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Theme: Sustainable Materials and Manufacturing

Lecture 3: Life Cycle Analysis

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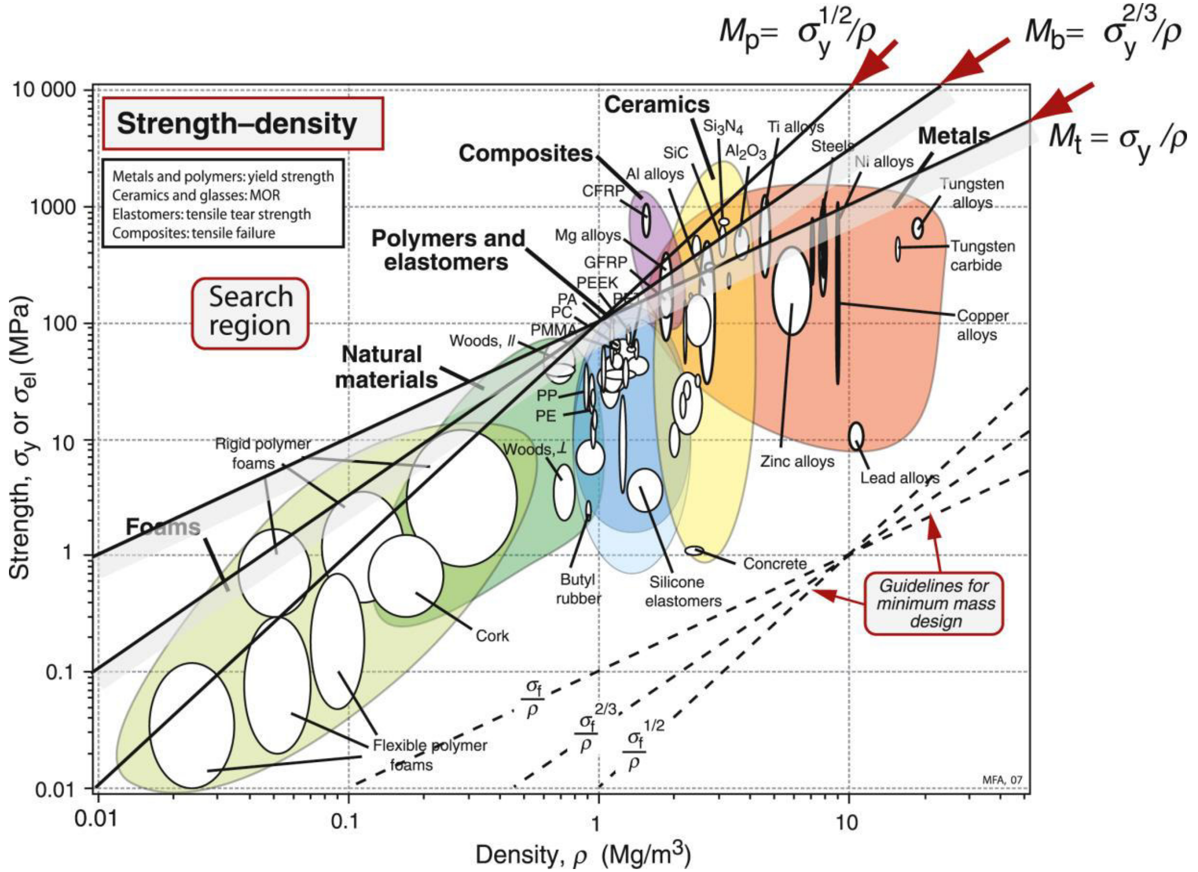
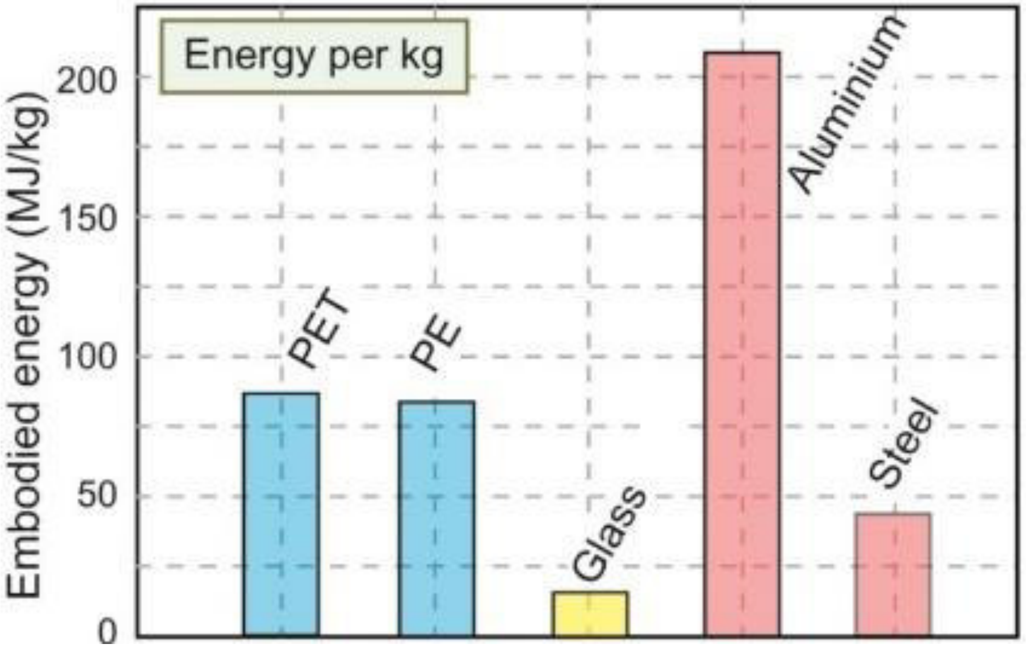
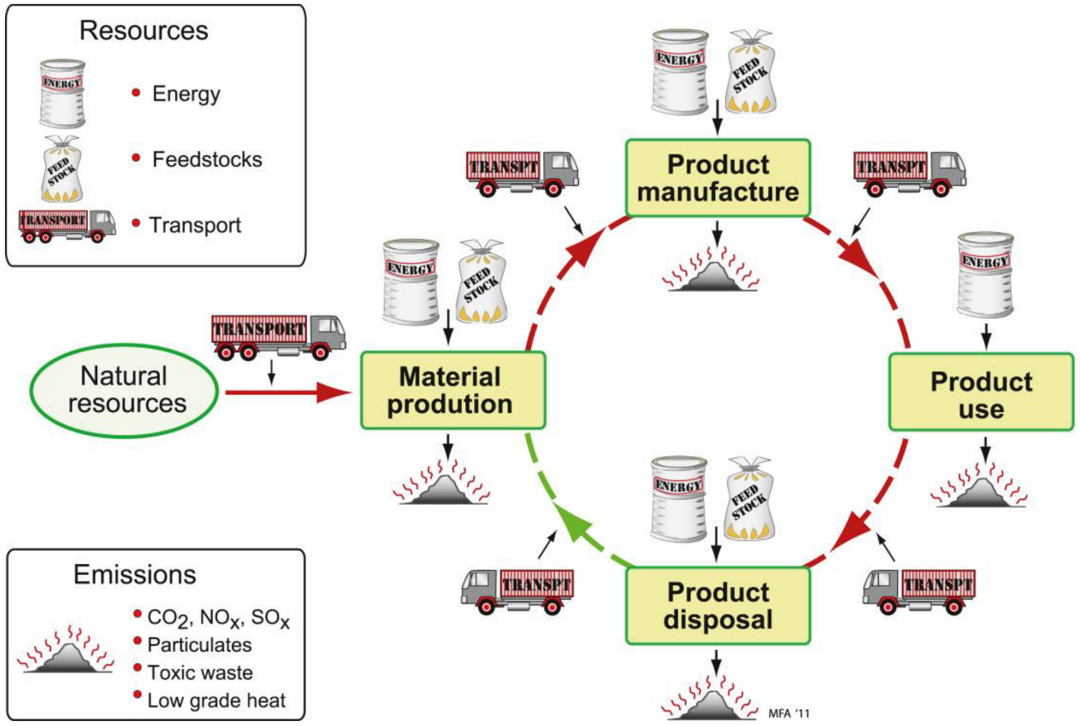
Previously… Ecodesign





Life Cycle Assessment

- Life cycle broken down into phases
  - production, manufacture, use, disposal.
- Energy and materials consumed in each phase
  - associated penalties CO_2, SO_x, NO_x other emissions (heat, gas, liquid, solid waste)
- Environmental 'stressors' catalogued, quantified by life-cycle analysis (LCA)
  - Examines life cycle of product, gives detailed assessment of eco-impact

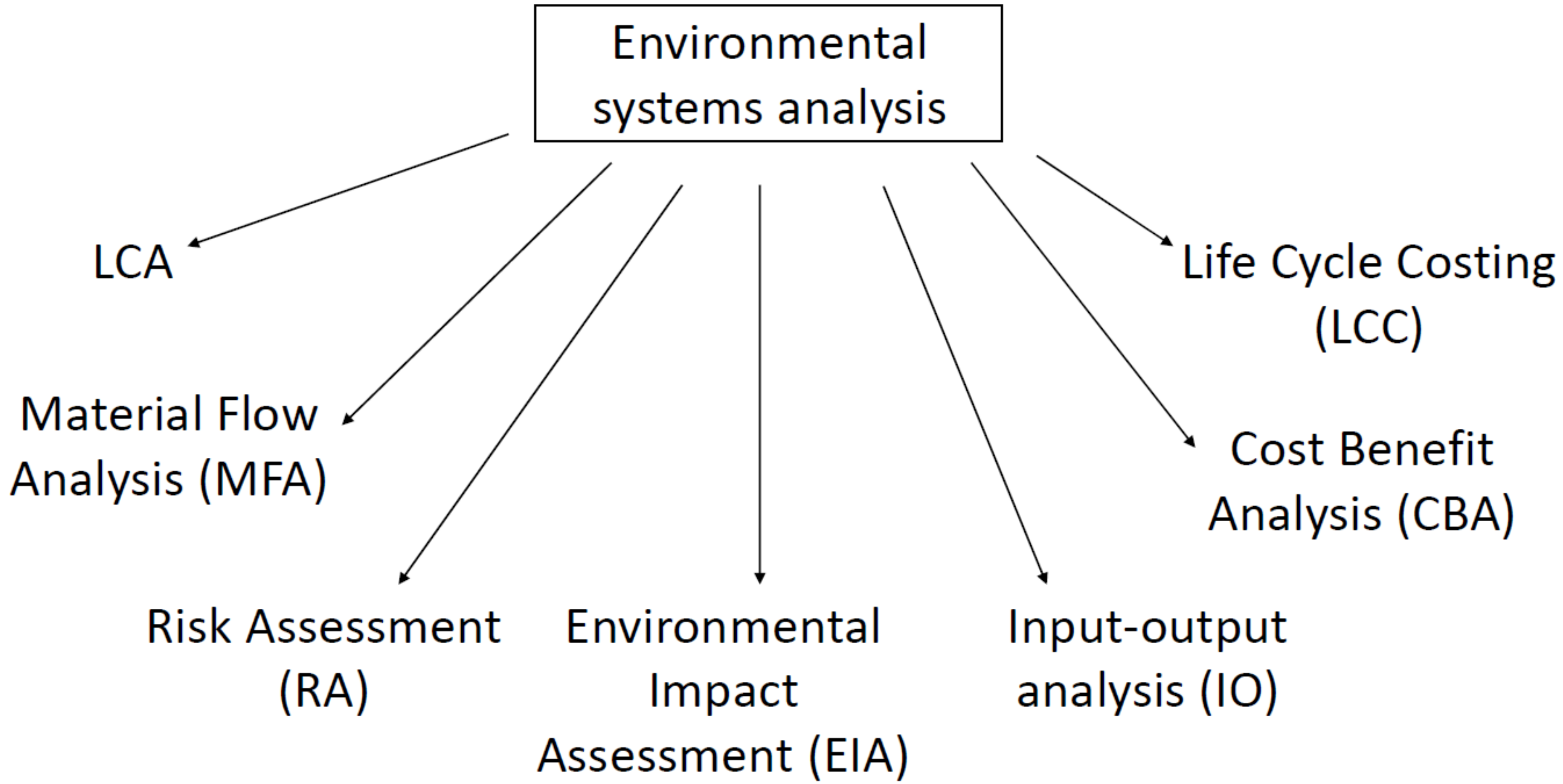


The material life cycle (see Fig. 20.3)

Definition

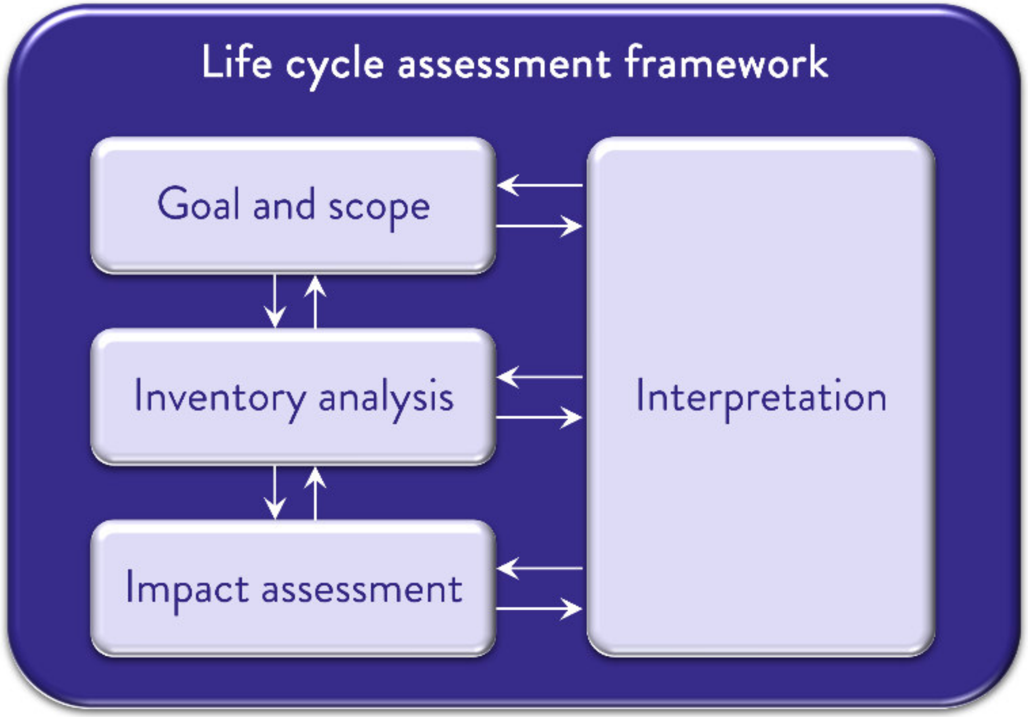
- Indicates the scale of environmental and resource impacts associated with a product system (activity or function) from the extraction of raw materials, through to ‘end use’ impacts.
  - To improve product design
  - To support internal sustainability efforts
  - To support corporate reporting
  - To support development of environmental product declarations (EPDs), or other types of environmental declaration

Evaluating environmental impact

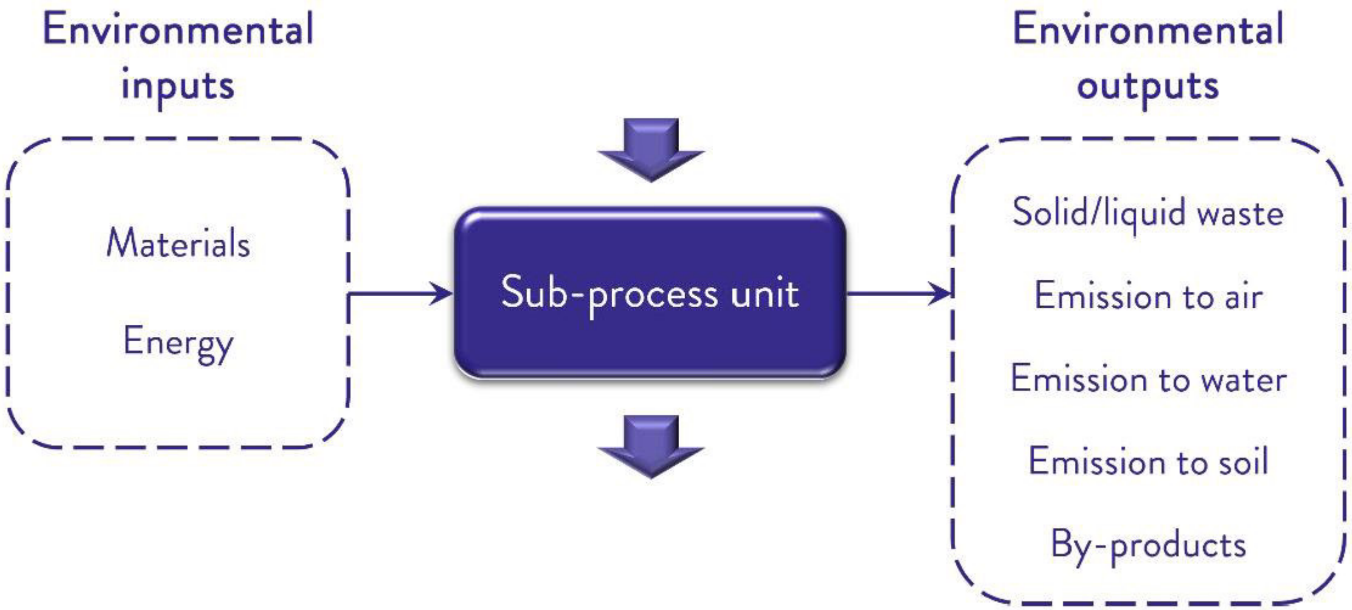


Life Cycle Assessment - Steps

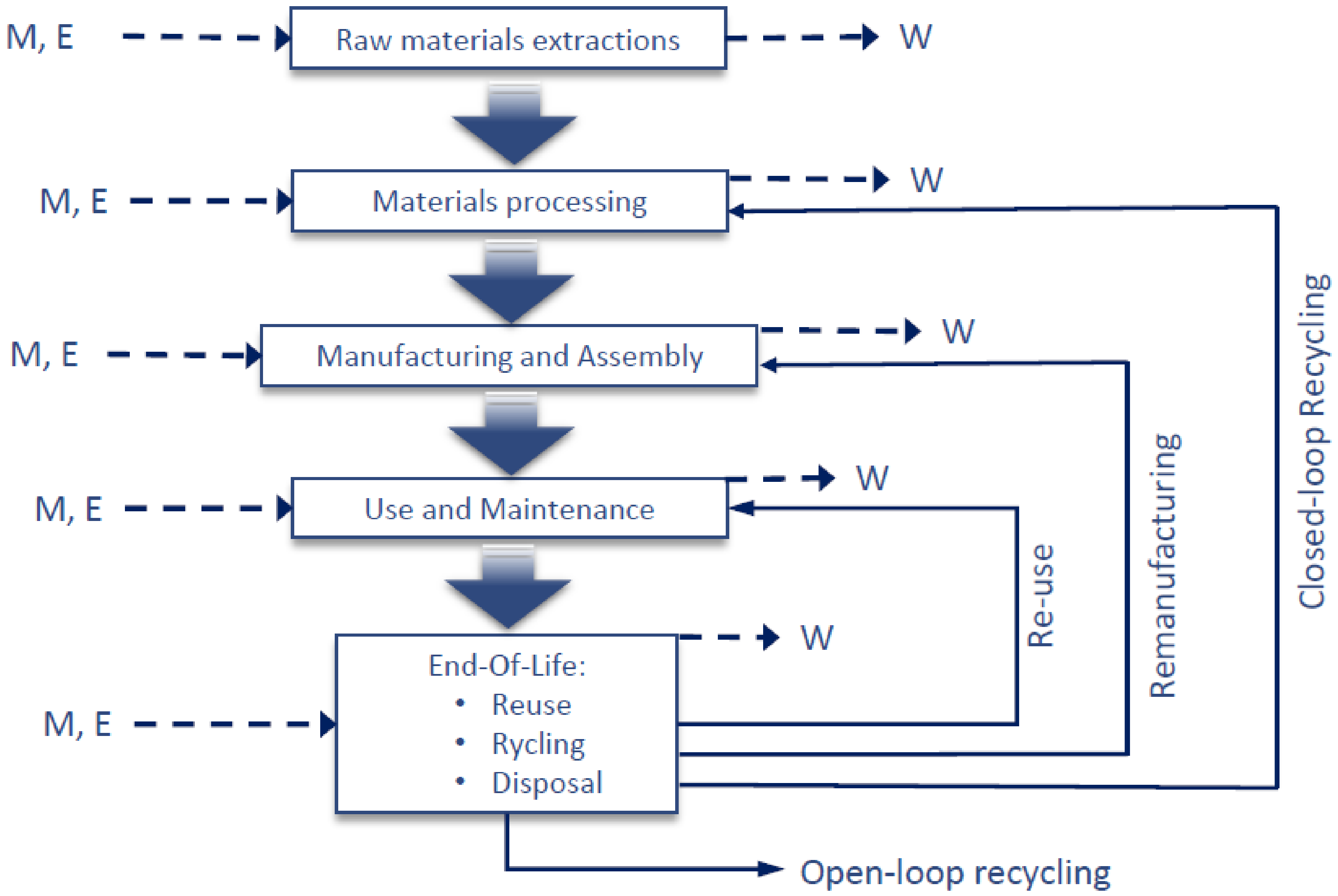
- **Goals and scope:** Why do the assessment? What is the subject and which bit(s) of its life are assessed?
- **Inventory compilation:** What resources are consumed? What emissions are excreted?
- **Impact assessment:** What do the resource consumption and emissions do to the environment—particularly, what bad things?
- **Interpretation:** What do the results mean? If they are bad, what can be done about it?



Process diagram



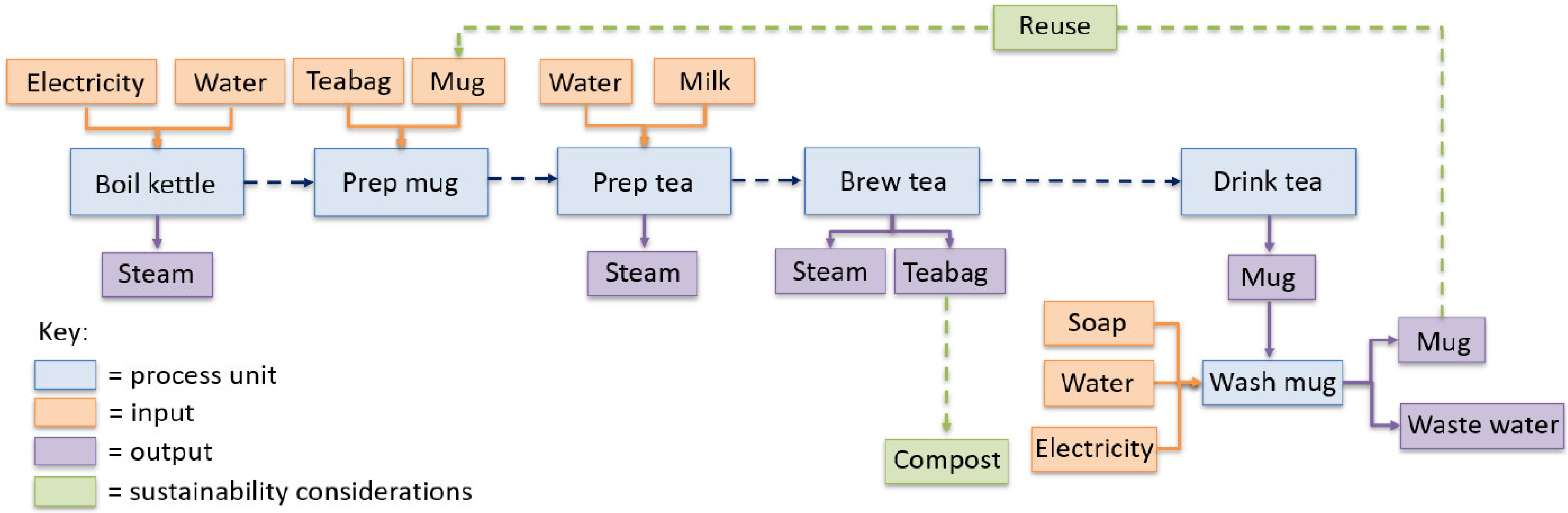
Process flow diagram



M, E = Materials and Energy flows

W = solid/liquid waste, emissions to air/water, by-products

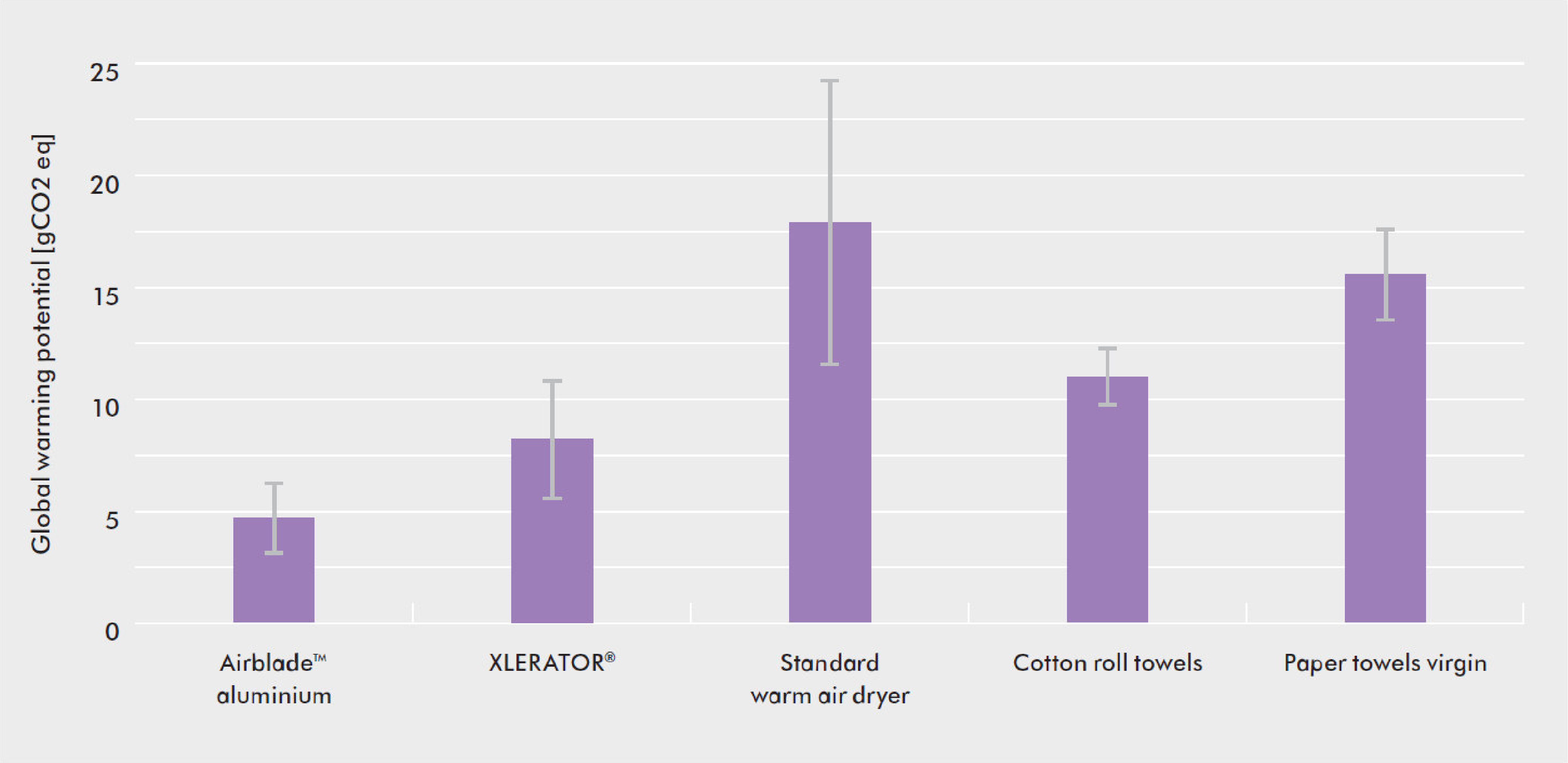
Process flow for making a cup of tea



Functional unit

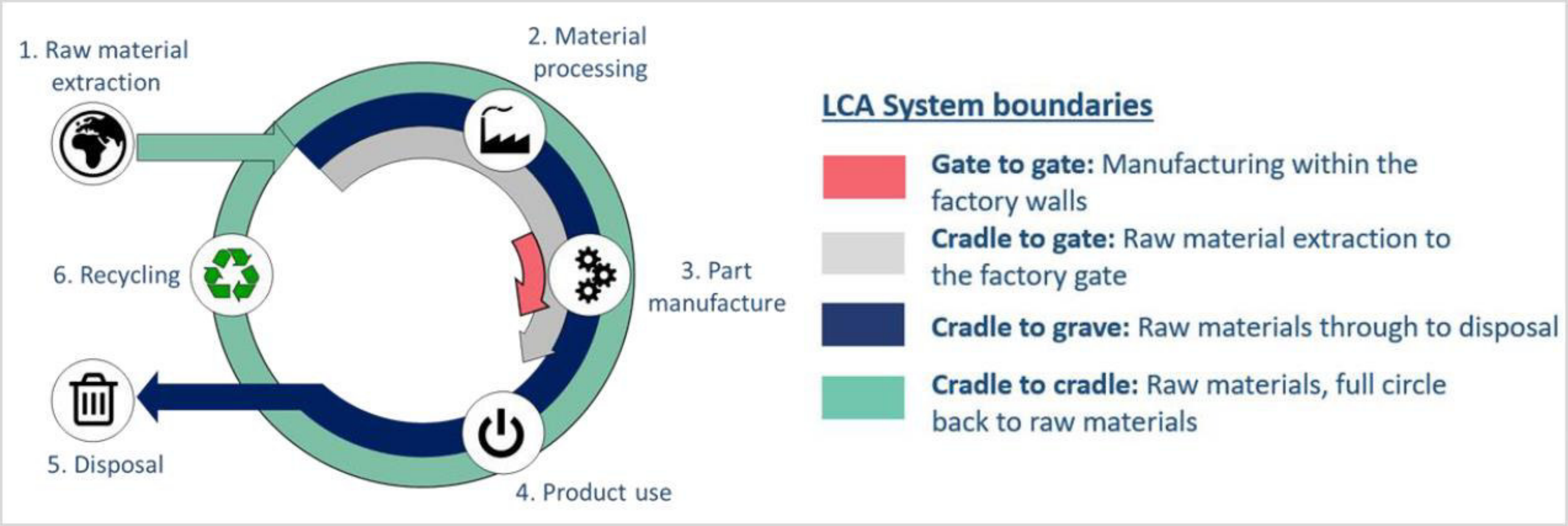
- ***Function***: performance characteristics of the product / service
- ***Functional Unit (F.U.)***: quantifiable performance characteristic of a product system to be used as a reference in a life cycle assessment study
  - It must describe the system, in line with defined goals and objectives
  - It is useful if different products are to be compared
  - The life time of the product/service must also be taken into account
- Example: Dishwasher vs. Hand washing - one mug or a whole load

Hand dryer case study

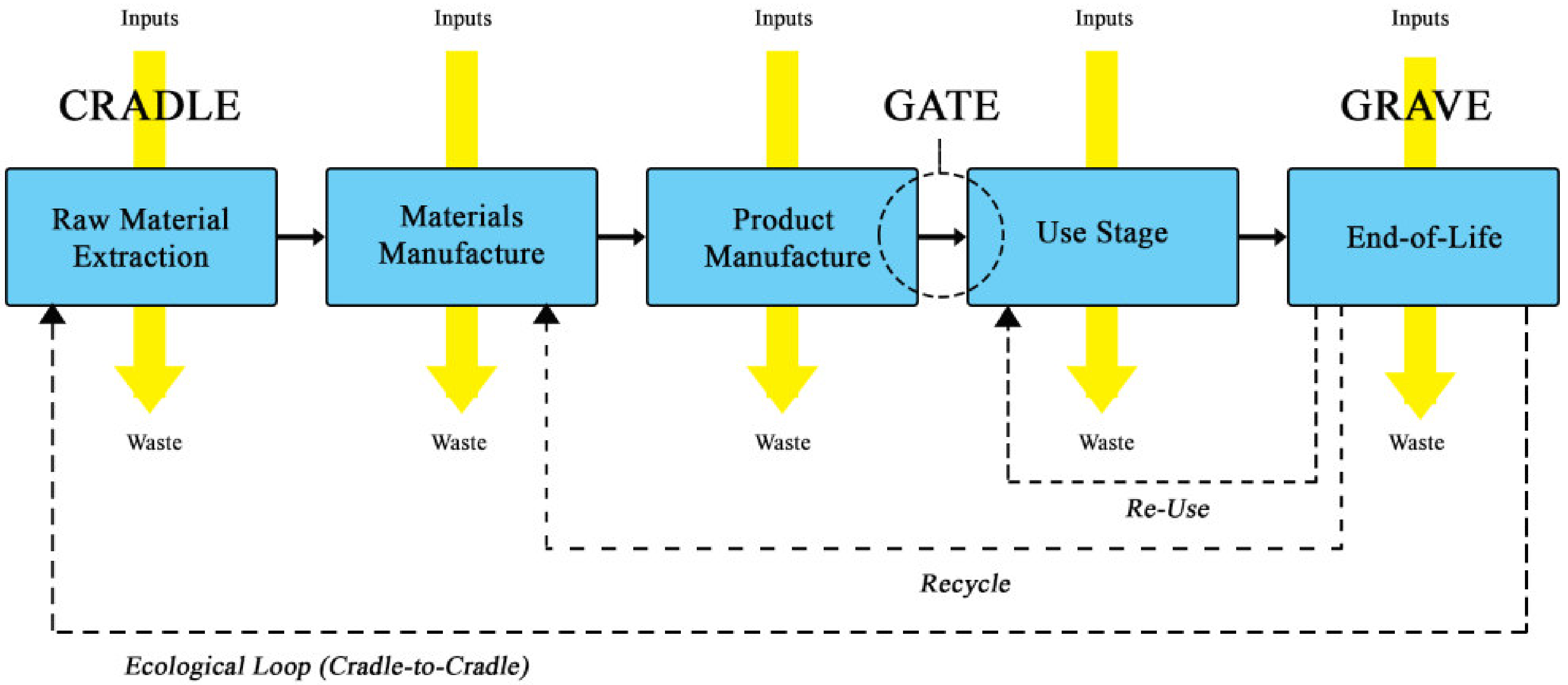


https://www.silvaporto.com.br/wp-content/uploads/2017/09/ACV_SECADOR_MIT.pdf

Setting the boundary

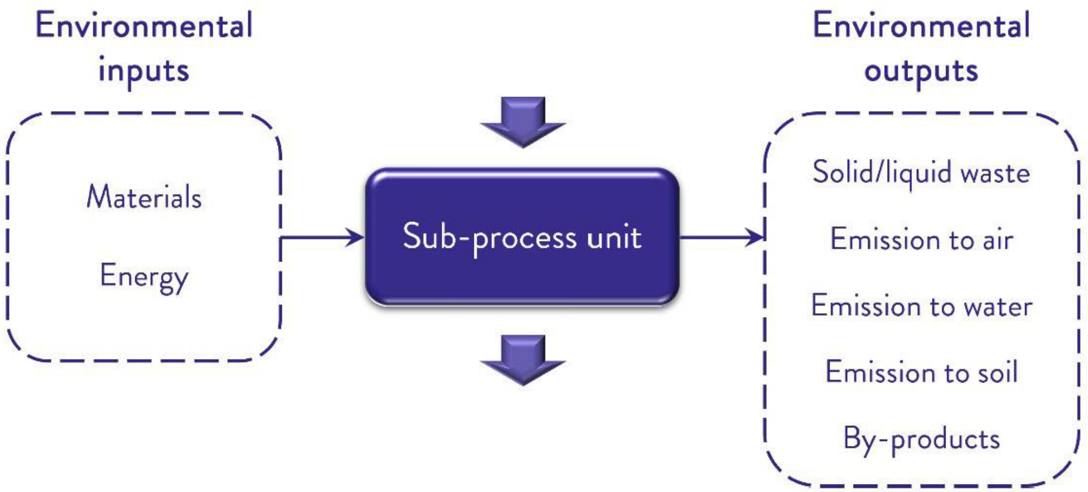


Cradle – to – cradle loop



Life cycle inventory

- LCI lists all inputs and outputs from/to earth
- System here is: the production of **1 kg steel product** from Iron ore



	Major Articles*	Units	Average 11 sites
Inputs:	(r) Coal (in ground)	kg	0.643398982
	(r) Dolomite (CaCO3.MgCO3, in ground)	kg	0.01626926
	(r) Iron (Fe)	kg	1.748361164
	(r) Limestone (CaCO3, in ground)	kg	0.011457251
	(r) Natural Gas (in ground)	kg	0.030582934
	(r) Oil (in ground)	kg	0.047137374
	(r) Zinc (Zn)	kg	2.15E-09
	Ferrous Scrap (net)	kg	1.45E-01
	Water Used (total)	litre	17.92589455
Outputs:	(a) Cadmium (Cd)	g	6.33E-05
	(a) Carbon Dioxide (CO2)	g	2128.117309
	(a) Carbon Monoxide (CO)	g	33.00088145
	(a) Dioxins (unspecified, as TEq)	g	3.60E-08
	(a) Hydrogen Chloride (HCl)	g	0.044157425
	(a) Hydrogen Sulphide (H2S)	g	0.068293481
	(a) Lead (Pb)	g	3.69E-03
	(a) Methane (CH4)	g	0.527704385
	(a) Nitrogen Oxides (NOx as NO2)	g	2.973955418
	(a) Nitrous Oxide (N2O)	g	0.112232902
	(a) Particulates (Total)	g	1.74E+00
	(a) Sulphur Oxides (SOx as SO2)	g	2.582408291
	(w) Chromium (Total)	g	9.36E-05
	(w) COD (Chemical Oxygen Demand)	g	0.331073716
	(w) Iron (Fe++, Fe3+)	g	0.030940552
	(w) Lead (Pb++, Pb4+)	g	4.88E-04
	(w) Nickel (Ni++, Ni3+)	g	2.16E-04
	(w) Nitrogenous Matter (unspecified, as N)	g	0.015650293
	Non-allocated byproducts (See Table Below)	kg	5.22E-02
	Waste (total)	kg	1.564155491

LCI analysis

- Inventory analysis can include data you collect yourself (primary data) or data from databases (secondary data)
- Data will include all (in scope) mass and energy inputs as well as outputs, by-products and emissions
- Data can come from a variety of places making consistency/ completeness challenging
- Main databases for inventory information are Ecoinvent, Gabi, and other product/sector specific databases

Energy grid mix

- The energy mix varies from country to country

Renewable





Non-Renewable

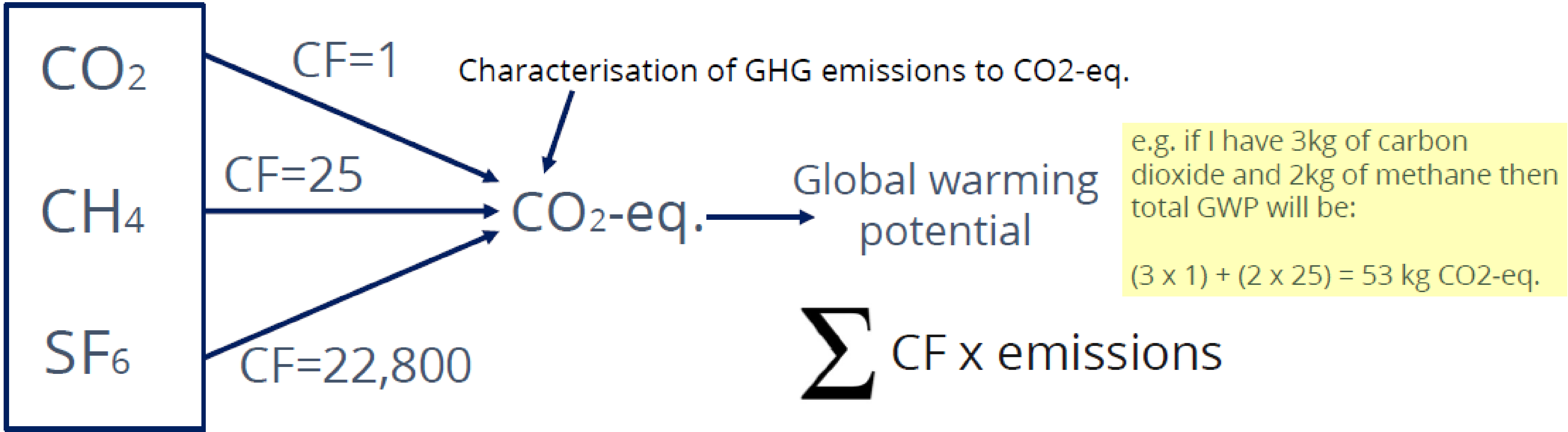


Impact categories

Example elementary flows	Impact categories	Macro-categories
CO_2, CH_4, N_2O, CFC, HFFCs, CH_3Br	Greenhouse effect	Ecosystems deterioration
SO_x, NO_x, HCl, HF, NH_4	Acidification	
PO_4, NO, NO_2, Nitrates, NH_4	Eutrophication	
Pesticides, PCB, Pb, Cd, Hg	Ecotoxicity	
Pesticides, PCB, Pb, Cd, Hg	Human toxicity	Human health
HCFCs, CFCs, CH_3Br, CH_3Cl	Stratospheric Ozone layer reduction	
CO_2, NO_2, CH_4, CFCs, HCFCs, CH_3Br	Photochemical smog	
NMHC (C_xH_y) NO_x	Winter smog	
Minerals, fossil fuels, uranium	Reduction of non-renewable resources	Resource reduction
Wood, wind or hydroelectric power	Reduction of renewable resources	

Impact assessment

- Global Warming Potential (GWP) is a measure for climate change based on radiative forcing for a mass unit of greenhouse gas (GHG).
- Here carbon dioxide has a characterization factor of 1 with all GHGs are equivalent to this (hence units of CO2 equivalents).
  - Methane has a characterization factor of 25 indicating it has a 25 times greater impact on radiative forcing than CO2.



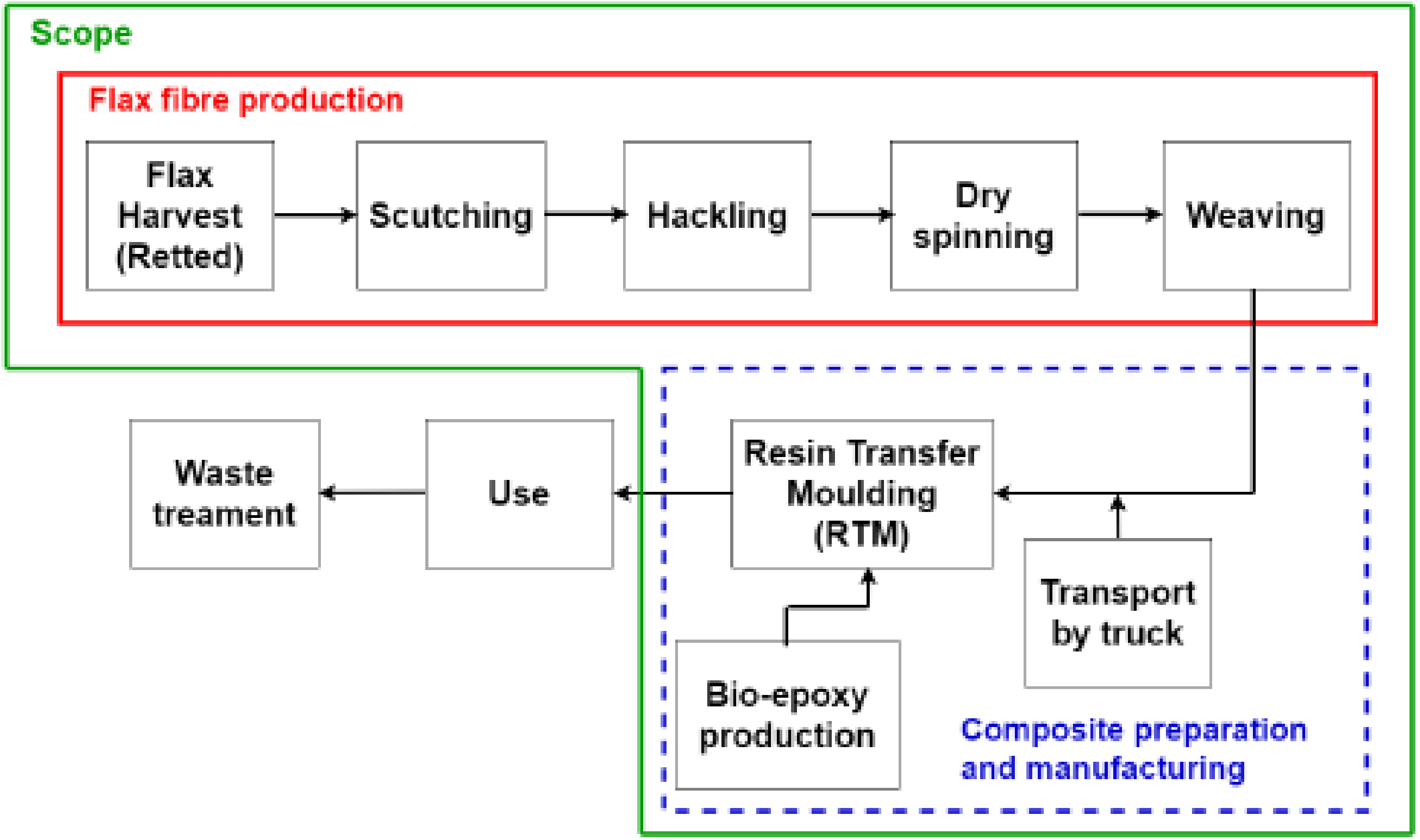
Time dependence

Gas name	Chemical formula	Molecule's life [years]	GWP for a specific timeframe [kg CO_2 – eq]		
			20 years	100 years	500 years
Carbon dioxide	CO_2	-	1	1	1
Methane	CH_4	12	72	25	7.6
Nitrous oxide	N_2O	114	289	298	153
CFC-12	CCl_2F_2	100	11 000	10 900	5 200
HCFC-22	$CHClF_2$	12	5 160	1 810	549
Tetrafluoromethane	CF_4	50 000	5 210	7 390	11 200
Hexafluoroethane	C_2F_6	10 000	8 630	12 200	18 200
Sulfur hexafluoride	SF_6	3 200	16 300	22 800	32 600
Nitrogen trifluoride	NF_3	740	12 300	17 200	20 700

Interpretation

- Completeness check – analysis of any missing or incomplete information.
- Sensitivity check – analysis to understand how the final results are influenced by data uncertainty, assumption, calculation procedures etc.
- Coherence check – assessment of how well the study meets the objectives.

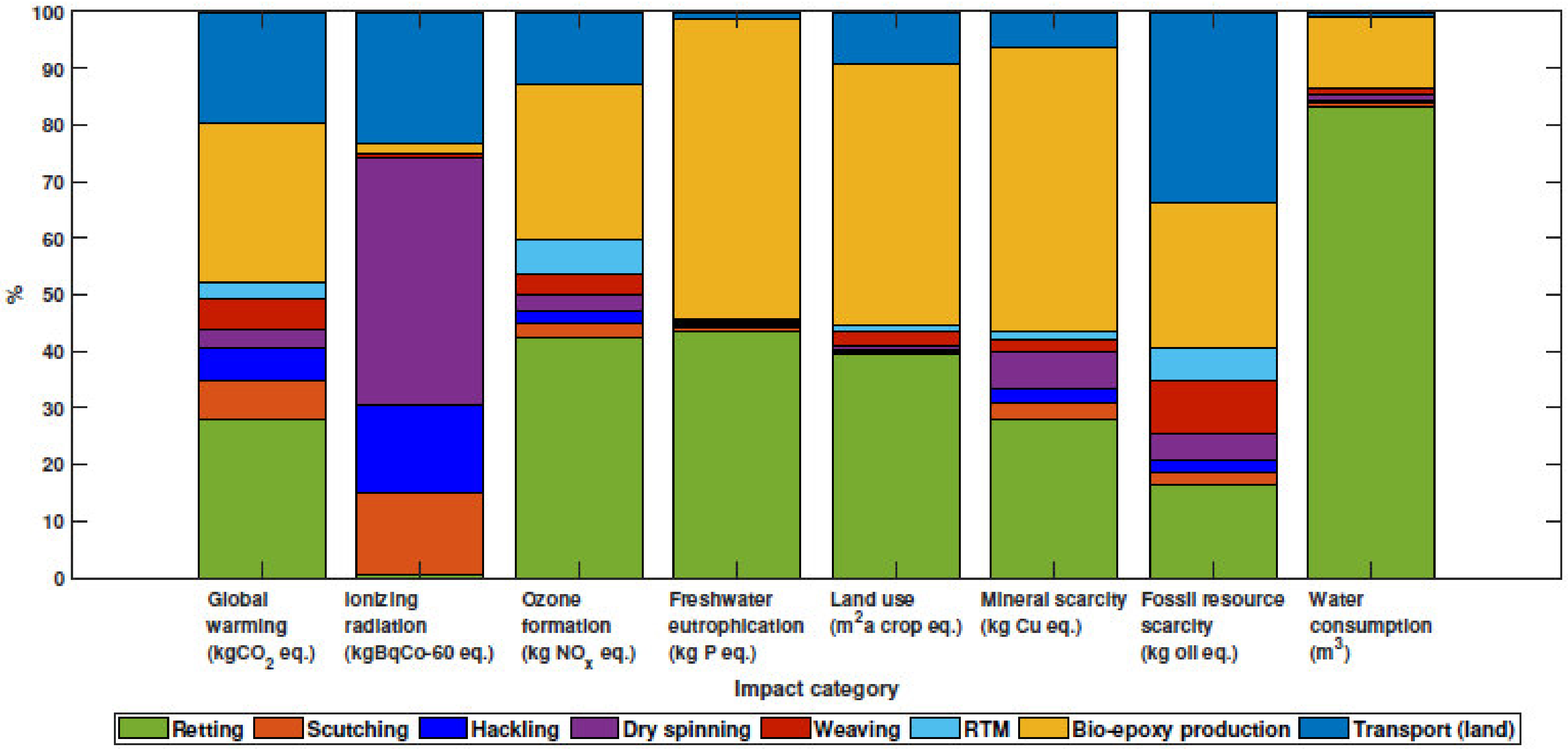
Example – Flax fibre composite



LCI

Unit process	Input			Output			Waste and emission		
	Material/ Energy	Unit	Quantity	Material/ Energy	Unit	Quantity	Waste/ emission	Unit	Quantity
				Flax					
Flax harvest (retting)	Flax plant	kg	55.2	Retted flax stem	kg	48.9	Solid waste to incineration	kg	6.3
	(EcoInvent "Flax plant, harvested flax production {RoW}")						(EcoInvent "Solid waste, treatment of incineration {FR}")		
Scutching	Retted flax stem	kg	48.9	Long flax fibres	kg	11.3	Solid waste to incineration	kg	4.9
	Electricity	kWh	5.68	Flax shives, seeds, flakes	kg	44.0			
	(EcoInvent "Electricity, medium voltage {FR}")								
Hackling	Long flax fibres	kg	11.3	Hackled fibres	kg	7.3	Solid waste to incineration	kg	4.0
	Electricity	kWh	7.26						
Dry spinning	Hackled fibres	kg	7.3	Yarn/fibre	kg	7.0	Solid waste to incineration	kg	0.3
	Electricity	kWh	17.44						
Weaving	Yarn/fibre	kg	7.0	Flax fabric	kg	6.8	Solid waste to incineration	kg	0.2
	(EcoInvent "Weaving, synthetic fibre {Global}")								
Resin transfer moulding	Flax fabric	kg	6.8	Flax/epoxy composite	kg	**12.9**	Solid waste to incineration	kg	1.9
	Transport (land)	tkm	1414	(Flax fibre 4.9 kg)					
	Electricity	kWh	24.66						
	Bio-epoxy	kg	8.0						
	Refer to "Epoxidized linseed oil (ELO) production" [14]								

Hotspot analysis



Electric vs Internal Combustion engine car

- A **life cycle assessment (LCA)** compares the environmental impact of **ICEVs** and **EVs** across their entire lifecycle, including production, use, and disposal phases.
- EV production, particularly battery manufacturing (lithium, cobalt, nickel extraction), has a higher carbon footprint than ICEVs due to mining and energy-intensive processes.
- No tailpipe emissions during operation, but the environmental impact depends on the electricity mix used for charging.
- Batteries present challenges in terms of recycling, as processes for recovering lithium, cobalt, and nickel are still developing but improving.
- Higher total emissions over their lifecycle, dominated by the use phase for ICEV. Fossil fuel dependency limits emission reductions.

Breakeven point

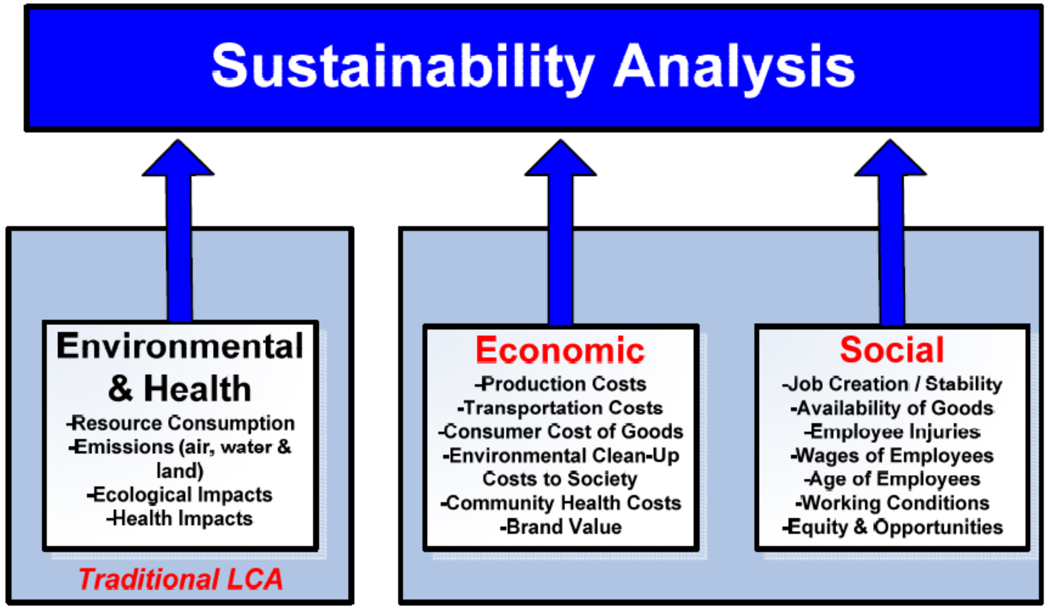
Factors Influencing the Breakeven Point:

- **Battery Size and Manufacturing Impact**: Larger batteries require more energy to produce, delaying the breakeven point.
- **Electricity Grid Mix**: Cleaner grids (e.g., high renewable energy content) shorten the breakeven point, as charging EVs produces fewer emissions.
- **Vehicle Efficiency**: More efficient EVs and ICEVs can alter the breakeven timeline.

- Most studies estimate the breakeven occurs after driving **10,000–20,000 miles** (~16,000–32,000 km) for an average EV, depending on regional electricity sources and manufacturing conditions.

LCA in decision making

- Learning about the environmental performance of products and services
- Minimizing production and regulatory costs
- Minimizing environmental and human health damage
- Understanding trade-offs between multiple impact categories and product phases
- Supporting equitable economic distribution and profitable operations
- **Triple Bottom Line**

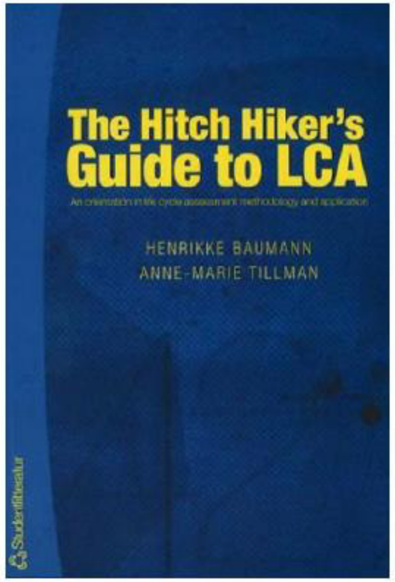


J.S. Golden & P. White (2007): Arizona State University

Some reflections

- Is it better to build more robust products (higher LCI), for extended service life ?
- Is it better to use more energy intensive materials (higher LCI), to gain the fuel efficiency benefit from use phase light-weighting ?
- Should we compromise functional efficiency to make products more recyclable?
- All recycling processes (and transport) have impacts, so what is the value of recycling ? What does recycling/reuse actually offset/avoid ?
- Sometimes LCA results can be counter-intuitive. For example, is it better to design for end-of-life recycling and/or to source material from recycled sources.

More resources on LCA

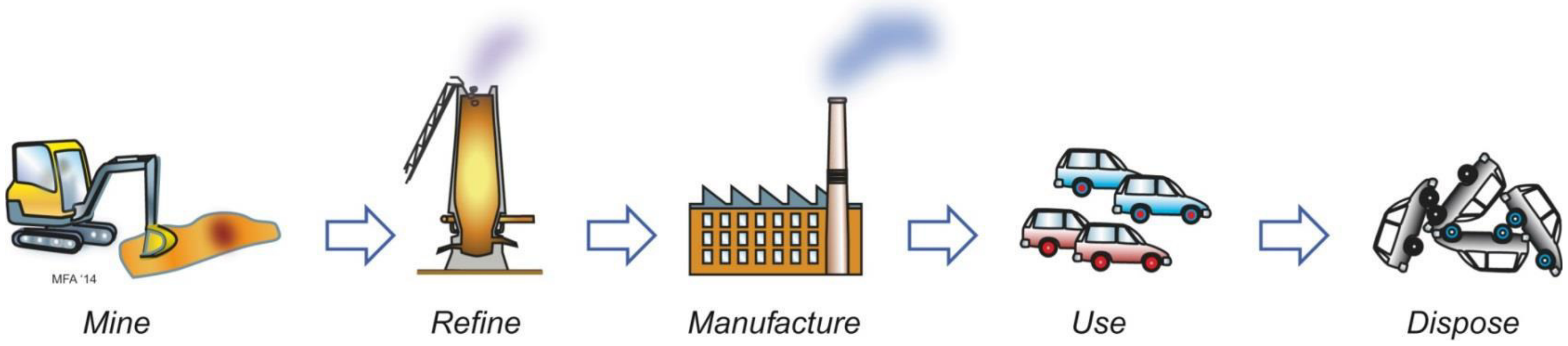


Very good introduction to LCA principles – great introductory text for those getting into LCA for the first time

- ILCD Handbook for LCA - https://eplca.jrc.ec.europa.eu/uploads/ILCD-Handbook-General-guide-for-LCA-DETAILED-GUIDANCE-12March2010-ISBN-fin-v1.0-EN.pdf
- Global Life Cycle Data network (GLAD) (a good source to search for inventory data) https://www.globallcadataaccess.org/
- OpenLCA https://www.openlca.org/trainings/
- Simapro https://pre-sustainability.com/solutions/training/effective-lca-with-simapro/
- GaBi https://gabi.sphera.com/support/training/

The Linear Materials Economy

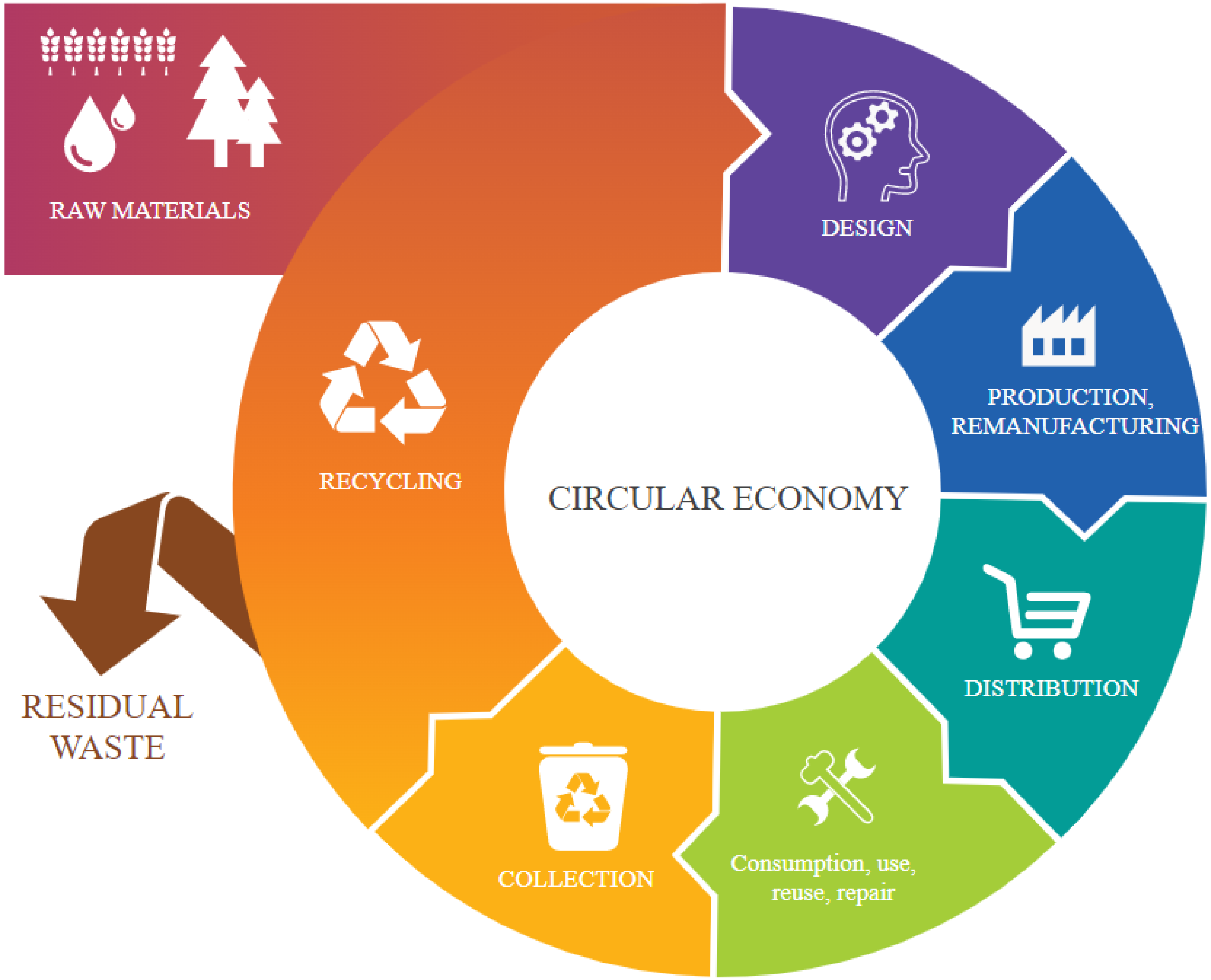
Traditional (historical) approach to materials production and use was often wasteful and unsustainable.



The linear materials economy: take – make – use – dispose (Materials Section in Mechanical Design, Fig. 16.5)

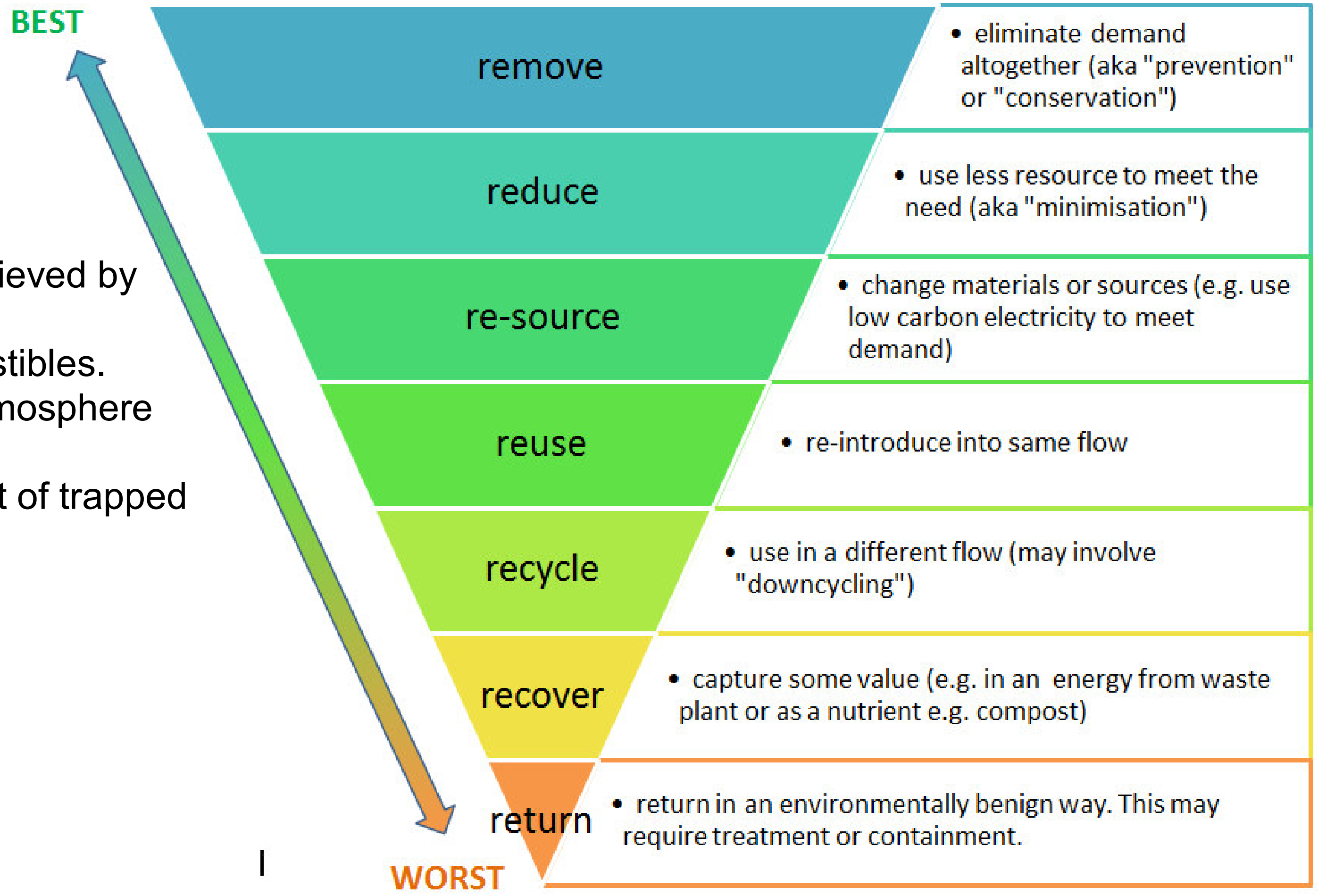
Remember: At a global growth rate of just 3% per year we will mine, process, and dispose of more 'stuff' in the next 25 years than in the entire history of human engineering.

The Circular Materials Economy



‘End of Life’ Options for Materials

- Landfill
  - most rejected products
  - big pressures on land availability
  - landfill tax currently €50/tonne and rising.
- Combustion with heat recovery
  - allows some energy stored in material to be retrieved by controlled combustion.
  - Requires primary sorting to remove non combustibles.
  - Expensive equipment to control temperature/atmosphere and limit residue/trap fumes.
  - Imperfect as incomplete reaction and latent heat of trapped moisture.
- Recycling
  - Upgrades product or recoverable components.
- Reconditioning (re–engineering)
  - Upgrades product or recoverable components.
- Re-use
  - Redistribution of product to a component sector willing to accept it in used state.



Source: https://www.sustainsuccess.co.uk/wp-content/uploads/2013/08/heirarchy-full.png

End of life

https://www.desertusa.com/desert-arizona/airplane-graveyards.html

https://www.texasmonthly.com/news-politics/sweetwater-wind-turbine-blades-dump/

Sustainability in aircraft construction

- Sustainable engineering is a key issue in the design, manufacture and in-service support of aircraft and helicopters.
- An important component to sustainable engineering is the use of materials that can be recycled with little or no impact on the environment.
- As a minimum, recycling should be less harmful to the environment than the production of new material from non-renewable resources.

Recycling of metals

Table 24.1 Energy needed to produce metal from ore or scrap

Metal	Energy ($MJ\ kg^{-1}$) Primary from ore	Secondary from scrap	Average energy ratio (ore/scrap)
Magnesium	350–400	8–10	42
Aluminium	200–240	18–20	12
Titanium	600–740	230–280	2.6
Nickel	135–150	34–38	3.9
Steel	32–38	9–11	3.6

Table 24.2 Carbon dioxide generation in the production of metal from ore or scrap

Metal	Carbon dioxide production ($kg\ kg^{-1}$) Primary from ore	Secondary from scrap	Average CO_2 ratio (ore/scrap)
Magnesium	22–25	1.8–2.0	12.5
Aluminium	11–13	1.1–1.2	10.5
Titanium	38–44	14–17	2.6
Nickel	7.9–9.2	2.0–2.3	4.0
Steel	2.0–2.3	0.6	3.6

- Extraction of metal from ore
  - Energy intensive
- Recycling process cost
  - removing the material from the retired aircraft
  - cleaning
  - cutting and grinding
  - transporting the scrap and
  - the recycling process itself

Recycling of aluminium

- Recycling simply involves re-melting the metal, which is much cheaper and less energy intensive than producing new aluminium by electrolytic extraction (via the Bayer process) from bauxite ore.
- The quality of aluminium is not impaired by recycling; the metal can be recycled repeatedly without any adverse affect on the properties.
- It is estimated that recycling 1 kg of aluminium saves up to 6 kg of bauxite, 4 kg of chemical products used in the electrolytic refinement process, and 14 kWh of electricity.

Recycling: Ideals and Realities

Why not recycle more often?

Two types of 'scrap'

- in-house (off cuts, ends, below spec. material left in production facility)
- Post consumer waste (mixed, contaminated, finished)

Recycling can be economic (in terms of cash and energy)

- Particularly for metals, less so for some plastics

Contamination of polymers can make some unusable (PVC in PET)

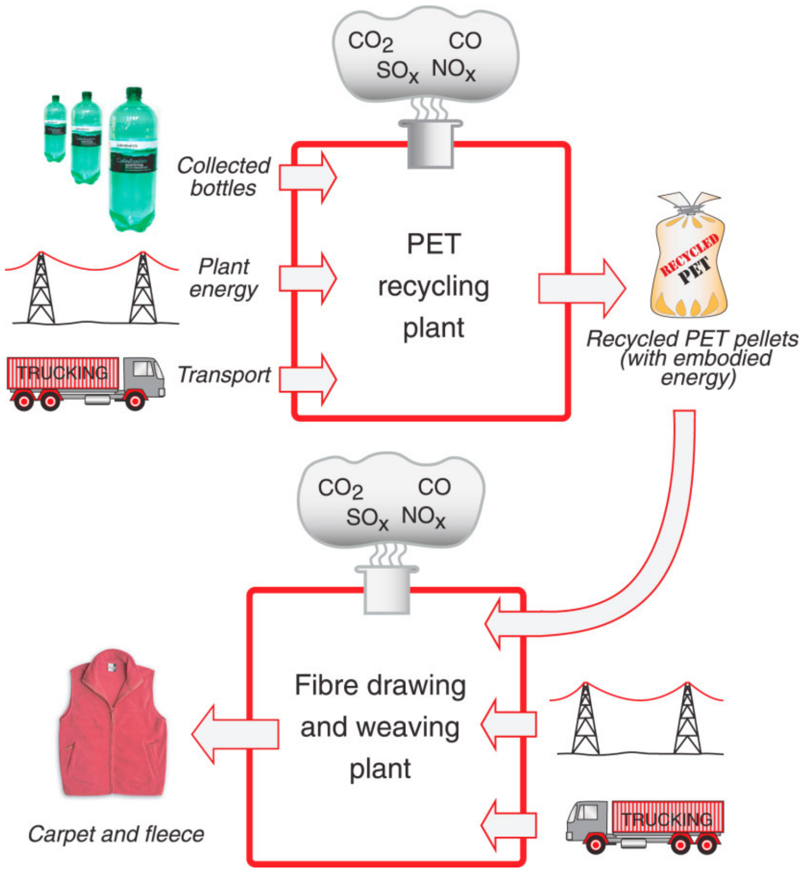
- Fit only for 'down cycling'
- Recycled PET cannot be used for bottles

PET (and PP) bottles collected/delivered to recycling plant (mixed)

- Mixed waste stream must be separated

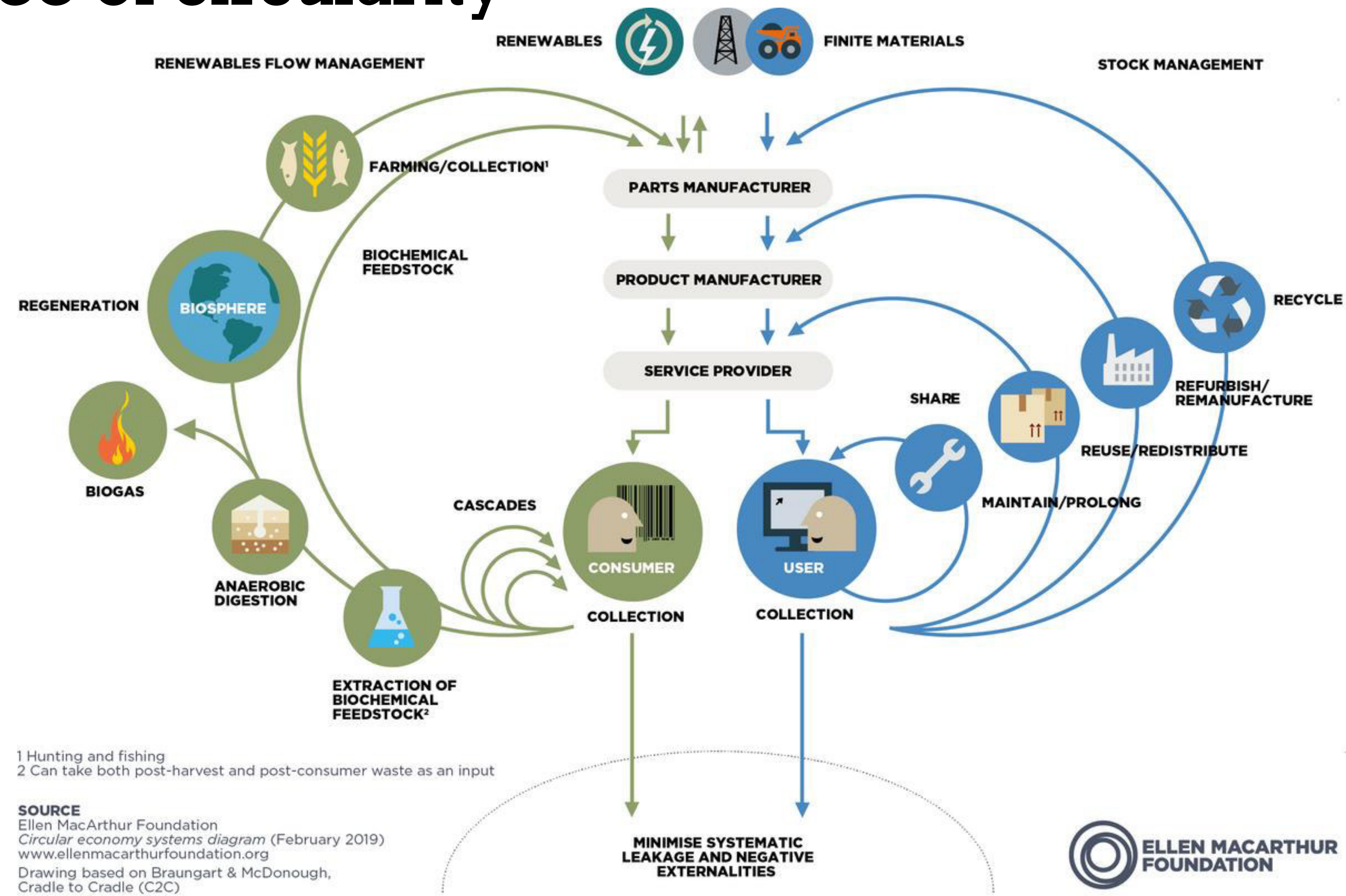
Energy absorbing steps in recycling PET

- Collection, inspection, chopping, washing, flotation-separation, drying, melting, filtration, pelletising, packaging, plant heating/lighting, transport



An input-output diagram for PET recycling (see Fig. 20.5)

Degree of circularity



1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input

SOURCE
Ellen MacArthur Foundation
Circular economy systems diagram (February 2019)
www.ellenmacarthurfoundation.org
Drawing based on Braungart & McDonough, Cradle to Cradle (C2C)

ELLEN MACARTHUR FOUNDATION

Summary

- A materials life cycle comprises production, manufacture, use, and disposal.
- Life Cycle Assessment (LCA) is a quantitative tool for evaluating environmental impact
- Steps involved in LCA: Scope, LCI, Impact, Interpretation
- Linear vs Circular economy
- Hierarchy of end of life options