Techno-Economic Analysis of Waste Heat Recovery with ORC from Fluctuating Heat Sources

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Outline

1. Waste heat from Heavy Industry
2. Waste Heat Fluctuations
3. Modelling and Methods
4. Results
5. Summary and outlook
1. Waste heat from industrial processes

Definition: “Waste heat is thermal energy (or heat), which is not used for the primary purpose of converting the raw material into a product.”

Industrial waste heat can amount up to 70% of the industrial demand of a country (Canada)

EU27: 2708 PJ/a (9.1-22.2% industrial consumption)
Germany: 218-566 PJ/a (~12-30%)

Figure: Miro, 2015.
1. Waste heat from industrial processes

Definition: “Waste heat is thermal energy (or heat), which is not used for the primary purpose of converting the raw material into a product.”

The available waste heat can be computed from:

\[ \dot{Q} = \dot{m} c_p (T - T_{ref}) \]

Most important sectors:
- Cement
- Steel
- Non-ferrous metal (aluminium)
- Glass
- Chemicals

Figure: Hammond, 2014.
1. Where does waste heat come from?

Rolling mill hot reheating furnace. Figure: De Freitas, 2014.

Waste heat 400°C
2. Heat source fluctuations

**Cement industry**
- Fluctuating temperature
  - Profile: Legmann, 2002.

**Steel: hot rolling mill**
- Fluctuating mass flow rate

**Steel: electric arc furnace**
- Fluctuating temperature
- Fluctuating mass flow rate
  - Profile: Brandt, 2014.

How should I design my system?
2. Design dilemma

For design $\rightarrow$ classical approach: fixed load point (classical nuclear plants for base-load)
Relatively easy, design based on single point

If the system operates for long-time in off-design (common ICE for vehicles, wind)
A trade-off has to be found

Figure: Zhang, 2013
3. Proposed procedure

Main parts:
- Design
- Off-design
- Economics
3. Off-design of ORC systems

When the load drops, the components are not working any more in the optimal point.

Correlations curves for off-design

Comparison with real system (qualit.)

3. Off-design of ORC systems

When the load drops, the components are not working any more in the optimal point
3. Techniques to convert fluctuations in temperature into fluctuations in mass flow rate

Temperature drops $\rightarrow$ lower Carnot efficiency
Additional components
But…
…better part-load
3. Storage options


Sensible

Latent
3. Economic model

Based on Turton (-25%/+40%), already used in several publications for ORCs

Correlations for costs related to heat exchanger areas, turbine power, pump power, etc. Corrections for pressure and material
3. Important figures

Electricity produced: \[ E_k = \bar{P}_k \Delta t \]

CO₂-savings: \[ CO_2S = f \ E_k \]
\[ f = 535 \text{ tCO}_2/\text{kWh in Germany (source: Statista, 2016)} \]

Levelized cost of electricity:
- interest rate i 4%
- number of cash flows N (10)
\[ LCOE = \frac{\sum_{k=1}^{N} \frac{C_k}{(1 + i)^k} + C_0}{\sum_{k=1}^{N} \frac{E_k}{(1 + i)^k}} \]

1. No costs for fuel
2. Independent from electricity price!
4. Results – Cement clinker (cooling air)

Lowest LCOE: Latent heat buffer
Highest CO$_2$-savings: Latent heat buffer
4. Results – Hot rolling mill

Lowest LCOE: Design for minimum source mass flow rate (rest bypassed)

Highest CO₂-savings: 75% CPD of source mass flow rate
4. Results – Electric Arc Furnace

Lowest LCOE: Latent heat buffer or direct evaporation (T50%M100%)
Highest CO$_2$-savings: Latent heat buffer
5. Summary

A techno-economic procedure for the design and analysis of ORCs subjected to fluctuating heat sources has been developed.

The model is based on thermodynamic optimization tools, investment cost estimation and correlation for ORC off-design behavior.

Different configurations with and without storage were analysed.

Temperature fluctuations affect more the performance of the ORC and cannot be easily bypassed.

No storage and simple bypass appears the most economic solution for fluctuating mass flow rate.

For fluctuating temperature, the latent heat buffer appeared a good solution both for the economic and the environmental performance of the waste heat recovery systems.
5. Future outlook

Analysis of additional profiles

More in-depth models of heat exchangers

Comparison of different working fluids in off-design

Development of dynamic models

Analysis of different control strategies
6. References


**De Freitas, 2014.** De Freitas Pereira Marques M W. Potential for ORC Application in the Portuguese Manufacturing Industry. Faculty of Science and Technology, New University of Lisbon, 2014.


Thank you very much for your attention.
Assumptions – Thermodynamic design

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Unit</th>
<th>Value</th>
<th>Quantity</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. heat source temperature</td>
<td>[°C]</td>
<td>150</td>
<td>Turbine efficiency</td>
<td>[%]</td>
<td>75</td>
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<tr>
<td>Pinch-point</td>
<td>[K]</td>
<td>10</td>
<td>Generator efficiency</td>
<td>[%]</td>
<td>97</td>
</tr>
<tr>
<td>Pump efficiency</td>
<td>[%]</td>
<td>70</td>
<td>Recuperator effectiveness*</td>
<td>[%]</td>
<td>80</td>
</tr>
<tr>
<td>Pump motor efficiency</td>
<td>[%]</td>
<td>85</td>
<td>Condensation temperature</td>
<td>[°C]</td>
<td>30</td>
</tr>
</tbody>
</table>

*When used (for water, set to zero)

Output: evaporation pressure and superheating at nominal point
Design

Flue gas

1) Possible design point

Rolling mill Reheating furnace

2-3) Pressure, temperature

4) Pinch-Point

7) Pinch-Point

5-6) Pinch-Point + Condensing temperature
Assumptions for heat storage

<table>
<thead>
<tr>
<th>Storage</th>
<th>Heat source</th>
<th>Medium</th>
<th>Temperatures (°C)</th>
<th>Quantity (t)</th>
<th>ORC working fluid</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-tank</td>
<td>Clinker cooling air</td>
<td>Therminol VP-1</td>
<td>220/92.5*</td>
<td>159.07</td>
<td>Pentane</td>
<td>If source temp. &lt; 230°C, source bypass</td>
</tr>
<tr>
<td></td>
<td>Flue gas HRF</td>
<td>Therminol VP-1</td>
<td>370/92.5*</td>
<td>17.87</td>
<td>Toluene</td>
<td></td>
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<tr>
<td></td>
<td>Flue gas EAF</td>
<td>HITEC®</td>
<td>400/225*</td>
<td>10.80</td>
<td>Toluene</td>
<td>If source temp. &lt; 410°C, source bypass</td>
</tr>
<tr>
<td>Single tank</td>
<td>Clinker cooling air</td>
<td>Therminol VP-1</td>
<td>variable</td>
<td>1000</td>
<td>Pentane</td>
<td></td>
</tr>
<tr>
<td>Latent heat buffer</td>
<td>Clinker cooling air</td>
<td>LiNO₃</td>
<td>254</td>
<td>70.44</td>
<td>MM</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flue gas EAF</td>
<td>50wt-NaCl/50-wt MgCl₂</td>
<td>450</td>
<td>9.96</td>
<td>Toluene</td>
<td></td>
</tr>
</tbody>
</table>

(*temperature given as A/B: A: high temperature tank/B: low temperature tank)
Design data

Table A1. Thermodynamic optimization at design point (CC = Clinker Cooling, HRF = Hot Reheating Furnace, EAF = Electric Arc Furnace).

<table>
<thead>
<tr>
<th>Case</th>
<th>Heat source temperature (°C)</th>
<th>Heat source mass flow rate (kg/s)</th>
<th>Working fluid</th>
<th>Turbine inlet temperature (°C)</th>
<th>Evaporation pressure (bar)</th>
<th>Condensation pressure (bar)</th>
<th>Electrical efficiency (%)</th>
<th>Net power output (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC 25%</td>
<td>237.1</td>
<td>53.9</td>
<td>Pentane</td>
<td>221.9</td>
<td>26.96</td>
<td>0.82</td>
<td>21.16</td>
<td>1017.9</td>
</tr>
<tr>
<td>CC 50%</td>
<td>254.8</td>
<td>53.9</td>
<td>MM</td>
<td>211.6</td>
<td>9.59</td>
<td>0.07</td>
<td>21.54</td>
<td>1246.7</td>
</tr>
<tr>
<td>CC 75%</td>
<td>277.1</td>
<td>53.9</td>
<td>MM</td>
<td>234.5</td>
<td>14.02</td>
<td>0.07</td>
<td>22.69</td>
<td>1598.6</td>
</tr>
<tr>
<td>CC Max</td>
<td>328.1</td>
<td>53.9</td>
<td>MM</td>
<td>259.6</td>
<td>15.51</td>
<td>0.07</td>
<td>23.49</td>
<td>2331.0</td>
</tr>
<tr>
<td>CC oil loop</td>
<td>220.0*</td>
<td>40.4*</td>
<td>Pentane</td>
<td>143.9</td>
<td>11.82</td>
<td>0.82</td>
<td>15.63</td>
<td>1554.0</td>
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<tr>
<td>CC Air inj.</td>
<td>220.0</td>
<td>82.5</td>
<td>Pentane</td>
<td>209.6</td>
<td>11.42</td>
<td>0.82</td>
<td>19.61</td>
<td>1156.1</td>
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<tr>
<td>CC latent</td>
<td>264.0</td>
<td>53.9</td>
<td>MM</td>
<td>219.6</td>
<td>10.90</td>
<td>0.07</td>
<td>21.91</td>
<td>1383.5</td>
</tr>
<tr>
<td>CC Two Tank</td>
<td>220.0*</td>
<td>23.1*</td>
<td>Pentane</td>
<td>210.0</td>
<td>11.83</td>
<td>0.82</td>
<td>15.81</td>
<td>898.9</td>
</tr>
<tr>
<td>CC Single Tank</td>
<td>214.1*</td>
<td>15.7*</td>
<td>Pentane</td>
<td>161.1</td>
<td>18.15</td>
<td>0.82</td>
<td>17.21</td>
<td>825.2</td>
</tr>
</tbody>
</table>

*Refer to heat source as oil/storage heat carrier
### Design data

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<tr>
<th>Case</th>
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<th>Working fluid</th>
<th>Turbine inlet temperature (°C)</th>
<th>Evaporation pressure (bar)</th>
<th>Condensation pressure (bar)</th>
<th>Electrical efficiency (%)</th>
<th>Net power output (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRF Min</td>
<td>403.5</td>
<td>2.5</td>
<td>Toluene</td>
<td>328.0</td>
<td>33.01</td>
<td>0.05</td>
<td>29.37</td>
<td>260.8</td>
</tr>
<tr>
<td>HRF 25%</td>
<td>403.5</td>
<td>4.5</td>
<td>Toluene</td>
<td>328.0</td>
<td>33.01</td>
<td>0.05</td>
<td>29.37</td>
<td>367.6</td>
</tr>
<tr>
<td>HRF 50%</td>
<td>403.5</td>
<td>5.6</td>
<td>Toluene</td>
<td>328.0</td>
<td>33.01</td>
<td>0.05</td>
<td>29.37</td>
<td>436.8</td>
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<tr>
<td>HRF 75%</td>
<td>403.5</td>
<td>7.0</td>
<td>Toluene</td>
<td>328.0</td>
<td>33.01</td>
<td>0.05</td>
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<td>541.8</td>
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<tr>
<td>HRF Max</td>
<td>403.5</td>
<td>9.5</td>
<td>Toluene</td>
<td>328.0</td>
<td>33.01</td>
<td>0.05</td>
<td>29.37</td>
<td>738.8</td>
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<tr>
<td>HRF Two Tank</td>
<td>370.0*</td>
<td>2.5*</td>
<td>Toluene</td>
<td>238.3</td>
<td>14.06</td>
<td>0.05</td>
<td>24.81</td>
<td>368.9</td>
</tr>
</tbody>
</table>

*Refer to heat source as oil/storage heat carrier
### Design data

Table A1. Thermodynamic optimization at design point (CC = Clinker Cooling, HRF = Hot Reheating Furnace, EAF = Electric Arc Furnace).

<table>
<thead>
<tr>
<th>Case</th>
<th>Oil hot temperature (°C)</th>
<th>Oil mass flow rate (kg/s)</th>
<th>Working fluid</th>
<th>Turbine inlet temperature (°C)</th>
<th>Evaporation pressure (bar)</th>
<th>Condensation pressure (bar)</th>
<th>Electrical efficiency (%)</th>
<th>Net power output (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EAF 360/220 best</td>
<td>360</td>
<td>22.0</td>
<td>Toluene</td>
<td>344.9</td>
<td>13.54</td>
<td>0.05</td>
<td>24.77</td>
<td>826.2</td>
</tr>
<tr>
<td>EAF Two Tank</td>
<td>400</td>
<td>9.4</td>
<td>Toluene</td>
<td>352.7**</td>
<td>33.01</td>
<td>0.05</td>
<td>29.99</td>
<td>772.7</td>
</tr>
<tr>
<td>EAF Latent 230</td>
<td>460.0</td>
<td>22.3</td>
<td>Toluene</td>
<td>353.1**</td>
<td>33.00</td>
<td>0.05</td>
<td>30.37</td>
<td>1646.1</td>
</tr>
<tr>
<td>EAF Latent 150</td>
<td>460.0</td>
<td>22.3</td>
<td>Toluene</td>
<td>345.9</td>
<td>33.01</td>
<td>0.05</td>
<td>30.10</td>
<td>2177.4</td>
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<tr>
<td>EAF Air 230</td>
<td>450.0</td>
<td>37.8</td>
<td>Toluene</td>
<td>344.9</td>
<td>33.01</td>
<td>0.05</td>
<td>29.77</td>
<td>3531.2</td>
</tr>
<tr>
<td>EAF Air 150</td>
<td>450.0</td>
<td>37.8</td>
<td>Toluene</td>
<td>351.5**</td>
<td>33.00</td>
<td>0.05</td>
<td>30.02</td>
<td>2632.1</td>
</tr>
</tbody>
</table>

**Higher than the limit of 350° C, because of small tolerances in the code (error within 1%).**
Economic assumptions

Interest rate $i = 4\%$
Number of years $= 10$
Load hours 7000 h/y (EAF), 8000 h/y (cement, HRF)

<table>
<thead>
<tr>
<th>Heat exchanger</th>
<th>Type</th>
<th>Material</th>
<th>$U$ (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat source/oil</td>
<td>U-tube</td>
<td>CS</td>
<td>80</td>
</tr>
<tr>
<td>Oil/evaporator</td>
<td>U-tube</td>
<td>CS</td>
<td>600</td>
</tr>
<tr>
<td>Heat source/evaporator</td>
<td>U-tube</td>
<td>CS</td>
<td>80</td>
</tr>
<tr>
<td>Recuperator</td>
<td>U-tube</td>
<td>CS</td>
<td>200</td>
</tr>
<tr>
<td>Condenser</td>
<td>Air cooler</td>
<td>CS</td>
<td>80</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump</td>
<td>Centrifugal pump</td>
<td>CS</td>
</tr>
<tr>
<td>Turbine</td>
<td>Axial gas turbine</td>
<td>CS</td>
</tr>
<tr>
<td>Compressor</td>
<td>Centrifugal fan</td>
<td>CS</td>
</tr>
<tr>
<td>Tank</td>
<td>API – fixed roof</td>
<td>CS (Process vessel)</td>
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</tbody>
</table>
## Economic assumptions

<table>
<thead>
<tr>
<th>Material</th>
<th>Type</th>
<th>Unit</th>
<th>Cost</th>
<th>Quantity Type</th>
<th>Unit</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Therminol VP-1</td>
<td>Sensible</td>
<td>[€/kg]</td>
<td>1.60</td>
<td>LiNO₃</td>
<td>[€/kg]</td>
<td>8.00</td>
</tr>
<tr>
<td>HITEC® Heat Transfer Salt</td>
<td>Sensible</td>
<td>[€/kg]</td>
<td>0.74</td>
<td>50wt-NaCl / 50-wt MgCl₂</td>
<td>[€/kg]</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Pipe: 92.22 €/m  
USD/EUR = 1.25
Investment Cement

![Investment Bar Chart for Cement](image-url)
Investment Rolling mill

Investment [Mio. €]

Min 25% 50% 75% Max TwoTank
Investment EAF

![Investment costs (Mio. €) graph]

- **T100M100**
- **T75M100**
- **T50M100**
- **T100M75**
- **T75M75**
- **T50M75**
- **T100M50**
- **T75M50**
- **T50M50**

- **360/220**
- **360/140**
EAF oil loop temperature: 360/220°C-340/150°C

![Graph showing LCOE and CO2 savings](image-url)