COMBINED EXERGY AND PINCH ANALYSIS FOR OPTIMAL ENERGY CONVERSION TECHNOLOGIES INTEGRATION

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Content
- Process integration technique
- Minimum energy requirement
  - Exergy analysis
  - Process integration
- Integration of the energy conversion system
  - Analyse the energy requirement
  - Heat pumps
  - Combined heat and power
- Optimal integration
- Graphical representation
- Results
Process integration vs system

- Environment
  - Air
  - Energy
  - Water - solvent

- Raw materials

- Processes
  - Energy Transformation
  - Production support

- Waste treatment
  - Waste heat
  - Emissions
  - Water
  - Solids

- Energy
  - Products
  - By-products

Process integration

- Hot & cold composite curves
  - Minimum energy requirement
    - Hot
    - Cold
    - Refrigeration
    - Heat recovery

- Q (kW)
- T (K)
- DTmin/2
- DTmin/2
- 1709 kW
- 6948 kW
- 13343 kW
- 6854 kW
- Hot utility
- Heat recovery
Carnot composite curves

Table 3
Exergy of the hot and cold process composite curves

<table>
<thead>
<tr>
<th>Energy</th>
<th>Exergy Total</th>
<th>Exergy $\Delta T_{\text{min}}$ corrected</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot streams [kW]</td>
<td>20291.0</td>
<td>5521.4</td>
<td>$\dot{E}_{\text{hot},a}$</td>
</tr>
<tr>
<td>below $T_0$ [kW]</td>
<td>1709.0</td>
<td>131.5</td>
<td>$\dot{E}_{\text{hot},r}$</td>
</tr>
<tr>
<td>Cold streams [kW]</td>
<td>20197.0</td>
<td>4599.3</td>
<td>$\dot{E}_{\text{cold},a}$</td>
</tr>
<tr>
<td>below $T_0$ [kW]</td>
<td>0.0</td>
<td>0.0</td>
<td>$\dot{E}_{\text{cold},r}$</td>
</tr>
<tr>
<td>$\Delta T_{\text{min}}$ losses [kW]</td>
<td>-</td>
<td>381.2</td>
<td></td>
</tr>
</tbody>
</table>
Requirements

Table 2
Minimum energy and exergy requirements of the process

<table>
<thead>
<tr>
<th>Name</th>
<th>Energy</th>
<th>Exergy</th>
<th>Balance [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating [kW]</td>
<td>+6854</td>
<td>+567</td>
<td>-550</td>
</tr>
<tr>
<td>Cooling [kW]</td>
<td>-7145</td>
<td>-1269</td>
<td></td>
</tr>
<tr>
<td>Refrigeration [kW]</td>
<td>+1709</td>
<td>+157</td>
<td></td>
</tr>
</tbody>
</table>
Exergy requirement above the pinch point

Exergy by combustion

Exergy requirement above the pinch point
**Exergy composite Heat exchange losses**

- Exergy loss combustion
- Exergy loss - Heat exchange
- Exergy requirement

**Exergy composite -self-sufficient pockets**

- Exergy loss combustion
- Exergy loss - Heat exchange
- Exergy requirement
**CHP: define the steam network**

\[
\dot{E} = \dot{q}_e \left( \frac{T_v - T_c}{\eta_e} - (T_v - T_c) \right) = \frac{A}{T_v - (T_v - T_c)}
\]

**Fuel consumption**

\[
\dot{m}_{fuel} \times LHV_{fuel} = \dot{Q}_{MER} + \sum_{i=1}^{n_{CHP}} \dot{E}_i
\]

---

**Integration of the energy conversion system**

**Technology w with nominal flow**

- Hot/cold streams
  - \( T_{w,i}^{in}, P_{w,i}^{in}, \dot{m}_{w,i}, x_{w,i} \)
  - \( q_w = \dot{m}_{w,i} (h_{w,i}^{in} - h_{w,i}^{out}) \)
  - \( T_{w,i}^{out}, P_{w,i}^{out}, \dot{m}_{w,i}, x_{w,i} \)

**Mechanical power/electricity**

- \( e_w \)

**Costs**

- \( C1_w, C2_w, C11_w, C12_w \)

**Decision variables**

- Level of usage of w
  - \( f_w \)
  - \( y_w \)

**Creative engineers?**
MILP formulation

\[
\begin{align*}
\min & \quad R_T, y_w, f_w, E^+, E^- \\
\text{Subject to:} & \quad \text{Heat cascade constraints} \\
& \quad \sum_{w=1}^{n_w} f_w y_{w,r} + \sum_{s=1}^{n_s} q_{s,r} + R_{r+1} - R_r = 0 \quad \forall r = 1, \ldots, n_r \\
& \quad \text{Feasibility} \quad R_r \geq 0 \quad \forall r = 1, \ldots, n_r; R_{n_r+1} = 0; R_1 = 0 \quad E^+ \geq 0; E^- \geq 0 \\
& \quad \text{Electricity consumption} \quad \sum_{w=1}^{n_w} f_w e_w + E^+ - E^- \geq 0 \\
& \quad \text{Electricity production} \quad \sum_{w=1}^{n_w} f_w e_w + E^+ - E^- = 0 \\
& \quad \text{Energy conversion Technology selection} \quad f_{min,w} y_w \leq f_w \leq f_{max,w} y_w \\
& \quad y_w \in \{0, 1\}
\end{align*}
\]

Application

Maximum energy recovery

<table>
<thead>
<tr>
<th>Energy</th>
<th>Exergy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating (kW)</td>
<td>+6854 +567</td>
</tr>
<tr>
<td>Cooling (kW)</td>
<td>-6948 -1269</td>
</tr>
<tr>
<td>Refrigeration (kW)</td>
<td>+1709 +157</td>
</tr>
</tbody>
</table>

Hot utility

- Boiler house: NG (44495 kJ/kg)
- Air Preheating
- Gas turbine: NG (el. eff = 32%)

Steam cycle

<table>
<thead>
<tr>
<th>Header</th>
<th>P (bar)</th>
<th>T (K)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP2</td>
<td>92</td>
<td>793</td>
<td>superheated</td>
</tr>
<tr>
<td>HP1</td>
<td>39</td>
<td>707</td>
<td>superheated</td>
</tr>
<tr>
<td>HPU</td>
<td>32</td>
<td>510</td>
<td>condensation</td>
</tr>
<tr>
<td>MPU</td>
<td>7.66</td>
<td>442</td>
<td>condensation</td>
</tr>
<tr>
<td>LPU2</td>
<td>4.28</td>
<td>419</td>
<td>condensation</td>
</tr>
<tr>
<td>LPU3</td>
<td>2.59</td>
<td>402</td>
<td>condensation</td>
</tr>
<tr>
<td>DEA</td>
<td>1.29</td>
<td>380</td>
<td>condensation</td>
</tr>
</tbody>
</table>

Heat pumps

- Fluid R123

Refrigeration

- Refrigerant: R717 Ammonia
- Reference flowrate: 0.1 kmol/s
- Mechanical power: 394 kW

<table>
<thead>
<tr>
<th>P (bar)</th>
<th>T_W (K)</th>
<th>Q (kW)</th>
<th>ΔT min/2 (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>340</td>
<td>304</td>
<td>2274</td>
</tr>
<tr>
<td>3</td>
<td>264</td>
<td>264</td>
<td>1880</td>
</tr>
</tbody>
</table>
Consider exergy losses

- New objective function

\[ \text{Min}_w \sum_{w=1}^{n_w} \sum_{r=1}^{n_w} \left( f_w \cdot \left( \hat{E}^+_{w,r} - \hat{E}^-_{w,r} \right) - \Delta T_{\text{min}} \right) \]

- Thermal exergy:

\[ (\hat{E}^-_{w,r}) \Delta T_{\text{min}} = \sum_{s=1}^{n_s} \hat{Q}^-_{s,r} \cdot (1 - \frac{T_0 \cdot \ln(\frac{T_{r+1}}{T_r})}{T_{r+1} - T_r}) \]

- Chemical Exergy:

\[ \hat{E}^+_{w} = \sum_{f=1}^{n_{f,\text{fuel}}} \hat{M}_{f,w} \Delta h_f^0 \]

- Work:

\[ \hat{E}^-_{w} \]

Table 7

<table>
<thead>
<tr>
<th>Technology</th>
<th>Service</th>
<th>( \sum_{r=1}^{n_r} \hat{E}^-_{w,r} )</th>
<th>( \sum_{r=1}^{n_r} \hat{E}^+_{w,r} )</th>
<th>( \Delta T_{\text{min}} )</th>
<th>( \Delta T_{\text{max}} )</th>
<th>( \hat{E}^-_{w} )</th>
<th>( \hat{E}^+_{w} )</th>
<th>( \hat{L}_{w} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas turbine</td>
<td>Hot stream</td>
<td>485.72</td>
<td>481.05</td>
<td>-4.67</td>
<td>1160.3</td>
<td>3228.98</td>
<td>1587.63</td>
<td></td>
</tr>
<tr>
<td>Heat pump 1</td>
<td>Hot stream</td>
<td>48.91</td>
<td>40.14</td>
<td>-8.77</td>
<td>63.08</td>
<td>0</td>
<td>22.94</td>
<td></td>
</tr>
<tr>
<td>Heat pump 2</td>
<td>Hot stream</td>
<td>64.09</td>
<td>55.89</td>
<td>-8.2</td>
<td>84.77</td>
<td>0</td>
<td>28.88</td>
<td></td>
</tr>
<tr>
<td>Heat pump 3</td>
<td>Hot stream</td>
<td>27.55</td>
<td>18.83</td>
<td>-8.72</td>
<td>34.72</td>
<td>0</td>
<td>15.89</td>
<td></td>
</tr>
<tr>
<td>Refrigeration</td>
<td>Cold stream</td>
<td>158.23</td>
<td>141.96</td>
<td>-16.27</td>
<td>209.59</td>
<td>0</td>
<td>67.63</td>
<td></td>
</tr>
</tbody>
</table>
### Results

<table>
<thead>
<tr>
<th>Opt</th>
<th>Fuel LHV $kW_e$</th>
<th>GT $kW_e$</th>
<th>CHP $kW_e$</th>
<th>Cooling $kW_e$</th>
<th>HP $kW_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7071</td>
<td>-</td>
<td>-</td>
<td>8979</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>10086</td>
<td>2957</td>
<td>9006</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>16961</td>
<td>5427</td>
<td>2262</td>
<td>9160</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2800</td>
<td>485</td>
</tr>
<tr>
<td>5</td>
<td>666</td>
<td>-</td>
<td>738</td>
<td>2713</td>
<td>496</td>
</tr>
</tbody>
</table>

- **HP1**: 34 kWe
- **HP2**: 323 kWe
- **HP3**: 129 kWe

#### Share between heat pumps

Balanced composite curves (option 5)

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**Laboratory for Industrial Energy Systems**
LENI - ISE - STI - EPFL
Fig. 8. Integrated composite curves of the heat pumps
Integrated composite curve: steam network

Visualising the results: Carnot efficiency

Tricks for creative engineers: reduce the green area!
Carnot integrated composite curves

Comparing results

- Energy efficiency
  - NGCC equivalence of electricity
    \[ \text{Total1} = \dot{m}_{\text{fuel}} \times \text{LHV}_{\text{fuel}} + \frac{(E^+ - E^-)}{\eta_{el}} = 55\% (\text{NGCC}) \]
  - EU mix for electricity
    \[ \text{Total2} = \dot{m}_{\text{fuel}} \times \text{LHV}_{\text{fuel}} + \frac{(E^+ - E^-)}{\eta_{el}} = 38\% (\text{EU mix}) \]
  - Exergy efficiency
    \[ \eta_{ex} = \frac{\dot{E}_{\text{cold}} + \dot{E}_{\text{hot}} + \dot{E}_{\text{grid}}^{-}}{\dot{E}^{+} + \dot{E}_{\text{cold}} + \dot{E}_{\text{hot}}} \] with
    \[ \dot{E}^{+} = \sum_{\text{fuel}=1}^{n_{\text{fuels}}} \dot{M}_{\text{fuel}}^{+} \Delta k_{\text{fuel}}^{0} + \dot{E}_{\text{grid}}^{+} \]
    \[ \dot{L} = (1 - \eta_{ex}) (\dot{E}^{+} + \dot{E}_{\text{cold}} + \dot{E}_{\text{hot}}) \]
Results

\[ \text{Total1} = \dot{m}_{\text{fuel}} \cdot LHV_{\text{fuel}} + \frac{(E^+ - E^-)}{\eta_{el}} (= 55\% (\text{NGCC})) \]

\[ \text{Total2} = \dot{m}_{\text{fuel}} \cdot LHV_{\text{fuel}} + \frac{(E^+ - E^-)}{\eta_{el}} (= 38\% (\text{EUmix})) \]

Table 9

<table>
<thead>
<tr>
<th>Option</th>
<th>Fuel</th>
<th>( E^+_{\text{grid}} )</th>
<th>Total 1 [kW_LHV]</th>
<th>Total 2 [kW_LHV]</th>
<th>( \eta_{ex} )</th>
<th>Losses [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comb. + frg</td>
<td>7071.0</td>
<td>371</td>
<td>7745.5</td>
<td>8029.7</td>
<td>34.9</td>
<td>8868.0</td>
</tr>
<tr>
<td>Comb. + stm + frg</td>
<td>10086.0</td>
<td>-2481.0</td>
<td>5575.1</td>
<td>3675.1</td>
<td>44.5</td>
<td>8830.0</td>
</tr>
<tr>
<td>GT + stm + frg</td>
<td>16961.0</td>
<td>-7195.0</td>
<td>3879.2</td>
<td>-1630.7</td>
<td>51.3</td>
<td>11197.2</td>
</tr>
<tr>
<td>hpmp + frg</td>
<td>0.0</td>
<td>832.0</td>
<td>1512.7</td>
<td>2149.9</td>
<td>72.4</td>
<td>2408.1</td>
</tr>
<tr>
<td>hpmp + stm + frg</td>
<td>666.0</td>
<td>125.0</td>
<td>893.3</td>
<td>989.0</td>
<td>72.6</td>
<td>1831.6</td>
</tr>
</tbody>
</table>

Sensitivity of the grid electricity mix

![Graph showing sensitivity of the grid electricity mix](image)
Exergy losses of the options

Energy conversion system configurations

Fig. 6. Exergy losses of the different options

Share of the exergy losses

Energy conversion system configurations

Fig. 7. Share of the exergy losses in the different options
Conclusions

- Energy conversion system integration
  - Satisfy the process requirement with minimum resources
  - Valorise the available process exergy
- Combined exergy - Process integration
  - Analyse the requirements
  - Opportunities for energy conversion integration (Carnot composite)
  - Type of technologies
  - Generate optimal integrated systems
    - MILP method
    - Exergy objective
  - Evaluate & compare solutions
    - Graphical representations: Carnot composite & area
    - Integrated composite curves
    - Exergy efficiency wrt minimum process exergy requirement (+&-)

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