Energy Audits

Calculating the energy bill
Identifying the energy drivers

Prof François Marechal

EPFL Steps in decarbonisation

Efficiency
Materials recovery
Heat recovery

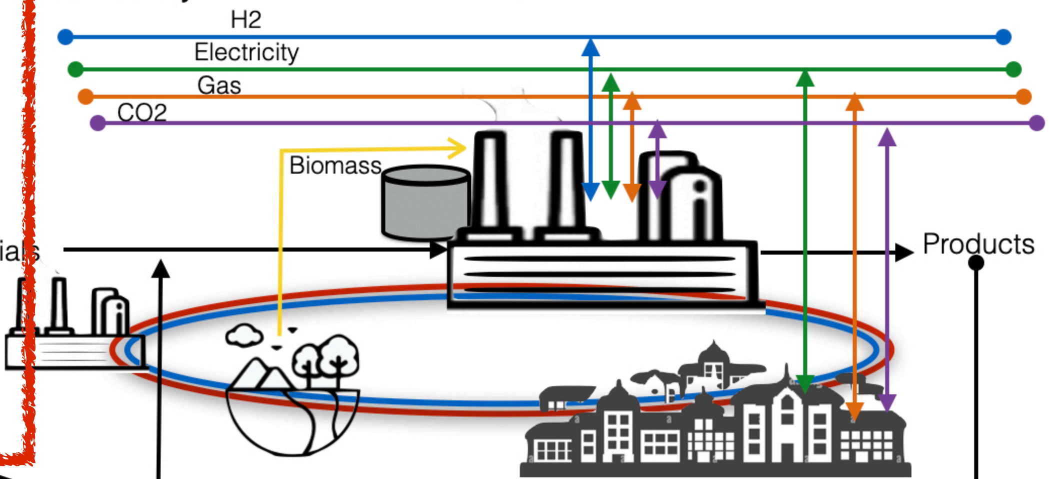
Heat valorisation
Heat pumping
Waste heat to electricity

Energy conversion
Renewable energy sources
Combined Heat and Power
Combined Heat and Fuel

Technology efficiency
Optimal operation
Technology improvement
Technology innovation

CO2
Capture, reuse, sequestrate

Energy Audits
Energy Drivers
Efficiency KPI
Monitoring



Energy system integration
Energy grids
Heat and electricity storag
Hydrogen
Power2Tanks2Power

System expansion
District heating/coolir
Industrial symbiosis
Waste-water-energy
Circular economy

Sustainability metrics
CO2 footprint
Resources usage
Environmental impact

Thermodynamic metrics
Energy Efficiency
Mass balances
Exergy

Economic metrics
CAPEX-OPEX
Technology Readiness
Retrofit and pay-back

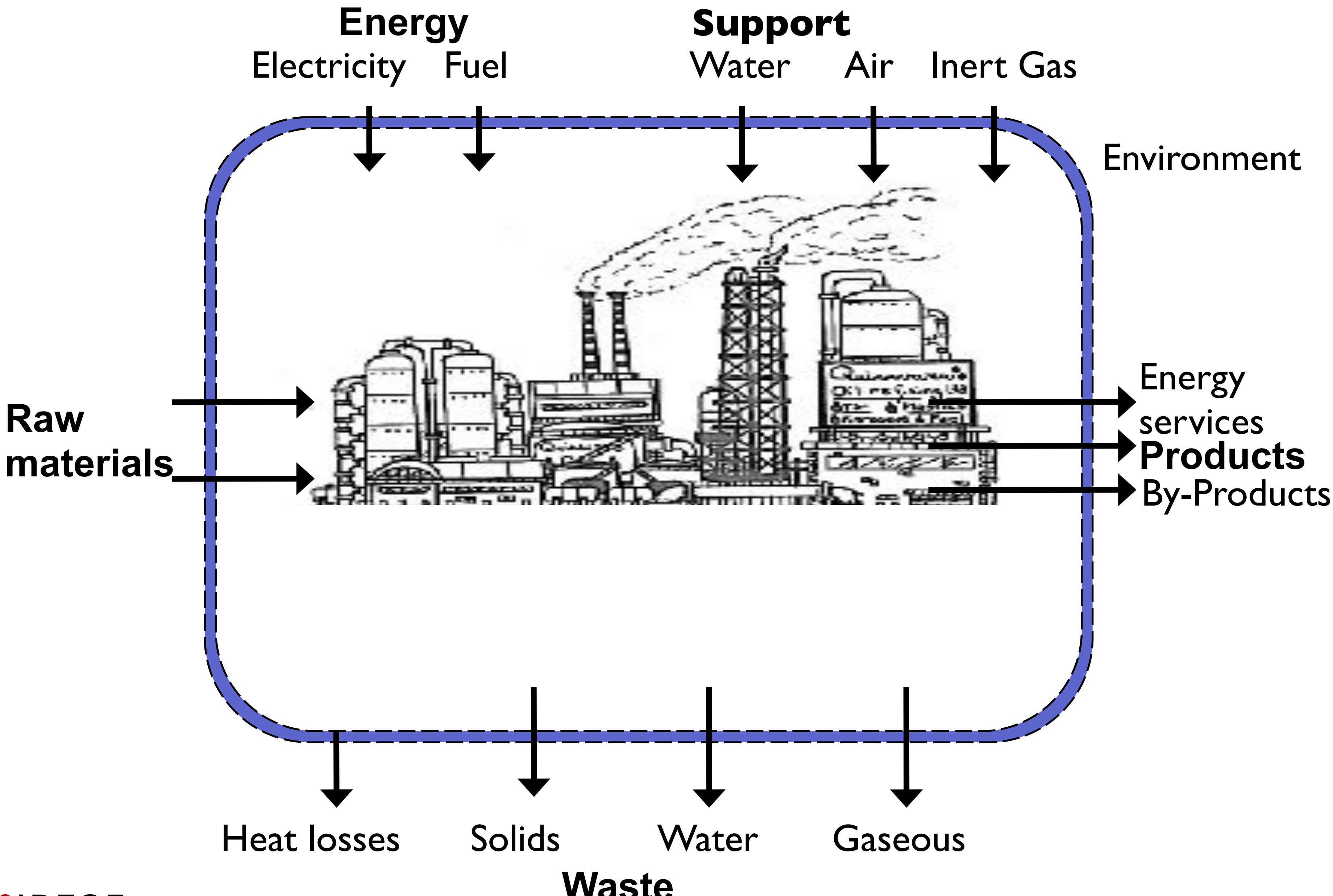
Competences needed ?

- **Task 1 :** What is the energy usage ? => **energy audits**
  - energy bill $[CHF/kg_{product}]$ and $[CHF/year]$?
  - CO2 emissions and sensitivity to market ?
  - How good are we ? => benchmark
  - How good are we thermodynamically ? => exergy analysis
  - What are the energy requirement of the process ?
- **Task 2 :** What are the **heat recovery** options ?
  - What are the heating and the cooling needs ?
  - Can we recover heat ?
  - What are the heat recovery exchangers to buy
- **Task 3** : How to **supply at best the energy** to the process ?
  - What are the (renewable) energy resources to be used to close the energy balance
  - What are the best energy conversion technologies
  - Can we convert our waste into products or energy ? e.g. biogas
- **Task 4 :** Can we **expand the system boundaries** ?
  - Convert waste into product (Integration of Rivella production ? => look for synergies)
  - Capture and sequestrate CO2 ?

Analysing process systems energetics

- Lecture 1
  - Mass and energy balance to characterize the energy demands

The process system flows



Characterising flows

- Using balance equations to calculate values when other values are known (measured) => AGIR
  - **A**.1 Define what you are looking for : the list of the flows + indicators
    - definition
    - physical units
    - expected ranges
  - A.2 Define what you know
    - Knowledge (e.g. thermodynamics, transfer phenomena, unit operation principles)
    - Process Analytics : Measurements
  - **G**.1 Establish the equation system : mass and energy balances
    - $\dot{Q} = \dot{m} \cdot cp \cdot (T_{in} - T_{out})$
  - G.2 Solve the system of equations to calculate what you are looking for from what you know
  - **IR**: Efficiencies
    - Specific consumptions
    - Energy bills

energy review

main requirements (ISO 50001:2011)

analyse energy consumption → energy resources
energy consumption trends
+energy baseline

identify areas of significant energy use : energy drivers → energy consumption breakdown
Main processing steps
Influencing factors

determine the energy performance → energy needs
+energy performance indicators

identify, prioritise & record energy savings opportunities → analysis & classification

What do we see first ?

Energy

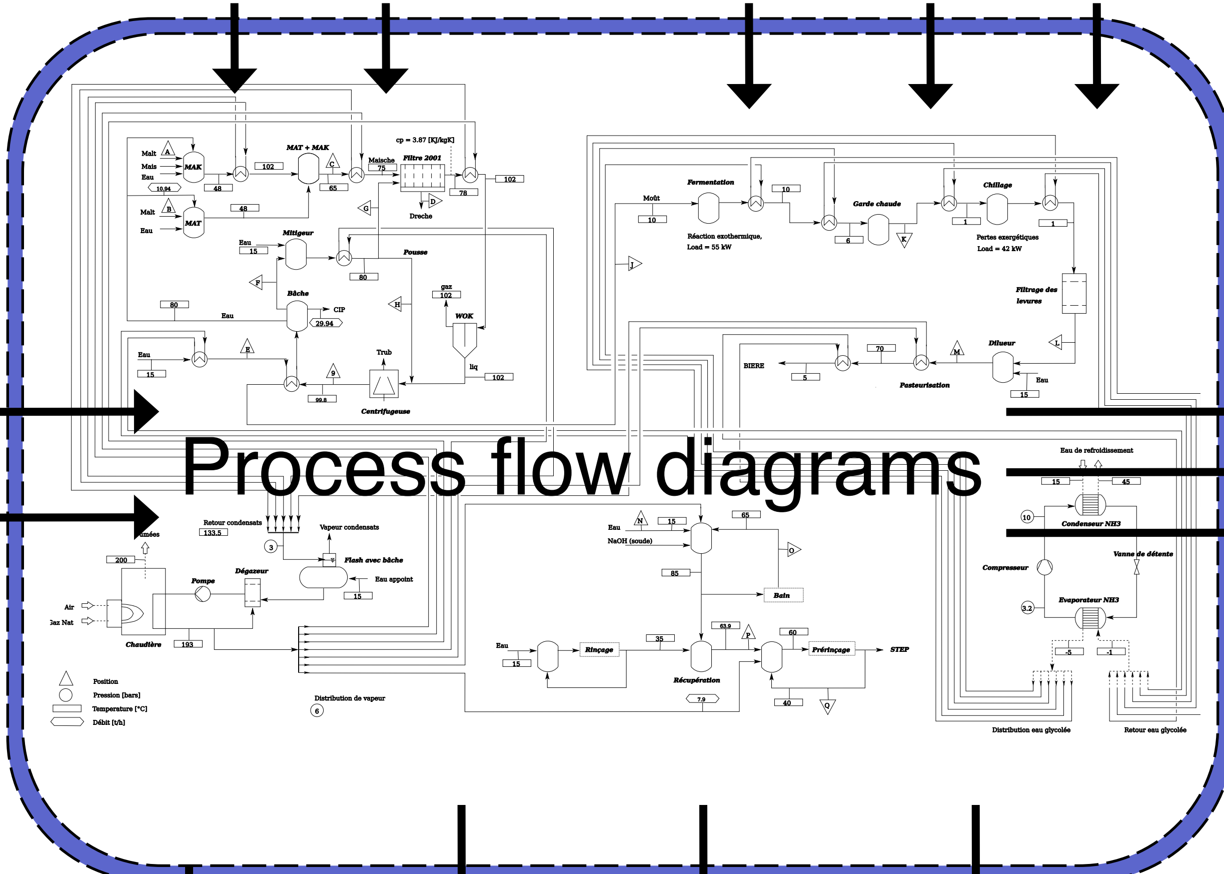
Electricity Fuel

Support

Water Air Inert Gas

Environment

Raw materials



Energy services

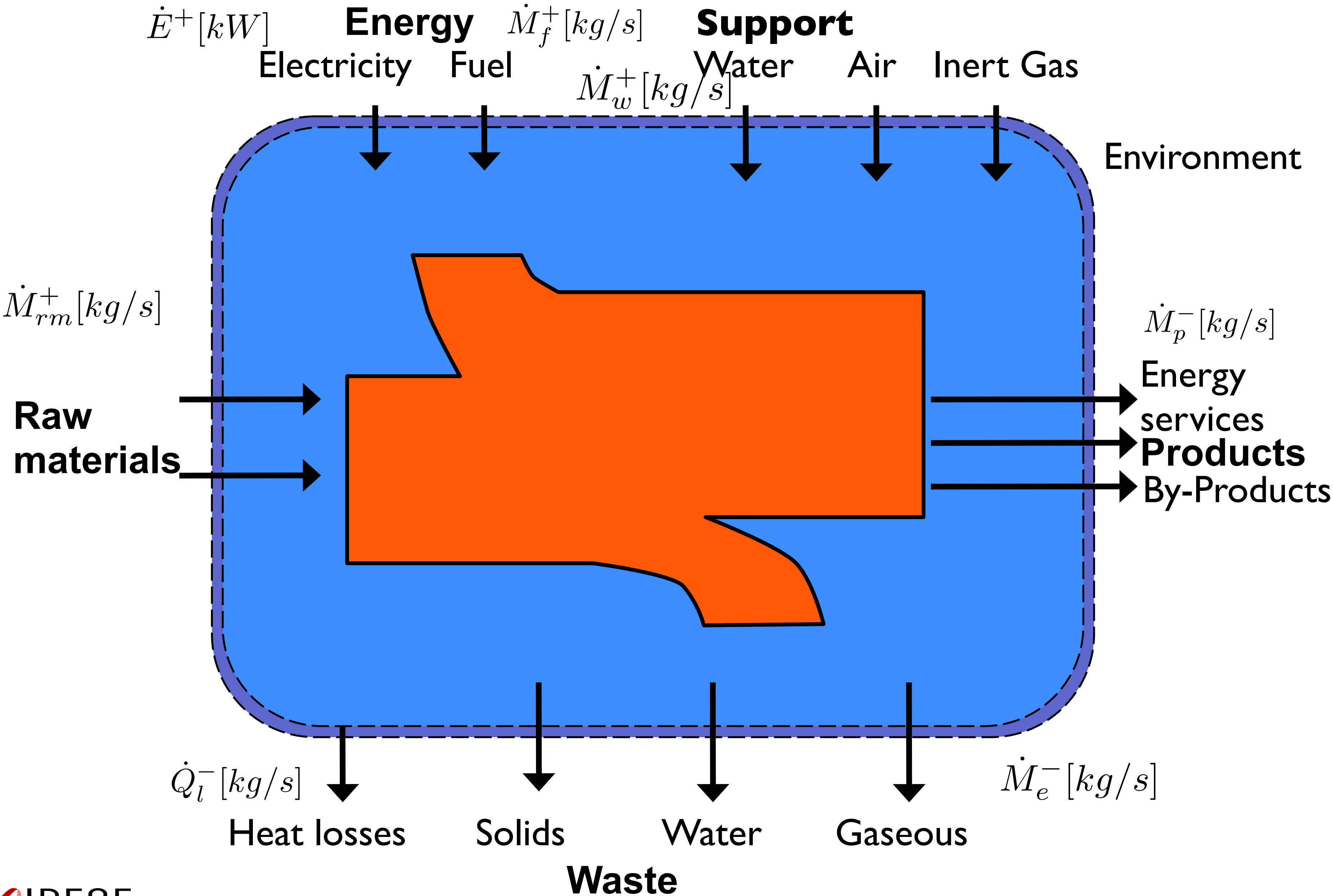
Products

By-Products

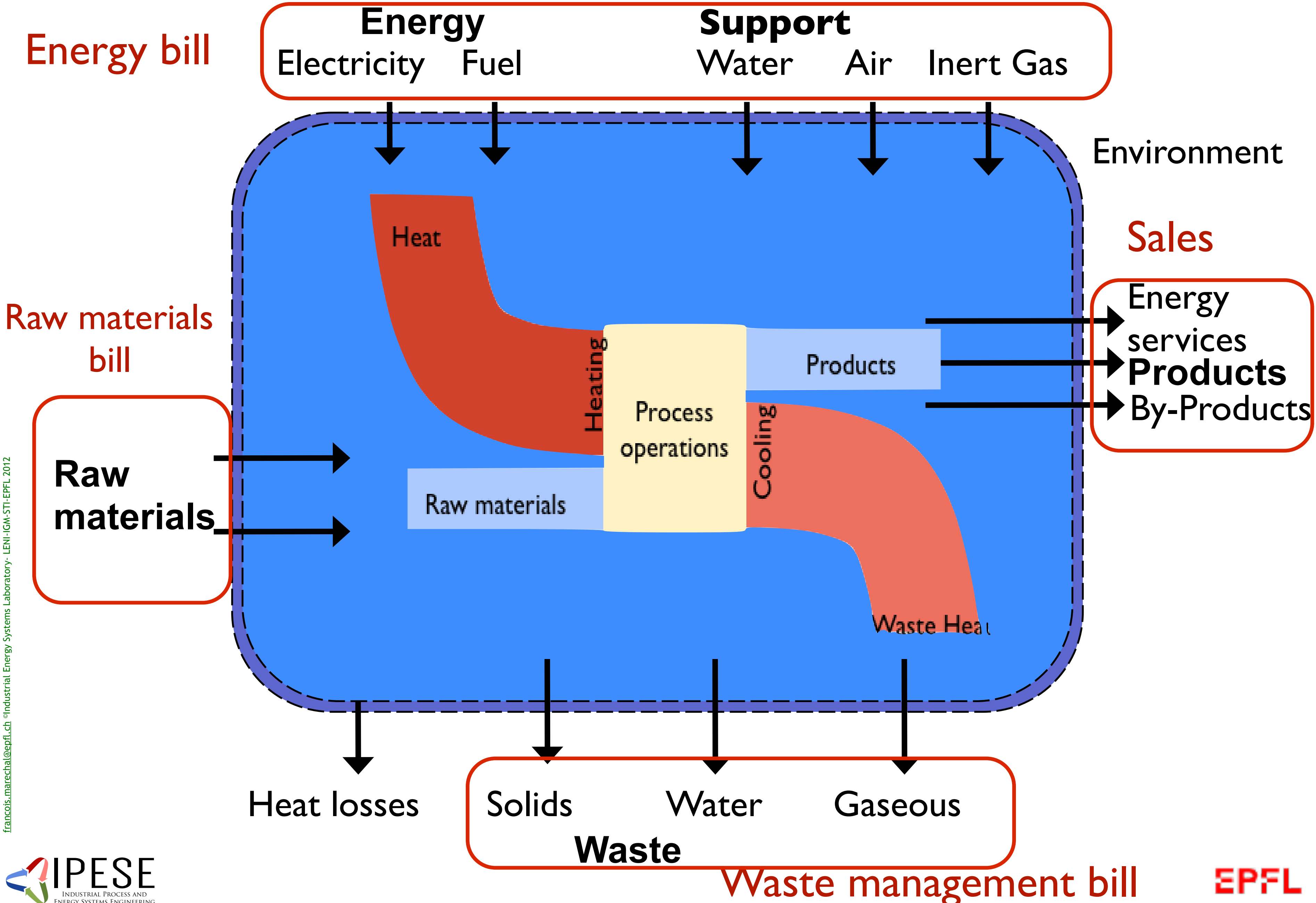
Heat losses Solids Water Gaseous

Waste

Mass and Energy Flows of the process



The Economic Balance



Characterising process flows

- For each flow (in and out)
  - Flows $[kg/s]$
    - Typical production rate
  - Conditions at tanks or entrance
    - Temperature, pressure, quality
  - Energy content $[kJ/kg]$
    - typically Lower Heating Value
  - Cost $[CHF/kg]$
    - perspective over 25 years needed
  - Emissions $[kg_{CO2}/kg]$
    - Consider Life Cycle of Supply $[kg_{CO2_{eq}}/kg]$

Economic evaluation

Revenues

Sales (CHF/year)

Products — Electricity

$$\int_{t_0}^{t_f} \left(\sum_{P=1}^{n_P} \dot{M}_P^-(t) c_P^-(t) + E^-(t) c_e^- \right) dt$$

Costs

Operating costs or OPEX (OPerating EXpenditure) (CHF/Year)

Raw materials — Fuel — Electricity — Waste

$$-\int_{t_0}^{t_f} \left(\sum_{R=1}^{n_R} \dot{M}_R^+(t) c_R^+(t) + \sum_{F=1}^{n_F} \dot{M}_F^+(t) c_F^+(t) + E^+(t) c_e^+ + \sum_{W=1}^{n_W} \dot{M}_W^-(t) c_W^-(t) \right) dt$$

Energy Bill

$$EnergyBill = \int_{t_0}^{t_{year}} \left(\sum_{F=1}^{n_F} \dot{M}_F^+(t) c_F^+(t) + E^+(t) c_e^+ - E^-(t) c_e^- + \sum_{CO_2=1}^{n_{CO_2}} \dot{M}_{CO_2}^-(t) c_{CO_2}^-(t) \right) dt \quad [CHF/year]$$

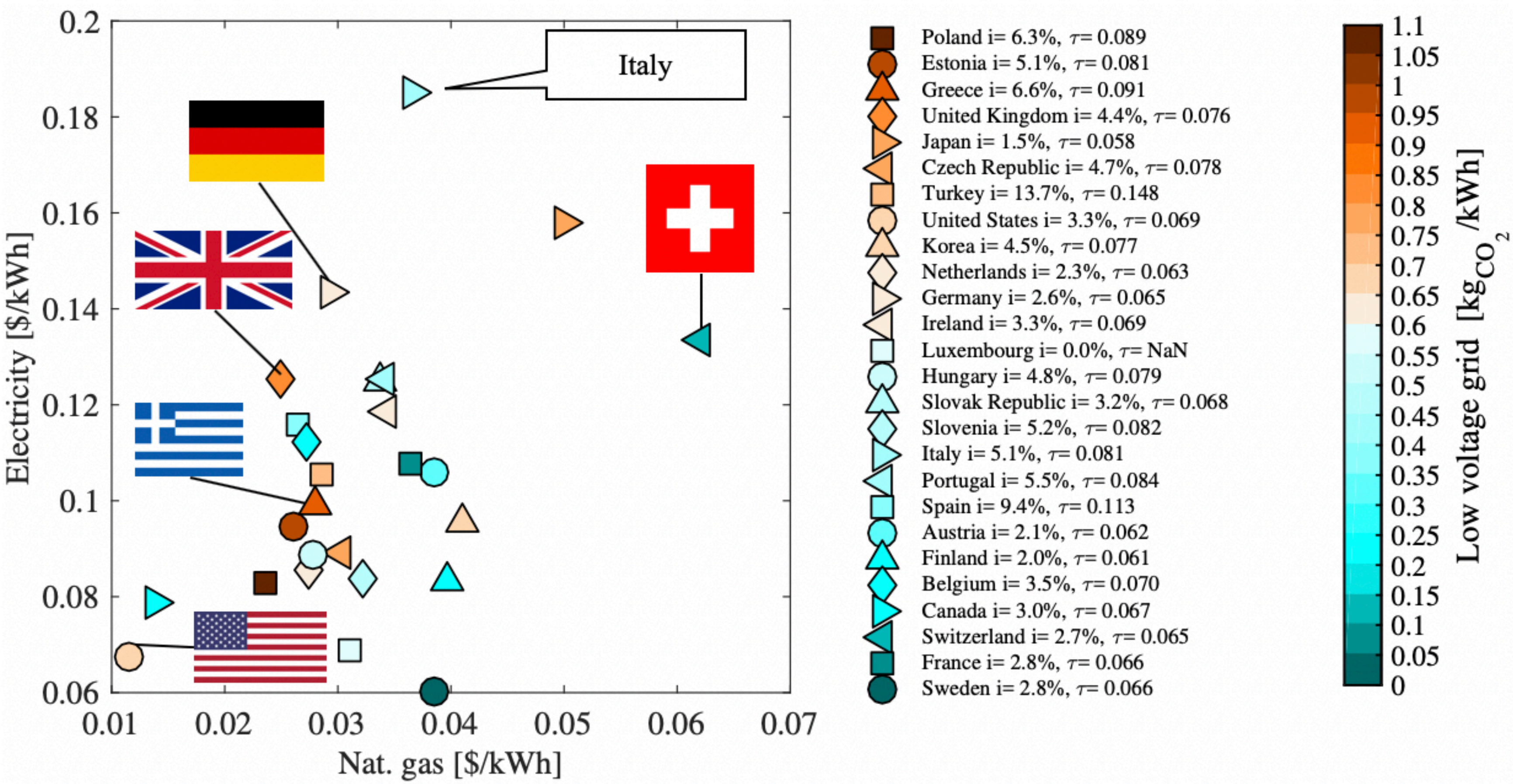
Steady State Operation

- Replace $\int_{t_0}^{t_{year}} \dot{m}_t \cdot dt$ by $\tilde{\dot{m}} \cdot (t_{end} - t_0)$

- We will define the time of operation :
  $t_{op} = t_{year} - t_0$ [s/year]

- In case the baseline has periods
  $$\_ \sum_{period} \dot{m}_{period} \cdot t_{op_{period}}$$

Energy prices



Source: *A.S. Wallerand, Thesis EPFL 2018*

Values from IEA report : Key World Energy Statistics

Environmental impact and its value

- Mass flow :

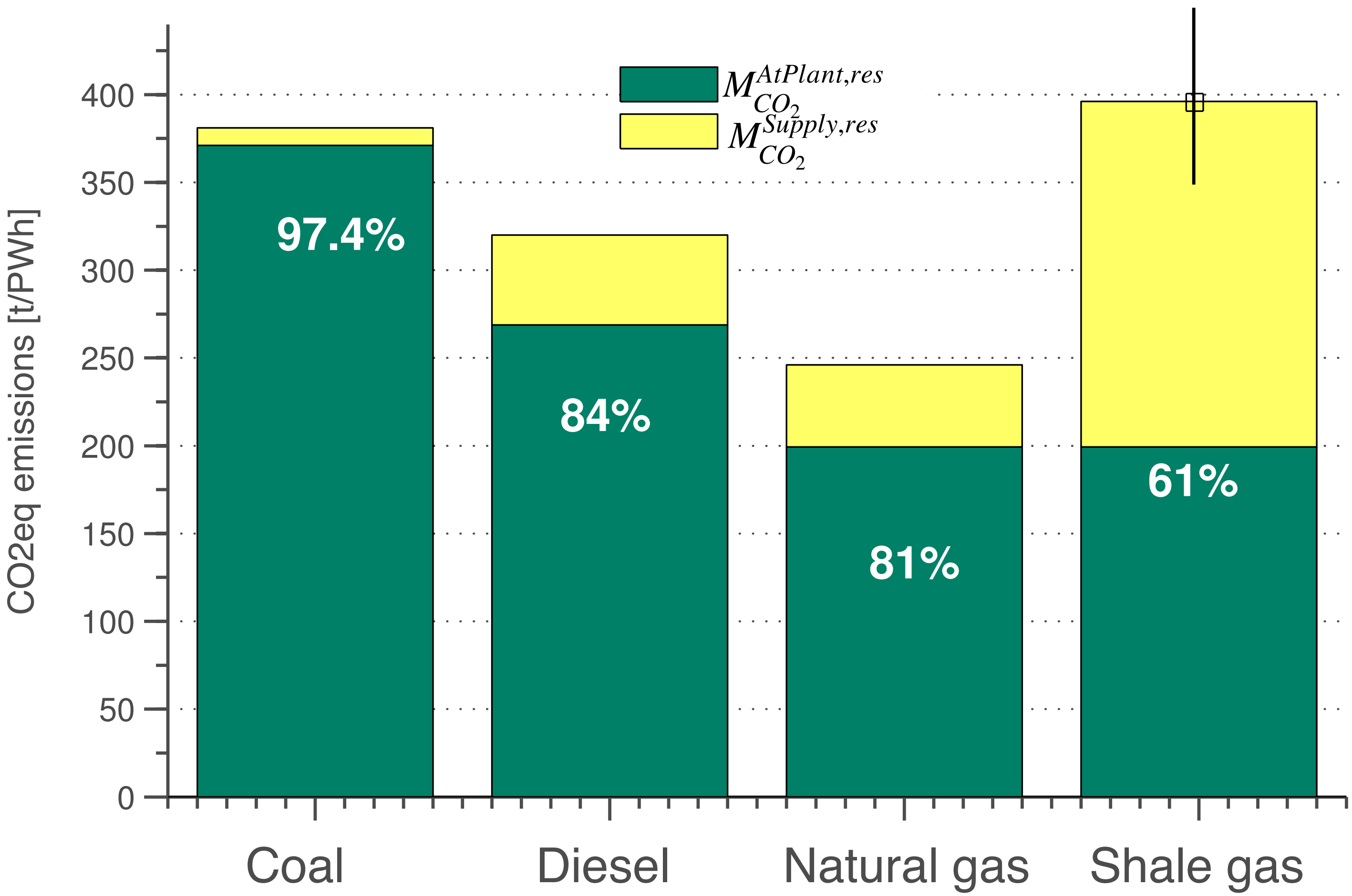
$$\dot{M}_{CO_2}[kg_{CO_2}/h] = \dot{M}_{res}[kg_{res}/h] \cdot (M_{CO_2}^{AtPlant,res} + M_{CO_2}^{Supply,res})[kg_{CO_2}/kg_{res}]$$

  - AtPlant => emissions during combustion
  - Supply => emissions for the extraction, the preparation and the distribution
  - kg_{CO_2} => Only CO2 or equivalent global warming potential (GWP) expressed in kg CO2

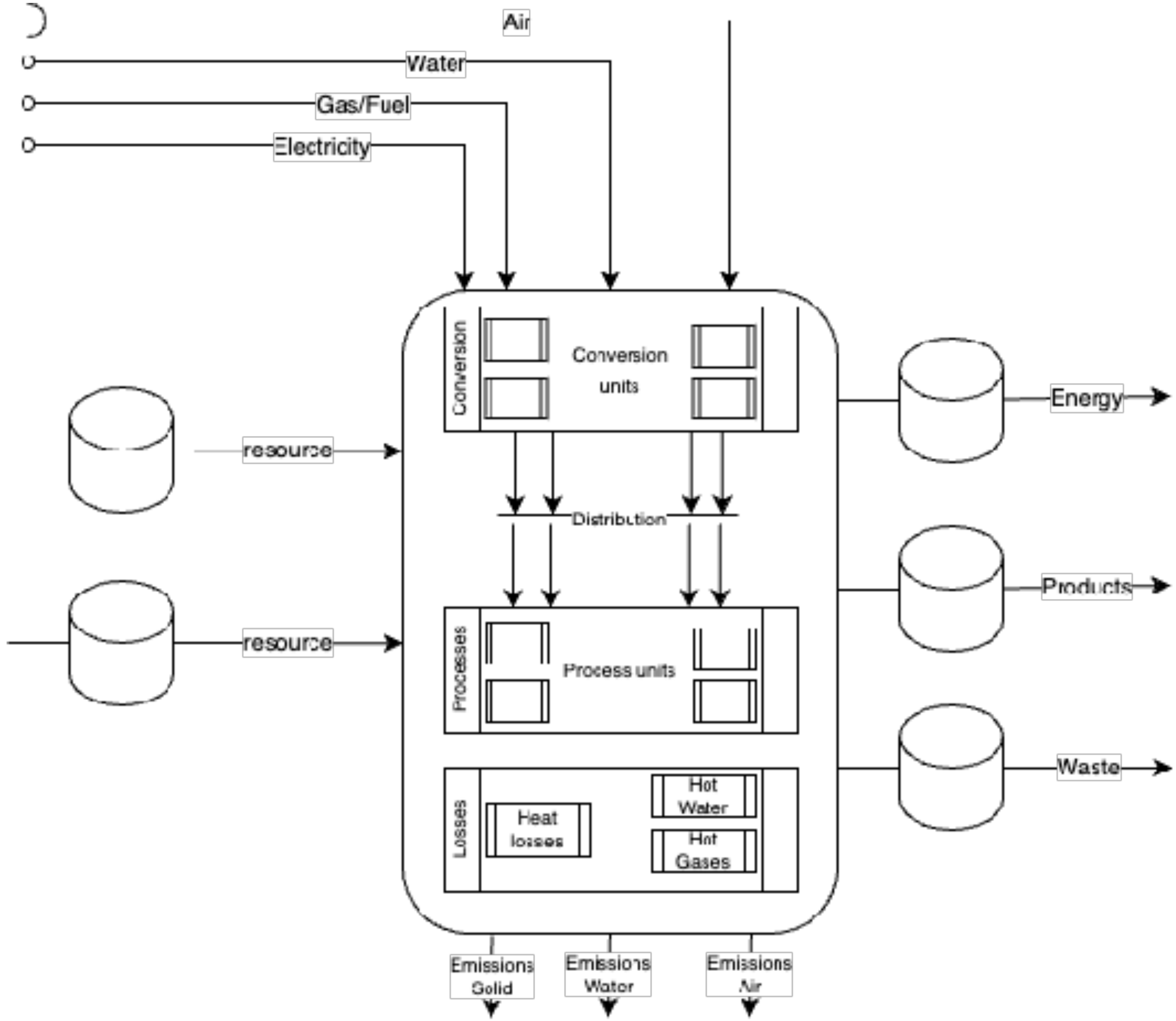
- Tax : 96 - 220 CHF/ton

$$C_{CO_2}[CHF/year] = \int_{h0}^{h_{year}} (tax_{CO_2}[CHF/kg_{CO_2}] \cdot \dot{M}_{res}[kg_{res}/h] \cdot M_{CO_2}^{res,AtPlant}[kg_{CO_2}/kg_{res}]) \quad dt$$

direct and indirect CO2 emissions of fuels



Understanding the energy bills



Connectivity

- **From the main grids**
  - list of resources : raw materials, energy, support
- **Distributed flows**
  - Energy sent to the process units
  - Material flows

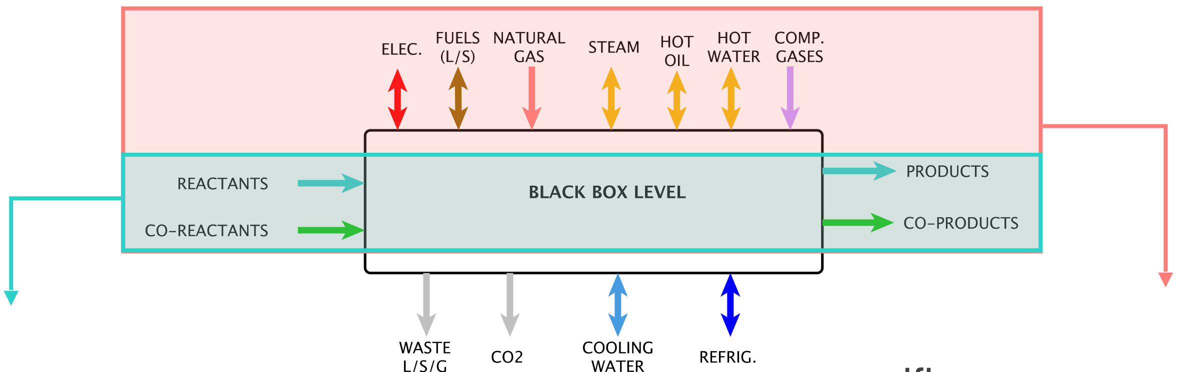
Defining the baseline

IPESE Industrial Process and Energy Systems Engineering

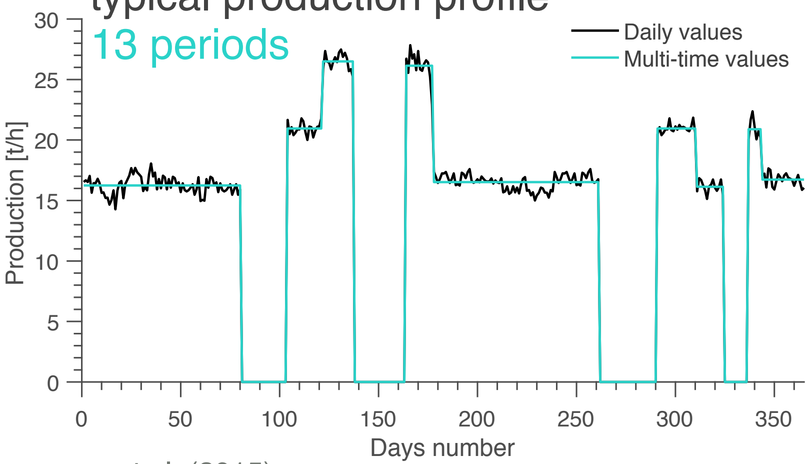
$$\dot{m}_p[kg/s] = f_p[\%_{nominal}] \cdot \dot{m}_{nominal}[kg_{nominal}/s] \qquad \dot{m}_{u,p} = f_p \cdot \dot{m}_{nominal} \cdot \eta_u(f_p \cdot \dot{m}_{nominal})$$

production model x specific energy consumption models = energy baseline

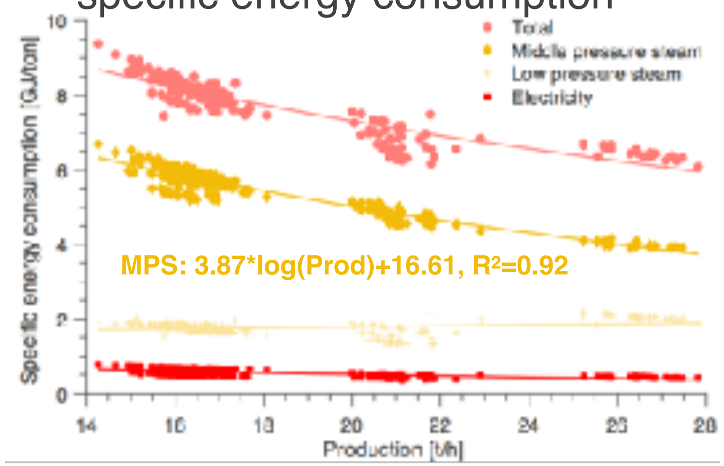
(> to be approved)



typical production profile



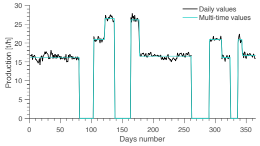
specific energy consumption

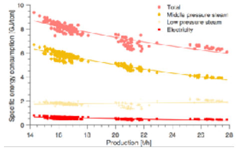


NB: Bungener et al. (2015)

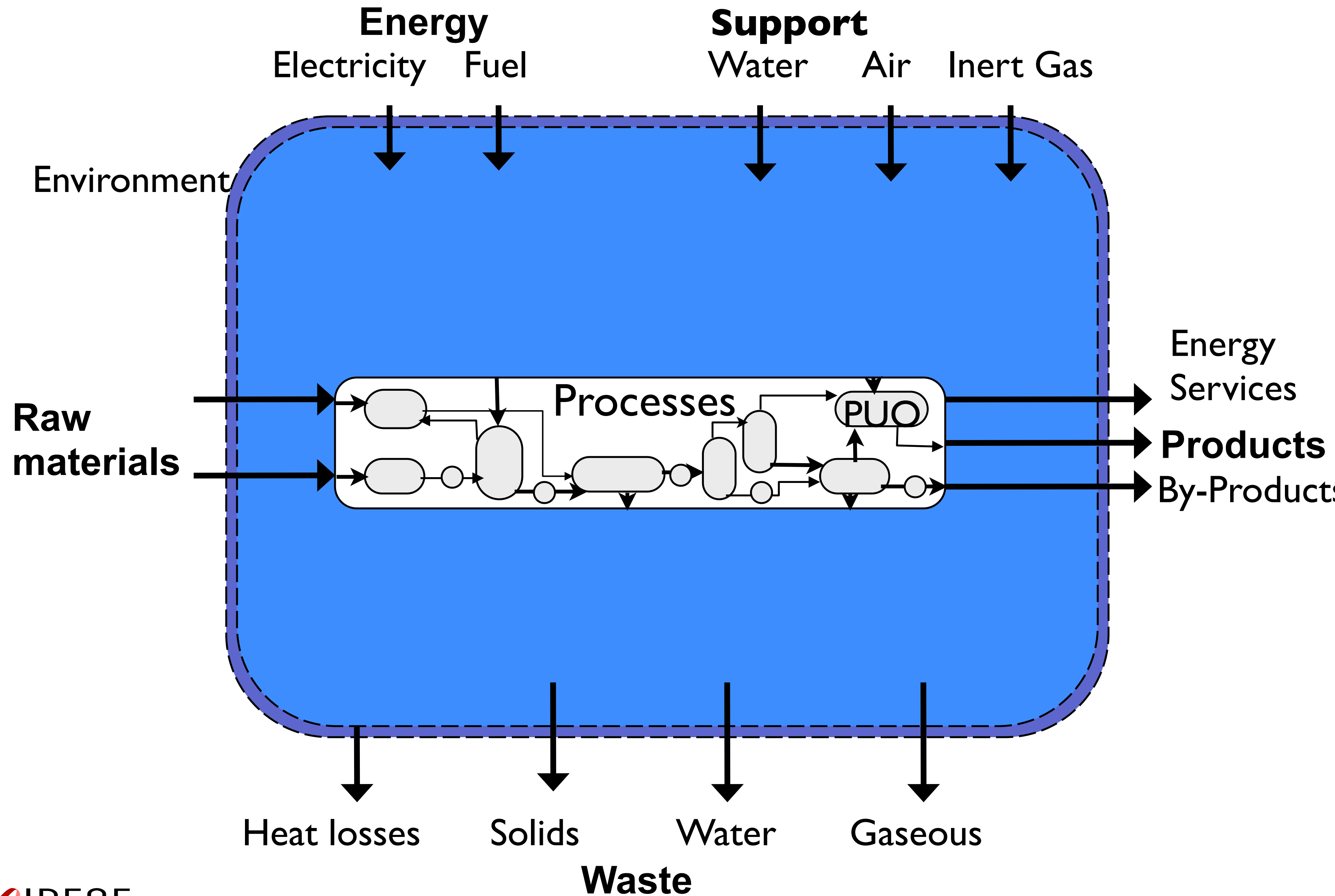
Process performances

- **Production model**
  - yearly production of main product $[kg_{product}/year]$
    - Typical flow $[kg/s]$
    - operating time for each of the typical flow $[s/year]$
- **Consumption models**
  - Raw Materials
    - Atom/product efficiency $[kg_{rm}/kg_{product}]$
  - Products
    - for each by-product $[kg_{by-product}/kg_{product}]$
  - Energy
    - Electricity $[kJ_e/kg_{product}]$
    - Fuels $[kJ_{LVH}/kg_{product}]$
    - Distributed energy $[kJ_{steam}/kg_{product}]$
  - Waste and emissions
    - $[kg_{waste}/kg_{product}]$



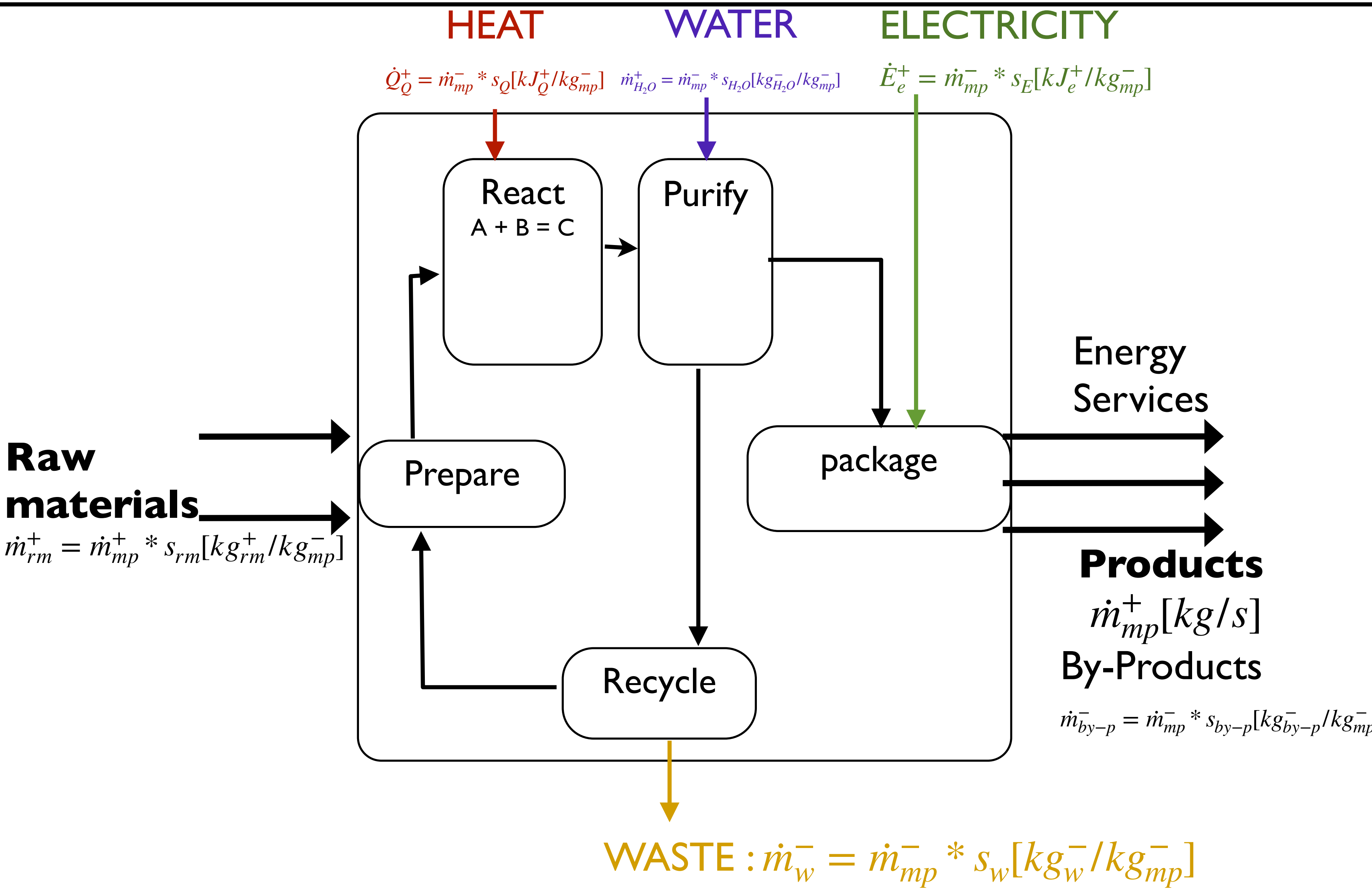


The process requirements



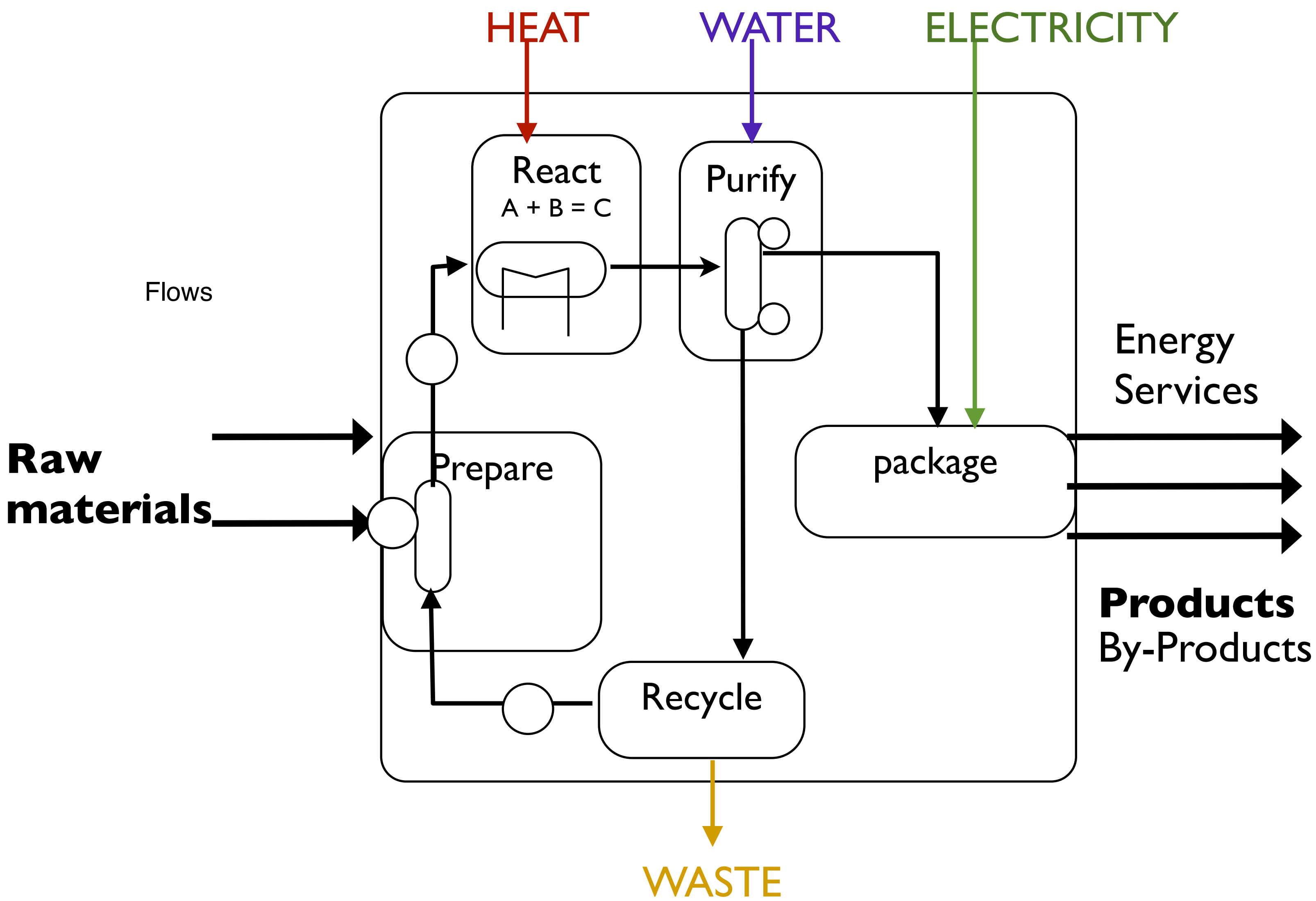
francois.marechal@epfl.ch

Process analysis : block flow diagram : the process recipe



Process steps defined by their function in the production

Process analysis : Process flow diagram : the kitchen

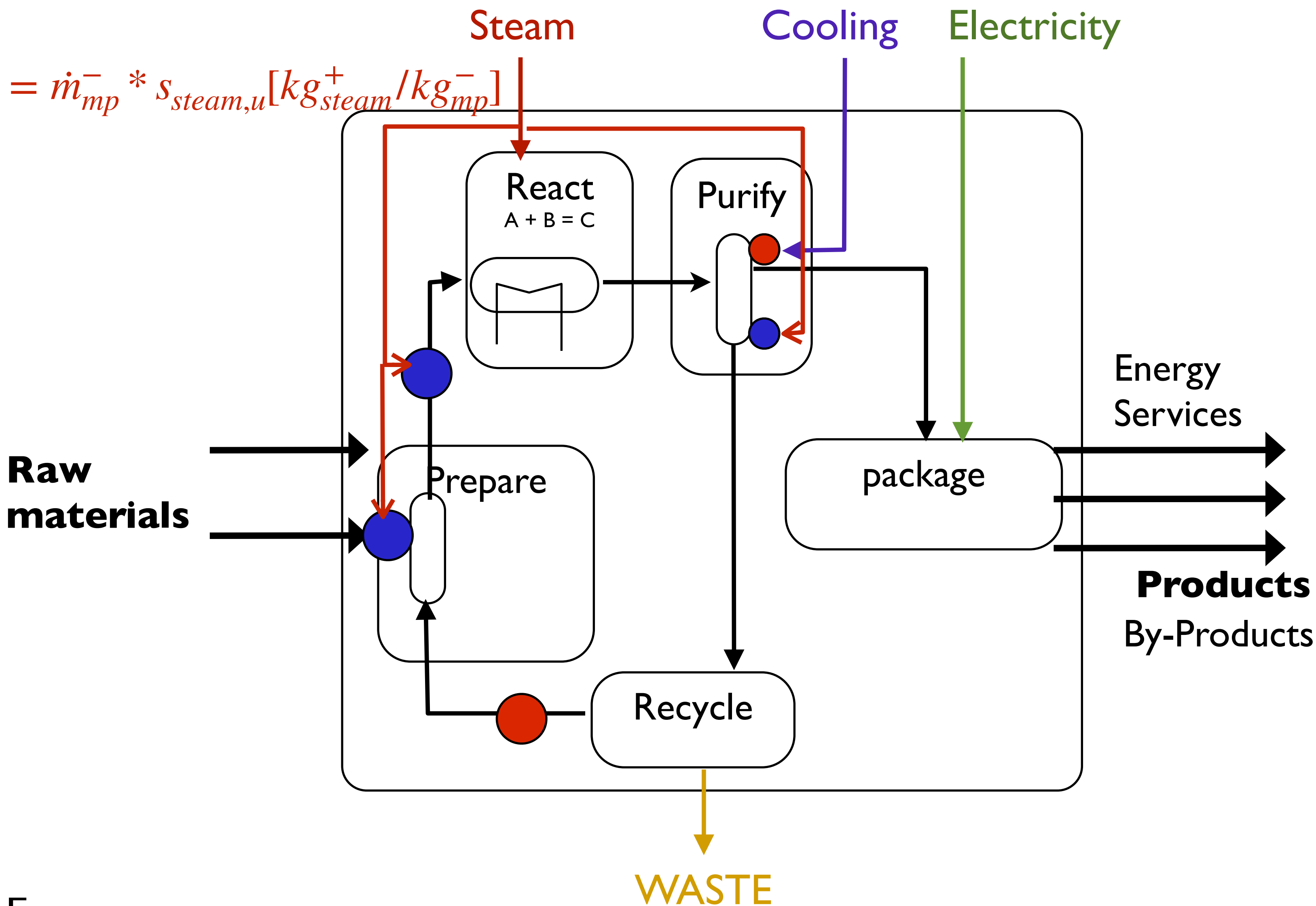


Each function is replaced by the process unit operation u that realise it

Process analysis : energy distribution

For each distribution system (e.g. steam) and process unit operation u

$$\dot{m}^{+}_{steam,u} = \dot{m}^{-}_{mp} * s_{steam,u}[kg^{+}_{steam}/kg^{-}_{mp}]$$



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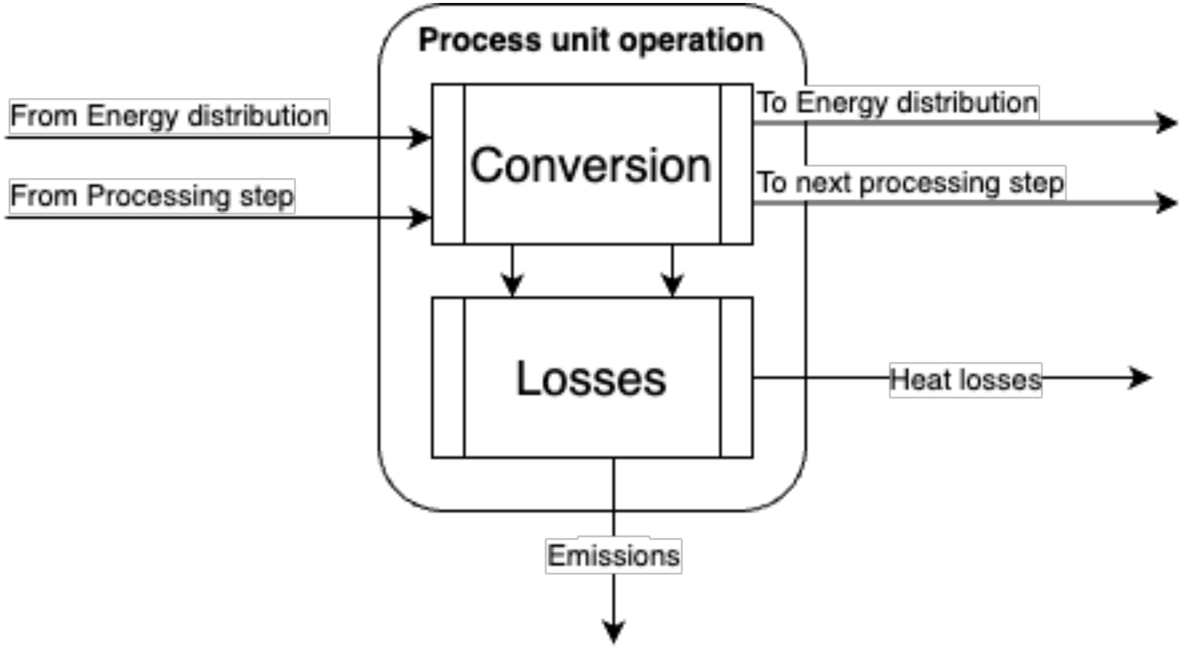
Process units and losses

- To close the energy balance you have to identify the losses mechanisms
  - Technology Inefficiency
- Heat losses
  - Heat in a pipe : hot water - hot air
  - Radiation : released due to lack of insulation



Energy demand characterisation

- Mass flow

$$\text{Mass flow}: \dot{M}_i^+ \quad [kg/s]$$
$$\text{Molar flow}: \dot{N}_i^+ \quad [kmol/s]$$
$$\text{Composition}: \dot{x}_{i,j} \quad [\%]$$

- Energy of mass flows

$$\text{Thermodynamic State}: T_i, P_i, v_i, hi, si$$
$$\text{Constitutive equations}: h_i[kJ/kg] = f(T, P, x_j)$$
$$H_i[kJ/year] = \int_{year} \dot{M}_i^+(t) \cdot h_i(t)dt$$

- Electricity
  – compression, pumps, drives : $\dot{E}^+[kW_e]$

How to calculate the enthalpy content

Thermodynamic properties of a flow, knowing its state : T,P,x

- Flowsheeting softwares
  - Aspen, Belsim, gPROMS, Prosim, **ThermoCycle**, **DWSIM**
- Software packages
  - Refprop, Simulis, **Coolprop**
- Data base
  - NIST - webbook, DIPPR, wikipedia
- **Bold are open source**

Mass Balance and Energy Balance

- Accumulation = IN - OUT
  - 1rst principle of thermodynamics

- Mass Balance (stationary : No accumulation)

$$\forall a \in atoms : \sum_{i=input} \dot{M}_i^+ \cdot x_{o,a} = \sum_{o=output} \dot{M}_o^- \cdot x_{o,a}$$

- Energy Balance (steady state : No accumulation)

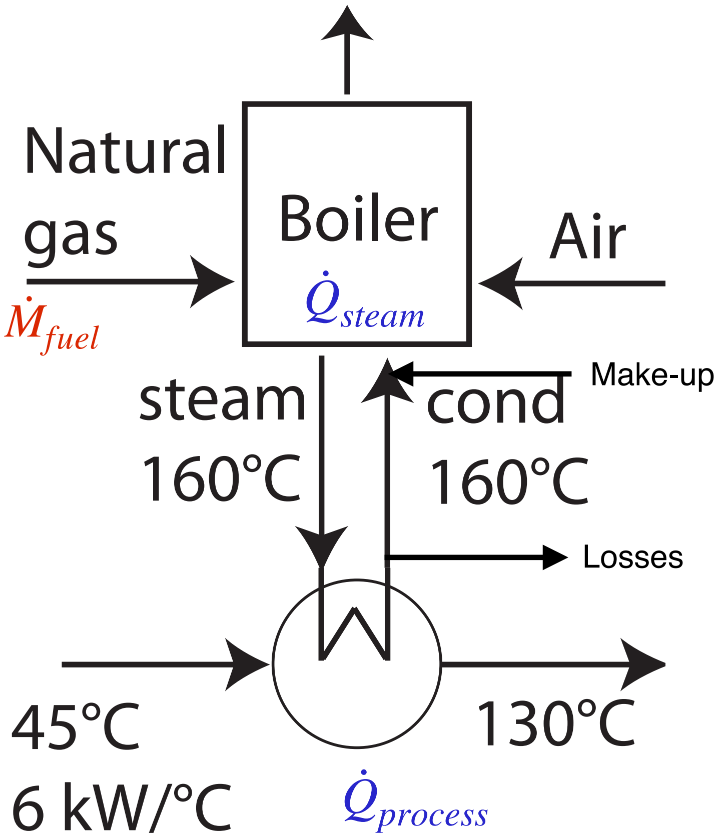
$$\sum_{i=el_{input}} \dot{E}_i^+ + \sum_{i=input} \dot{M}_i^+ \cdot h_i = \sum_{o=el_{output}} \dot{E}_o^- + \sum_{o=output} \dot{M}_o^- \cdot h_o + \sum_{l=losses} \dot{Q}_l^-$$

Mass Balance and Energy Balance : important to note

- Mass balance
  - No mass losses
  - Chemical reactions
- Energy Balance
  - Energy is conserved but can be lost in the environment
  - Enthalpy includes energy of formation (chemical reactions)
  - Lower Heating Value is the energy of formation of a fuel
  - Losses ≠ Ignorance (i.e. not the error of the energy balance)
  - Energy flows to the environment to be characterized

  - Mass flows : $$\sum_{o=output \notin products} \dot{M}_o^- \cdot h_o$$
  - Heat $$\sum_{l=losses} \dot{Q}_l^-$$

Energy conversion & Distribution



- Conversion => efficiencies
  - **Fuel** ($\dot{M}_{fuel}$ [kg/s]) to heat $[kW_{heat}]$
  - Heat $[kW_{heat}]$ to steam $[kW_{steam}]$
  - $\dot{Q}_{steam} = \dot{m}_{steam} \cdot (h_{steam,condreturn}(T_c, P_c, \alpha_c) - h_{steam,supply}(T_s, P_s, \alpha_s))$

$$\eta_b = \frac{\dot{Q}_{steam}}{\dot{M}_{fuel} \cdot LHV_{fuel}}$$

- Distribution
  - Steam $[kW_{steam}]$ to **process heat** $[kW_{process}]$
  - $\dot{Q}_{steam,d} = \dot{m}_{steam,d} \cdot (h_{steam,supply}(T_s, P_s, \alpha_s) - h_{steam,return}(T_r, P_r, \alpha_r))$
- Process Heat needs
  - $\dot{Q}_p[kW_{process}] = q_{process}[kJ/kg_{nominal}] \cdot f_p \cdot \dot{m}_{nominal}$

$$q_{process}[kJ/kg_{nominal}] = (h_{pf,in} - h_{pf,out}) \cdot \frac{\dot{m}_{pf}}{\dot{m}_{nominal}}$$

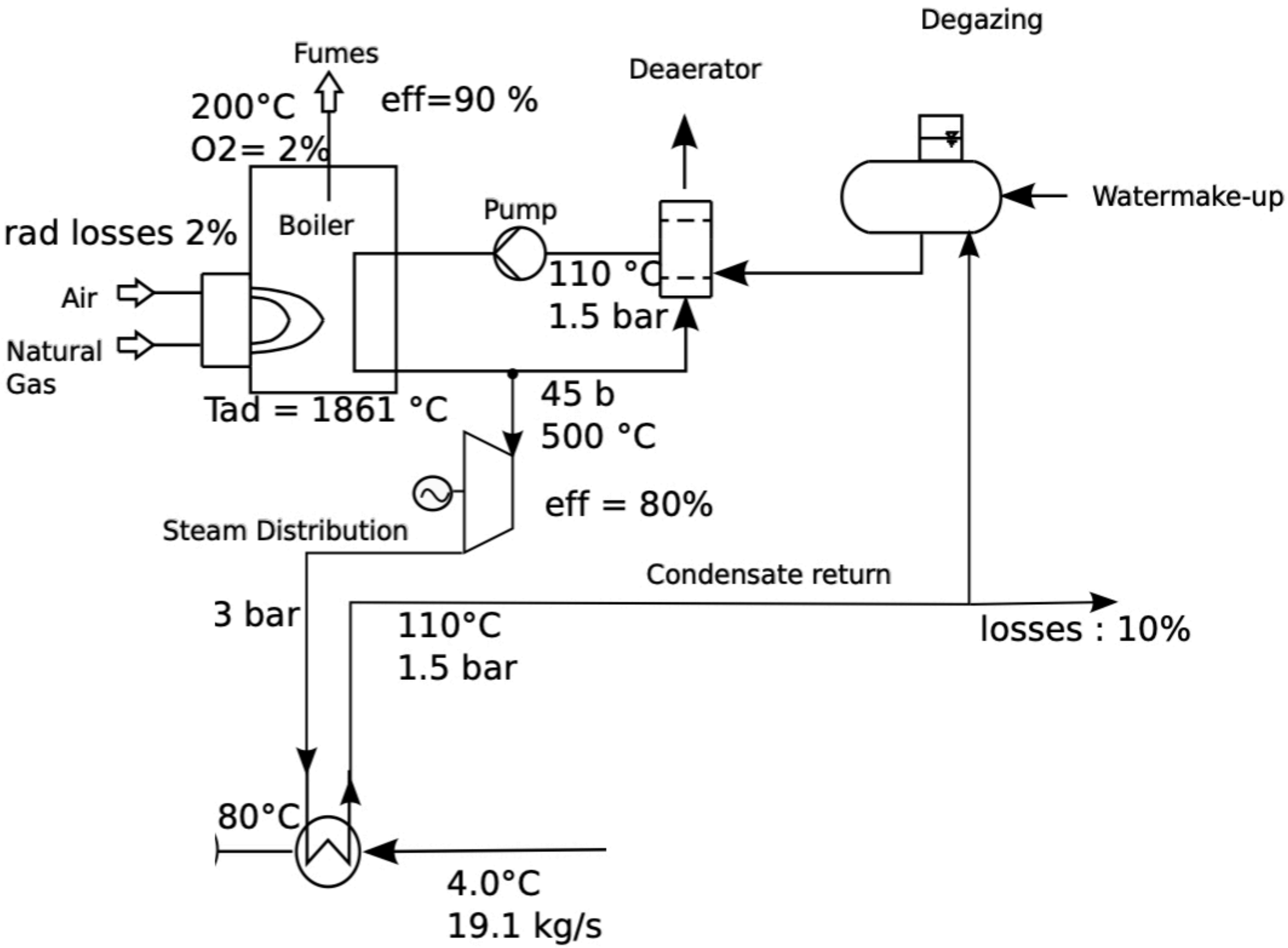
Efficiency of distribution

$$\eta_{dist} = \frac{\dot{Q}_p}{\dot{Q}_{steam}}$$

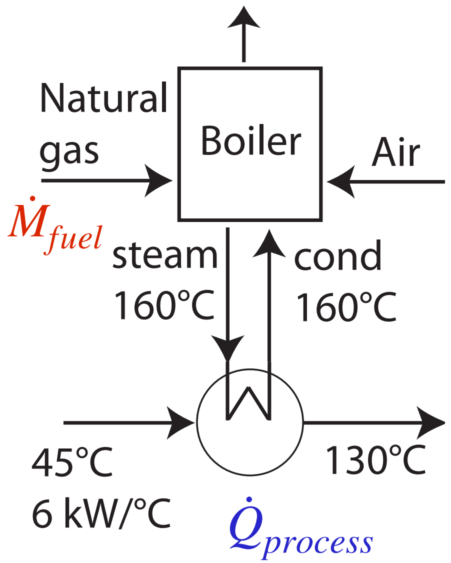
Losses can be on the return line, e.g. due to flash steam and purges
Make-up is mixed with the return to calculate

$$h_{steam,condreturn}(T_{cr}, P_{cr}, \alpha_{cr}) = \frac{(\dot{m}_{steam} - \dot{m}_{losses}) \cdot h_{steam,return}(T_r, P_r, \alpha_r)) + \dot{m}_{make_up} \cdot h_{make_up}(T_{mu}, P_{mu}, \alpha_{mu}))}{\dot{m}_{steam}}$$

Boiler system can be more complex



Energy bill from energy distribution



Process heat

$$\dot{Q}_{process,fuel} \quad [kW_{process}] = \dot{M}_{process}[kg/s] \cdot cp_{process}[kJ/kg/C] \cdot (T_{out} - T_{in})[C]$$

Fuel Conversion Efficiency

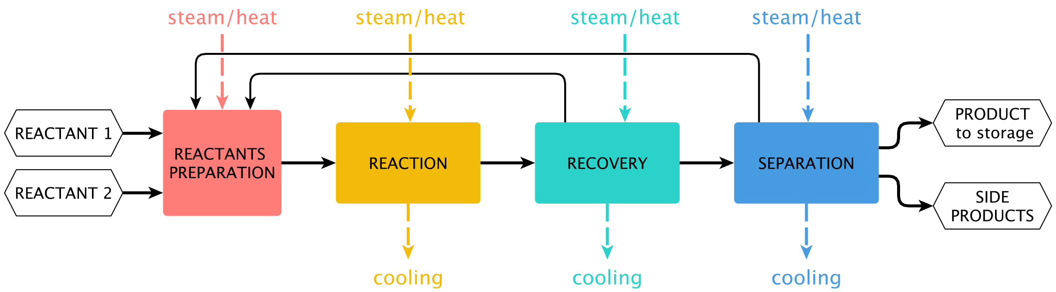
$$\eta_{conv,fuel}[\frac{kW}{kW_{fuel}}] = \frac{\dot{Q}_{process,fuel}[kW]}{\dot{M}_{fuel}[kg_{fuel}/h] \cdot LHV_{fuel}[kWh_{fuel}/kg_{fuel}]}$$

Cost of energy supply

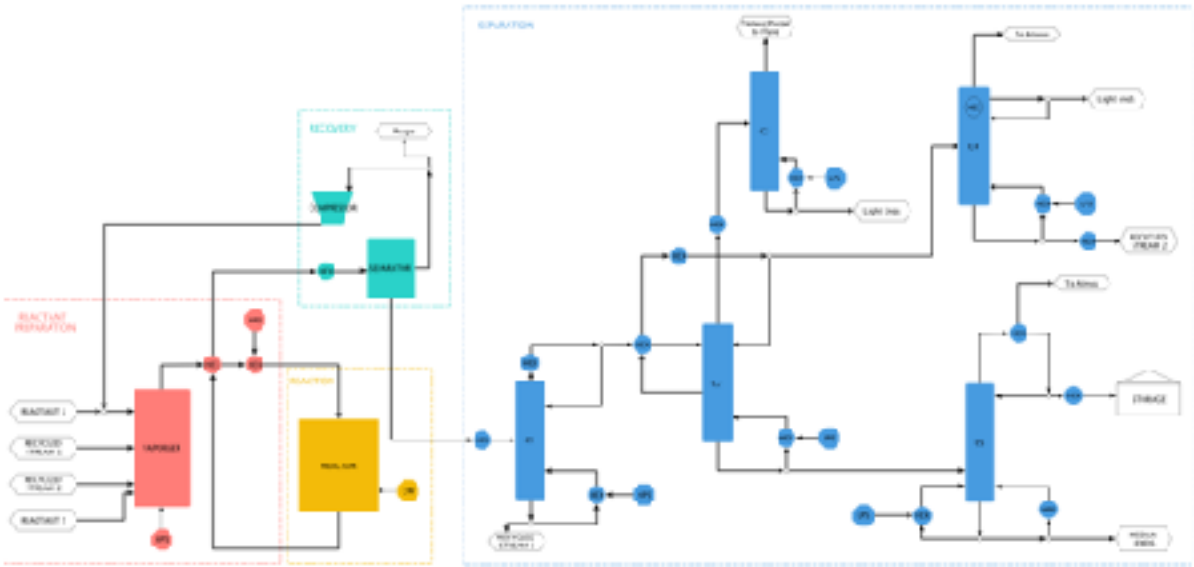
$$OPEX[CHF/year] = \sum_{fuel} \frac{\dot{Q}_{process,fuel}[kW]}{\eta_{conv,fuel}[kW/kW_{fuel}]}[kW_{fuel}] \cdot t_{op}[h/year] \cdot c_{fuel}[CHF/kWh]$$

The process energy interfaces

- energy is the driving force of the process unit operations
- block flow diagram
  - **grey box level**
  - utility/process



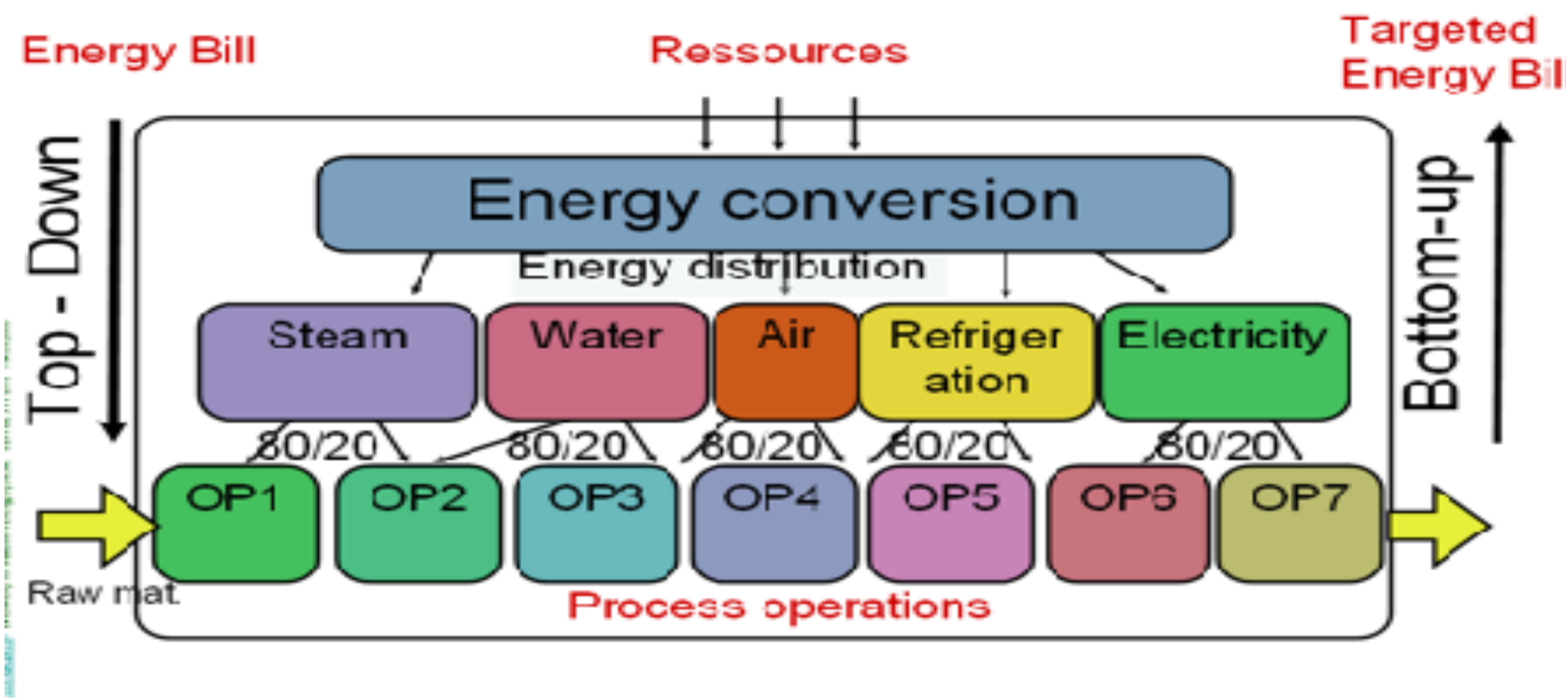
- flowsheet
  - **white box level**
  - heat transfer



Process energy drivers

- A top-down approach
  - What is the function of energy in the process
  - What are the most important units ?
    - **80/20 Rule** (80 % of consumption explained with 20% of your effort)
    - Apply on each distributed energy sub-system
  - Characterise the units that are the most important consumers/producers
    - for every type of the energy needs (energy requirement)

Pareto Principle



Muller, D, and F Marechal. "Energy Management Method in the Food Industry." In *Handbook of Water and Energy Management in Food Processing*, Woodhead Publishing Ltd, 2008.

data consistency check

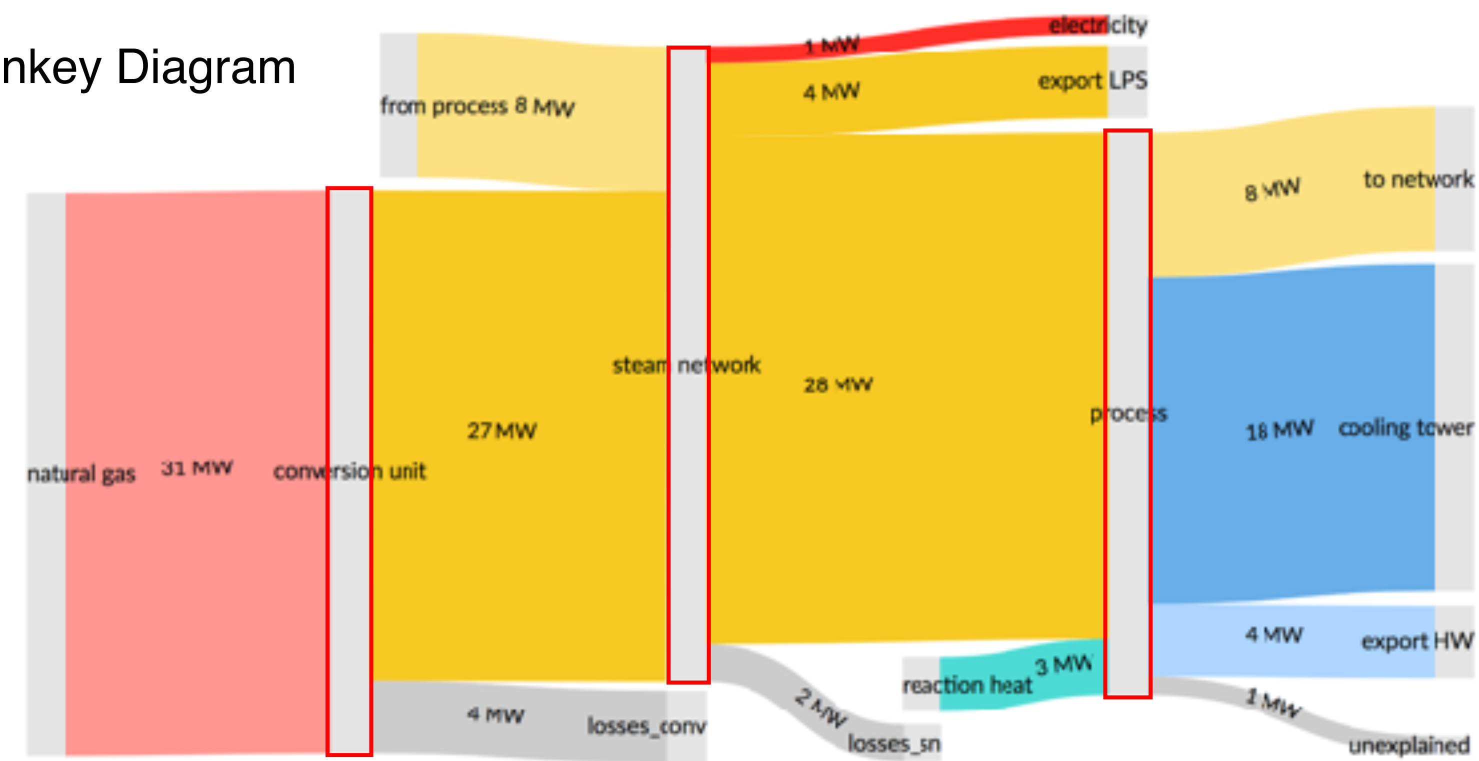
- Key heat and mass balances
- Objective:
  - minimise the system inconsistencies
  - Maximise your process understanding : minimise the errors + identify the losses

imbalance

=

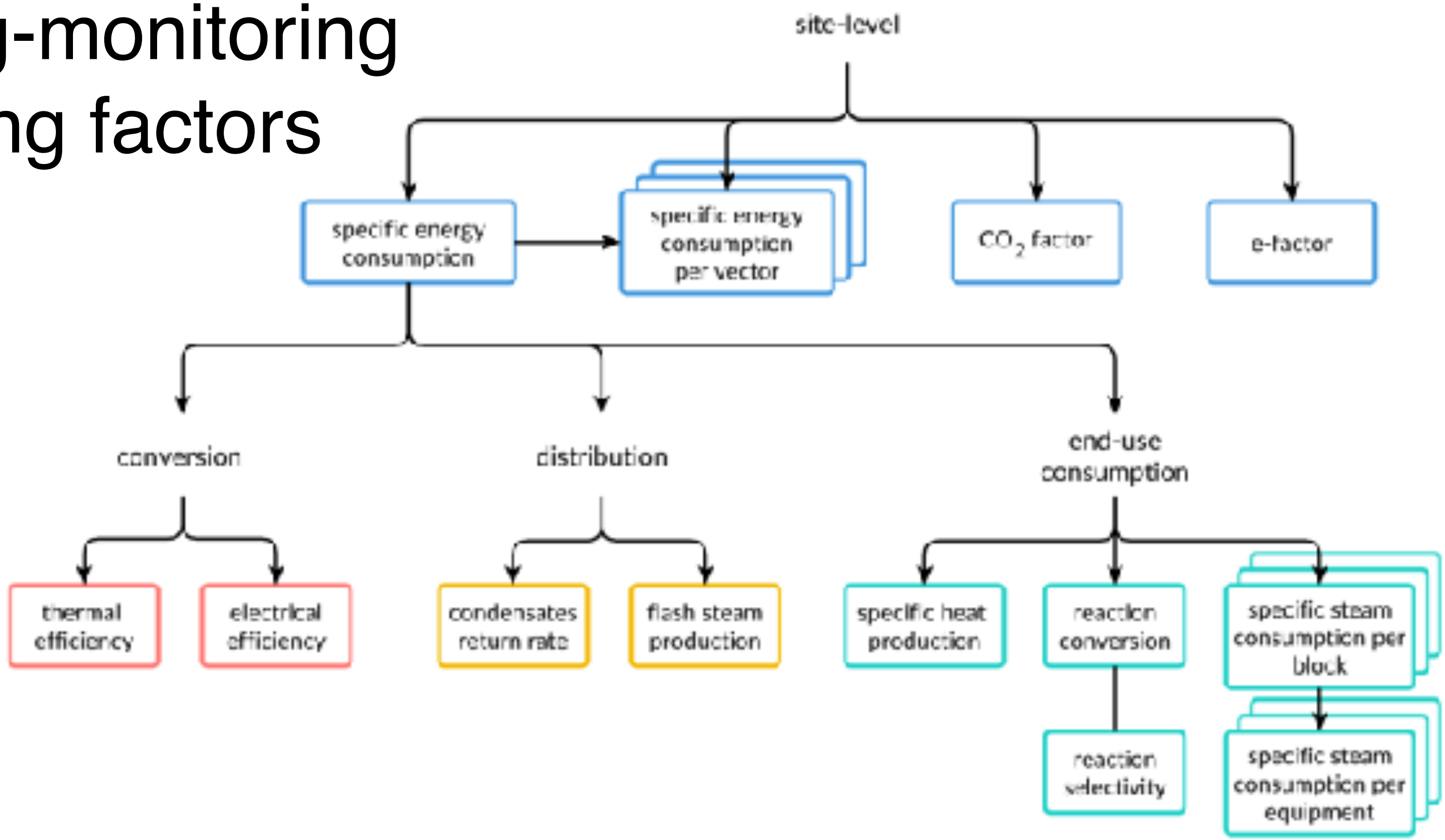
errors + losses

Sankey Diagram



key performance indicators

- Specific consumptions
- Mass and Energy Efficiency
- Targeting-monitoring
- Influencing factors



Indicators can be developed for the whole process or for a process unit

Key Performance indicators : Energy efficiency

- Cost (CHF energy/ CHF products)

$$\frac{\int_{t_0}^{t_f}(\sum_{F=1}^{n_F}\dot{M}_F^+(t)c_F^+(t)+E^+(t)c_e^+)dt}{\int_{t_0}^{t_f}(\sum_{P=1}^{n_P}\dot{M}_P^-(t)c_P^-(t)+E^-(t)c_e^-)dt}$$

- Specific Cost (CHF/kg products)

$$\frac{\int_{t_0}^{t_f}(\sum_{F=1}^{n_F}\dot{M}_F^+(t)c_F^+(t)+E^+(t)c_e^+-E^-(t)c_e^-)dt}{\int_{t_0}^{t_f}(\sum_{P=1}^{n_P}\dot{M}_P^-(t))dt}$$

- Energy (kJ/kg) ?

$$\frac{\int_{t_0}^{t_f}(\sum_{F=1}^{n_F}\dot{M}_F^+(t)lhv_F+E^+(t)-E^-(t))dt}{\int_{t_0}^{t_f}(\sum_{P=1}^{n_P}\dot{M}_P^-(t))dt}$$

- Exergy (kJ/kJ)

$$\frac{\int_{t_0}^{t_f}(\sum_{F=1}^{n_F}\dot{M}_F^+(t)k_F(t)+E^+(t))dt}{\int_{t_0}^{t_f}(\sum_{P=1}^{n_P}\dot{M}_P^-(t)k_P(t)+E^-(t))dt}$$

Comparing different forms of energy

- Electricity
  - kJe ?
  - Energy mix
    - Compute the primary energy required to produce the electricity (efficiency, emissions)
      - Natural combined cycle (60% , 0.376 kg CO2/kWhe)
      - Coal power plant (46%, 0.828 kg CO2/kWhe)
      - Hydro power plant (85%, 0.00534 kg CO2/kWhe)
      - PV => LCA (16%, utilisation rate 13% , 0.0625 kg CO2/ kWhe)
      - Wind (utilisation rate : 23%, 0.0161 kg CO2/kWhe)
  - Availability / Substitution
    - Annual energy vs power

Allocation when multiple products

- Overall energy consumption per unit of product
  - MJ/kg

$$\frac{\int_{t_0}^{t_f} (\sum_{F=1}^{n_F} \dot{M}_F^{+} lhv_f + \dot{E}^{+} - \dot{E}^{-})dt}{\int_{t_0}^{t_f} (\sum_{p=1}^{n_p} \dot{M}_p^{-})} \cdot K_p$$

- Allocation by
  - Mass $\quad K_p = 1$
  - Market Value

Market value of product p

$$K_p = \frac{\int_{t_0}^{t_f} (\dot{M}_p^{-} \cdot c_p)}{\int_{t_0}^{t_f} (\sum_{k=1}^{n_p} \dot{M}_k^{-} \cdot c_k)}$$

  - Exergy Value

$$K_p = \frac{\int_{t_0}^{t_f} (\dot{M}_p^{-} \cdot k_p)}{\int_{t_0}^{t_f} (\sum_{k=1}^{n_p} \dot{M}_k^{-} \cdot k_k)}$$

Conclusions

- Systemic analysis
  - Define inlet and outlet flows
  - Apply and Verify mass and energy balances (Sankey)
  - Power : kg/s - kW from nominal production in kg/s
  - Energy bill :
    - value [CHF/kg] * quantity [$kg/kg_{nominal}$] * rate [$kg_{nominal}/s$] * operating time [$s_{nominal}/year$]
- Production process
  - Process recipe => block flow diagram
    - Process steps for 1 kg of main product
  - Process flow sheet (the kitchen) => Process flow diagram
    - Process unit operation
    - Role of energy for the transformation in the unit
- Performances
  - System Specific consumptions
  - Energy drivers
  - Process unit operations

Module 1 questions

B1: Mass and energy balance

1. Explain the calculation of Mass and energy balance (First law of thermodynamics) for process units in a flowsheet.
2. Explain what is the meaning of the assumption of steady-state operation (no accumulation)?
3. Explain the use of a Sankey diagram for understanding energy flows in a process
4. Explain heat and mass balances of Mixer and splitters
    a. Energy and mass balance
    b. What is happening with pressures, concentration and phase changes ?
    c. If the heat capacities are considered constant, how can it be simplified? Is it still applicable in case of a phase change?
5. Heat exchanger
    f. Draw the hot and cold streams. How is the slope defined?
    g. Define and explain the minimum temperature difference in a heat exchanger
    h. Explain the energy balance of a heat exchanger
6. Evaporator
    g. explain the mass and energy balances of an evaporator
    h. explain the phase equilibrium calculation
    i. explain the energy balance and the energy efficiency of a multi-effect evaporator.

B1: Current Energy Bill

a. Explain how to calculate the operating costs of a refrigeration cycle
b. Explain how to calculate the operating cost of the heat supply by using steam
c. Explain how to calculate the operating cost of a process
d. Explain how to calculate the impact of a CO2 tax on a process