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Fig. 1. Waste water treatment plant configuration and reconciled operational data.
Fig. 2. Distributed and micro CHP systems’ life cycle phases and processing steps for comparative LCA.
GWP -836.17 kg CO₂ equivalent

- AD plant construction: 0.23%
- Digested matter application in agriculture: -31.57%
- Biogas production: -68.67%

AP 0.076 kg SO₂ equivalent

- Digested matter application in agriculture: 93.42%
- AD plant construction: 6.58%
- Biogas production: 0%
**EP 2.479 kg Phosphate equivalent**

- AD plant construction: 0.081%
- Biogas production: 0%
- Digested matter application in agriculture: 99.919%

**ODP 1.047 × 10^{-7} kg CFC equivalent**

- AD plant construction: 100%
- Biogas production: 0%
- Digested matter application in agriculture: 0%
FAETP 23.609 kg DCB equivalent

- AD plant construction: 2.8%
- Biogas production: 0%
- Digested matter application in agriculture: 97.2%

HTP 136.367 kg DCB equivalent

- AD plant construction: 1.53%
- Biogas production: 0%
- Digested matter application in agriculture: 98.47%
**MAETP 20870 kg DCB equivalent**

- AD plant construction: 4.95%
- Digested matter application in agriculture: 95.05%
- Biogas production: 0%

**POCP 7.214 \times 10^{-3} \text{ kg ethylene equivalent}**

- AD plant construction: 11.812%
- Digested matter application in agriculture: 0%
- Biogas production: 88.188%
Fig. 3. Primary impact characterisations: comparison between individual processes in the biogas to grid system on the basis of 11340 MJ biogas production. CFC: Chlorofluorocarbon; DCB: 1,4 Dichlorobenzene. Both embedded and operational impacts are included.
AD plant infrastructure | Digested matter application to agriculture | Biogas production | Biogas combustion in PEMFC | Total
--- | --- | --- | --- | ---
1.96 | -263.95 | -574.18 | 634.18 | -836.17

GWP in kg CO\(_2\) equivalent

AP in kg SO\(_2\) equivalent

POCP in kg ethylene equivalent

PEMFC cradle to grave system

**Fig. 4.** GWP, AP and POCP: comparison between individual processes in the PEMFC cradle to grave micro-generation system on the basis of 11340 MJ biogas production and processing. The x-axis shows the processing steps, thus the hotspot in each category.
Fig. 5. Summary of environmental performance comparison results of sewage sludge products.

<table>
<thead>
<tr>
<th>Cradle to grave system</th>
<th>Avoided emissions by</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GWP, kg CO₂ Eq.</td>
<td>AP, kg SO₂ Eq.</td>
<td>POCP, kg Ethylene-Eq.</td>
</tr>
<tr>
<td>Biogas grid, per MJ</td>
<td>0.0793</td>
<td>4.47×10⁻⁴</td>
<td>6.59×10⁻⁶</td>
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<tr>
<td>Biogas – PEMFC, per MJ</td>
<td>0.1200</td>
<td>7.57×10⁻⁴</td>
<td>1.11×10⁻⁵</td>
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<tr>
<td>Biogas – SOFC, per MJ</td>
<td>0.0951</td>
<td>5.18×10⁻⁴</td>
<td>7.65×10⁻⁶</td>
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<tr>
<td>Biogas – SOFC-GT, per MJ</td>
<td>0.0916</td>
<td>4.59×10⁻⁴</td>
<td>7.20×10⁻⁶</td>
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<td>Biogas – Micro GT, per MJ</td>
<td>0.0982</td>
<td>4.26×10⁻⁴</td>
<td>7.64×10⁻⁶</td>
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<td>DM, per kg</td>
<td>0.44-0.77</td>
<td>0.01186</td>
<td>0.00093</td>
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</tbody>
</table>

1. Gas grid
2. Proton exchange membrane fuel cell (PEMFC) – Micro CHP generation
3. Solid oxide fuel cell (SOFC) – Distributed CHP generation
4. SOFC-Gas Turbine (GT) – Distributed CHP generation
5. Micro-GT – Distributed CHP generation
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