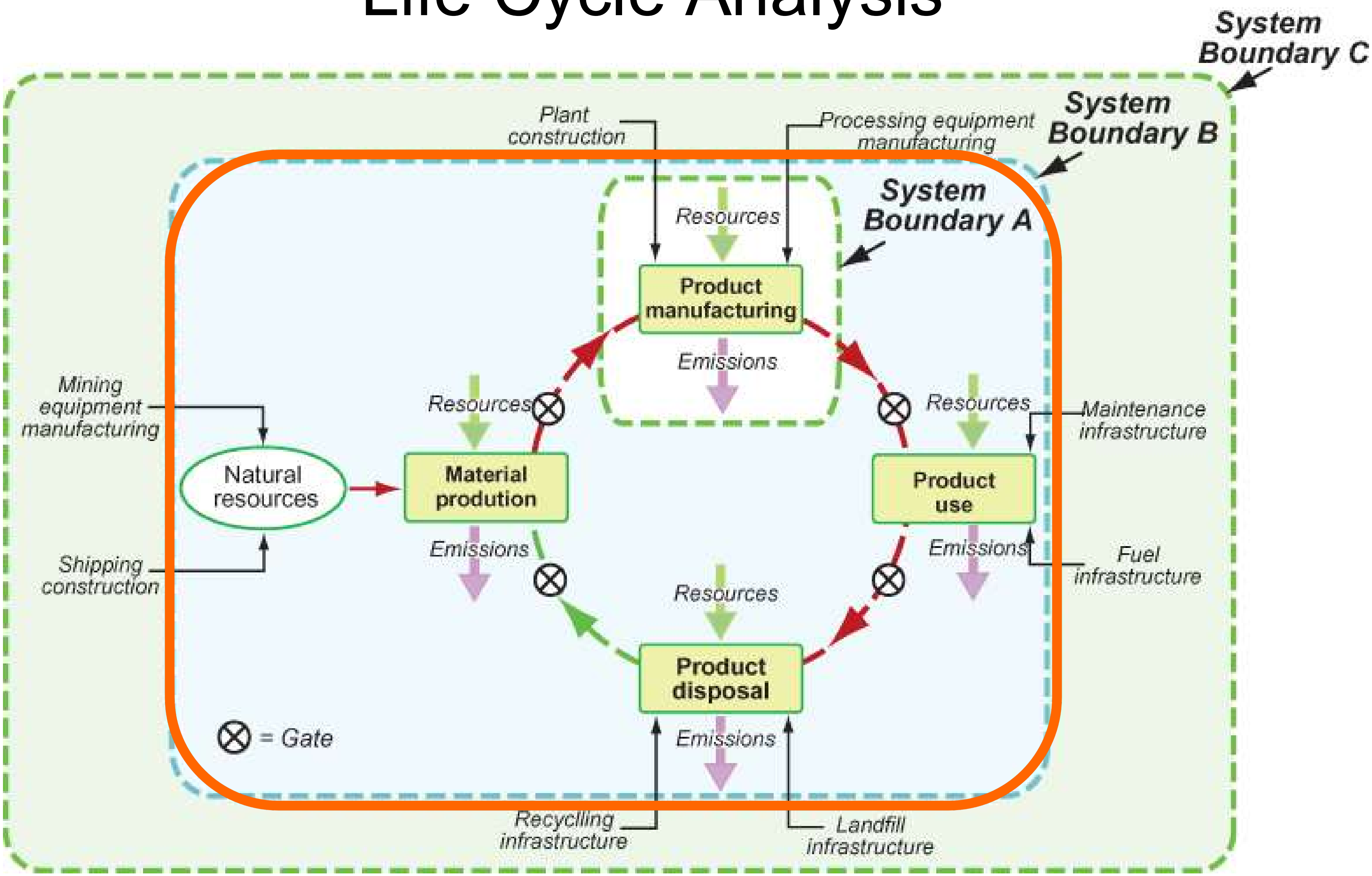


M F Ashby, Materials and the Environment (2013)

The Life Cycle of Products



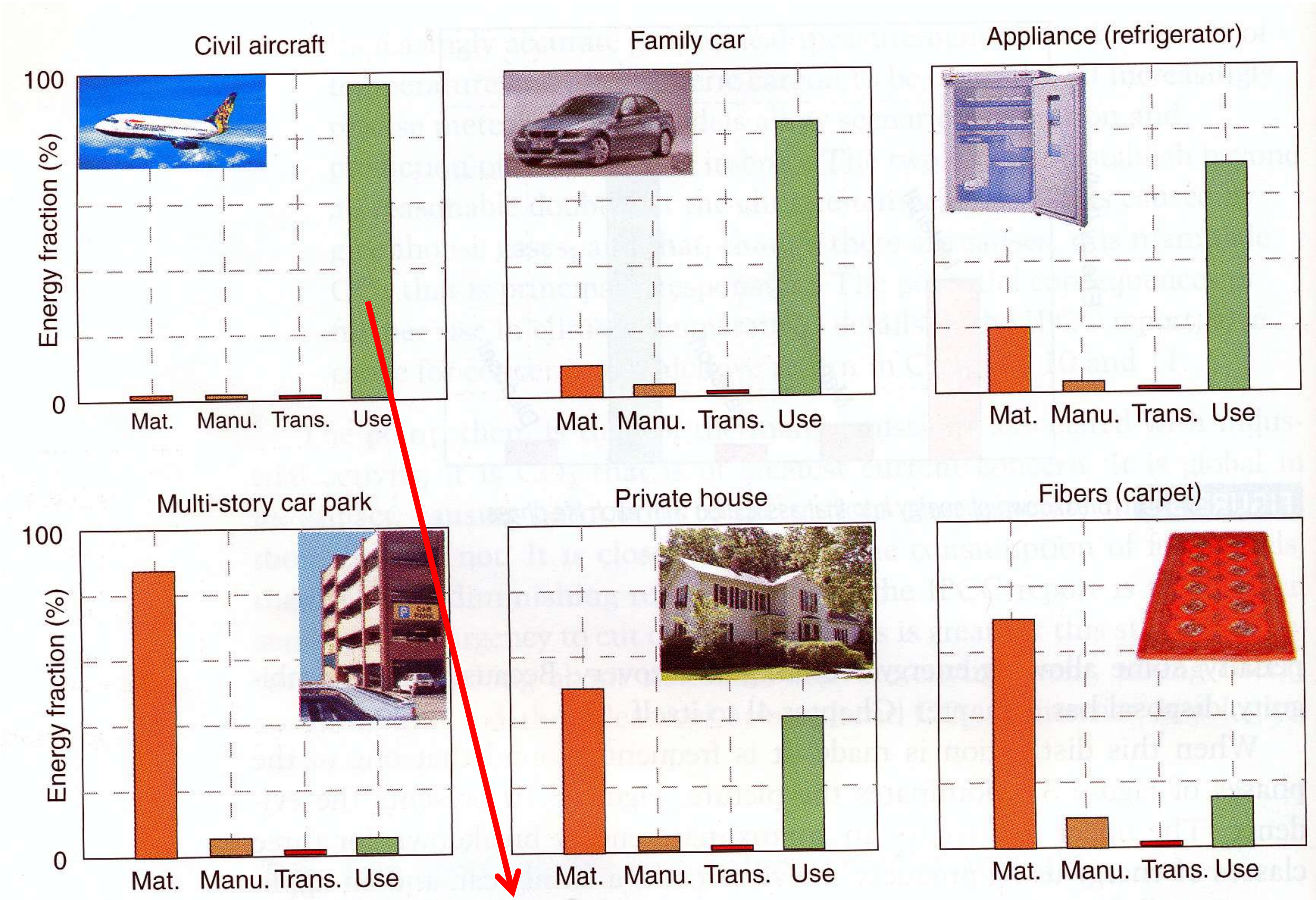
Life Cycle Analysis



Limited boundaries (such as *A*) give a *misleading answer*!

Boundaries B are typical; for C, need input-output analysis

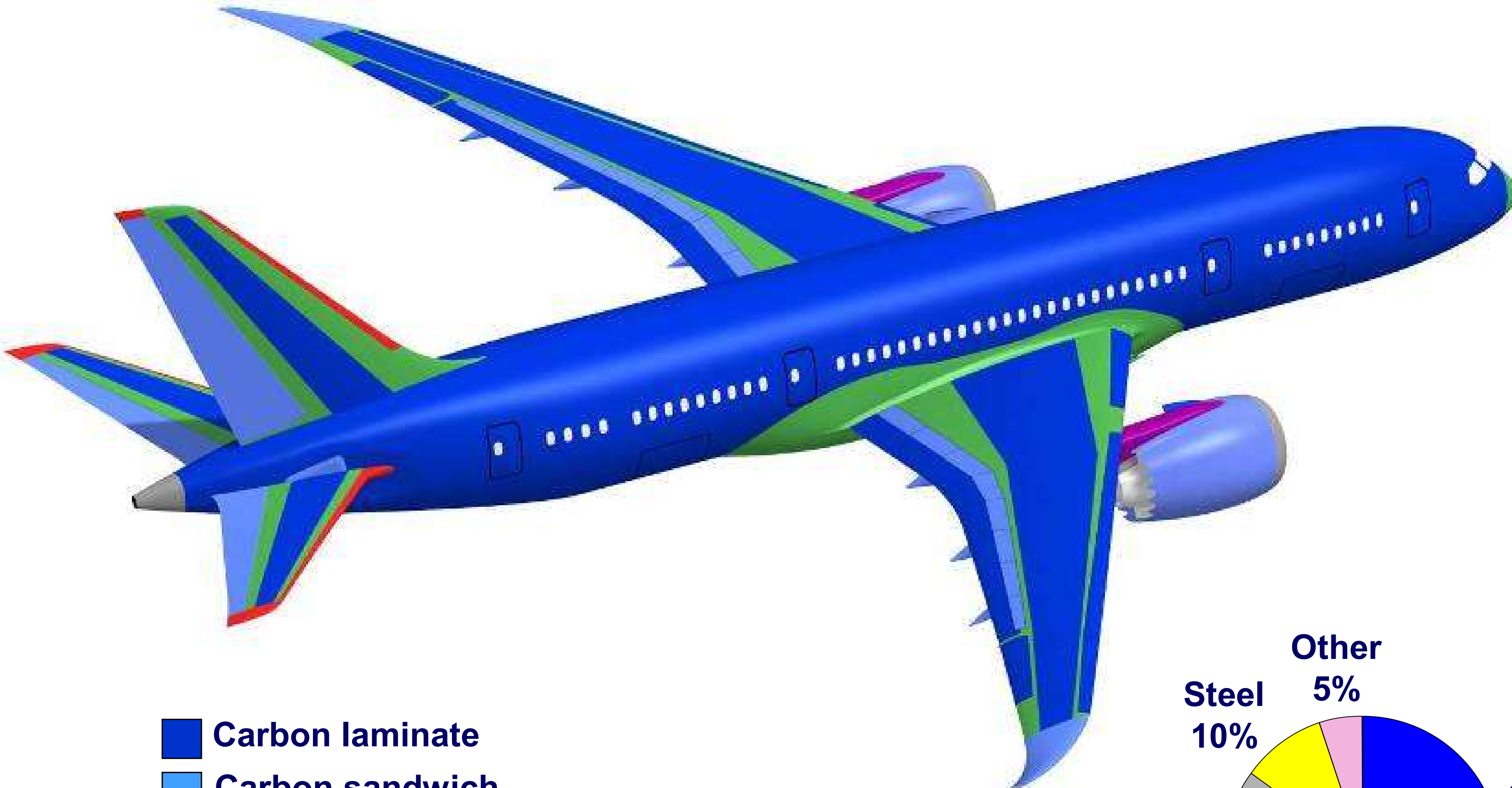
Compare Energy Use in Products

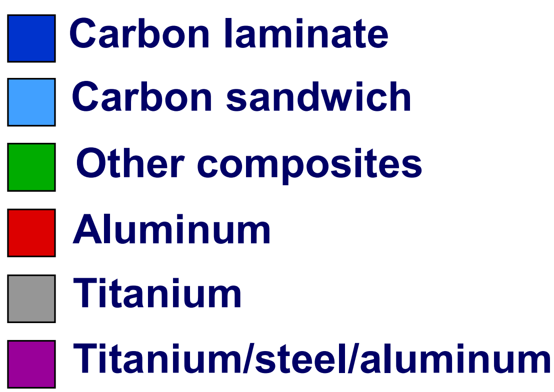


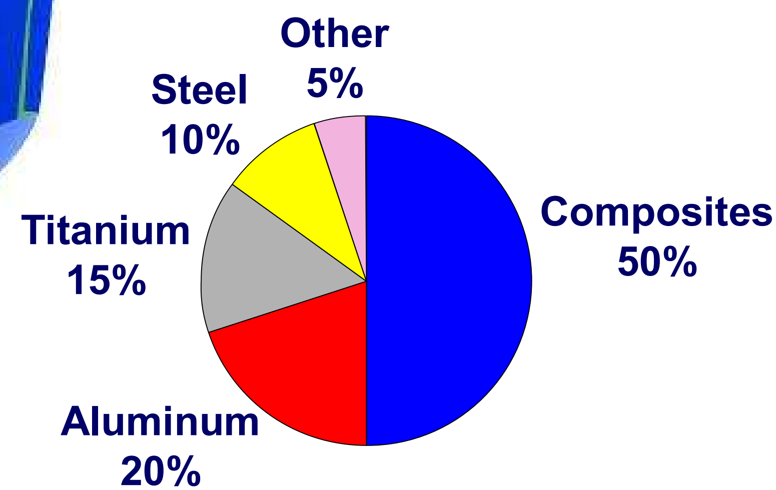
Boeing 747-8 can carry 239,000 liters of fuel

Composites Serve as Primary Structural Material

787 DREAMLINER







Ansys "Eco-Data" for ~ 4000 Materials!

Table 6.1 Eco-attributes of a material

Aluminum alloys	
Geo-economic data for principal component	
Annual world production	33×10^6–34×10^6 tonnes/yr
Reserve	20×10^9–2.2×10^9 tonnes
Ecoproperties: material production	
Embodied energy, primary production	200–240 MJ/kg
CO_2 footprint, primary production	11–13 kg/kg
Water usage	125–375 l/kg
Eco-indicator	740–820 millipoints/kg
Ecoproperties: processing	
Casting energy	2.4–2.9 MJ/kg
Casting CO_2 footprint	0.14–0.17 kg/kg
Deformation processing energy	2.4–2.9 MJ/kg
Deformation processing CO_2 footprint	0.19–0.23 kg/kg
Recycling	
Embodied energy, recycling	18–21 MJ/kg
CO_2 footprint, recycling	1.1–1.2 kg/kg
Recycle fraction in current supply	33–55%

Container : How Much Energy & CO_2 Associated with Phases of Life Cycle?

Synthesize polymer

Mold bottle and cap

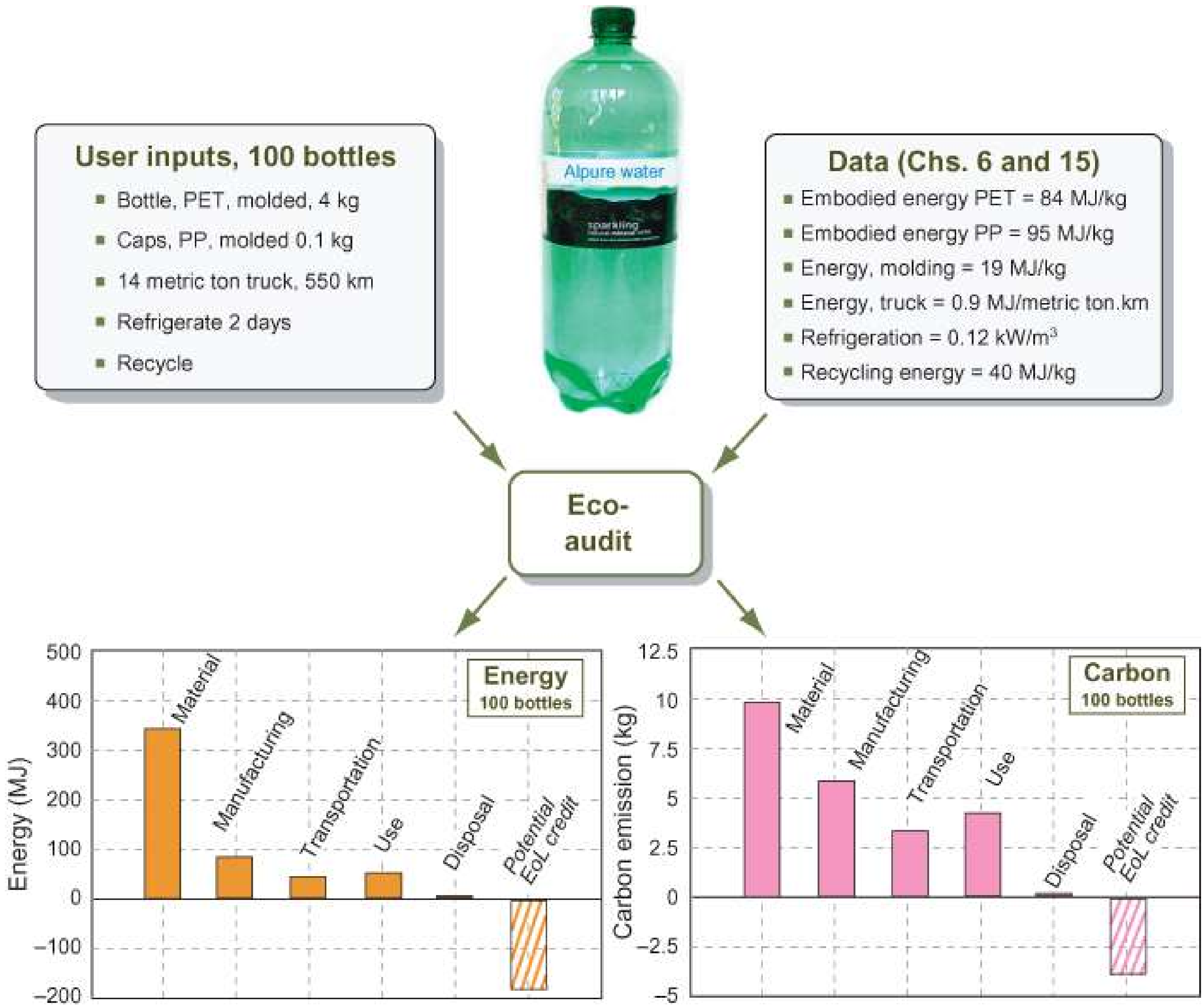
(Fill in French Alps)

Ship to Cambridge

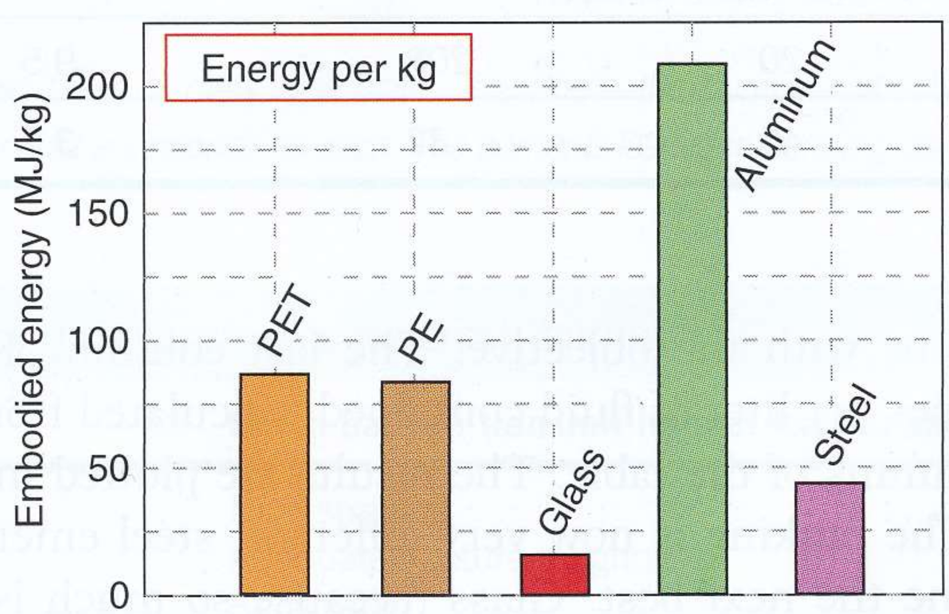
Refrigerate 2 days

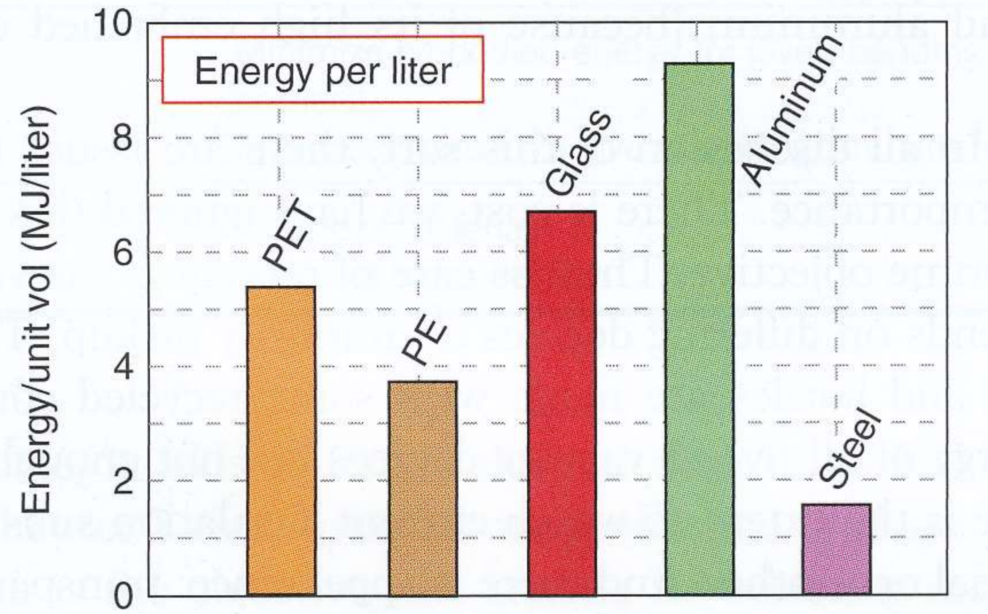
Recycle

Life Cycle Assessment from Ansys EduPack

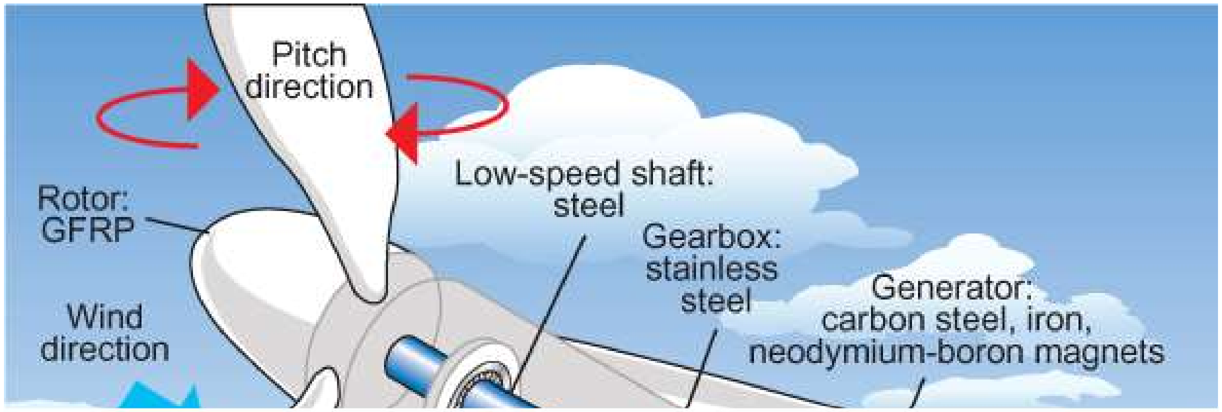


Basis for Comparison: Unit of *Function*





Renewable Energy : Materials of Construction !



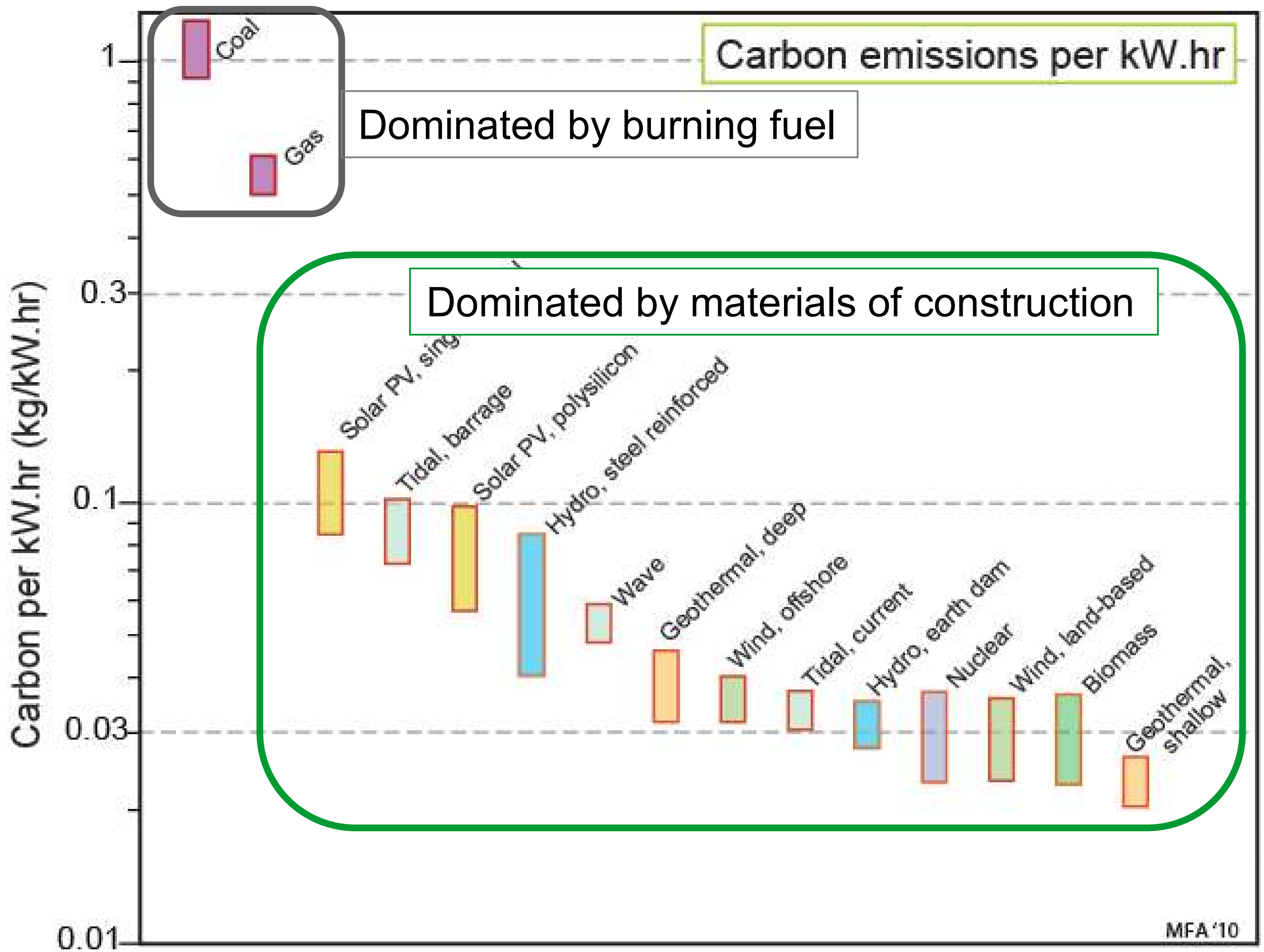
Onshore wind

Material	kg/kW
Aluminum	0.8–3
CFRP	5.0–10
Concrete	380–600
Copper	1.0–2
GFRP	5.0–10
Steel	85–150
Neodymium	0.04
Plastics	0.2–10
Total mass, all materials	**500–750**

Materials and quantitites from Ardente et al. (2006), Crawford (2009), Vindmølleindustrien (2007), Vestas (2008), and Martinez et al. (2007).

www1.eere.energy.gov/windandhydro

Life Cycle Analysis – Energy Sources



MF Ashby, Materials and the Environment (2013)

Sustainable Development

Mission

Provide framework for critical, independent assessment of "Sustainable Development"

What is a "Sustainable" Development?

One that provides products or services in ways that minimize the drain on resources, is legal, economically viable and acceptable to all stakeholders.

"Articulation" of Sustainable Development

A proposal that claims to move us from a less to a more sustainable state

Slides by Mike Ashby and Tatiana Vakhitova

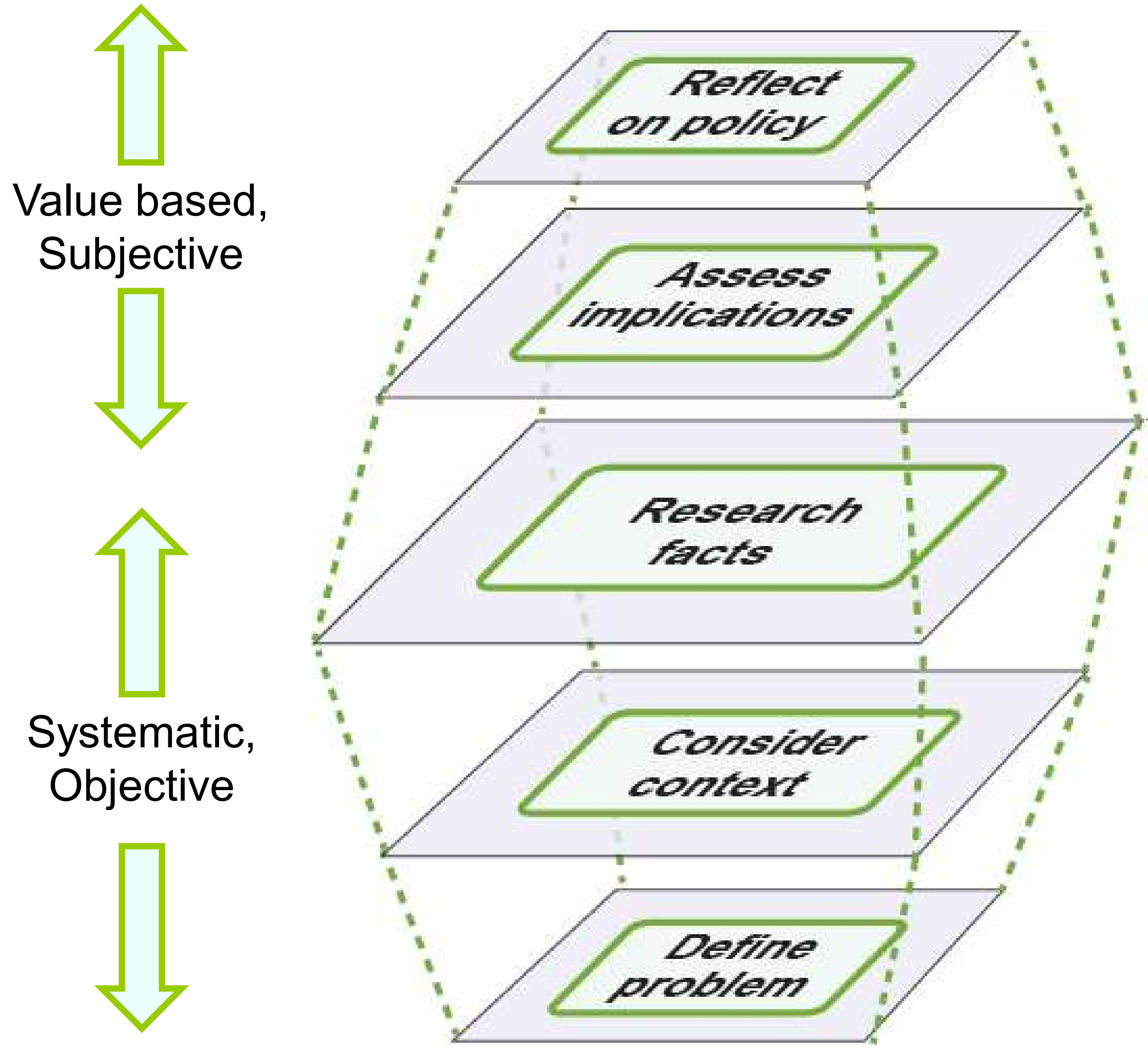
Articulations of sustainable technology

Many single actions ("articulations") claim to support sustainable technology

Motivation *(Prime objective)*	**Articulation**	**Unintended consequence**
Reduce dependence on oil, gas, coal	**Bio-fuels Bio-polymers**	*Competition with food production (People)*
Stimulate low-carbon economy	**Carbon taxes**	Increase energy price *(Prosperity)*
Stimulate circular materials economy	**Mandatory recycling**	Inhibits use of advanced materials *(Planet)*

Each has a **Prime Objective** with a { **physical scale**, **time scale** }

Dealing with complexity



Layer 1 : Define the problem

The problem | **The proposed solution**

20 % of carbon emission is from cars

Subsidies to achieve 10 % electric cars by 2020

280 million tonnes of oil-based plastics per year

20 % bio-plastics by 2025

17 % of domestic electricity is lighting

Mandatory change of lamp technology by 2014 (2 billion lamps per year in US)

Each “articulation” has an

- ***Objective***
- ***Size scale***
- ***Time scale***

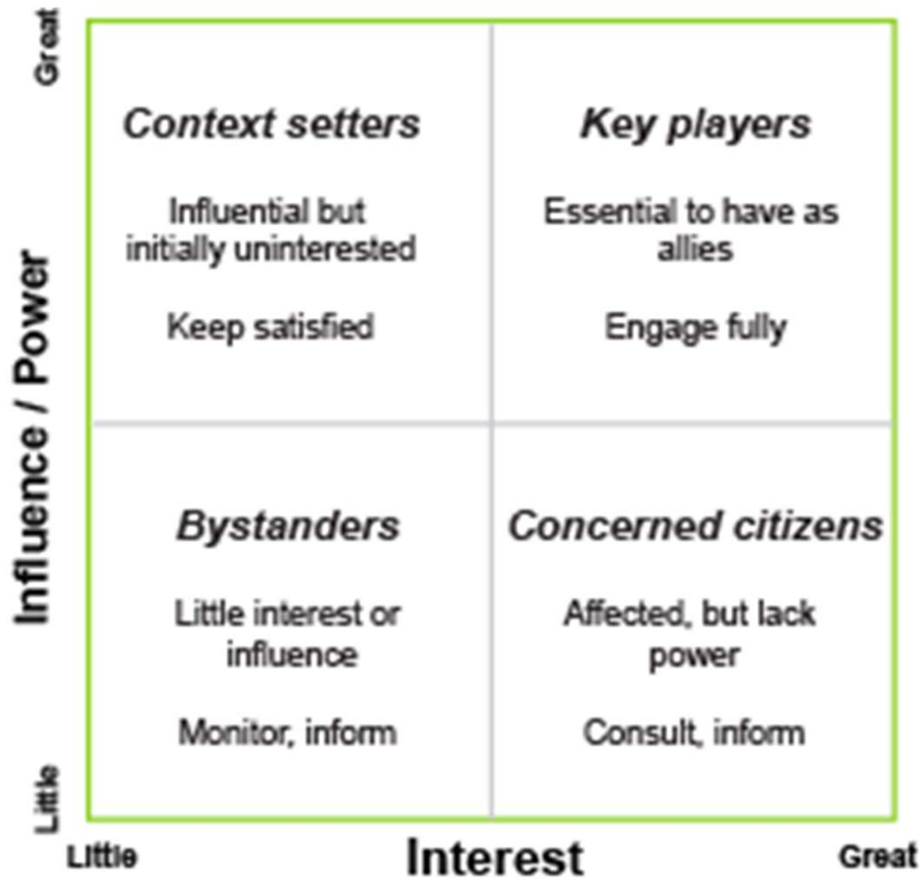
Layer 2 : Context – the Stakeholders

Stakeholders

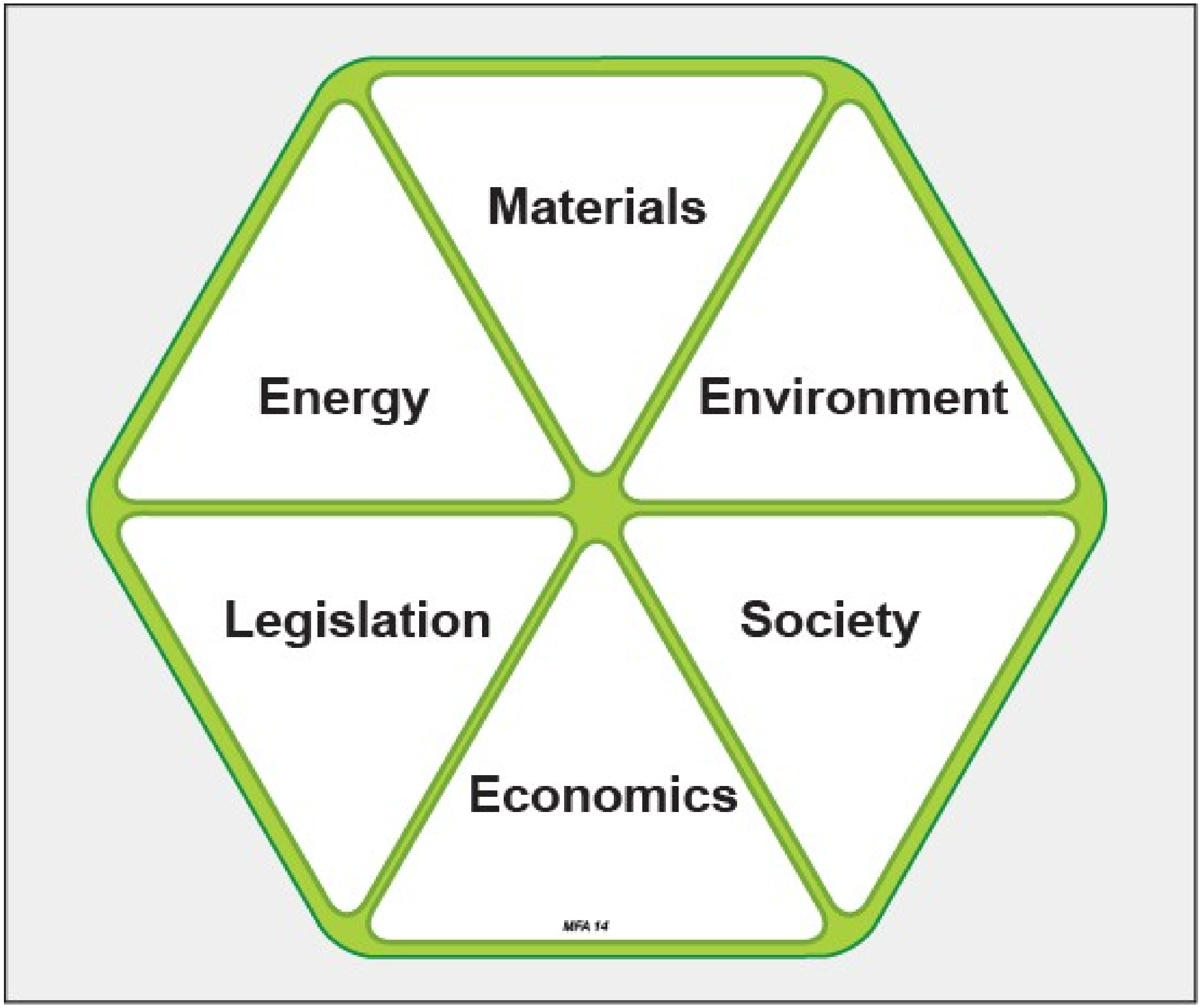
- *Who are they?*
- *What are their concerns?*
- *What power do they have?*

- *Government*
- *The public*
- *Local communities*
- *Owners*
- *Manufacturers*
- *Suppliers*
- *Trade unions*
- *Customers*
- *Lobbyists*
- *Investors*
- *National press*
- *Managers, colleagues, team*

Mandatory recycling of cars



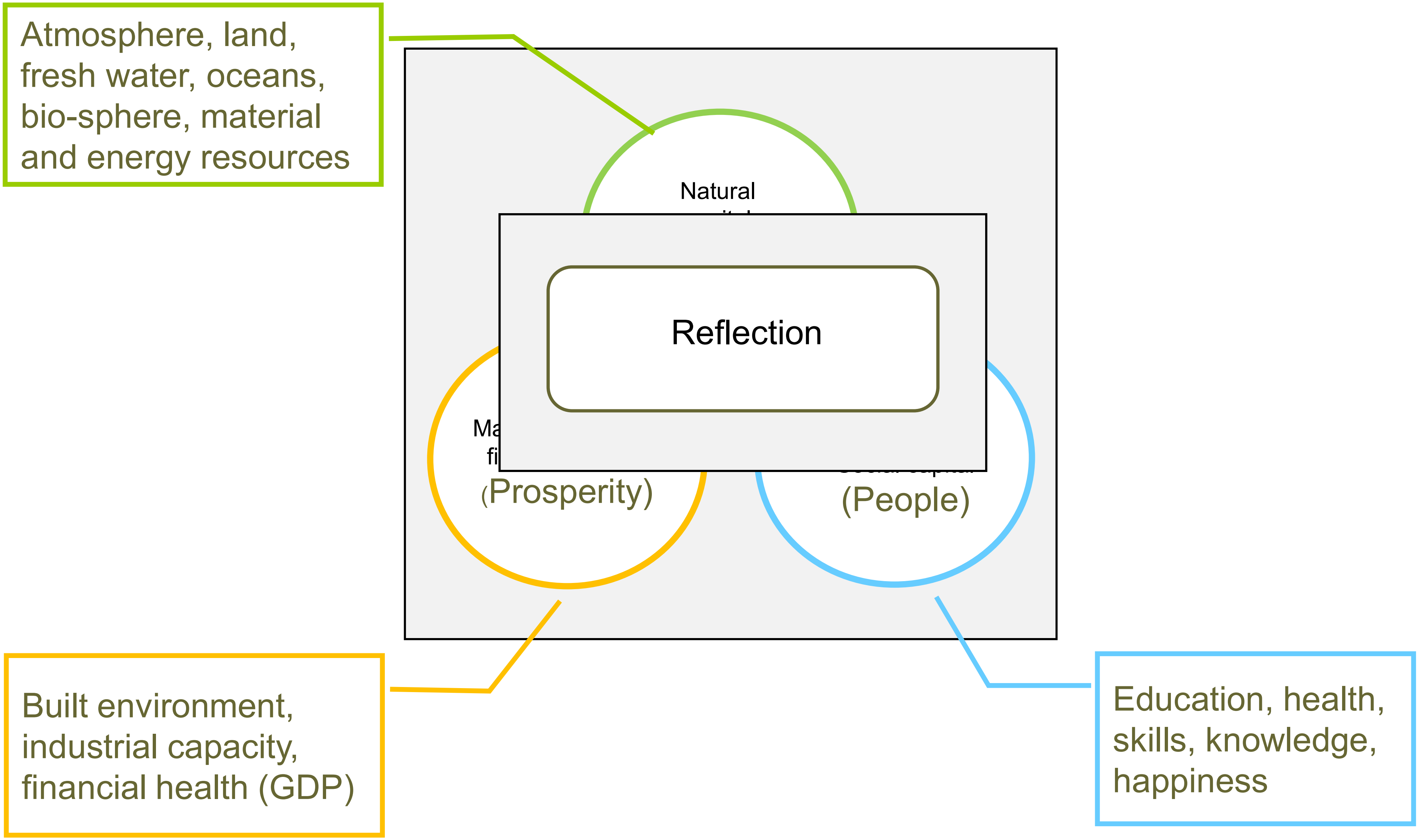
Layer 3 : Research the facts



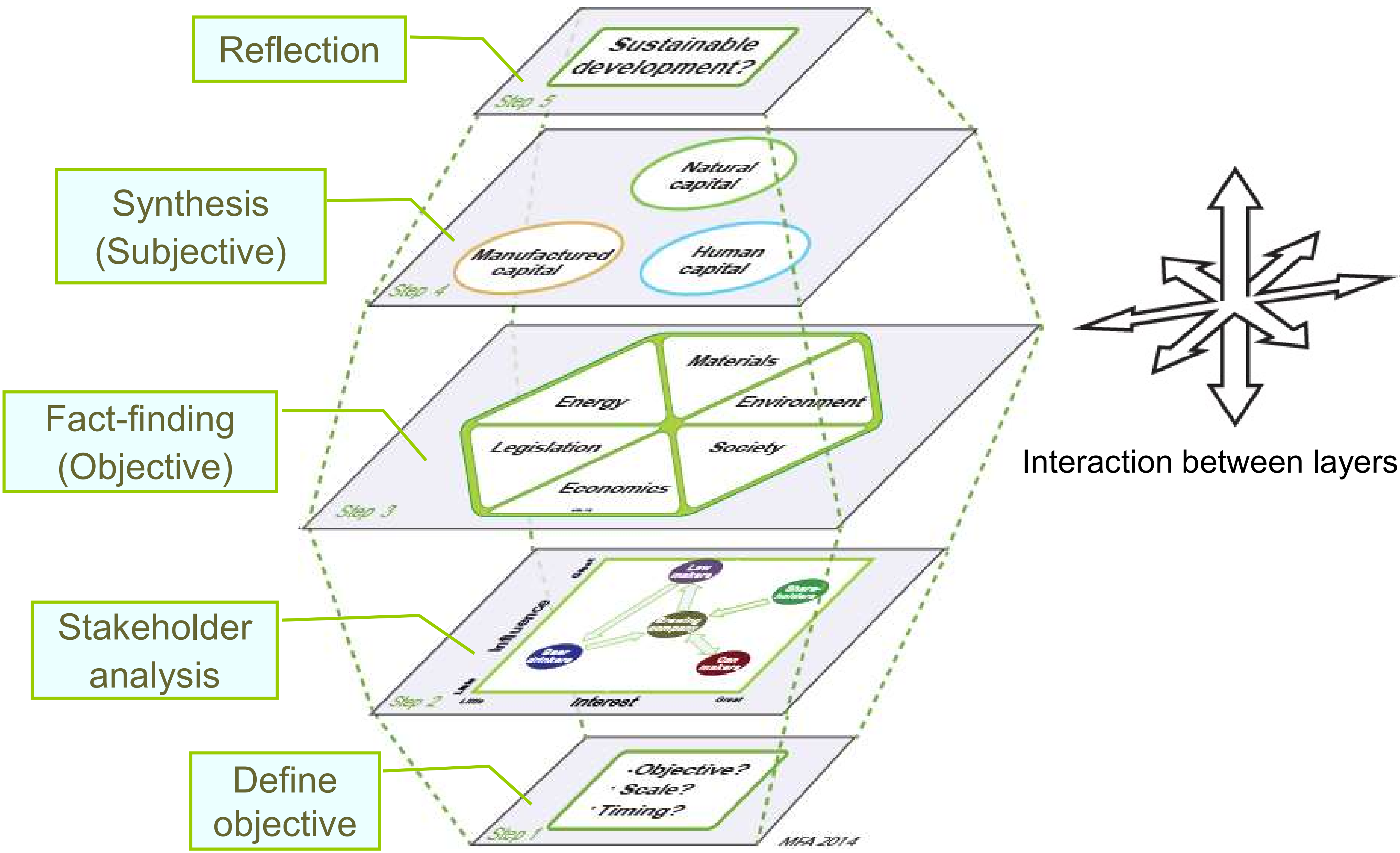
- Material-efficient design
- Resource-efficient design
- Eco-design

Sustainable design

Layers 4, 5 : Three essential Capitals



Analyzing an “articulation”



Materials and Sustainable Development

A worked example

Greener beer cans

Layer 1 : Objective, scale and timing

Background

- Beneficial Brewery markets beer in 16 oz (473 ml) aluminum cans.
- Sales: 500 million cans per year.
- Eco-aware shareholders request switch to steel cans.
- Reasoning: steel has lower embodied energy, lower CO_2 footprint, lower cost } than aluminum

The articulation: objective, scale and timing

- Reduce energy and CO_2 emission by change from Al to Fe cans
- 5×10^8 cans per year
- Progress in a year

Layer 2 : Stakeholders and concerns

- Shareholders

– reduce energy and CO_2 emissions

- Can makers

– loss or gain of market share

- Beer drinkers

– little interest in can material

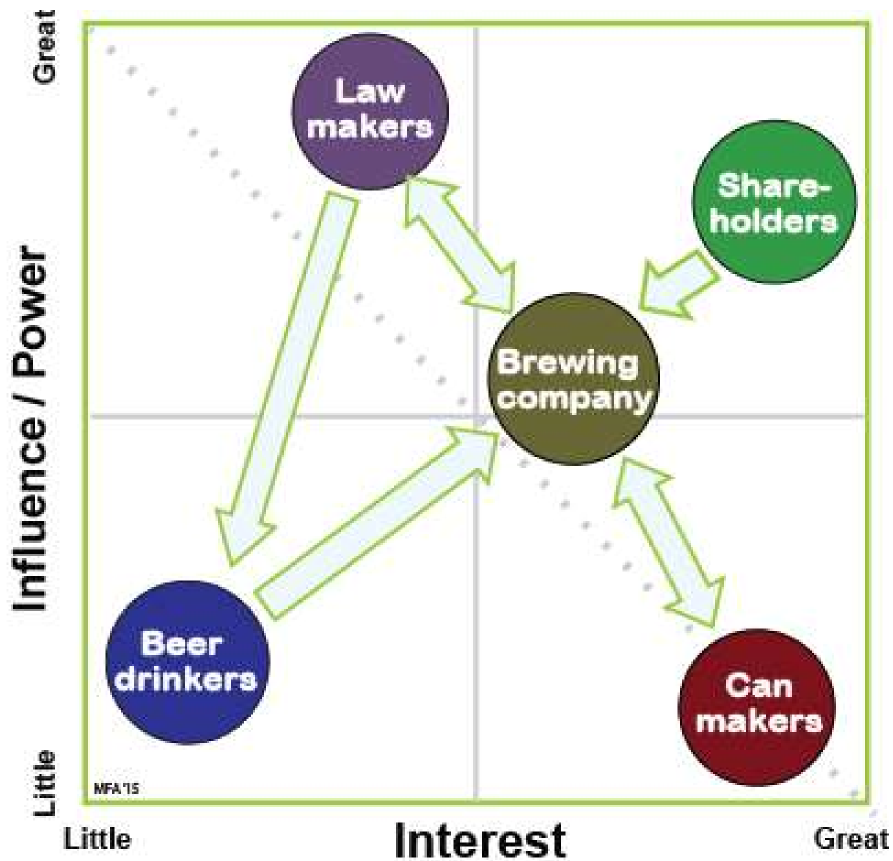
- Law makers

– recycling targets

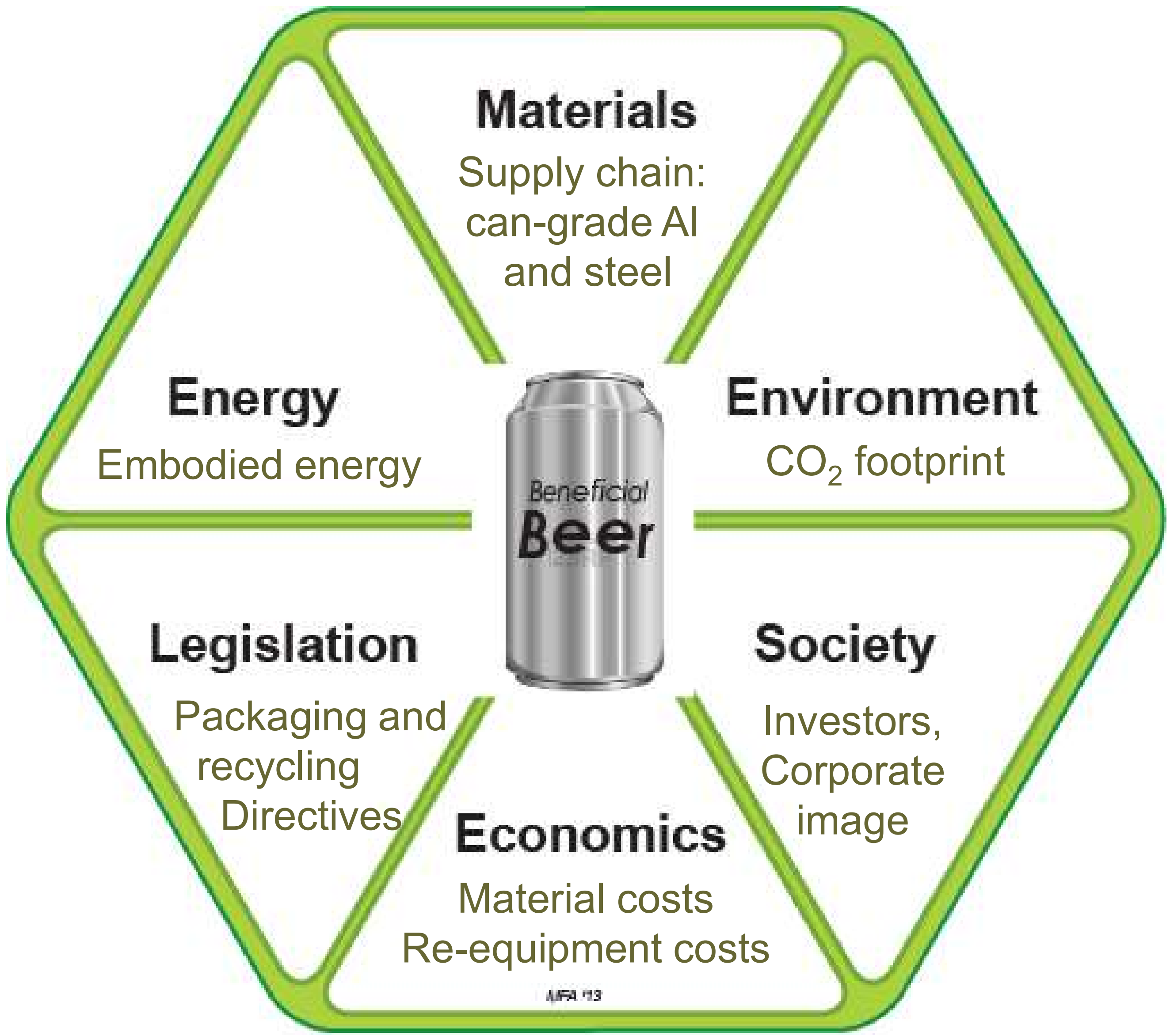
- Beneficial Brewery

– respond to shareholder concerns

Stakeholder diagram



Layer 3 : Fact-finding



Fact-finding : Materials, energy

Materials

- Neither aluminum nor steel are “critical” materials
- Can weight : Aluminum 13 grams

  Steel 44 grams

Aluminum Steel

Energy *

Embodied energy, can-grade Al	110 MJ/kg	Factor 6
Embodied energy, can-grade steel	18 MJ/kg	
Embodied energy, Al can	1.4 MJ	Factor 1.7
Embodied energy, steel can	0.8 MJ	

* Eco-data (typical recycled fraction) from the Ansys EduPack Sustainability DB

Fact-finding : Eco-audit, 1000 cans

Materials

Steel
44 g

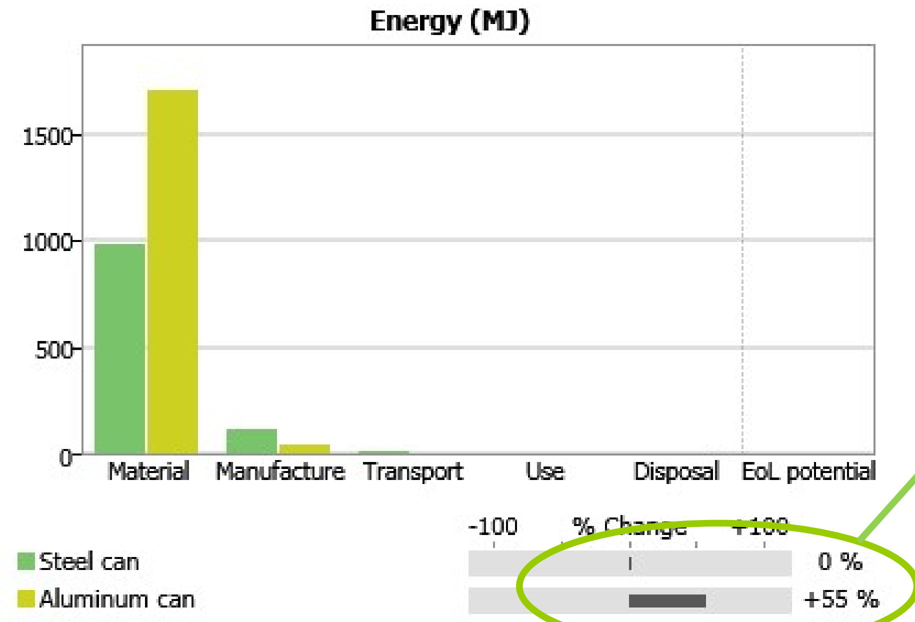
Aluminum
13 g

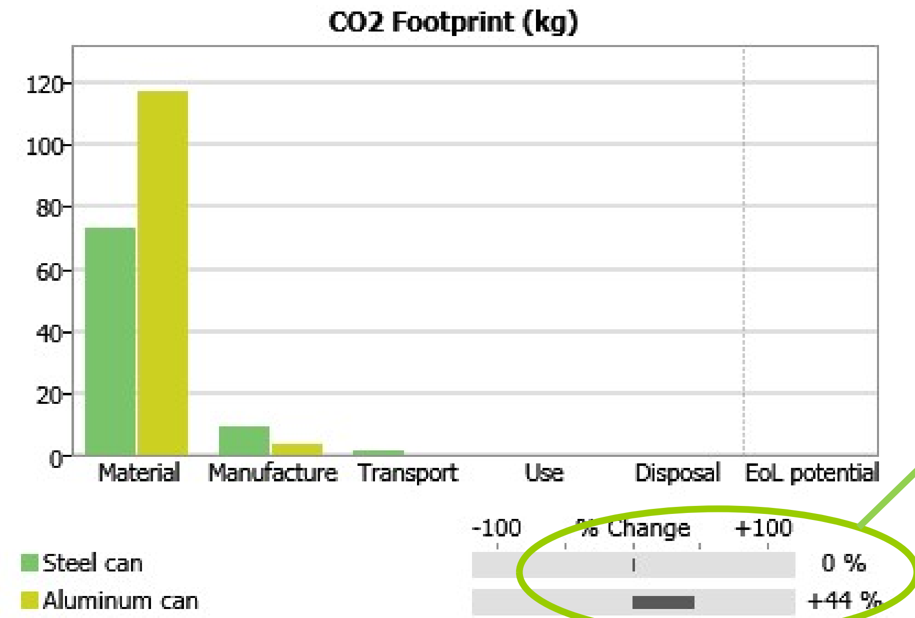
Manufacture

- Primary: rolling
- Secondary: cropping
- Painting / Printing

Transport

- 1000 km
- 32 tonne truck





Energy:
Factor 1.55

Carbon:
Factor 1.44

Fact-finding : Environment, Legislation

Environment

Full LCA: difference in final energy and carbon per can is negligible

http://www.apeal.org/uploads/Library/LCA%20study.pdf

Legislation*

EU Packaging Directive (1994) – Maximize recovery and recycling of packaging

* Legislation from the CES EduPack Sustainability DB

Fact-finding : Economics

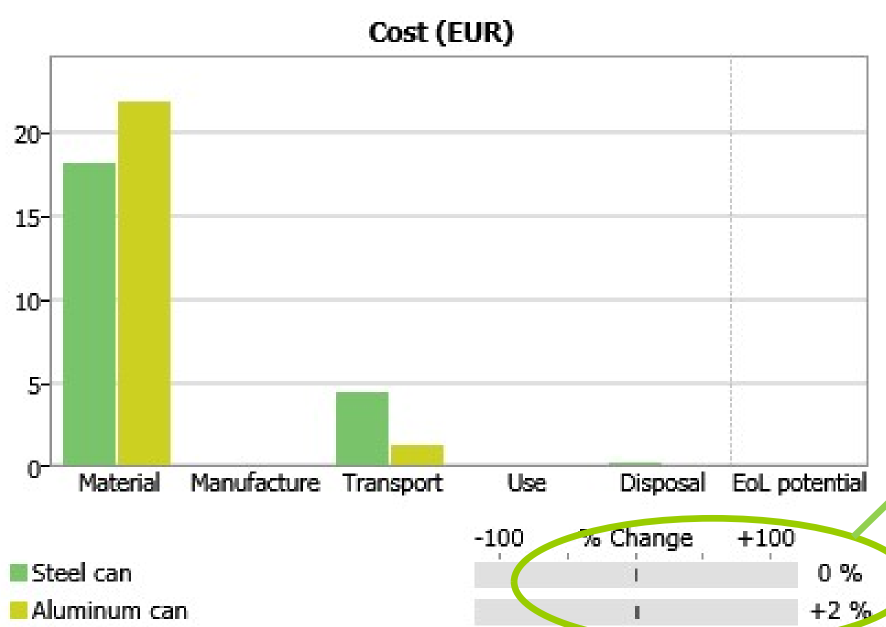
Economics

- Cost, can-grade Al ≈ 1.7 $/kg
- Cost, can-grade steel ≈ 0.4 $/kg

Factor 4

- Material cost, Al can ≈ 2.2 ¢
- Material cost, steel can ≈ 2.0 ¢

Factor 1.1



Cost:
Factor 1.02

Layer 4 : Impact on the Three Capitals

- Negligible reduction in emissions – Objective not achieved

- Does it cause irreversible change?
- Is a rebound effect possible?

Natural capital

Manufactured capital

Human capital

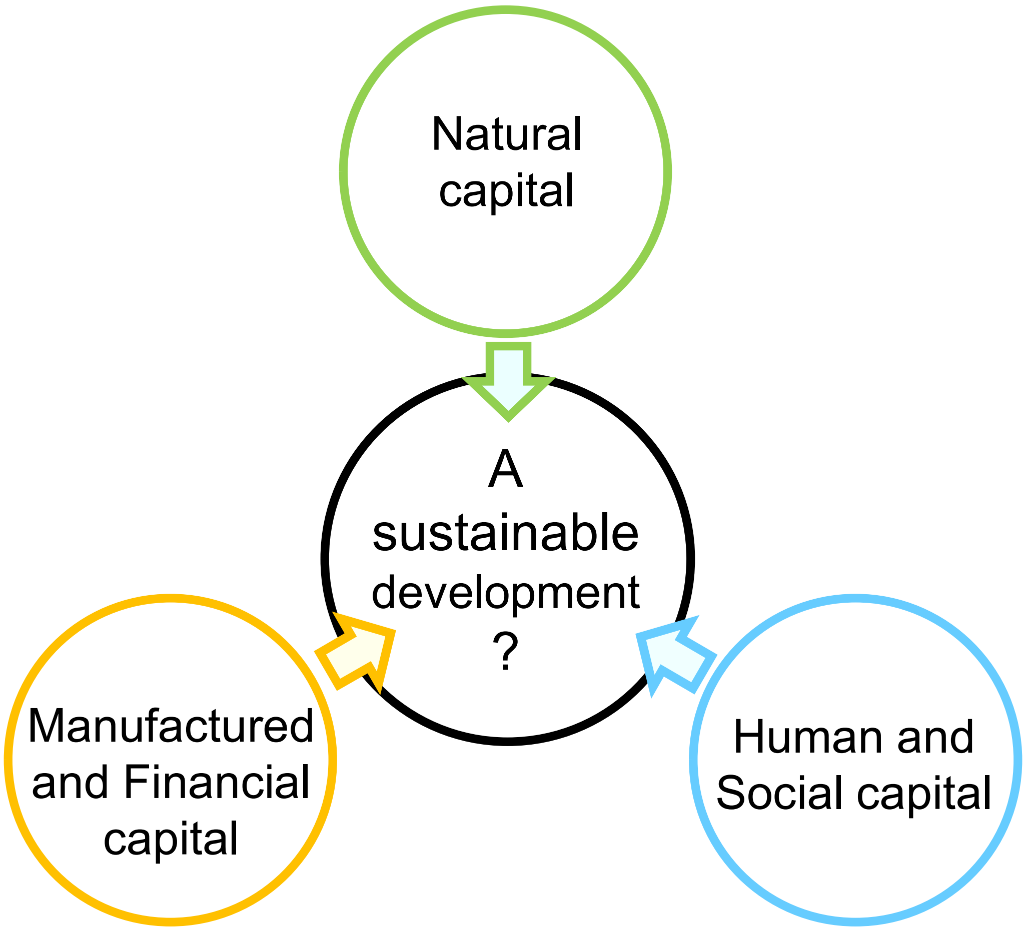
- Re-equipping filling line to deal with difference can material is expensive and disruptive

- Are opportunities for development created?

- Shareholder are influential stakeholders – seek other ways to meet their eco-concerns

- Are the st
- Effect on
- Increased
- Is it cultur
- Is it consistent with freedom of information, free speech, good governance, democracy?

Layer 5 : Reflection



Short term

- Many negatives (uncertain eco benefit, costly, disruptive change)

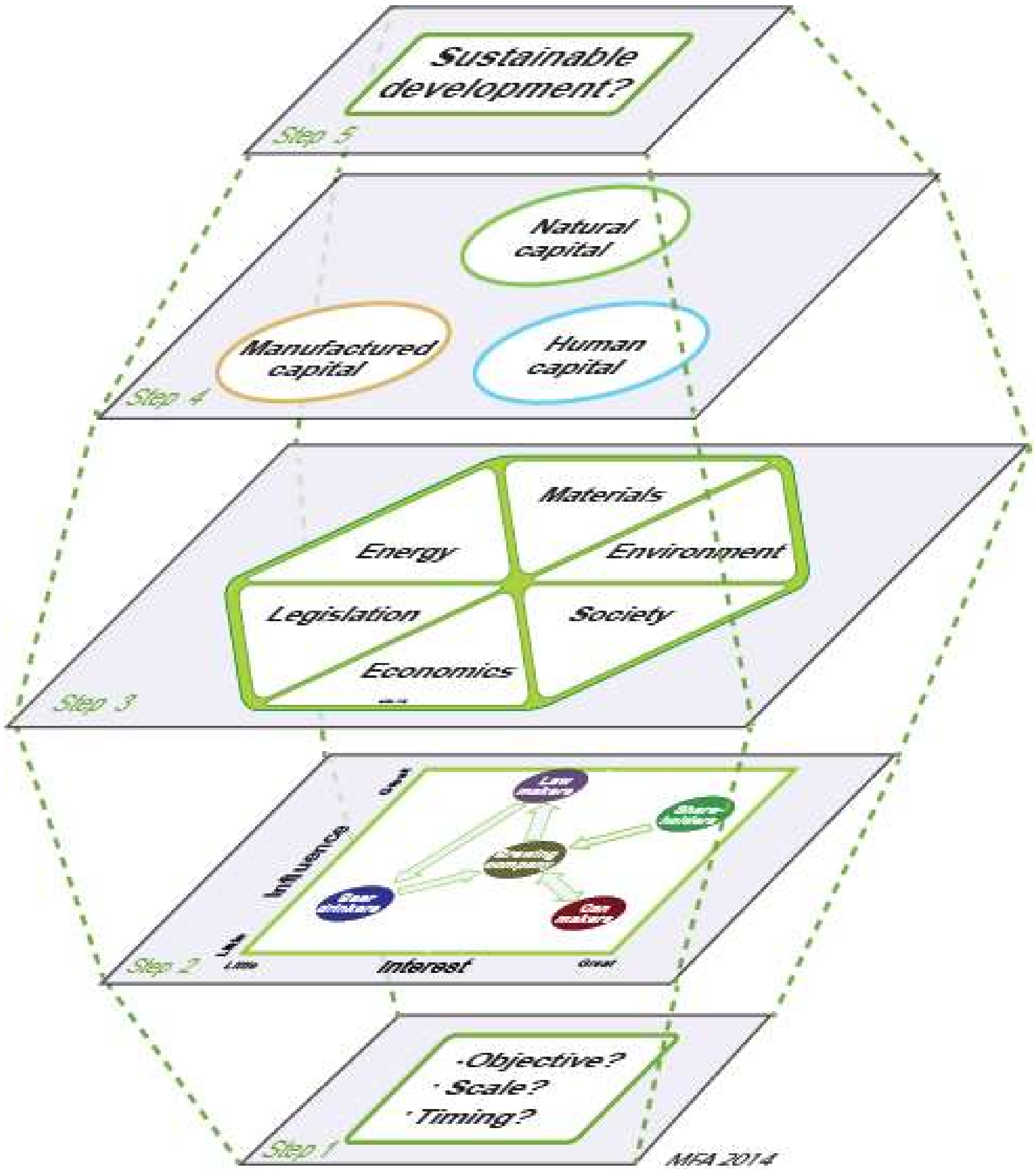
Longer term

- Could reconsider if re-equipping for other reasons

Alternative strategies?

- Support legislation for deposit on cans and mandatory recycling ?

Reminder – the layers



So What ?

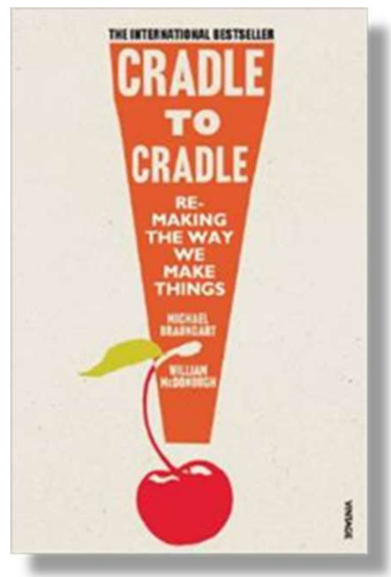
- **No completely "right" answer to questions of Sustainability**
- **Layer-based approach provides a framework – assembling the pieces in simple, progressive way**
- **It enables a thoughtful, well-researched response recognizing the conflicting facts, seeking best compromise**

Proposal : Plastic books

Cradle to Cradle by William McDonough and Michael Braungart :

“This book is not a tree. It is…a product that can be broken down and circulated infinitely in industrial cycles. The use of (plastic) expresses our intention to evolve away from the use of wood fibers for paper.”

Plastic edition:
Weight 562 grams
Price $ 27



Paper edition:
Weight 157 grams
Price $ 13

Printed in China

Are Real Situations Like This ?

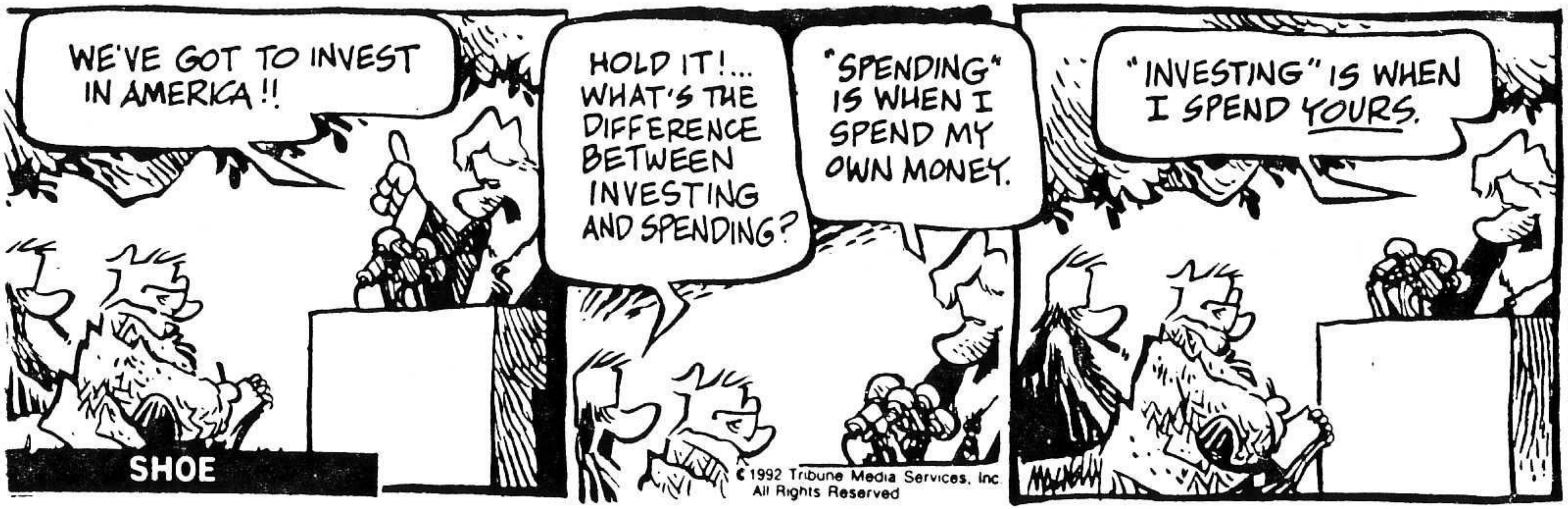
A Job Advertisement :

“Our research team is recruiting a postdoctoral scientist to work on a decision analysis problem involving the selection of restoration project investments. At its essence the problem is one of portfolio selection, but it is made difficult by ambiguity around stakeholder objectives and uncertainty in project outcomes.

We hope to develop this work under an adaptive framework in which formal linkages are made between outcome monitoring, predictive models, and future decision making. We seek an individual with experience in modeling and decision analysis.

Because the postdoc will be meeting with government and private stakeholders, the individual should have excellent communication skills and must be comfortable participating in these [professional] environments.”

Economic Viewpoints



Big Picture Questions

Stakeholders: What groups of people, or regions of the world, are most affected by this issue?

Time scale: How soon does this issue become critical enough to impact a major stakeholder? Can changes be implemented in time to offset major consequences?

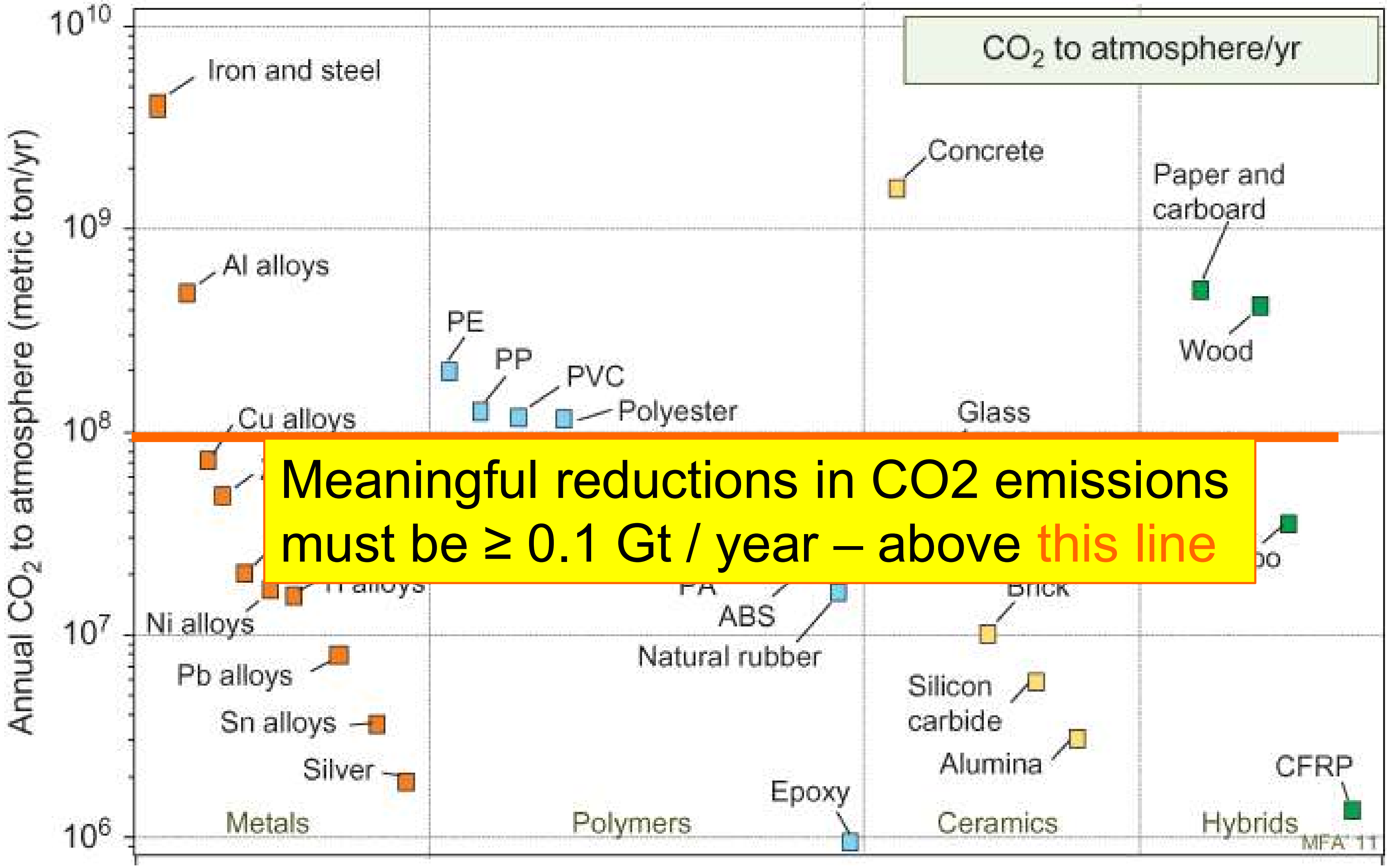
Solutions: Do there exist technologies or policy approaches that can make a substantial reduction in impact? What are the challenges to implementation?

Physical scale: Can the proposed technology be employed *at scale*, meaning enough units, soon enough? This involves a *manufacturing supply chain*.

Fundamental tradeoffs: *There does not exist a solution that simultaneously maximizes all benefits and minimizes all consequences*. Typically, we can lower environmental impact by investing up-front in a more efficient system.

Ecosystem services: Human activity – economic activity – cannot occur without impact on the earth and its ecosystem. Do the levels of activity lead to a new equilibrium or to a constant degradation?

CO2 from Materials Production



MF Ashby, Materials and the Environment (2013)

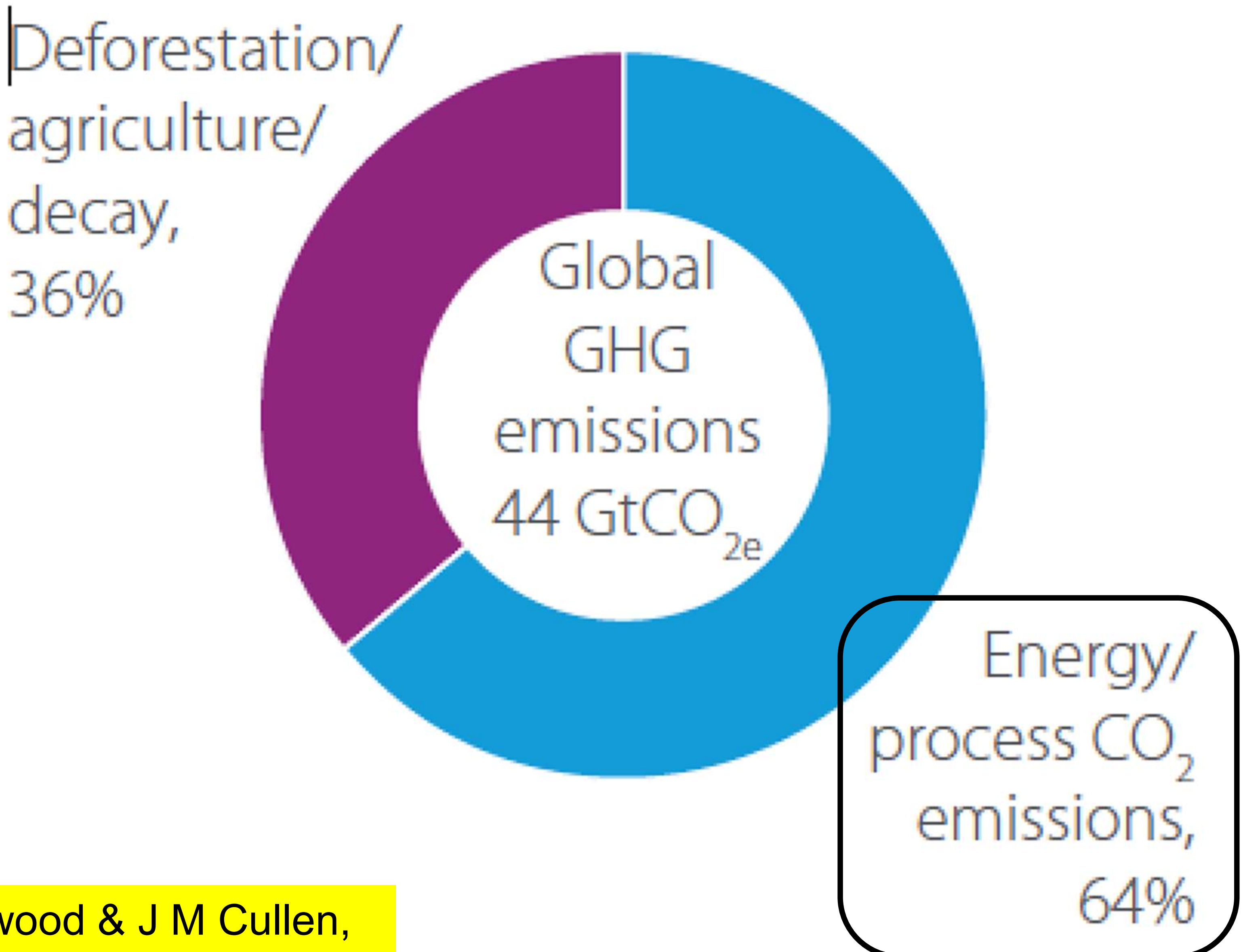
Human Development Index (HDI)

Dimension	Indicator	Minimum	Maximum
Health	Life expectancy (years)	20	85
Education	Expected years of schooling (years)	0	18
	Mean years of schooling (years)	0	15
Standard of living	Gross national income per capita (2011 PPP $)	100	75,000

$$\text{Dimension index} = \frac{\text{actual value} - \text{minimum value}}{\text{maximum value} - \text{minimum value}}$$

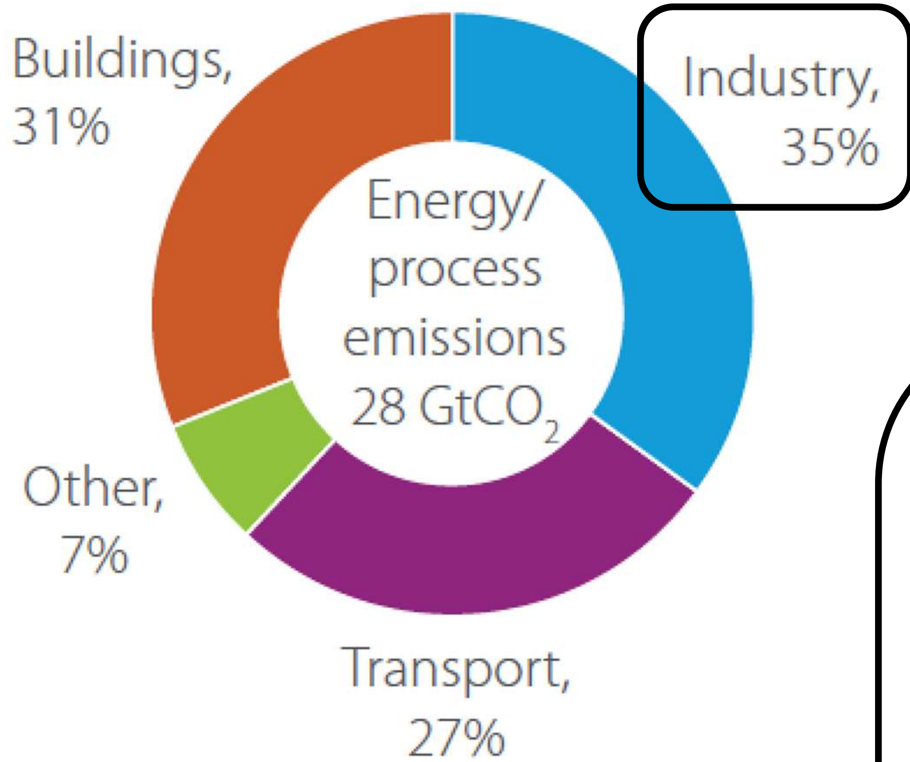
$$\boxed{HDI = (I_{Health} \cdot I_{Education} \cdot I_{Income})^{1/3}}$$

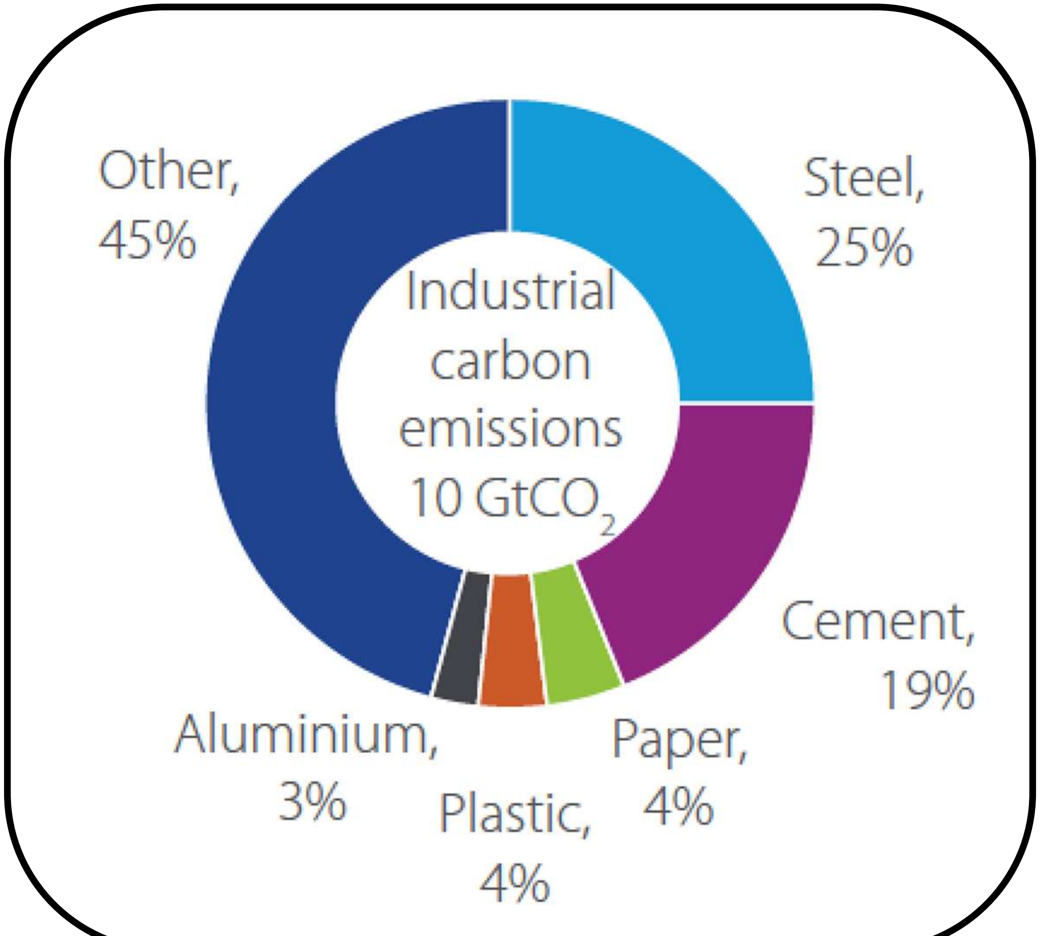
Global Anthropogenic $CO2_e$ Emissions



J M Allwood & J M Cullen, Sustainable Materials (2012)

$CO2_e$ Emissions





J M Allwood & J M Cullen, Sustainable Materials (2012)