Progettazione di Materiali e Processi

Modulo 1 – Lezione 7
Progettazione e selezione di materiali e processi
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Selection of materials and processes according to sustainability criteria

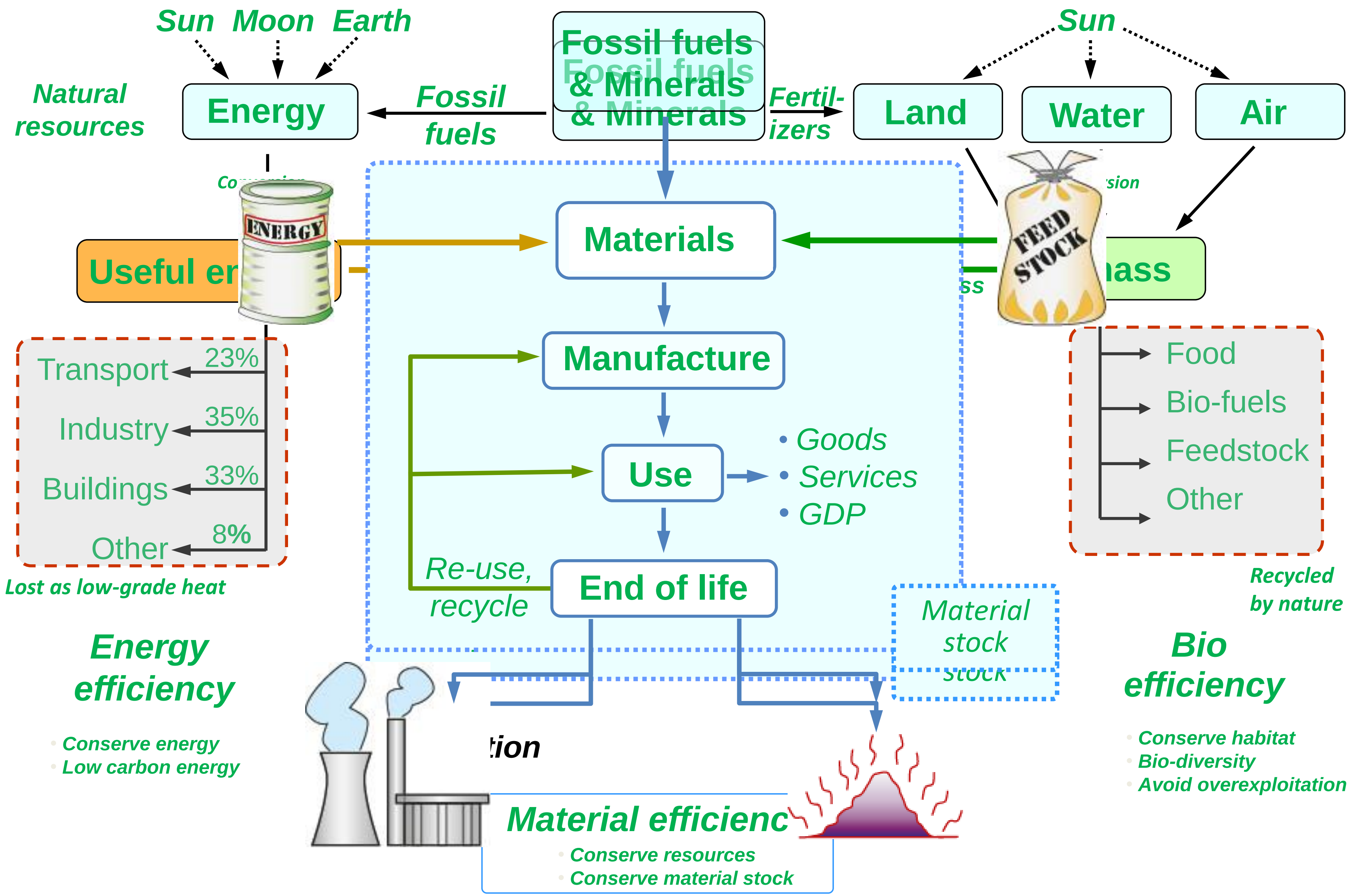
Sustainability

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

Report of the Brundtland commission of the UN, 1987

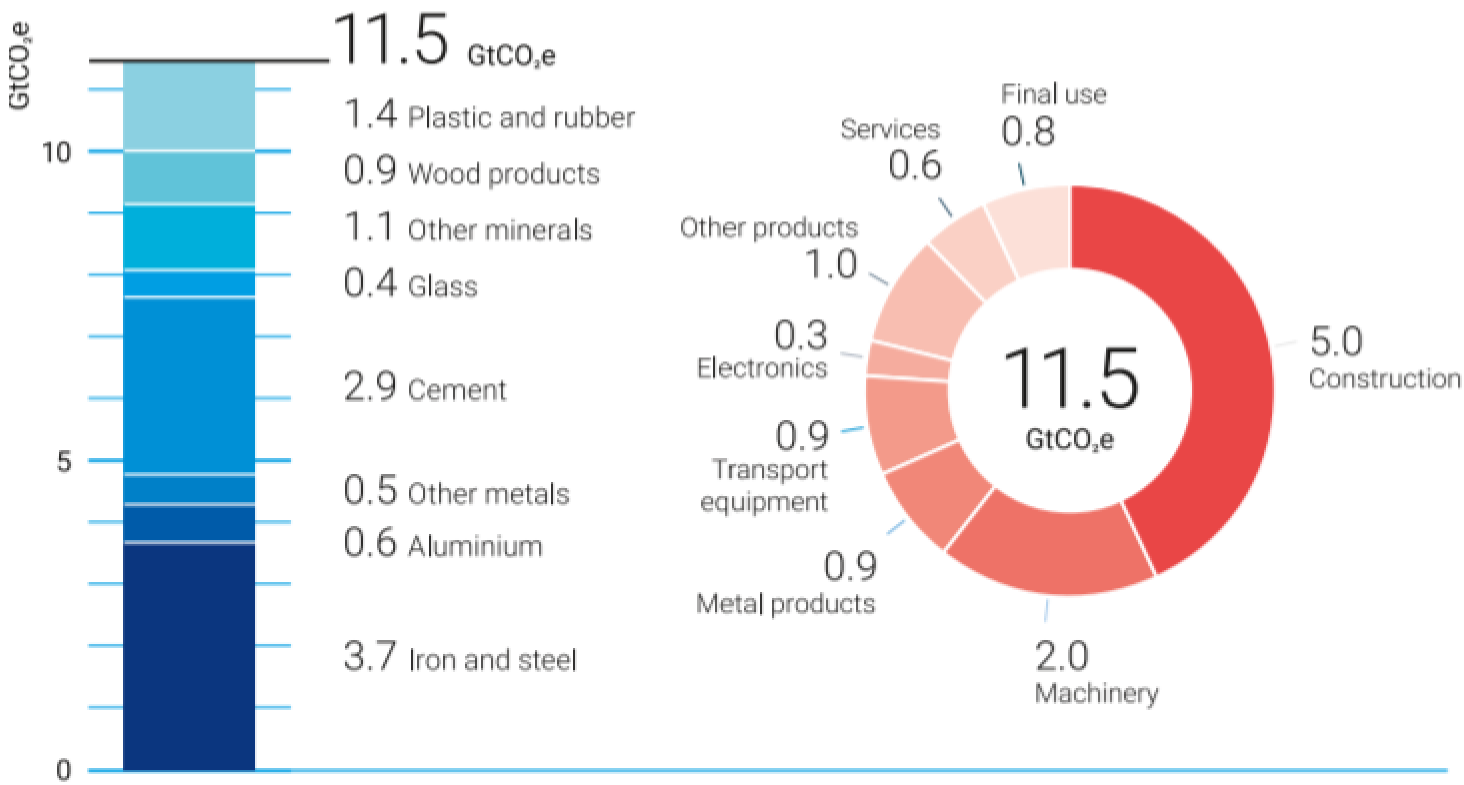
But where do materials fit in?

Sustainability in a Materials context



GHG emissions associated to materials production

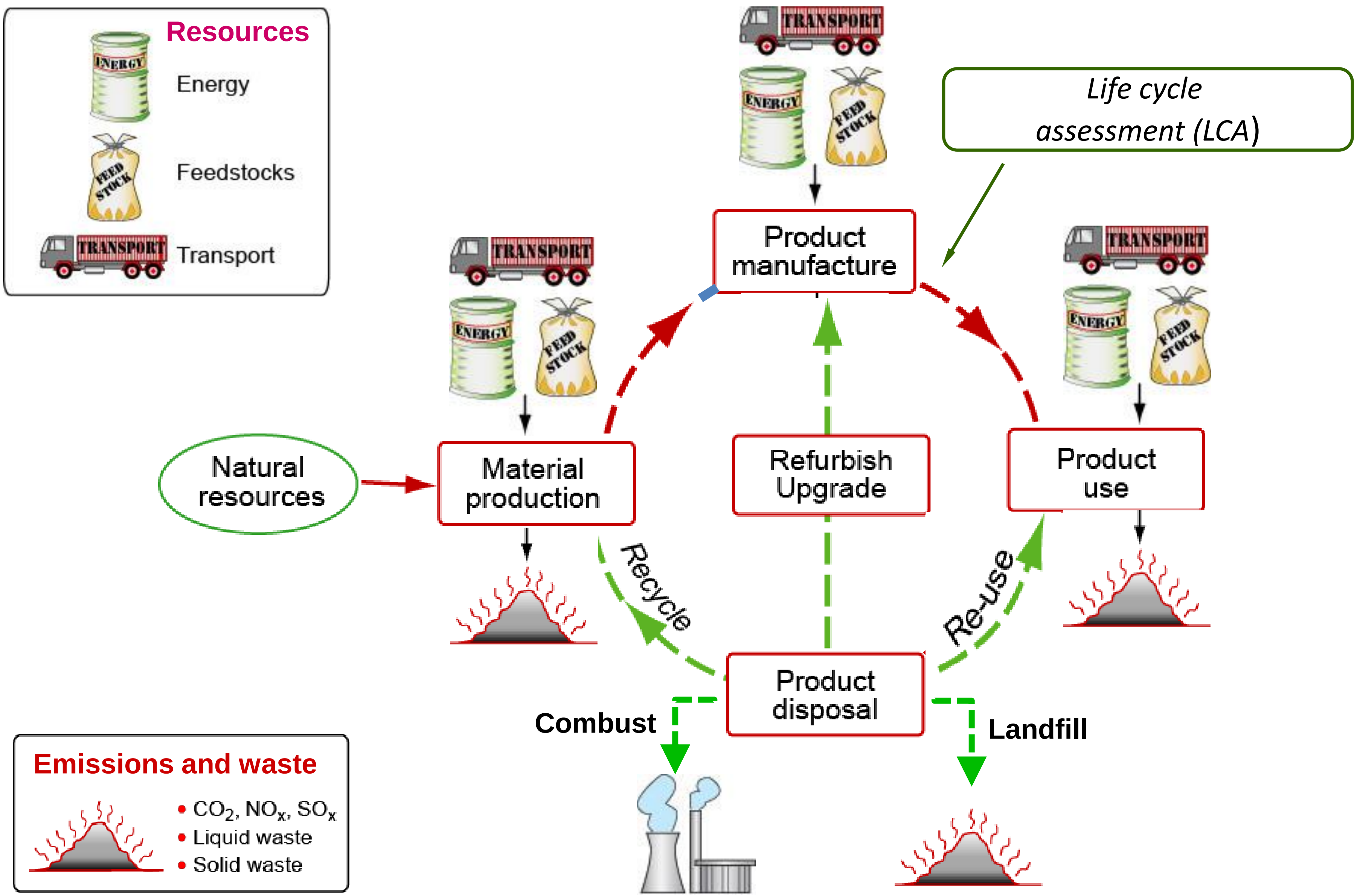
Figure 7.1. GHG emissions in $GtCO_2e$ associated with materials production by material (left) and by the first use of materials in subsequent production processes or final consumption (right)



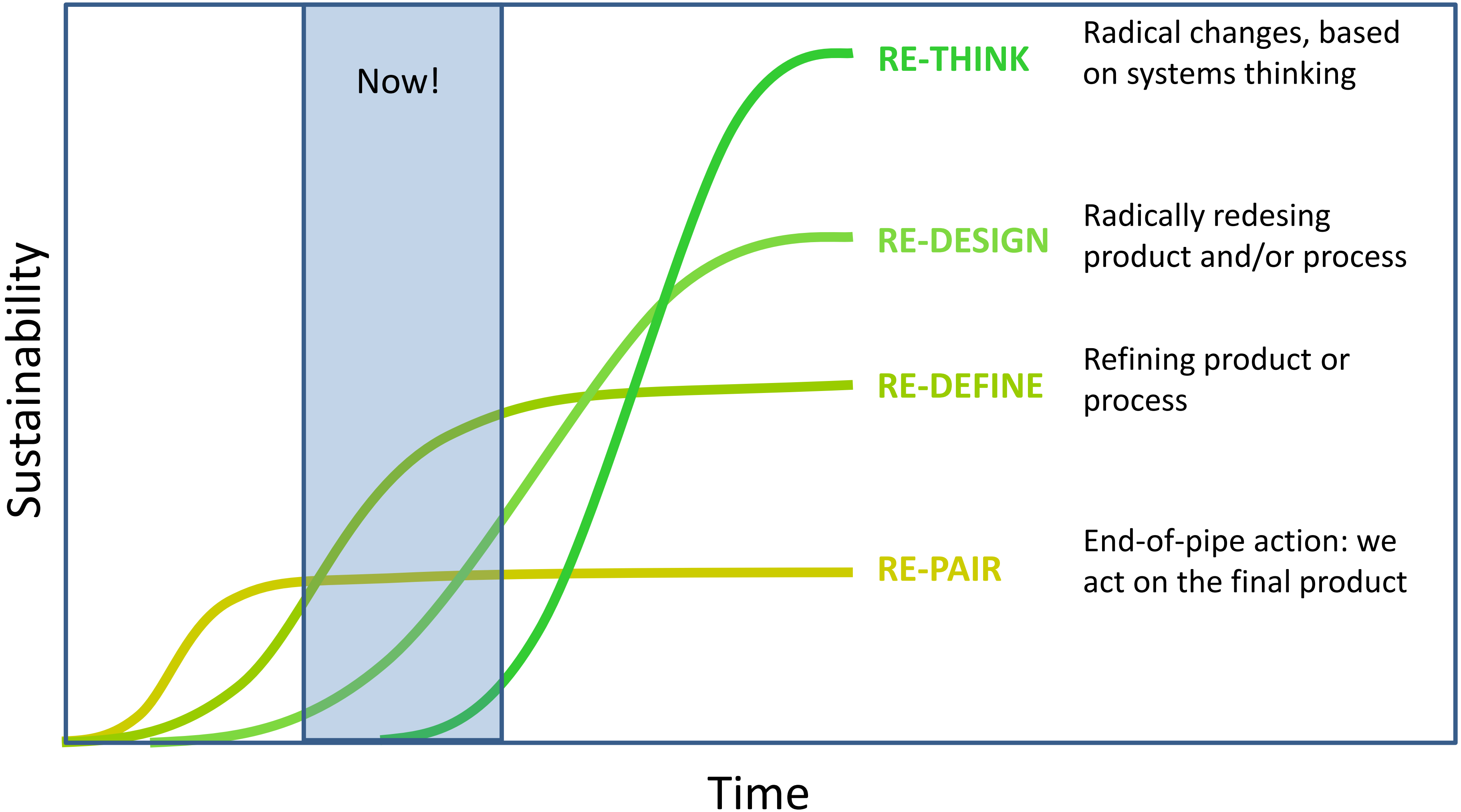
Note: The data excludes emissions from land-use change and credits for carbon storage.
Source: Based on Hertwich *et al.* (2019).

Emission Gap Report – UN 2019

The product life-cycle



Improving life-cycle sustainability



Life cycle assessment (LCA)

ISO 14040 series

PAS 2050

Typical LCA output

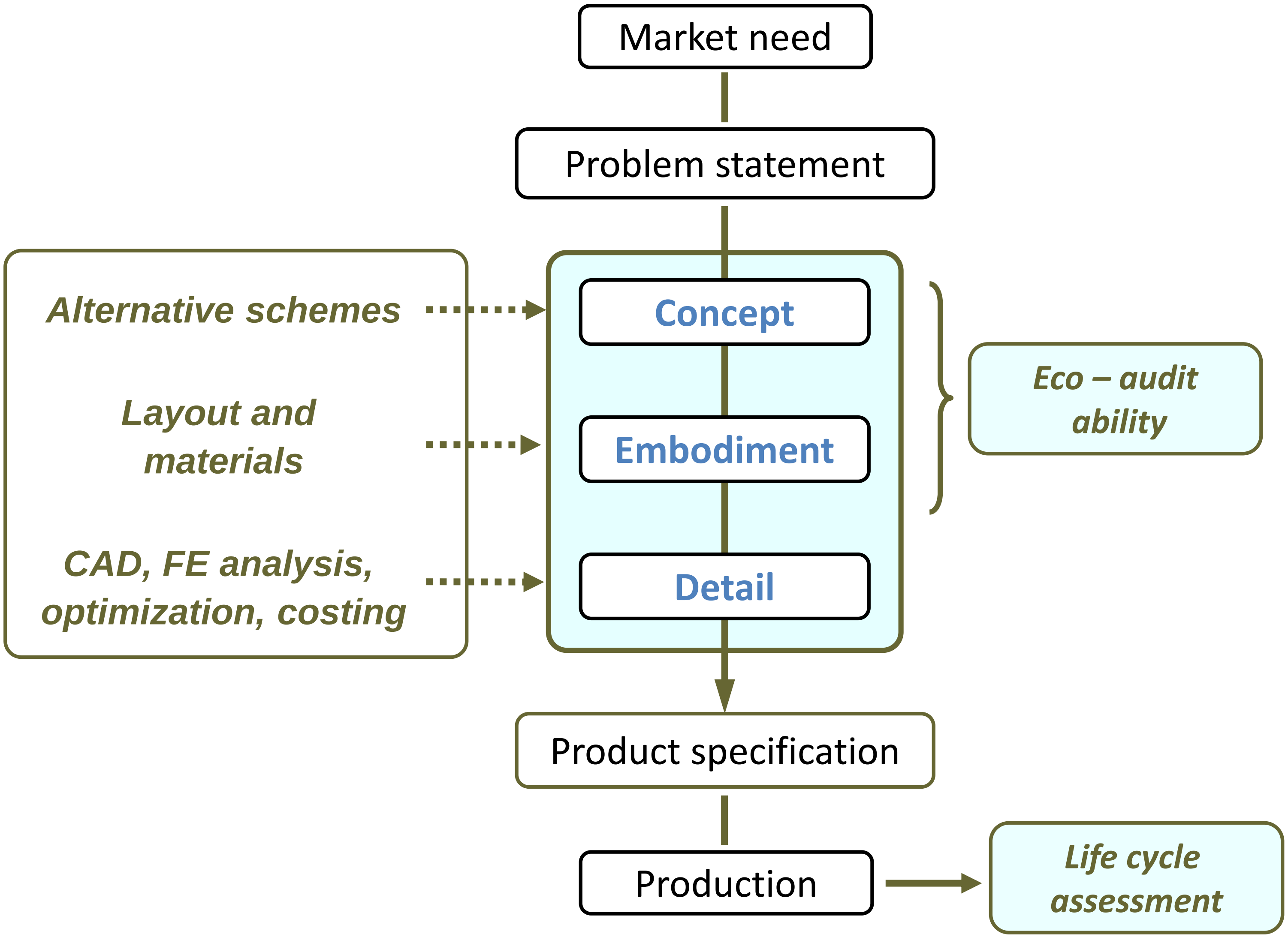
Aluminum cans, per 1000 units

Resource consumption	*Bauxite*	*59*	*kg*
	Oil fuels	*148*	*MJ*
	Electricity	*1572*	*MJ*
	Energy in feedstock	*512*	*MJ*
	Water use	*1149*	*kg*
Emissions inventory	*Emissions: CO_2*	*211*	*kg*
	Emissions: CO	*0.2*	*kg*
	Emissions: NO_x	*1.1*	*kg*
	Emissions: SO_x	*1.8*	*kg*
	Particulates	*2.47*	*kg*
Impact assessment	*Ozone depletion potential*	*0.2×10^{-9}*	
	Global warming potential	*1.1×10^{-9}*	
	Acidification potential	*0.8×10^{-9}*	
	Human toxicity potential	*0.3×10^{-9}*	

Roll up into an *"eco-indicator"* ?

- Full LCA *expensive*, and requires great *detail and skill* – and even then is subject to uncertainty
- How can a designer use these data?

Design guidance vs. product assessment

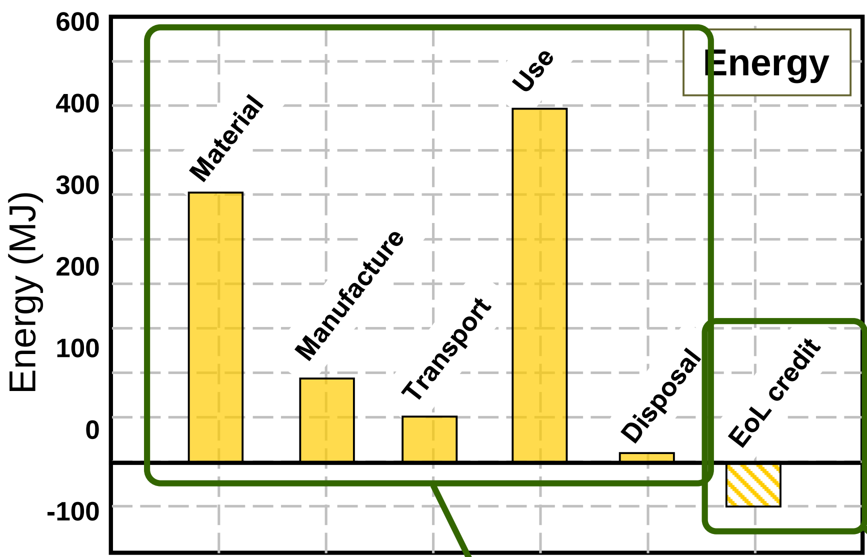


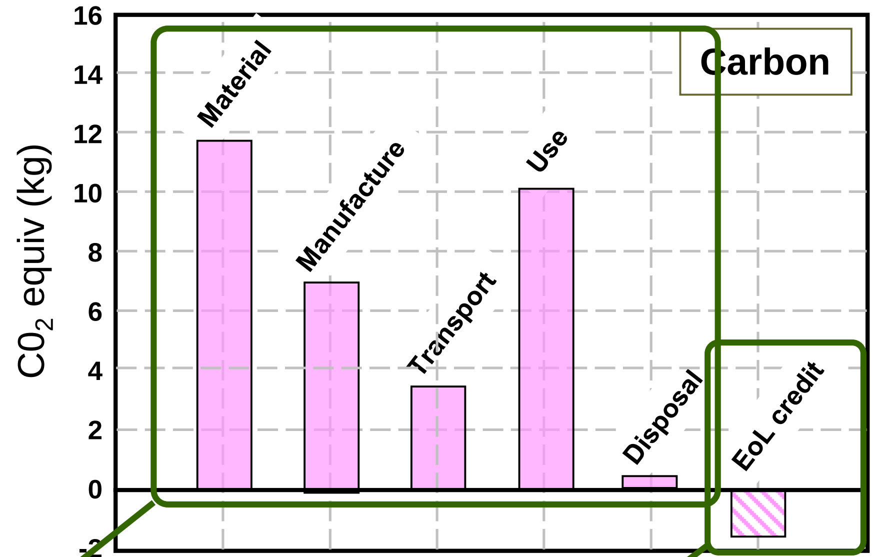
Eco-audit for design

Need: Fast **Eco-audit** with sufficient precision to guide decision-making

- **1 resource** – ***energy*** ***(oil equivalent)*** **1 emission** – ***CO_2 equivalent***

- **Distinguish life-phases**



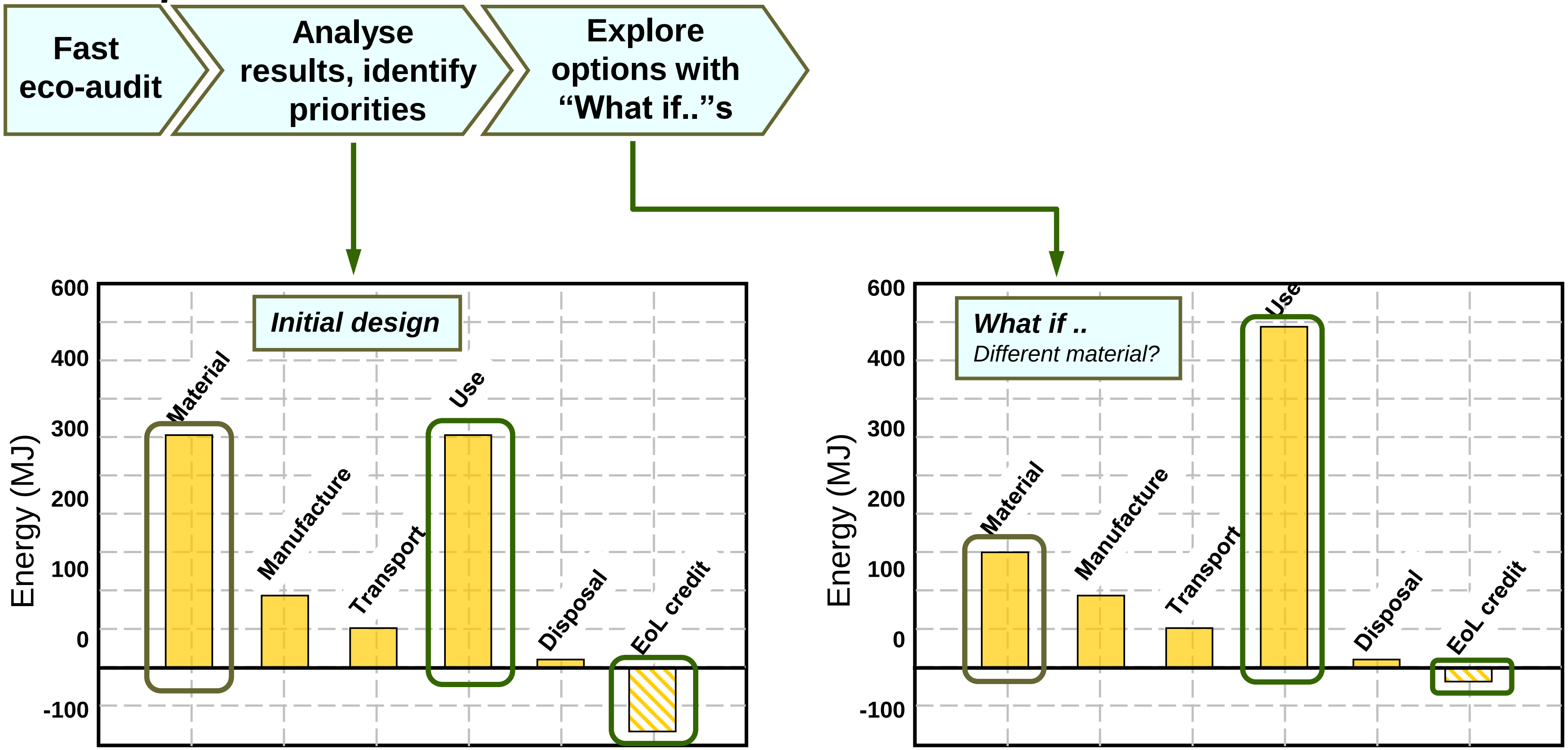


This is the life-energy and life-CO_2
(as prescribed in ISO 14040 and PAS 2050)

These are potential benefits
(could be recovered at end of life)

Eco-aware design: the strategy (1)

The steps



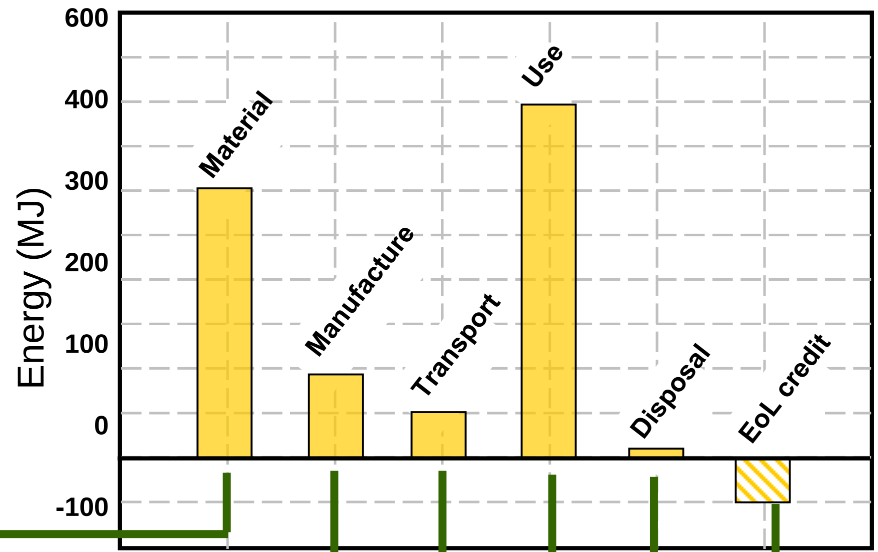
Eco-aware design: the strategy (2)

The steps

Look at the first three steps

Fast eco-audit → **Analyse results, identify priorities** → **Explore options with "What if.."s** → **Use CES to select new Materials and/or Processes** → **Recommend actions & assess potential savings**

Use eco-audit to indentify design objective



Material
Minimize:
- material in part
- embodied energy
- CO_2 / kg

Manufacture
Minimize:
- process energy
- CO_2/kg

Transport
Minimize:
- mass
- distance
- transport type

Use
Minimize:
- mass
- thermal loss
- electrical loss

End of life
Select:
- non-toxic materials
- recyclable materials

The CES Eco-audit tool

User inputs

User interface

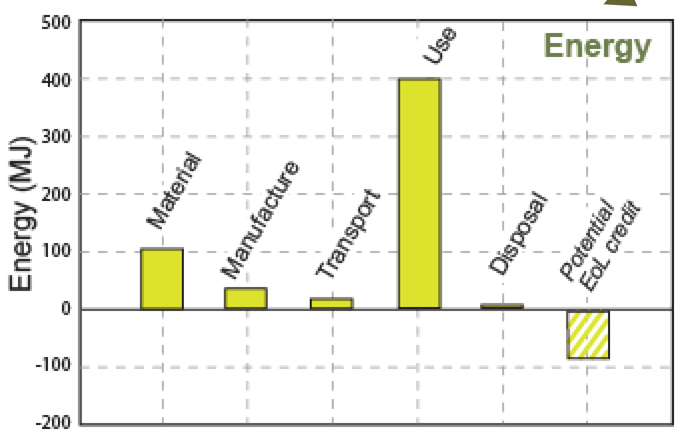
- ***Bill of materials***
- ***Manufacturing process***
- ***Transport needs***
- ***Duty cycle***
- ***End of life choice***

Data from CES

Eco database

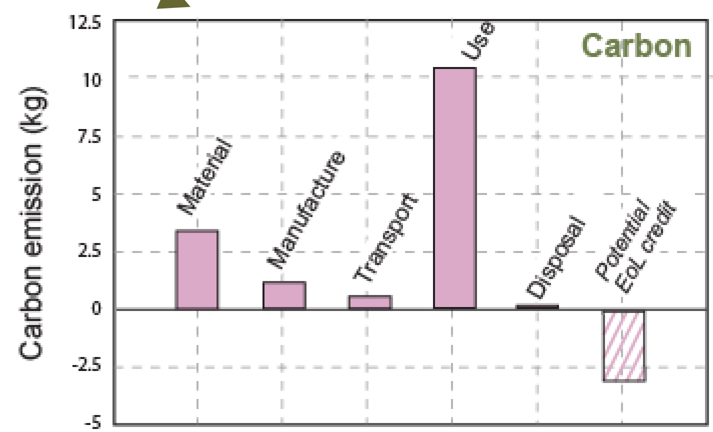
- ***Embodied energies***
- ***Process energies***
- ***CO_2 footprints***
- ***Unit transport energies***
- ***Recycling / combustion***

Eco audit model



Outputs

(including tabular data)



Typical record showing eco-properties

Database: CES EduPack 2010 Levels 1 & 2 Change...

Table: MaterialUniverse

Subset: Edu Level 2 with Eco properties

- MaterialUniverse
  - Ceramics and glasses
  - Hybrids: composites, foams, natural materials
  - Metals and alloys
  - Polymers and elastomers
    - Elastomers
    - Polymers
      - Thermoplastics
        - Acrylonitrile butadiene styrene (ABS)
        - Cellulose polymers (CA)
        - Ionomer (I)
        - Polyamides (Nylons, PA)
        - Polycarbonate (PC)
        - Polyetheretherketone (PEEK)
        - Polyethylene (PE)
        - Polyethylene terephthalate (PET)
        - Polyhydroxyalkanoates (PHA, PHB)
        - Polylactide (PLA)
        - Polymethyl methacrylate (Acrylic, PMMA)
        - Polyoxymethylene (Acetal, POM)
        - Polypropylene (PP)
        - Polystyrene (PS)
        - Polytetrafluoroethylene (Teflon, PTFE)
        - Polyurethane (tpPUR)
        - Polyvinylchloride (tpPVC)
        - Starch-based thermoplastics (TPS)
      - Thermosets

Polyethylene terephthalate (PET)

Layout: Edu Level 2 with Eco properties Show/Hide

Machinability	3	-	4	
Weldability	5			

Geo-economic data for principal component

Annual world production	9e6	-	9.2e6	tonne/yr
Reserves	* 2.58e8	-	2.6e8	tonne

Primary material production: energy, CO2 and water

Embodied energy, primary production	79.6	-	88	MJ/kg
CO2 footprint, primary production	2.21	-	2.45	kg/kg
Water usage	* 14.7	-	44.2	l/kg
Eco-indicator 95	380			millipoints/kg
Eco-indicator 99	276			millipoints/kg

Material processing: energy

Polymer molding energy	* 20.4	-	22.5	MJ/kg
Polymer extrusion energy	* 7.92	-	8.73	MJ/kg
Polymer machining energy (per unit wt removed)	* 2.03	-	2.24	MJ/kg

Material processing: CO2 footprint

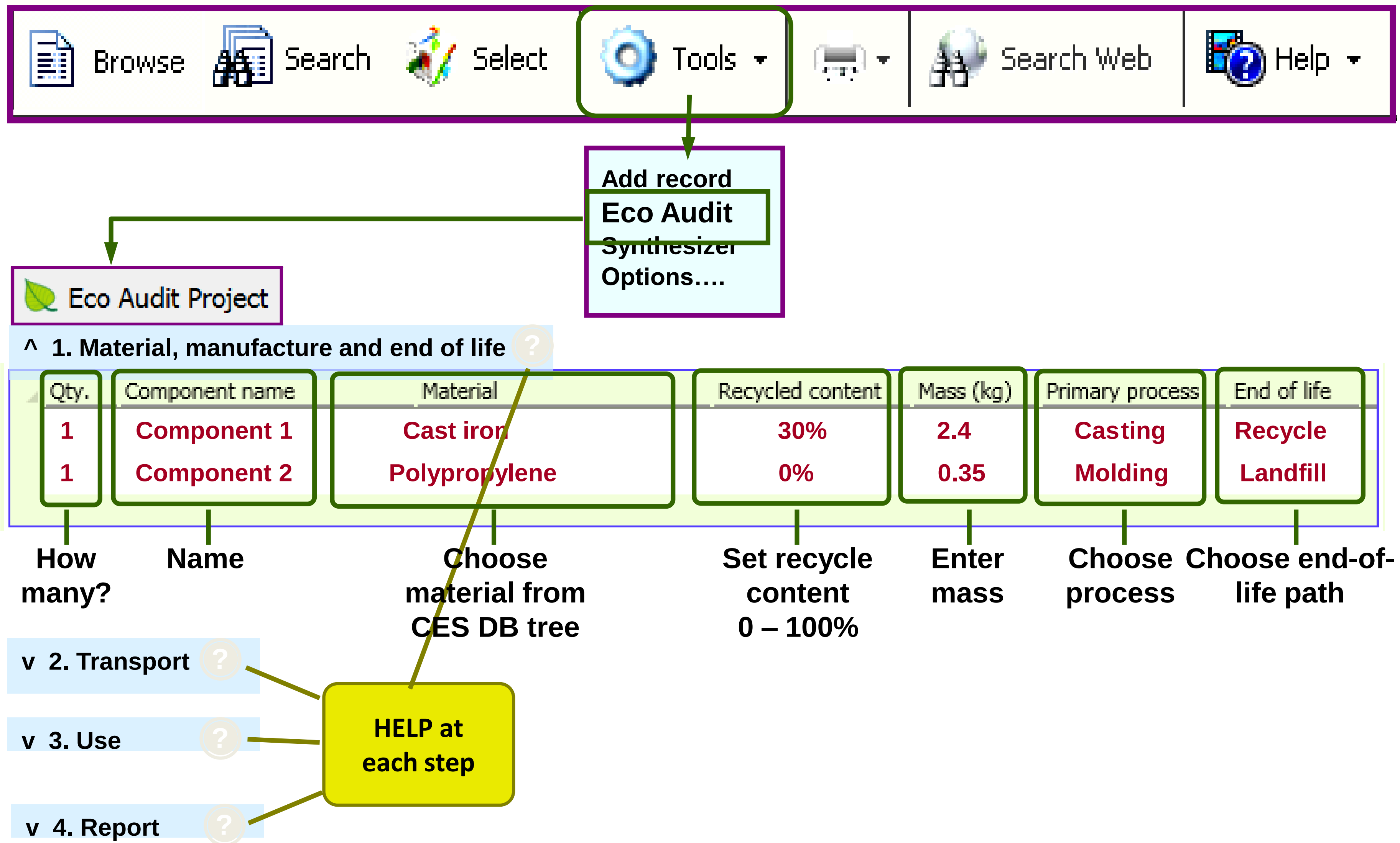
Polymer molding CO2	* 1.63	-	1.8	kg/kg
Polymer extrusion CO2	* 0.633	-	0.698	kg/kg
Polymer machining CO2 (per unit wt removed)	* 0.162	-	0.179	kg/kg

Material recycling: energy, CO2 and recycle fraction

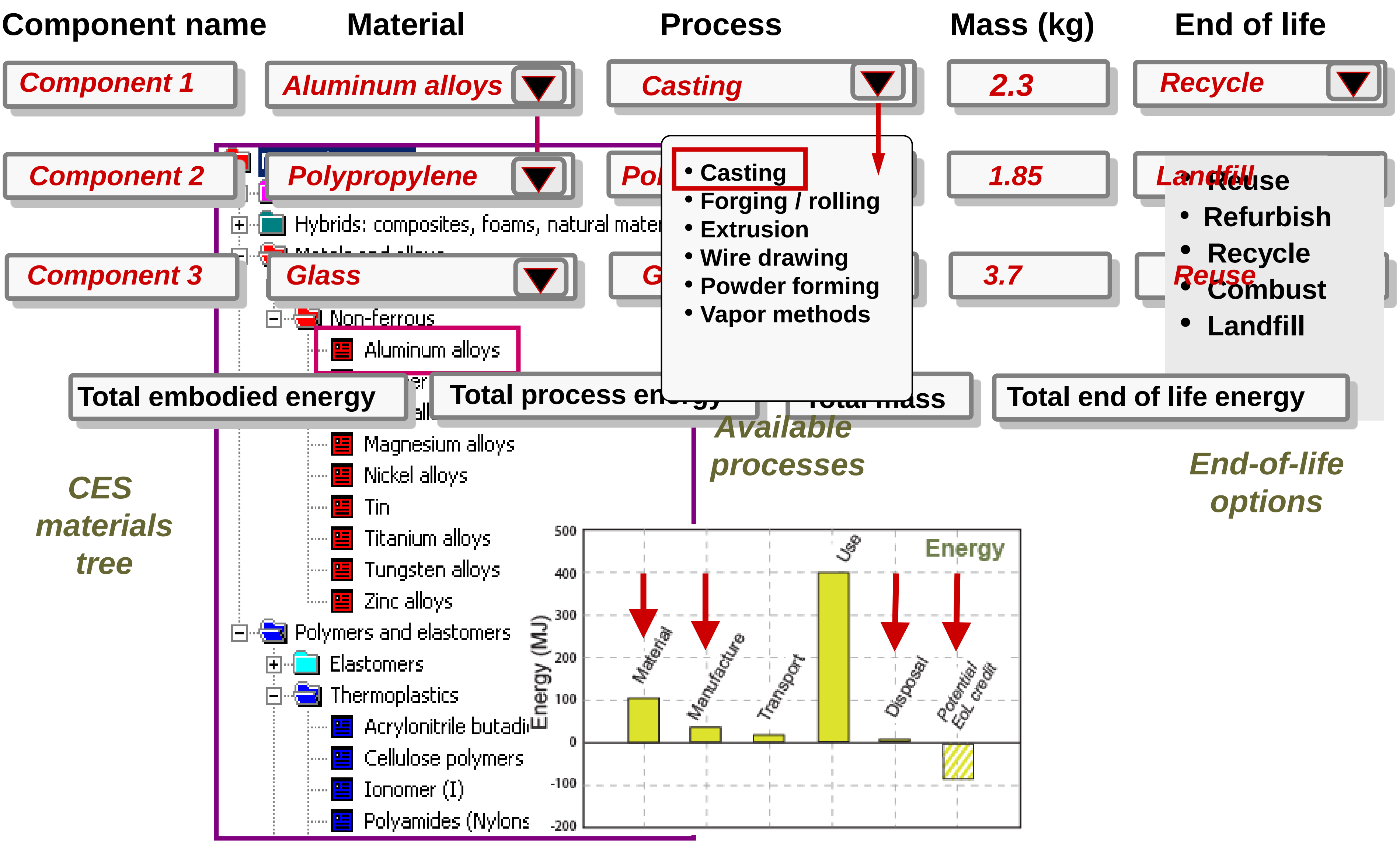
Recycle	✓			
Embodied energy, recycling	33.4	-	37	MJ/kg
CO2 footprint, recycling	0.928	-	1.03	kg/kg
Recycle fraction in current supply	20	-	22	%
Downcycle	✓			
Combust for energy recovery	✓			
Heat of combustion (net)	* 23	-	24.2	MJ/kg
Combustion CO2	* 2.24	-	2.35	kg/kg
Landfill	✓			
Biodegrade	✗			
Toxicity rating	Non-toxic			
A renewable resource?	✗			

Environmental notes

The simple Audit tool: Levels 1, 2 and 3



Material and process energy / CO_2



Transport

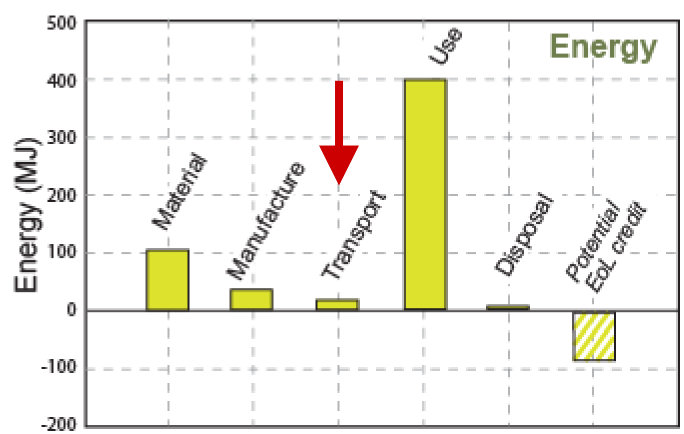
Transport stage | **Transport type** | **Distance (km)**

Transport stage	Transport type	Distance (km)
Stage 1	*32 tonne truck*	*350*
Stage 2		*12000*

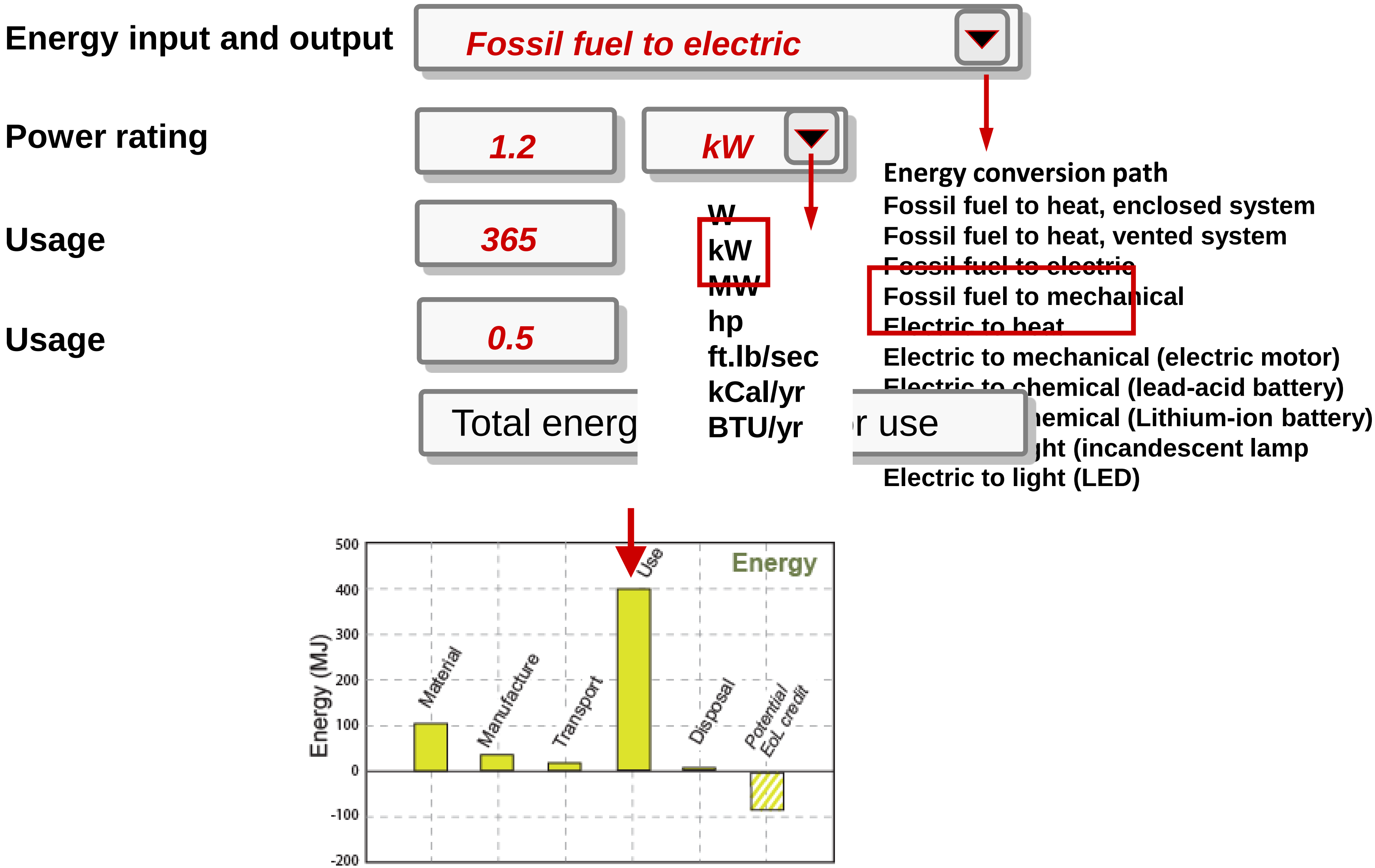
- Sea freight
- River / Canal freight
- Rail freight
- 32 tonne truck
- 14 tonne truck
- Light goods vehicle
- Air freight - short haul
- Air freight - long haul
- Helicopter (Eurocopter AS 35)

Transport energy

Transport CO_2



Use phase – static mode



Example: Bottled water (100 units)

- 1 litre PET bottle with PP cap
- Blow moulded
- Filled in France, transported 550 km to UK
- Refrigerated for 2 days, then drunk

Number	Name	Material	Process	Mass (kg)	End of life
100	Bottles	PET	Molding	0.04	Recycle
100	Caps	Polyprop	Molding	0.001	Recycle
100	Water			1.0	

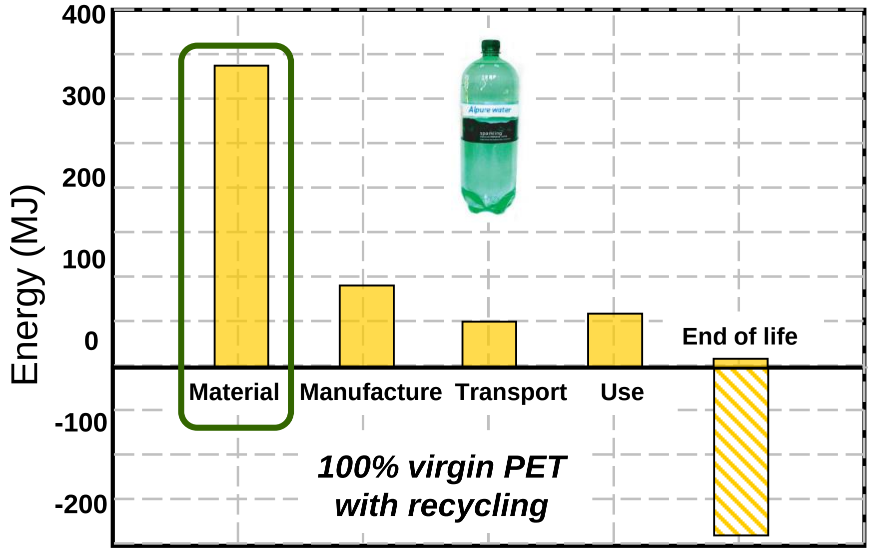
Transport

Stage 1	14 tonne truck	550 km

Use - refrigeration

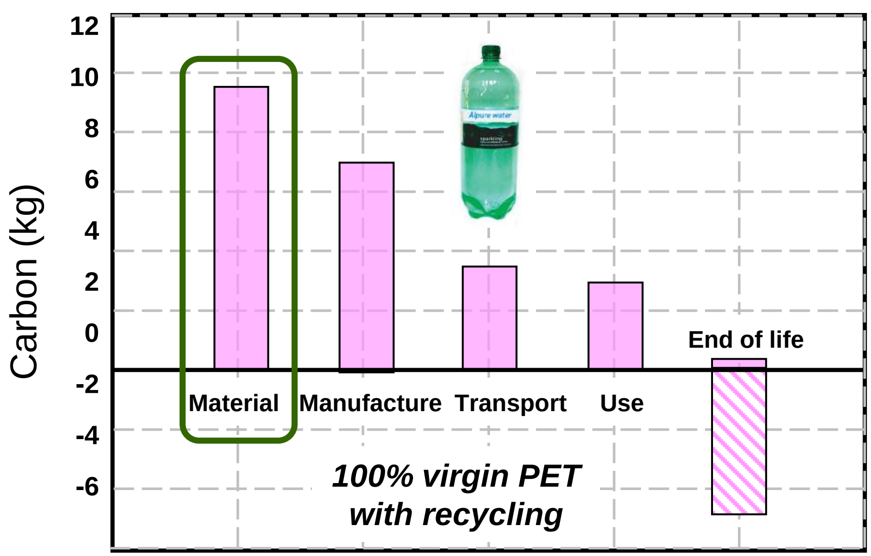
Fossil to electric	0.12 kW	2 days	24 hrs/day

The output: drink container



The audit reveals the most energy and carbon intensive steps…

… and allows rapid "What if…"



PET ***Glass ?***

"What if…": Change the materials

- 1 litre glass bottle with aluminum cap
- Glass moulded
- Filled in France, transported 550 km to UK
- Refrigerated for 2 days, then drunk

Number	Name	Material	Process	Mass (kg)	End of life
100	Bottles	Soda glass	Glass mold	0.45	Recycle
100	Caps	Aluminum	Rolling	0.002	Recycle
100	Water			1.0	

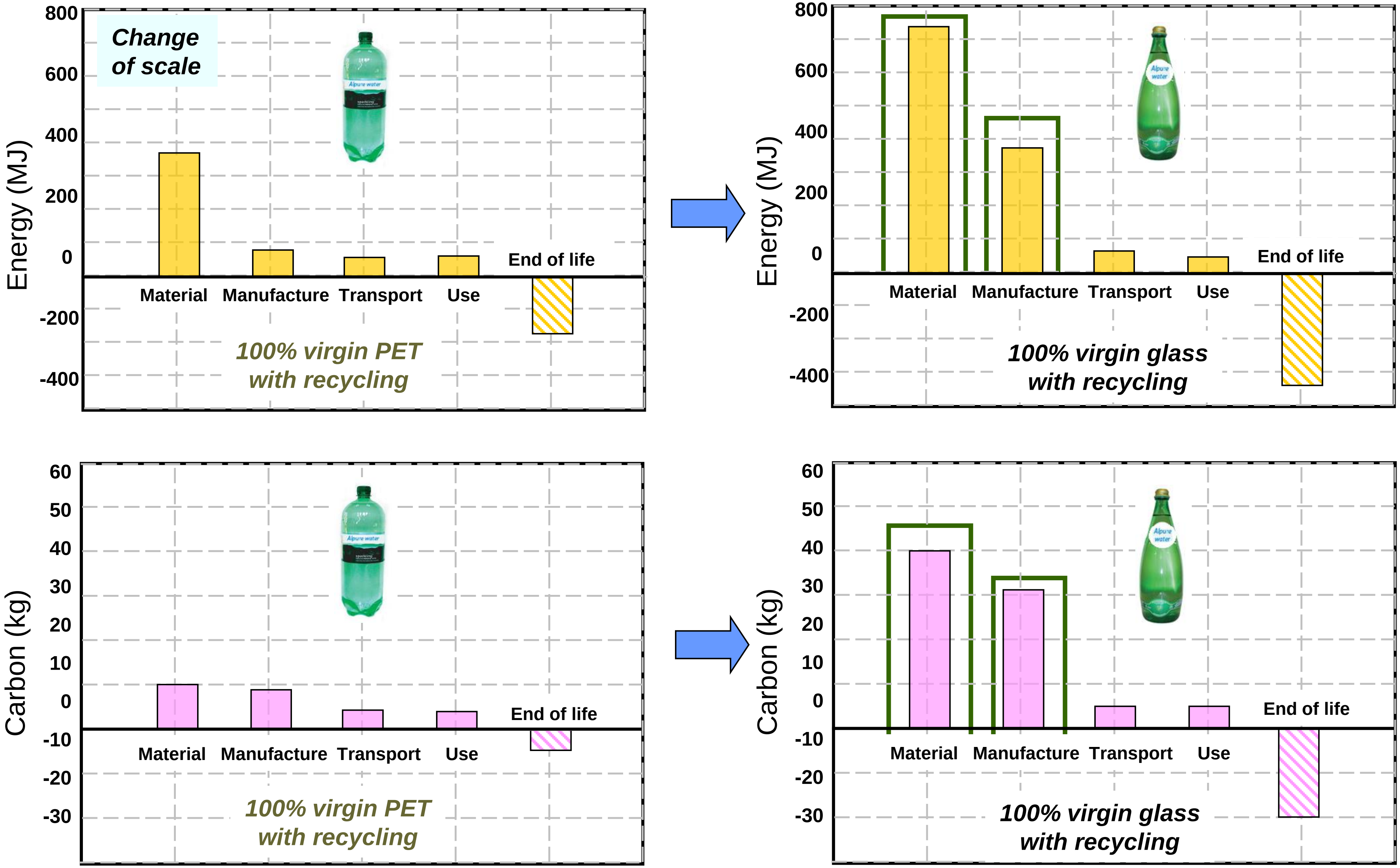
Transport

Stage 1	14 tonne truck	550 km

Use - refrigeration

Fossil to electric	0.12 kW	2 days	24 hrs/day

“What if…”: Glass bottle replacing PET



"What if…": Combust for energy instead of recycle

- 1 litre PET bottle with PP cap
- Blow moulded
- Filled in France, transported 550 km to UK
- Refrigerated for 2 days, then drunk

Number	Name	Material	Process	Mass (kg)	End of life
100	Bottles	PET	Molding	0.04	Combust
100	Caps	Polyprop	Molding	0.001	Combust
100	Water			1.0	

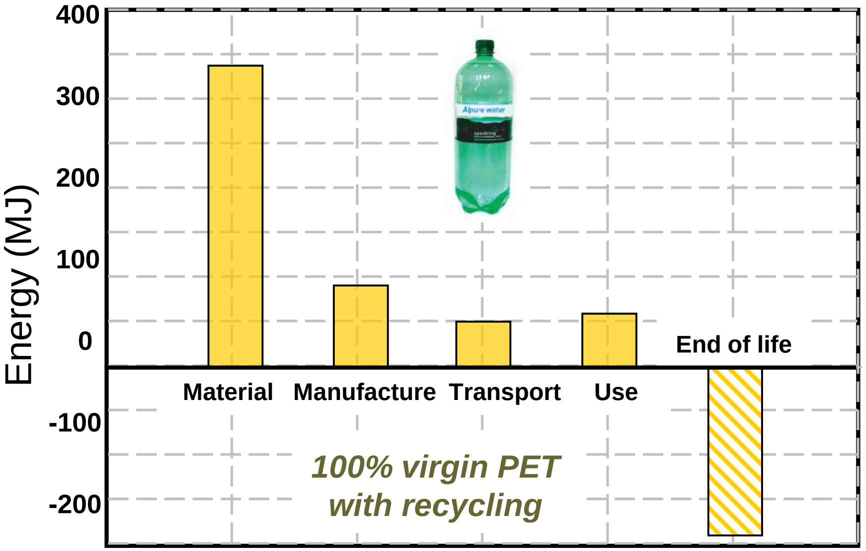
Transport

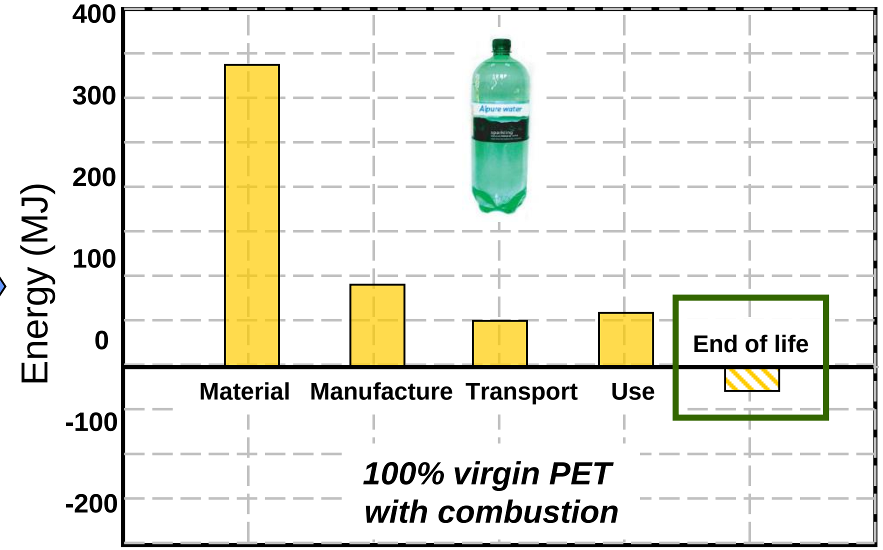
Stage 1	14 tonne truck	550 km

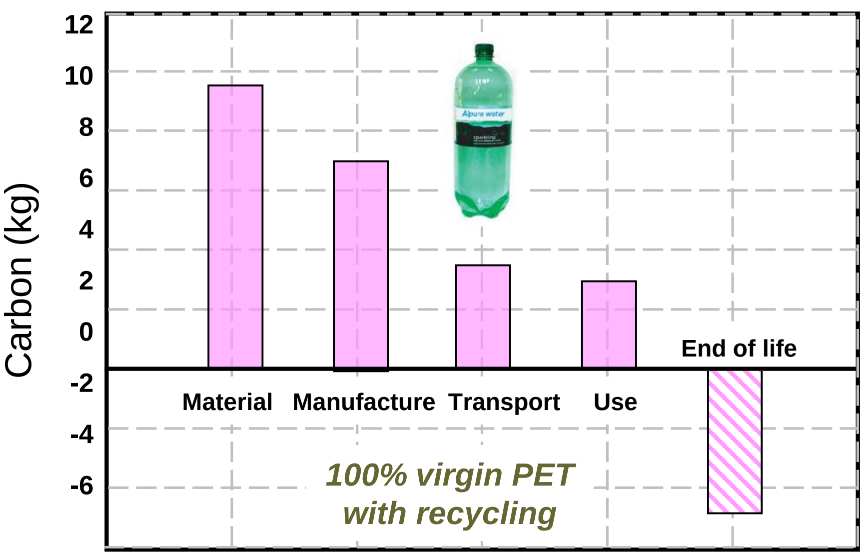
Use - refrigeration

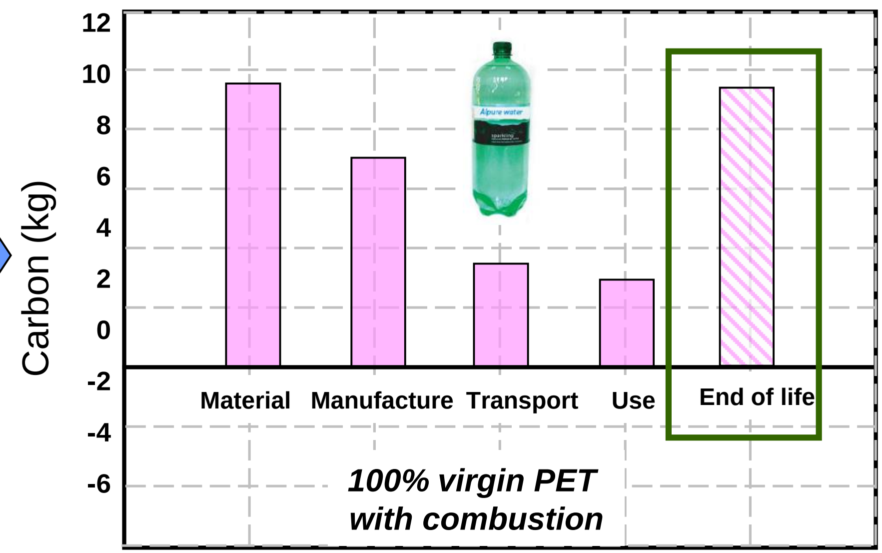
Fossil to electric	0.12 kW	2 days	24 hrs/day

“What if…”: Combust instead of recycle

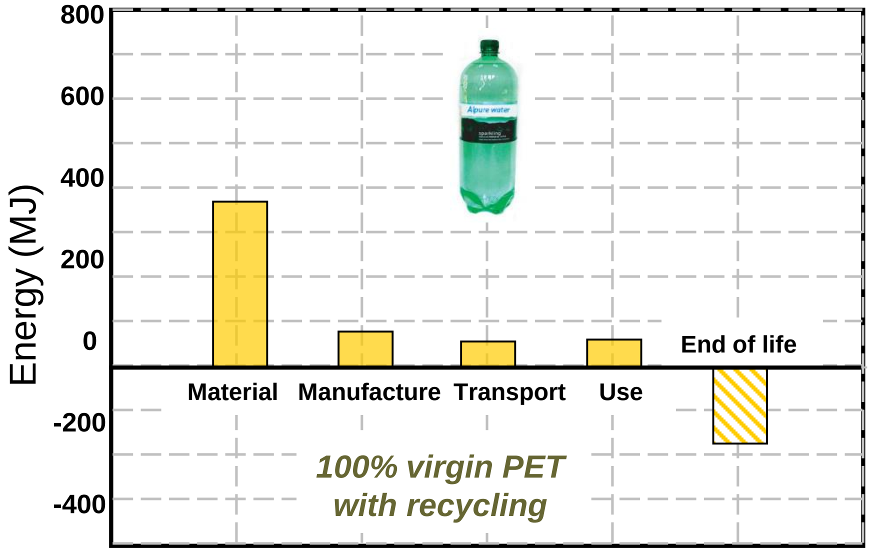


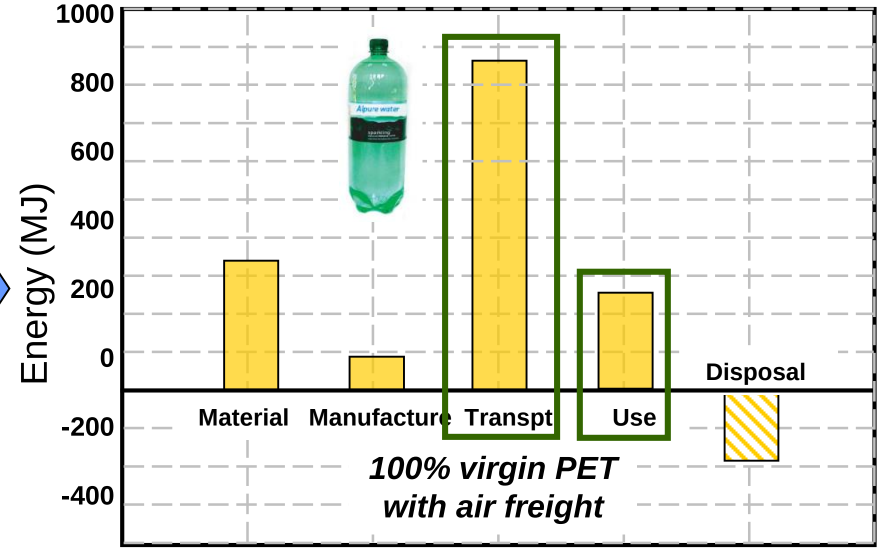


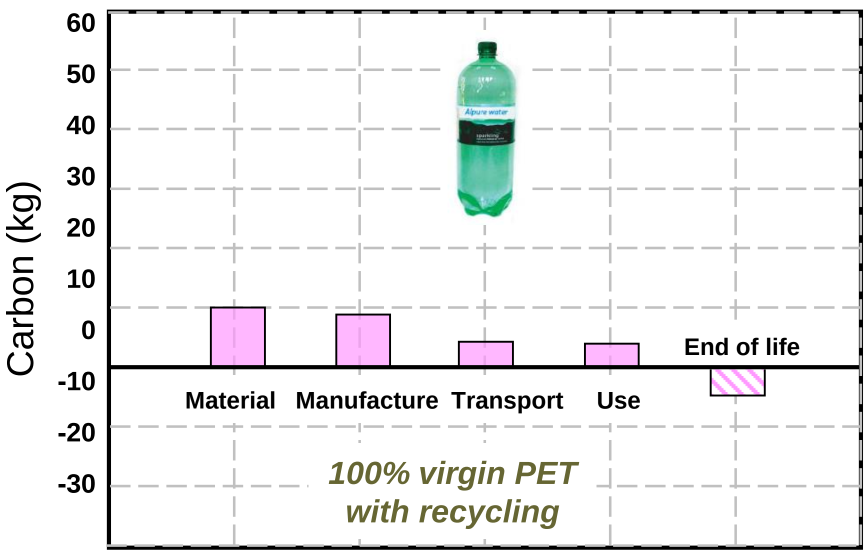


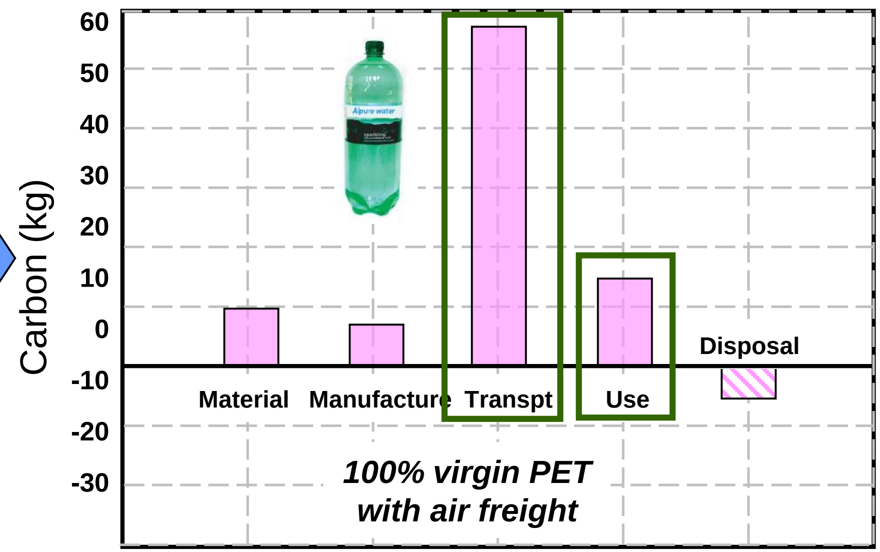


"What if…": Ship by air freight, refrigerate 10 days







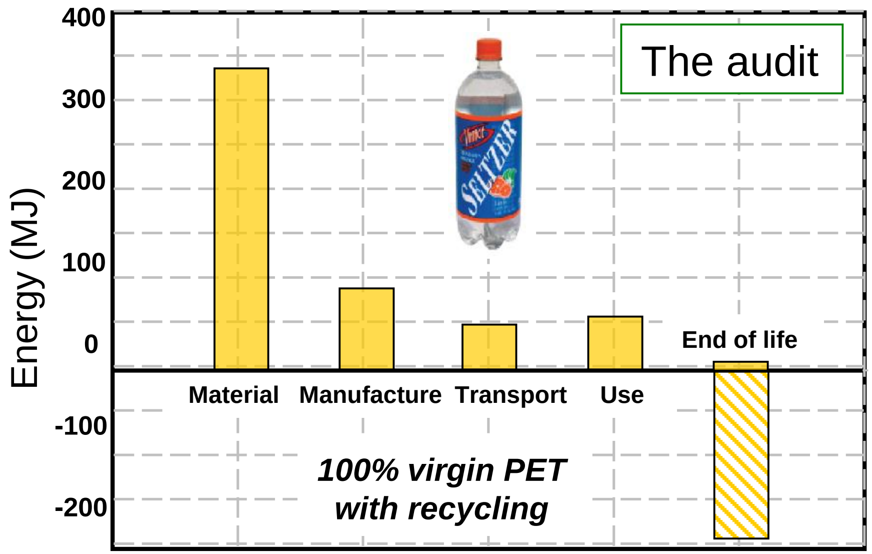


Eco-informed selection: the strategy

The steps

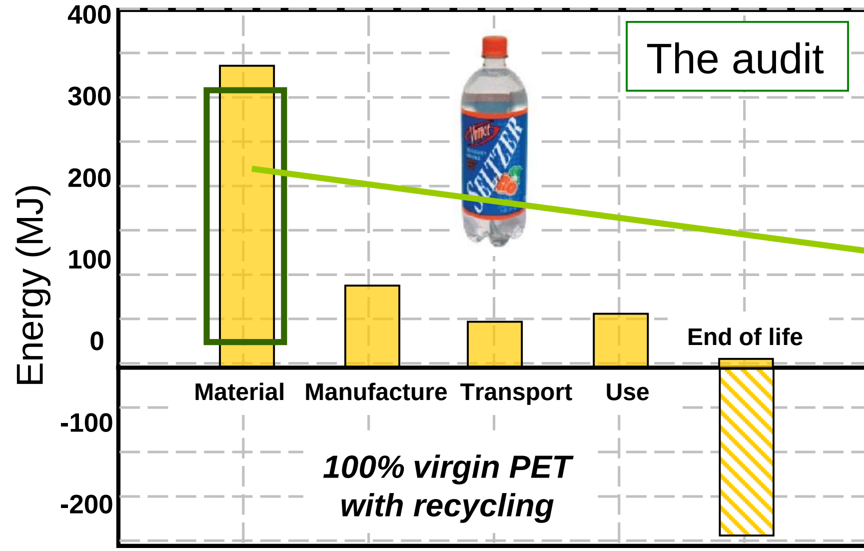
Fast eco-audit → **Analyse results, Identify priorities** → **Explore options with "What if.."s** → **Use CES EduPack to select new Materials and/or Processes** → **Recommend actions & assess potential savings**

Use eco-audit to indentify design objective



Back to the initial example: materials phase dominates

Eco-selection for a fizzy drink bottle



Material
dominates

Minimize embodied energy

Translation

Design brief

Improve green credentials of bottle

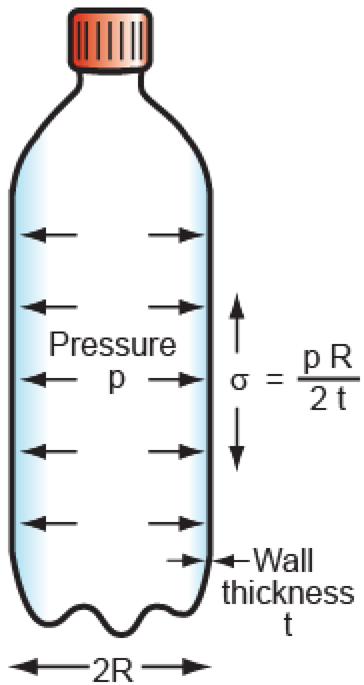
Constraints

- **Able to be molded**
- **Transparent / translucent**
- **Able to contain pressure**

Objectives

- **Minimize embodied energy of bottle**
- **Minimize material cost of bottle**

Modelling the bottle



R= Bottle radius
t = Thickness of bottle wall
p = Internal pressure
σ_y = Yield strength of material
ρ = Density of material
H_m = Embodied energy of material/kg
E = Embodied energy/m^2 of wall
C_m = Material cost per kg

Cylindrical pressure vessel

- Circumferential stress $\sigma = \frac{pR}{t} < \sigma_y$
- Embodied energy per unit area of wall

$$E = t H_m \rho = pR \frac{H_m \rho}{\sigma_y}$$

Embodied energy / kg of material

- Find material with lowest energy, seek largest

$$\frac{\sigma_y}{H_m \rho}$$

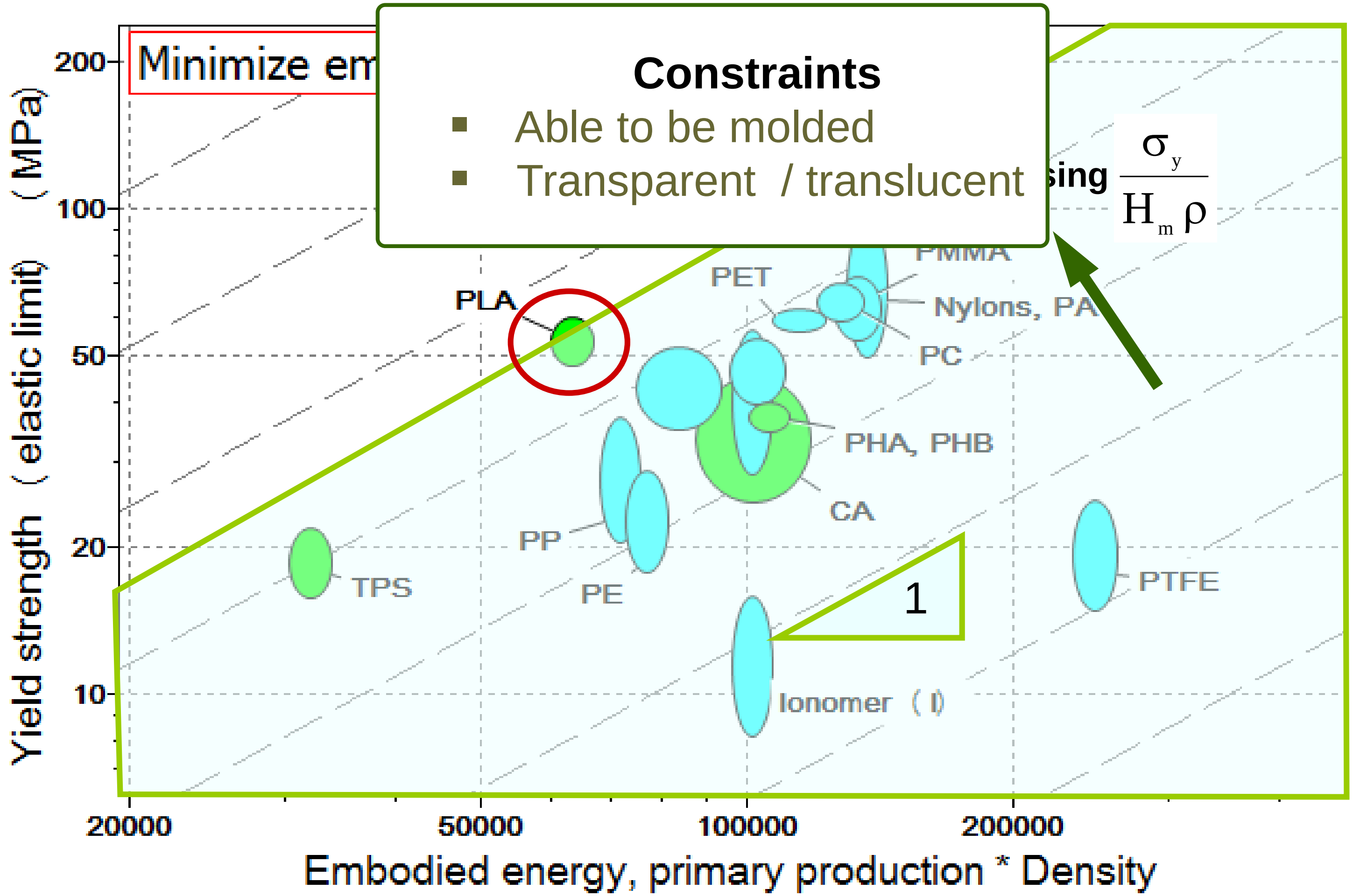
- Find material with lowest cost, seek largest

$$\frac{\sigma_y}{C_m \rho}$$

Price / kg of material

Selection to minimize embodied energy

First apply constraints, then use index to optimize choice

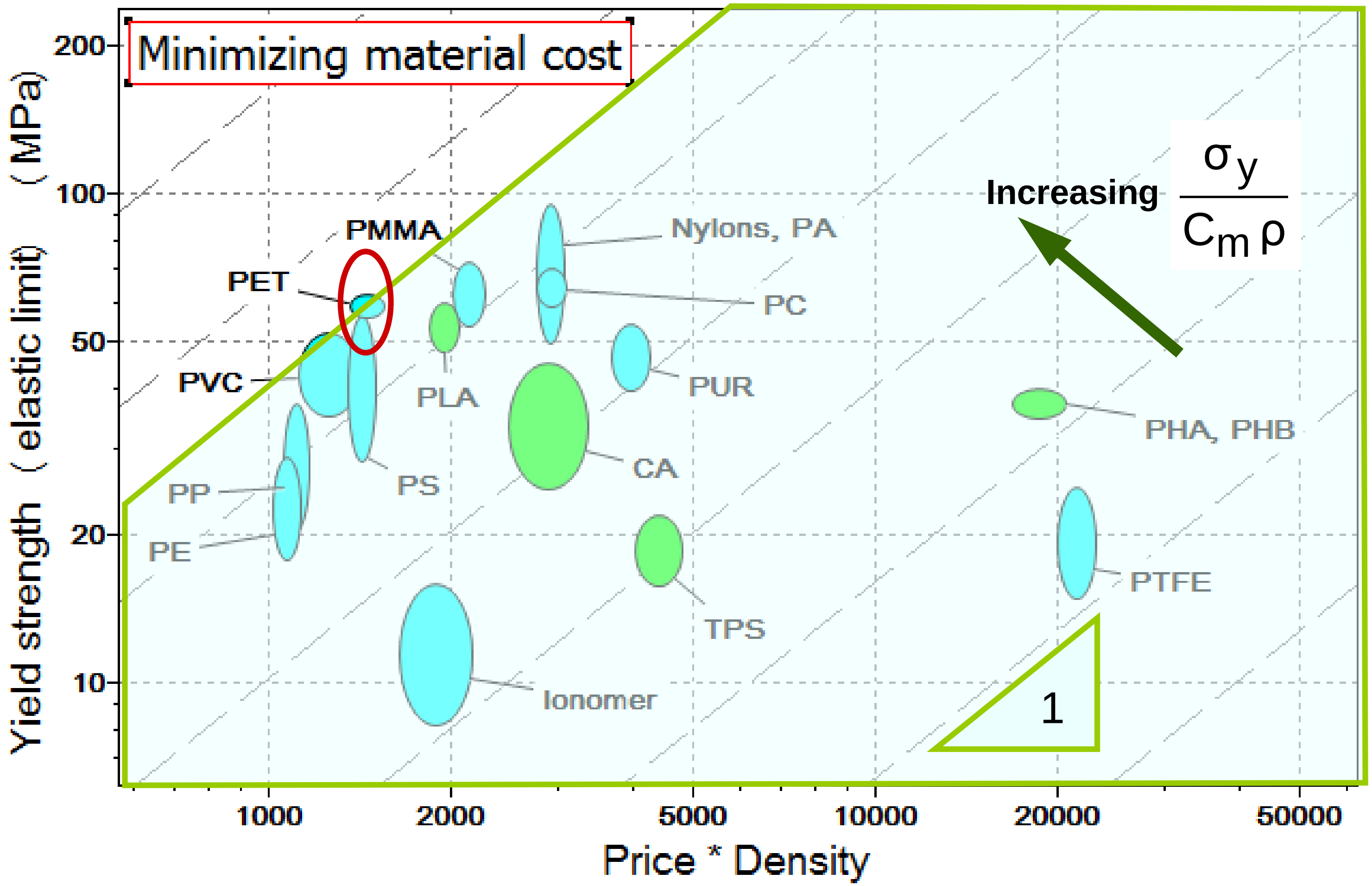


Bio-polymers are colored green

PLA meets the constraints at lowest embodied energy

Selection to minimize cost

Can't ignore cost



Bio-polymers are colored green

PET meets the constraints at lowest cost

Another example: Jug kettle

2 kW jug kettle

- Made SE Asia
- Air freight to UK
- Life: 3 years

Bill of materials and processes

Qty.	Component name	Material	Recycled content	Mass (kg)	Primary process	End of life
1	Kettle body	Polypropylene (PP)	Virgin (0%)	0.86	Polymer molding	Recycle
1	Heating element	Nickel-chromium alloys	Virgin (0%)	0.026	Wire drawing	Recycle
1	Casing, heating element	Stainless steel	Virgin (0%)	0.09	Rough rolling, forging	Recycle
1	Internal insulation	Alumina	Virgin (0%)	0.03	Incl. in material value	Landfill
1	Thermostat	Copper alloys	Virgin (0%)	0.02	Rough rolling, forging	Recycle
1	Plug body	Phenolics	Virgin (0%)	0.037	Polymer molding	Landfill
1	Plug pins	Brass	Virgin (0%)	0.03	Extrusion, foil rolling	Recycle
1	Cable sheath, 1 meter	Natural rubber (NR)	Virgin (0%)	0.06	Polymer molding	Landfill
1	Cable core, 1 meter	Copper	Virgin (0%)	0.015	Wire drawing	Recycle
1	Packaging, foam	Rigid Polymer Foam (MD)	Virgin (0%)	0.015	Polymer molding	Landfill
1	Packaging, cardboard	Paper and cardboard	Virgin (0%)	0.125	Incl. in material value	Recycle
1	Residual components	Polycarbonate (PC)	Virgin (0%)	0.04	Polymer molding	Downcycle

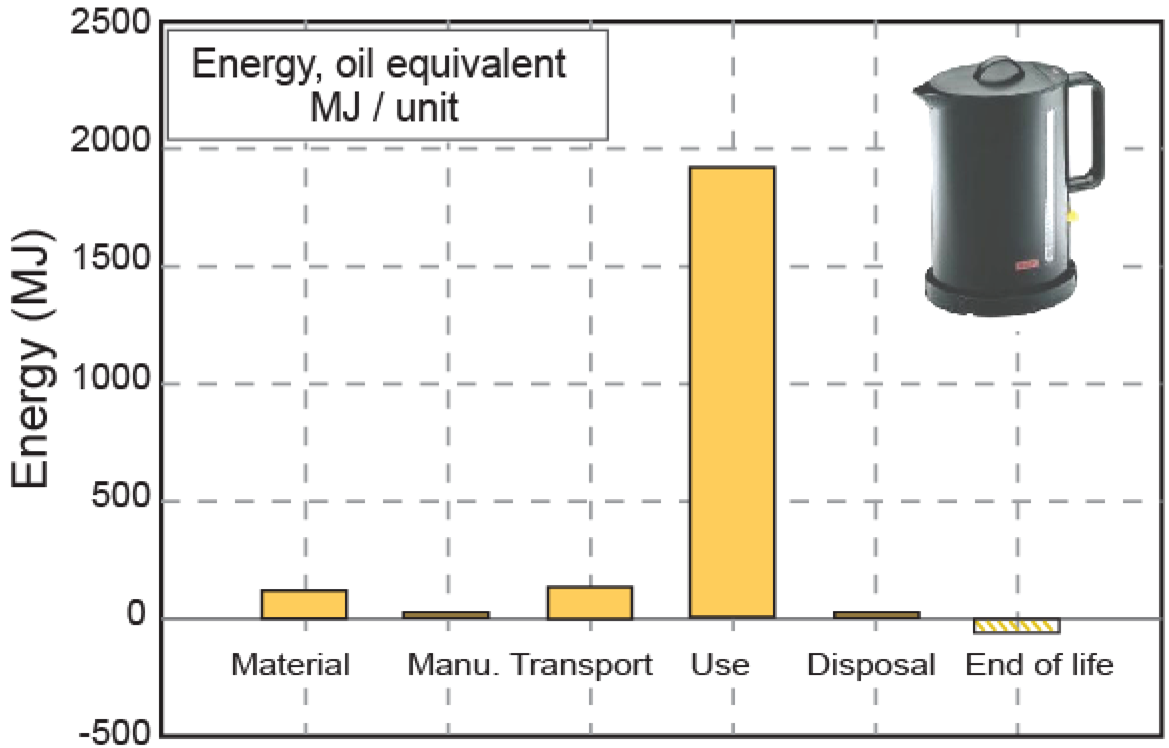
Transport

- 12,000 km, air freight
- 250 km 14 tonne truck

Use

- 6 minutes per day
- 300 days per year
- 3 years

Eco audit: the jug kettle

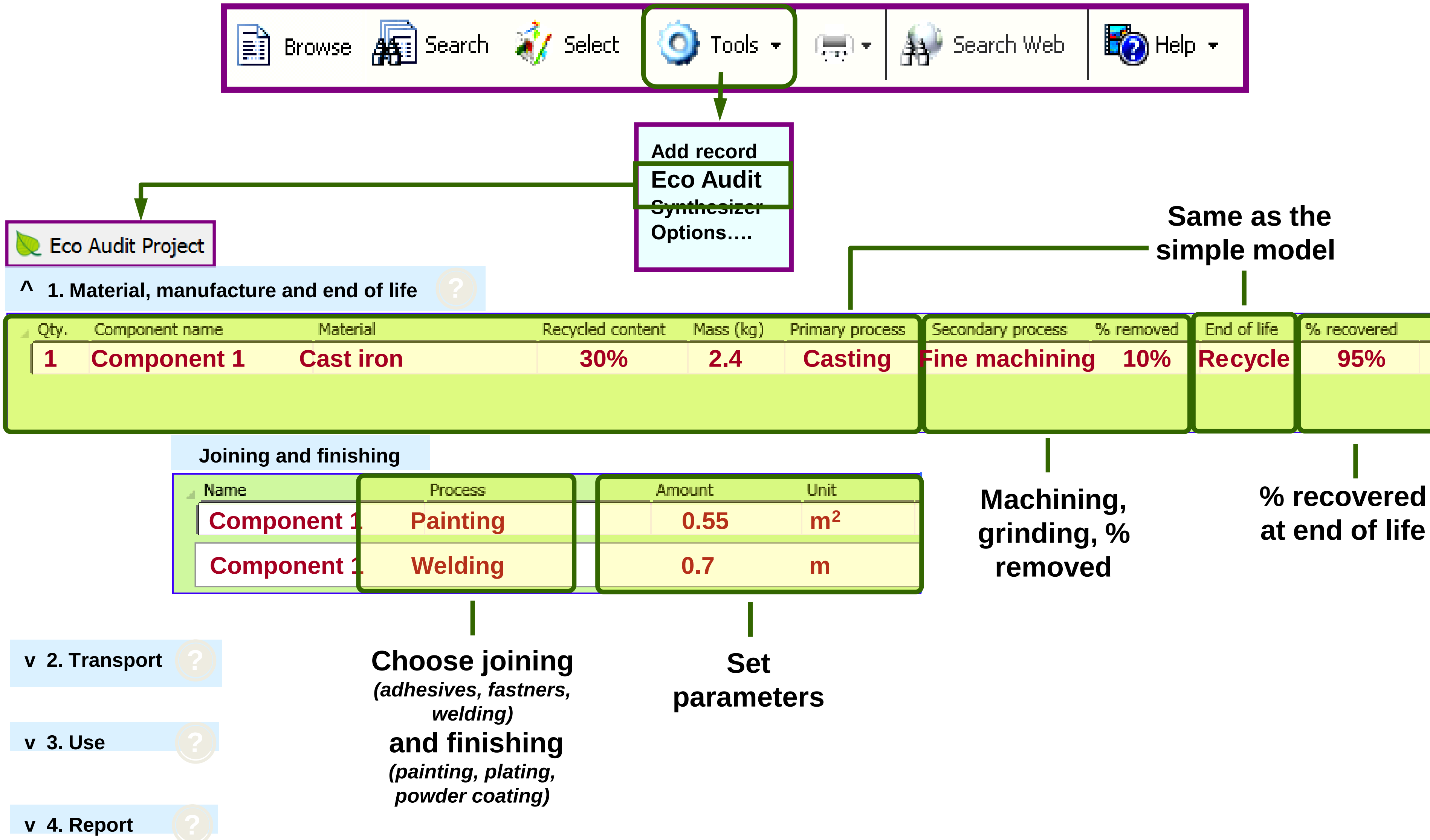


What do we learn?

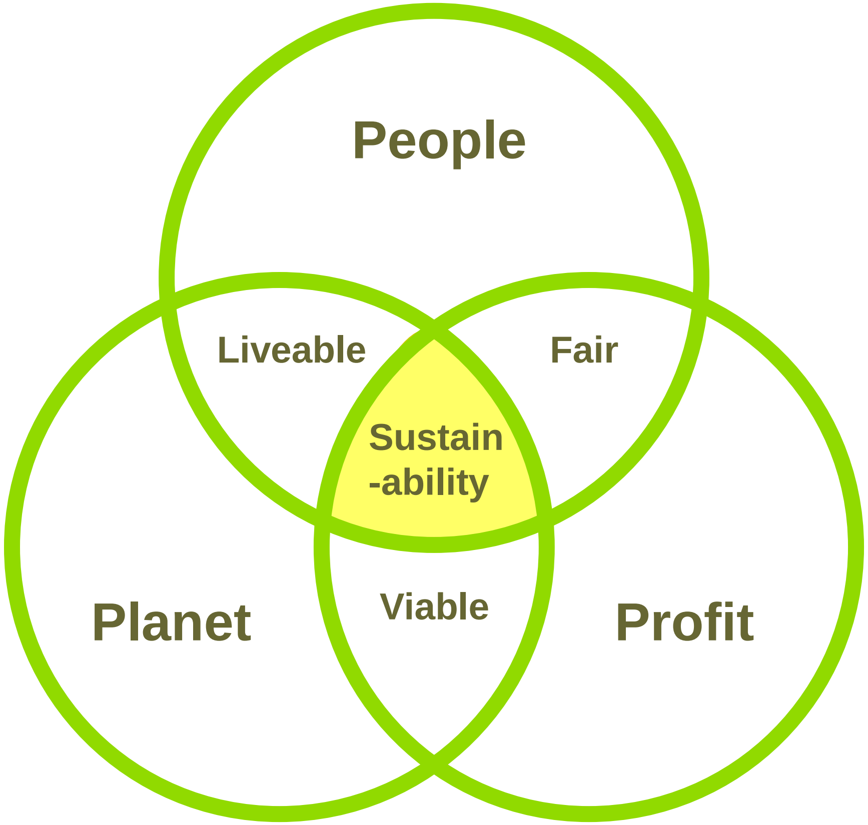
- **Little gained by change of material for its own sake**
- **Much gained by insulation – double wall with foam or vacuum**
- **Or new concept: make hot water on the fly – only as much as needed**

Eco-audit tool includes pre-stored projects

The advanced Audit tool: EcoSelector



Back to the big picture: the "triple bottom line"



Noble but vague

Where do materials fit in?

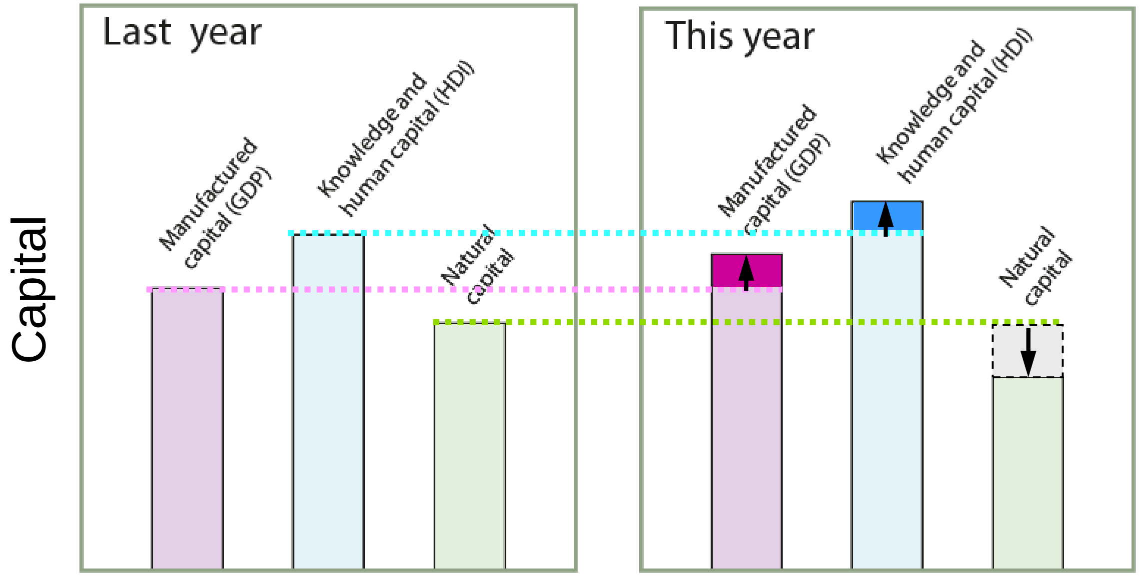
View through eyes of economist

Manufactured capital – Industrial capacity, infrastructure, roads, built environment (GDP)

Human capital – Education, health, skills, happiness (UN Human Development Index, HDI)

Natural capital – Atmosphere, fresh water, land, oceans, minerals and fossil energy

Comprehensive capital – the sum of all capital assets. A number, measured (say) in dollars



Sustainability: The comprehensive capital is positive

Maximize material utility = Material efficiency

See, for example, P. Dasgupta (2010) "Natures role in sustaining economic development" Phil Trans Roy Soc B, Vol. 365, pp 5 – 11.

Material efficiency