Sustainability in Civil Engineering

IV. Assessing and reaching sustainability

Today's questions

- How do we quantify the unsustainability of an engineering process / infrastructure system?
- What are some general methods of moving to sustainability in engineering systems?

Why would we want *to measure un/sustainability?*

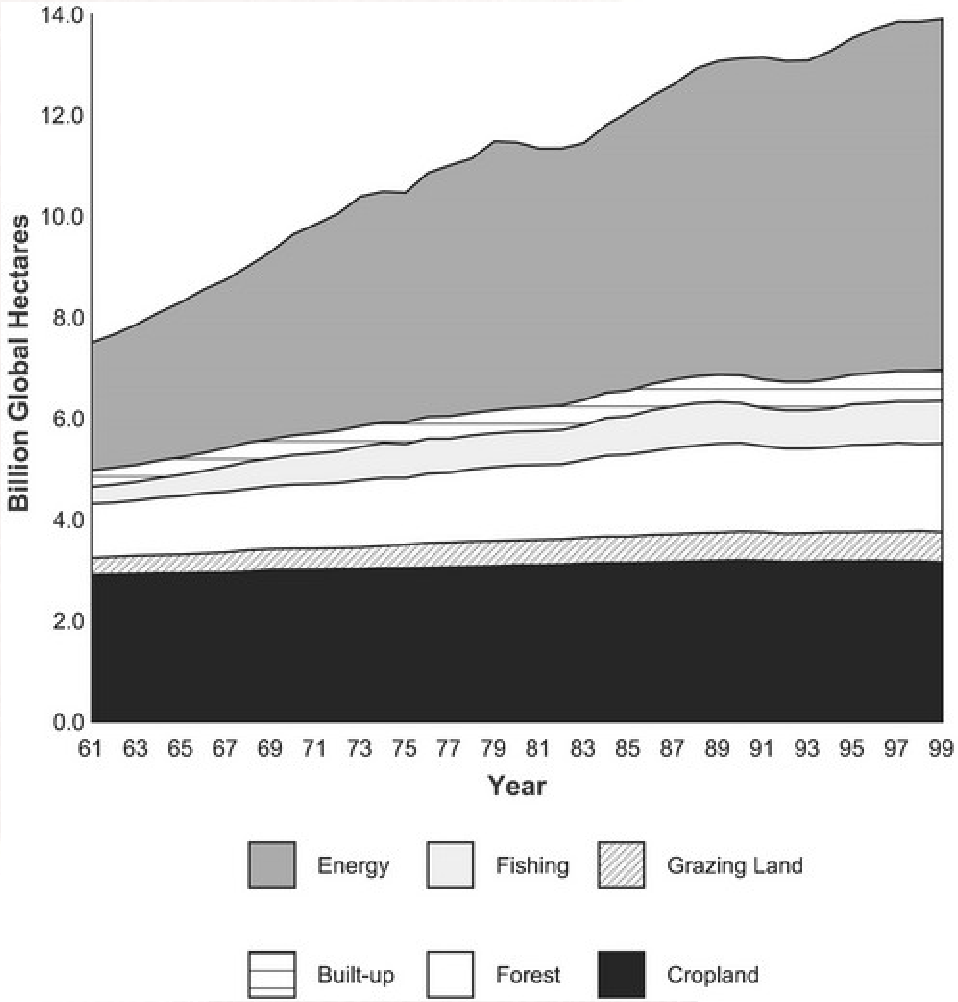
- Decide where to prioritize changes
- Compare different design choices, processes, or options
- Evaluate the impact of current or proposed policies

Ecological footprint: One attempt to quantify large-scale sustainability

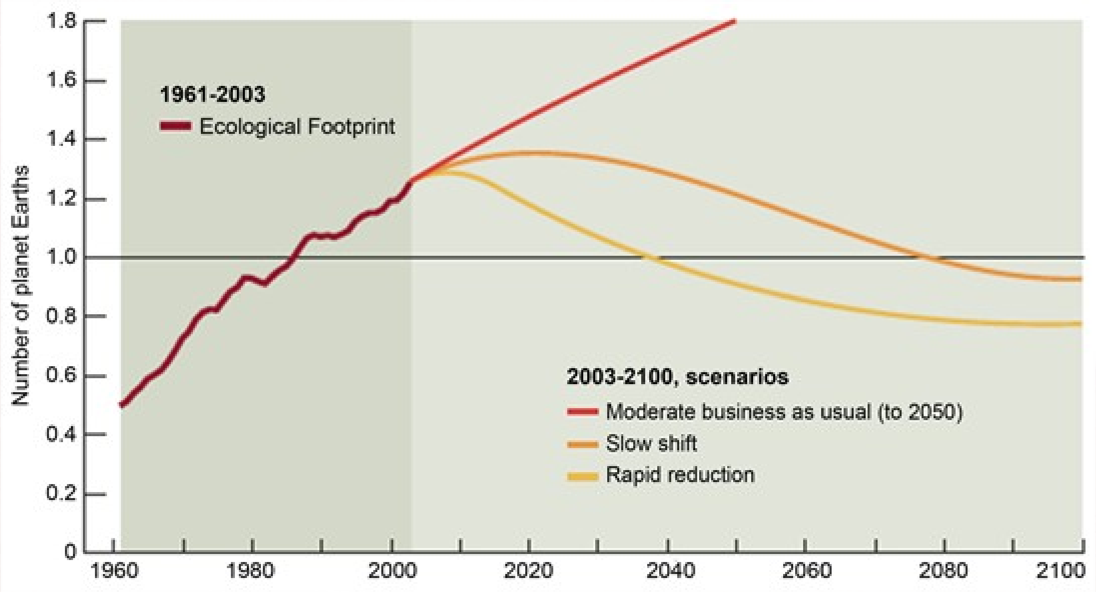
- Assumes that all resources used are met renewably (as ecological services)
- Footprint: How much average-productivity earth surface area is needed to supply resources
- Can be downscaled to personal level: footprintcalculator.org

Ecological footprint categories

- Agricultural land
- Grazing land
- Built-up area
- Timber
- Fishing
- Uptake of fossil-fuel CO_2



Picturing global eco-overshoot

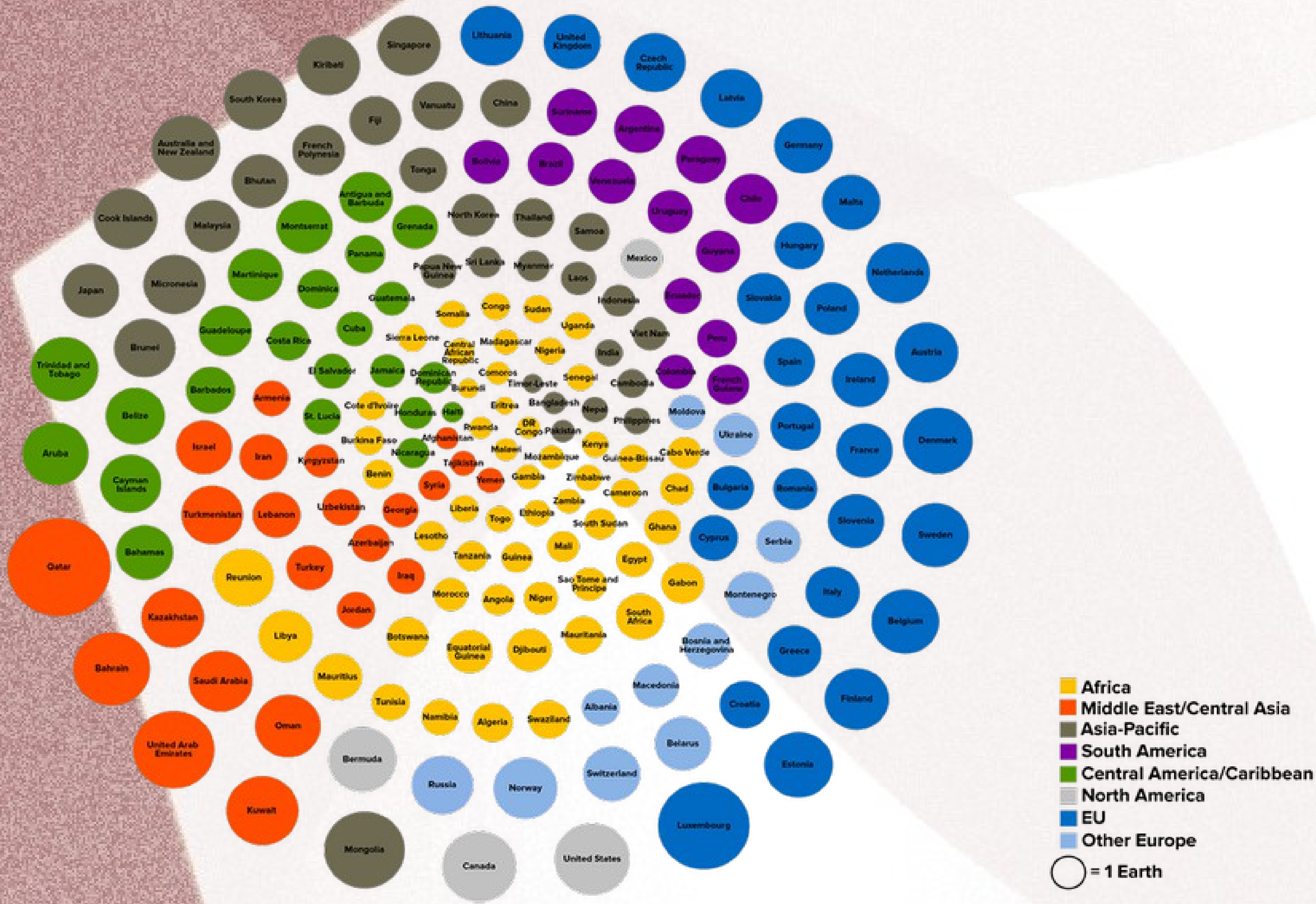


Kitzes et al., "Shrink and Share" (2008)

Global Footprint Network

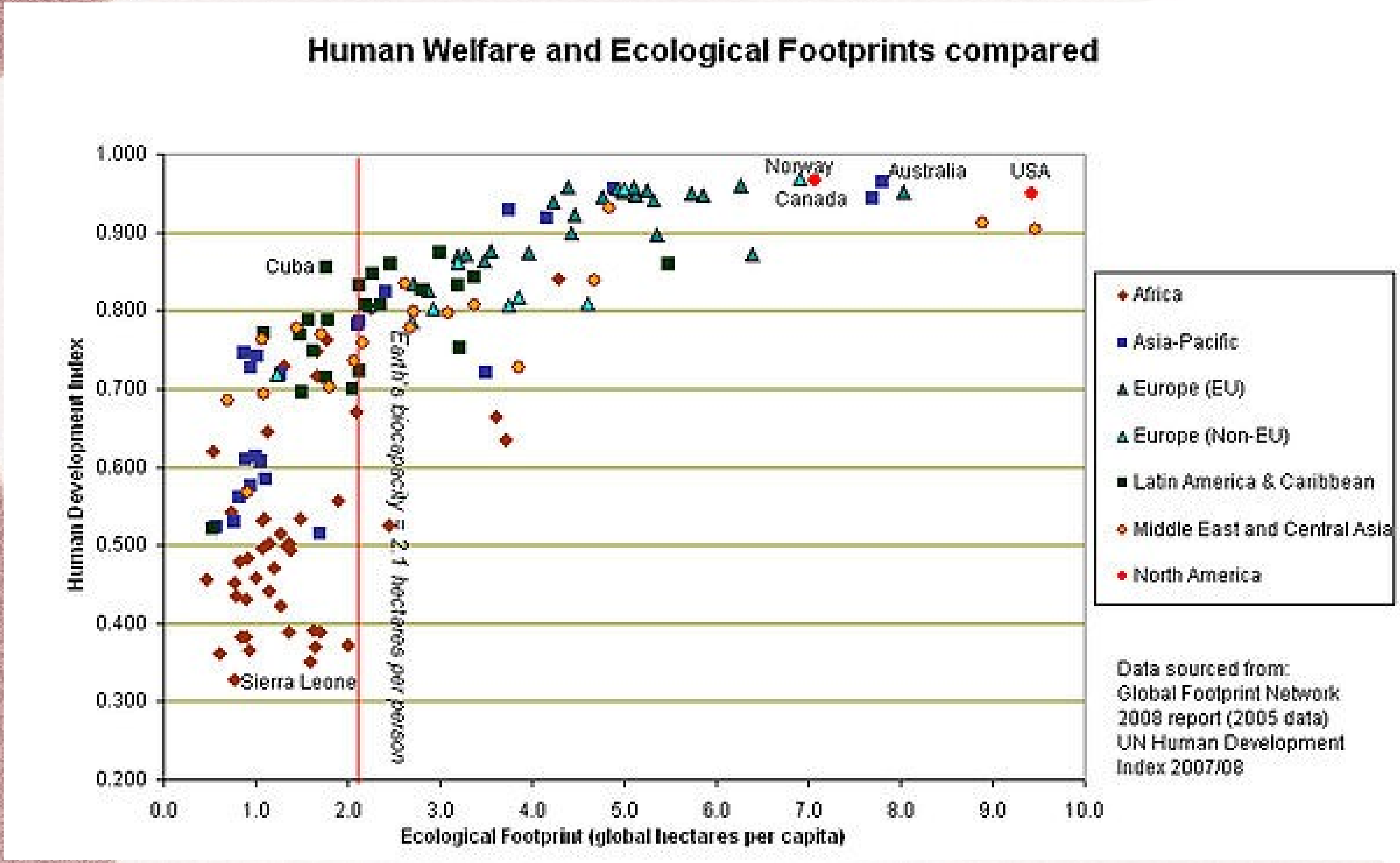
"By July 28, 2022, we will have used more from nature than our planet can renew in the whole year."
("Earth Overshoot Day" – usu. earlier each year) overshootday.org

National ecological footprints



footprintnetwork.org

Ecological footprint and human welfare



arguably, diminishing returns of consuming more

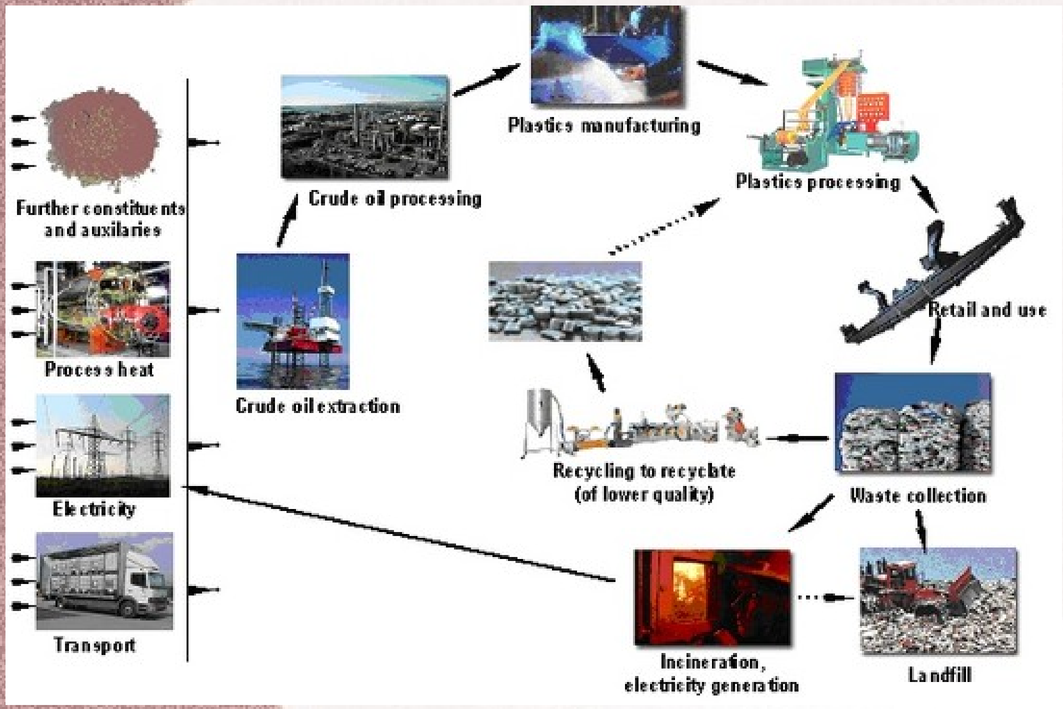
Limitations of the ecological footprint

- Not all impacts well captured by land basis:
  - Forests actually can't fully sequester fossil fuel CO_2
  - Other greenhouse gas and pollutant emissions are ignored
- Biocapacity includes unsustainable productivity (e.g. irrigation and synthetic fertilizer)
- No provision for other species

Quantifying the sustainability of specific products

- The domain of life-cycle assessment (and variants)
- Not simple, because things are interconnected
  - Infrastructure, especially, affects what else is built and bought
  - Input-output tables (Leontief): output from one production sector is used for other production sectors as well as directly

A product "life cycle": "cradle to grave"



- General stages:
  - (1) Raw material acquisition
  - (2) Materials manufacture
  - (3) Production
  - (4) Use/reuse/ maintenance
  - (5) Waste management
- Individual LCAs vary in *scope*

LCA phases

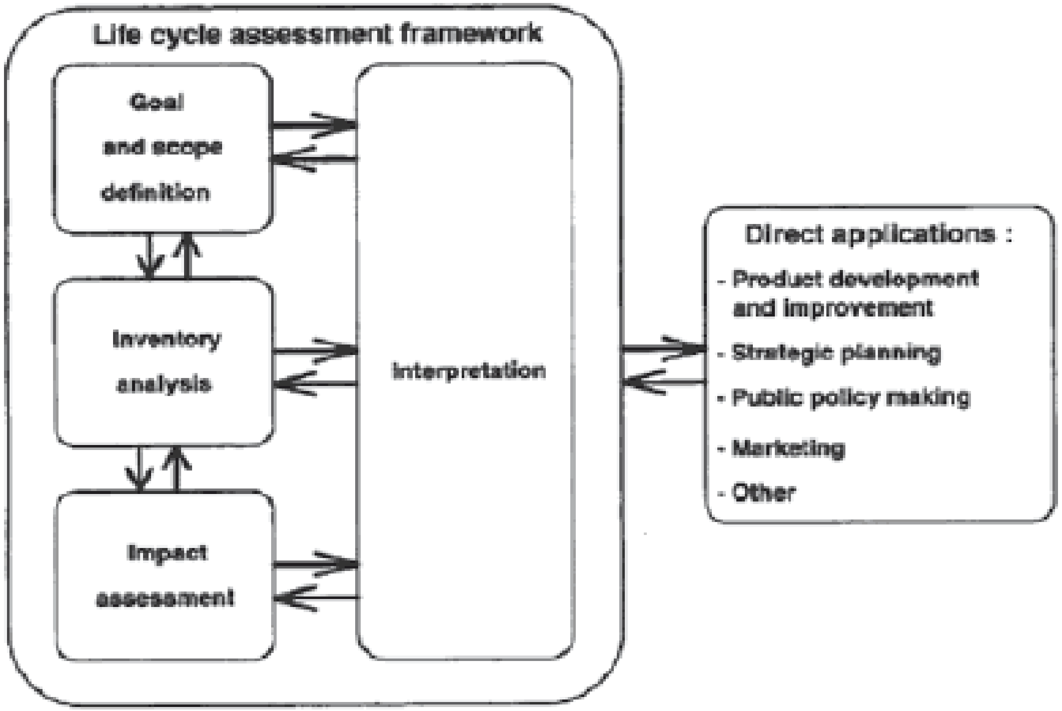


Figure 1 Phases of a LCA Study (ISO14040: 2006)

Goal/Scope Definition
Inventory
Impact Assessment
Interpretation
Applications

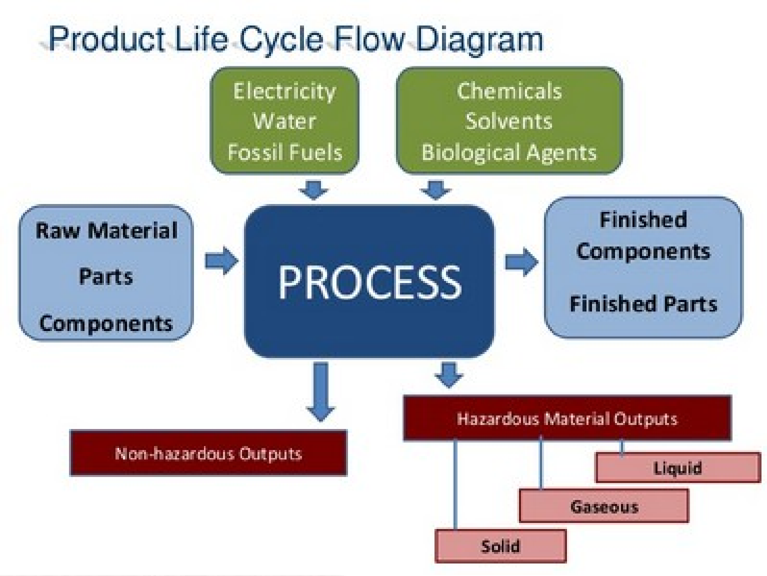
- Example (EPA): LCA of solders in electronics (compare lead-containing solder with alternatives – some combination of tin, silver, bismuth, and copper)

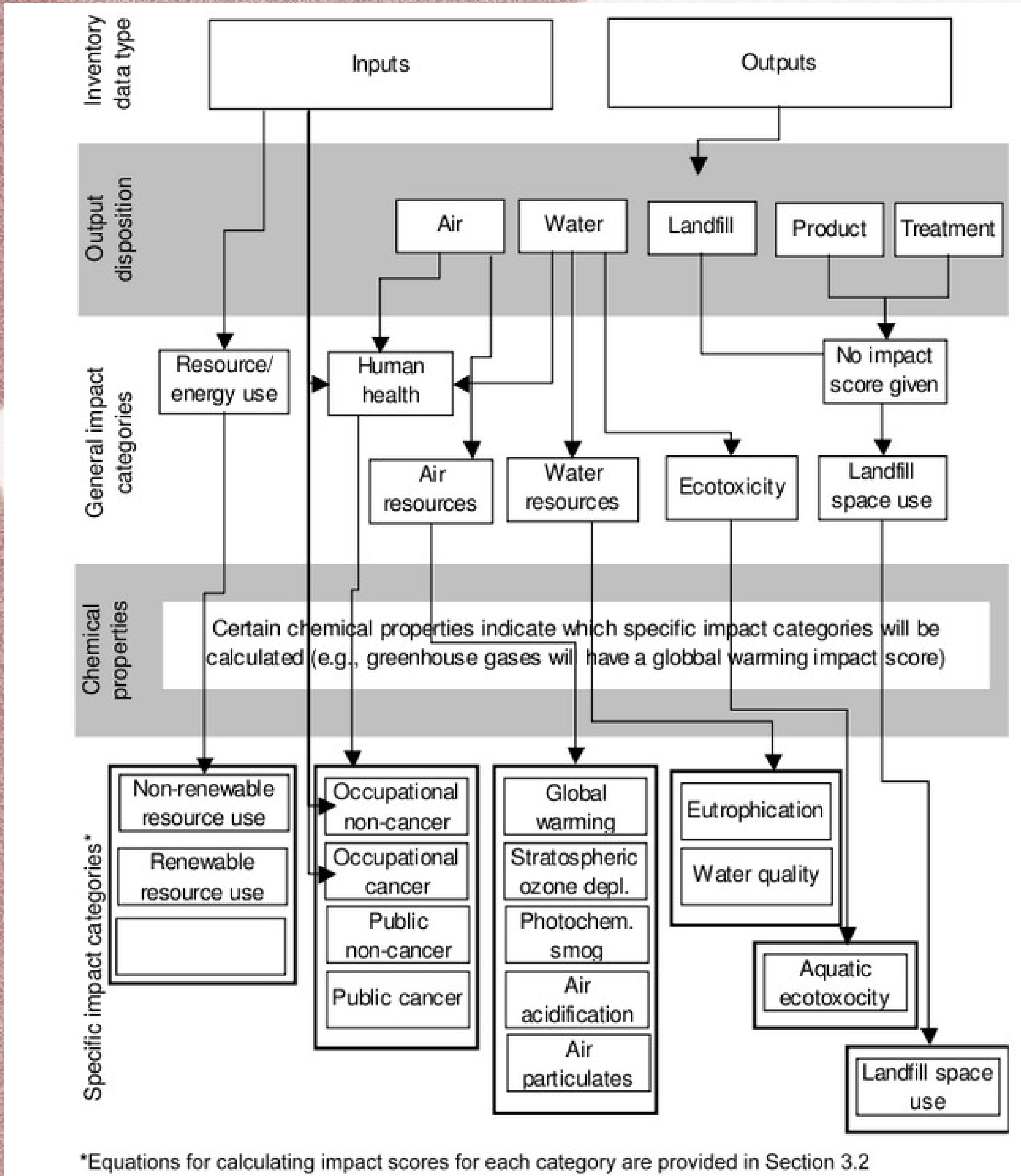
(1) Scope

- What is the goal(s)? What aspects related to the product need to be considered to meet the goal?
- Goal: Compare environmental and health impacts between alternative solder materials
- Scope included metal mining and refining, solder manufacture, solder application, and recycling or landfilling; excluded components believed small (<1%), transportation, demand for electronics/solder

(2) Inventory

- Measure or estimate the material and energy flows at each included stage of the life cycle, including emissions to air, water and soil
- Sources of data: Literature search, direct observation/measurement, databases (NREL LCI, ICE, proprietary)
- E.g.: mining emissions were obtained from literature; material and energy use during soldering by experiment; recycling emissions by asking companies; some solder recovery efficiencies were assumed





(3) Impacts

- Group and aggregate inventoried matter and energy flows into impact categories
- There are conventions (like GWP) for conversion factors from inventory to impact units

(4) Interpretation

- Highlight "noteworthy" results of analysis
- Evaluate uncertainties in data and methods used
- Develop conclusions, recommendations
- Bring in economic and technical factors
- E.g.:
  - Lead solder resulted in more toxic emissions than alternatives, but less greenhouse gas emissions
  - Using recycled metal for solder can greatly reduce life-cycle impacts

Construction vs. operating energy

- Ratio is around 1:10 for motor vehicles (with another 1 for roadway construction), 1:20 for trains and aircraft
- Building construction energy ≈ 10 years of operation
- Favors investing more in building infrastructure that has low operating energy, e.g. superinsulated buildings, electric vehicles
- Close to or under 1:1 for customer electronics

Limitations of LCA

- No objective way of weighting the various impact categories
  - (Subjective) weights are nonetheless available, e.g. Eco-Indicator 99
  - Can test the sensitivity of rankings to weights
- At best, gives a relative (more/less unsustainable) indication
- Different analyses usually not directly comparable because of different scopes, etc.
- Still, considered to be better than nothing, if only for raising awareness

High-profile applications of LCA

- Paper vs. plastic cups, cloth vs. plastic diapers (1990-)
- Biofuels: are they actually carbon-neutral?
- California low-carbon fuel standard (2007) and EPA Renewable Fuel Standard (2010): fuel GWP (carbon intensity) to be determined using LCA

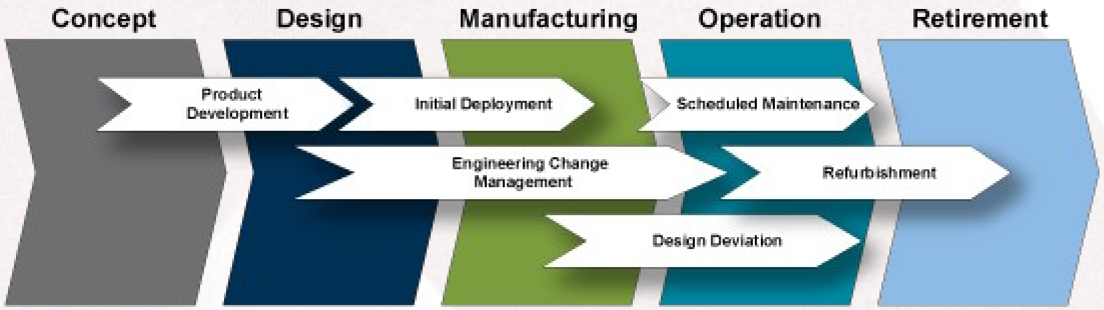
Variants of LCA

- Exergy LCA: express impacts as exergy requirements and wastes
- Express impacts in terms of ecological footprint, carbon footprint, water footprint, etc.
- “Streamlined” LCA with only semi-quantitative evaluation of impacts by type and life-cycle stage

Design for Sustainability

How can engineering be re-thought?

The design/build process



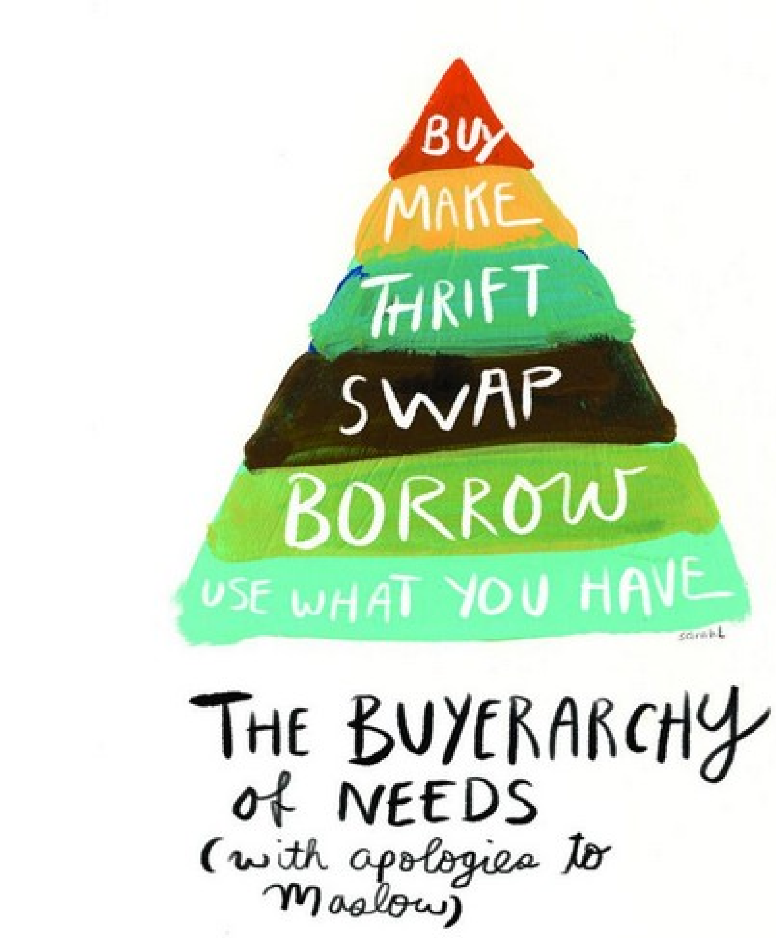
Easier to modify approach early in design stages

Green engineering principles

- Avoid hazardous materials
- Choose renewable materials and energy
- Prevent waste
- Design for durability and “afterlife”
- Cf. EU regulations: Restriction of Hazardous Substances (applies to Pb, Hg, Cd, Cr^{+6}, PBB, PBDE), Registration, Evaluation and Authorisation of Chemicals (REACH), Waste Electrical and Electronic Equipment

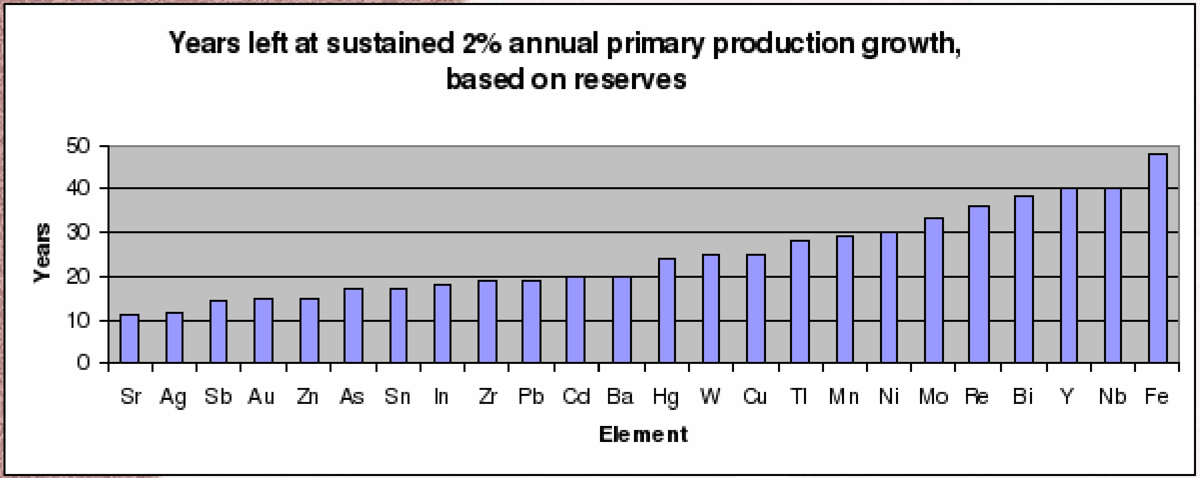
Design for reuse

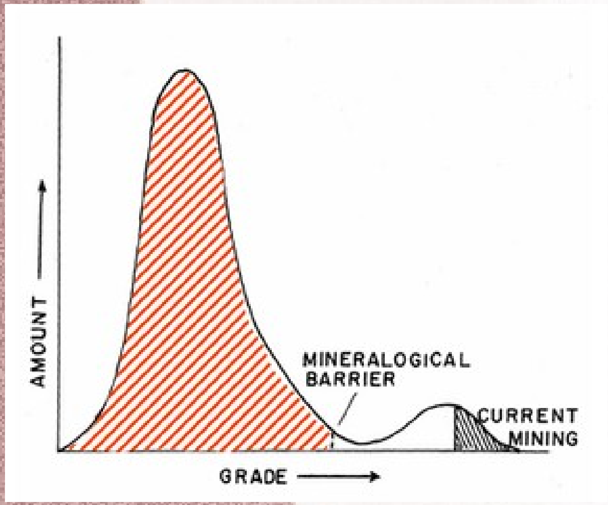
- Priority: reuse-refurbish-remanufacture-recycle(closed-loop)-downcycle(open-loop)
- Use few materials and components
- Modularize (allow failed component to be replaced) [e.g. fridges, washing machines]
- Mark components (e.g. types of plastic, steel beams)
- Make separation easy (e.g. bolts rather than welds)
- Dissipative components should be benign/biodegradable (e.g. tire rubber)



The Story of Stuff

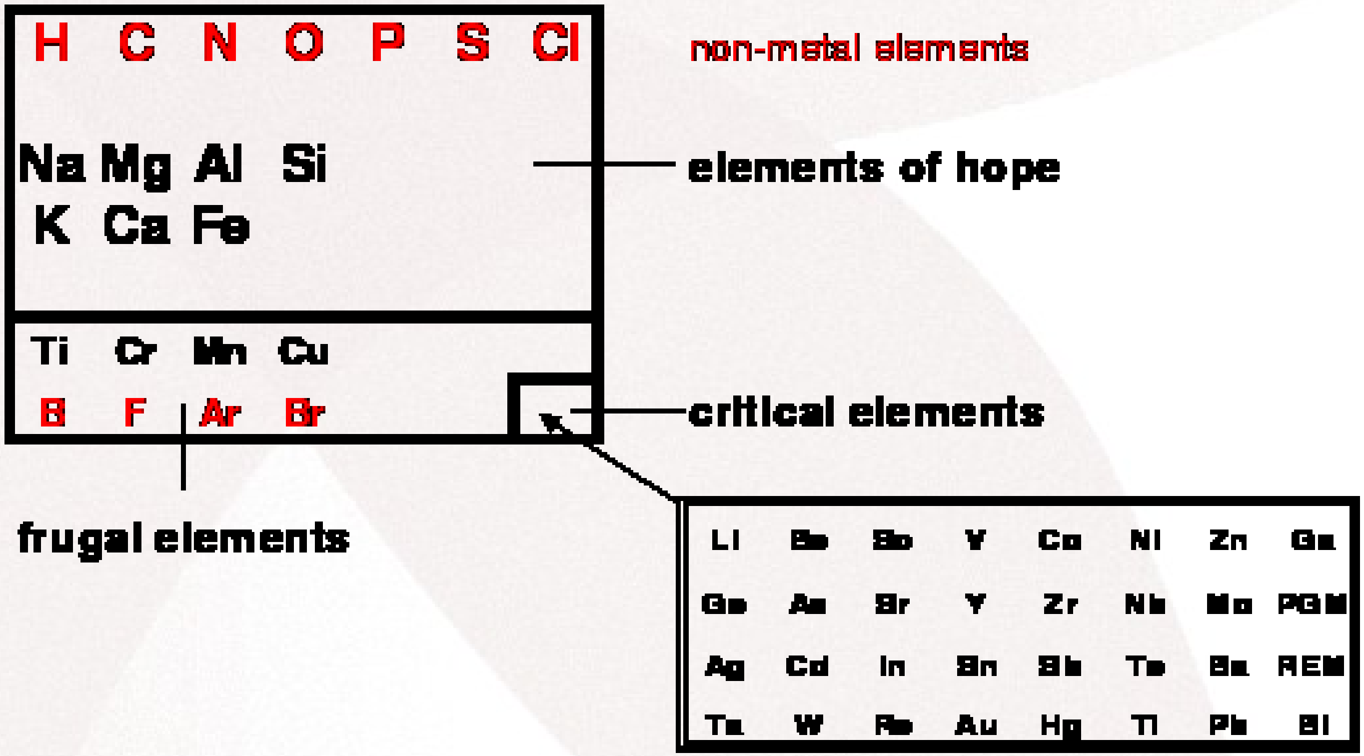
Choice of elements





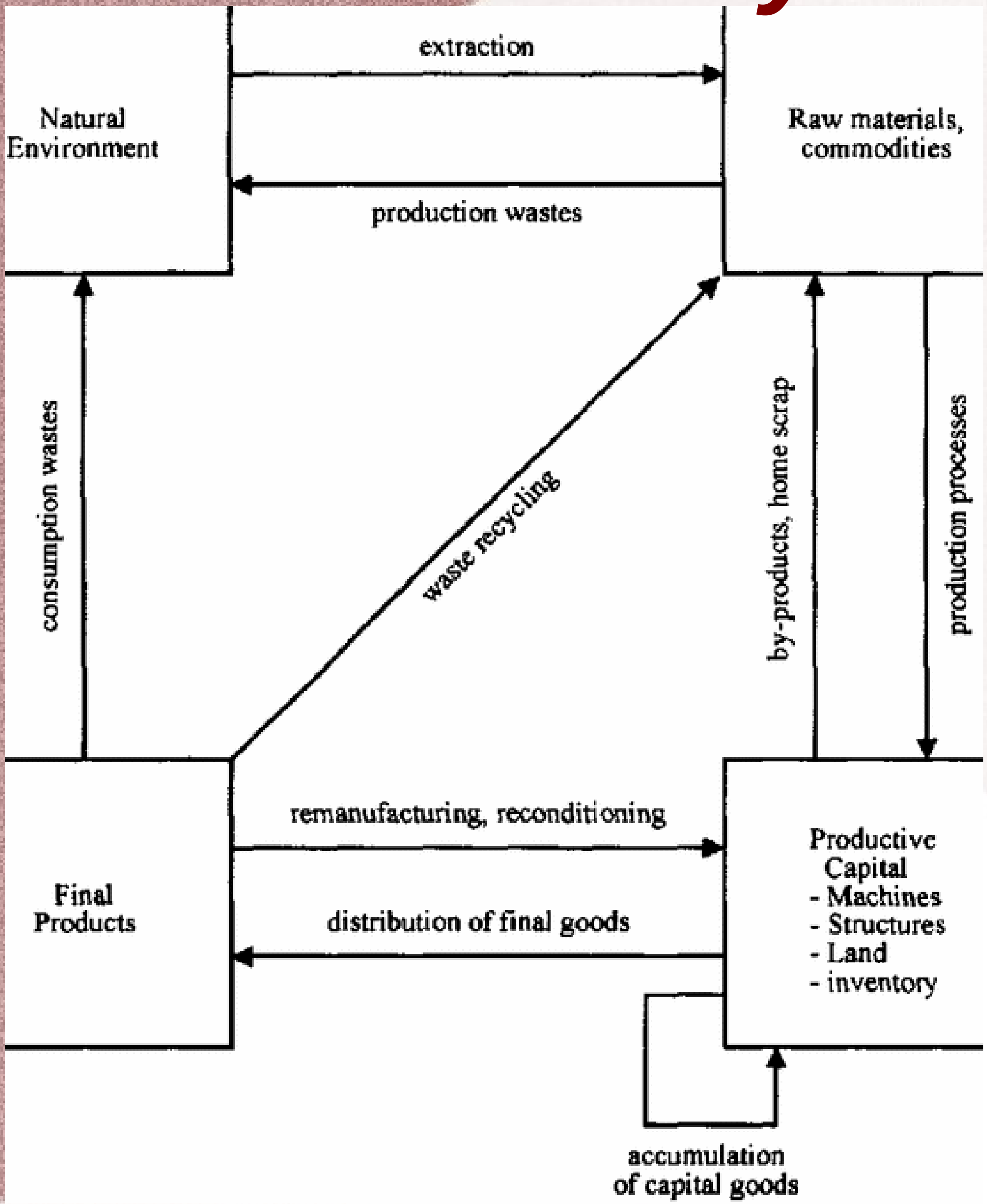
- High-grade reserves of many elements used in high-tech applications are scarce
- Low-grade reserves require much more energy to exploit
- Production may be concentrated in a single country, e.g. REEs
- Health/pollution considerations

A sustainable designer's periodic table (Andre Diederen)



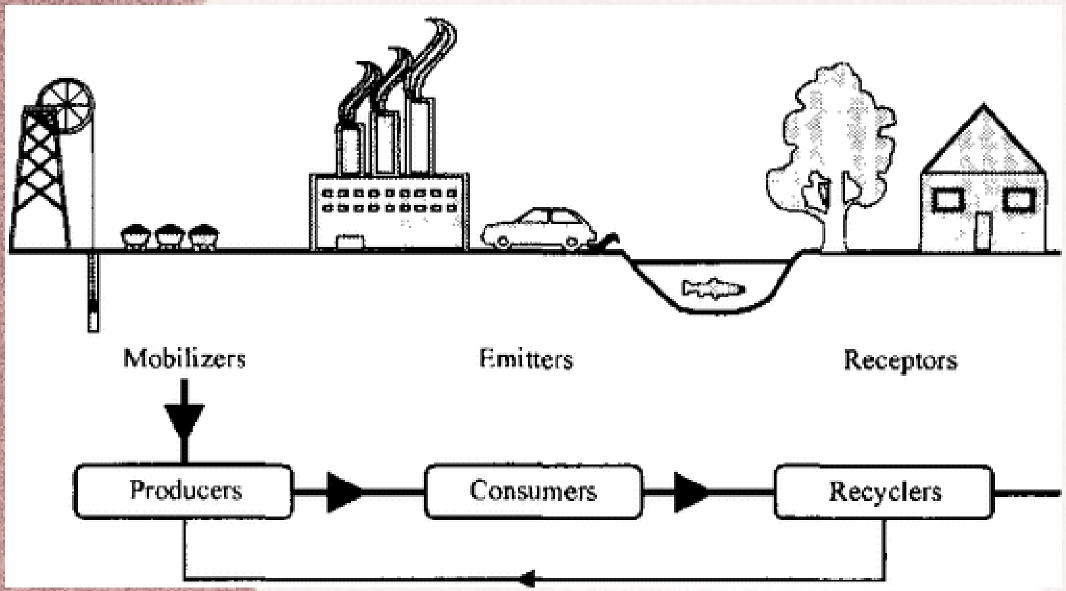
- **Elements of hope**: abundant, rely on those
- **Frugal elements**: less abundant, limit use
- **Critical elements**: hard to get, avoid if possible

The ecology metaphor for human industry matter-energy flows



- Technical processes, like life, consume exergy to transform matter
- Energy and material flows can be thought of as a technical metabolism
- Niches, evolution, life cycle, recycling

Learning from ecosystems



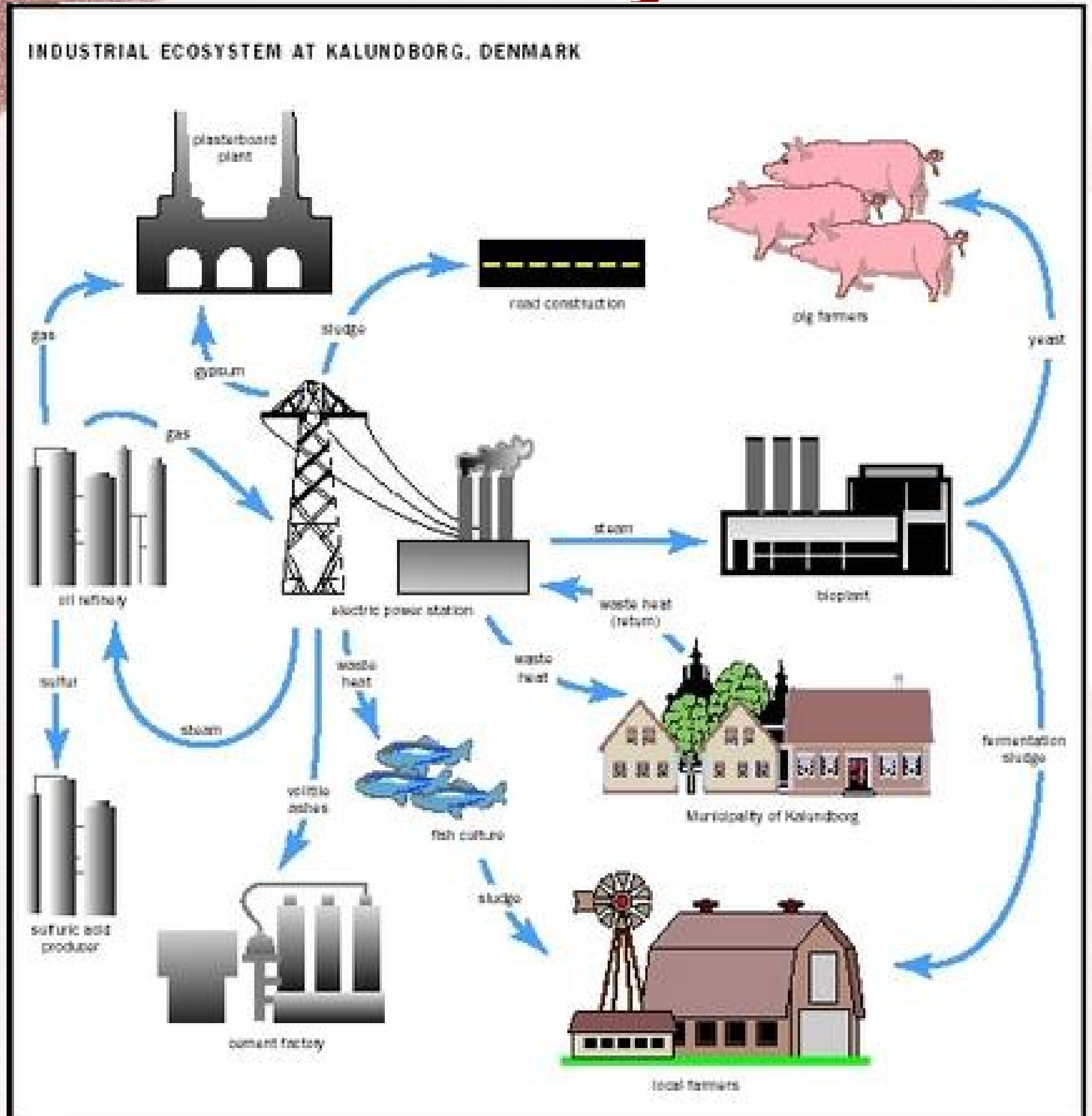
- Matched to prevailing energy flows
- High connectivity, symbiosis
- Local recycling of most wastes
  - Common underlying biochemistry facilitates recycling
- Diversity and resilience (multiple ways of meeting function, multiple functions per item)

Systems attributes (seen in ecosystems -- and infrastructure?)

- Interdependence
- Holism, holarchy
- Goal seeking
- Inputs-outputs-transformation
  - nonlinearity
- Regulation-feedback
  - adaptation may be unpredictable
- Differentiation
- Equifinality
- Multifinality

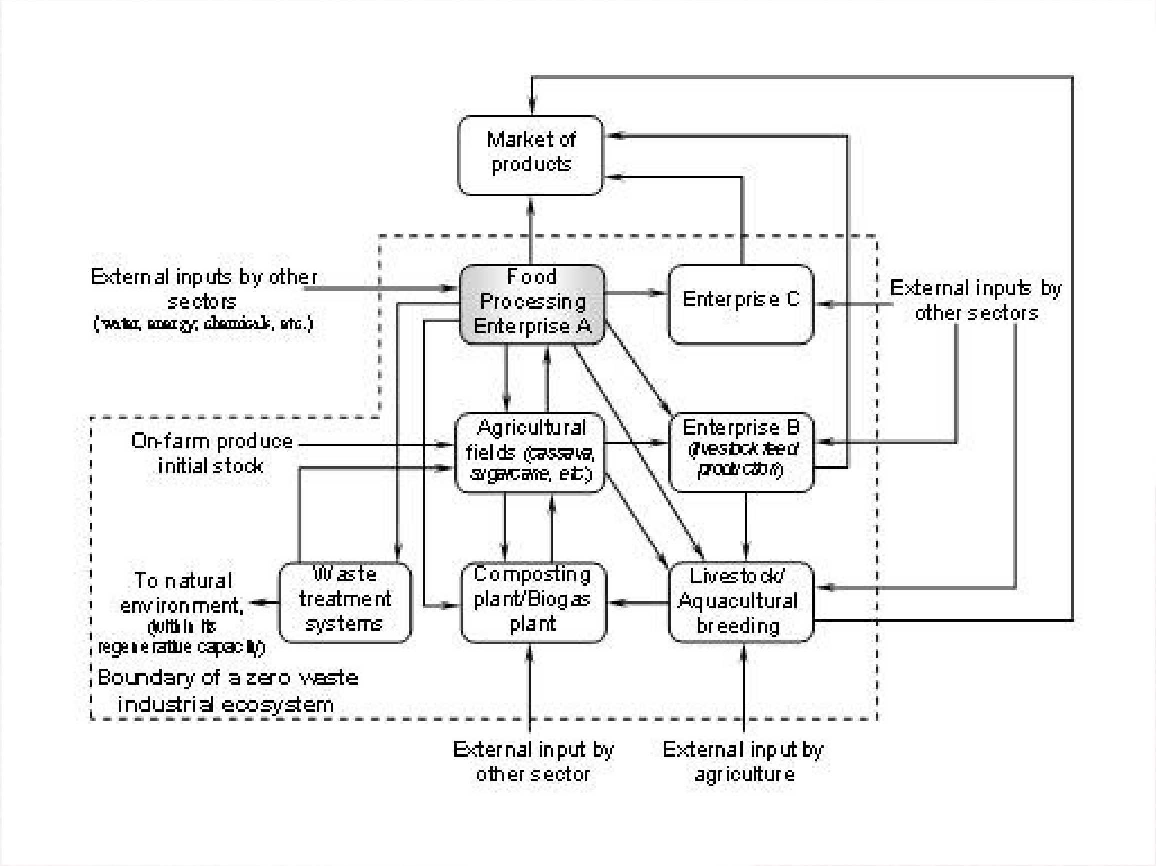
cf. Donella Meadows,
Thinking in Systems: A Primer

Industrial symbiosis



The classical example (but most exergy from fossil fuel)

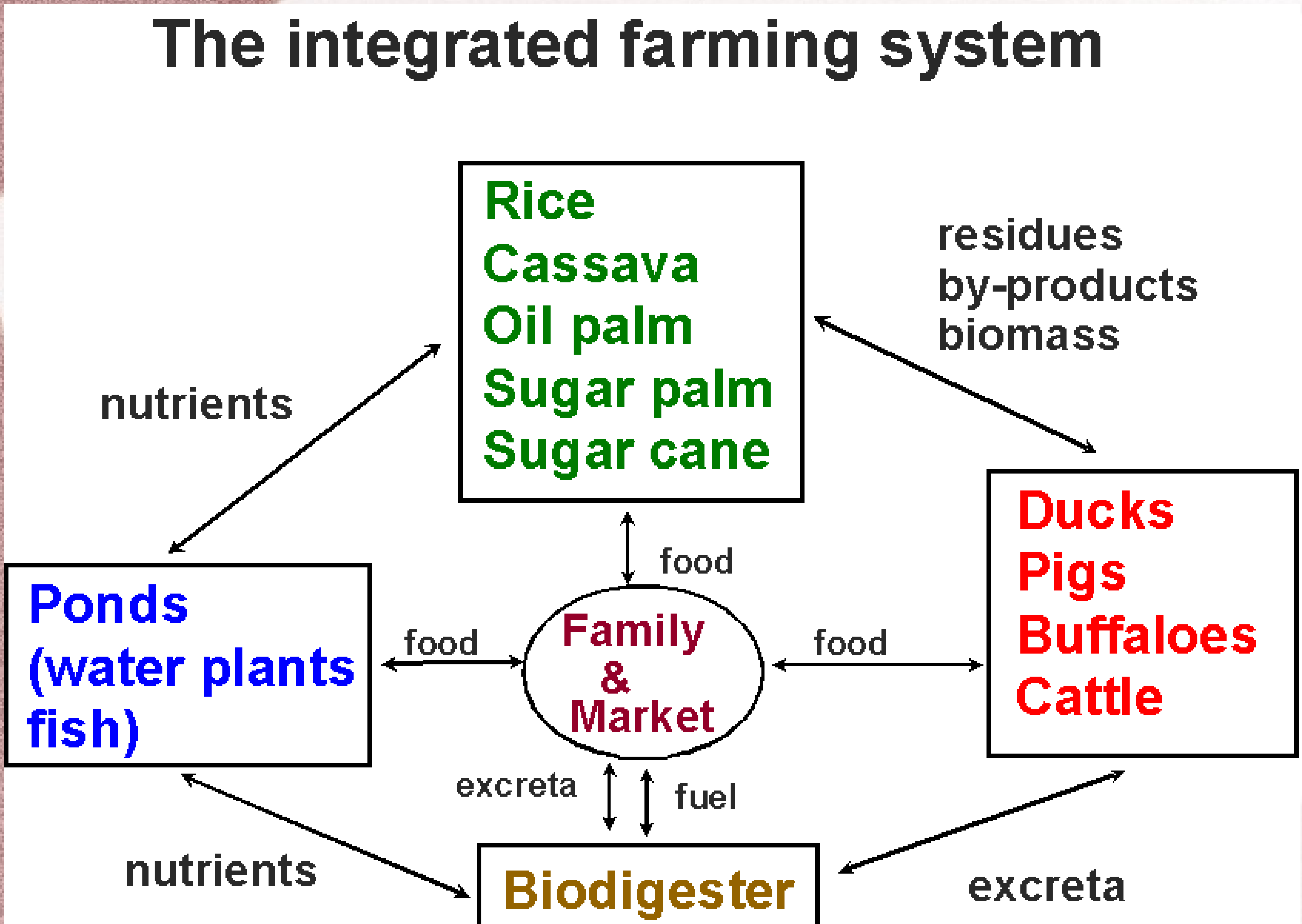
Agriculture-based symbiosis



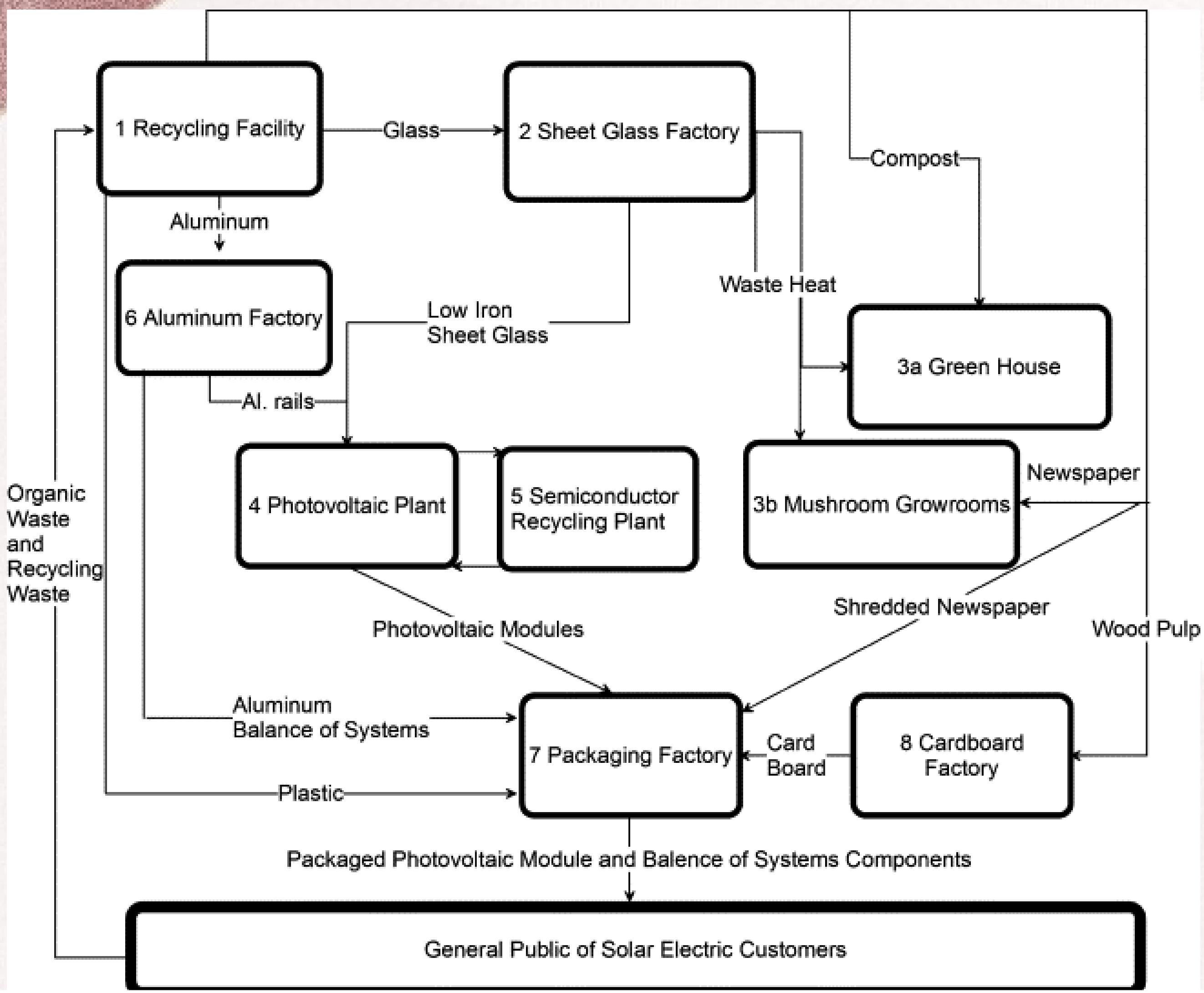
Partly/largely solar source of exergy

Dieu, *Greening Food Processing Industries In Vietnam: Constraints And Opportunities*

Small-scale agricultural integration



Symbiosis for PV production

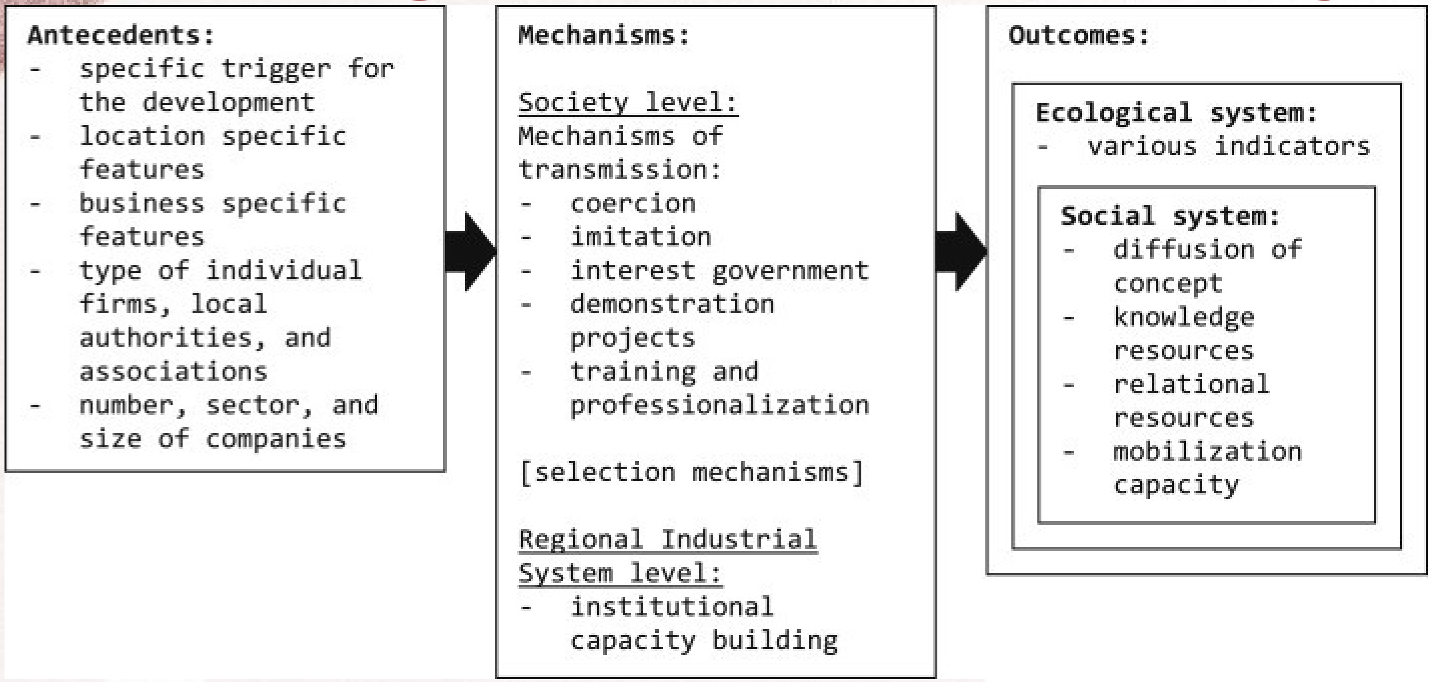


Pearce, “Industrial symbiosis of very large-scale photovoltaic manufacturing“ (2008)
advocated as “a medium-term investment by any government”

Supportive Logistics and Policy

Boons et al. (2011), "The dynamics of industrial symbiosis"

Rosa and Beloborodko (2015), "A decision support method for development of industrial synergies"



- Proximity matters: "within the National Industrial Symbiosis Programme in United Kingdom, 1/4 of exchanges occurred within 15.4 km radius, 1/2 occurred within 32.6 km radius, and 3/4 occurred within 62.6 km radius"
- What policies/infrastructure would you suggest to encourage symbiosis?