Energy & Environment

Life Cycle Assessment

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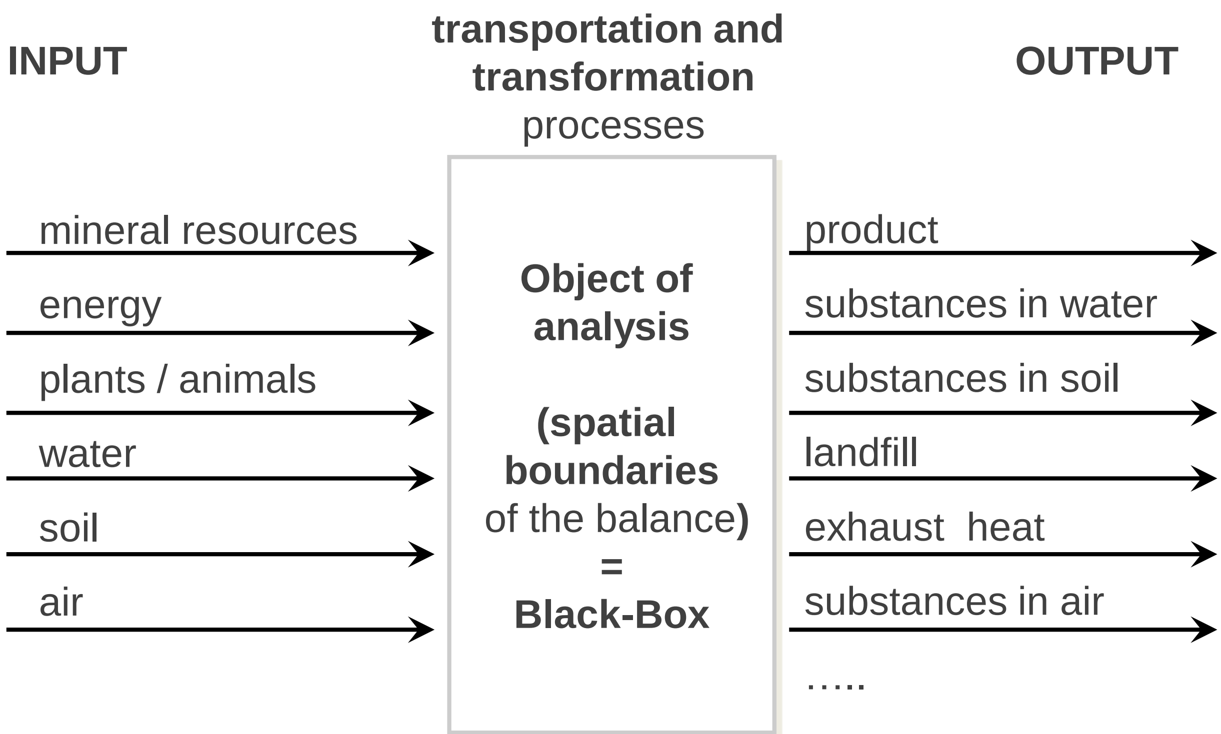
- Material flow management
- Life Cycle Assessment (LCA)
- Life Cycle Assessment of photovoltaic systems
- Environmental performance of energy systems

Material flow management

Material flow management

- Efficiently manage materials (economic and ecologic)
- Cost savings
  - Material costs represent biggest cost factor in the manufacturing sector!
- Reasons
  - Scarcity of resources leads to rising costs
  - Manufacturing companies reduce vertical integration and use higher quality materials
  - Previous cost reduction programs focused largely on labour costs or on improvements in the organizational structure
- Lowering the cost of materials is essential in order to remain globally competitive

Material and energy balance



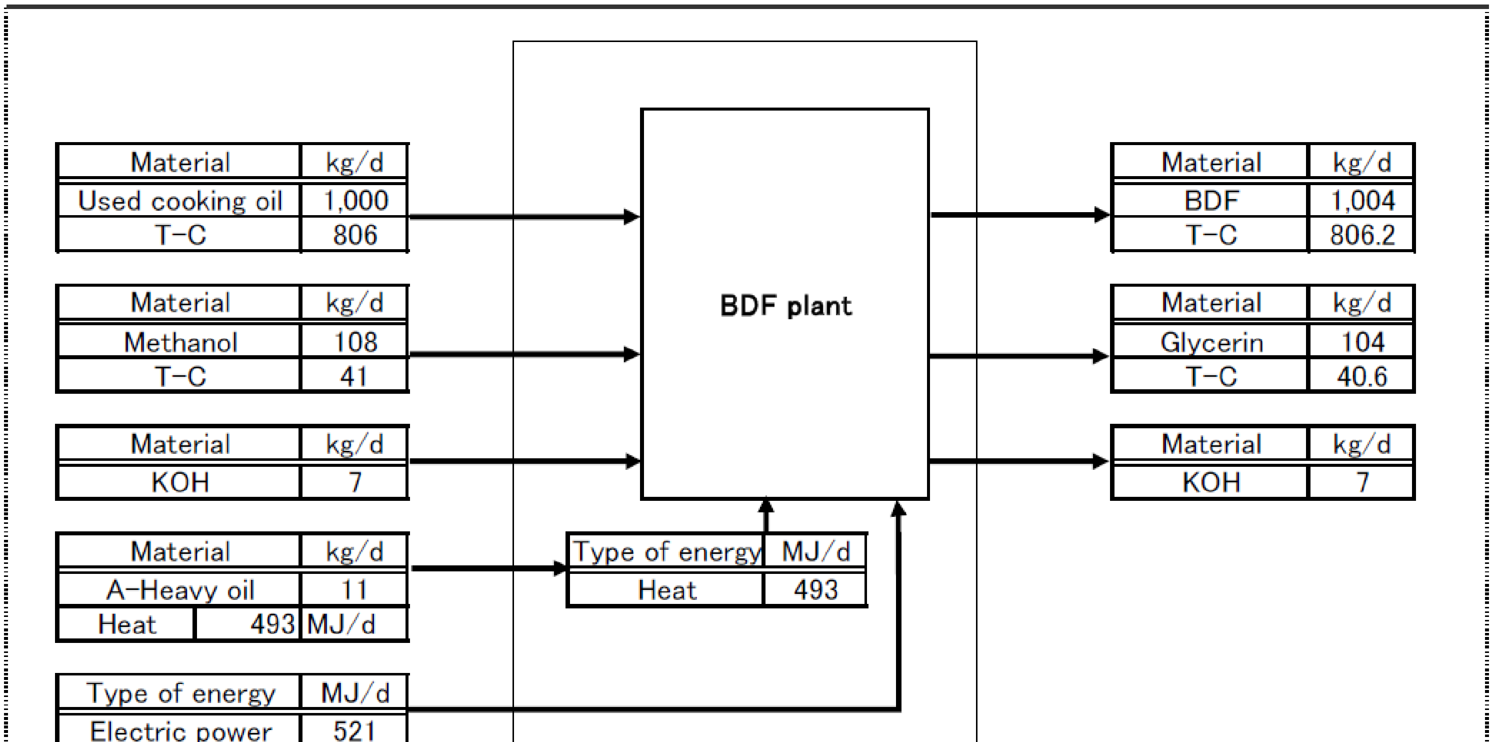
By accounting for material and energy entering and leaving a system, mass flows can be identified which might have been unknown, or difficult to measure.

First law of thermodynamics!

Material and Energy Balances in BDF production

Used cooking oil, Capacity; 5t/d

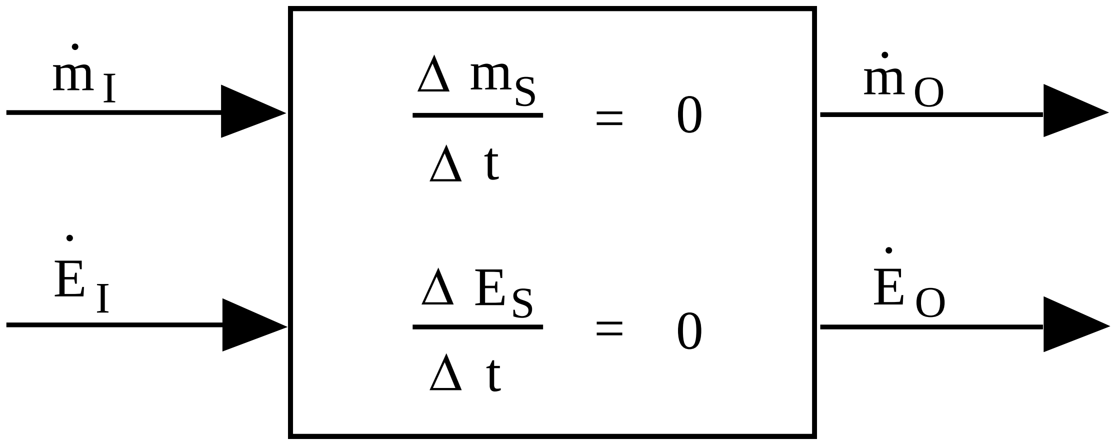
BDF(5t/d)



BDF…biodiesel fuel production

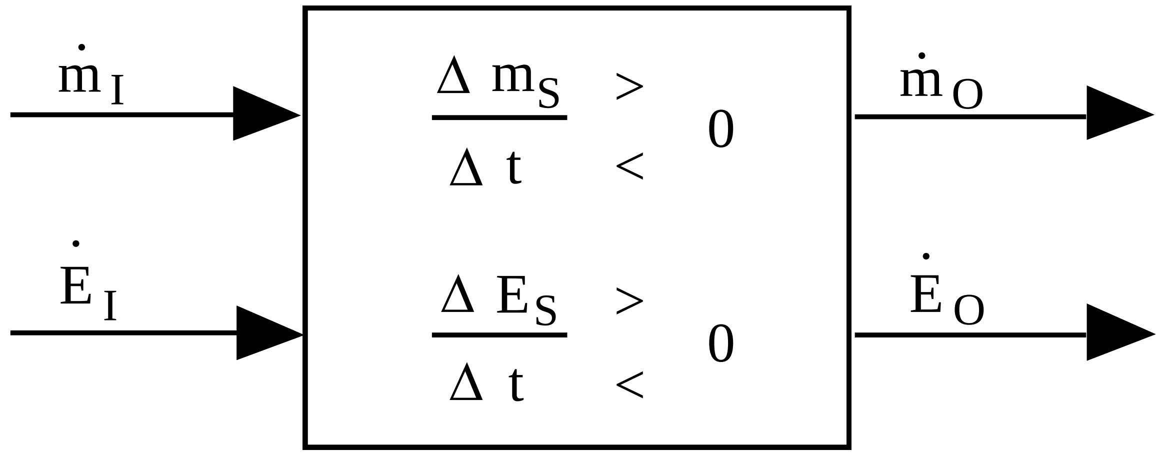
Source: http://www.intechopen.com/books/liquid-gaseous-and-solid-biofuels-conversion-techniques/biofuel-sources-extraction-and-determination

Steady-state processes



$$\sum \dot{m}_I = \sum \dot{m}_O \qquad \sum \dot{E}_I = \sum \dot{E}_O$$

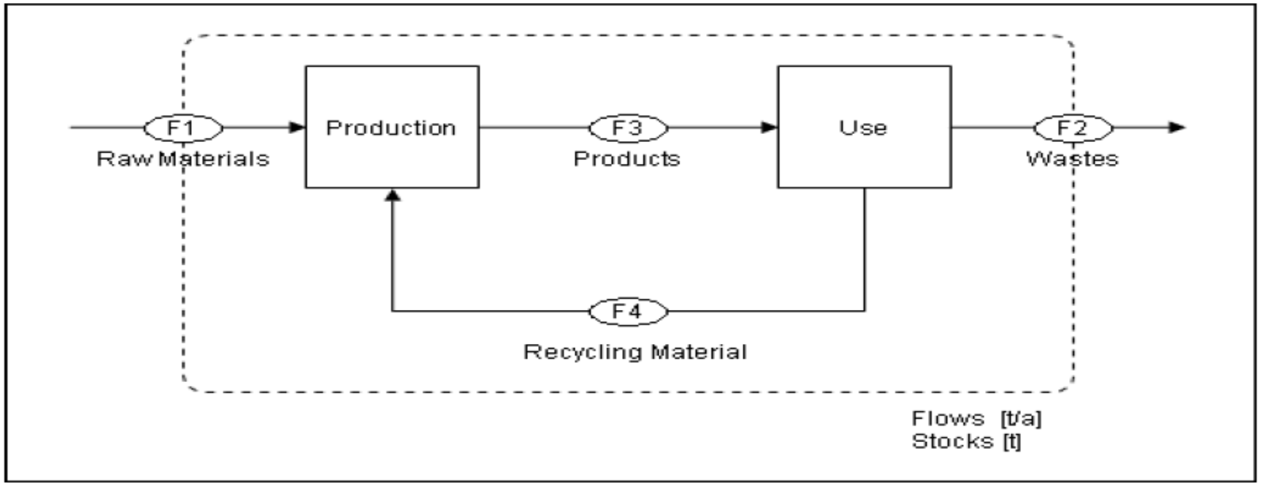
Dynamic processes



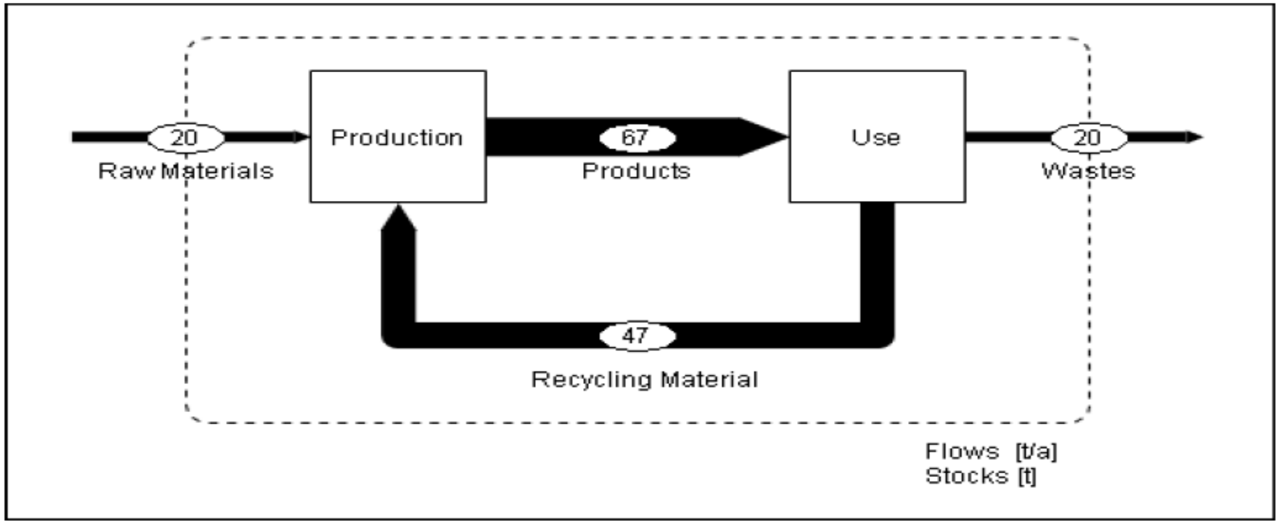
$$\sum \dot{m}_I = \sum \dot{m}_O - \frac{\Delta m_S}{\Delta t}$$

$$\sum \dot{E}_I = \sum \dot{E}_O - \frac{\Delta E_S}{\Delta t}$$

Example: Material Flow Analysis



Raw Materials = 20 t/a, Recycling Rate = 0.70



Source: Stan 2.5

Stocks and flows

Mass / energy balance

Balance of flows
(inputs/outputs)

- mineral resources [t]
- energy resources [kJ]
- products [t]
- residuals [t, kJ]
- …

Balance of stocks

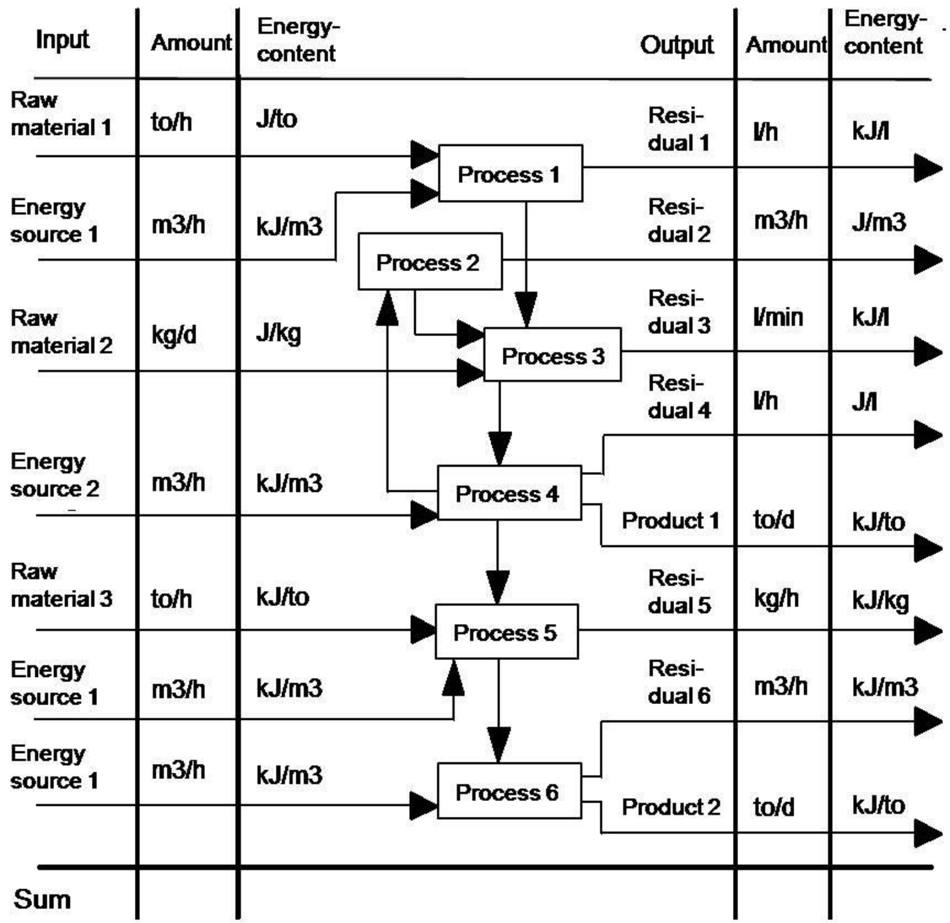
- soil sealing [m^2]
- contaminated sites [m^2]
- facilities [t]
- buildings [m^2, t]
- …

Input-Output-Table

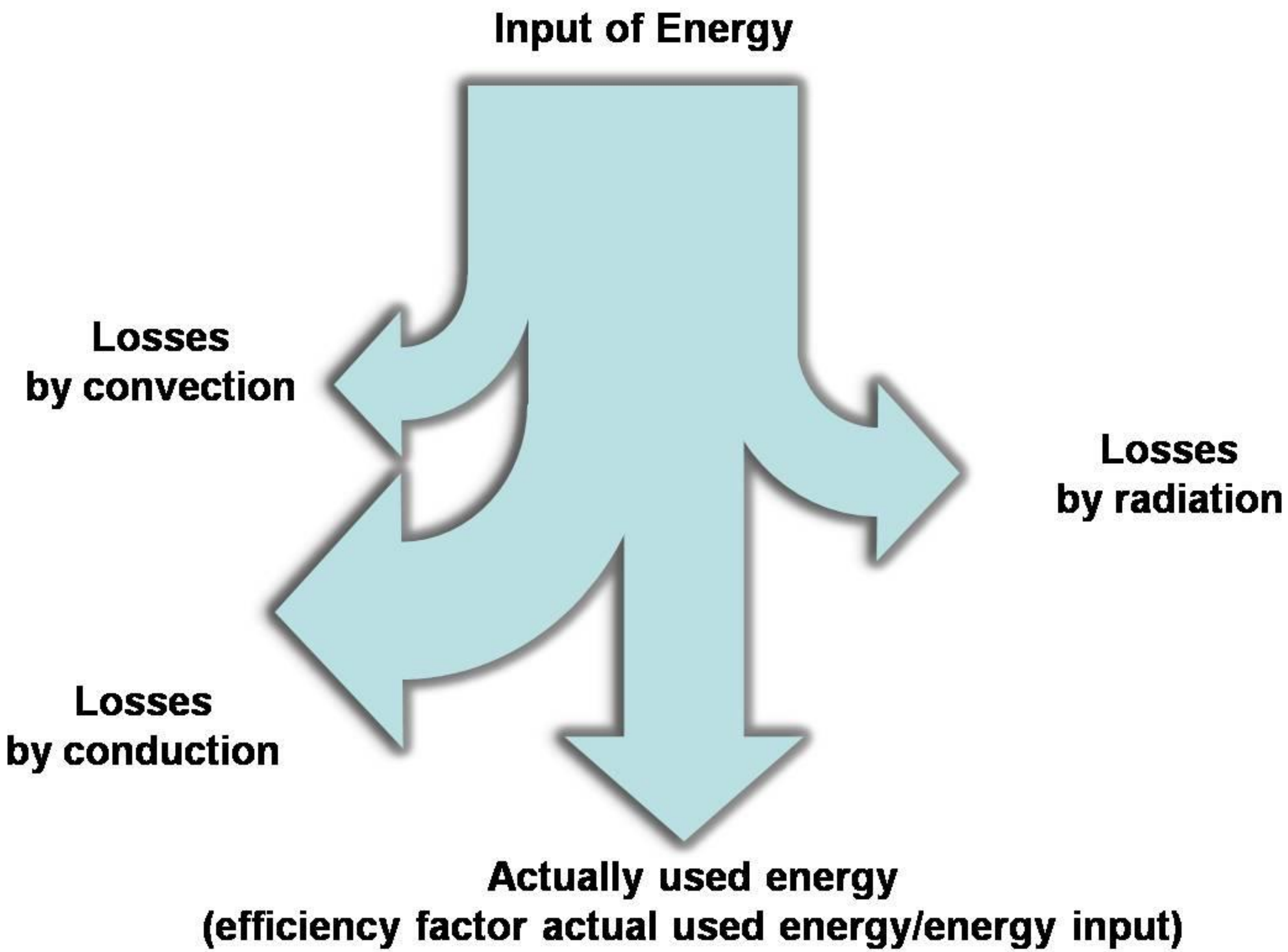
INPUT	Amount	Unit	state of matter	origin	etc.
I. materials					
- raw materials					
- additives					
- operating materials					
II. source of energy					
- solid					
- liquid					
- gas					

OUTPUT	Amount	Unit	state of matter	origin	etc.
I. products					
II. residuals					
1. material					
- solid					
- liquid					
- gas					
2. energy					
- exhaust heat					
- by convection					
- by radiation					
- by conduction					
- light					
- noise, vibration					
- ionising radiation					

Combination of table and flow chart



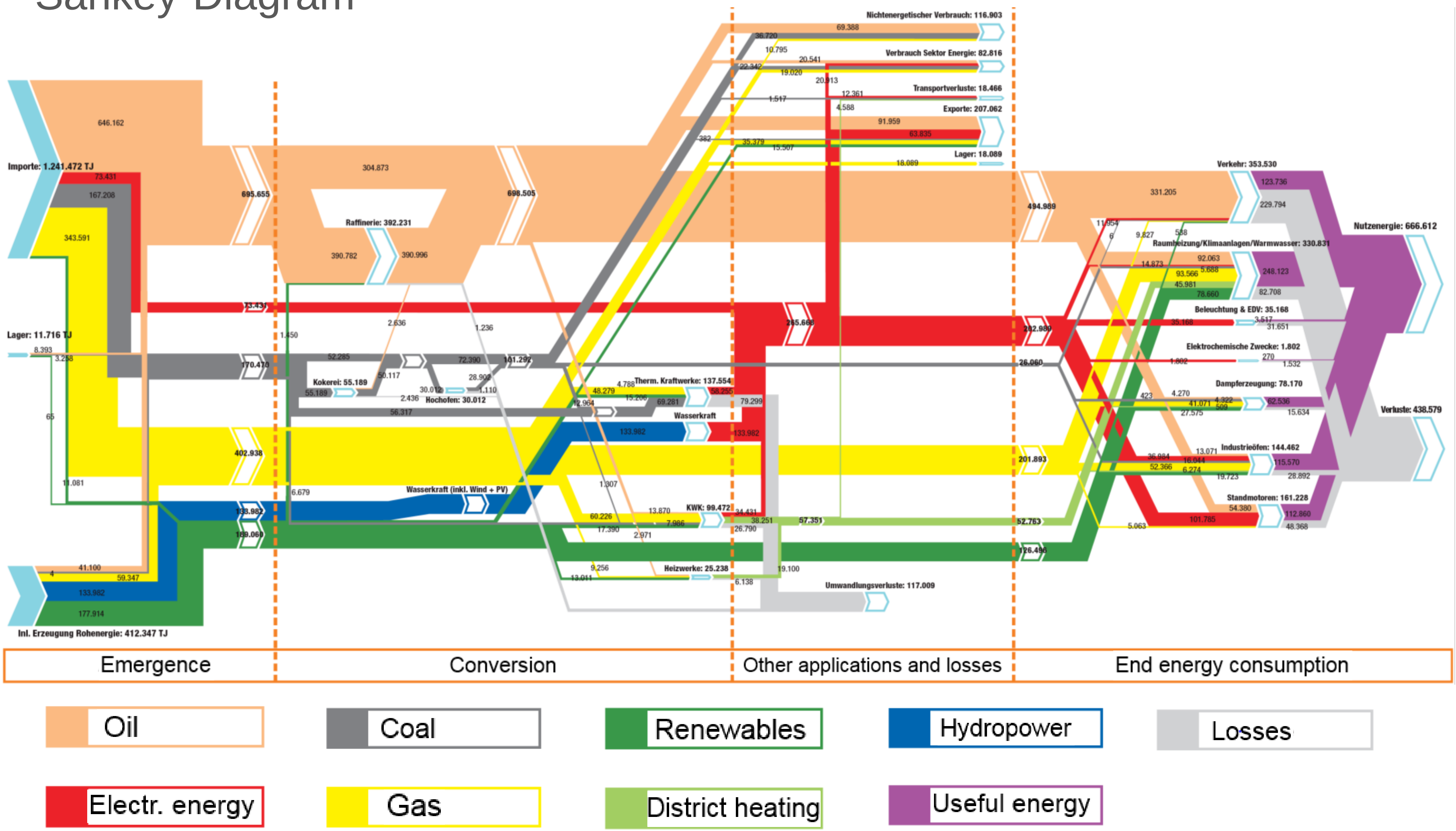
Sankey-Diagrams



Examples see at www.sankey-diagrams.com

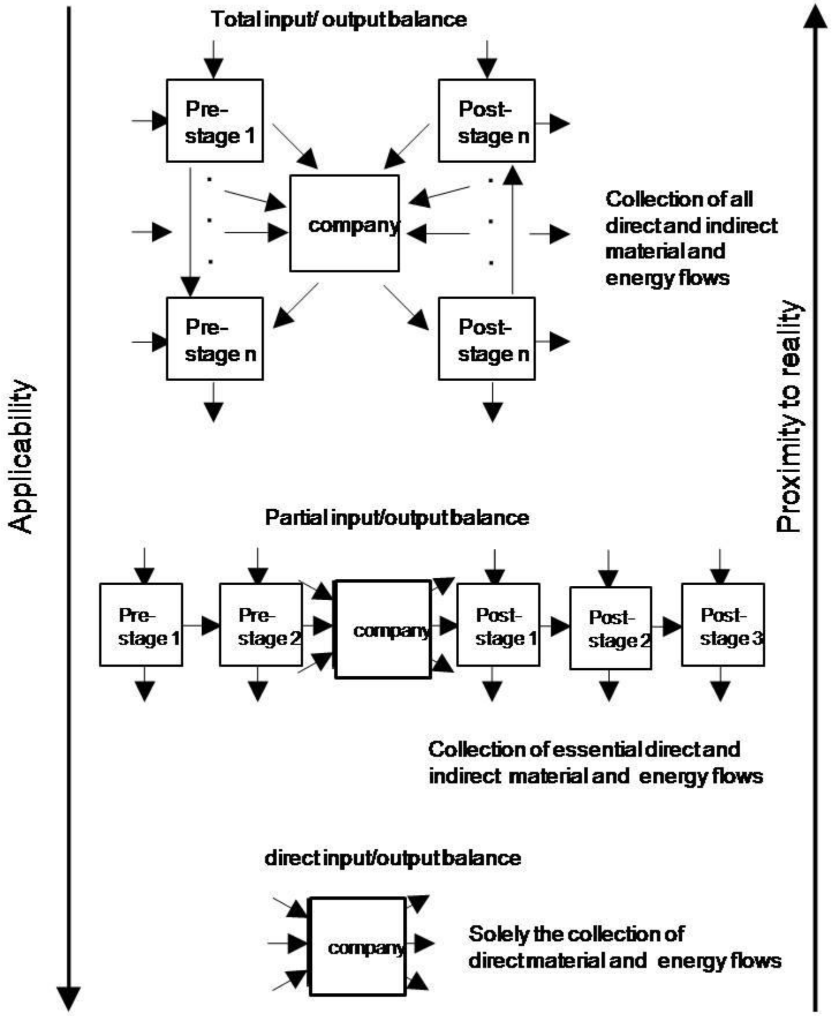
Energy flow diagram Austria

Sankey-Diagram



Source: Austrian Energy Agency

System boundaries



- Boundaries between the technological system and nature
- Geographical area
- Time horizon
- Boundaries between the current life cycle and related life cycles of other technical systems

Material and energy balances

Sources of information

- Cost-accounting
- Purchase
- Accounting
- Asset management
- Responsible employees (e.g. special officers)
- Measurements, calculations, observation

Life cycle assessment (LCA)

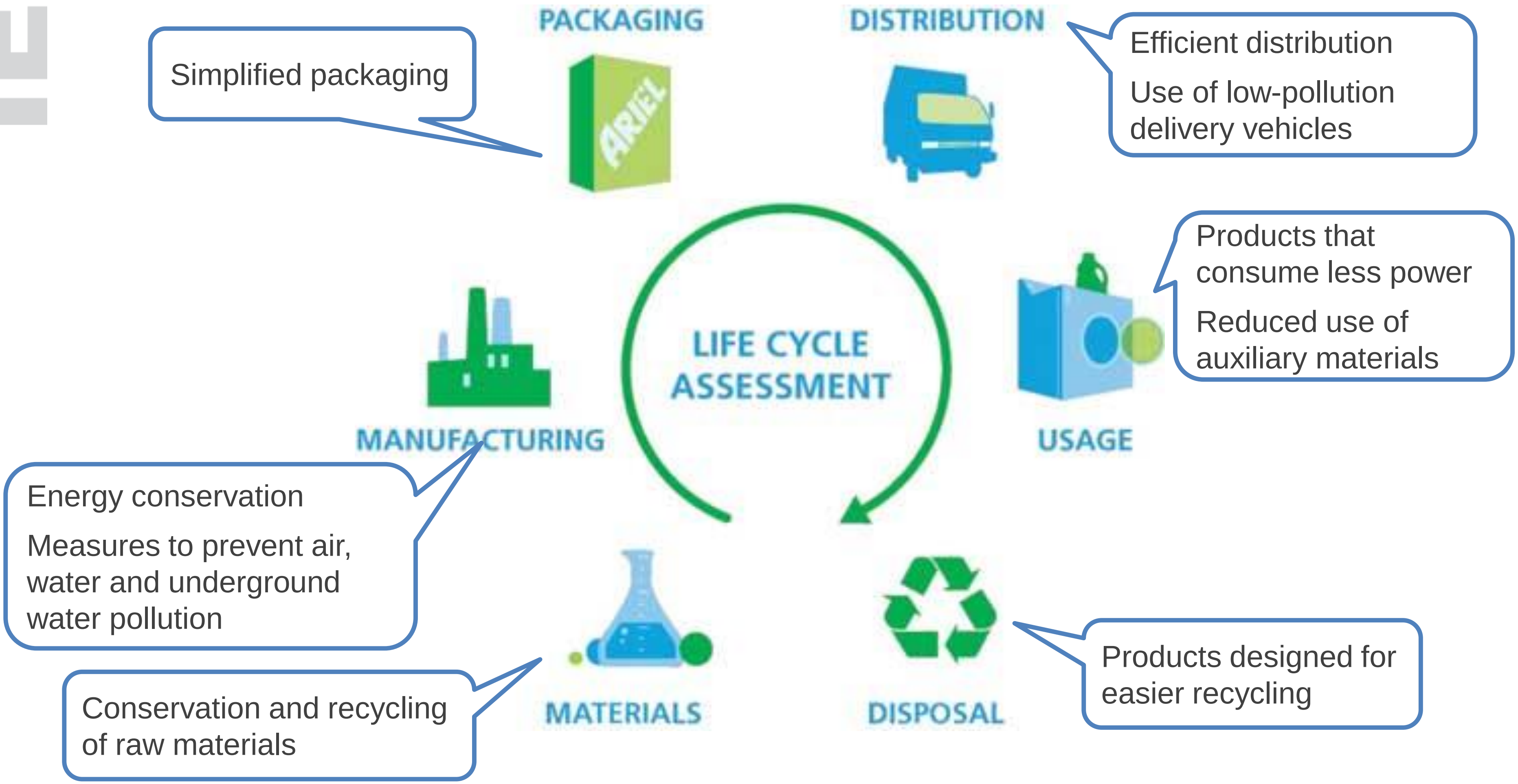
What is a LCA?

*Life-cycle assessment is a technique to assess **environmental impacts associated with all the stages of a product's life** from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling.*

Also known as

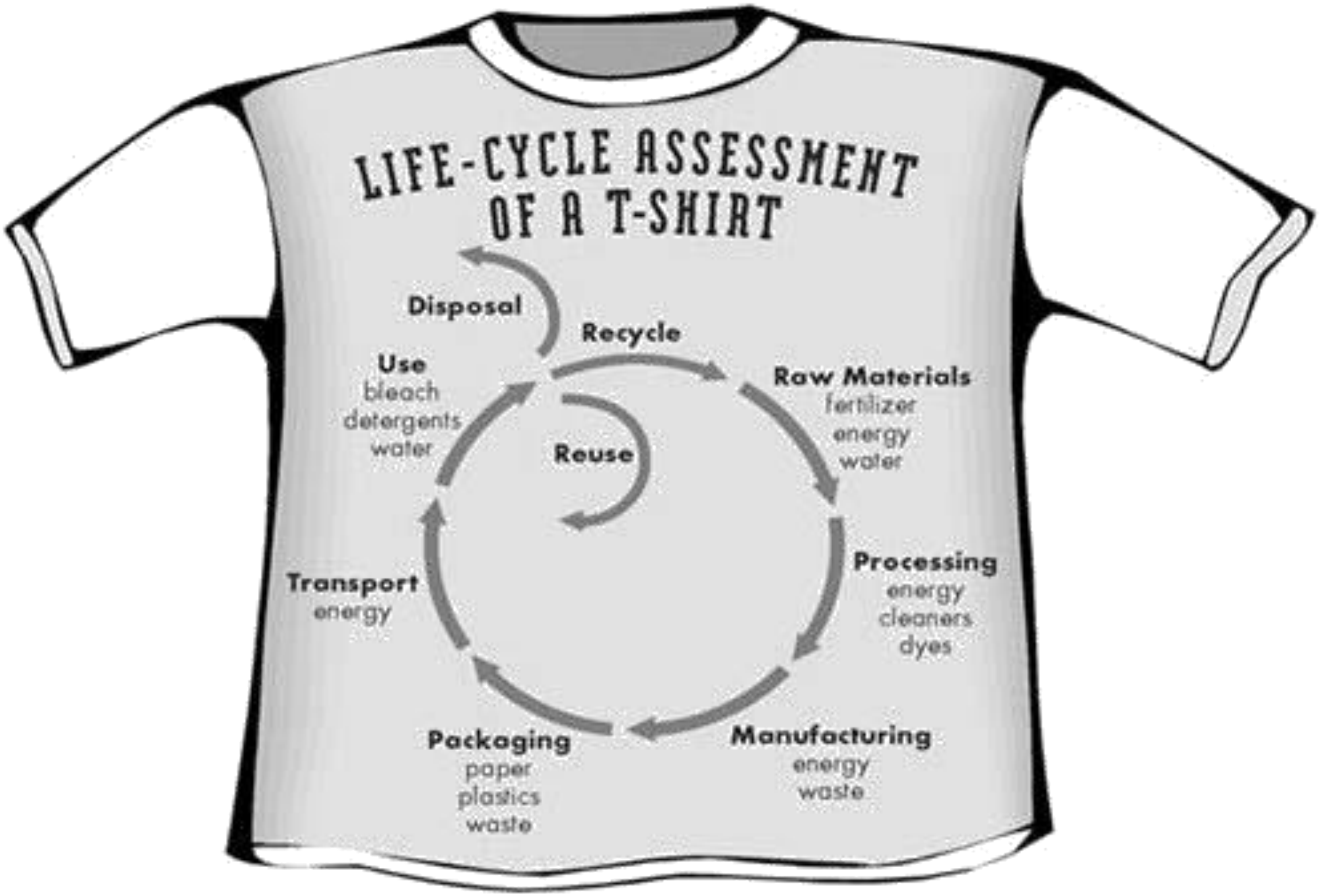
- Life cycle analysis
- Eco-Balance (Ökobilanz)
- Cradle-to-grave analysis

LCA



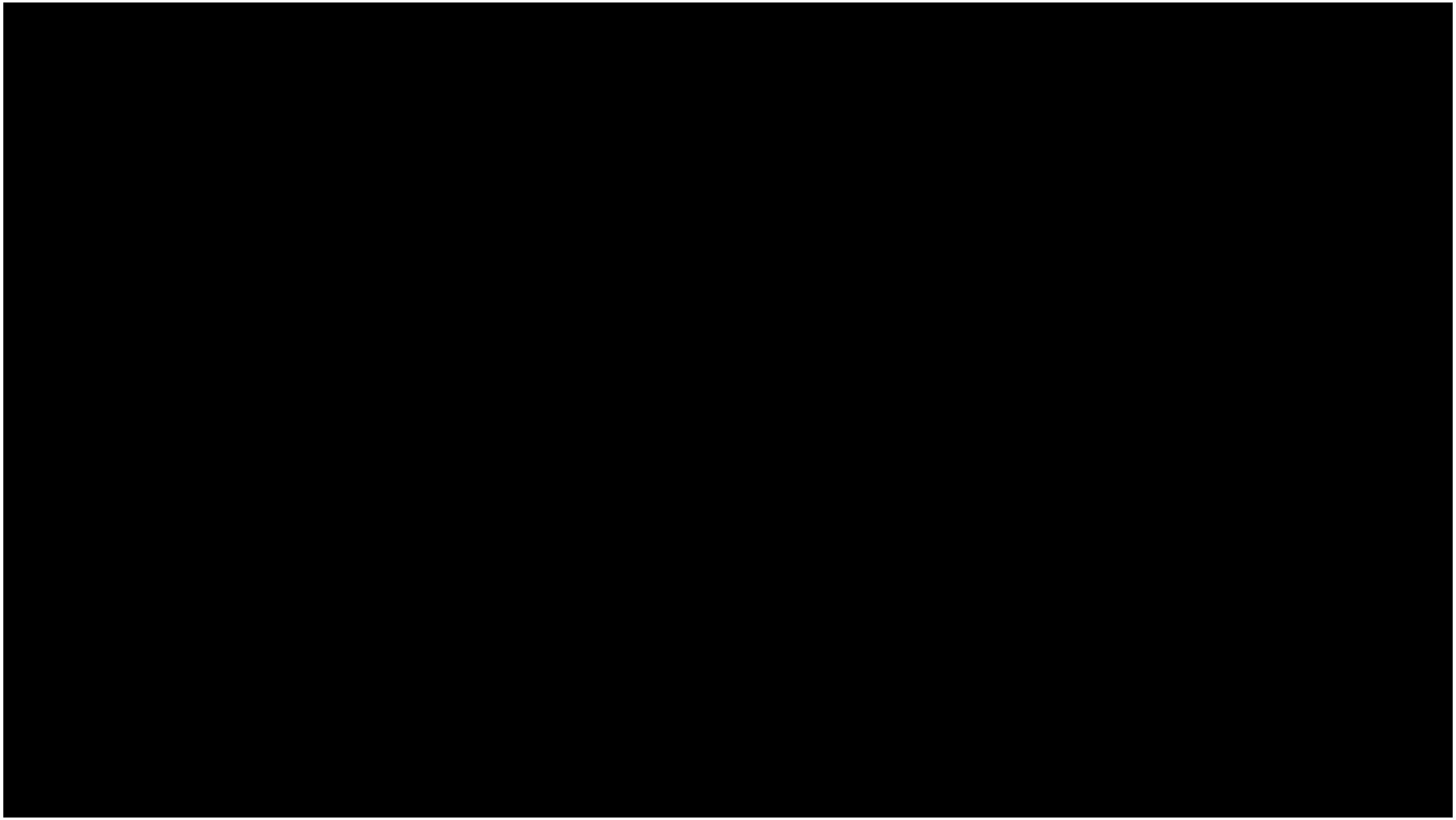
Source: www.sites.davidson.edu

LCA



Worldwatch Institute, Worldwatch Paper 166: Purchasing Power: Harnessing Institutional Procurement for People and the Planet, July 2003, www.worldwatch.org

LCA



Life Cycle Assessment in accordance with ISO 14040/14044

Definition of the goal and scope of the LCA (ISO 14040)

Life Cycle Inventory (ISO 14044)

Life cycle impact assessment (ISO 14044)

I. classification
II. characterization
III. normalization / weighting

Interpretation (ISO 14044)

Reporting, critical review, limitations

Direct applications:

- ✓ Product development and improvement
- ✓ Strategic planning
- ✓ Public policy making
- ✓ Marketing
- ✓ Other

Goal and scope definition

Goal definition

- Intended application
  - Product development and improvement
  - Strategic planning
  - Public decision making
  - Marketing
  - …
- Reasons for conducting the study
- Intended audience, communication

Scope definition

- Functional unit: reference to which inputs and outputs can be related
- Assumptions and limitations
- Critical review and other procedural aspects
- Define system boundaries based on goal and scope

Goal and scope definition

- Functional unit
  - Comparison on the basis of an equivalent (function)
  - Reference to which the inputs and outputs can be related
- Example
  - 1000 litres of milk packed in glass bottles or packed in carbon
  - Instead of 1 glass bottle versus 1 carton

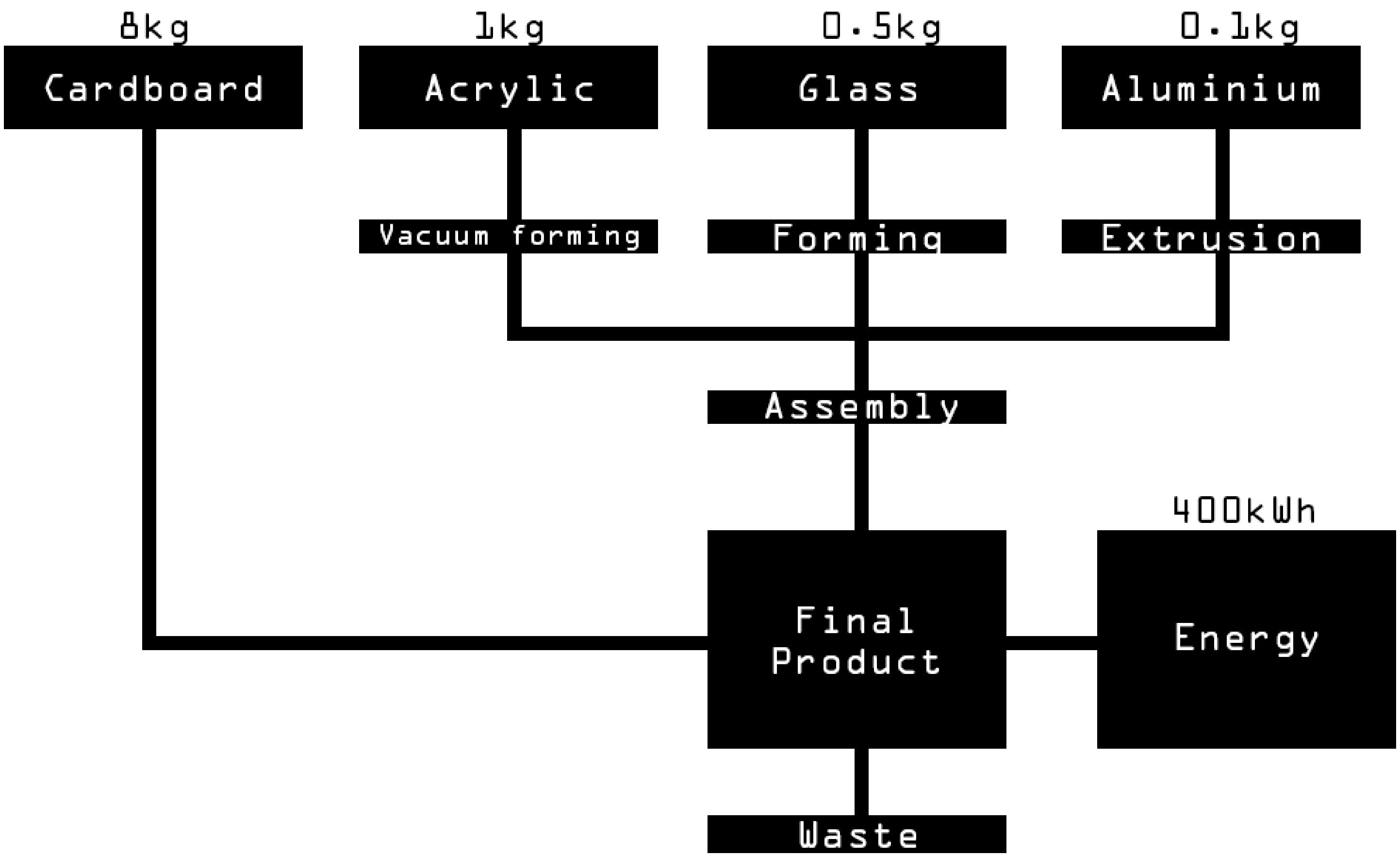
Inventory analysis

- *Data collection part* of the LCA
- Inventory analysis is the LCA phase involving the **compilation and quantification of inputs and outputs** for a given product system throughout its life cycle.
- Involves creating an inventory of flow from and to nature for a product system
- Inventory flows
  - Inputs of water, energy, raw materials
  - Releases to air land, water
- Construct a flow model using data on inputs and outputs

Inventory analysis

- Steps
  1. Preparing for data collection
  2. Data collection
  3. Calculation procedures
  4. Allocation and recycling
- Examples
  - Electricity production by coal combustion
  - Recycling of aluminium scrap
  - Use of a passenger car

Inventory analysis



Source: https://commons.wikimedia.org/w/index.php?curid=33018258

Sources for generic LCI data

- BUWAL (Schweizerisches Bundesamt für Umwelt, Wald und Landschaft)
- APME (Association of Plastics Manufactures in Europe)
- ECOSOL (European LCI Surfactant Study Group with Administrative Support of the CEFIC/ECOSOL Sector Group)
- ProBas (Prozessorientierte Basisdaten für Umweltmanagement-Instrumente)
- GEMIS (Gesamt-Emissions-Modell Integrierter Systeme)

Life cycle impact assessment

- Evaluating the significance of potential environmental impacts based on the LCI flow results
- LCIA consists of the following mandatory elements:
  1. Selection of impact categories, category indicators, and characterization models;
  2. the **classification** stage, where the inventory parameters are sorted and assigned to specific impact categories; and
  3. impact measurement, where the categorized LCI flows are **characterized**, using one of many possible LCIA methodologies, into common equivalence units that are
  4. then summed to provide an overall impact category total (**normalization**).

ISO LCIA: Classification

- ISO definition: assignment of LCI results to impact categories
- Examples
  - CO_2 and CH_4 are assigned to climate change
  - Copper to water eco-toxicity

ISO LCIA: Characterization

- ISO definition: calculation of category indicator results
- Impact measurement

$$Indicator\ Result_{Cat} = \sum_{subs} CharFact_{cat,subs} \times InventoryResult_{subs}$$

- Unit of characterisation results
  - kg CO_2equ (climate change)
  - kg SO_2equ (acidification)
  - …

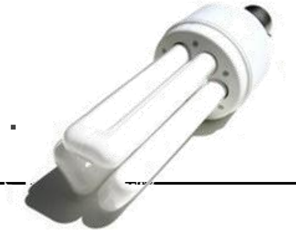
5 kg CO_2, 3 kg CH_4, GWP

1 x (5/1000) + 21 x (3/1000) = 0,068t CO_2equ

ISO LCIA: Characterization

Example of a characterization/impact table

Impact category	Incandescent lamp	Fluorescent lamp
Climate change	120.000 kg CO_2-equ	40.000 kg CO_2-equ
Eco-toxicity	320 kg DCB-equ	440 kg DCB-equ
Acidification	45 kg SO_2-equ	21 kg SO_2-equ
Depletion of resources	0,8 kg antimony-equ	0,3 kg antimony-equ
etc.		…



ISO LCIA: Normalization

- ISO definition: calculation of the magnitude of category indicator results to reference information
- Reference information (over a given period of time)
  - Area (e.g. Austria, Europe, the world)
  - Person (e.g. a Chinese citizen)
  - Product (e.g. the most frequently used product)
- Aim: better understand the relative magnitude for each indicator results of the product system under study:
  - Checking for inconsistencies
  - Providing and communicating information on the relative significance of the indicator results
  - Preparing for additional procedures

$$Normalized\ Indicator\ Result_{cat} = \frac{Indicator\ Result_{cat}}{Reference\ Value_{cat}}$$

Methods for environmental impact assessment

Qualitative evaluation methods
- Verbal evaluation
- ABC-Analysis
- Value-benefit-analysis/decision matrix

Quantitative, non-monetary evaluation methods
- Critical volumes
- Cumulated energy demand (CED)
- Eco-points
- Material Input per Service Unit (MIPS)
- Sustainable Process Index (SPI)
- ECO-Indicator 99
- CML

Quantitative, monetary evaluation methods
- Costs of substitution
- Potential or compensatory price
- EPS-method

CML

- Evaluates impacts of emissions on environmental issues/impact categories
- Impact-oriented classification
  - Emissions are classified by environmental impact categories
  - Usually there is no aggregation but a development of an environmental profile
- Impact categories
  - Biotic/Abiotic resource depletion
  - Climate change
  - Stratospheric ozone depletion
  - Human toxicity, eco-toxicity (aquatic, terrestrial etc.)
  - Photo-oxidant formation
  - Acidification
  - …

CML: Impact categories

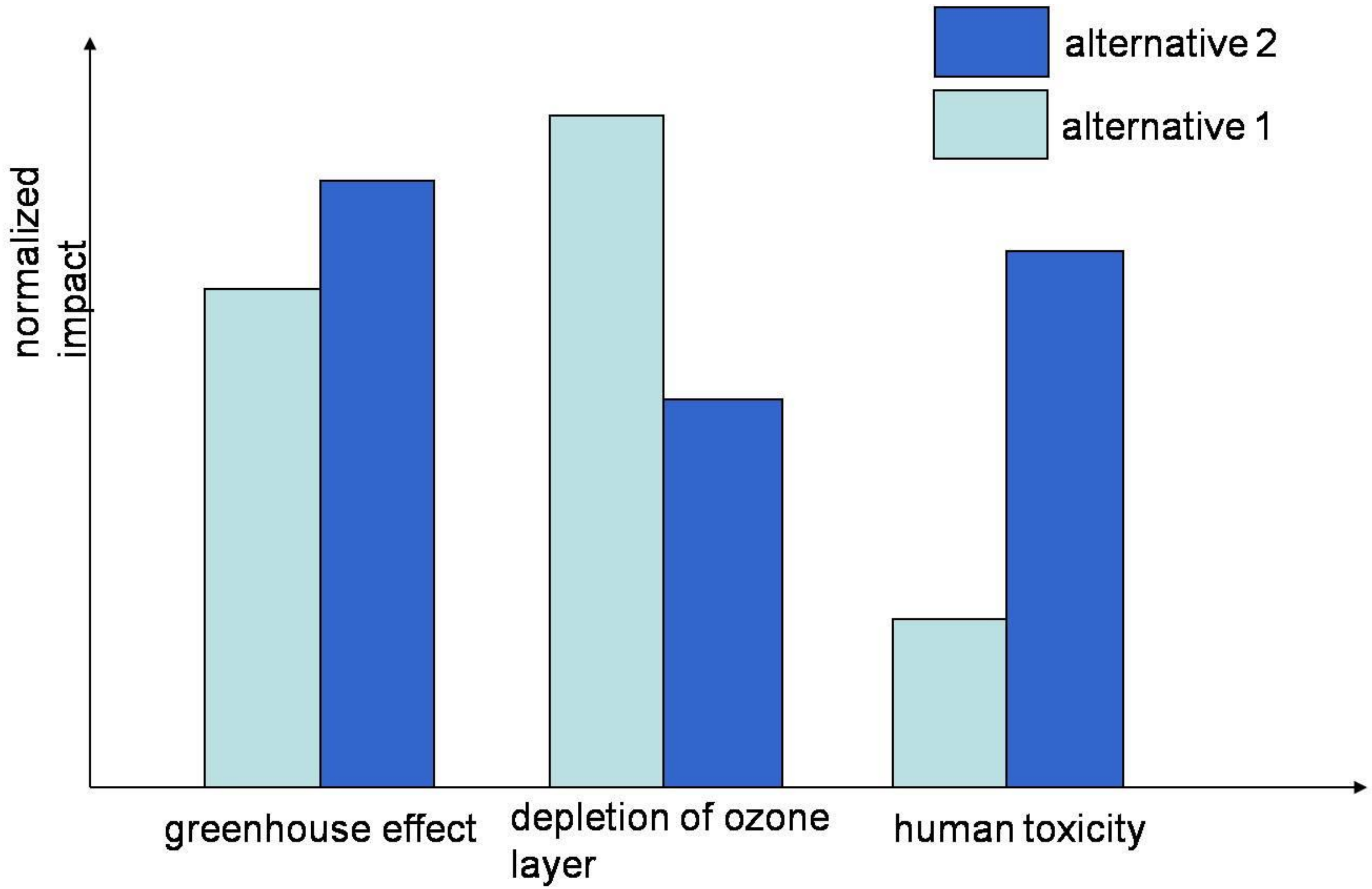
Impact category	Category indicator	Characterisation model	Characterisation factor
Abiotic depletion	Ultimate reserve in relation to annual use	Guinee and Heijungs 95	ADP[9]
Climate change	Infrared radiative forcing	IPCC model[3]	GWP[10]
Stratospheric ozone depletion	Stratospheric ozone breakdown	WMO model[4]	ODP[11]
Human toxicity	PDI/ADI[1]	Multimedia model, e.g. EUSES[5], CalTox	HTP[12]
Ecotoxicity (aquatic, terrestrial, etc)	PEC/PNEC[2]	Multimedia model, e.g. EUSES, CalTox	AETP[13], TETP[14], etc
Photo-oxidant formation	Tropospheric ozone formation	UNECE[6] Trajectory model	POCP[15]
Acidification	Deposition critical load	RAINS[7]	AP[16]
Eutrophication	Nutrient enrichment	CARMEN[8]	EP[17]

1 PDI/ADI Predicted daily intake/Acceptable daily intake
2 PEC/PNEC Predicted environmental concentrations/Predicted no-effects concentrations
3 IPCC Intergovernmental Panel on Climate Change
4 WMO World Meteorological Organization
5 EUSES European Union System for the Evaluation of Substances
6 UNECE United Nations Economic Commission For Europe
7 RAINS Regional Acidification Information and Simulation
8 CARMEN Cause Effect Relation Model to Support Environmental Negotiations
9 ADP Abiotic depletion potential
10 GWP Global warming potential
11 ODP Ozone depletion potential
12 HTP Human toxicity potential
13 AETP Aquatic ecotoxicity potential
14 TETP Terrestrial ecotoxicity potential

CML: Example

1. Selection of the considered environmental impacts
   - Emission of 1.000t CH_4
2. Classification by a certain environmental impact category **(classification)**
   - Category: greenhouse effect
3. Form index values for each category **(characterization)**
   - Greenhouse effect with Global Warming Potential (GWP)
   - CH_4 has a 21 times stronger impact than CO_2; therefore 21.000t CO_2equ
4. Compare to benchmarking value **(normalization)**
   - Austria 2006: $93*10^6$t CO_2equ
   - Share of our emission: $2{,}3*10^{-4}$ CO_2equ

CML: Example


alternative 2
alternative 1
normalized impact
greenhouse effect
depletion of ozone layer
human toxicity

Cumulated energy demand

- Energy as a measurement for the environmental impact
- Total amount of primary energy required during the production, use and disposal of a product or service or the required amount of energy originally related to a good

$$CED = CED_{Production} + CED_{Use} + CED_{Disposal}$$

$CED_{Production}$

- Electricity 3,19 MJ_{Prim}/MJ_{Sec}
- Steel 27,1 MJ/kg
- Aluminum 154,7 MJ/kg

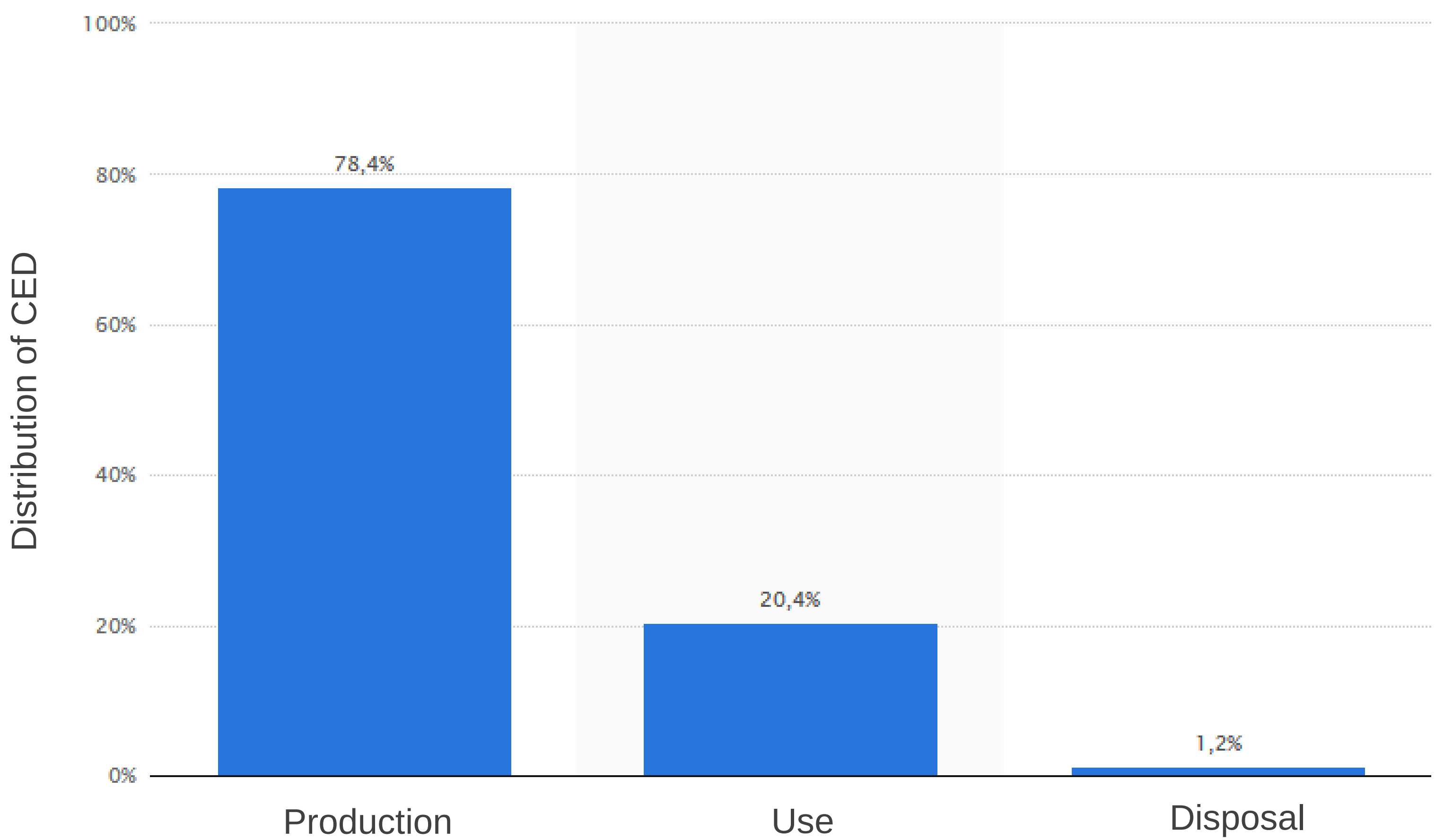
CED_{Use}

- Diesel 48,5 MJ/kg

Excurse: offshore wind farm *alpha ventus*

- Start of operation: April 27, 2010
- 250 Mio €, 4.100 €/kW
- Power generation
  - Units operational: 12 x 5 MW
  - Nameplate capacity: 60 MW
- Energy fed into the grid
  - Annual average 2011-2014: 248,76 GWh

CED of *alpha ventus* per life cycle phase



Source: Energiewirtschaftliche Tagesfragen

Eco-points/ecological scarcity method

- Energy and material flows refer to ecological scarcity
- Eco-factors express the distance between the current and the target state in regard to the respective substance
- The less eco-points a process causes the better its ranking
- Eco-factor

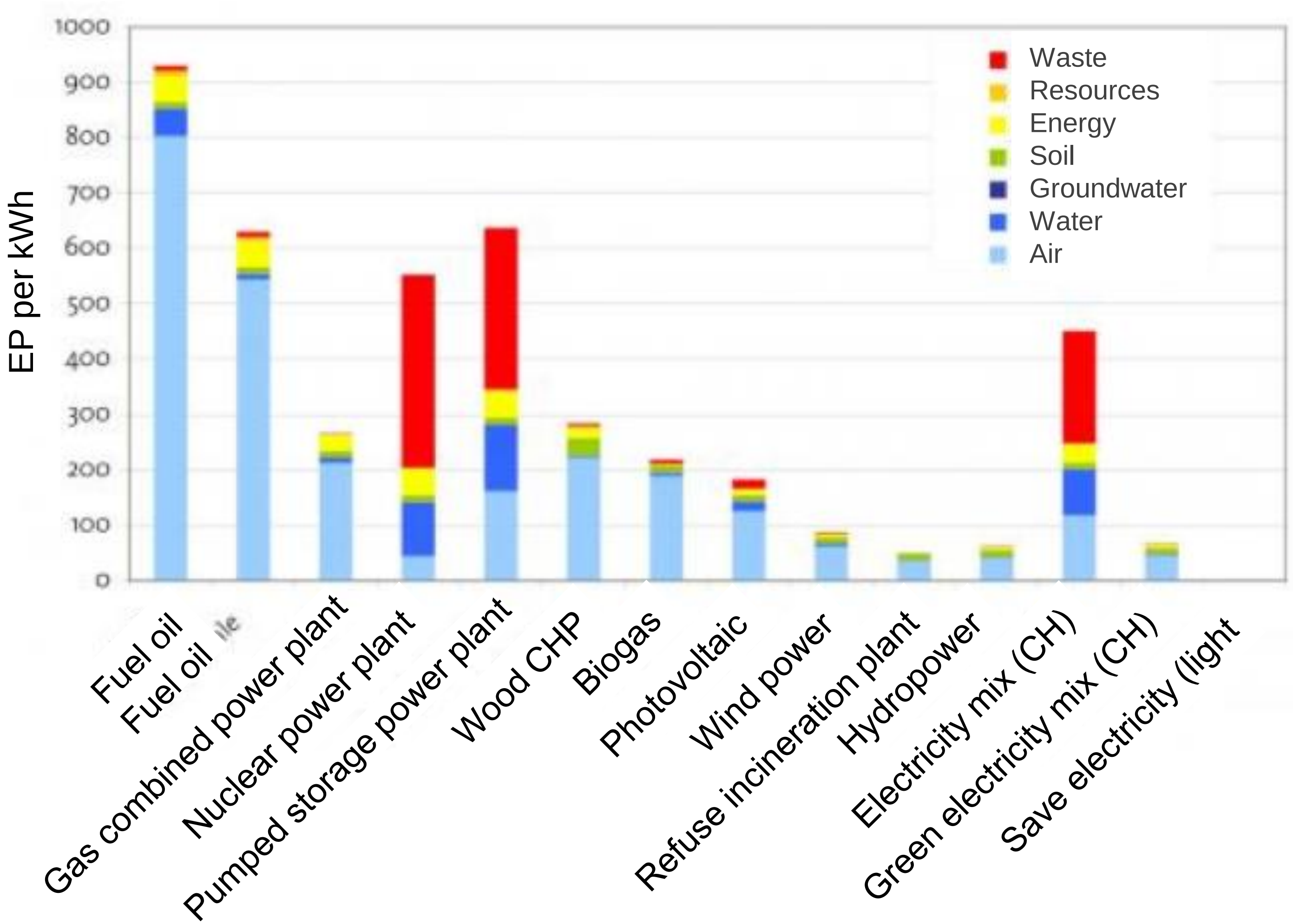
$$EF = (c * \frac{1}{Fc_i} * \frac{F_i}{Fc_i})$$

- Eco-points

$$EP = EF * emission\ (consumption)$$

[EP/g]
c…constant (10^{12})
F_i…current flow
Fc_i…critical flow, scarcity

Eco-points


EP per kWh
1000
900
800
700
600
500
400
300
200
100
0
Waste
Resources
Energy
Soil
Groundwater
Water
Air
Fuel oil
Fuel oil
Gas combined power plant
Nuclear power plant
Pumped storage power plant
Wood CHP
Biogas
Photovoltaic
Wind power
Refuse incineration plant
Hydropower
Electricity mix (CH)
Green electricity mix (CH)
Save electricity (light

Material Input per Service (MIPS)

- Environmental issues are related to the extend of material flows
- Measure of raw material intensity

$$MIPS = {}^{MI}/_{S}$$

$$Material\ Intensity\ MI = \sum P_i * MI_i$$

$$Service\ Unit\ S = n * p$$

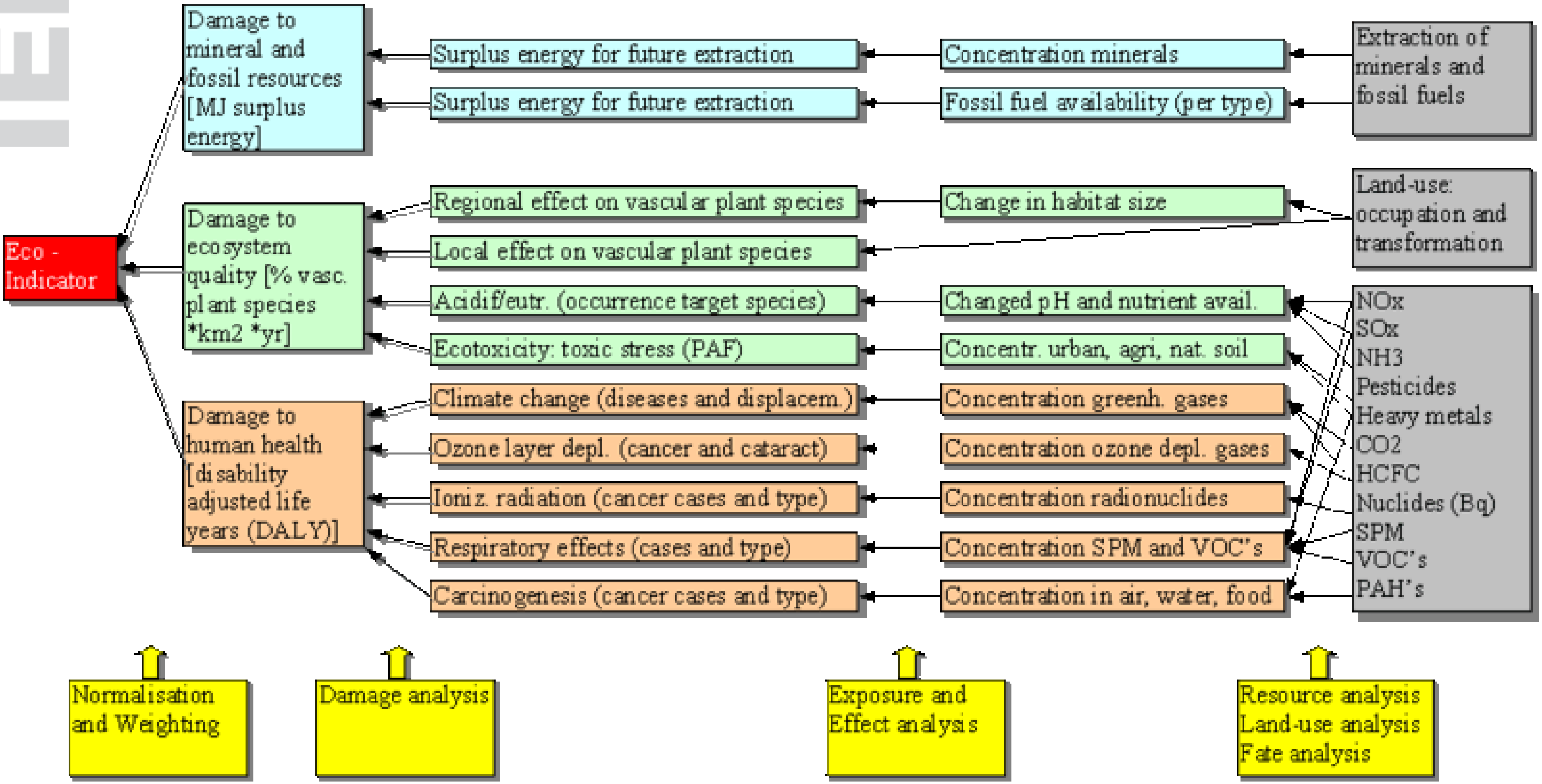
P_i…mass of substance i
MI_i…material intensity of substance i, „ecological backpack“
n…number of services/uses
p…number of persons that can use the product simultaneously

Eco-Indicator 99

Damage oriented environmental impact assessment (endpoint)

- Three types of damage
  - **Human health**
  - Number and duration of illnesses and losses in people‘s lifetimes caused by climate change, depletion of the ozone layer, carcinogenic substances
  - Measured in DALY: disability adjusted life years
  - Indicator of the world bank and WHO
  - Includes deaths and illnesses caused by:
    - Respiratory and carcinogenic effects
    - Effects caused by climate change, depletion of ozone layer and radioactive radiation
  - **Quality of ecosystems**
  - Biodiversity or the loss in biodiversity due to eco-toxicity, acidification, eutrophication, land consumption
  - **Resources**
  - Additional energy consumption that will be required in future to extract difficultly accessible resources

Eco-Indicator 99



Source: http://openwetware.org/wiki/Ecost

Sustainable Process Index (SPI)

- Developed by Krotscheck & Narodoslawsky (1995), TUG
- Based on the assumption that a sustainable society is built only on solar exergy.
- Surface area is needed for the conversion of energy into products and services. Due to the fact that surface area is finite on earth, it is a limited resource.
- Area is the underlying dimension of the SPI, the more area a process needs to fulfil a service, the more it ‘costs‘ from a sustainable point of view.

Source: TU Graz, Institute for Resource Efficient and Sustainable Systems
http://spionexcel.tugraz.at/index.php?option=com_content&task=view&id=14&Itemid=28

SPI

- SPI as the ratio of the area a process/service needs and the average available area per person
- SPI << 1:
  A process/service is very cheap from a sustainable point of view
- 0,001 < SPI < 1:
  The process/service can be used for a sustainable development
- SPI > 1:
  The process/service is too inefficient for sustainability, too expensive from a sustainable point of view

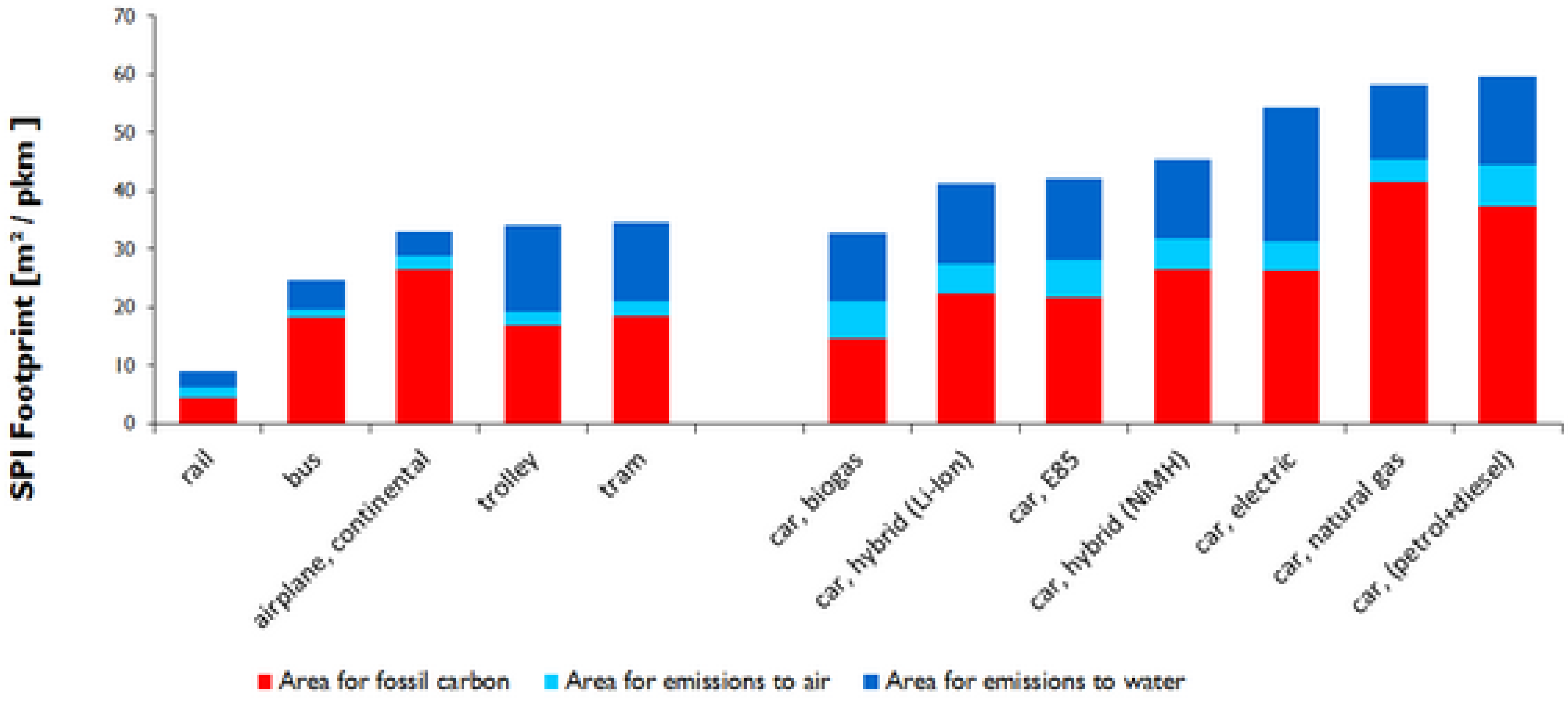
SPI

- All partial footprints calculated by the mass and energy inputs/outputs of all processes are added up
- Result: Overall ecological footprint A_{tot}
- Inputs divided into seven categories

  - Area consumption
  - Non renewables consumption
  - Renewables consumption
  - Fossil C consumption
  - Emissions in air
  - Emissions in water
  - Emissions in soil

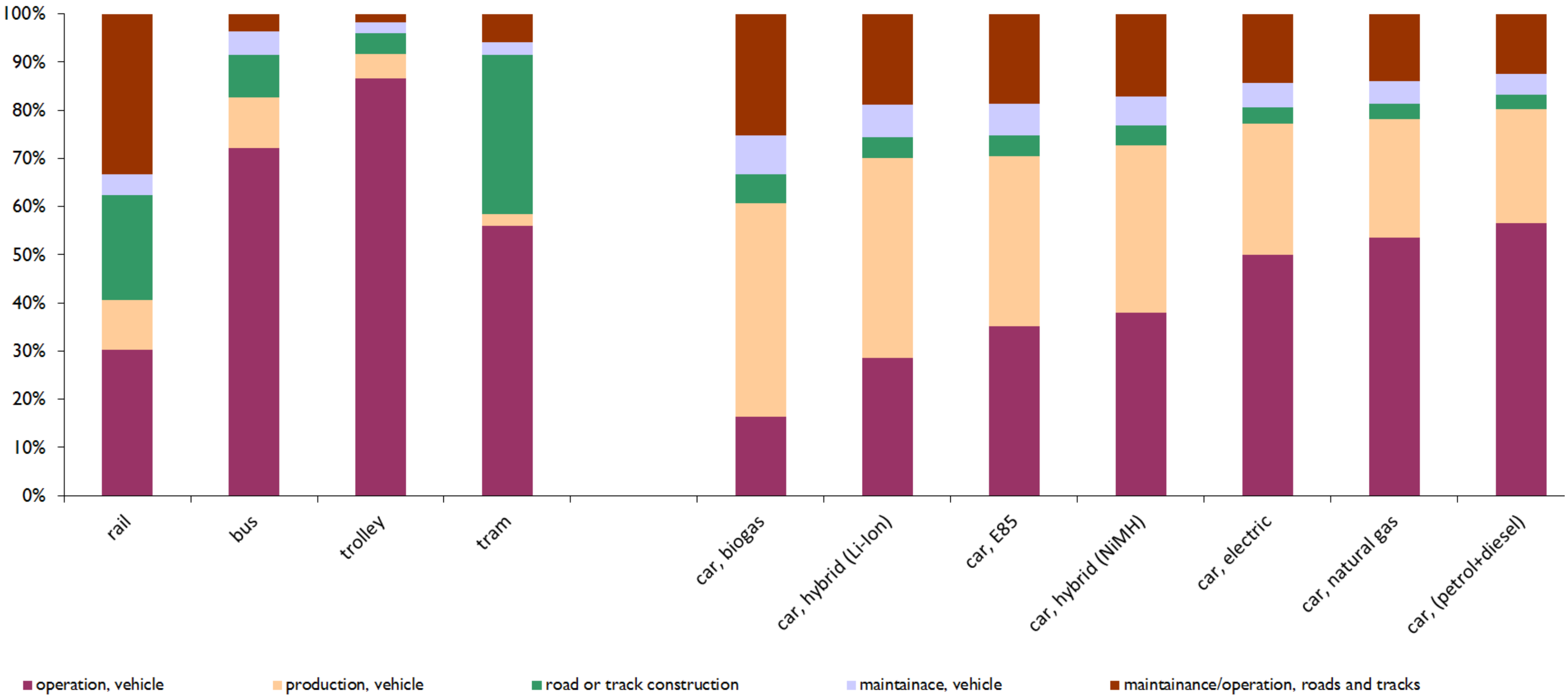
Source: TU Graz, Institute for Resource Efficient and Sustainable Systems
http://spionexcel.tugraz.at/index.php?option=com_content&task=view&id=14&Itemid=28

SPI: Comparison of different means of transportation



Source: http://www.sustainability.org.il/home/transportation-news/Ecological-footprint-comparison-of-different-means-of-transportation-based-on-Sustainable-Process-Index-SPI-methodology

SPI: Comparison of different means of transportation



www.sustainability.org.il/home/transportation-news/Ecological-footprint-comparison-of-different-means-of-transportation-based-on-Sustainable-Process-Index-SPI-methodology

Source:

Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems, IEA PVPS Task 12, Subtask 20, LCA Report IEA-PVPS T12-02:2011

Life Cycle Assessment of Photovoltaic Systems

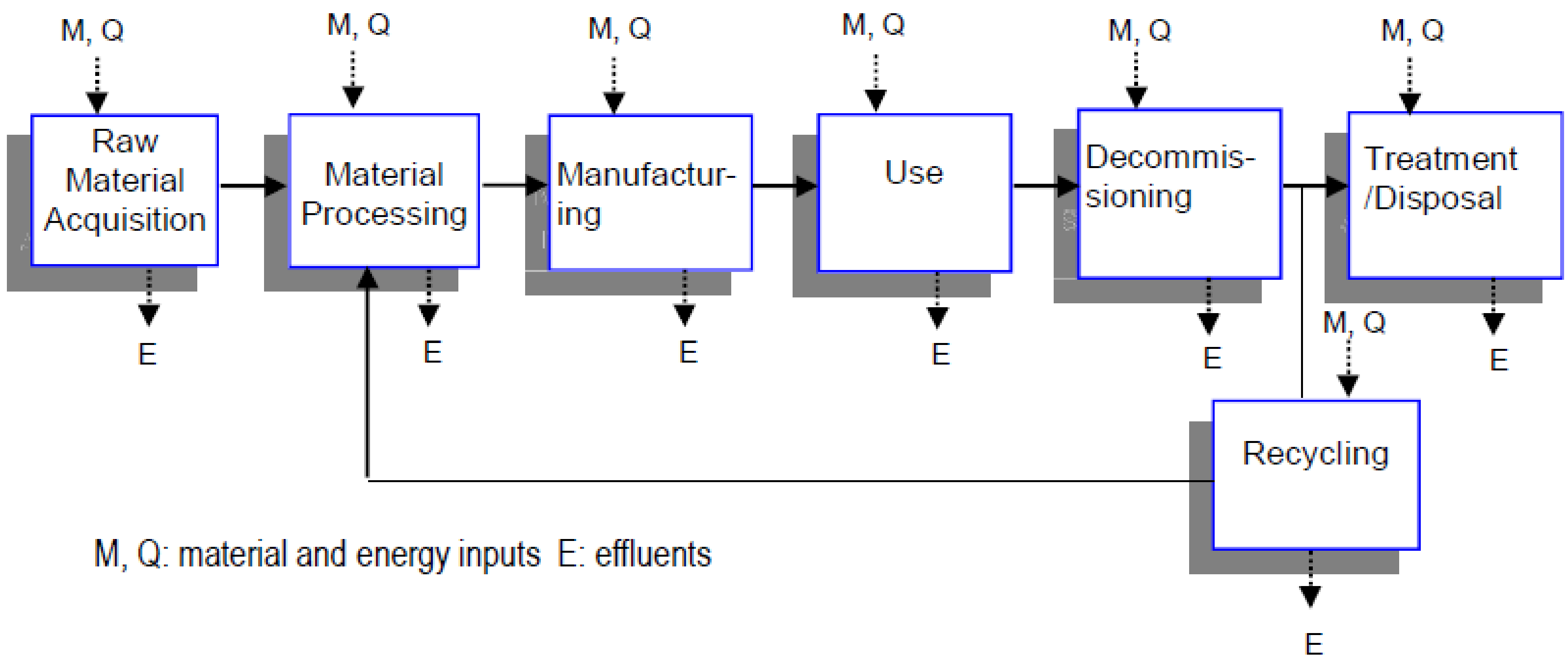
LCA PV

- Consensus limited to four technologies
  - Mono- and multi-crystalline Si, CdTe and high concentration PV using III/V cells

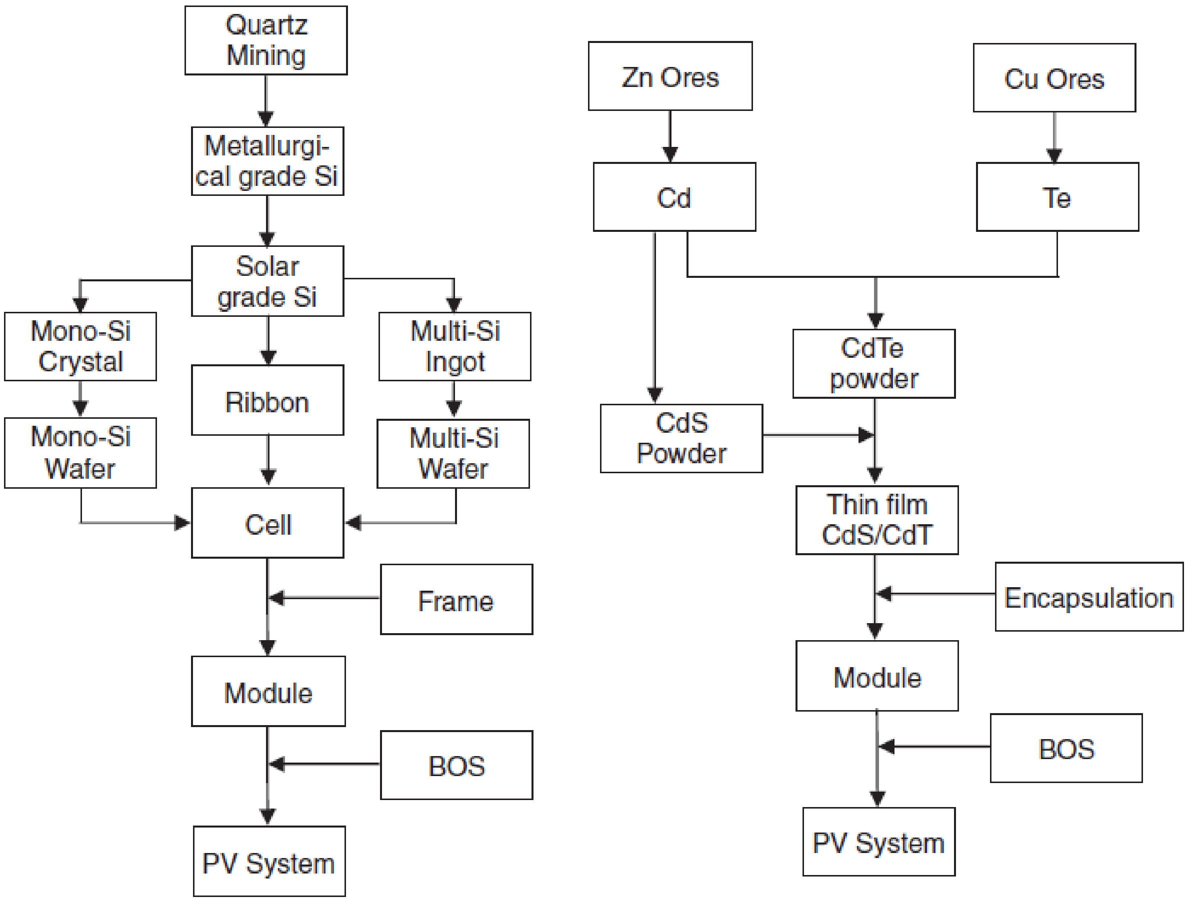
- Detailed LCI data
  - Inputs and outputs during manufacturing of cell, wafer, module, and balance-of-system (structural- and electrical- components)
  - Operational data of rooftop and ground-mount PV systems and country-specific PV-mixes

Life Cycle of PV

Life-cycle starts from the extraction of raw materials **(cradle)** and ends with the disposal **(grave)** or recycling and recovery **(cradle)**



Material flow diagram



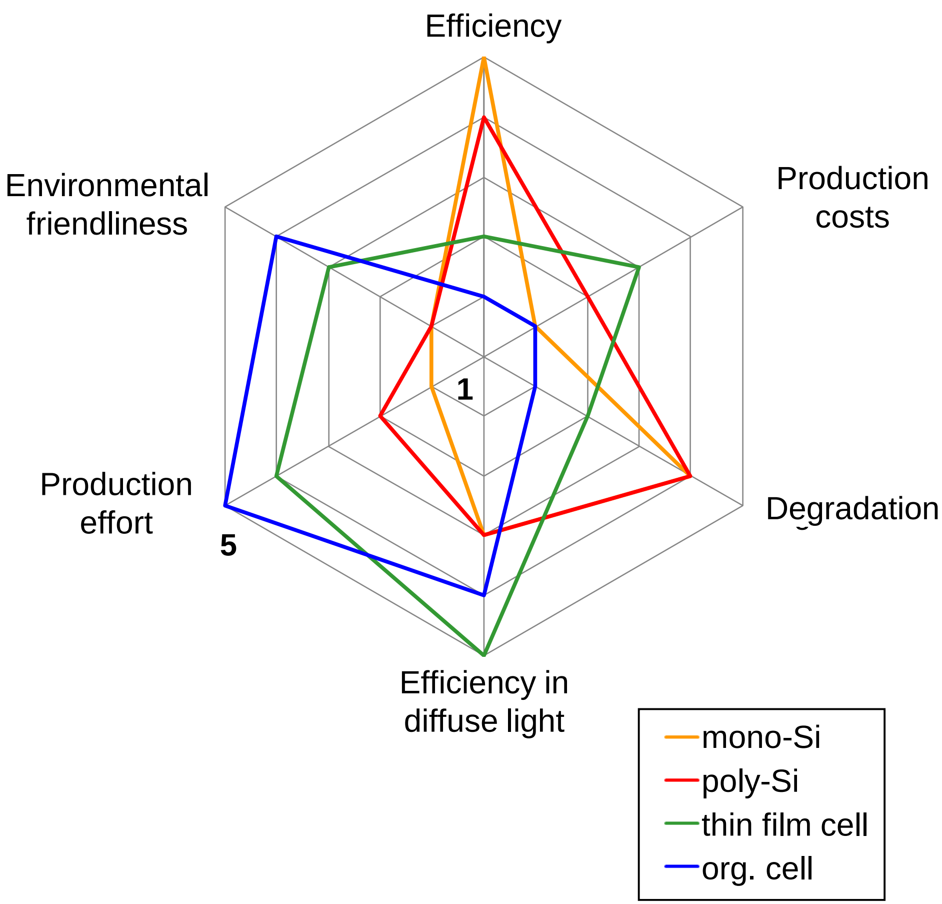
(a) Silicon PVs

(b) CdTe PVs (frameless)

Source: Fthenakis et al., 2008

Advantages and disadvantages of PV cell technologies

- Mono-Si
  - High efficiency (25%)
  - High production effort
- Multi-Si
  - Low production effort compared to mono-Si
- Thin film cells (CdTe)
  - Advantages in diffuse light
- Organic cells
  - Low material losses during production
  - Degradation in the first 1000h



LCA PV

Assumptions:

- Rooftop mounted PV systems
- Southern European irradiation of 1.700 kWh/m^2/yr
- Performance ratio of 0.75
- 30 years lifetime

LCA indicators

- Energy Payback Time
- Greenhouse Gas emissions
- Criteria pollutant emissions (SO2, NOX)
- Heavy metal emissions

Energy Payback Time (EPBT)

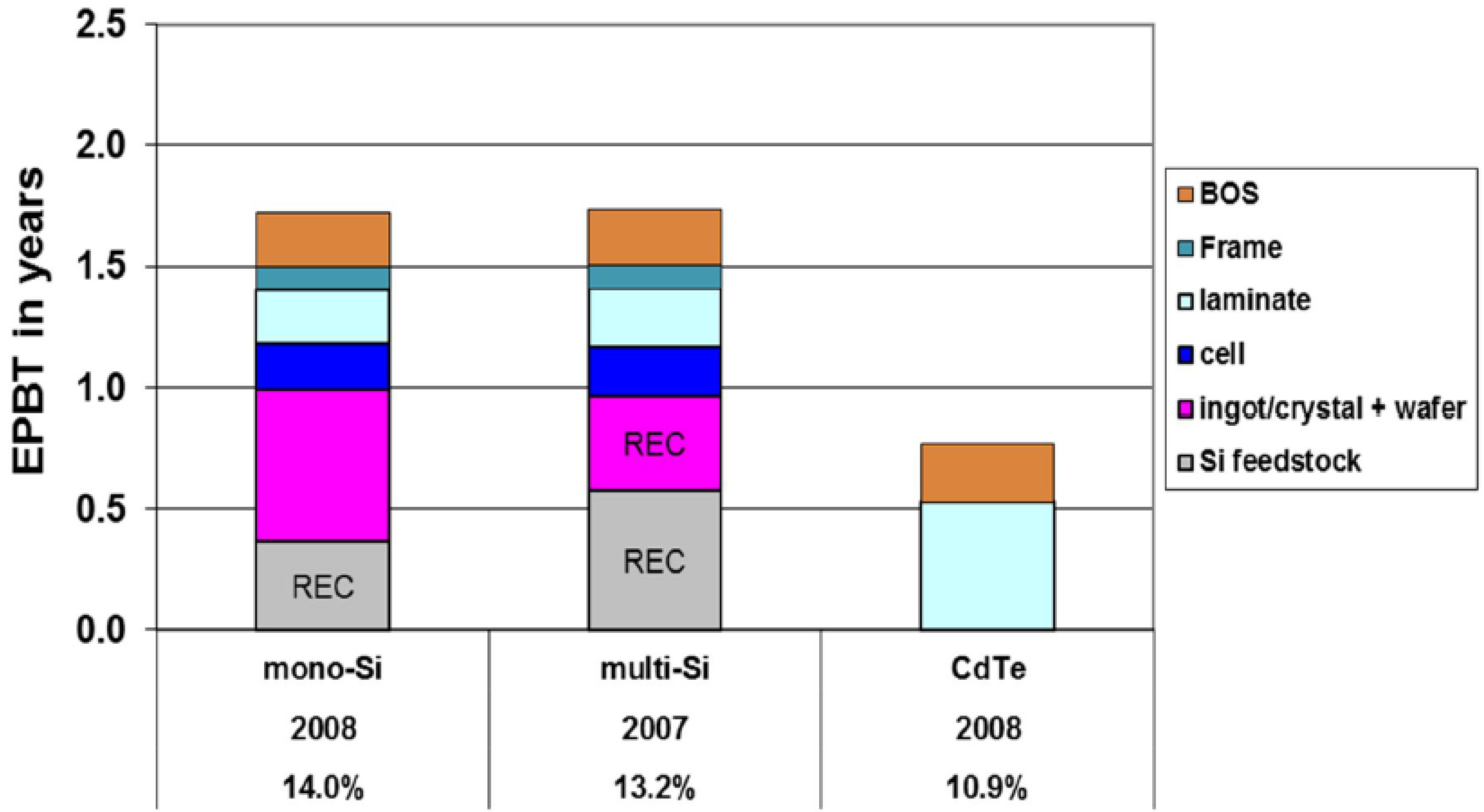
= the period required for a renewable energy system to generate the same amount of energy that was used to produce the system itself

In terms of primary energy equivalent

$$EPBT = \frac{(E_{mat} E_{manuf} E_{trans} E_{inst} E_{EOL})}{(E_{agen} \eta_G) - E_{aoper}}$$

E_{mat} =	Primary energy demand to produce materials comprising PV system
E_{manuf} =	Primary energy demand to manufacture PV system
E_{trans} =	Primary energy demand to transport materials used during the life cycle
E_{inst} =	Primary energy demand to install the system
E_{EOL} =	Primary energy demand for end-of-life management
E_{agen} =	Annual electricity generation
E_{aoper} =	Annual energy demand for operation and maintenance in primary energy terms
η_G =	Grid efficiency, the average primary energy to electricity conversion efficiency at the demand side

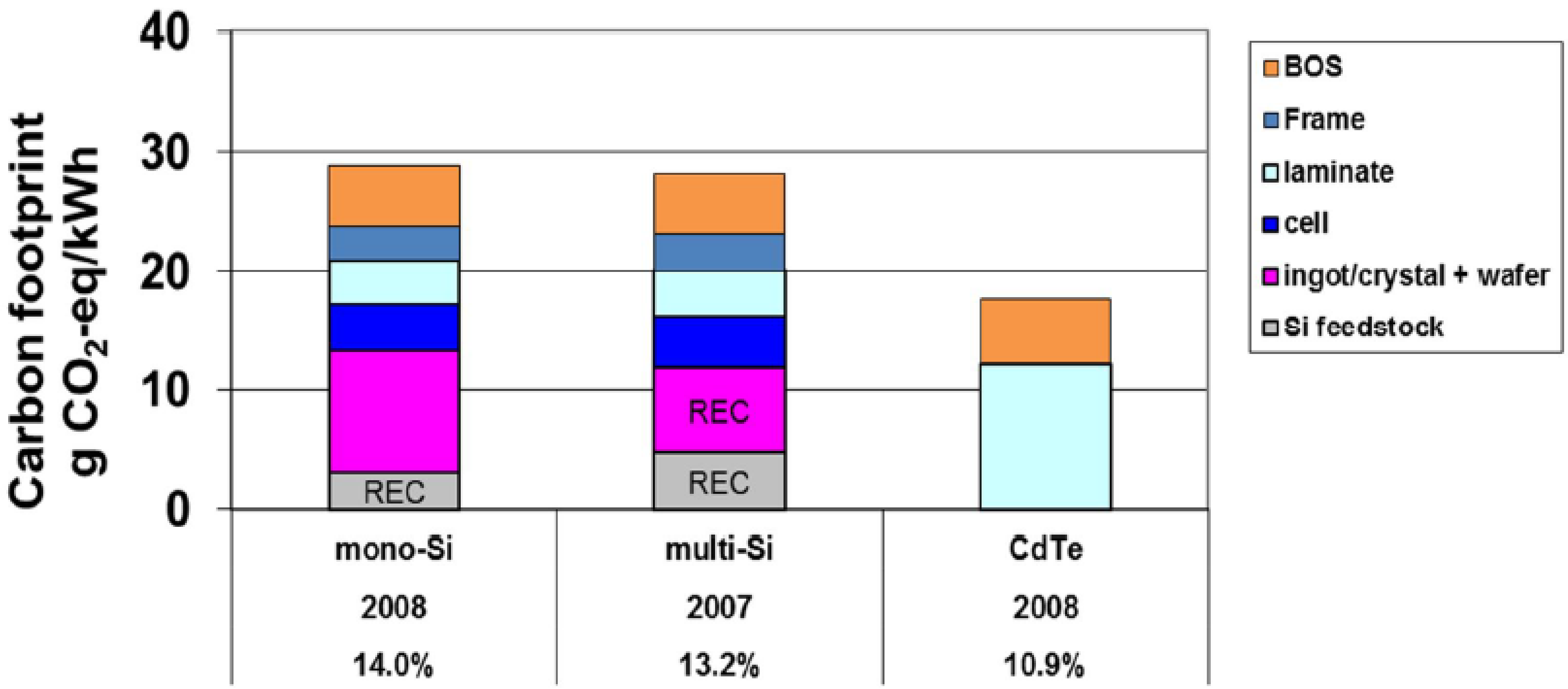
EPBT


2.5
2.0
1.5
1.0
0.5
0.0
EPBT in years
REC
REC
REC
mono-Si
2008
14.0%
multi-Si
2007
13.2%
CdTe
2008
10.9%
BOS
Frame
laminate
cell
ingot/crystal + wafer
Si feedstock

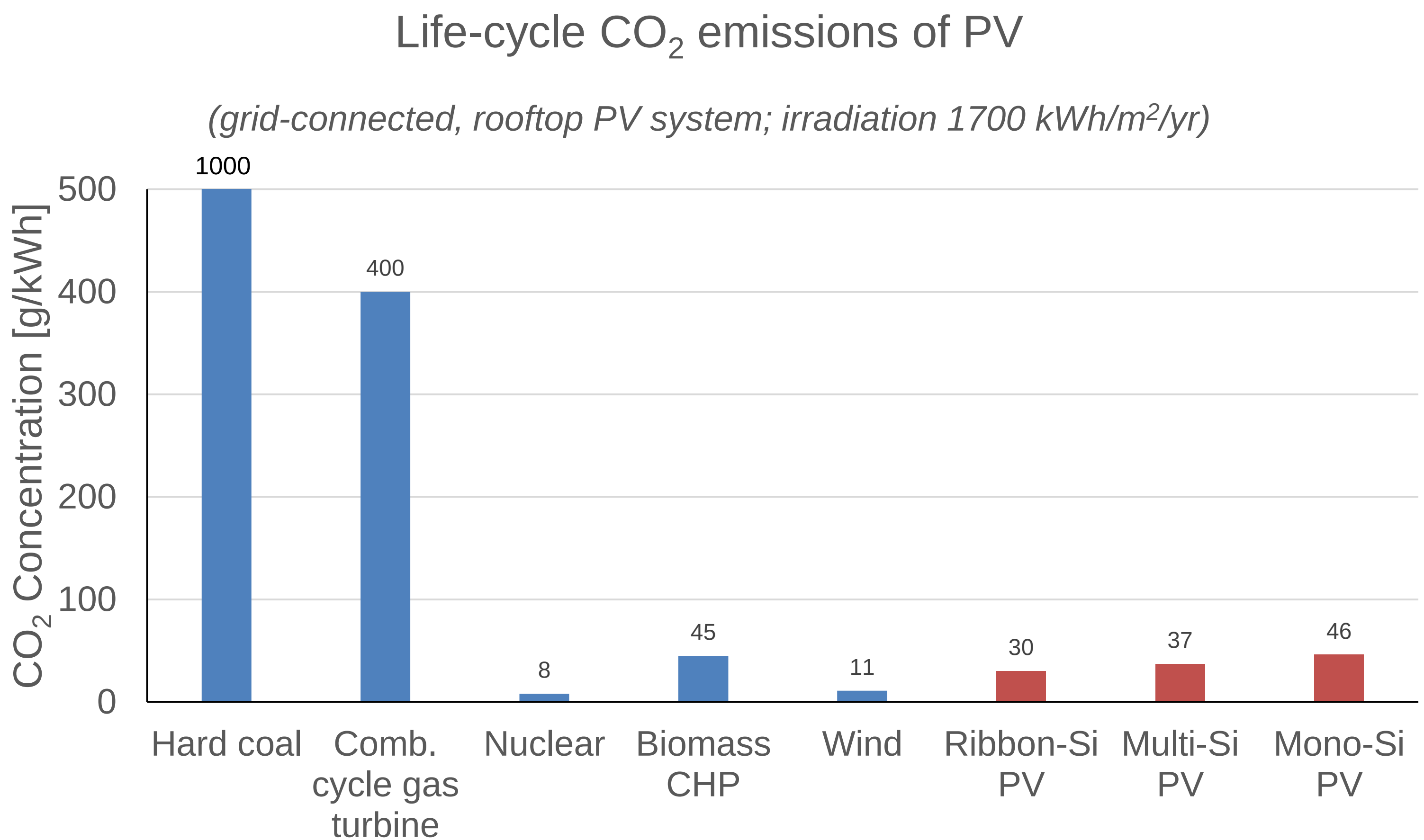
Greenhouse Gas Emissions

- CO_2 equu using an integrated time horizon of 100 years
- Major emissions included as GHG emissions are:
  - CO_2 (GWP = 1)
  - CH_4 (GWP = 25)
  - N_2O (GWP = 298)
  - Chlorofluorocarbons (GWP = 4.750-14.400)

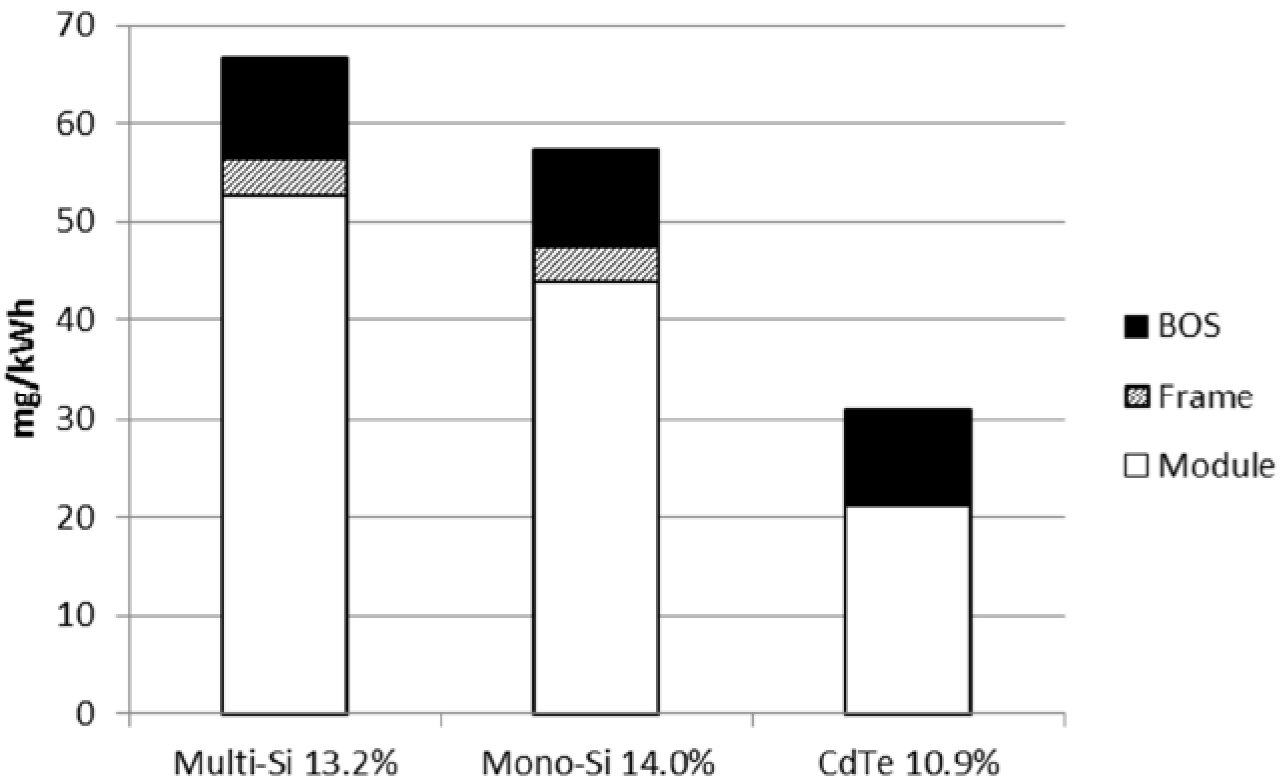
Greenhouse Gas Emissions



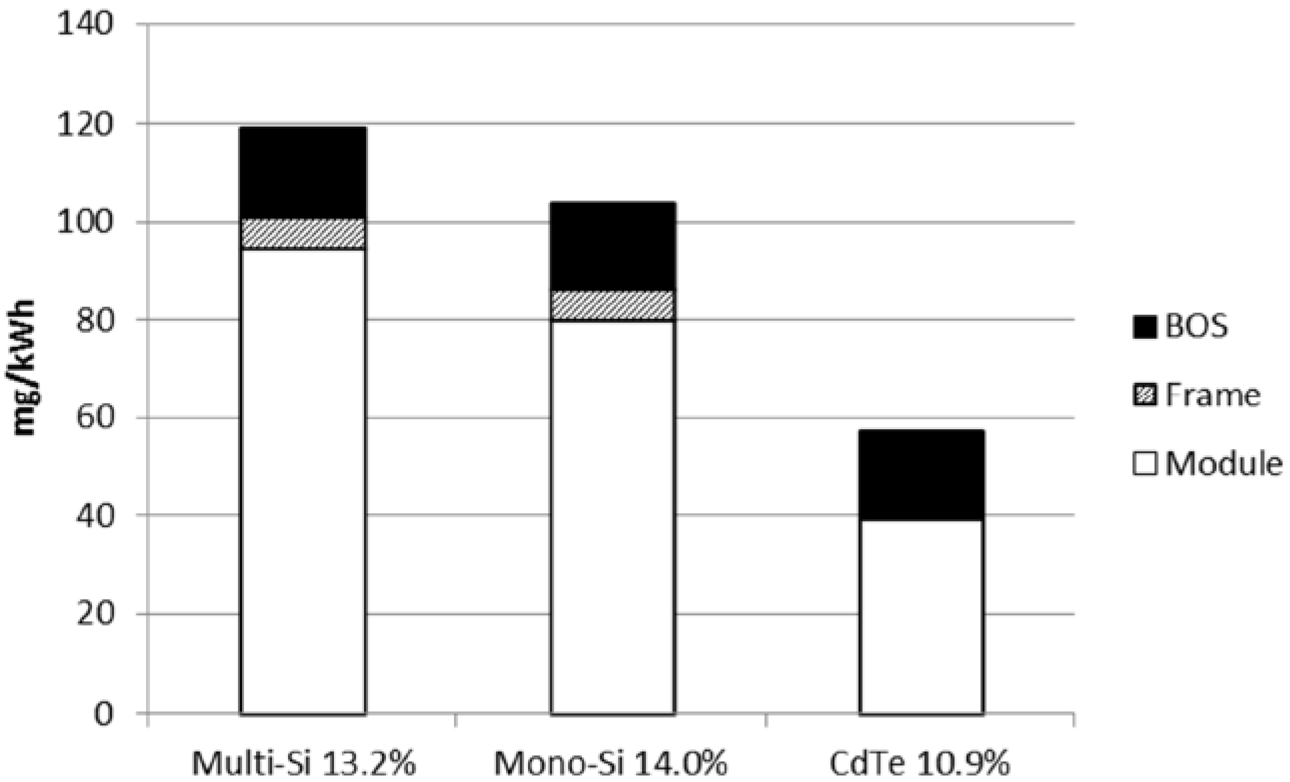
Comparison


Life-cycle CO_2 emissions of PV
(grid-connected, rooftop PV system; irradiation 1700 kWh/m^2/yr)
CO_2 Concentration [g/kWh]
0
100
200
300
400
500
1000
400
8
45
11
30
37
46
Hard coal
Comb. cycle gas turbine
Nuclear
Biomass CHP
Wind
Ribbon-Si PV
Multi-Si PV
Mono-Si PV

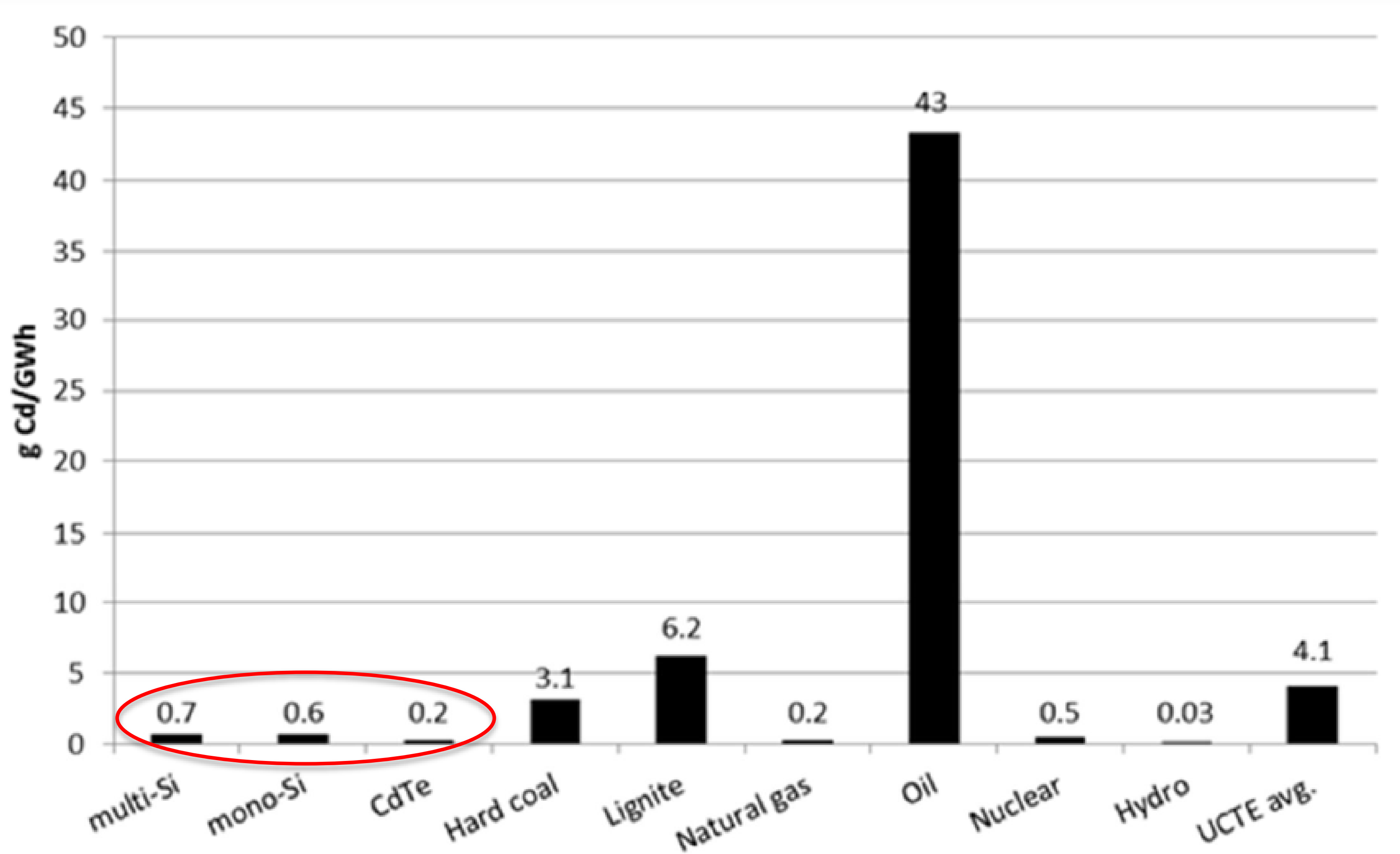
Criteria Pollutant Emissions: NO_X



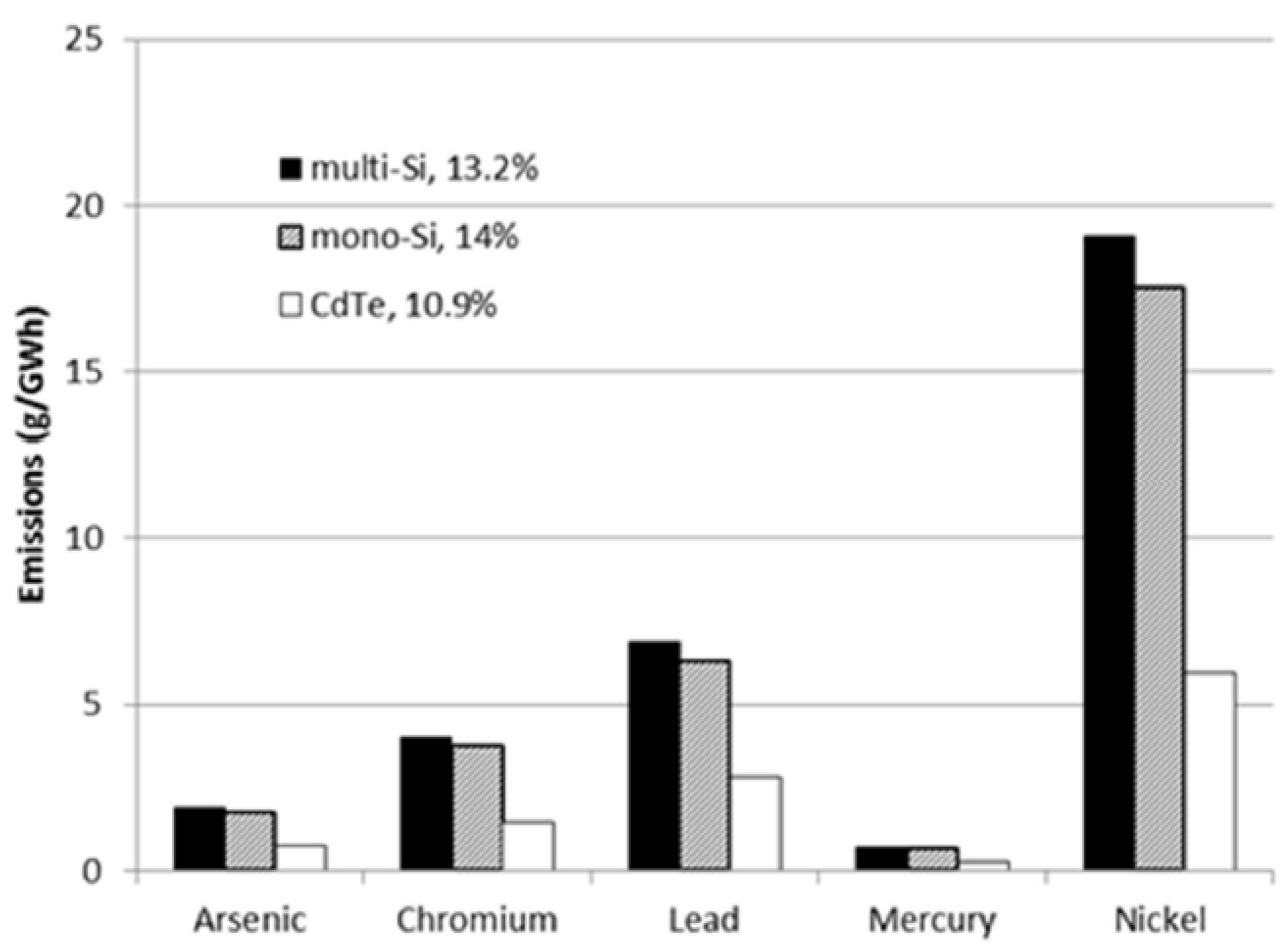
Criteria Pollutant Emissions: SO_2



Heavy Metal Emissions

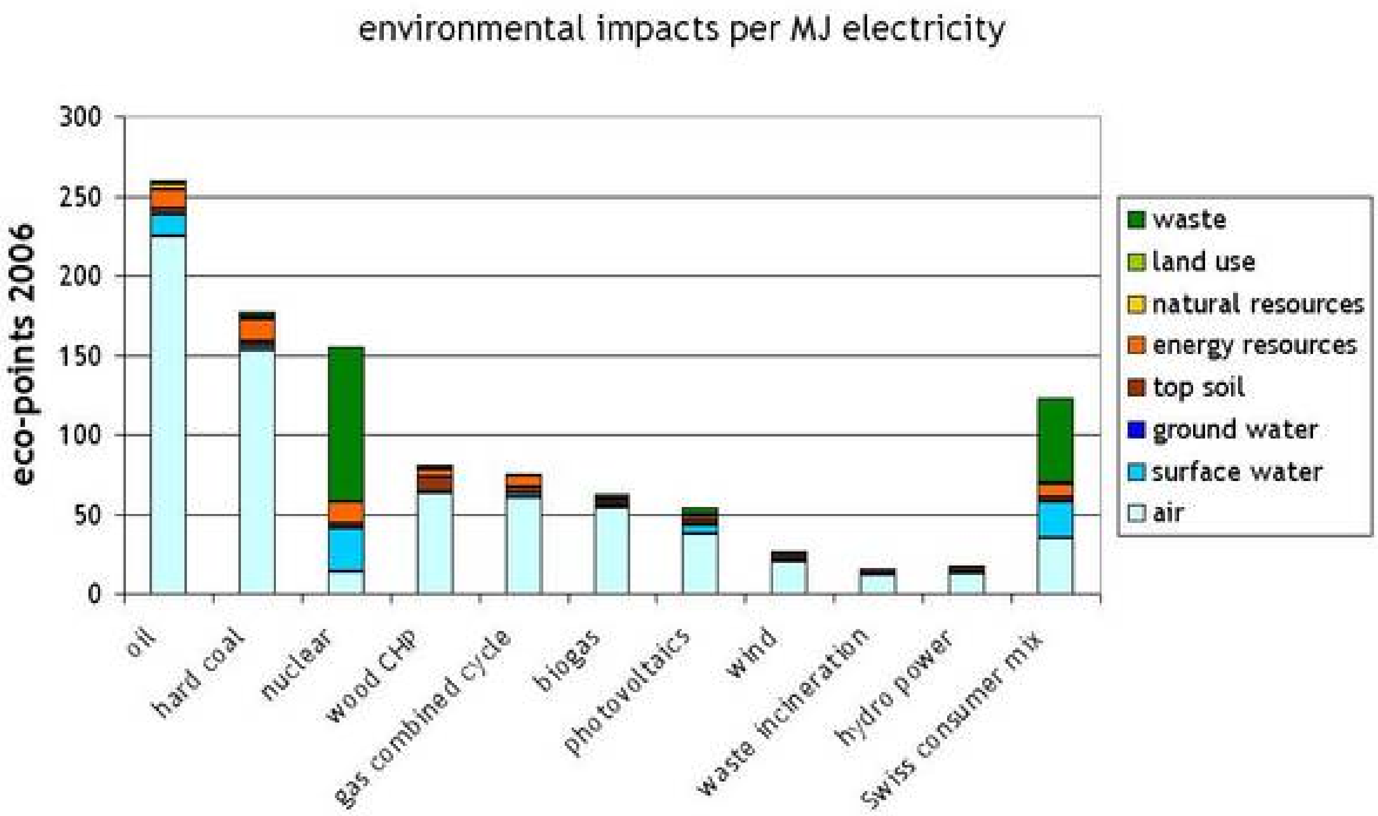


Heavy Metal Emissions



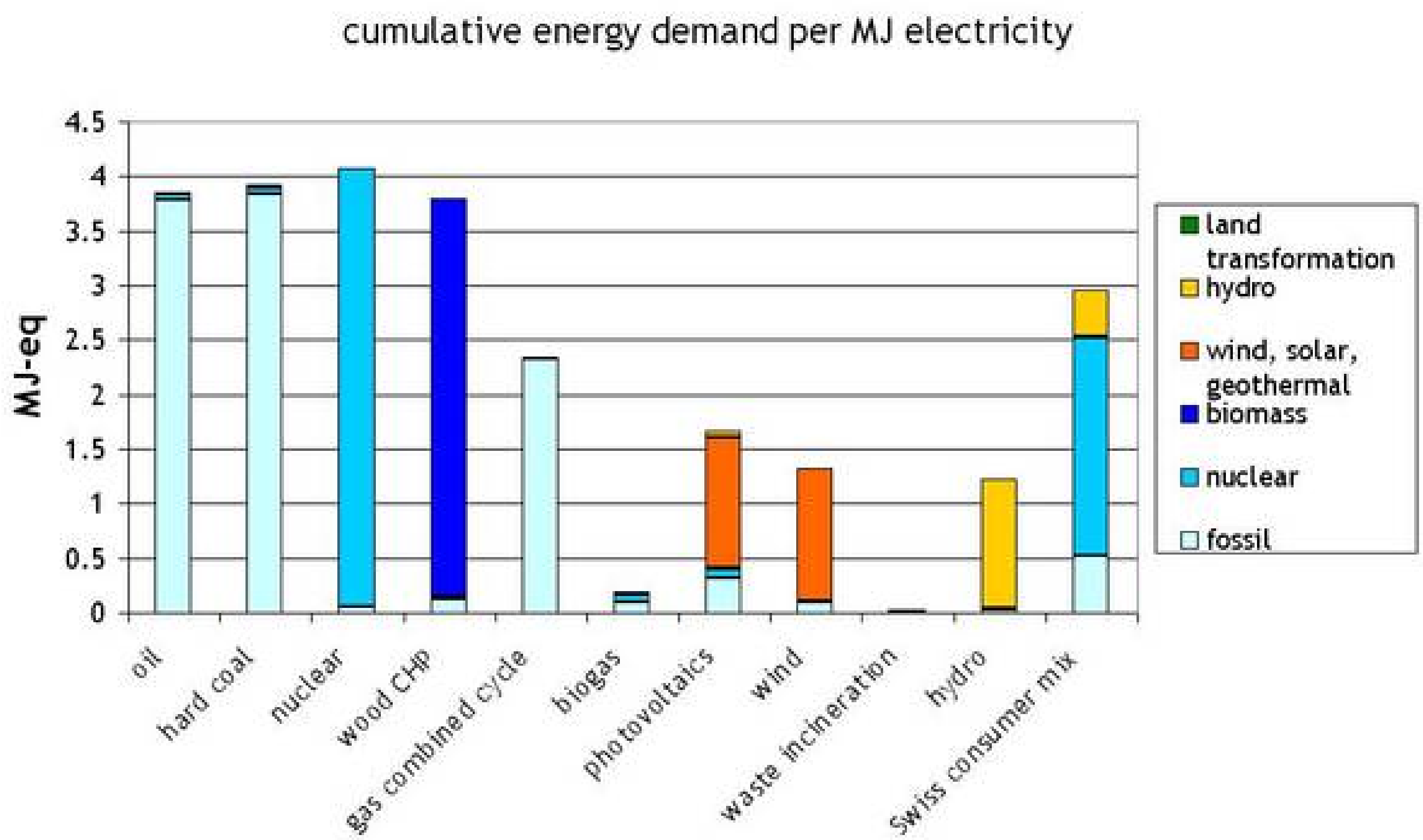
Environmental performance of energy systems

Environmental performance of energy systems

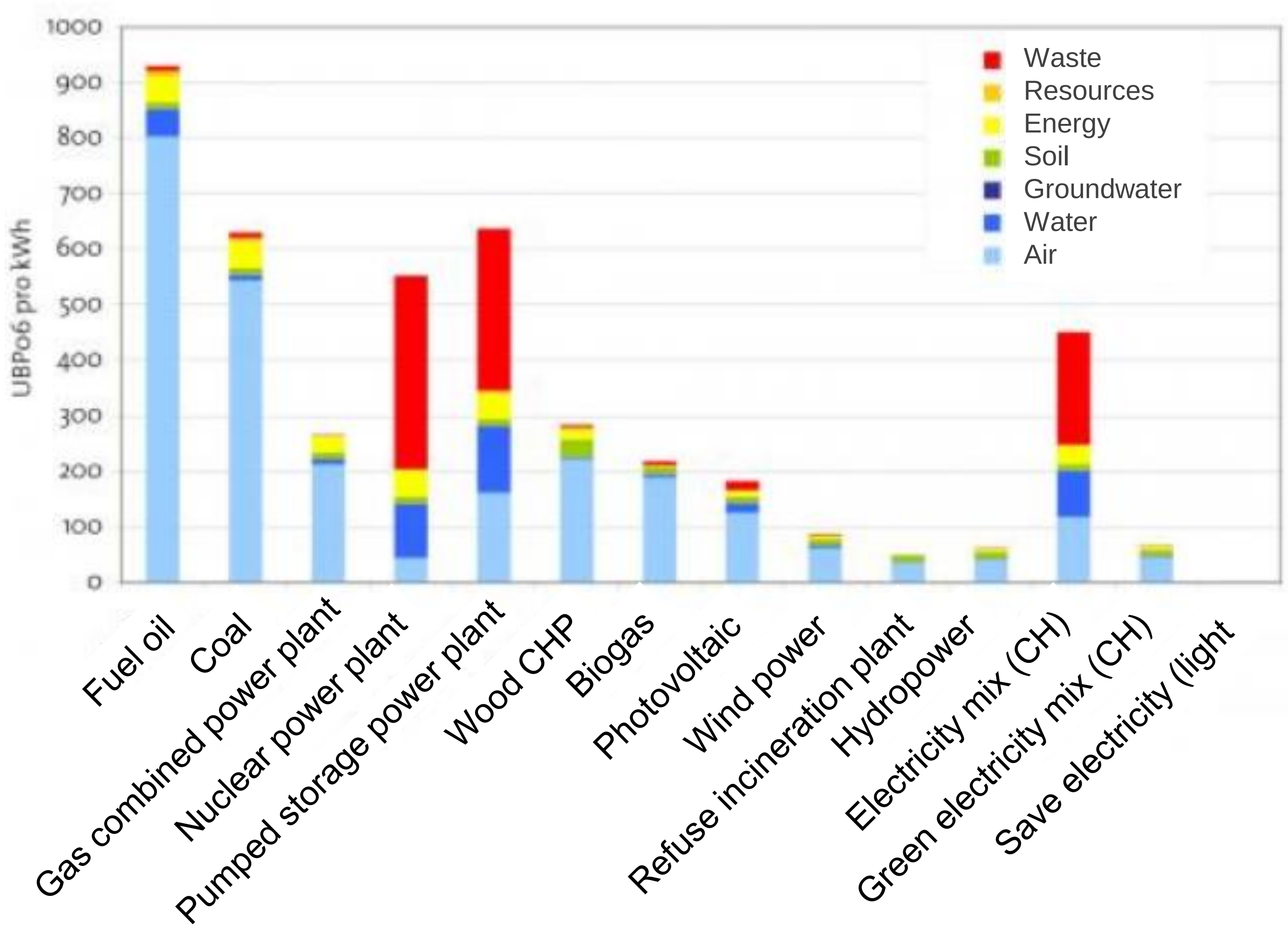


Source: http://www.esu-services.ch/projects/energy-supply/

Environmental performance of energy systems



Eco-points


1000
900
800
700
600
500
400
300
200
100
0
UBP06 pro kWh
Waste
Resources
Energy
Soil
Groundwater
Water
Air
Fuel oil
Coal
Gas combined power plant
Nuclear power plant
Pumped storage power plant
Wood CHP
Biogas
Photovoltaic
Wind power
Refuse incineration plant
Hydropower
Electricity mix (CH)
Green electricity mix (CH)
Save electricity (light

Thank you for your attention!

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