Integrating thermal storage and solar energy in the industry

with a Case study of a dairy process

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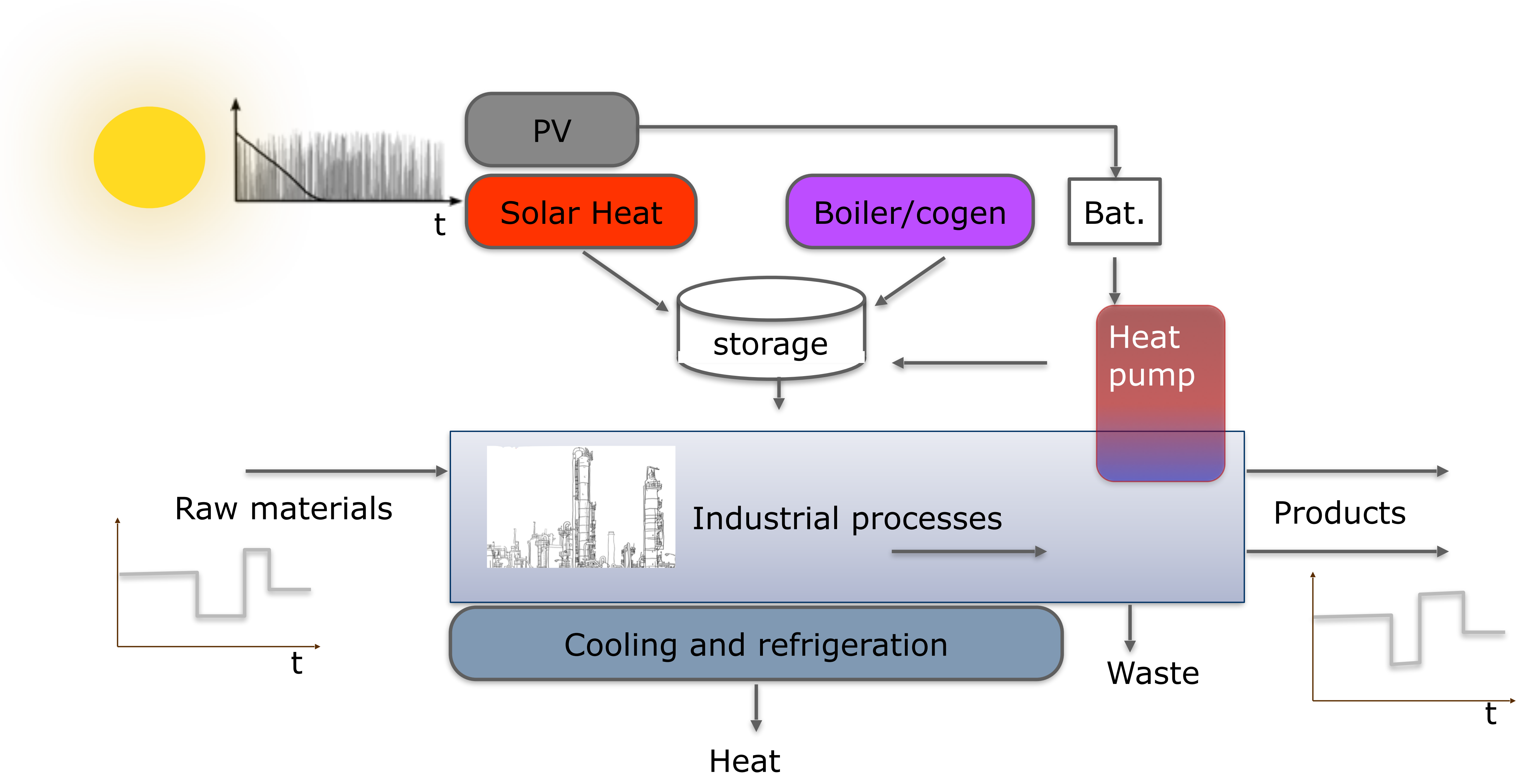
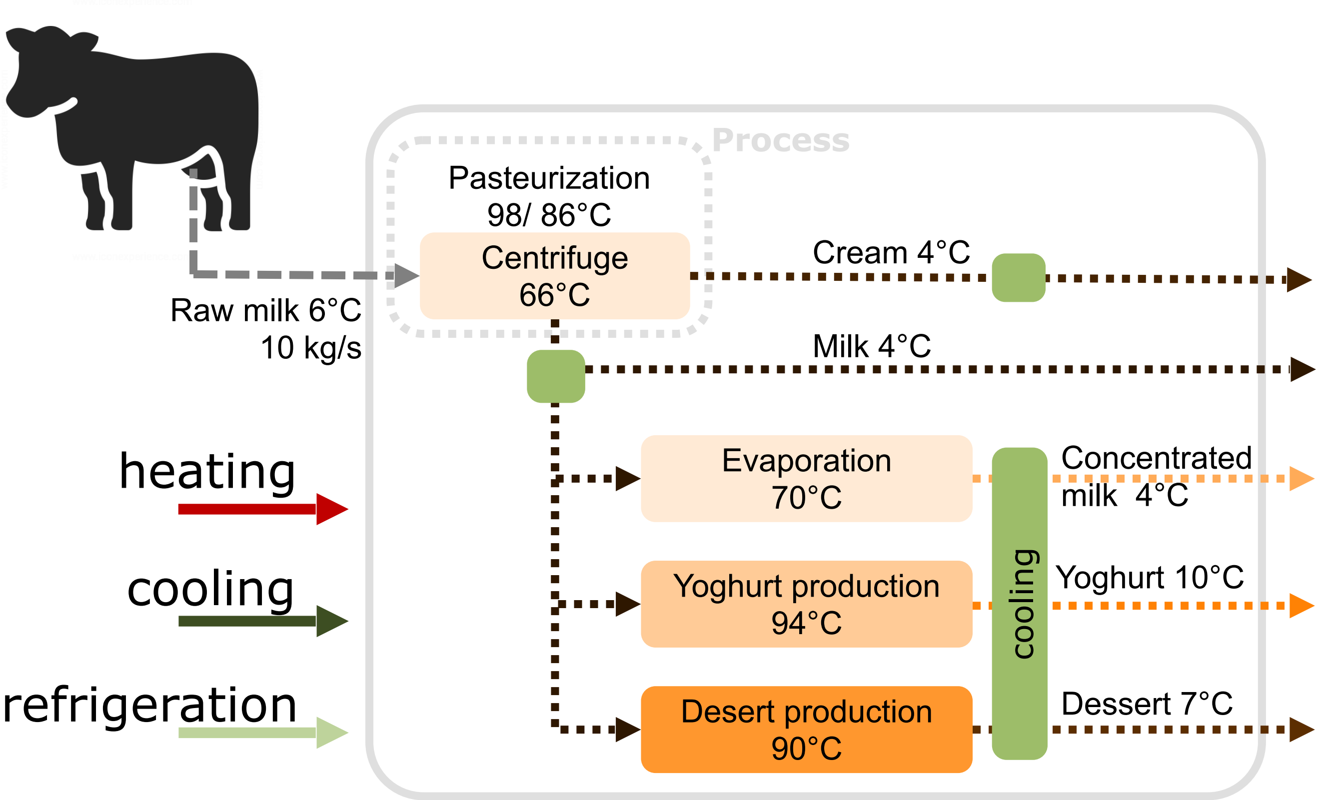
Integrating Solar energy in a process



Case study : A dairy process

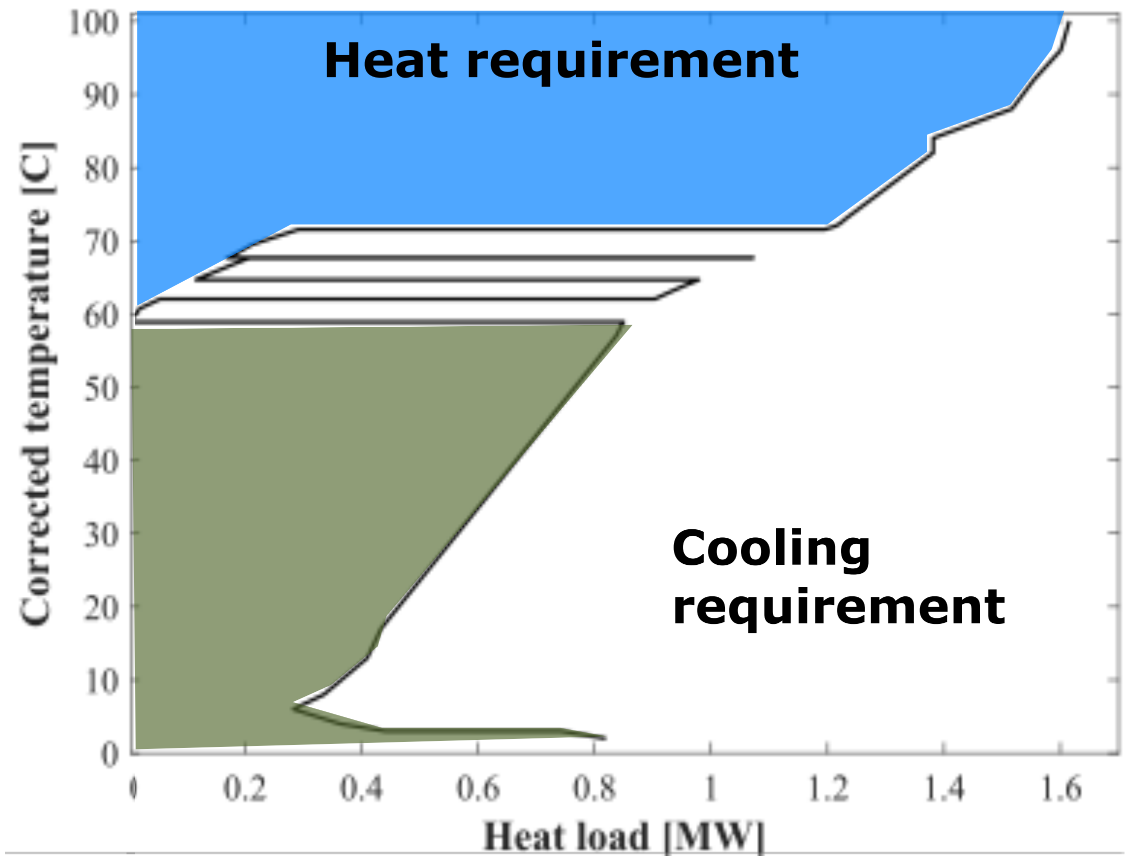


Which are the best technologies to satisfy the needs?

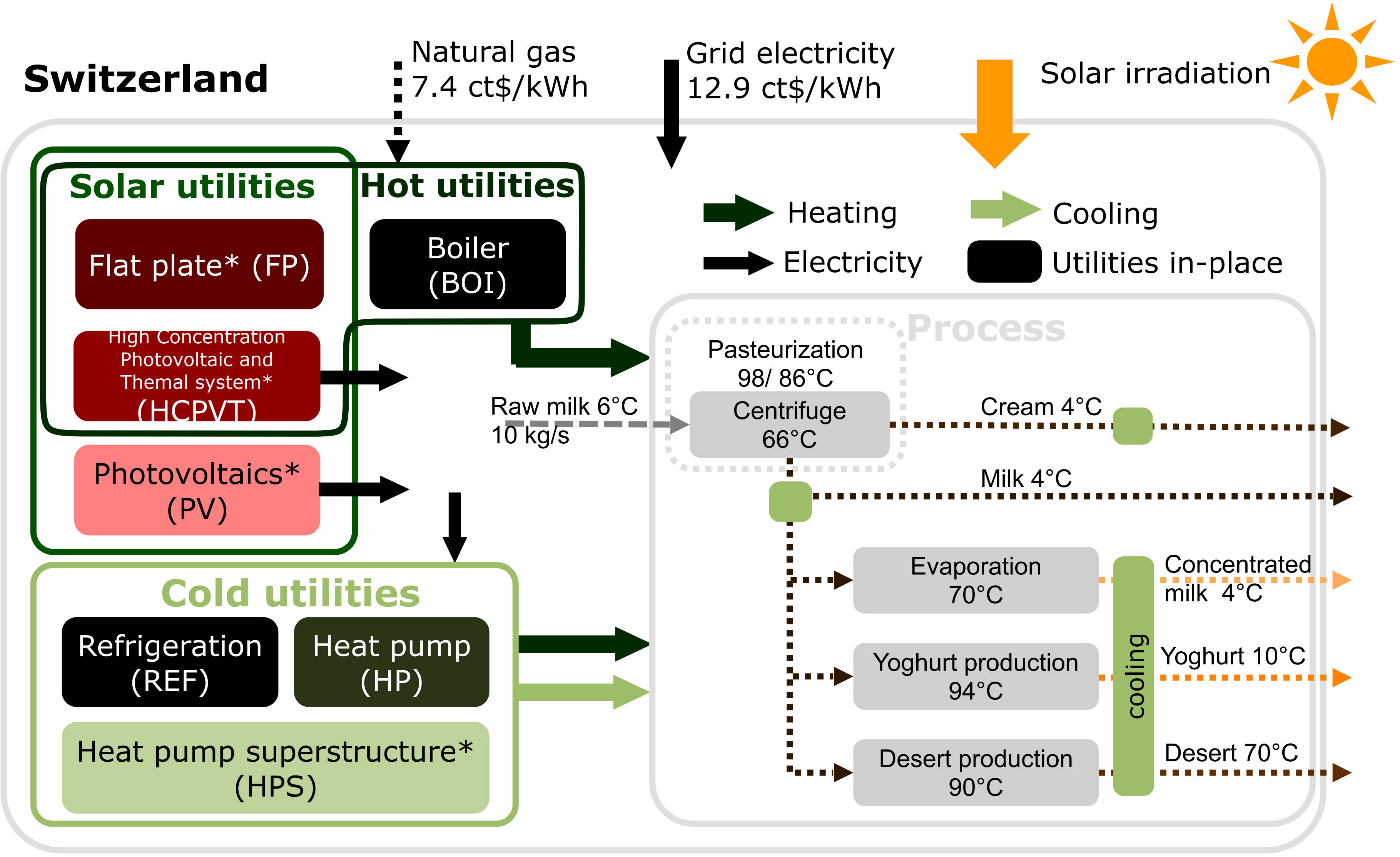
➢ Cases (different sets of technologies)

Case study : Heat requirement & heat recovery

Grand composite curve

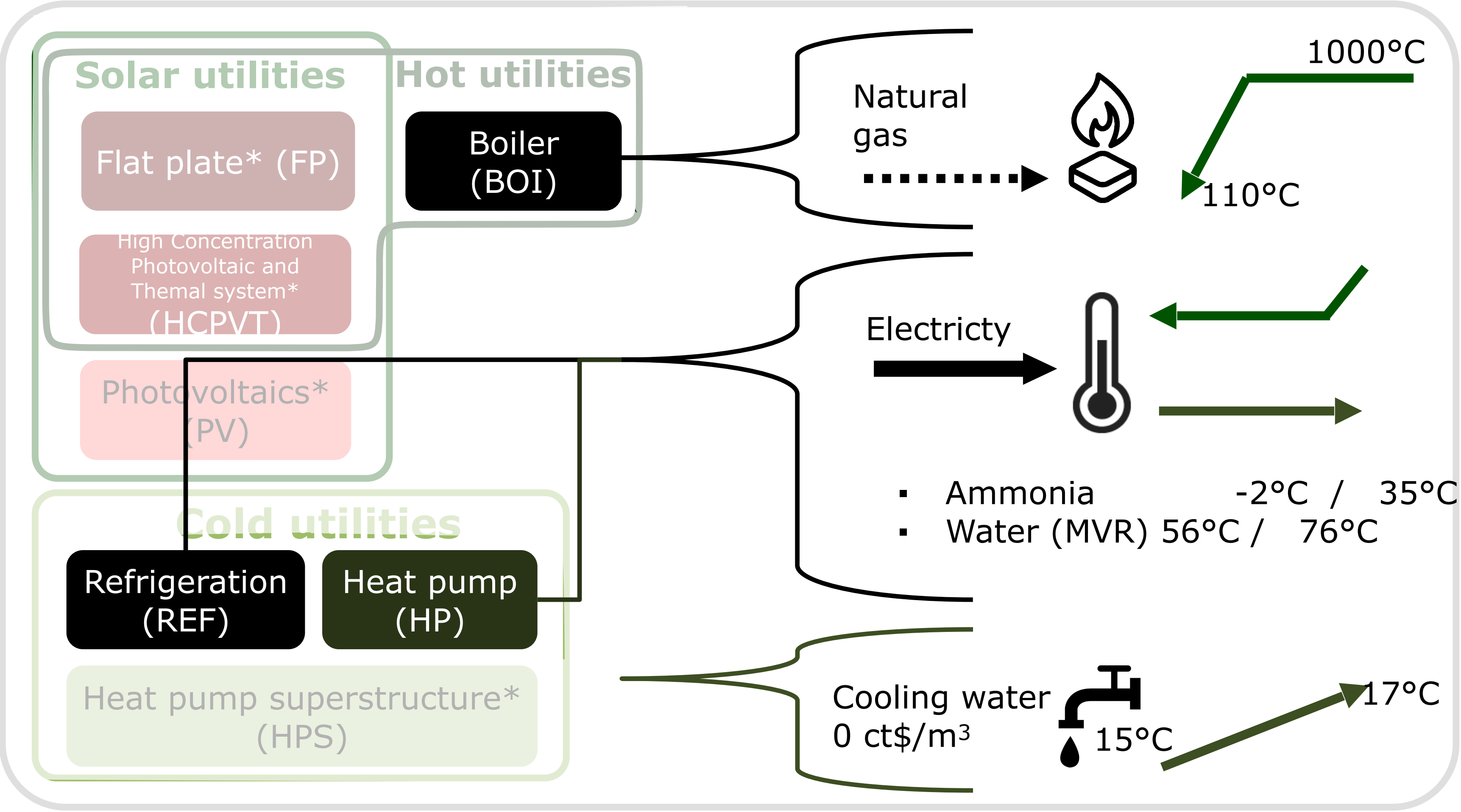


Utilities



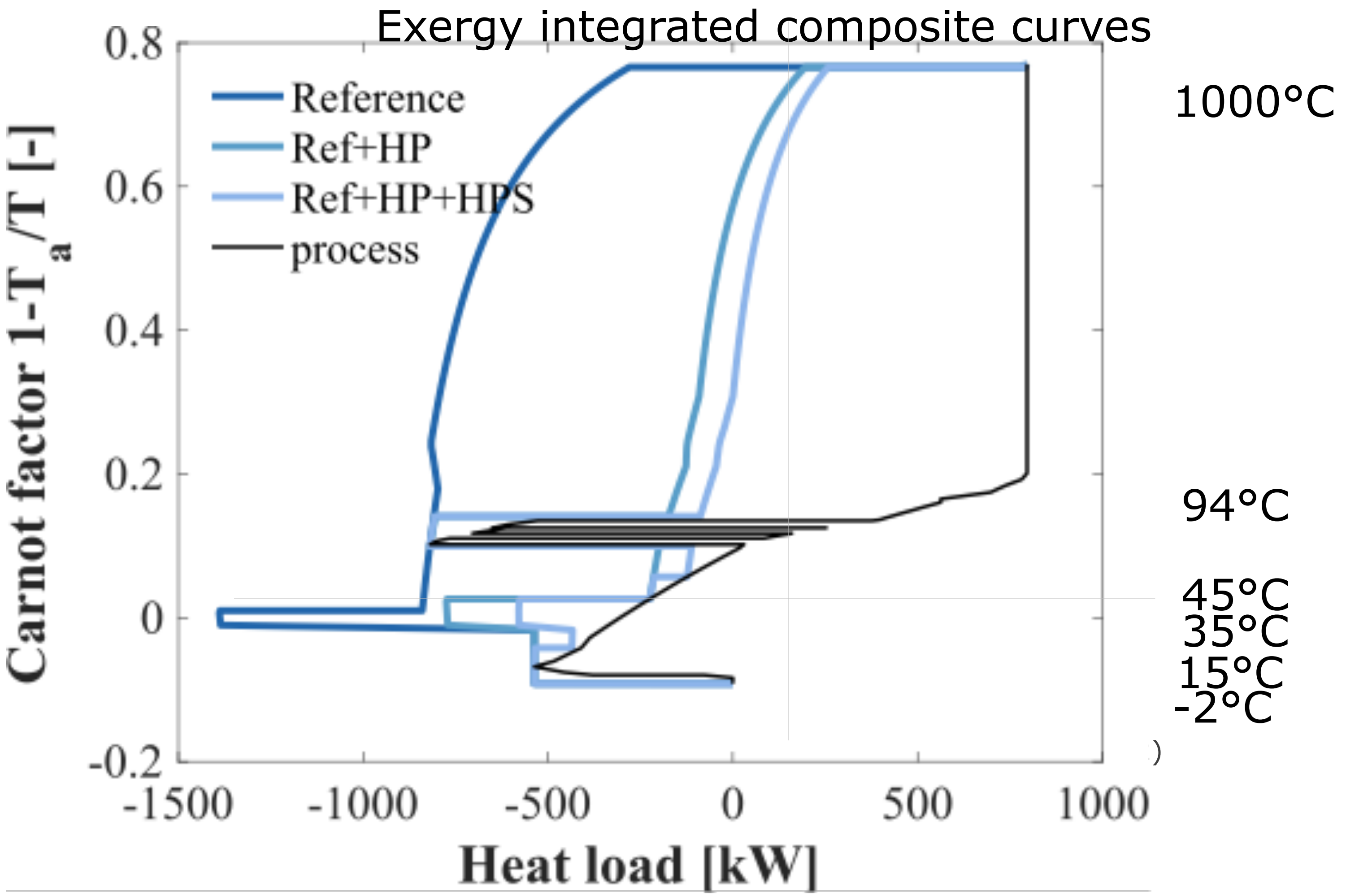
IEA Key Energy Statistics 2015
Helen Becker (2012)

Case study: utilities in-place



Helen Becker (2012)

Heat pump integration



Boiler

Reference
46 kWh/t_{raw}

-60%

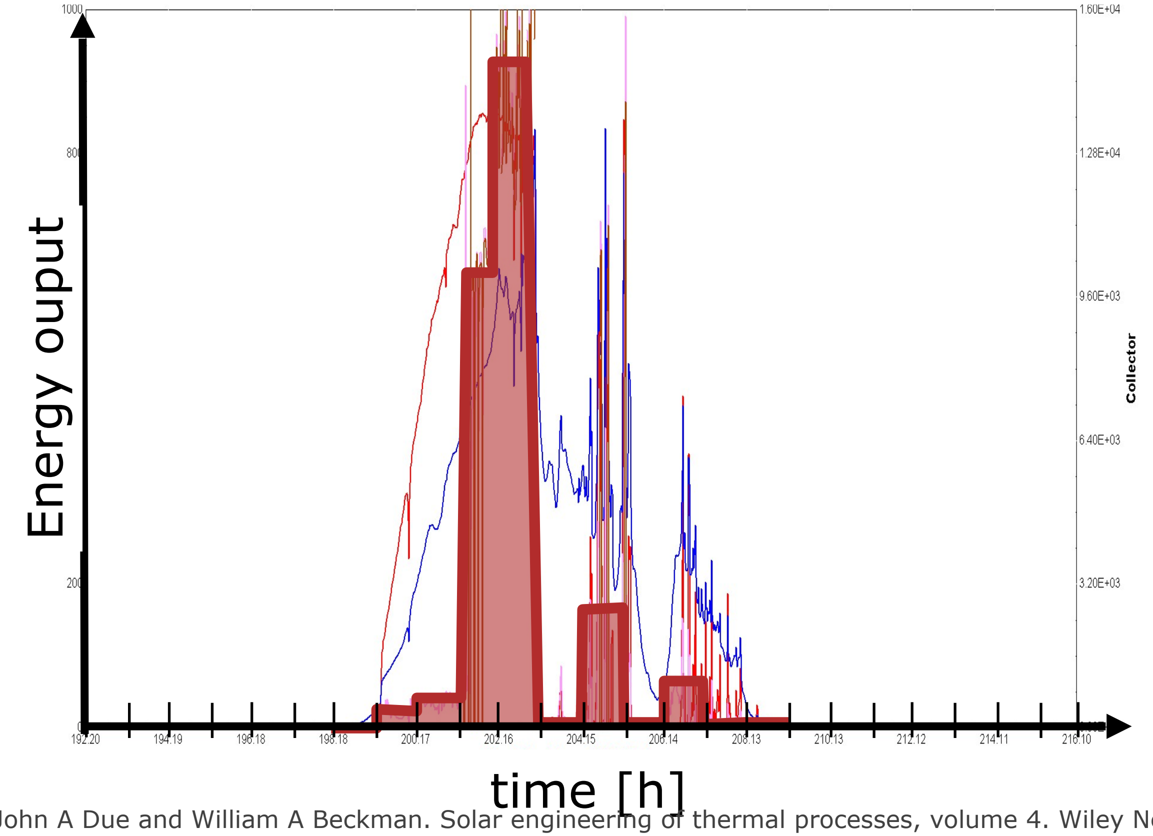
Ref+HP
26 kWh/t_{raw}

-64%

Ref+HP+HPS
23 kWh/t_{raw}

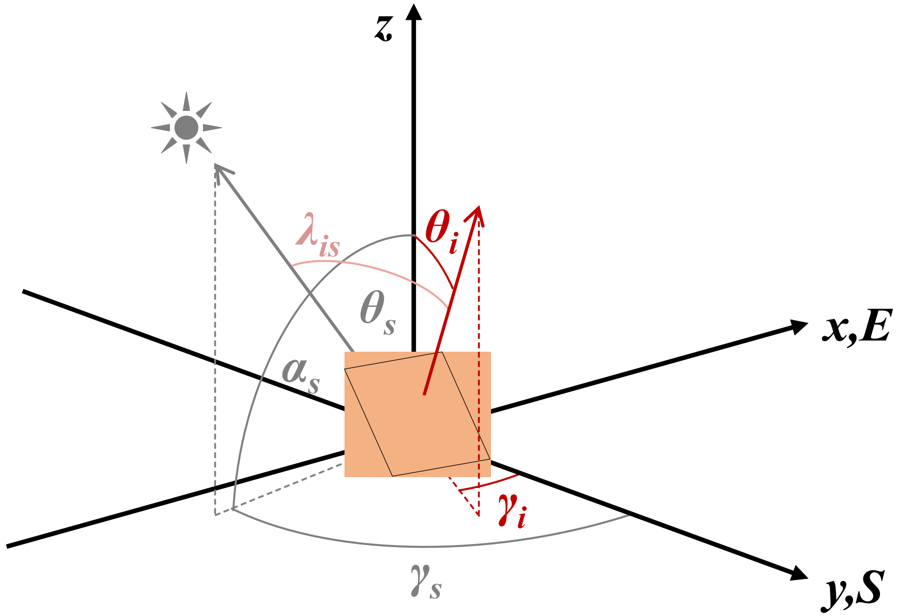
Integrating solar conversion technologies

- Based on hourly means



(1) John A Due and William A Beckman. Solar engineering of thermal processes, volume 4. Wiley New York etc., 2012.

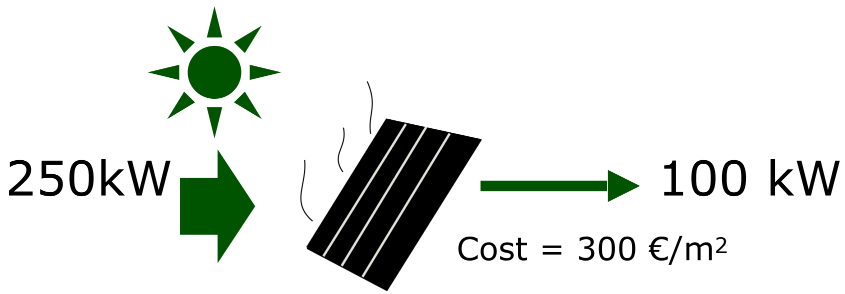
- Considering sun position and location



$$\mathbf{g_i} = \underbrace{\mathbf{b_n} \cdot \cos(\boldsymbol{\lambda}_{\mathbf{is}})}_{\mathbf{b_i}} + \underbrace{\mathbf{d_h} \cdot \left(\frac{1+\cos(\theta_i)}{2}\right)}_{\mathbf{d_i}} + \underbrace{\mathbf{g_h} \cdot \rho_g \cdot \left(\frac{1-\cos(\theta_i)}{2}\right)}_{\mathbf{g_{gr,i}}}$$

$$= \mathbf{b_i} + \mathbf{d_i} + \mathbf{g_{gr,i}}$$

Flat plate solar thermal collector (FP)



- Radiation on slope
  - Angle of incidence
  - Diffuse/direct rad.
- Incidence angle modifier

$$\mathbf{g_i} = \mathbf{b_n} \cdot \cos(\lambda_{is}) + \mathbf{d_h} \cdot \left(\frac{1+\cos(\theta_i)}{2}\right) + \mathbf{g_h} \cdot \rho_g \cdot \left(\frac{1-\cos(\theta_i)}{2}\right)$$

$$f_{IAM}^{FP}(\lambda) = 1 - \tan^a\left(\frac{\lambda}{2}\right)$$

- Efficiency
  - Panel/ambient temperature
  - Radiation on slope

$$\eta_p^{FP} = \eta_0^{FP} - a_1^{FP} \cdot \frac{T_m^{FP} - T_{p,a}}{g_{p,i}} - a_2^{FP} \cdot g_{p,i} \cdot \left(\frac{T_m^{FP} - T_{p,a}}{g_{p,i}}\right)^2$$

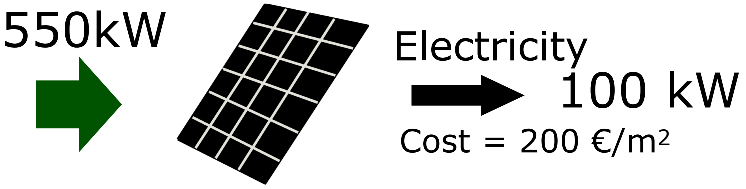
- Thermal output
  - Incidence angle modifier
  - Field losses
  - Diffuse/direct rad.

$$Q_p^{FP} = \eta_p^{FP} \cdot f_{field}^{FP} \cdot \left(b_{p,i} \cdot f_{p,IAM,ib}^{FP} + d_{p,i} \cdot f_{IAM,id}^{FP} + g_{p,gr,i} \cdot f_{IAM,ir}^{FP}\right) \cdot A^{FP}$$
$$\forall p \in \mathbf{P}$$

Tehnomont, Solarna Oprema Pula. SKT 100, Tested 2012

Thermo-economic model
Photovoltaic panel (PV)

- Radiation intensity factor
- Panel temperature
  - Ambient temperature
  - Incident radiation
- Electrical output
  - Panel temperature
  - Conversion losses
  - Radiations intensity



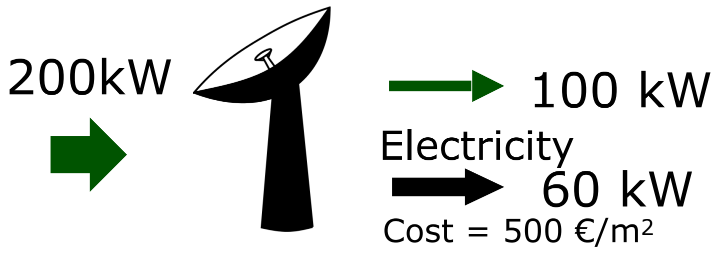
$$f_{p,g}^{PV} = f_{200} + \left(g_{p,i} - g_{200}\right) \cdot \frac{1 - f_{200}}{g_{STC} - g_{200}} \quad \forall p \in \mathbf{P}$$

$$T_{p,c}^{PV} = T_{p,a} + \frac{g_{p,i}}{g_{NOCT}} \cdot \frac{9.5}{5.7 + 3.8 \cdot v_{p,a}} \cdot \left[1 - \frac{\eta_m^{PV}}{(\tau\alpha)}\right] \cdot \left(T_{NOCT}^{PV} - T_{a,NOCT}\right)$$

$$E_p^{PV} = \eta_m^{PV} \cdot f_{gen}^{PV} \cdot f_{p,g}^{PV} \cdot \left[1 - f_T^{PV} \cdot \left(T_{p,c}^{PV} - T_{STC}^{PV}\right)\right] \cdot g_{p,i} \cdot A^{PV}$$

SunTech. HyPro, STP 290se20, Monocrystalline silicon.

Thermo-economic model
High Concentration PV-T (HCPVT)



- Direct radiation

$$\mathbf{b_n} = \mathbf{b_h} \cdot \frac{1}{\cos(\theta_s)}$$

- Efficiency
  - Radiation independent

Fixed based on simulation values

- Electrical & thermal output
  - Field losses

$$E_p^{HCPVT} = f_{gen}^{HCPVT} \cdot \eta_{el}^{HCPVT} \cdot b_{p,n} \cdot A^{HCPVT} \qquad \forall p \in \mathbf{P}$$

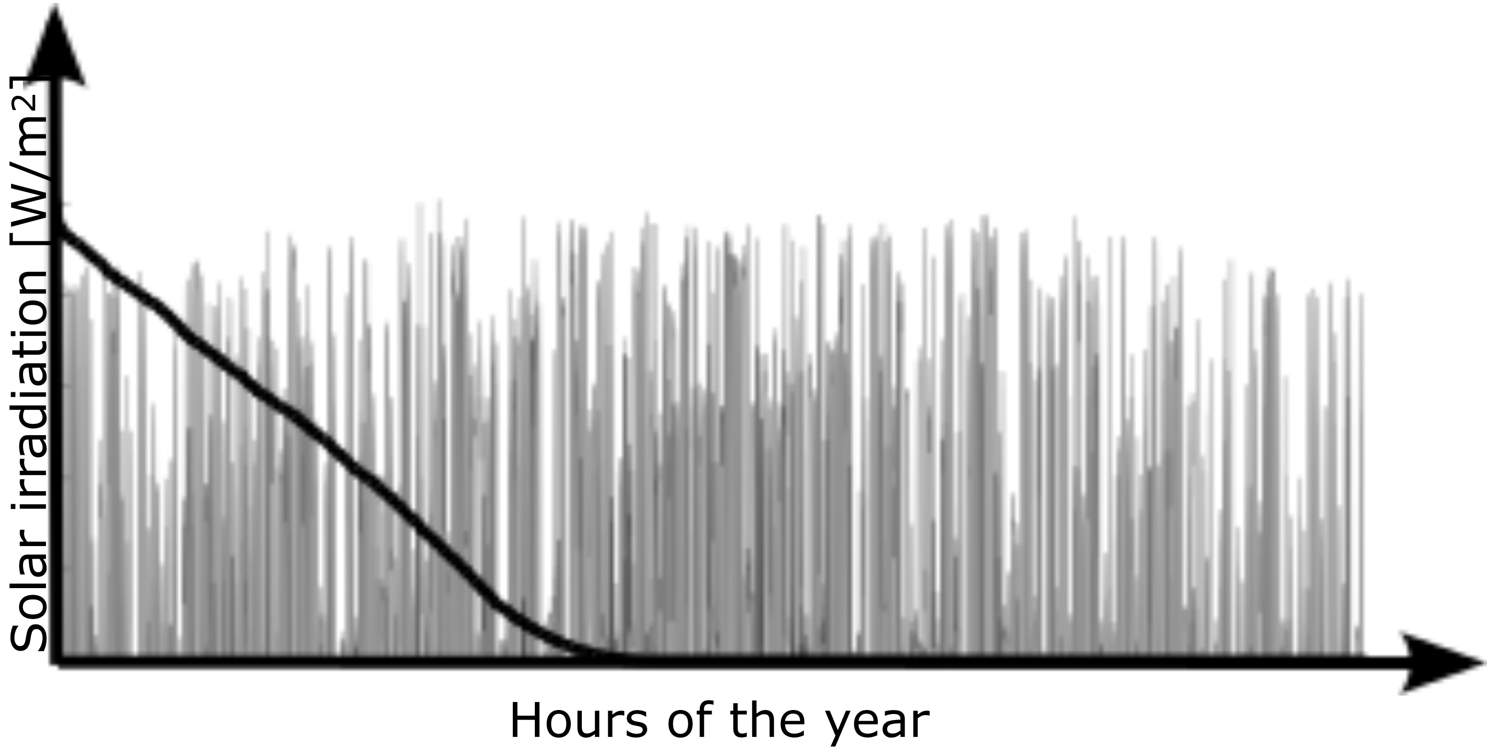
$$Q_p^{HCPVT} = Q_{p,prim}^{HCPVT} \Big|_{T_{in,prim}^{HCPVT}}^{T_{out,prim}^{HCPVT}} + Q_{p,sec}^{HCPVT} \Big|_{T_{out,prim}^{HCPVT}}^{T_{out,sec}^{HCPVT}}$$

$$= f_{field}^{HCPVT} \cdot \left(\eta_{th,\,prim}^{HCPVT} + \eta_{th,\,sec}^{HCPVT}\right) \cdot b_{p,n} \cdot A^{HCPVT}$$

Airlight Energy SA, HCPVT system, 2014

Modeling the solar irradiation

Do we have realy to model 174’400 hours (20*8720h) ?



(1) Meteonorm 7.0. Technical report; (2) Kaufman, L., and Rousseeuw, P. J. (2009)

Clustering of operating conditions

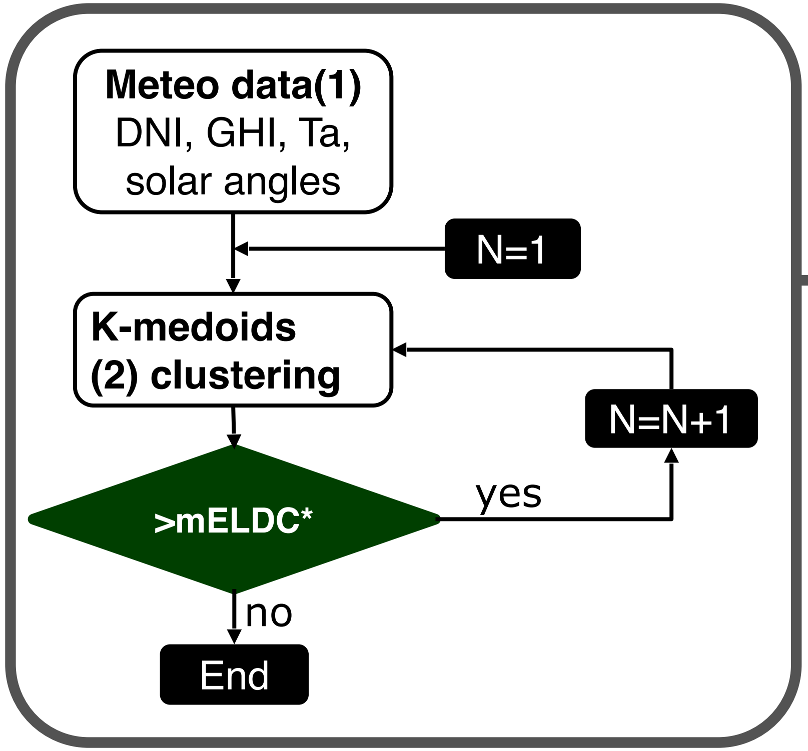
- The goal is to represent, over the expected lifetime of the equipment, the conditions that will be seen by the system with a minimum of pertinent information.
- The method :
  - define features to be considered :
    - solar irradiation, production schedule, presence of people, ambient temperature
  - for each feature generate the profiles of the 20 years of expected operation
  - identify typical sequences that can be used to represent the features
    - define typical sequence using machine learning techniques (clustering)
      - medioids or k-means
    - define the probability of appearance of each sequence (%time)
    - define the quality of the representation (%error/feature)
  - identify the sizing sequences (extreme conditions)
  - minimise the number of typical sequences (clusters)

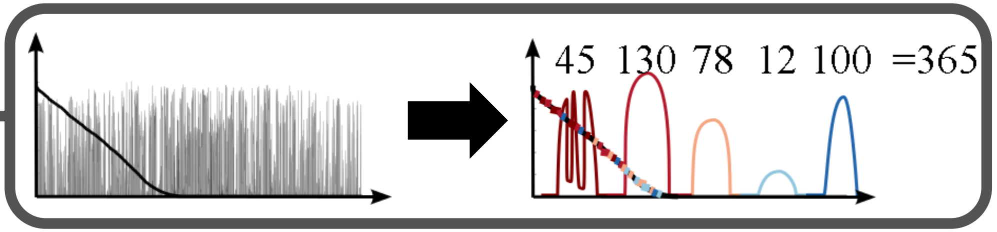
Meteorological data clustering

Sequence = days (24 hours profiles)

Quality of feature : Load Duration Curve LDC

$$\mathrm{mELDC} = \frac{\sum_{t=1}^{8760}\left(\mathrm{LDC}_{\mathrm{original}}(t) - \mathrm{LDC}_{\mathrm{typical\ days}}(t)\right)^2}{8760}$$





mELDC : 3.5e-4
Location: Sion, Switzerland
8 typical + 2 extreme = 10x24h = 240 hours

- 24 hours profiles
- frequence of appearance (days/year)

N = Number of clusters

(1) Meteonorm 7.0. Technical report
(2) Kaufman, L., and Rousseeuw, P. J. (2009)

Clustered data

Occurence : number of days represented by a typical day

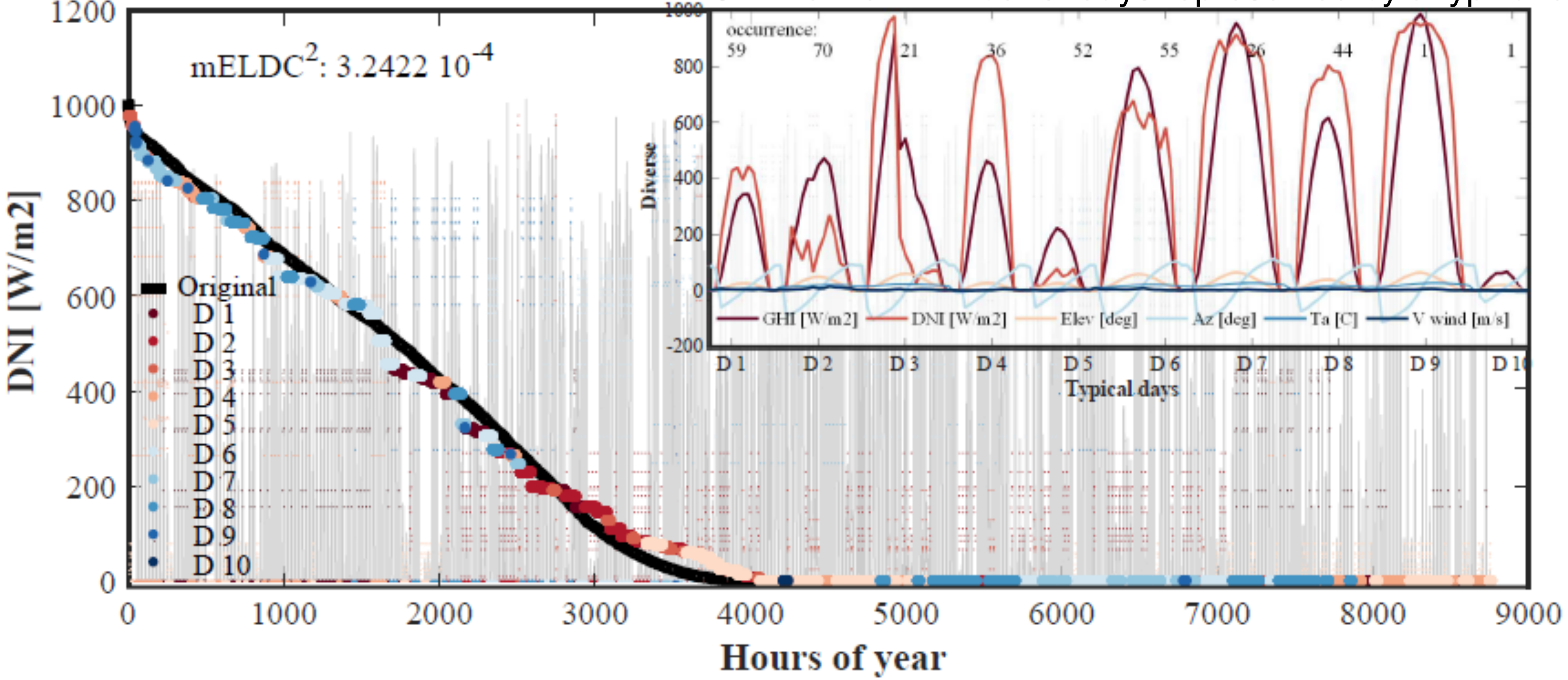
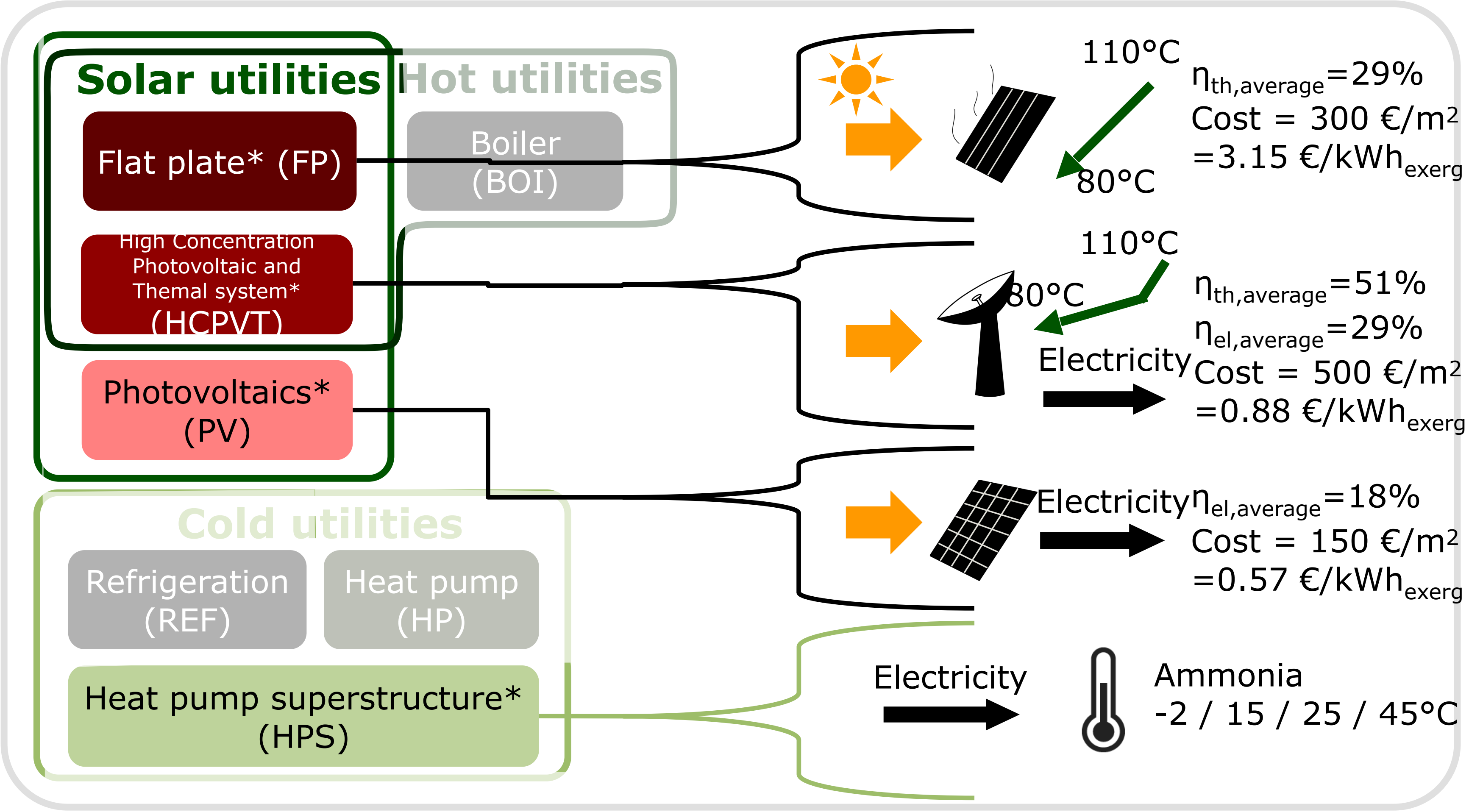


Fig. 5: Load duration curve of DNI for Sion, Switzerland, of original data and 8 typical plus 2 extreme days. In background yearly distribution of DNI of original and typical days.

Case study: Solar and heat-pumps



(1) Tehnomont, Solarna Oprema Pula. SKT 100; (2) SunTech, HyPro, STP 290S-20; (3) Airlight Energy Holding SA

Targeting problem : multi-period problem

$$\min_{R_r^p, y_w^p, u_w^p, y_w^{\max}, u_w^{\max}} \sum_{p=1}^{P}\left(\sum_{w=1}^{W} \mathrm{OP}_{1,p}^{w} \cdot y_p^w + \mathrm{OP}_{2,p}^{w} \cdot u_p^w\right) \cdot \Delta t_p \cdot occ_p + ann \cdot \sum_{w=1}^{W} \mathrm{IV}_1^w \cdot y^{w,\max} + \mathrm{IV}_2^w \cdot u^{w,\max}$$

$$u_p^w \in ¢^+ \quad \forall w \in \mathrm{W}, p \in \mathrm{P}$$

$$y_p^w \in \{0,1\} \quad \forall w \in \mathrm{W}, p \in \mathrm{P}$$

P={1,2,3...,240}

subject to

heat cascade constraints:

$$\sum_{w=1}^{W} u_p^w \cdot \mathrm{Q}_{p,r}^w + \sum_{s=1}^{S} \mathrm{Q}_{s,r} \cdot \mathrm{L}_{s,r} + R_{p,r+1} - R_{p,r} = 0 \quad \forall p \in \mathrm{P}, r \in \mathrm{RT}$$

thermodynamic feasibility:

$$R_{p,1} = 0, R_{p,N_{RT}+1} = 0, R_{p,r} \geq 0 \quad \forall r \in 1,\ldots,N_{RT}+1, p \in P$$

maximum size of operation and existence of technology w:

$$u^{w,\max} - u_p^w \geq 0 \quad \forall w \in W, p \in P$$

$$y^{w,\max} - y_p^w \geq 0 \quad \forall w \in W, p \in P$$

$$\mathrm{U}^{w,\min} \cdot y_p^w \leq u_p^w \leq \mathrm{U}^{w,\max} \cdot y_p^w \quad \forall w \in W, p \in P$$

Solar technologies

$$u^{ws,\max} - u_p^{ws} = 0 \quad \forall ws \in W_s, p \in P$$

Optimal operation of process operation

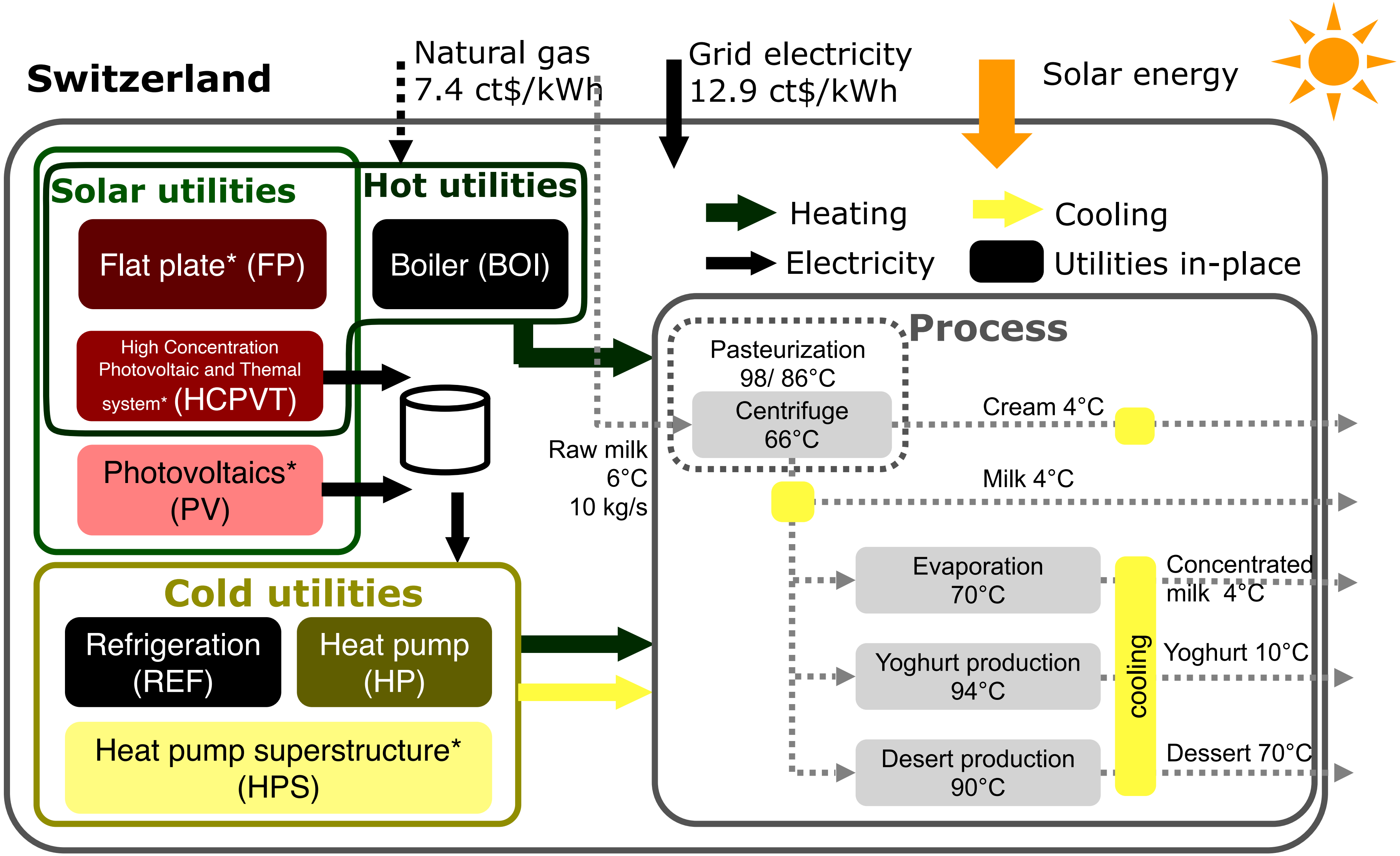
- Typical days definition to be adapted to account for process scheduling

Saturday																								
Period2	hours																							
streams	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
other																								
pasto1																								
pasto2																								
pasto3																								
pasto4																								
pasto5																								
evapo																								
proc6																								
proc7																								
proc8																								
proc9																								
proc10																								
heat																								
CIP																								
Times	T1	T2	T3		T4	T5	T6		T7		T8	T9	T10	T11	T12			T13	T14	T15				

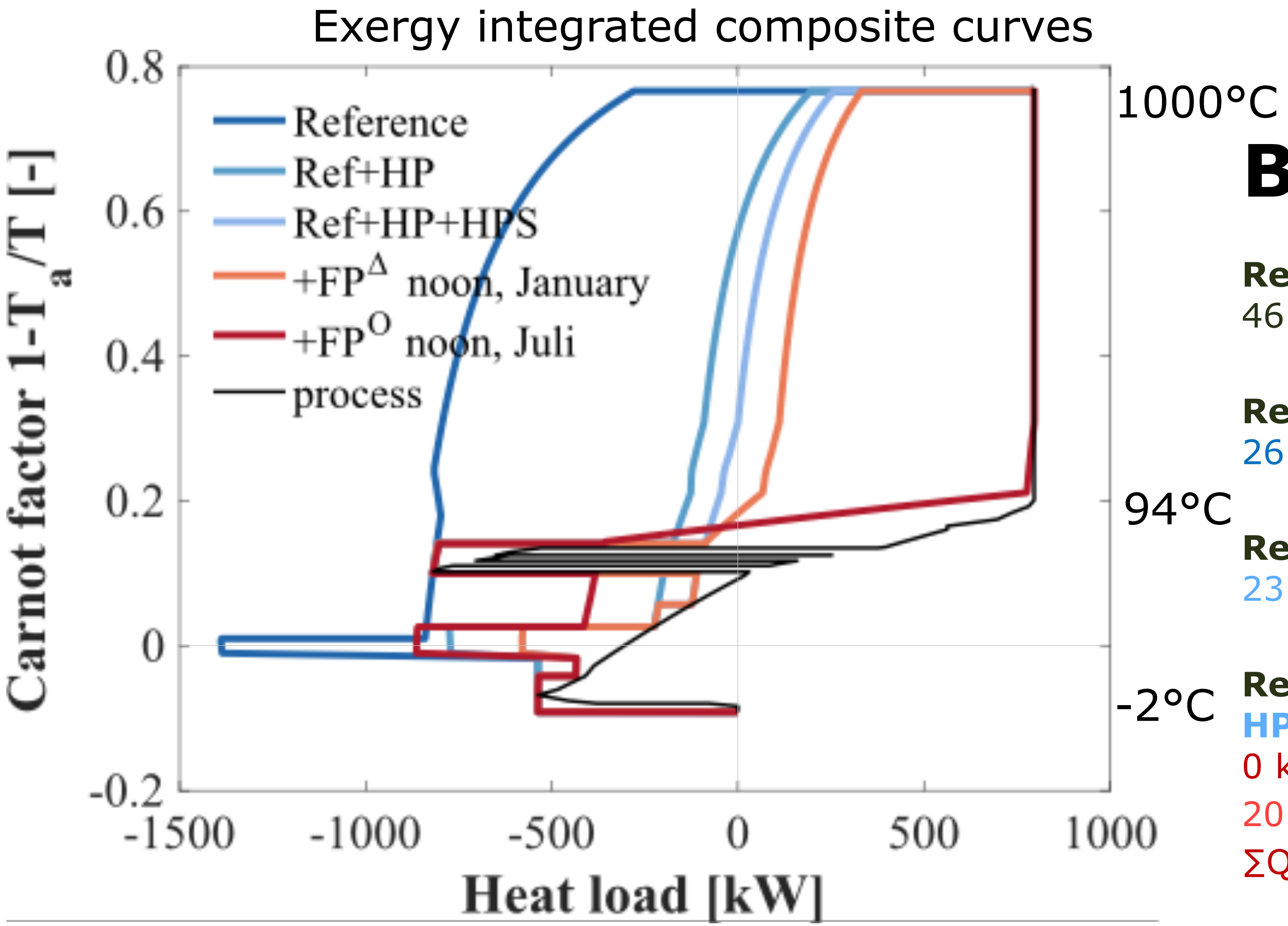
Becker, H.,& Maréchal, F. (2012). Targeting industrial heat pump integration in multi-period problems. *Comput. Aided Chem. Eng*, *31*, 415.

System Optimisation

IEA Key Energy Statistics 2015
Helen Becker (2012)



Integrating solar heat



Boiler

Reference
46 kWh/t_{raw}

-60%

Ref+HP
26 kWh/t_{raw}

-64%

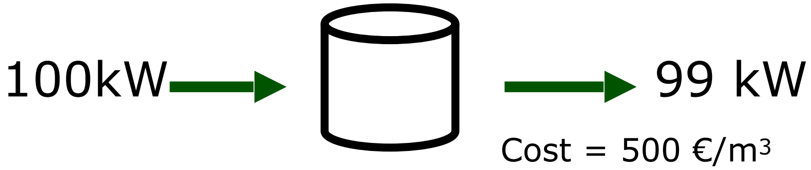
Ref+HP+HPS
23 kWh/t_{raw}

-100%

Ref+HP+ HPS+Solar
0 kWh/t_{raw}
20 kWh/t_{raw}
ΣQ_t kWh/t_{raw}

Thermo-economic model : Thermal storage

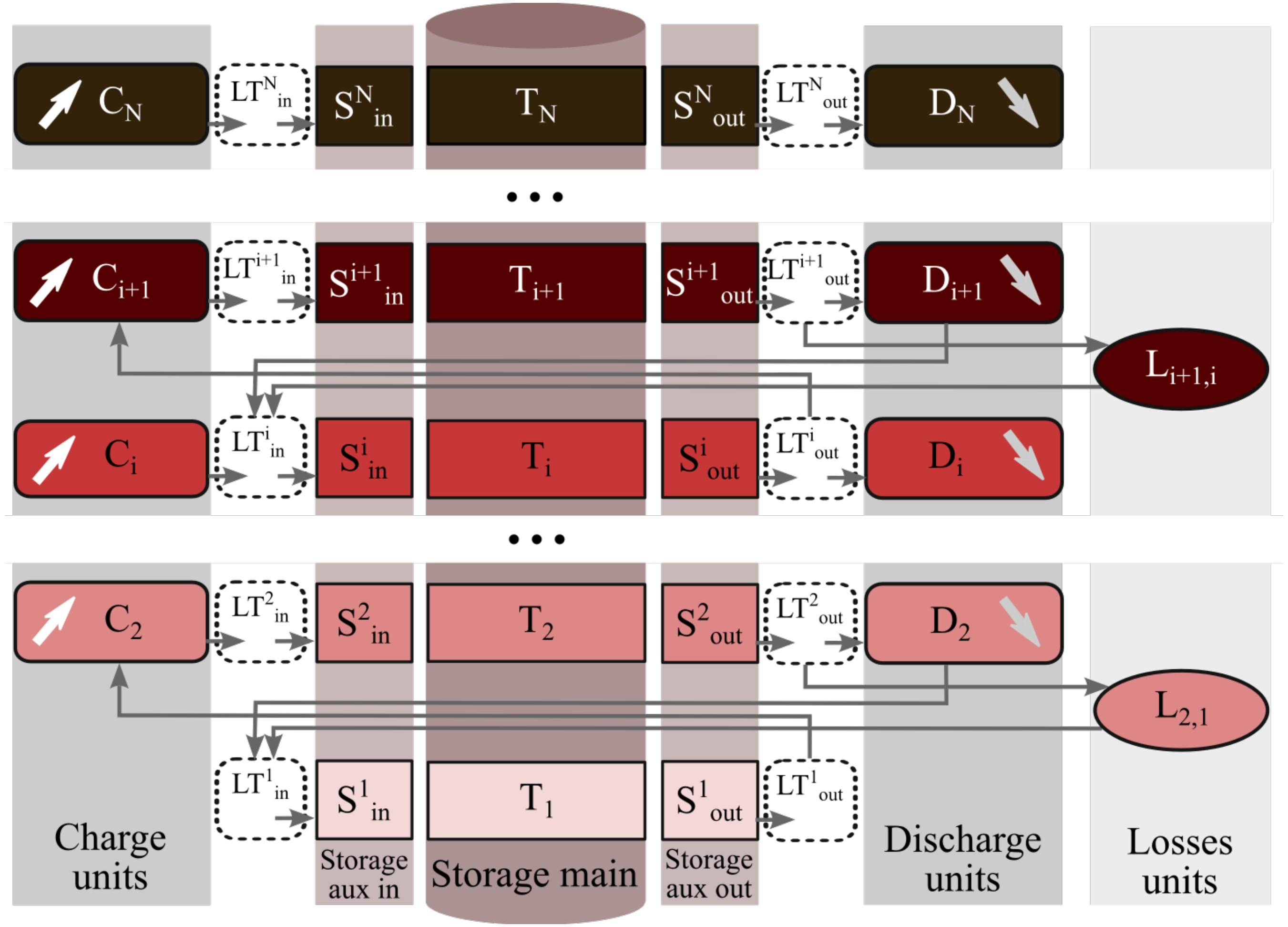
- Allows heat exchange between non simultaneous process units
- Allows matching between solar energy and process needs



▪ Mass conservation ▪ Temperature	Storage level and temperature depends on inflow and outflow
▪ Cyclic constraint	At the end of the period, the storage level should be the same as the initial level
▪ Dis/charge constraints	No charge and discharge at the same time, temperatures to compatible with source and sink
▪ Losses constraint	Storage losses are dependent on storage temperature and filling
▪ Energy conservation	Requirements are given by thermodynamic properties

Modeling Thermal storage

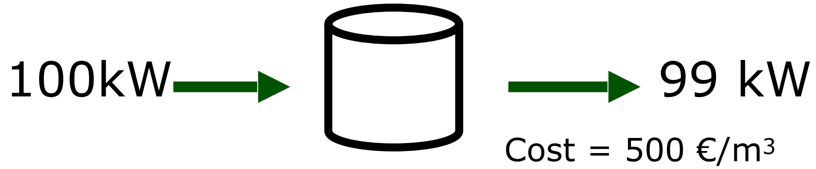
Discretized temperature levels



Max volume

Modeling Thermal storage

Temperature is discretized
Heat cascade + timewise cascade



Cost = 500 €/m3

- Mass conservation

$$u_p^s = \begin{cases} u_{p-1}^s + u_p^{s,in} - u_p^{s,out}, \forall p \in \mathbf{P} \setminus \{1\} \\ u_{|\mathbf{P}|}^s + u_p^{s,in} - u_p^{s,out}, p = 1 \end{cases} \quad \forall s \in \mathbf{STO}$$

$$u_p^{s,out} = u_p^{s+1,C} + u_p^{s,D} + u_p^{s,L} \qquad u_p^{s,in} = u_p^{s+1,D} + u_p^{s,C} + u_p^{s+1,L}$$

- Cyclic constraint

$$u_{|\mathbf{P}|}^s = u_c^s \quad \forall c = \Omega \cdot l, \; l \in \{1, 2, \ldots, |\mathbf{P}|/\Omega\}$$

- Dis/charge constraints

$$u_p^{s,C} + u_p^{s,D} \leq 1$$

$$u_p^{s,C} - u_p^{s-1,C} + \left(1 - y_p^s\right) \cdot \mathrm{u}_p^{s-1,C,\max} - \left(1 - y_p^{s-1}\right) \cdot \mathrm{u}_p^{s,C,\min} \geq 0$$

$$u_p^{s,C} - u_p^{s-1,C} + \left(y_p^{s-1} - 1\right) \cdot \mathrm{u}_p^{s,C,\max} - \left(y_p^s - 1\right) \cdot \mathrm{u}_p^{s-1,C,\min} \leq 0$$

- Losses constraint

$$u_p^{s,L} = u_p^s$$

$$\mathrm{Q}_p^{s,L} = \frac{4 \cdot \mathrm{U}}{\mathrm{c_p} \cdot \rho \cdot \mathrm{d}} \cdot \left(\mathrm{T}^s - \mathrm{T_a}\right)$$

- Energy conservation

$$\mathrm{Q}_p^{s,C/D} = \mathrm{c_p} \cdot \rho \cdot \Delta \mathrm{T}$$

Between two temperatures of the temperature discretisation =>> also for PCM

Targeting problem : multi-period + storage problem

$$\min_{R_r^p, y_w^p, u_w^p, y_w^{\max}, u_w^{\max}} \sum_{p=1}^{P}\left(\sum_{w=1}^{W} \mathrm{OP}_{1,p}^{w} \cdot y_p^w + \mathrm{OP}_{2,p}^{w} \cdot u_p^w\right) \cdot \Delta t_p \cdot \mathrm{occ}_p + \mathrm{ann} \cdot \sum_{w=1}^{W} \mathrm{IV}_1^w \cdot y^{w,\max} + \mathrm{IV}_2^w \cdot u^{w,\max}$$

$u_p^w \in ¢^+ \quad \forall w \in W, p \in P$

$y_p^w \in \{0,1\} \quad \forall w \in W, p \in P$

P={1,2,3...,240}

subject to

Storage model

$$M_{S,t} - M_{0,S} = \sum_{st=1}^{t} d_t \cdot \left(\dot{M}_{h,S,st} + \dot{M}_{h_{losteq},S,st} - \dot{M}_{c,S,st}\right)$$

$S \in STO : S = 1,\ \forall\ t = 1, \dots T$

$$M_{S,t} - M_{0,S} = \sum_{ts=1}^{t} d_{ts} \cdot \left(\dot{M}_{c,S-1,ts} + \dot{M}_{h,S,ts} + \dot{M}_{h_{losteq},S,ts} - \dot{M}_{c,S,ts} + \dot{M}_{h,S+1,ts} - \dot{M}_{h_{losteq},S-1,ts}\right)$$

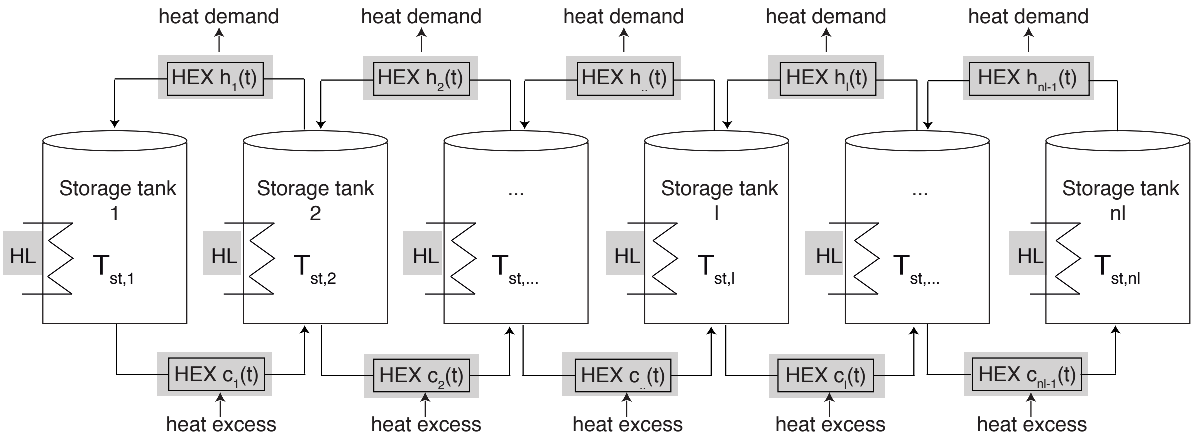
$\forall\ S \in STO : S = 2, \dots N_S - 1,\ \forall\ t = 1, \dots T$

$$M_{S,t} - M_{0,S} = \sum_{ts=1}^{t} d_{ts} \cdot \left(\dot{M}_{c,S-1,ts} - \dot{M}_{h,S-1,ts} - \dot{M}_{h_{lost},S-1,ts}\right)$$

$\forall\ S \in STO,\ S = N_S,\ \forall\ t = 1, \dots T$

$y_u^t = 0 - 1$

$y_u \ = 0 - 1 \quad \forall\, u\ \in\ FU$

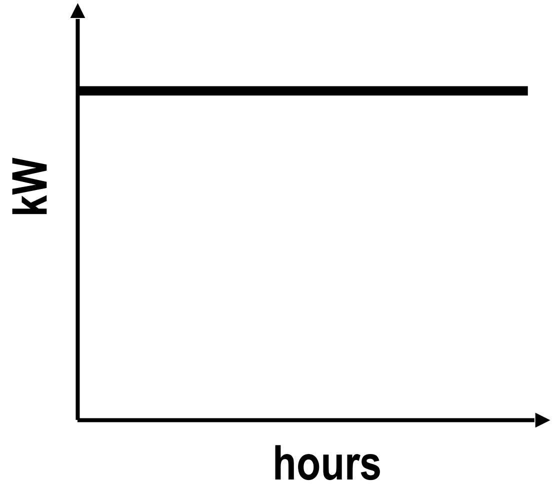


Units for heat integration

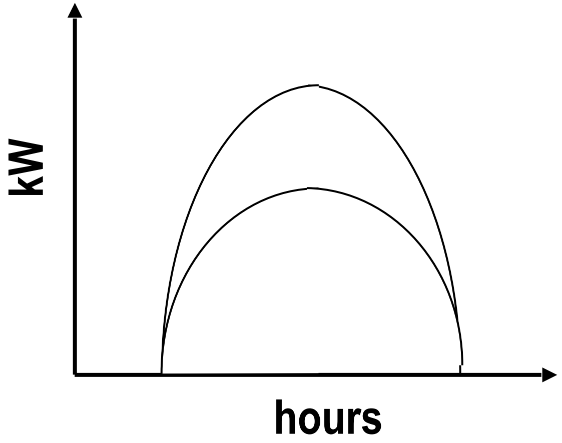
HEX: Heat exchangers
HL: Heat losses

Solar & storage sizing

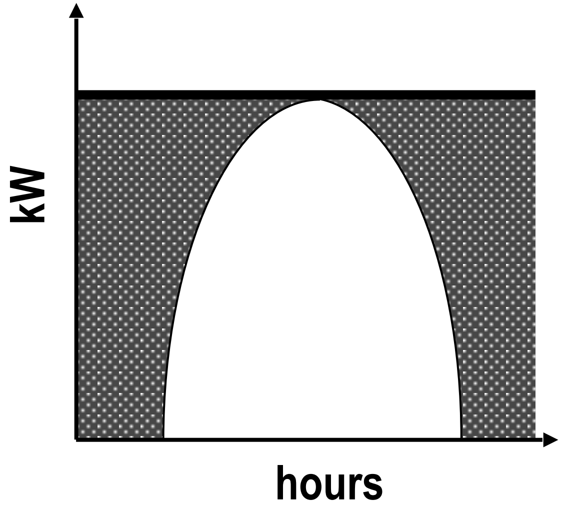
- Process

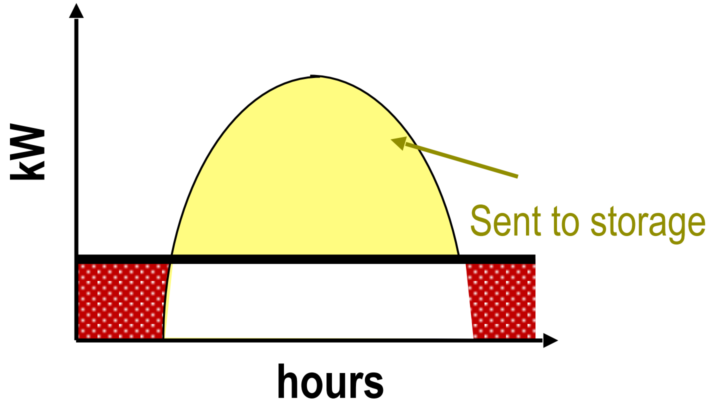


- Solar



- Process & solar





Minimum and maximum sizes

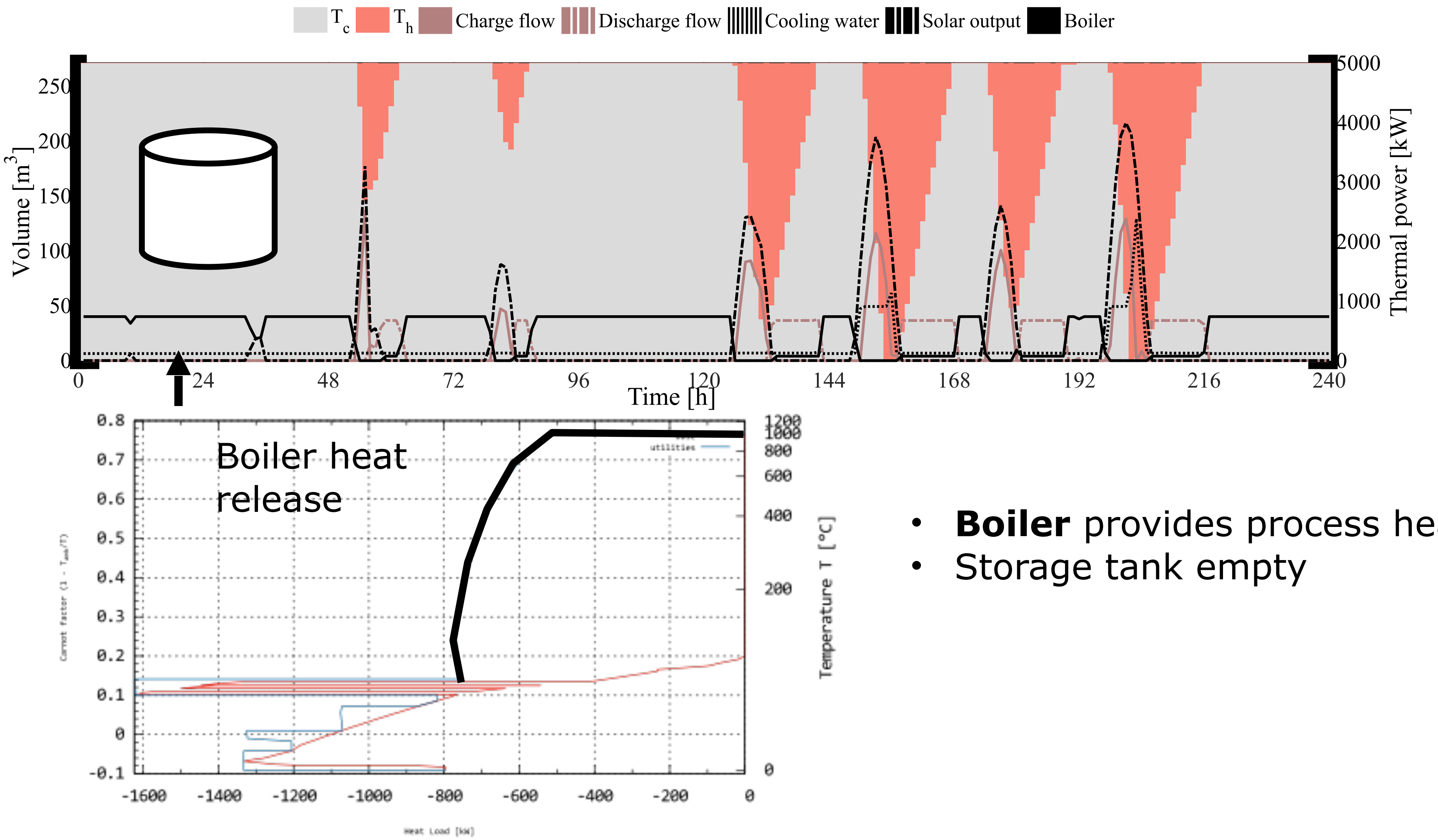
- Max volume associated to cost and performances

$$u^{w,\max} - u_p^w \geq 0 \quad \forall w \in W, p \in P$$

$$y^{w,\max} - y_p^w \geq 0 \quad \forall w \in W, p \in P$$

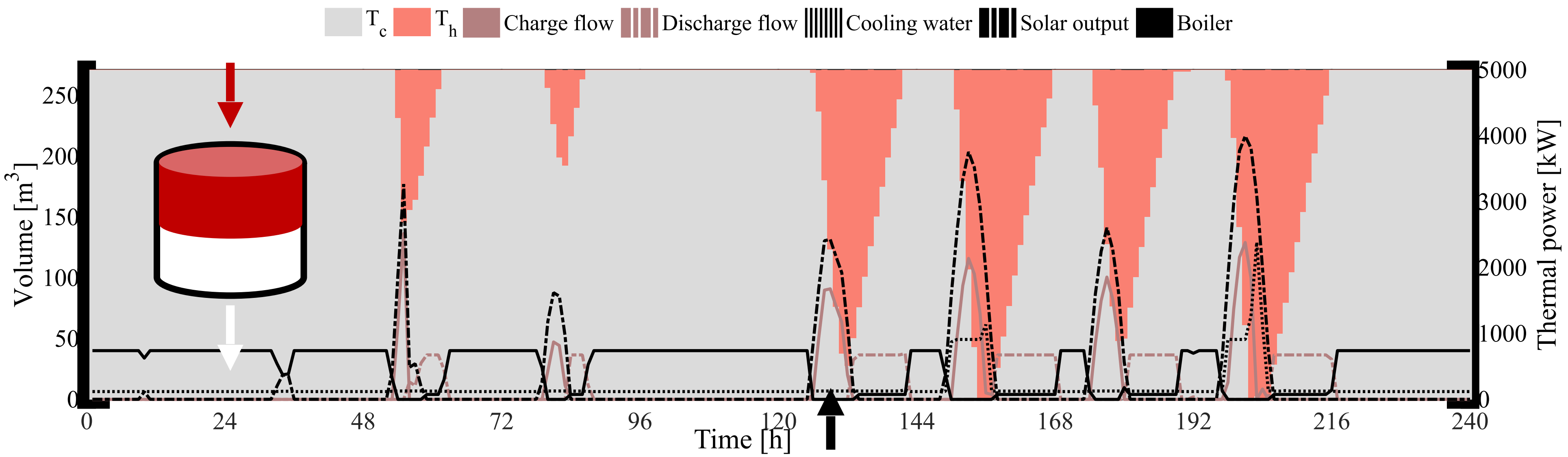
$$\mathrm{U}^{w,\min} \cdot y_p^w \leq u_p^w \leq \mathrm{U}^{w,\max} \cdot y_p^w \quad \forall w \in W, p \in P$$

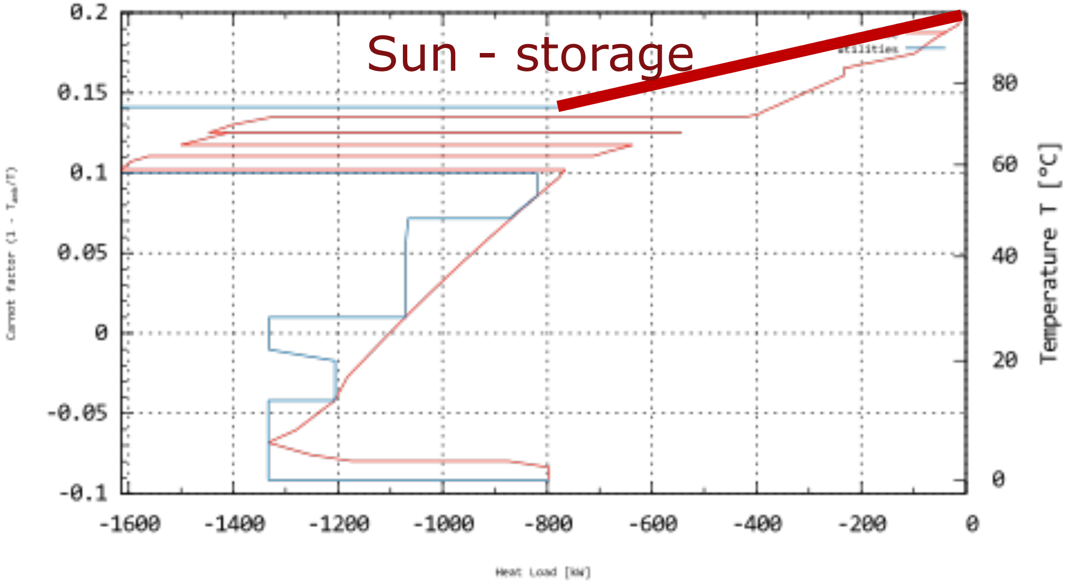
Operating principle



- **Boiler** provides process heat demand
- Storage tank empty

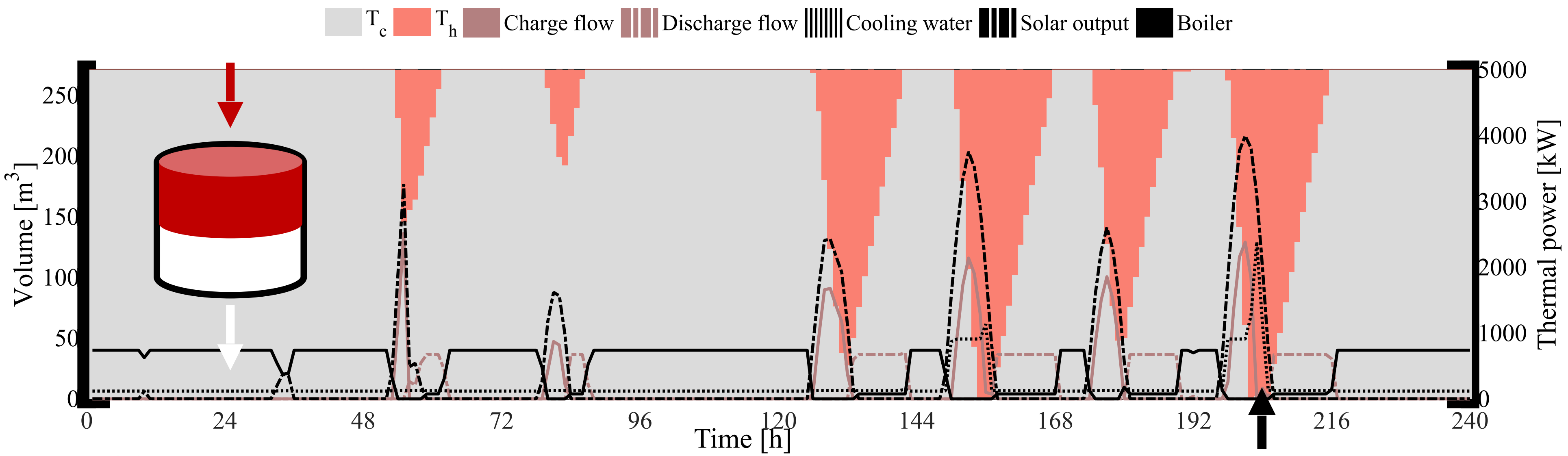
Operating principle

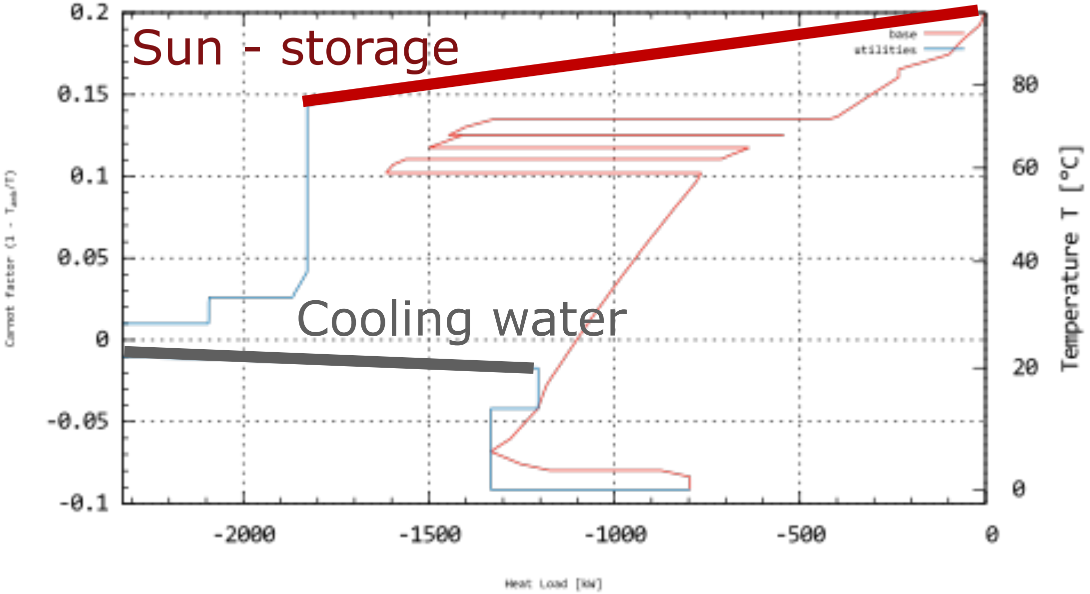




- Solar collectors provide 100% of process heat demand
- Storage tank is filled

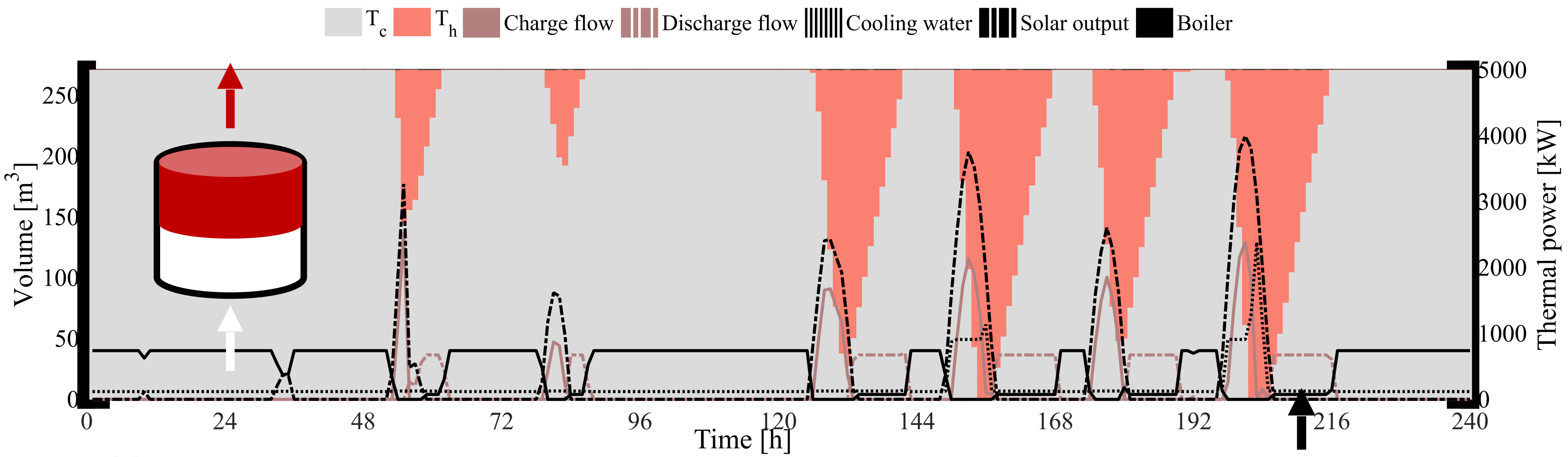
Operating principle

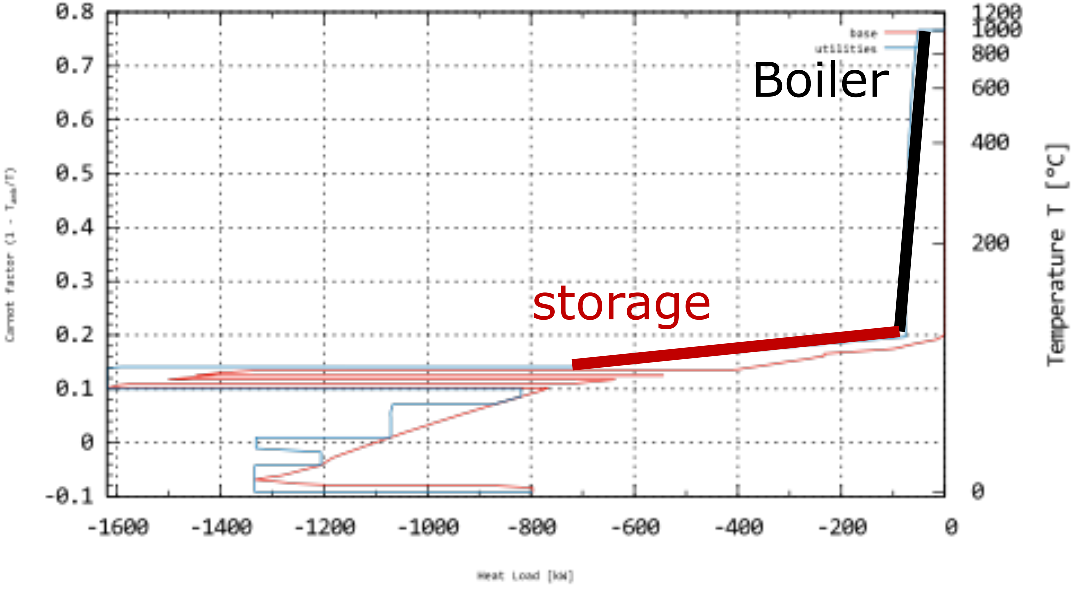




- **Solar collectors** provide **more than 150%** of process heat demand
- Storage tank is filled
- Extra cooling water is consumed

Operating principle



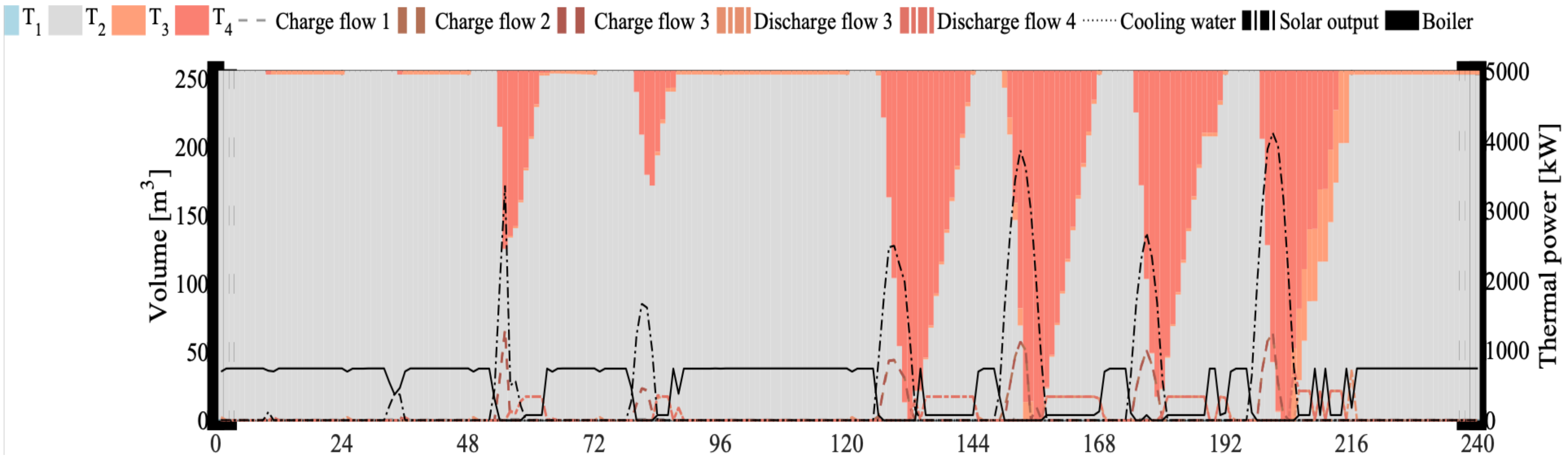


- Storage tank is emptied
- Boiler provides additional high temperature heat requirement

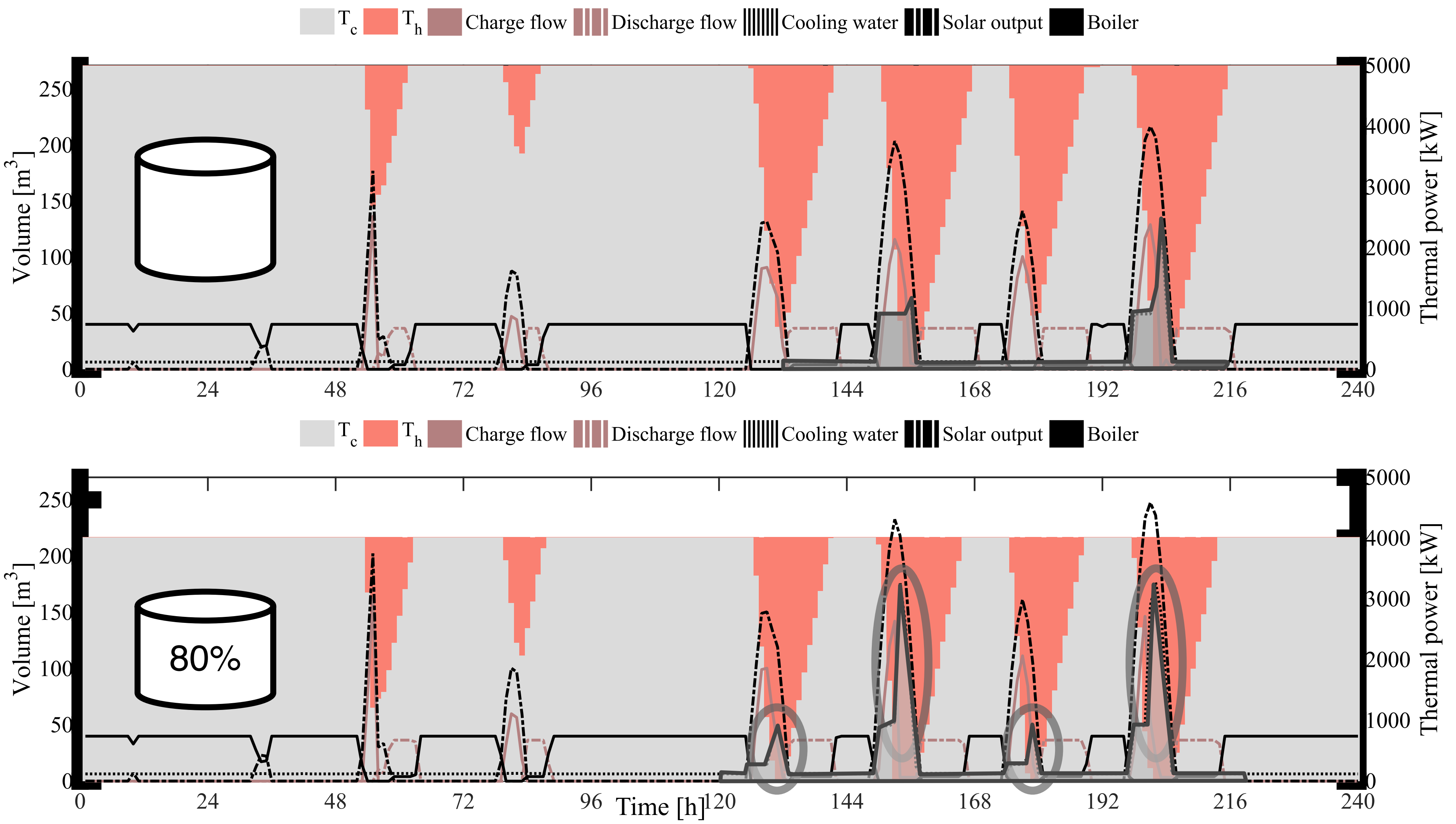
Outlook: multi-temperature tanks

- Temperature discretization: 5 temperature levels

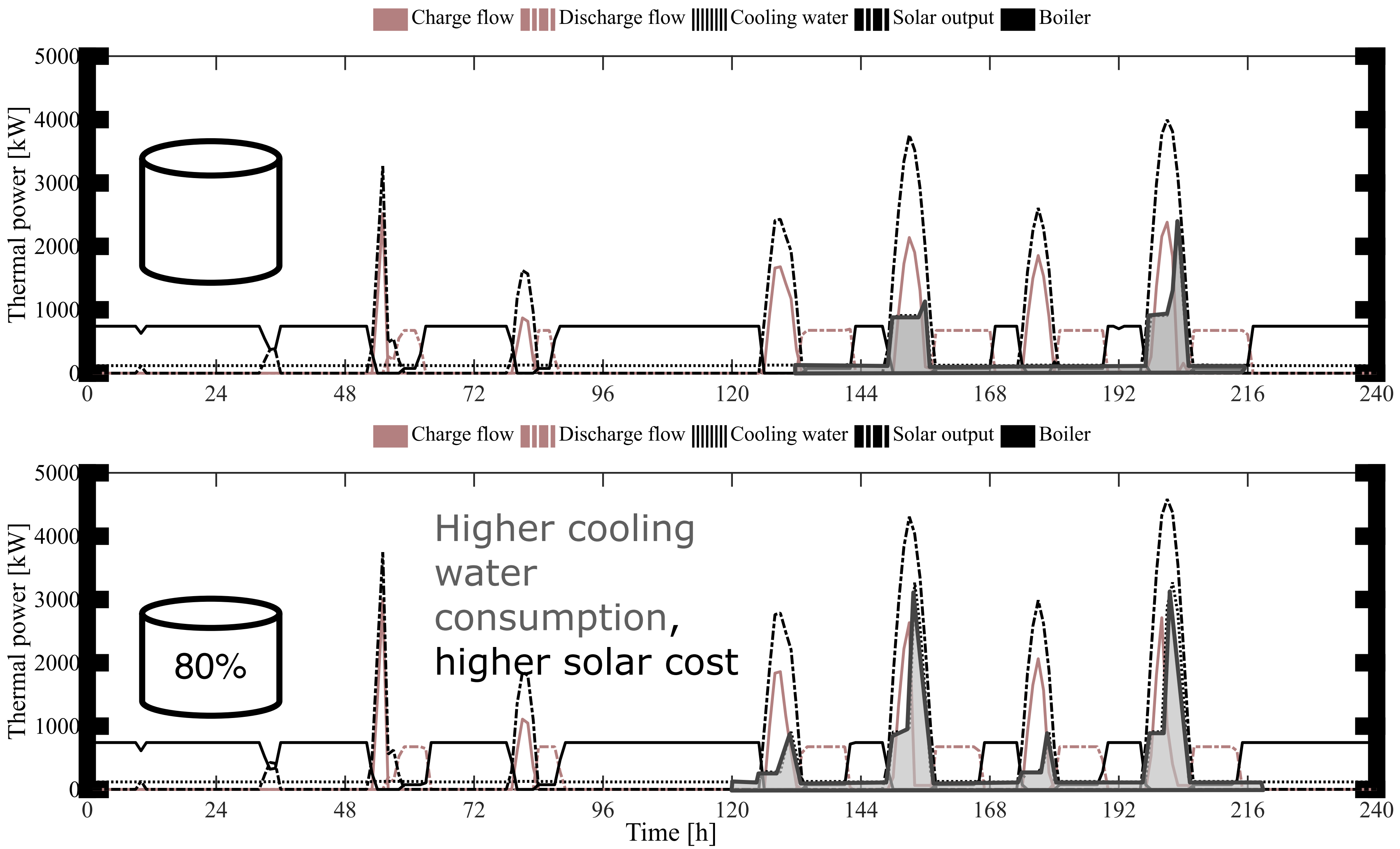
! Calculation effort !



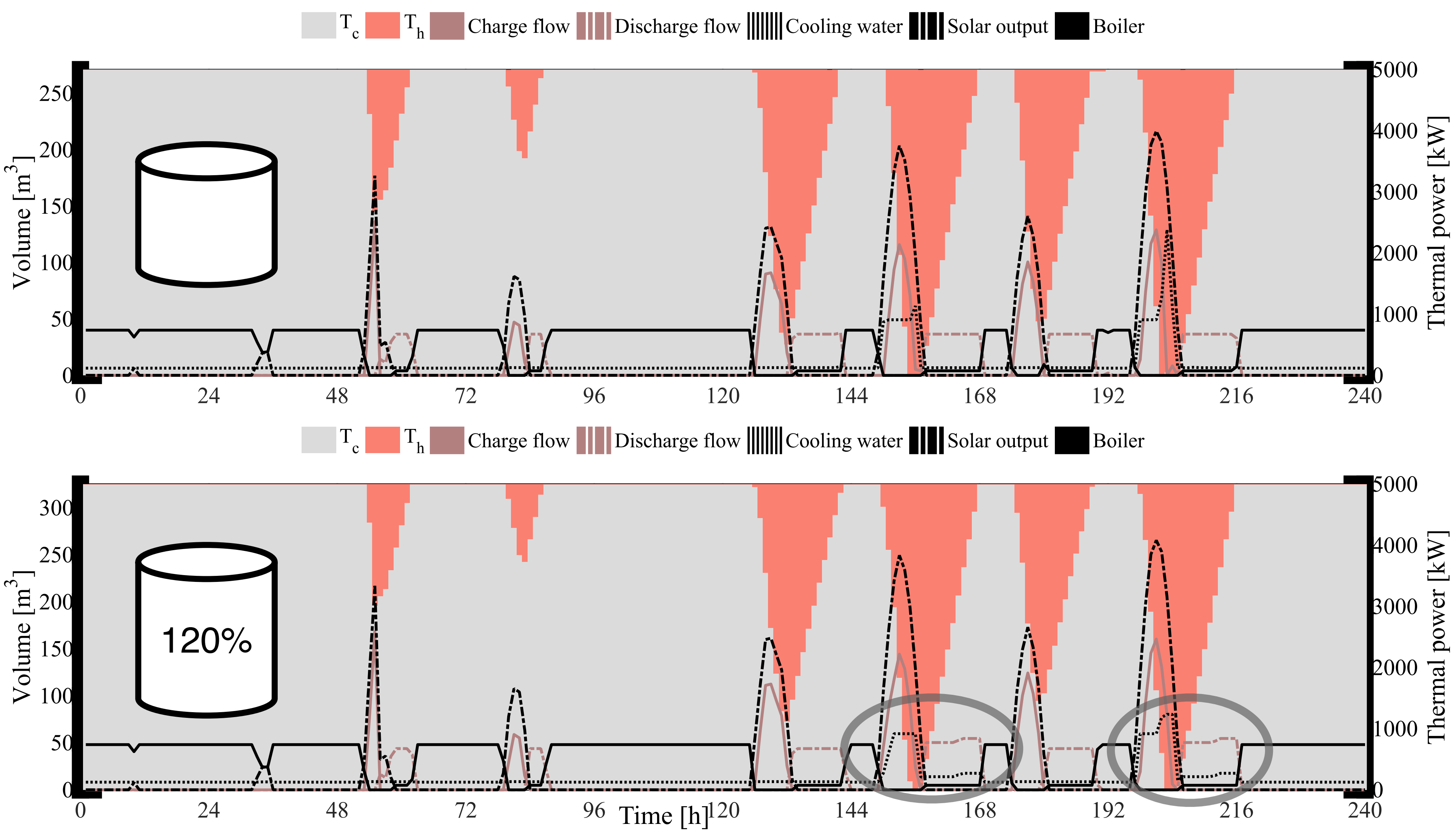
Storage: size constraint



Storage: size constraint



Storage: size constraint



Multi-objective Optimization problem

- Objective function:

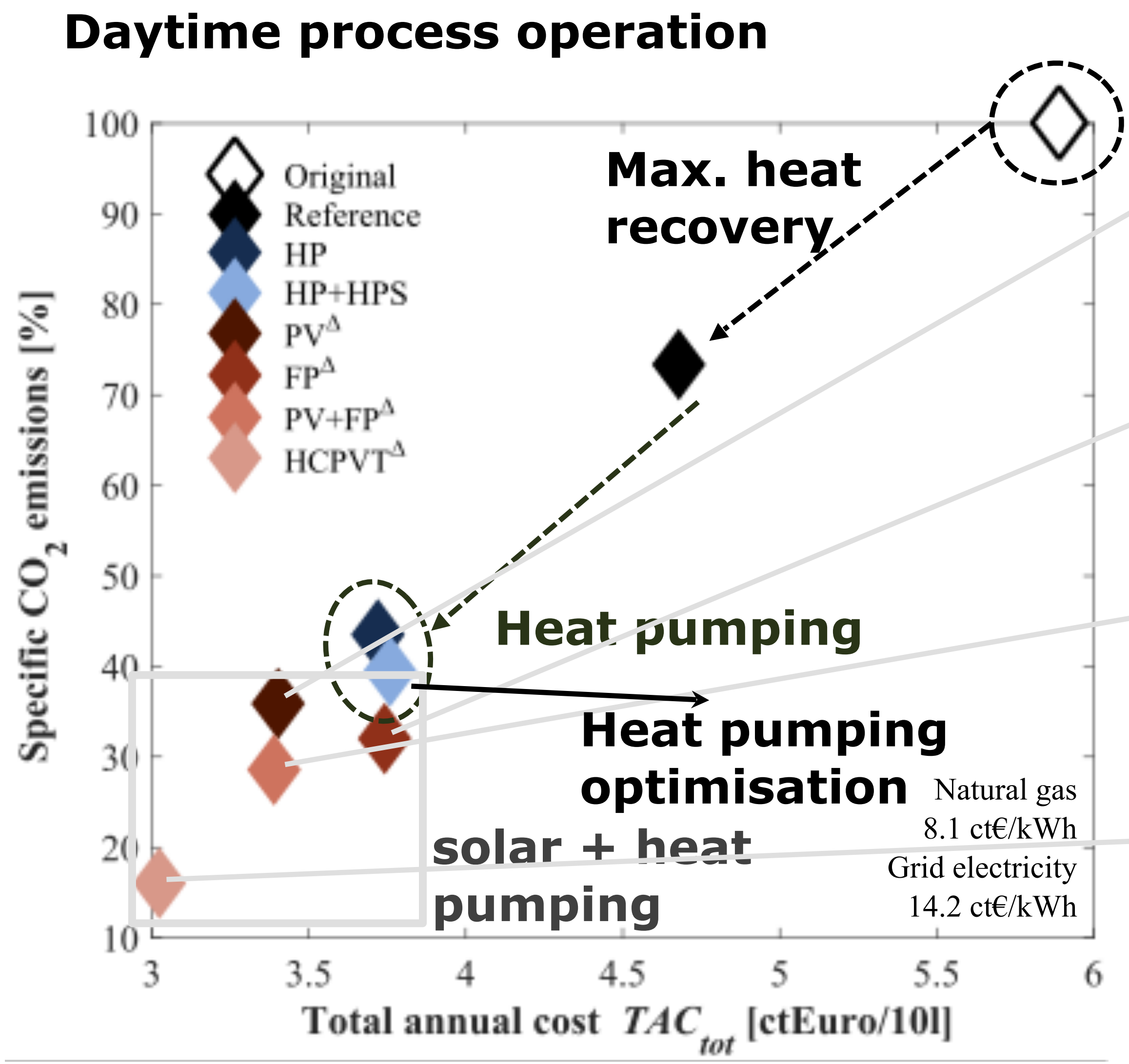
$$\min_{R_r^p, y_w^p, u_w^p, y_w^{\max}, u_w^{\max}} \sum_{p=1}^{P} \left(\sum_{w=1}^{W} \mathrm{OP}_{1,p}^{w} \cdot y_p^w + \mathrm{OP}_{2,p}^{w} \cdot u_p^w \right) \cdot \Delta t_p \cdot \mathrm{occ}_p + \mathrm{ann} \cdot \sum_{w=1}^{W} \mathrm{IV}_1^w \cdot y^{w,\max} + \mathrm{IV}_2^w \cdot u^{w,\max}$$

- Epsilon constraint on CO2 emissions:

$$\sum_{p=1}^{P} \left(\sum_{w=1}^{W} \mathrm{CO}_2^w \cdot u_p^w \right) \cdot \Delta t_p \cdot \mathrm{occ}_p \le \varepsilon$$

- Constraints
  - Energy and mass conservation
  - Heat cascade
  - Utility sizes

Comparison of the different solutions



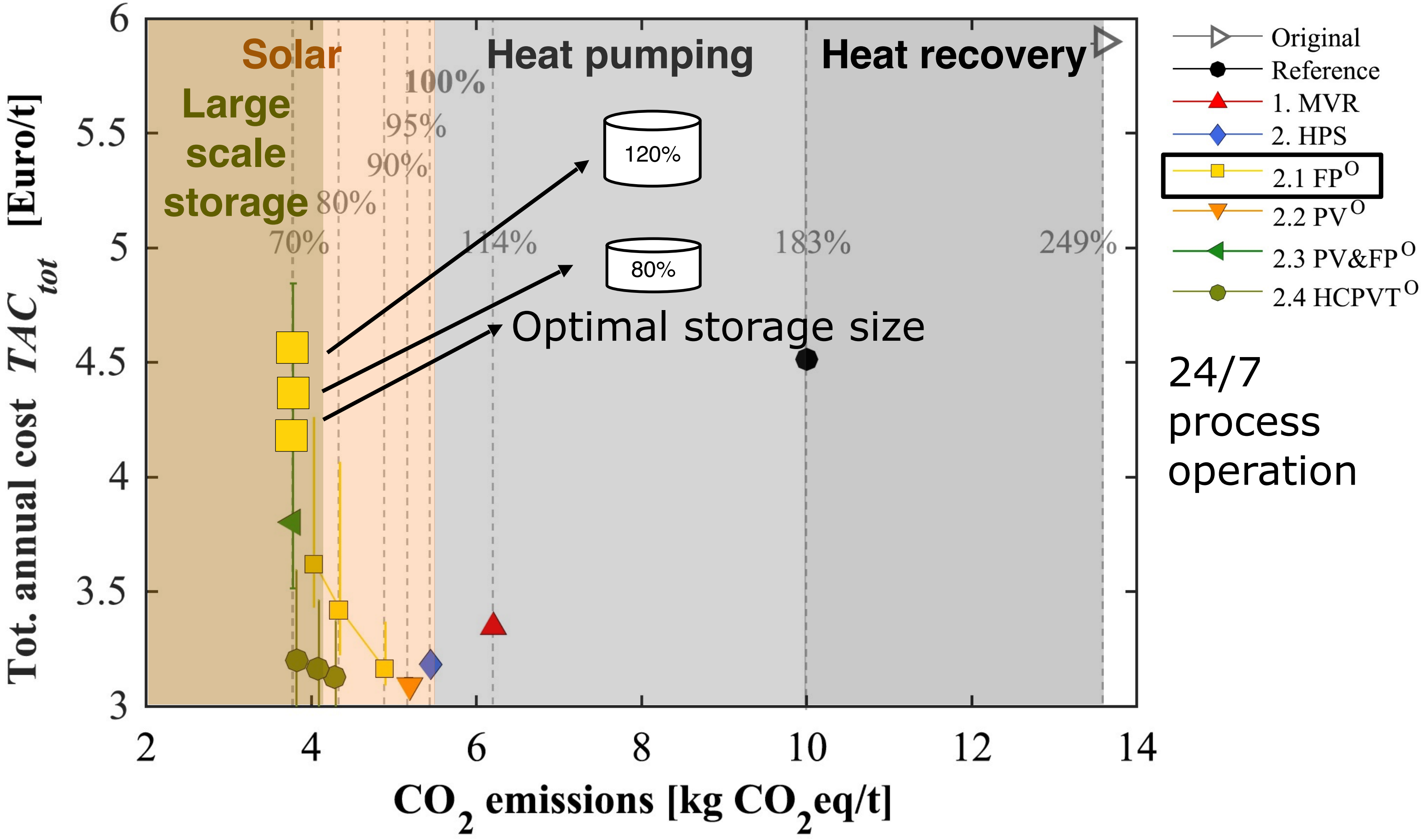
Photovolatic Electricity (150€/m²)
2'245m² → 2.38m²/10t

Flat plate thermal
Heat (300€/m²)
1'369m² →1.45 m²/10t

Plate plate + PV
Hybrid
Low efficiency

HCPVT
Hybrid (500€/m²)
High efficiency
1'988m²→ 2.10m²/10t

Overall cost and emissions



24/7 process operation

Wallerand, A. S., Kermani, M., Voillat, R., Kantor, I.,&Maréchal, F. (2017). Optimal design of solar-assisted industrial processes considering heat pumping: Case study of a dairy. *Renewable Energy, in press*.

Storage: summary

	Electricity kWh/t	Gas kWh/t	Cooling water kWh/t	Solar ha	Reductions %/ha solar	Storage m3/kt	Solar + Storage $/t
Non-optimal scheduling	4.6	16.2	6	1.1	26.7	0.81	1.42
Constrained size 120%	5.0	16.0	4.0	0.88	34.2	1.03	1.14
Optimal size	**4.8**	**16.1**	**3.8**	**0.85**	**34.9**	**0.85**	**1.10**
Constrained size 80%	4.7	16.2	4.8	1.0	30.4	0.69	1.25

Conclusions : Integrating renewable energy in industrial processes

- Optimal integration of solar energy in industry
  - Combined design and scheduling of storage tanks
- Typical period selection algorithm
- The entire energy system to be investigated
  - Heat recovery, process scheduling
  - Heat pumping, Energy conversion, Energy harvesting
  - Storage tanks
- Resulting optimal operation strategy