Multi-objective optimal design of energy conversion systems

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Thermo-economic optimisation of energy conversion systems

Methodology

- Problem
  - Goals
  - Constraints
  - Context

- System
  - Options list
  - Superstructure
  - Models
  - Performances

Optimal System
- Multi-objectives Optimisation
- Multi-criteria evaluation
- Analysis

Technologies
- Thermodynamic
- Data bases
- thermo-econo-env. models

Solutions

Emissions
Configuration
Operating conditions
Size of equipment
Costs
**Optimization strategy**

- **Process flow model**
  - **BELSIM-VALI**

- **Equipment rating and costing**
  - State variables
  - Heat exchange requirements

- **Energy integration**
  - EASY

- **Optimisation MOO**
  - (Evolutionary)
  - Decision variables
  - Thermodynamic targets

- **Step 1: Energy flow model**

  - **Equipment models**
    - $\dot{m}_i, \dot{W}_i, P_i, T_i \Rightarrow \text{Size}_i$
    - $\text{Cost}_i = f(\text{Size}_i, P_i)$

  - **Thermo-economic module**

  - **System Performances**
    - Interconnected equipment
    - State Variables in the system
    - $T, P, M_i \Rightarrow H, S, E$
    - consumptions + emissions
Energy conversion superstructure

 Equipments options
 Low Nox burner, O2 burning

 Equipments selection
 1 / 2 gas turbines, CO2 separation

 Equipments interconnection
 draw-off, recycle,...

 System integration
 heat exchanger network

 Mixed integer (Y/N) & continuous decision variables:
 Target T, P, Flow, conversion,... i.e. Thermodynamic targets

 Process integration

 Hot & cold composite curves

 Minimum energy requirement
  - Hot
  - Cold
  - Refrigeration
  - Heat recovery

 Cost (CHF/year) Total Energy Invest

 DTmin

 Cold composite curve
 Hot composite curve

 DTmin/2

 6854 kW

 Hot utility

 1709 kW

 Cooling utility

 6948 kW

 13343 kW

 Refrigeration

 Q(kW) T(K)

 0 500 1000 1500 2000 2500 3000

 250 300 350 400 450 500 550 600

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**Step 2: Steam cycle superstructure**

- Systematic generation
- Only T,P for each level
  - Mechanical power
    \[ w_{i,j} = \min((h_i - h_j), \eta_s(h_i - h_{is}(P_i, T_i, P_j))) \]
  - Hot & cold streams
- DTmin/2
- Level heat & mass balance

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**MILP model of the steam network**

\[
\begin{align*}
\text{max } W & \quad w \in \{(i, j), (j, k), (k, i)\} \\
\text{Heat cascade equation} & \quad \sum_{w \in \{(j, k); (k, i); c\}} f_w q_{w,r} + \sum_{s=1}^{n_s} Q_{s,r} + R_{r+1} - R_r = 0 \quad \forall r = 1, \ldots, n_r \\
& \quad R_r \leq 0 \quad \forall r = 1, \ldots, n_r; R_{n_r+1} = 0; R_1 = 0 \\
\text{Pressure level balance} & \quad \sum_{i=1}^{n_i} k_{i,w} f_{i,w}^t + \sum_{k=1}^{n_k} f_{k,w} - \sum_{k=1}^{n_k} f_{w,k} - \sum_{i=1}^{n_i} f_{w,i} - \sum_{i=1}^{n_i} f_{i,w}^t = 0 \quad \forall w \\
\text{Mechanical power balance} & \quad \sum_{w \in \{(i, j)\}} f_{w,w}^t w_w - \sum_{w \in \{(k, i)\}} f_{w,w} p_w = W \\
\text{Existence of heat exchange or expansion} & \quad f_{\min w} y_w \leq f_w \leq f_{\max w} y_w \quad y_w \in \{0, 1\}
\end{align*}
\]

---

General formulation: min exergy losses

- New objective function

\[ \min_{R_r, y_w, f_w} \sum_{w=1}^{n_w} (f_w \cdot (\Delta E_w^+ - \sum_{r=1}^{n_r} \Delta E_q_{wr}^{-} - w_w^{-})) \]

- Thermal exergy: \( \Delta E_{q_{wr}}^- = \sum_{s=1}^{n_s_w} q_{sr} \cdot (1 - T_0 * \ln \left( \frac{T_{r+1} + \Delta T_{min}/2}{T_{r+1} - \Delta T_{min}/2} \right) \)

- Chemical Exergy: \( \Delta E_w^+ \)

- Work: \( w_w^- \)

Visualising the integration

- Carnot composite curves
  - Exergy conversion

![Diagram showing Carnot composite curves with gas turbine power, heat transfer losses, and stack losses.]

Conventional cycles

![Diagram showing conventional cycles with air preheating and draw off, cycle with reheating + draw off + air preheating, and Rankine cycle.]

Exergy conversion
Nuclear power plant

- Exergy conversion
- Efficiency: 38%
- Based on the thermal energy

Heat exchange system optimisation

- Optimisation
  - Decision variables
- Optimal performances
  - Pressure and temperature
  - superheating/reheating
- Optimal cost
  - $DT_{min}/2$
Optimization strategy

- Optimisation MOO (Evolutionary)
  - Equipment rating and costing
    - Decision variables
    - State variables
  - Process flow model: BELSIM-VALI
  - Energy integration: EASY

Step 3: Thermo-economic model

Sizing and costing of equipments apply heuristics - expert system - optimisation

Compressors [14]:

\[ C_C = \frac{f_{M&S}}{1069.9} \cdot \frac{C_{C,r}}{0.95 - \eta_C} \cdot \left( \frac{\dot{m}_C}{\dot{m}_{C,r}} \right)^{0.7} \cdot \ln(\eta_C) \]

Turbines [14]:

\[ C_T = \frac{f_{M&S}}{1069.9} \cdot \frac{C_{T,r}}{0.94 - \eta_T} \cdot \left( \frac{\dot{m}_T}{\dot{m}_{T,r}} \right)^{0.7} \cdot \ln(\eta_T) \left( 1 + e^{0.025(T_r - 1570)} \right) \]

Combustion Chamber [14]:

\[ C_{CC} = \frac{f_{M&S}}{1069.9} \cdot \frac{C_{CC,r}}{0.995 - \pi_{CC}} \cdot \left( \frac{\dot{m}_{CC}}{\dot{m}_{CC,r}} \right)^{0.7} \cdot \left( 1 + e^{0.015(T_{CC} - 1540)} \right) \]

Steam Turbine with alternator [14]:

\[ C_{ST} = \frac{f_{M&S}}{1069.9} \cdot 1.15E_{ST} \cdot C_{ST,r} \left( \frac{\dot{E}_{ST}}{E_{ST,r}} \right)^{0.7} \]

Oxygen Transport Membrane [5],[4]:

\[ C_{OTM} = \frac{C_{OTM,r} \cdot \dot{m}_{O_2}}{0.0022(P_{O_2})^{0.25} e^{-72000/RT}} \]
Estimating heat exchangers cost

\[ A_{h,c,i} = \frac{(Q_{h,c})_i}{(U_{h,c})_i \cdot \Delta(T_{lm})_i} = \left( \frac{1}{h_{i,h}} + \frac{1}{h_{i,c}} \right) \cdot \frac{Q_i}{\Delta(T_{lm})_i} \]

With

\[ (\Delta T_{lm})_i = \frac{(T_{h,i} - T_{c,i}) - (T_{h,i-1} - T_{c,i-1})}{\ln\left(\frac{T_{h,i} - T_{c,i}}{T_{h,i-1} - T_{c,i-1}}\right)} \]

Real temperatures

Overall exchange area:

\[ A_{HX} = \sum_{i=1}^{n_v} A_i = \frac{Q_i}{\sum_{j=1}^{n_{streams}} \sum_{i=1}^{\left(\frac{n_{streams}}{i}\right)} \left( \frac{1}{h_{i,j}} \right)} \]

Estimated cost:

\[ C_{HX} = \frac{f_{M&S}}{1069.9} \cdot C_{HX}(A_{HX})^{0.7948} \]

Objectives: thermo-economic optimisation

- Multi-objective optimisation:
  - Maximum efficiency
  - Minimum investment cost
  - Minimum overall cost
  - Minimum environmental impact
  - ....
- Thermo - economy
  - 1 thermodynamic (or environomic) performance
  - 1 economic performance
Multi-objective optimisation

1. Efficiency
   \[ \eta = \frac{\dot{E}_{\text{steam}} + \dot{E}_{\text{AIRGT}} + \dot{E}_{\text{CO}_2} - \dot{E}_{\text{CO}_2}}{m_{\text{fuel}} LHV_{\text{fuel}}} \]

2. Specific cost

Pareto Analysis

- Maximum efficiency for a given cost
- Minimum cost for a given efficiency
- Each point corresponds to 1 configuration

Solving strategy

- QMOO
  - Evolutionary algorithm
  - Clustering techniques
  - Non dominated solutions preservation
- Hybrid method under study

NLP1 : Min O1
   \[ \text{st } O2 \geq O2^k \]

NLP2 : Max O2
   \[ \text{st } O1 \leq O1^k \]
**Example of application AZEP Plant**

**Decision variable**

<table>
<thead>
<tr>
<th></th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas turbine press. ratio</td>
<td>15 - 45</td>
</tr>
<tr>
<td>OTM inlet temp.</td>
<td>1050 - 1200 K</td>
</tr>
<tr>
<td>Oxygen sep. ratio</td>
<td>0.2 - 0.6</td>
</tr>
<tr>
<td>OTM outlet HX ΔT</td>
<td>30 - 100 K</td>
</tr>
<tr>
<td>Combustor outlet temp.</td>
<td>1500 - 1600 K</td>
</tr>
<tr>
<td>Steam head. press.</td>
<td>1 - 100, 1 - 50</td>
</tr>
<tr>
<td>Steam head. superheating</td>
<td>100 - 400 bar</td>
</tr>
<tr>
<td>Condensate head. press.</td>
<td>2x 1 - 10, 1x 1 - 100</td>
</tr>
<tr>
<td>ΔT multiplication factor</td>
<td>1 - 3</td>
</tr>
</tbody>
</table>

---

**Some results**

<table>
<thead>
<tr>
<th></th>
<th>Solution A</th>
<th>Solution B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Turb. press. ratio</td>
<td>18</td>
<td>41</td>
</tr>
<tr>
<td>OTM inlet temp.</td>
<td>1200 K</td>
<td>1200 K</td>
</tr>
<tr>
<td>Oxygen sep. ratio</td>
<td>21.8%</td>
<td>31.2%</td>
</tr>
<tr>
<td>OTM outlet HX ΔT</td>
<td>100 K</td>
<td>97 K</td>
</tr>
<tr>
<td>Combustor out. temp.</td>
<td>1600 K</td>
<td>1600 K</td>
</tr>
<tr>
<td>Steam head. press.</td>
<td>101 bar</td>
<td>102 bar</td>
</tr>
<tr>
<td></td>
<td>14 bar</td>
<td>13 bar</td>
</tr>
<tr>
<td></td>
<td>2 bar</td>
<td>1 bar</td>
</tr>
<tr>
<td>Steam head. superh.</td>
<td>357 K</td>
<td>365 K</td>
</tr>
<tr>
<td></td>
<td>311 K</td>
<td>214 K</td>
</tr>
<tr>
<td></td>
<td>283 K</td>
<td>290 K</td>
</tr>
<tr>
<td>Condensate head. press.</td>
<td>0.021 bar</td>
<td>0.020 bar</td>
</tr>
<tr>
<td>ΔT multiplication factor</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Specific Cost</td>
<td>690 US$/kW</td>
<td>1404 US$/kW</td>
</tr>
<tr>
<td>Efficiency</td>
<td>55.1%</td>
<td>62.5%</td>
</tr>
</tbody>
</table>
**Best solution**

- $P = 24.00$
- $T = 1200.00$
- $\dot{E} = 49069.20$
- $\dot{E} = 76519.10$
- $\dot{E} = 673.57$
- $Q = -6537.03$
- $E = 14146.10$

**Integrated composite curves**

- Integrated composite of the steam cycle
- Water condensation
- CHP?
Conclusion

- Multi-objective thermoeconomic optimisation method for preliminary design of advanced power plants
  - Energy conversion by process simulation
  - Fast steam cycle Evaluation
    - Limited data (T,P)
    - MILP process integration technique
    - Thermo-economic evaluation
- Prototyping system design
  - Discover system bottlenecks
  - Adapt steam cycle to the heat profile
  - Multi-streams processes (hybrid systems)
Energy flow model: superstructure

- PEM system modelling (VALI): define the process steps

Fuel processing → Fuel Cell → Post combustion

Heat exchange requirements

To energy integration (EASY)

Energy flow model of subsystems

Fuel processing → Fuel Cell → Post combustion

Fuel processing → Post processing → Cleaning
Subsystems superstructure

- Fuel processing
- Post processing
- Cleaning

Process Alternatives (energy flow level (VALI))

Energy flow model
Energy integration

- Pinch analysis to integrate system:
- Exergy analysis

Objectives: thermo-economic

- Two objectives:
  - Maximum Efficiency
  - Minimum Specific Cost

- Decision variables:
  - Steam to carbon ratio for the steam reforming [2;4]
  - Fuel processing temperature [873;1073]
  - Post Combustion Pressure [3;10]
  - PEM fuel utilization [0.5;0.95]
  - O2/carbon
  - DTmin/2
Pareto curves of PEMFC system design

Multiple solutions = Multiple configurations

Pareto Curve

Specific cost [US/$kW]

POX-a  SMR-a
POX-b  SMR-b
POX-c  SMR-c
POX-d

Efficiency

FP  PP  PROX  PEM  TC  Comb  HTX

Wood to methane conversion

\[ \text{CH}_{0.11}\text{O}_{0.84} + 0.5525 \text{ H}_2\text{O} \rightarrow 0.30375 \text{ CH}_4 + 0.69625 \text{ CO}_2 \]

\[ P = 50 \text{ bar} \]

13.3 < \( W_{s,n} \) < 15.7

**STI**

**ISE**

**Laboratory for Industrial Energy Systems - LENI**

**Marsh 2006**

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**Decision variables**

<table>
<thead>
<tr>
<th>Section</th>
<th>Variable</th>
<th>Intervalle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasification</td>
<td>( \Phi_{\text{w, gazélier}} )</td>
<td>2 – 30 %</td>
</tr>
<tr>
<td>Type</td>
<td>( p_g )</td>
<td>1–10/1–20 bar</td>
</tr>
<tr>
<td></td>
<td>( \Delta T_g )</td>
<td>± 50°C</td>
</tr>
<tr>
<td>Methanation</td>
<td>( T_{\text{p, agent}} )</td>
<td>400°C – ( T_g )</td>
</tr>
<tr>
<td>Number</td>
<td>( p_m )</td>
<td>1 – 50 bar</td>
</tr>
<tr>
<td></td>
<td>( T_{\text{m, entrée}} )</td>
<td>300 – 400°C</td>
</tr>
<tr>
<td></td>
<td>( T_{\text{m, sortie}} )</td>
<td>300 – 400°C</td>
</tr>
<tr>
<td></td>
<td>( r_{\text{H}_2\text{O}} )</td>
<td>0–20/5–30 %</td>
</tr>
<tr>
<td></td>
<td>( r_{\text{H}_2} )</td>
<td>0 – 12 %</td>
</tr>
<tr>
<td>Purification</td>
<td>( \text{div.} )</td>
<td>div.</td>
</tr>
<tr>
<td>Utilities</td>
<td>( T_{\text{p, air}} )</td>
<td>( T_a ) – 900°C</td>
</tr>
<tr>
<td>Steam</td>
<td>( \Delta T_{\text{min, add.}} )</td>
<td>0 – 70°C</td>
</tr>
<tr>
<td>network</td>
<td>( T_{\text{surchauffe}} )</td>
<td>380 – 580°C</td>
</tr>
</tbody>
</table>
Methane

Steam gasification algorithm of electrolysis has been performed by computed analysis for the electrolyser depicted in the figure. The results show that the optimal solution is achieved with electrolysis, which leads to the best electrolysis efficiency, as depicted in the figure. The figure also shows the variation of the electrolysis efficiency with different production rates.

The Pareto curve shows the trade-off between energetic efficiency and total production costs. The optimal solutions with electrolysis are depicted, along with the optimal solutions without electrolysis. The figure also shows the hydrogen addition to best COP and hydrogen addition to best η, as depicted in the figure.

The optimal configurations for the electrolyser are summarized in the table below:

<table>
<thead>
<tr>
<th>Section</th>
<th>Variable</th>
<th>Configuration 1</th>
<th>Configuration 2</th>
<th>Configuration 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasification</td>
<td>Φw</td>
<td>16 %</td>
<td>25 %</td>
<td>22 %</td>
</tr>
<tr>
<td>Technology</td>
<td>Steam</td>
<td>Oxygen</td>
<td>Steam</td>
<td></td>
</tr>
<tr>
<td>pg</td>
<td>1 bar</td>
<td>5.5 bar</td>
<td>4.3 bar</td>
<td></td>
</tr>
<tr>
<td>Tg</td>
<td>825°C</td>
<td>760°C</td>
<td>810°C</td>
<td></td>
</tr>
<tr>
<td>Tp,agent</td>
<td>600°C</td>
<td>600°C</td>
<td>600°C</td>
<td></td>
</tr>
<tr>
<td>Methanation</td>
<td>pm</td>
<td>13 bar</td>
<td>7.8 bar</td>
<td>4.3 bar</td>
</tr>
<tr>
<td></td>
<td>Tm,inlet</td>
<td>395°C</td>
<td>370°C</td>
<td>380°C</td>
</tr>
<tr>
<td></td>
<td>Tm,outlet</td>
<td>345°C</td>
<td>320°C</td>
<td>340°C</td>
</tr>
<tr>
<td></td>
<td>rH2O</td>
<td>15 %</td>
<td>22 %</td>
<td>15 %</td>
</tr>
<tr>
<td></td>
<td>rH2</td>
<td>-</td>
<td>0.24 %</td>
<td>-</td>
</tr>
<tr>
<td>Purification</td>
<td>Technology</td>
<td>PSA</td>
<td>PSA</td>
<td>PSA</td>
</tr>
<tr>
<td>Utilities</td>
<td>Tp,air</td>
<td>600°C</td>
<td>-</td>
<td>600°C</td>
</tr>
<tr>
<td>Steam network</td>
<td>Production</td>
<td>100 bar</td>
<td>-</td>
<td>80 bar</td>
</tr>
<tr>
<td></td>
<td>Tsurperheating</td>
<td>550°C</td>
<td>-</td>
<td>420°C</td>
</tr>
</tbody>
</table>
**Process integration**

Nominal power = 20 MWth
Integration of the steam network

**Configuration 3**

\[ P_{\text{GWS}}^- = 16.3 \text{MW}_{\text{th}} \]
\[ P_{\text{el}}^- = 0.2 \text{MW}_{\text{el}} \]
\[ \eta = 66.2\% \]

**Configuration 1**

\[ P_{\text{GWS}}^- = 15.5 \text{MW}_{\text{th}} \]
\[ P_{\text{el}}^- = 0.9 \text{MW}_{\text{el}} \]
\[ \eta = 65.7\% \]

**Correlation analysis along Pareto**

- additional H2

\[ \rho(X, Y) = \frac{E((X - \mu_x)(Y - \mu_y))}{\sigma_x \sigma_y} \]

<table>
<thead>
<tr>
<th>( \mu )</th>
<th>239°C</th>
<th>7.61%wt</th>
<th>7.58°C</th>
<th>531°C</th>
<th>5.38bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{\text{Gin}} )</td>
<td>( \phi_{\text{b, out}} )</td>
<td>Tg</td>
<td>( \rho_{\text{in}} )</td>
<td>T(_{\text{min}})</td>
<td>T(_{\text{out}})</td>
</tr>
</tbody>
</table>

Figure 3: Correlation of decision variables and \( \rho_{\text{H2}} \).
Sensitivity analysis: Economy of scale

\[ C_{GR} = C_{GR,0} \left( \frac{P_{el}}{P_{th,0}} \right)^{\text{exp}} \]

Sizes are handled only in phase 3: sizing and costing

Sensitivity analysis: Cost of energy

<table>
<thead>
<tr>
<th>producers</th>
<th>consumers</th>
<th>transport fuel</th>
<th>transport fuel with carbon tax (20 €/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>profit = 200 €/h</td>
<td>400 €/h</td>
<td>600 €/h</td>
<td>800 €/h</td>
</tr>
<tr>
<td>1000 €/h</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Swiss market

- wind
- nuclear
- base load operation of electrolysis
- electrolysis for O₂ production
- intermediate solutions
- unprofitable process

Gas price [€/MWh\(_{\text{SNG}}\)]

Electricity cost [€/MWh\(_{el}\)]
Conclusions

- 3 Steps thermo-economic model
  - energy flow
  - process integration
  - sizing and cost estimation
- Multi-objective optimisation
  - Thermodynamic performance
  - Economic performance
- Sensitivity analysis
  - Numerical results -> solutions
  - new problem?

Limitations of the proposed approach

- Detailed design?
  - use simulation
- Retrofit
  - use of existing equipments instead of thermodynamic target and sizing
  - adapt the models (? equation solvers)
- Multi-period systems
  - optimal operation
- Multi-scale models
  - CFD?
Examples credits

- **PEMFC system design**

- **Zero emission Power plants**

- **Power plants**
  - H. Li, F. Marechal, M. Buerer, and D. Favrat. Multi-objective optimization of an advanced combined cycle power plant including CO₂ separation options. *Accepted for publication in Energy, the international journal*, 2006.

- **Wood to methane process**