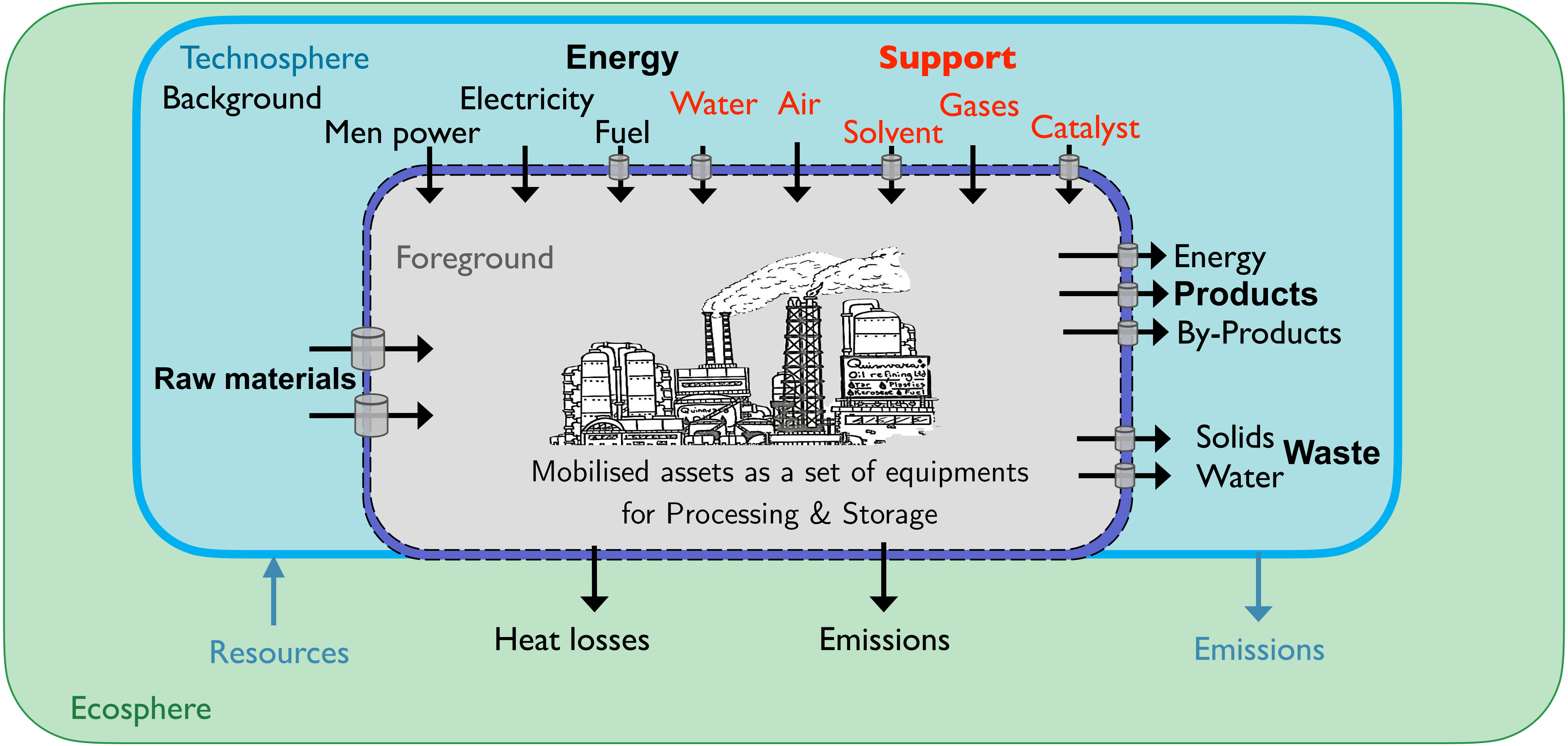
Energy Audits

Prof. François Marechal

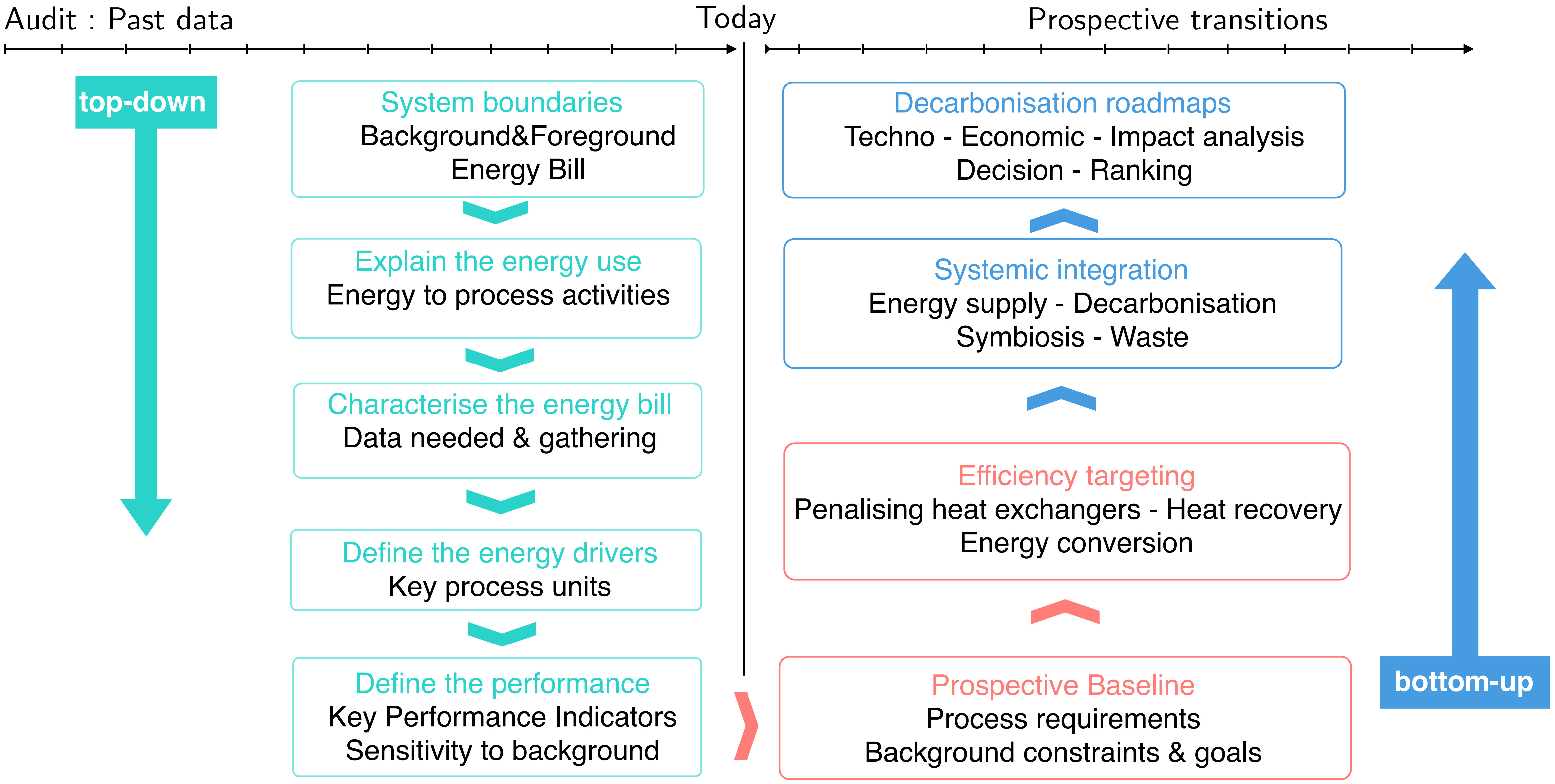
Industrial Process and
Energy Systems
Engineering

EPFL Valais-Wallis

An industrial process system



Overview of the industry decarbonisation methodology



Energy Audits : understanding the system's energetics

Define the energy requirements (ISO 50001:2018)
Energy management systems — Requirements with guidance for use

Background

Energy Markets
Extraction - Conditioning
Distribution - Storage
Emissions
Yearly Profiles

Products Markets
Raw materials
Products & by-products
Waste
Specifications - Supply chains
Yearly profiles

Foreground

Process capital
Equipment
Lifetime
Yearly Operation
End of Life

System boundaries
Background&Foreground
Energy Bill

→ **Energy resources**
Flows from the process
Values from context

Explain the energy use
Energy to process activities

→ **Energy consumption breakdown**
Main processing steps
Influencing factors

Characterise the energy bill
Data needed & gathering

→ **Data gathering**
Metering - Baseline
Consolidating

Define the energy drivers
Key process units

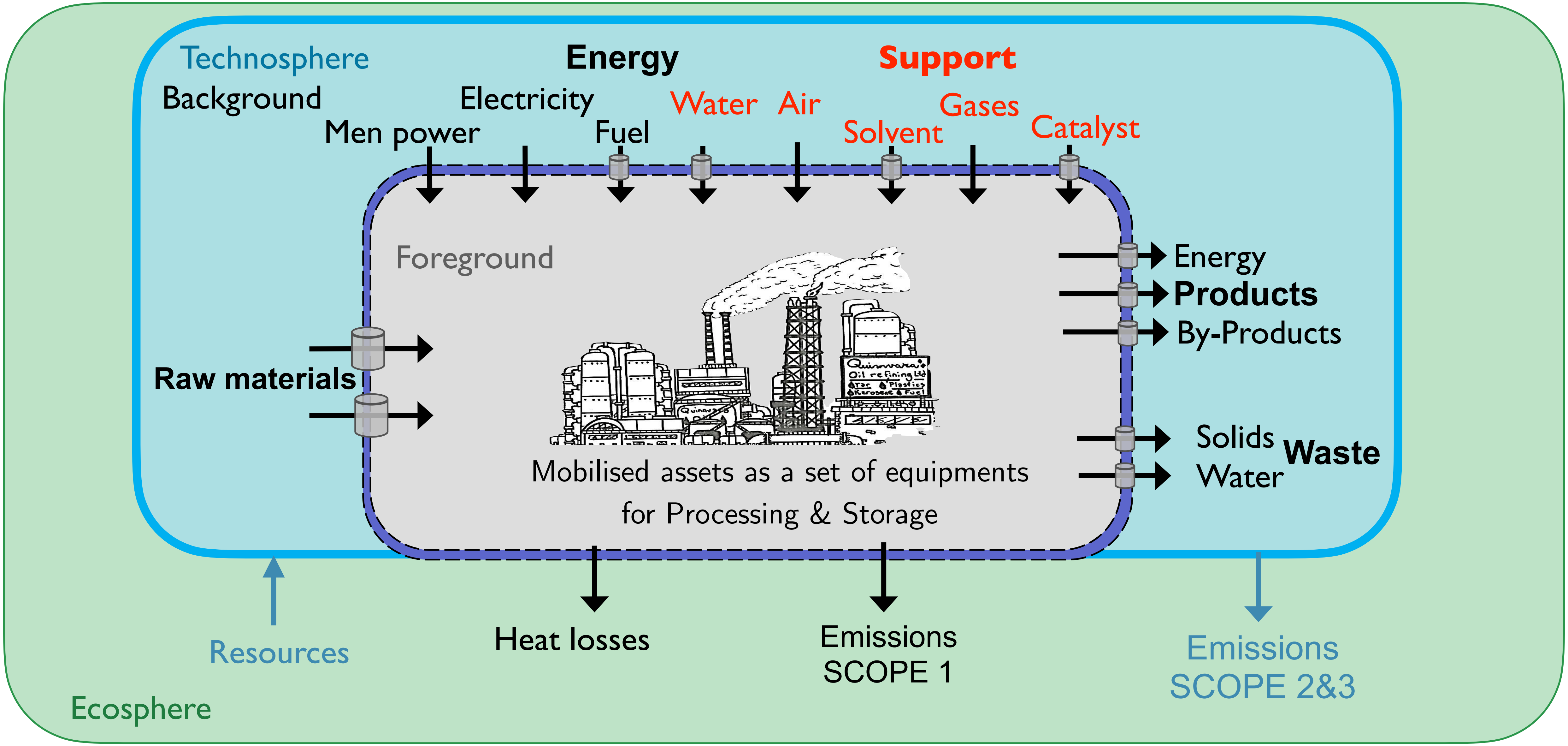
→ **Process Energy Needs**
Energy block flow diagram
Priority ranking

Define the performance
Key Performance Indicators
Sensitivity to background

→ **Performance metrics**
Give values to flows
Decision framework

Understanding Process Flows

What are the flows related to an industrial process ?



What is a process flow ?

- A flow is
  - a quantity of mass(M) [kg] or energy (E) [kJ or kWh] at a given rate [$/s$]
    - Note: kJ comes from **James Prescott Joule** (1818–1889)
  - $\dot{M}$: Mass or materials flows in kg/s or ton/h
  - $\dot{E}$: Energy flow (power): kW or MW
    - Note1: kW comes from **James Watt** (1736–1819)
    - Note2: kWh is an energy not a power
- Flows have qualities
  - Material flows : composition, T, P
  - Power : heat @T, electricity @voltage, shaft @rpm

Flows : Annotation convention

- $\dot{M}_f^+$: total flow $[kg/s]$ of material flow f

  $^+$ indicates positive when entering
  $^-$ indicates positive when leaving

- $\dot{E}_e^+$: total energy flow $[kW]$ of energy flow e

  $$\dot{E}_f^+ = \dot{M}_f^+ \,.\, LHV_f \quad [kW] = [kg_f/s] \,.\, [kJ/kg_f]$$

  - LHV_f: Lower Heating Value of material flow f

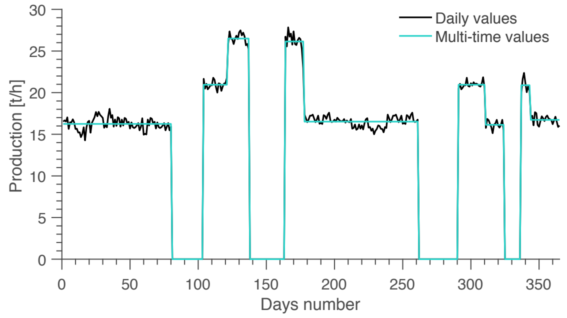
- $\dot{m}_f^+$: specific flow of material f per unit of reference flow ref in $[\frac{kg_f/s}{kg_{ref}/s}]$

  $$\dot{M}_f^+ = \dot{M}_{ref}^+ \,.\, \dot{m}_f^+$$

- $\tilde{\dot{M}}_f^+$: [kg/s] mean yearly value of $f = \dfrac{\int_{year} \dot{M}_f^+ \,.\, dt}{year}$

Materials and energy characterisation of flows with the technosphere

- Flows $[kg/s, l/s, Nm^3/h$ or $kW]$
  - Instantaneous: kg/s or kW
  - Mean Value: $kg/year$ or $kWh/year$
  - Yearly Profiles: $\dot{M}^+_{f,t} \rightarrow \overline{\dot{M}^+_f} \quad [kg/year] = \int_{year} \dot{M}^+_{f,t} \, . \, dt$
  - Specific values $\dot{m}_f \quad [\frac{kg_f/s}{kg_p/s}]$ or $[\frac{kW}{kg_p/s}]$



- Tanks & Supply chain
  - Temperature, Pressure, Quality, Levels
  - Safety
  - Supply chain : grids, roads,...
  - Max flows

Characterizing the flows with the techno-sphere

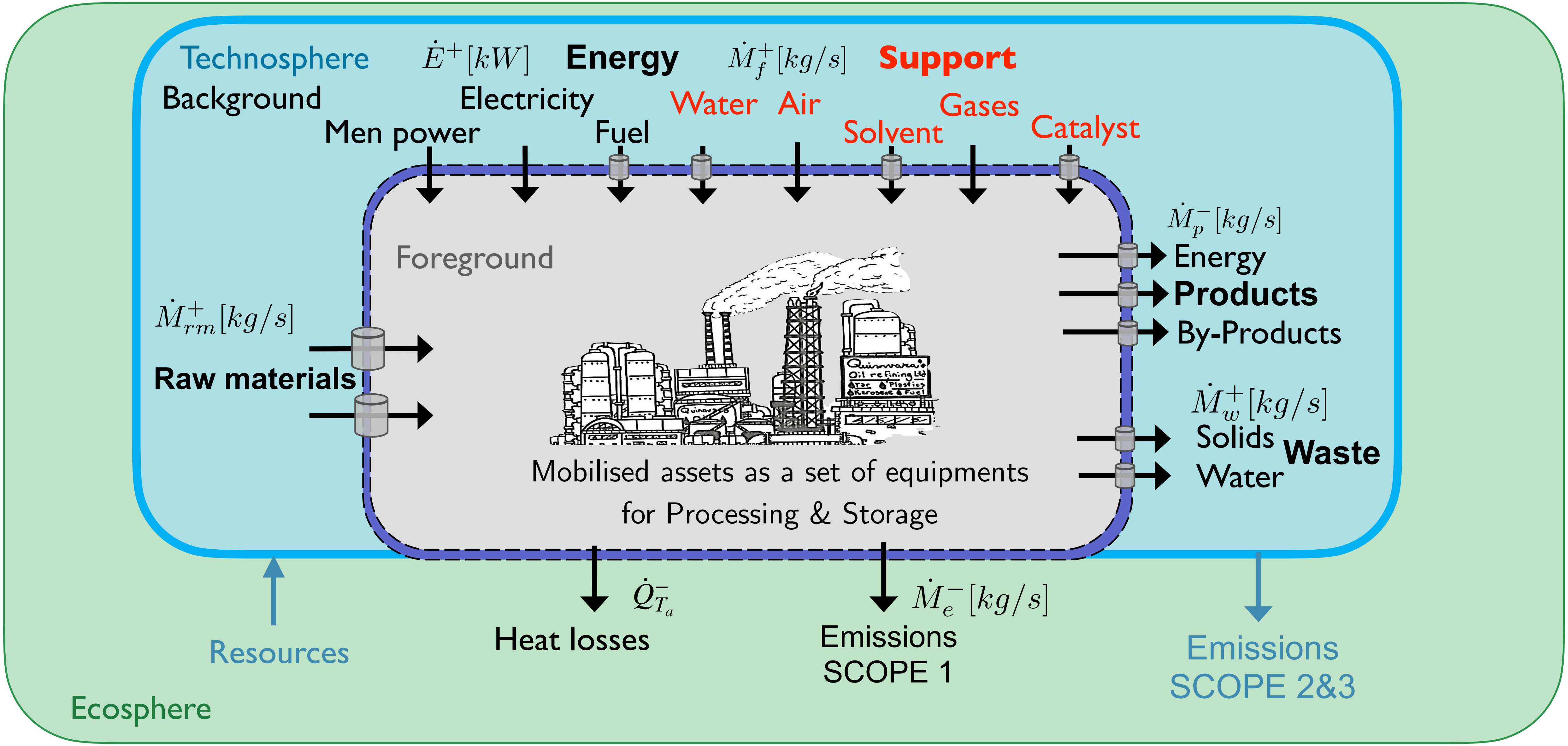
– Thermodynamic values

- Material flows : $\dot{M}_f^+$ $[kg/s, l/s, Nm^3/h]$
  - Thermodynamic state: $T, P, x_{m_{(C_cH_hO_oN_nS_sCl_{cl})}}, h, s, k, \delta, e$
- Energy flows: $\dot{E}_e^+$ $[kW]$ or $\dot{Q}_T^+$ $[kW]$

– Sustainability values of flows

- Economic: $v_f^+[\$/kg] \rightarrow \dot{V}_f^+ = \dot{M}_f^+ . v_f^+$
- Environmental: $i_f^+[impact/kg] \rightarrow \dot{I}_f^+ = \dot{M}_f^+ . i_f^+$
- Societal value: $r_f^+[externalities/kg] \rightarrow \dot{R}_f^+ = \dot{M}_f^+ . r_f^+$

What are the flows of an industrial process ?



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Characterizing the process flows

Sustainability of the flows exchanged with the techno-sphere

- **Thermodynamic**
  - Science based to qualify the foreground **(engineers)**
- **Economic**
  - Exchange with the techno-sphere **market** (**economists**)
- **Environmental**
  - Impact on our living environment (**scientists**)
- **Societal**
  - The values and the risks allocated by the society to guarantee or sustainable development (**authorities**)
  - Protect the future generations

Thermodynamic state of process flows

- Thermodynamic :
  - Thermodynamic state : T, P, α_{S-L-V}
    - $x_{m,f}$: concentration of molecule m in flow f
    - $c_{a,f}$: Ultimate composition in atom a in flow f. Molecule $m = C_c H_h O_o N_n S_s Cl_{cl}$
  - Energy content [e.g. kJ/kg or kWh/l]
    - ex: Lower Heating Value
    - Enthalpy (h) incl. Δh^0 enthalpy of formation
    - specific cinetic energy $c = \frac{1}{2} v^2 \quad [\frac{m^2/s^2}{kg/s}]$
    - relative altitude $g\Delta z \quad [kJ/kg]$
  - Entropy value [e.g. $kJ/K/kg$]
    - Entropy (s) incl. Δs^0 entropy of formation
  - Exergy value [e.g. kJ/kg]
    - $k = (h - T_a . s) - (h^a - T_a . s^a)$
    - a reference for the molecules in the ambient conditions

Economic/market values of flow exchanges with the technosphere

– Economic value ($v^+_{t,f}$) in [e.g. CHF/kg or CHF/MWh]

- Typically a range over a certain horizon of time (25 years)
  - based on historic profile
- Mean value or Yearly profiles
- Billing calculation formula:

$$\tilde{v}^+_i = \frac{v^+_{1,i} \,.\, max_t(\dot{M}^+_i) + \int_{period} v^+_{2,i} \,.\, \dot{M}^+_i \,.\, dt}{\int_{period} \dot{M}^+_i \,.\, dt}$$

- Markets
  - energy
  - interruptible
  - emission trading
- Taxes and regulation

Direct Emissions (SCOPE 1) to ecosphere

- Direct emissions (SCOPE1) [e.g. $kg_{CO2}/kg_{product}$]
  - effective flow to ecosphere: CO_2 $[kg_{CO_2}/kg_{product}]$
  - leakages: CH_4 $[kg_{Ch_4}/kg_{product}]$
  - fugitive Elementary Flows : $\dot{m}_{f_{ef}}$ $[kg_{ef}/kg_{product}]$
- Environmental impact [e.g. $kg_{CO2_{eq}}/kg_{product}$]
  - impact in area of concern (e.g. climate change): $i_f = \sum_{ef} i_{ef} \, . \, \dot{m}_{f_{ef}}$
  - mid-point indicators: $i_f^{MP} = \sum_{i} k_i^{MP} \, . \, (\sum_{ef} i_{ef} \, . \, \dot{m}_{f_{ef}})$
  - single point indicators: $i_f^{SP} = \sum_{MP} k_{MP}^{SP} \, . \, (\sum_{i} k_i^{MP} \, . \, (\sum_{ef} i_{ef} \, . \, \dot{m}_{f_{ef}}))$

Indirect emissions (SCOPE 2 &3) from the technosphere

- Environmental impact [e.g. $kg_{CO2_{eq}}/kg$]
  - Indirect emissions (SCOPE2 + SCOPE3) [e.g. $kg_{CO2_{eq}}/kg$]
  - Life Cycle Inventory (LCI)
    - Elementary Flows from LCI data bases: $\dot{m}_{f_{ef}}$ [kg_{ef}/kg_f]
    - impact in area of concern (e.g. climate change): $i_f = \sum_{ef} i_{ef} \, . \, \dot{m}_{f_{ef}}$
    - mid-point indicators: $i_f^{MP} = \sum_{i} k_i^{MP} \, . \, (\sum_{ef} i_{ef} \, . \, \dot{m}_{f_{ef}})$
    - single point indicators: $i_f^{SP} = \sum_{MP} k_{MP}^{SP} \, . \, (\sum_{i} k_i^{MP} \, . \, (\sum_{ef} i_{ef} \, . \, \dot{m}_{f_{ef}}))$

SCOPE 1 : societal values of process flows

- Taxes & regulations

  tax of elementary flow $ef : t_{ef}[\$/kg_{ef}] \rightarrow T_f = \sum_{ef} t_{ef} \,.\, \dot{M}_{f_{ef}}$

- Limits:

  flows: $\sum_{f} \dot{M}_{f_{ef}} \leq \dot{M}^{max}_{f_{ef}}$

  concentration: $\dfrac{\dot{M}_{f_{ef}}}{\dot{M}_f} \leq \dot{x}^{max}_{ef}$

  total flow: $\int_{t}^{year} \sum_{f} \dot{M}_{f_{ef}} dt \leq M^{max}_{ef}$

- Externalities

  _ Cost of repair: $r_f = \sum_{ef} r_{ef} \,.\, \dot{m}_{f_{ef}} \, [\$/kg_{ef}]$

Societal values of process flows

- Other aspects
  - Security of supply
    - Country of origin
    - Max power constraints
    - Grid/supply chain constraints
  - Safety
    - storage conditions
    - explosion
    - toxicity

Characterizing the process flows

- An industrial is processing flows
  - mass $\dot{M}_f^+$ and energy $\dot{E}^+$flows to make products $\dot{M}_p^-$ and waste $\dot{M}_w^-$ flows
- Each flow comes with a thermodynamic and a sustainability quality
- Performance Indicators:

$$\int_{t_0}^{t_{end}} \left(\sum_{f}^{flows} \dot{M}_f^+ . v_f^+ + \dot{E}_e^+ . v_e^+ + \sum_{w}^{waste} \dot{M}_w^- . v_w^- - \sum_{p}^{products} \dot{M}_p^- . v_p^- \right) dt$$