Small-scale Biomass Gasification CHP Systems: Comparative Performance Assessment and Char Valorization

Marco Baratieri

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Small scale gasification: EU facts & figures

Output of plants since 2009

- Capacity of plants in Germany
- Total capacity of plants
- Quantity of plants in Germany
- Total quantity of plants

Distribution of gasification plants in South-Tyrol

**Small scale gasification plants authorized in South Tyrol in the last years**
Outline of systems & monitoring activities

Analyzed parameters

- Feedstock and gasification products (gas, char, tar) characteristics
- Mass fluxes
- Energy fluxes

Biomass → GASIFIER → FILTER → HEAT EXCHANGER → INTERNAL COMBUSTION ENGINE → $P_{el}$

- Char
- $P_{th}$
  - gas cooling
- $P_{th}$
  - water/oil cooling
  - flue gases cooling
On site monitoring activities

**Mass fluxes**
- Woody biomass flow rate
- Gasifying agent (air) flow rate
- Producer gas flow rate
- Char flow rate

**Energy fluxes**
- Input fuel
- Producer gas
- Power and heat

**By-products characterization**
- Liquid: tar
- Solid: char
Mass balances of selected technologies

<table>
<thead>
<tr>
<th></th>
<th></th>
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</thead>
<tbody>
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<td>A</td>
<td>39.6</td>
<td>68.7</td>
<td>107.6</td>
<td>0.7</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>127.3</td>
<td>205.8</td>
<td>313.9</td>
<td>1.3</td>
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<tr>
<td>C</td>
<td>116.9</td>
<td>155.6</td>
<td>271.4</td>
<td>1.1</td>
<td>-</td>
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<tr>
<td>D</td>
<td>123.8</td>
<td>185.0</td>
<td>297.6</td>
<td>5.1</td>
<td>-2.0</td>
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<tr>
<td>E</td>
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<td>78.2</td>
<td>121.3</td>
<td>0.7</td>
<td>1.0</td>
</tr>
<tr>
<td>F</td>
<td>229.0</td>
<td>363.3</td>
<td>558.8</td>
<td>22.8</td>
<td>-1.8</td>
</tr>
<tr>
<td>G</td>
<td>338.4</td>
<td>663.0</td>
<td>990.4</td>
<td>3.6</td>
<td>-0.7</td>
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<tr>
<td>H</td>
<td>150.8</td>
<td>296.9</td>
<td>426.5</td>
<td>1.1</td>
<td>-4.5</td>
</tr>
</tbody>
</table>
Mass balance

variability (on considered technologies)

- **air**: $[\text{kg}_{\text{air}}/\text{kg}_{\text{biom}}]$
- **producer gas**: $[\text{kg}_{\text{gas}}/\text{kg}_{\text{biom}}]$
- **char**: [%]
Producer gas composition
Producer gas composition

variability (on considered technologies)
Small scale gasification: b.o.p.

**Diagram Legend:**
- Input biomass [kWh]
- ICE thermal output [kWh]
- ICE loss [kWh]
- Output char [kWh]
- ICE input [kWh]
- ICE electric output [kWh]
- Gasifier thermal loss [kWh]
- Gas-cooling thermal output [kWh]
# Gasification performance parameters

<table>
<thead>
<tr>
<th>Technology</th>
<th>A (ER)</th>
<th>B (ηEL)</th>
<th>C (ηTH)</th>
<th>D (ηTOT)</th>
<th>E (kg_{BIOM}/kWh_{EL})</th>
<th>F (ηEL)</th>
<th>G (ηTH)</th>
<th>H (ηTOT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ER</td>
<td>0.30</td>
<td>0.26</td>
<td>0.29</td>
<td>0.25</td>
<td>0.29</td>
<td>0.26</td>
<td>0.33</td>
<td>0.30</td>
</tr>
<tr>
<td>ηEL</td>
<td>18.3%</td>
<td>26.4%</td>
<td>16.8%</td>
<td>18.8%</td>
<td>19.9%</td>
<td>21.9%</td>
<td>19.9%</td>
<td>17.4%</td>
</tr>
<tr>
<td>ηTH</td>
<td>49.9%</td>
<td>42.1%</td>
<td>52.5%</td>
<td>51.2%</td>
<td>58.6%</td>
<td>47.7%</td>
<td>48.5%</td>
<td>36.1%</td>
</tr>
<tr>
<td>ηTOT</td>
<td>68.2%</td>
<td>68.6%</td>
<td>68.3%</td>
<td>69.9%</td>
<td>78.5%</td>
<td>69.6%</td>
<td>68.4%</td>
<td>53.5%</td>
</tr>
<tr>
<td>kg_{BIOM}/kWh_{EL}</td>
<td>0.93</td>
<td>0.71</td>
<td>0.97</td>
<td>0.83</td>
<td>0.95</td>
<td>0.82</td>
<td>0.83</td>
<td>1.05</td>
</tr>
</tbody>
</table>
Characteristic parameters

- ER
- $kg_{biom}/kWh_{el}$
- selfconsumptions [%]
Performance

Dual fuel engine (3 l/h of vegetable oil)
## Char characterization

<table>
<thead>
<tr>
<th>Technology</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash [%]</td>
<td>27.84</td>
<td>16.08</td>
<td>49.52</td>
<td>31.50</td>
<td>13.34</td>
<td>6.49</td>
<td>29.17</td>
<td>25.64</td>
</tr>
<tr>
<td>C [%]</td>
<td>68.63</td>
<td>80.23</td>
<td>48.03</td>
<td>66.96</td>
<td>78.97</td>
<td>91.59</td>
<td>69.46</td>
<td>69.49</td>
</tr>
<tr>
<td>H [%]</td>
<td>0.33</td>
<td>0.49</td>
<td>0.89</td>
<td>0.18</td>
<td>0.68</td>
<td>0.52</td>
<td>0.11</td>
<td>0.20</td>
</tr>
<tr>
<td>N [%]</td>
<td>0.83</td>
<td>0.23</td>
<td>0.25</td>
<td>0.16</td>
<td>0.20</td>
<td>0.25</td>
<td>0.12</td>
<td>0.46</td>
</tr>
<tr>
<td>O [%]</td>
<td>2.37</td>
<td>2.69</td>
<td>1.31</td>
<td>0.57</td>
<td>6.50</td>
<td>0.60</td>
<td>0.87</td>
<td>3.88</td>
</tr>
<tr>
<td>PAH [mg/kg]</td>
<td>4881.4</td>
<td>2625.6</td>
<td>2.76</td>
<td>315.6</td>
<td>1223.5</td>
<td>85.6</td>
<td>31.43</td>
<td>441.2</td>
</tr>
<tr>
<td>PCB [mg/kg]</td>
<td>339.5</td>
<td>10.7</td>
<td>0.03</td>
<td>0.56</td>
<td>1.83</td>
<td>0.40</td>
<td>0.20</td>
<td>107.8</td>
</tr>
<tr>
<td>BET [m²/g]</td>
<td>352</td>
<td>128</td>
<td>78</td>
<td>281</td>
<td>587</td>
<td>272</td>
<td>320</td>
<td>306</td>
</tr>
</tbody>
</table>
Small scale gasification: feedstock (critical issues).

- **Very low moisture content:** < 10%
  - Vs direct combustion: 15-20%
  - Need of a dryer
- **Constant characteristics**
  - Homogeneous granulometry (e.g. chips, pellets)
  - Constant typology (wood)
  - Very few (no) finer presence

- **Biomass higher cost:** approx. 130 – 150 € / ton
  - Vs direct combustion 70 – 80 € / ton
Small scale gasification: char (critical issues).

- **Char management**
  - char screw conveyors extract hot char from the gasifier, so they are subjected to deformation and breakage
  - char management and storage is often problematic because it is a very light material and easily transportable by air

- **High disposal cost:** approx. 200 – 400 € / ton
Small scale gasification: gas cleanup (critical issues).

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Example</th>
<th>Problems</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particulate</td>
<td>Ash, char</td>
<td>Erosion</td>
<td>Filtration, scrubbing</td>
</tr>
<tr>
<td>Alkali</td>
<td>Na, K compounds</td>
<td>Hot corrosion</td>
<td>Cooling, condensation, filtration, adsorption</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>Mainly NH₃, HCN</td>
<td>NOx formation</td>
<td>Scrubbing, SCR</td>
</tr>
<tr>
<td>Tar</td>
<td>Aromatic compounds</td>
<td>Filters clogging, combustion problems, deposits, catalysts poisoning</td>
<td>Removal, condensation, thermal/catalytic cracking</td>
</tr>
<tr>
<td>Sulfur, Chlorine</td>
<td>Mainly H₂S, HCl</td>
<td>Corrosion, gaseous emissions, catalysts poisoning</td>
<td>Scrubbing, with dolomite or lime, adsorption</td>
</tr>
</tbody>
</table>
Small scale gasification: others (critical issues).

- **Autonomy and control of the system**
  - low degree of automation, i.e. problems lead to complete shut down of the system; time to restore the operation

- **Feeding system**: (screw conveyors):
  - blockage/distortion for presence inhomogeneous or inert material or different woodchips geometry

- **Reactor and air nozzles**
  - high temperature can melt steel components
  - higher T values than expected ones
  - reactors must be periodically opened and cleaned to remove inert materials
Challenges for gasification

**short term**

CHP upgrade

- fuel flexibility
- partial load operation
- char utilization
  - filtering medium (ACS subs.)
  - catalyst

**medium term**

CHP $\rightarrow$ POLYGENERATION

- biofuels
- hydrogen
- SNG
  - PtG (Power2gas / CO$_2$ capture)
  - integration with other renewables
Use of char: tar cracking

**Plant type** Dual stage gasifier

**Feedstock** Wood chips

**Proximate and ultimate analysis**

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass fraction [wt% \text{dry}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash</td>
<td>22.20</td>
</tr>
<tr>
<td>C</td>
<td>78.97</td>
</tr>
<tr>
<td>H</td>
<td>0.68</td>
</tr>
<tr>
<td>N</td>
<td>0.20</td>
</tr>
<tr>
<td>S</td>
<td>0.31</td>
</tr>
<tr>
<td>HHV \text{dry} [MJ/kg]</td>
<td>25.53</td>
</tr>
<tr>
<td>S \text{BET} [m^2/g]</td>
<td>587</td>
</tr>
<tr>
<td>Pore volume [cm^3/g]</td>
<td>0.30</td>
</tr>
</tbody>
</table>

**Ash composition**

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass fraction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
<td>17.47</td>
</tr>
<tr>
<td>Mg</td>
<td>2.18</td>
</tr>
<tr>
<td>Fe</td>
<td>1.12</td>
</tr>
<tr>
<td>P</td>
<td>0.84</td>
</tr>
<tr>
<td>Mn</td>
<td>0.56</td>
</tr>
<tr>
<td>Na</td>
<td>0.40</td>
</tr>
<tr>
<td>Al</td>
<td>0.38</td>
</tr>
<tr>
<td>S</td>
<td>0.37</td>
</tr>
<tr>
<td>Cr</td>
<td>0.30</td>
</tr>
<tr>
<td>Ba</td>
<td>0.22</td>
</tr>
</tbody>
</table>

**Empty-reactor tests**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Toluene removal efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>900 °C</td>
<td>39.9</td>
</tr>
<tr>
<td>1000 °C</td>
<td>97.3</td>
</tr>
</tbody>
</table>

**Tests with char-bed**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Toluene removal efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>900 °C</td>
<td>60.3</td>
</tr>
<tr>
<td>1000 °C</td>
<td>99.0</td>
</tr>
</tbody>
</table>

*Cordioli et al., Energies (2019)*
Use of char: adsorption

Marchelli et al. (2019)
Benedetti et al. (2019)
Use of char: catalyst support for FT synthesis

Catalysts

Precursors:  
Co(NO$_3$)$_2$·6H$_2$O  
Fe(NO$_3$)$_3$·9H$_2$O

Supports:  
Char  
HNO$_3$ treated char  
CO$_2$ activated, HNO$_3$ treated char  
Commercial activated carbon

Method: Incipient wetness impregnation

<table>
<thead>
<tr>
<th>CO conv., %</th>
<th>Char, 20% Co</th>
<th>AC, 20% Co</th>
<th>Literature</th>
<th>Char, Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.6</td>
<td>27.7</td>
<td>15 – 80</td>
<td>26</td>
</tr>
</tbody>
</table>

- Fixed-bed reactor
- H$_2$ : CO = 2 : 1
- T = 240°C
- P = 16 bar
- WHSV = 3600 ml g$^{-1}$ h$^{-1}$
- t = 24 – 72 h
Towards advanced biofuels: polygeneration

**Renewable Energy Directive II (RED II)**
Renewable transport fuels target: 14% (3.5% advanced b.)

**SET plan & Action 8 Implementation plan**
Gasification is a key technology in 3 (of 7) value chains
required:  efficiency improvement, 30%, GHG savings, 60%
cost reduction, to 50 (2020) – 35 (2050) €/MWh

**Strategic Research and Innovation Agenda (ETIp, EERA Bioenergy)**
Major role for gasification value chains in agreement with SET pl.
Polygeneration

Today (... almost yesterday)

- **electricity**
  - EFF=30% (20%)
- **ICE**
  - EFF=60% (50%)
  - heat

Tomorrow (... almost today)

- Methanation
  - EFF=86%
- CO₂ removal
- CO₂
- SNG
- Producer gas

*Saric et al., Journal of CO₂ Utilization, 20 (2017) 81-90*
Power-to-gas (PtG)

Renewable energy and CO$_2$ hybrid storage techniques
Power-to-gas (PtG) and gasification

Tomorrow (PtG)

Tomorrow (biomethanation)

Syngas fermentation


Menin et al. (2019)
Remarks: main directions for gasification

- Increase fuel flexibility  [use of low-cost feedstock]
- Use char as co-product  [(!) legislative framework]
- Co-production of fuels/chemicals/materials  [poly-generation]
- Combining thermochemical and biochemical processes
- Optimization of resource efficiency  [wind, solar, hydro]
Thank you very much for your attention!

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