

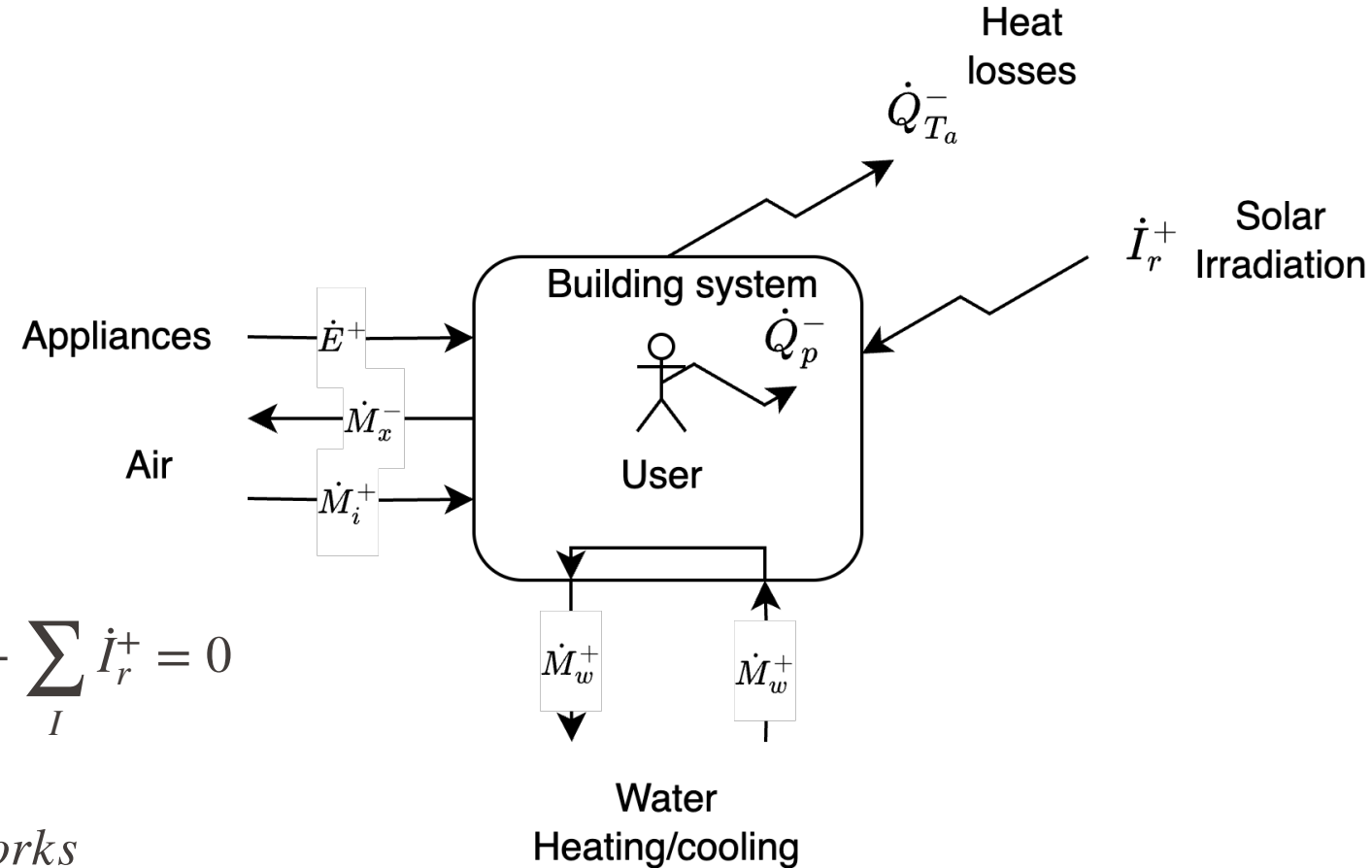
# Key performance indicators

Prof François Marechal

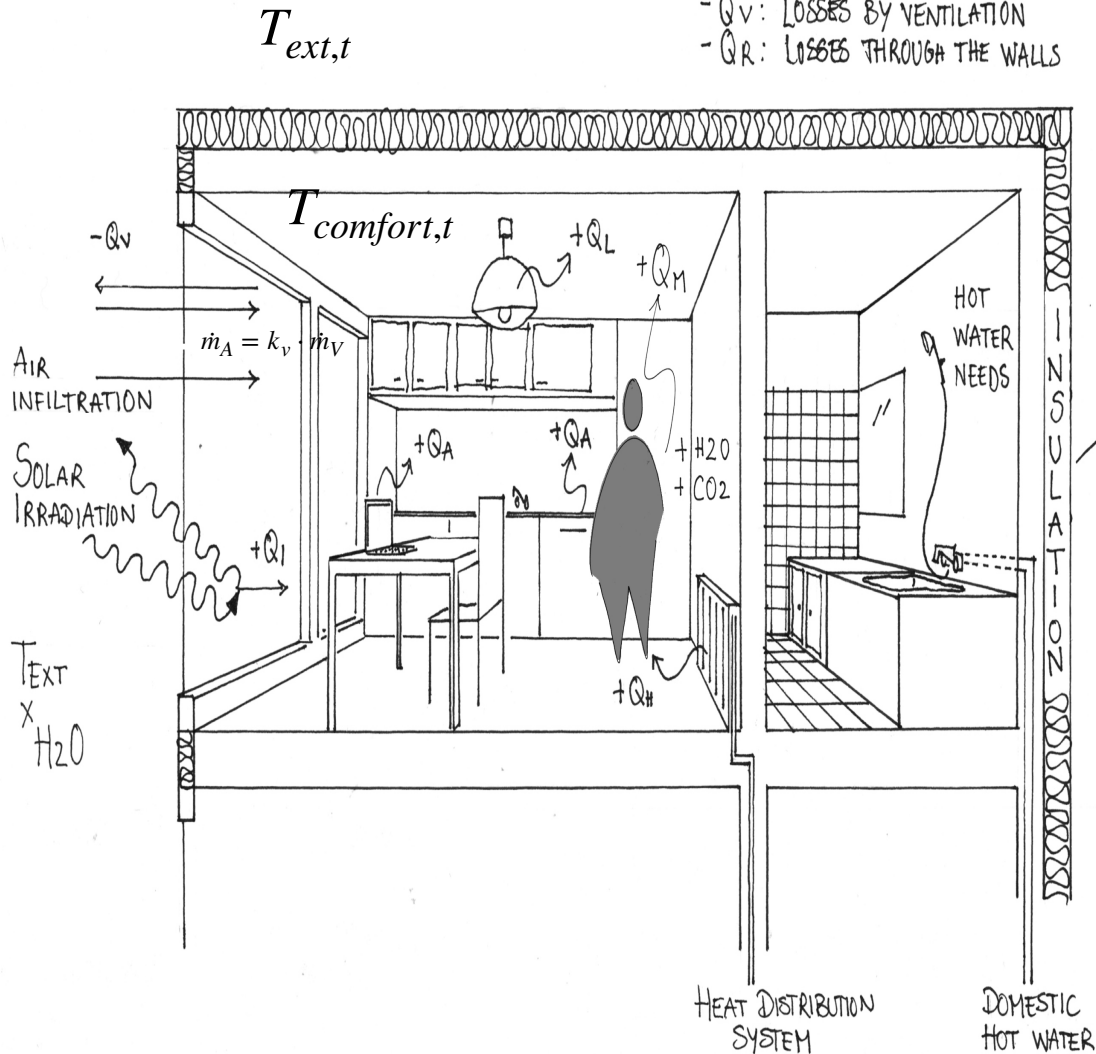
- Each flow  $x$  is characterized by
  - Mass flow: e.g.  $\dot{M}_x^-$
  - Thermodynamic state:  $T_x, P_x, n_x$
  - State variables :  $s_x$  e.g.  $h(T_x, P_x, n_x)$
- Transfers are modeled by
  - $\dot{Q}_k^+ = f(\pi_k, \dot{M}_x^+, s_x)$
- Energy balance :

$$\sum_f \dot{M}_f^+ \cdot h(T_f, P_f, x_f) + \sum_Q \dot{Q}^+ + \sum_E \dot{E}^+ + \sum_I \dot{I}_r^+ = 0$$

- Mass balance :  $\sum_f \dot{M}_{n,f}^+ = 0 \quad \forall n \in networks$



- + Q<sub>A</sub> : GAIN BY APPLIANCES
- + Q<sub>H</sub> : HEAT TO COMPENSATE LOSSES
- + Q<sub>L</sub> : GAIN BY LIGHTING SYSTEM
- + Q<sub>M</sub> : GAIN BY HUMAN
- + Q<sub>I</sub> : GAIN BY IRRADIATION
- Q<sub>V</sub> : LOSSES BY VENTILATION
- Q<sub>R</sub> : LOSSES THROUGH THE WALLS



Our knowledge :

The model of the building envelop heat balance

$$\dot{Q}_{A,t} [kW] = \dot{E}_{A,t}$$

$$\dot{Q}_{L,t} [kW] = \dot{E}_{L,t}$$

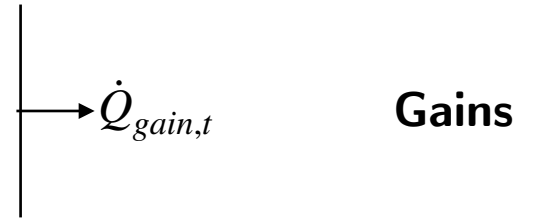
$$\dot{Q}_{M,t} [kW] = \dot{q}_{cap} \cdot \sum_{cap} cap_t$$

$$\dot{Q}_{I,t} [kW] = Irr_t \cdot k_{sun}$$

$$\dot{Q}_{V,t} [kW] = \dot{m}_v \cdot cp_{air} \cdot (T_{comfort,t} - T_{ext,t})$$

$$\dot{Q}_{R,t} [kW] = \sum_{wall} k_{wall} \cdot S_{wall} \cdot (T_{comfort,t} - T_{ext,t})$$

$$\dot{Q}_{V,t} + \dot{Q}_{R,t} = k_{th} (T_{comfort,t} - T_{ext,t})$$



Gains

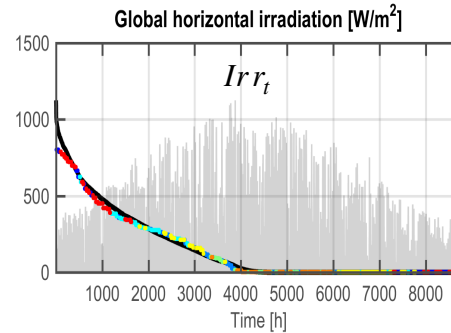
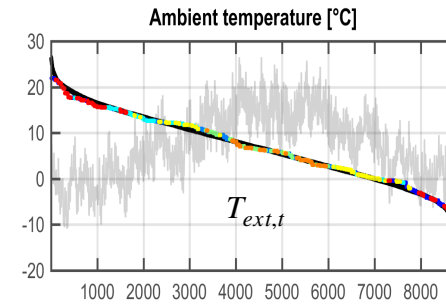
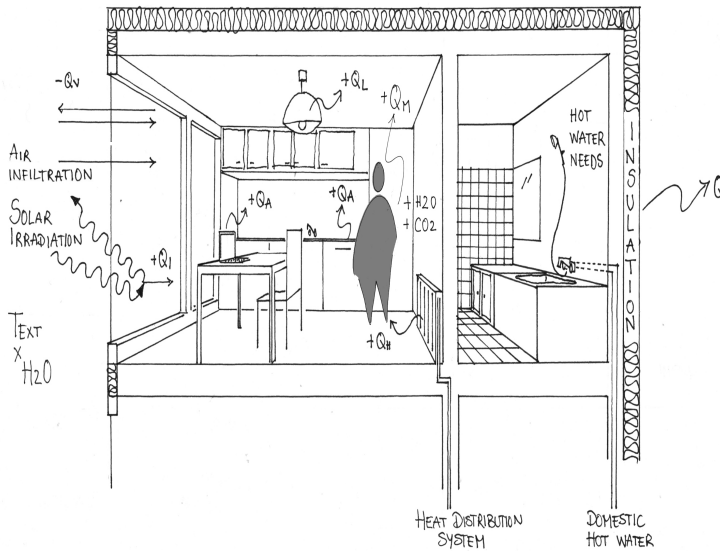
Losses

Energy balance :

what is the heat load to maintain the comfort ?

$$\dot{Q}_{H,t} [kW] = max(0, \dot{Q}_{V,t} + \dot{Q}_{R,t} - (\dot{Q}_{A,t} + \dot{Q}_{L,t} + \dot{Q}_{M,t} + \dot{Q}_{I,t}))$$

- +QA : GAIN BY APPLIANCES
- +QH : HEAT TO COMPENSATE LOSSES
- +QL : GAIN BY LIGHTING SYSTEM
- +QM : GAIN BY HUMAN
- +QI : GAIN BY IRRADIATION
- QV : LOSSES BY VENTILATION
- QR : LOSSES THROUGH THE WALLS



### Heat gains :

$$\text{Appliances : } \dot{Q}_{A,b,t} = \dot{E}_{A,b,t}$$

$$\text{Lighting : } \dot{Q}_{L,b,t} = \dot{E}_{L,b,t}$$

$$\text{People : } \dot{Q}_{M,b,t} = \dot{q}_{cap_b} \cdot \sum_{cap_b}$$

$$\text{Solar Irradiation : } \dot{Q}_{I,b,t} = Irr_t \cdot k_{sun_b}$$

### Losses

#### Ventilation

$$\dot{Q}_{V,b,t} = \dot{m}_{V_b} \cdot c_{p_{air}} \cdot (T_{comfort_{b,t}} - T_{ext,t})$$

#### Heat transfer through the walls

$$\dot{Q}_{R,b,t} = \sum_{wall_b} k_{wall_b} \cdot S_{wall_b} \cdot (T_{comfort_{b,t}} - T_{ext,t})$$

### Balance : Heat to supply

$$\dot{Q}_{H,t} = \dot{Q}_{b,t} = \max(0, \dot{Q}_{V,b,t} + \dot{Q}_{R,b,t} - (\dot{Q}_{A,b,t} + \dot{Q}_{L,b,t} + \dot{Q}_{M,b,t} + \dot{Q}_{I,b,t}))$$

### Heat supply [kW] function :

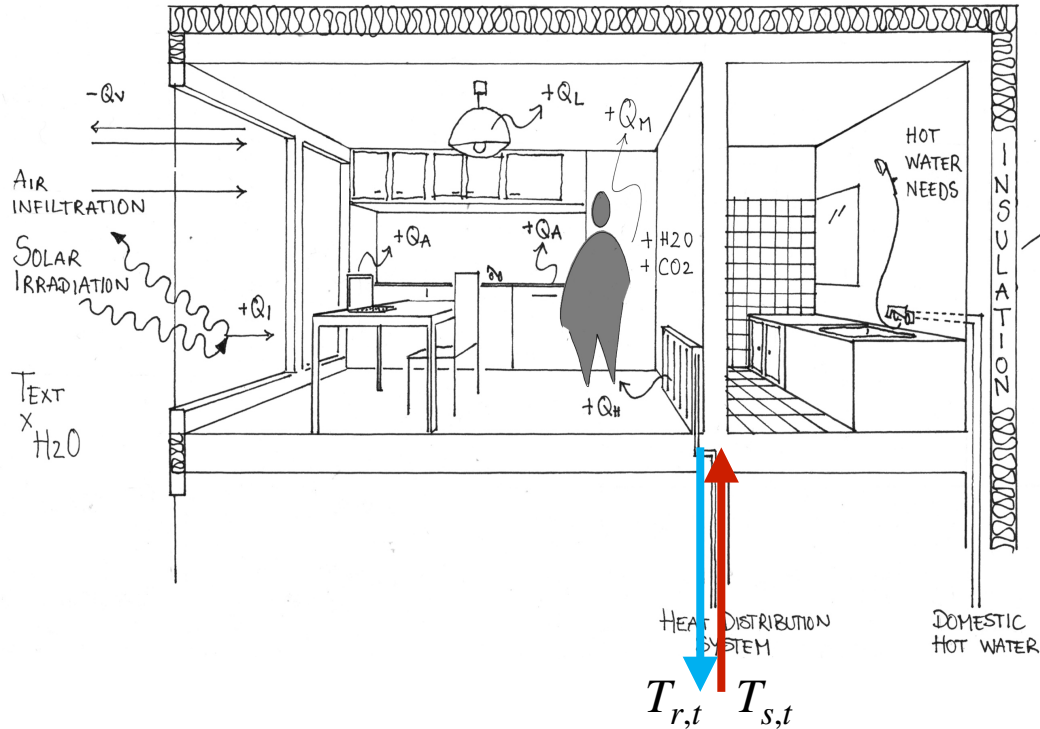
$$\dot{Q}_b(t) = \max(0, k_{th_b} \cdot (T_{comfort_{b,t}} - T_{ext,t}) - k_{sun_b} \cdot Irr_t - \dot{Q}_{gain_{b,t}})$$

### Heat energy [MJ/period] :

$$Q_b(t_0, t_{end}) = \int_{t_0}^{t_{end}} \dot{Q}_{b,t} \cdot dt = \int_{t_0}^{t_{end}} \max(0, k_{th_b} \cdot (T_{comfort_{b,t}} - T_{ext,t}) - k_{sun_b} \cdot Irr_t - \dot{Q}_{gain_{b,t}}) \cdot dt$$

# EPFL Temperature of the heat supply

- + Q<sub>A</sub> : GAIN BY APPLIANCES
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Temperatures of the heat distribution (hd) system: supply  $T_{s,t}$  and return  $T_{r,t}$  can be calculated

$$\dot{Q}_{b,t} = \dot{m}_{hd_b,t} \cdot c_{p_{hd_b}} \cdot (T_{s_b,t} - T_{r_b,t}) \quad [1]$$

$$T_{r_b,t} = T_{s_b,t} - \frac{\dot{Q}_{b,t}}{\dot{m}_{hd_b,t} \cdot c_{p_{hd_b}}} \quad [2]$$

$T_{s_b,t}$  is calculated by solving heat transfer equation

$$\dot{Q}_{b,t} = UA_{hd_b} \frac{(T_{s_b,t} - T_{r_b,t})}{\ln(T_{s_b,t} - T_{comfort_{b,t}}) - \ln(T_{r_b,t} - T_{comfort_{b,t}})} \quad [3]^*$$

with  $UA_{hd_b}$  calculated from the design conditions @  $T_{ext} = -10 \text{ }^\circ\text{C}$

$$UA_{hd_b} = \dot{Q}_{b,design} \cdot \frac{\ln(T_{s_b,design} - T_{comfort_{b,design}}) - \ln(T_{r_b,design} - T_{comfort_{b,design}})}{(T_{s_b,design} - T_{r_b,design})}$$

For each building and each time will obtain the minimum supply and return temperatures of the building.

\* use [1] and [2] in [3] to have an explicit formula of  $T_{s_b,t}$  as a function of  $\dot{Q}_{b,t}$ ,  $\dot{m}_{hd_b,t} \cdot c_{p_{hd_b}}$  and  $UA_{hd_b}$

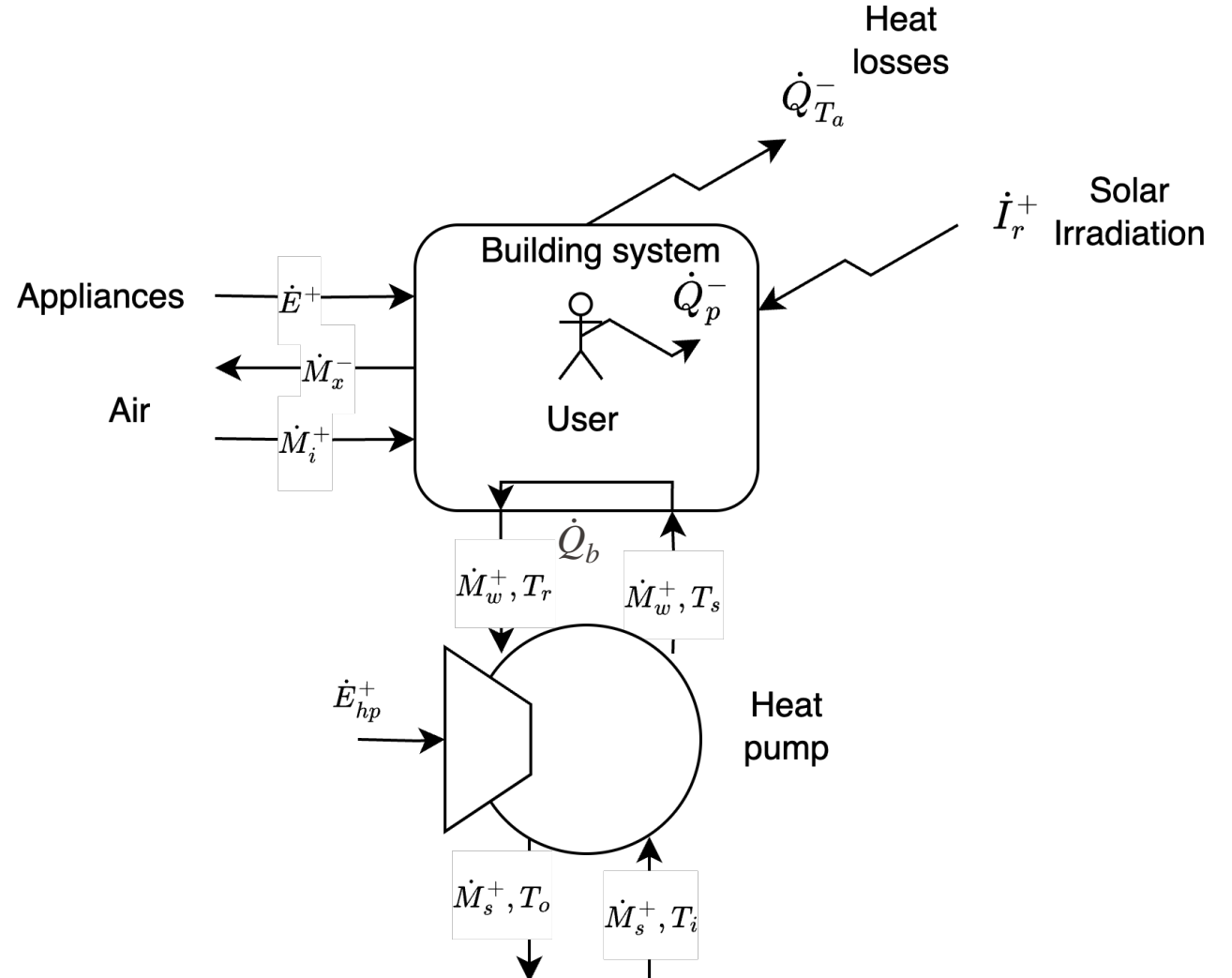
- Heat load to supply  $\dot{Q}_b$  [kW]
  - $T_s$  supply temperature
  - $T_r$  return temperature
  - $\dot{Q}_b = \dot{M}_w^+ \cdot cp_w \cdot (T_s - T_r)$
- Electricity to the heat pump

$$\dot{E}_{hp}^+ = \frac{\dot{Q}_b}{COP}$$

$$COP \approx \eta_{Carnot, hp} \cdot \frac{\tilde{T}_{r-s}}{\tilde{T}_{r-s} - \tilde{T}_{i-o}}$$

$$\text{with } \tilde{T}_{r-s} = \frac{T_s - T_r}{\ln(T_s) - \ln(T_r)}$$

$$\eta_{Carnot, hp} = 0.55$$



Operating expenditure over a time horizon (e.g year) :

$$OPEX = \int_{t=0}^{horizon} \left( \sum_{r=1}^{n_r} (\dot{m}_r^+(t) \cdot v_r^{+,OPEX}(t)) + \dot{E}^+(t) \cdot v_e^{+,OPEX}(t) \right) dt$$

$$OPEX \approx \sum_{p=0}^{n_p} \left( \sum_{r=1}^{n_r} (\dot{m}_r^+(p) \cdot v_r^{+,OPEX}(p)) + \dot{E}^+(p) \cdot v_e^{+,OPEX}(p) \right) \cdot d_p$$

$\dot{m}_{r,p}^+, \dot{E}_p^+$  [kg/s, kW] : flows calculated in the system configuration during conditions p

$d_p$  [s/lifetime] : probability of appearance of conditions p during the horizon of the system (e.g. year)

$v_{r,p}^{+,OPEX}$  [OPEX/kg] : value given to flows or investment to characterize the OPEX of the system configuration during conditions p

$v_{e,p}^{+,OPEX}$  [OPEX/kJ] : value given to Electricity to characterize the system configuration during conditions p

- Operating EXpenditure (we assume a typical year of operation) :

$$\text{Cost of resources} \sum_{r=1}^{n_{res}} \sum_u^{n_u} \left( \int_{t_0}^{year} c_{r,t} \cdot m_{r,u,t} \cdot \dot{Q}_{u,t} \cdot dt \right) \quad [CHF/year]$$

with  $m_{r,u,t}$  [ $kg/kJ_{th}$ ] mass of resource r to supply heat ( $\dot{Q}$ ) at time t.

+ Maintenance [CHF/year]

+ Men Power [CHF/year]

+ Taxes [CHF/year] :

fixed : e.g. based on installed power

$$\text{proportional} : \sum_{r=1}^{n_{res}} \sum_u^{n_u} \left( \int_{t_0}^{year} t_{r,t} \cdot m_{r,u,t} \cdot \dot{Q}_{u,t} \cdot dt \right) \quad [CHF/year]$$

with  $t_{r,t}$  [ $CHF/unit_r$ ] tax per unit of r

$$\text{e.g. } t_{r,t} = \tau_{CO_2} [CHF/kg_{CO_2}] \cdot m_{CO_2,r} [kg_{CO_2}/unit_r]$$

General formula of the KPI in KPI unit/lifetime

$$KPI = \int_{t=0}^{LifeTime} \left( \sum_{r=1}^{n_r} \dot{m}_r^+(t) v_r^{+,KPI}(t) + \dot{E}^+(t) v_e^{+,KPI}(t) - \dot{E}^-(t) v_e^{-,KPI}(t) + \sum_{u=1}^{n_u} f_u(t) v_{m,u}^{KPI} \right) dt + \sum_{u=1}^{n_u} v_u^{KPI}(I_u(S_u))$$

KPI [KPI unit/lifetime] for  $n_p$  conditions of operation over the lifetime of the system

$$KPI = \sum_{p=1}^{n_p} \left( \sum_{r=1}^{n_r} \dot{m}_{r,p}^+ v_{r,p}^{+,KPI} + \dot{E}_p^+ v_{e,p}^{+,KPI} - \dot{E}_p^- v_{e,p}^{-,KPI} + \sum_{u=1}^{n_u} f_{u,p} v_{m,u}^{KPI} \right) d_p + \sum_{u=1}^{n_u} v_u^{KPI}(I_u(S_u))$$

$\dot{m}_{r,p}^+, \dot{E}_p^+, \dot{E}_p^-$  [kg/s, kW] : flows calculated in the system configuration during conditions p

$d_p$  [s/lifetime] : probability of appearance of conditions p during the life time of the system

$v_{r,p}^{+,KPI}$  [KPI/kg] : value given to flows or investment to characterize the system configuration during conditions p

$v_{e,p}^{+,KPI}$  [KPI/kJ] : value given to Electricity to characterize the system configuration during conditions p

$v_{m,u}^{KPI}$  [KPI/use of u] : value of the maintenance cost of unit during the conditions p

$v_u^{KPI}$  [KPI/\$ invested] : value given to the investment of unit u in the system (typically in  $\frac{\$^{2020}}{year} \frac{1}{\$_{invested}}$ )

$I_u(S_u)$  [\$ invested/Size of u] : investment in the equipment of the system

$$TotalCost[CHF/year] = OPEX + CAPEX + Tax$$

$$OPEX = \sum_{p=1}^{n_p} \left( \sum_{r=1}^{n_r} \dot{m}_{r,p}^+ c_{r,p}^+ + \dot{E}_p^+ c_{e,p}^+ - \dot{E}_p^- c_{e,p}^- + \sum_{u=1}^{n_u} f_{u,p} c_{m_u} \right) d_p$$

$$CAPEX = \sum_{u=1}^{n_u} \frac{1}{\tau(n_{y,u}, i)} (I1_u y_u + I2_u f_u^{max})$$

$$Tax = CO_2^+ \gamma^{CO_2^+}$$

$$CO_2^+ = \sum_{p=1}^{n_p} \left( \sum_{r=1}^{n_r} \dot{m}_{r,p}^+ \epsilon_r^{CO_2} + \dot{E}_p^+ \epsilon_{e,p}^{CO_2^+} - \dot{E}_p^- \epsilon_{e,p}^{CO_2^-} \right) d_p$$

$$Impact = \zeta^{CO_2^+} (CO_2^+ + \sum_{u=1}^{n_u} \frac{1}{n_{y,u}} (\xi_{c_u}^{CO_2} + \xi_{d_u}^{CO_2}) f_u^{max})$$

$$RES = \sum_{p=1}^{n_p} \left( \sum_{r_{res}=1}^{n_{r_{res}}} \dot{m}_{r_{res},p}^+ + \sum_{u=1}^{n_u} f_{u,p} e_{u,p}^{res+} \right) d_p$$

$$\dot{E}_p^+ + \dot{E}_p^- + \sum_{u=1}^{n_u} f_{u,p} (e_{u,p}^{res+} - e_{u,p}^-) = 0 \quad \forall p = 1..n_p$$

$$OPEX[CHF/year] = \sum_{p=1}^{n_p} \left( \sum_{r=1}^{n_r} \dot{m}_{r,p}^+ c_{r,p}^+ + \dot{E}_p^+ c_{e,p}^+ - \dot{E}_p^- c_{e,p}^- + \sum_{u=1}^{n_u} f_{u,p} cm_u \right) d_p$$

with

$\dot{m}_{r,p}^+[kg/h]$  flow of resource r in period p

$c_{r,p}^+[CHF/kg]$  specific price of resource r in period p

$\dot{E}_p^+[kW]$  Electricity import in period p

$c_{e,p}^+[CHF/kWh]$  Electricity price at import in period p

$\dot{E}_p^-[kW]$  Electricity export in period p

$c_{e,p}^-[CHF/kWh]$  Electricity price at export in period p

$n_u[-]$  number of units

$f_{u,p}[-]$  level of use of unit u in period p

$cm_u[CHF/h]$  specific maintenance cost of unit u

$d_p[h/year]$  duration of period p

We assume that the specific prices are valid for the whole life time : 25 years !!!!

Capital Expenditure is the amount of money needed to buy the equipment, it is expressed on an annual basis

$$CAPEX[CHF/year] = \sum_{u=1}^{n_u} \frac{1}{\tau(n_{y,u}, i)} (I1_u y_u + I2_u f_u^{max})$$

$\frac{1}{\tau(n_{y,u}, i)}$	$[\frac{1}{year}]$	annualisation factor of unit u
$n_{y,u}$	$[year]$	expected life time of unit u
$I1_u$	$[CHF]$	fixed investment of unit u
$y_u$	$[-]$	existence unit u
$I2_u$	$[CHF]$	proportional investment cost of unit u
$f_u^{max}$	$[-]$	size of unit u

- Measures the amount of CO2 emissions associated to the operation of the system during the  $n_p$  operating conditions p.

$$CO_2^+ [kgCO_2/year] = \sum_{p=1}^{n_p} \left( \sum_{r=1}^{n_r} \dot{m}_{r,p}^+ \epsilon_r^{CO_2} + \dot{E}_p^+ \epsilon_{e,p}^{CO_2^+} - \dot{E}_p^- \epsilon_{e,p}^{CO_2^-} \right) d_p$$

$\epsilon_r^{CO_2} [kgCO_2/kg_r]$	kg CO2 emitted per unit of resource r burnt (local emissions)	-> SCOPE 1
$\epsilon_{e,p}^{CO_2^+} [kgCO_2/kWh_e]$	kg CO2 emitted per kWh of electricity consumed	
$\epsilon_{e,p}^{CO_2^-} [kgCO_2/kWh_e]$	kg CO2 avoided per kWh of electricity exported (substituted in the grid)	-> SCOPE 2

$$Tax [CHF/year] = CO_2^+ \gamma^{CO_2^+}$$

$$\gamma^{CO_2^+} [CHF/kgCO_2] \quad \text{CO2 tax per kg CO2 emitted}$$

SCOPE 1 emissions : directly emitted on site

SCOPE 2 emissions : indirectly emitted (i.e. emitted at the time of the production of the electricity or for the supply of the resource)

$$Impact[ImpactUnit/year] = \zeta^{CO_2^+} (CO_2^+ + \sum_{u=1}^{n_u} \frac{1}{n_{y,u}} (\xi_{c_u}^{CO_2} + \xi_{d_u}^{CO_2}) f_u^{max})$$

- $\zeta^{CO_2^+} [ImpactUnit/kgCO_2]$  Impact of CO2 emissions per kg of CO2 emitted
- $\xi_{c_u}^{CO_2} [kgCO_2]$  life cycle CO2 emissions during the construction of unit u
- $\xi_{d_u}^{CO_2} [kgCO_2]$  life cycle CO2 emissions during the dismantling of unit u

An impact value is given to an emission. It concerns SCOPE1, SCOPE 2 or SCOPE 3 (considering the life cycle)  
 The impact is typically measured by life cycle impact assessment indicators.