Design of Solar assisted industrial processes

How to integrate solar energy in industrial processes?
Towards optimal design of solar assisted industrial processes

Case study of a dairy
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Problem statement

- PV
- Solar Heat
- Boiler/cogen
- Bat.
- Storage
- Heat pump
- Industrial processes
- Raw materials
- Products
- Waste
- Cooling and refrigeration
- Heat

Common element is the energy planning:
- Energy consumption profile determination
- Energy performance evaluation
- Energy baseline generation
- Identification and evaluation of improvement options
- Implementation and monitoring

Step 1

Step 2

- Systematic approach
- Methodologies
- Tools

Context

Literature review

Problematic

1st year research

Research plan

Conclusion
Case study

Pasteurization 98/86°C
Centrifuge 66°C
Evaporation 70°C
Yoghurt production 94°C
Desert production 90°C
Cream 4°C
Concentrated milk 4°C
Yoghurt 10°C
Dessert 7°C

Which are the best technologies to satisfy the needs?
➢ Cases (different sets of technologies)
Case study: Heat requirement after heat recovery

Grand composite curve

Heat requirement

Cooling requirement

Corrected temperature [°C]

Heat load [MW]

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6
Methodology

Data collection
- Meteorological data clustering
  - Meteo data(1)
    - DNI, GHI, Ta, solar angles
  - K-medoids (2) clustering
  - > mELDC*

Optimal sizing & operation
- Heat pump superstructure
- Process data
- Solar components & storage

Post Computational analysis
- Recalculation of non-linear investment costs estimations
- CO2 eq emissions
  \[ CO_{2\text{eq}} = \sum \left( CO_{2\text{eq}} \cdot E_{\text{eff}}^P \cdot u_p \cdot \frac{CO_{2\text{eff}}}{\text{PFO}} \cdot Q_{\text{tot}}^P \cdot u_{\text{tot}}^P \right) \cdot \Delta t_p \cdot \text{occ}_p \]
- min TAC
  \[ \text{TAC} = \text{OPEX} + \text{CAPEX} \]
  Optimization with multi-period mixed integer linear programming (MILP)

subject to
- heat cascade constraints:
  \[ \sum_{k=1}^{w} u_k^r \cdot Q_{\text{tot}}^r + \sum_{z=1}^{s} Q_{z,j} \cdot L_{z,j} + R_{p,r+1} - R_{p,r} = 0 \quad \forall p \in P, r \in RT \]
- thermodynamic feasibility:
  \[ R_{p,1} = 0, R_{p, N_{\text{RT}}} + 1 = 0, R_{p,r} \geq 0 \quad \forall r \in 1, ..., N_{\text{RT}}, p \in P \]
Methodology*

- **Data collection**
  - Targeting problem
  - Post computational analysis

- Meteorological data clustering

Methodology

* Meteorological data clustering

** Data collection **

- Meteorological data clustering

** Targeting problem **

- Post computational analysis

** Data collection **

- Meteorological data clustering

** K-medoids (2) clustering **

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

Methodology

Data collection ➢ Targeting problem ➢ Post computational analysis

➢ Meteorological data clustering

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: dairy process & utilities

Solar utilities
- Flat plate* (FP)
- Photovoltaics* (PV)
- High Concentration Photovoltaic and Thermal system* (HCPVT)

Hot utilities
- Boiler (BOI)
- Pasteurization 98/86°C
- Centrifuge 66°C

Cold utilities
- Refrigeration (REF)
- Heat pump (HP)
- Heat pump superstructure* (HPS)

Utilities in-place
- Photovoltaics* (PV)
- High Concentration Photovoltaic and Thermal system* (HCPVT)

Energy Sources
- Natural gas 7.4 ct$/kWh
- Grid electricity 12.9 ct$/kWh

Utilities
- Heating
- Electricity
- Cooling

Process
- Cream 4°C
- Milk 4°C
- Evaporation 70°C
- Yoghurt production 94°C
- Desert production 90°C
- Concentrated milk 4°C
- Yoghurt 10°C
- Desert 70°C

IEA Key Energy Statistics
2015
Helen Becker (2012)
Case study: utilities in-place

Solar utilities
- Flat plate* (FP)
- High Concentration Photovoltaic and Thermal system* (HCPVT)
- Photovoltaics* (PV)

Cold utilities
- Refrigeration (REF)
- Heat pump superstructure* (HPS)

Hot utilities
- Boiler (BOI)

Utilities:
- Natural gas
- Electricity
  - Ammonia -2°C / 35°C
  - Water (MVR) 56°C / 76°C
- Cooling water 0 ct$/m³
  - 15°C
  - 17°C

Helen Becker (2012)
Case study: Solar and heat-pumps

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

Data collection
➢ Meteorological data clustering
➢ Process data
➢ Solar components* & storage*

Targeting problem
Post computational analysis

Radiation on slope (1)
\[ g_i = b_n \cdot \cos(\lambda_n) + d_n \cdot \left( \frac{1 + \cos(\theta_n)}{2} \right) + g_b \cdot \rho_s \cdot \left( \frac{1 - \cos(\theta_n)}{2} \right) \]
\[ = b_i + d_i + g_{gr,i} \]

Flat plate thermal collectors (FP)

Energy output

Hourly modeling

(1) JA Duffie and WA Beckman, 2012
Methodology*

Data collection
➢ Meteorological data clustering
➢ Process data
➢ Solar components* & storage*
➢ Heat pump superstructure*

Targeting problem

Post computational analysis
All adapted from: Del Nogal et al. (2008)

- Units: condensers, evaporators, flash drums?
- Sizing/flow rates: ?
- Pressure levels: ?
- Fluid: ?
- Operating points: de/superheating, subcooling
Targeting problem: multi-period problem

\[
\min_{R^x_p, y^w_p, u^w_p, y^w_p, u^w_p} \sum_{p=1}^{P} \left( \sum_{w=1}^{W} OP_{1,p}^w \cdot y^w_p + OP_{2,p}^w \cdot u^w_p \right) \cdot \Delta t \cdot \text{occ}_p + \text{ann} \cdot \sum_{w=1}^{W} IV_1^w \cdot y^w_{\text{max}} + IV_2^w \cdot u^w_{\text{max}}
\]

subject to

heat cascade constraints:

\[
\sum_{w=1}^{W} u^w_p \cdot Q_{p,r}^w + \sum_{s=1}^{S} Q_{s,r}^w \cdot L_{s,r} + R_{p,r+1} - R_{p,r} = 0 \quad \forall p \in P, r \in \text{RT}
\]

thermodynamic feasibility:

\[
R_{p,1} = 0, R_{p,N_{RT}+1} = 0, R_{p,r} \geq 0 \quad \forall r \in \{1,...,N_{RT}+1\}, p \in P
\]

maximum size of operation and existence of technology \( w \):

\[
u^w_{\text{max}} - u^w_p \geq 0 \quad \forall w \in W, p \in P
\]

\[
y^w_{\text{max}} - y^w_p \geq 0 \quad \forall w \in W, p \in P
\]

Solar technologies:

\[
u^w_{\text{max}} - u^w_p = 0 \quad \forall w \in W, p \in P
\]

\[
y^w_{\text{max}} - y^w_p \geq 0 \quad \forall w \in W, p \in P
\]
Targeting problem: multi-period problem

\[
\min_{R^w_\ell, y^w_\ell, u^w_\ell, y^w_u, u^w_u} \sum_{p=1}^{P} \left( \sum_{w=1}^{W} \left( \text{OP}^w_{1,p} \cdot y^w_p + \text{OP}^w_{2,p} \cdot u^w_p \right) \right) \cdot \Delta t \cdot \text{occ}_p + \text{ann} \cdot \sum_{w=1}^{W} \text{IV}^w_1 \cdot y^w_{\text{max}} + \text{IV}^w_2 \cdot u^w_{\text{max}}
\]

subject to

\[
M_{S,t} - M_{0,S} = \sum_{st=1}^{t} d_{st} \left( \dot{M}_{h,S,st} + \dot{M}_{h_{\text{lost}},S,st} - \dot{M}_{c,S,st} \right)
\]

\(S \in \text{STO}: S = 1, \forall t = 1, \ldots, T\)

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

\(\forall S \in \text{STO}: S = 2, \ldots, N_S - 1, \forall t = 1, \ldots, T\)

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

\(\forall S \in \text{STO}, S = N_S, \forall t = 1, \ldots, T\)

\[
y^w_\ell = 0 - 1
\]

\[
y_u = 0 - 1 \quad \forall u \in \text{FU}
\]
Heat pump integration

Exergy integrated composite curves

Carnot factor $1-T_a/T_{\text{ref}}$ vs. Heat load [kW]

- Reference
- Ref+HP
- Ref+HP+HPS
- process

Boiler

Reference
46 kWh/t_{\text{raw}}

Ref+HP
26 kWh/t_{\text{raw}}

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

-60% reduction
-64% reduction
Integrating solar heat

Exergy integrated composite curves

- Boiler
  - Reference: 46 kWh/t
  - Ref+HP: 26 kWh/t
  - Ref+HP+HPS: 23 kWh/t
  - Ref+HP+HPS+Solar: 0 kWh/t

- Heat load [kW]
  - Heat load range: -1500 to 1000 kW

- Carnot factor 1-T/a [-]
  - Carnot factor range: 0 to 0.8

- Temperature levels:
  - 1000°C
  - 94°C
  - -2°C
Comparison of the different solutions

Daytime process operation

- **Photovoltaic 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