Application of Organic Rankine Cycle systems to Anaerobic Digester

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Anaerobic Digestion

- AD is a growing industry in Northern Ireland.
- 500,000 tons of food waste generated annually in NI: enough biomethane to displace 10% of diesel.
- Typical feedstocks: pig and cattle, slurry, poultry litter, energy crops and food waste.

<table>
<thead>
<tr>
<th></th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD Plants (operating/planned)</td>
<td>-</td>
<td>42/86</td>
</tr>
<tr>
<td>Total installed capacity (2016)</td>
<td>MWe</td>
<td>23.99</td>
</tr>
<tr>
<td>Feedstock demand (2016)</td>
<td>tpa/y</td>
<td>479,950</td>
</tr>
<tr>
<td>Biogas production capacity (2016)</td>
<td>Nm³</td>
<td>31.74 (millions)</td>
</tr>
<tr>
<td>Potential biogas capacity</td>
<td>Nm³</td>
<td>133 – 585 (millions)</td>
</tr>
<tr>
<td>Potential electric energy capacity</td>
<td>GWhel/yr</td>
<td>458 - 2020</td>
</tr>
<tr>
<td>Potential heat energy capacity</td>
<td>GWhth/yr</td>
<td>655 - 2885</td>
</tr>
</tbody>
</table>
Example: AgriAD system

AgriAD biogas production plant
Banbridge (Northern Ireland)

<table>
<thead>
<tr>
<th>AD production and consumption</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedstock consumption</td>
<td>15000 ton/y</td>
</tr>
<tr>
<td>Biogas production</td>
<td>10391 MWhₑ/y</td>
</tr>
<tr>
<td>CHP engine (eff. 41%)</td>
<td>500 kWₑ</td>
</tr>
<tr>
<td>Thermal energy output</td>
<td>4375 MWhₑ/y</td>
</tr>
<tr>
<td>Thermal energy recovered</td>
<td>1363 MWhₑ/y</td>
</tr>
<tr>
<td>Electricity produced (net)</td>
<td>3526 MWhₑ/y</td>
</tr>
</tbody>
</table>

The system does not exploit all heat generated by the engine. This heat might be used to produce electricity by means of an ORC, increasing the overall performance of the system.
Organic Rankine Cycles (ORCs) are **Rankine cycles** using an **organic substance** as working fluids.

- Exploitation of low temperature heat sources to produce electricity;
- Supercritical cycles are achievable without special efforts (<60bar).
- Advantageous efficiency in a small-scale concept.
Organic Rankine Cycle

Subcritical cycle

Supercritical cycle
The ORC installation potential is about 2705 MW in Europe, which "would lead up to about 21.6 TWh of electricity production, with savings of about 1900M€ and of over 8.1 Mtonnes of greenhouse gases".¹


Potential exploitation in the AD market

- It corresponds to a biogas production of 162200 GWh_t/y.
- About 29% of this thermal heat is currently wasted (~47000GWh_t)
- The exploitation of this heat by using Organic Rankine Cycles in AD plants will increase the electric energy production of 5000-7000 GWh_e/y.
- In terms of money, it corresponds to about £900M/y.
WHR-ORC concept for ADs

- **Biogas**
  - **High-temp thermal energy**
  - **Low-temp. thermal energy**
  - **Feedstocks**
  - **Electricity**
  - **To the ambient**

**S ORC**

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How can we collect the heat efficiently to maximise the primary energy saving?
ORC system at QUB
## ORC system at QUB

### T-S diagram

### P-h diagram

<table>
<thead>
<tr>
<th>State</th>
<th>Pump Inlet</th>
<th>Pump Outlet</th>
<th>REG Outlet</th>
<th>HE1 Outlet</th>
<th>HE2 Outlet</th>
<th>HE3 Outlet</th>
<th>EXP Outlet</th>
<th>REG Outlet</th>
<th>Cond Outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>State 1</td>
<td>815.3 kPa</td>
<td>4500.0 kPa</td>
<td>4500.0 kPa</td>
<td>4500.0 kPa</td>
<td>4500.0 kPa</td>
<td>815.3 kPa</td>
<td>815.3 kPa</td>
<td>815.3 kPa</td>
<td></td>
</tr>
<tr>
<td>State 2</td>
<td>8.2 bar</td>
<td>45.0 bar</td>
<td>45.0 bar</td>
<td>45.0 bar</td>
<td>45.0 bar</td>
<td>8.2 bar</td>
<td>8.2 bar</td>
<td>8.2 bar</td>
<td></td>
</tr>
<tr>
<td>State 3</td>
<td>305.1 K</td>
<td>308.1 K</td>
<td>358.1 K</td>
<td>373.1 K</td>
<td>398.1 K</td>
<td>473.1 K</td>
<td>427.2 K</td>
<td>332.0 K</td>
<td></td>
</tr>
<tr>
<td>State 4</td>
<td>32 °C</td>
<td>34.9 °C</td>
<td>84.9 °C</td>
<td>100.0 °C</td>
<td>125.0 °C</td>
<td>200.0 °C</td>
<td>154.0 °C</td>
<td>58.9 °C</td>
<td></td>
</tr>
<tr>
<td>State 5</td>
<td>244.6 kJ/kg</td>
<td>248.8 kJ/kg</td>
<td>327.6 kJ/kg</td>
<td>360.8 kJ/kg</td>
<td>464.1 kJ/kg</td>
<td>570.46 kJ/kg</td>
<td>542.15 kJ/kg</td>
<td>443.55 kJ/kg</td>
<td></td>
</tr>
<tr>
<td>State 6</td>
<td>1.153 kJ/kgK</td>
<td>1.156 kJ/kgK</td>
<td>1.393 kJ/kgK</td>
<td>1.483 kJ/kgK</td>
<td>1.753 kJ/kgK</td>
<td>1.999 kJ/kgK</td>
<td>2.062 kJ/kgK</td>
<td>1.801 kJ/kgK</td>
<td></td>
</tr>
<tr>
<td>State 7</td>
<td>0</td>
<td>#Subcooled liquid with p&gt;pc</td>
<td>#Subcooled liquid with p&gt;pc</td>
<td>#Subcooled liquid with p&gt;pc</td>
<td>#Supercritical state (T&gt;Tc, p&gt;pc)</td>
<td>#Supercritical state (T&gt;Tc, p&gt;pc)</td>
<td>#Superheated vapor</td>
<td>#Superheated vapor</td>
<td></td>
</tr>
<tr>
<td>State 8</td>
<td>Density</td>
<td>kg/m³</td>
<td>1179.6</td>
<td>1192.2</td>
<td>943.7</td>
<td>782.9</td>
<td>235.0</td>
<td>140.2</td>
<td>24.5</td>
</tr>
<tr>
<td>State 9</td>
<td>Exergy</td>
<td>kJ/kg</td>
<td>35.7</td>
<td>38.9</td>
<td>49.6</td>
<td>56.6</td>
<td>82.2</td>
<td>117.7</td>
<td>71.3</td>
</tr>
</tbody>
</table>

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THERMOECONOMIC OPTIMIZATION OF AN ORC SYSTEM FOR BIOGAS POWER PLANT APPLICATION

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The Thermodynamics Laboratory
University of Liège
ORC potential configurations for ADs
Based on a 500kWe Biogas Engine

**CURRENT CONFIGURATION (NO ORC)**

- Production of hot water (97°C) used to heat the digester.
- 200kWt used
- 506kWt wasted

**243kWt 470°C**

**263kWt 88°C**
ORC potential configurations for ADs

Based on a 500kWe Biogas Engine

CONF 1: DIGESTER PRIORITY

The thermal demand of the digester has the priority:

- 243kWt at 470°C
  - 95kWt to the digester
  - 148kWt to the ORC

- 263kWt at 88°C
  - 105kWt to the digester
  - 158 kWt wasted
ORC potential configurations for ADs
Based on a 500kWe Biogas Engine

CONF 2: Partial ORC priority (EG)
All exhaust gas heat is used to feed the ORC:

243kWt 470°C → 243kWt to the ORC

263kWt 88°C →
- 105kWt to the digester
- 158 kWt wasted
- 95kWt supplied by a gas/oil boiler to reach the desired temperature.
**ORC potential configurations for ADs**

Based on a 500kWe Biogas Engine

**CONF 3: Full ORC priority (EG and CW)**

All heat rejected by the engine (506kWt) is used to feed the ORC. The heat required by the digester is provided by an external gas/oil burner.

- 243kWt at 470°C
- 263kWt at 88°C
Investment costs

![Bar chart showing investment costs for AD priority, EG ORC priority, and ORC ONLY. The chart includes categories for Expander, Condenser, and Evaporator.]
Analysis of the investment

~15% efficiency
Analysis of the investment

<table>
<thead>
<tr>
<th></th>
<th>AD priority</th>
<th>EG ORC priority</th>
<th>ORC only (fuel)</th>
<th>ORC only (gas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBP [years]</td>
<td>2,784041</td>
<td>3,774817</td>
<td>7,480324</td>
<td>2,697244</td>
</tr>
<tr>
<td>Net electrical production [1e4 W]</td>
<td>1,469923</td>
<td>3,621568</td>
<td>7,856931</td>
<td>7,856931</td>
</tr>
<tr>
<td>CO2 emission reduction [1e5 kg]</td>
<td>0,339811</td>
<td>-1,27206</td>
<td>-2,64776</td>
<td>1,816337</td>
</tr>
<tr>
<td>Fluid</td>
<td>R134a</td>
<td>n-Pentane</td>
<td>n-Pentane</td>
<td>n-Pentane</td>
</tr>
<tr>
<td>expander</td>
<td>2 screws</td>
<td>Turbine</td>
<td>Turbine</td>
<td>Turbine</td>
</tr>
<tr>
<td>Cycle</td>
<td>Trans-critical</td>
<td>Trans-critical</td>
<td>Trans-critical</td>
<td>Trans-critical</td>
</tr>
</tbody>
</table>
Conclusions

• AD is a growing industry in Northern Ireland with more than 40 operational plants for electricity production.
• ORC technology would allow to produce even more renewable electric energy by exploiting the heat rejected by the biogas engines.
• QUB is currently investigating the potential market of AD-ORC systems in Northern Ireland. An experimental system working in transcritical condition is currently under construction at QUB.
• In the framework of a KCORC grant, a thermoeconomic optimisation of ORC systems for AD plants is ongoing in collaboration with the University of Liege.
• Preliminary results have shown that PBP between 2.8 and 7.5 years could be achieved depending on the system configuration and on the technology adopted.
Thanks for your attention