Forest residues valorisation for energy purposes through a small-scale CHP system

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Introduction: Energy from woody residues management

Alpine forests → Wood chips → Producer Gas → CHP
Feedstock: forest residues

- They can be effectively used as additional energy resource and,
  - avoid safety problems in the forest, such as the spreading of tree diseases, pests, and forest fires
  - provide an economic advantage of operating the plant
  - a strategy to increase the local clean energy production.
  - a buffer material in the seasons in which the maintenance activities are not performed – can feed gasifier throughout the year regardless of the seasonal changes

Reduction of operational costs of plants and valorisation of a resource which is currently unused
Sieve test analysis

After sieving both feedstock (FR and WC), three different fractions were obtained:

1. **8 mm** – feedstock collected on sieve of aperture size 8 mm (range 16 mm – 8 mm)
2. **3.15 mm** – feedstock collected on sieve of aperture size 3.15 mm (range 8 mm – 3.15 mm)
3. **Dust** – feedstock collected on the bottom plate (i.e., < 3.15 mm)
CHP system setup: open-top gasifier + dual fuel engine

- biomass
- gasification
- reduction
- combustion
- reduction

b. reactor
- cyclone
- scrubber
- moisture trap
- flare
- exhaust pipe
- fabric filter
- blower
- orifice plate
- engine

- char tank
- water tank
- char
- p.gas
- primary air
- secondary air
small-scale CHP system – dual fuel engine + gasifier
Open-top gasifier behavior

unburned biomass

reactor level

inlet air

non reactive char

char
Open-top gasifier behavior

unburned biomass
control level
non reactive char

1st air

2nd air

char combustion
Open-top gasifier behavior

1\textsuperscript{st} air

unburned biomass
control level

2\textsuperscript{nd} air

gasification reactive char char combustion reactive char

non reactive char
Open-top gasifier behavior

1^st air

unburned biomass
control level

2^nd air

reactive char
char combustion
reactive char
non reactive char

gasification
Open-top gasifier behavior

1st air

unburned biomass
control level

gasification

2nd air

reactive char
char combustion
reactive char
char discharge

non reactive char
Open-top gasifier behavior
Open-top gasifier behavior

Diagram showing the behavior of an open-top gasifier, with layers labeled as unburned biomass, control level, gasification, reactive char, char combustion, reactive char, and non-reactive char. An arrow labeled '1st air' points up, and another labeled '2nd air' points down.
cycle of fuel charge and char discharge

time range for mass balance

cycle start
steady conditions
char discharge
biomass refill

biomass weight
\( \dot{m}_{\text{biom}} \)

char weight
\( \dot{m}_{\text{char}} \)

\[
\text{mass} = \frac{\text{weight}}{(t_{\text{end}} - t_{\text{start}})}
\]
CHP system mass balance

\[ m_{\text{biomass}} \rightarrow \text{LabAnalisis}_{\text{biomass}} \]

\[ m_{\text{1st air}} \]

\[ m_{\text{2nd air}} \]

\[ m_{\text{char}} \rightarrow \text{LabAnalisis}_{\text{char}} \]

\[ m_{\text{PGas}} \rightarrow \text{GasAnalisis}_{\text{PGas}} \]

\[ m_{\text{PGas_to_flare}} \]

\[ m_{\text{exh_gases}} \rightarrow \text{ExhGasAnalisis} \]

\[ m_{\text{diesel}} \rightarrow \text{LabAnalisis}_{\text{diesel}} \]

\[ m_{\text{PGas_to_engine}} \]

\[ m_{\text{air}} \]
Methods

Data acquisition and mass balances

\[ m_{\text{biomass\_wet}} + m_{\text{air}} = m_{\text{pgas\_dry}} + m_{\text{pgas\_H2O}} + m_{\text{char\_dry}} \]

\[ m_{\text{biomass\_wet}} \cdot [N]_{\text{biomass\_wet}} + m_{\text{air}} \cdot [N]_{\text{air}} = m_{\text{pgas\_dry}} \cdot [N]_{\text{pgas\_dry}} \]

\[ m_{\text{biomass\_wet}} \cdot [C]_{\text{biomass\_wet}} = m_{\text{pgas\_dry}} \cdot [C]_{\text{pgas\_dry}} + m_{\text{char\_dry}} \cdot [C]_{\text{char\_dry}} \]

\[ SGE \left[\frac{MJ}{kg}\right] = \frac{m_{\text{pgas\_dry}} \cdot LHV_{pg}}{m_{\text{biomass}}} \]

\[ CGE \% = \frac{m_{\text{pgas\_dry}} \cdot LHV_{pg}}{m_{\text{biomass}} \cdot LHV_{\text{biomass}}} \]
Experiments

- Feedstocks:
  1. 100WC
  2. 75WC25FR
  3. 50WC50FR
  4. 25WC75FR

Three different Producer gas mass flows rate to engine

Position A: 3.92 ± 0.06 kg/h
Position B: 4.78 ± 0.03 kg/h
Position C: 5.57 ± 0.04 kg/h

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>C (%)</th>
<th>H (%)</th>
<th>N (%)</th>
<th>S (%)</th>
<th>O* (%)</th>
<th>Moisture (%)</th>
<th>Ash (%)</th>
<th>LHV (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100WC</td>
<td>48.21</td>
<td>6.17</td>
<td>0.41</td>
<td>0.22</td>
<td>40.87</td>
<td>3.84</td>
<td>0.28</td>
<td>17.69</td>
</tr>
<tr>
<td>75WC25FR</td>
<td>49.09</td>
<td>6.26</td>
<td>0.52</td>
<td>0.13</td>
<td>39.56</td>
<td>4.00</td>
<td>0.44</td>
<td>17.68</td>
</tr>
<tr>
<td>50WC50FR</td>
<td>48.59</td>
<td>6.13</td>
<td>0.41</td>
<td>0.19</td>
<td>39.89</td>
<td>4.17</td>
<td>0.62</td>
<td>17.60</td>
</tr>
<tr>
<td>25WC75FR</td>
<td>50.08</td>
<td>6.20</td>
<td>0.47</td>
<td>0.15</td>
<td>36.41</td>
<td>5.45</td>
<td>1.24</td>
<td>17.09</td>
</tr>
</tbody>
</table>

Two different Electrical load of engine

Position A: 2 kw, 3 kw
Position B: 2 kw, 3 kw
Position C: 2 kw, 3 kw
High variability was observed in the ER for feedstocks with higher FR

- The non-uniform particle size and non-homogeneity of different components
- The influence of the valve position to the pression drop of the gasifier gas line
Setup – Engine

1. Paguro 4000 engine-generator set
2. Siemens Sitrans MAG 1100 flow sensor
3. K-type thermocouples in cooling water line
4. MRU Vario Plus exhaust gas analyzer
5. Grimm Mini-WRAS 1371PM analyzer particle counter (diameter 10 nm - 35 µm)
6. Load cell
7. Fuel tank
8. PG-Air mixing chamber
9. PG control valve with orifice meter,
10. HT PQA820 power meter
11. Electrical loads
12. Data acquisition in PC.
Methods

Data acquisition and mass balances

\[
\dot{m}_{\text{gas}} + \dot{m}_{\text{diesel}} + \dot{m}_{\text{air}} = \dot{m}_{\text{exh,dry}} + \dot{m}_{\text{exh,H}_2\text{O}}
\]

\[
\dot{m}_{\text{gas}} \cdot [N]_{\text{gas}} + \dot{m}_{\text{air}} \cdot [N]_{\text{air}} = \dot{m}_{\text{exh,dry}} \cdot [N]_{\text{exh,dry}}
\]

\[
\dot{m}_{\text{gas}} \cdot [C]_{\text{gas}} = \dot{m}_{\text{exh,dry}} \cdot [C]_{\text{exh,dry}}
\]

Electrical efficiency

\[
\text{efficiency} [\%] = \frac{\text{Power}_{\text{electrical}}}{\dot{m}_{\text{gas}} \cdot LHV_{\text{gas}} + \dot{m}_{\text{diesel}} \cdot LHV_{\text{gas}}}
\]

Thermal Efficiency

\[
\text{efficiency} [\%] = \frac{\dot{m}_{\text{water}} \cdot C_p_{\text{water}} \cdot \Delta T}{\dot{m}_{\text{gas}} \cdot LHV_{\text{gas}} + \dot{m}_{\text{diesel}} \cdot LHV_{\text{gas}}}
\]

Diesel Substitution Rate

\[
DSR = \frac{\dot{m}_{D} - \dot{m}_{d}}{\dot{m}_{D}}
\]

\[\dot{m}_{D} = \dot{m}_{\text{diesel}} \text{ (only diesel)}\]

\[\dot{m}_{d} = \dot{m}_{\text{diesel}} \text{ (in dual fuel mode)}\]
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**Carbon monoxide - 2 kW<sub>el</sub>**

- **100WC**: Blue
- **75WC25FR**: Red
- **50WC50FR**: Green
- **25WC75FR**: Yellow

- **100WC**: Blue
- **75WC25FR**: Red
- **50WC50FR**: Green
- **25WC75FR**: Yellow

**Carbon monoxide - 3 kW<sub>el</sub>**

- **100WC**: Blue
- **75WC25FR**: Red
- **50WC50FR**: Green
- **25WC75FR**: Yellow

- **100WC**: Blue
- **75WC25FR**: Red
- **50WC50FR**: Green
- **25WC75FR**: Yellow

**Nitrogen oxides - 2 kW<sub>el</sub>**

- **100WC**: Blue
- **75WC25FR**: Red
- **50WC50FR**: Green
- **25WC75FR**: Yellow

- **100WC**: Blue
- **75WC25FR**: Red
- **50WC50FR**: Green
- **25WC75FR**: Yellow

**Nitrogen oxides - 3 kW<sub>el</sub>**

- **100WC**: Blue
- **75WC25FR**: Red
- **50WC50FR**: Green
- **25WC75FR**: Yellow

- **100WC**: Blue
- **75WC25FR**: Red
- **50WC50FR**: Green
- **25WC75FR**: Yellow
Carbon monoxide - $2\text{ kW}_\text{el}$

- $100\text{WC}$
- $75\text{WC25FR}$
- $50\text{WC50FR}$
- $25\text{WC75FR}$

Carbon monoxide - $3\text{ kW}_\text{el}$

- $100\text{WC}$
- $75\text{WC25FR}$
- $50\text{WC50FR}$
- $25\text{WC75FR}$

Nitrogen oxides - $2\text{ kW}_\text{el}$

- $100\text{WC}$
- $75\text{WC25FR}$
- $50\text{WC50FR}$
- $25\text{WC75FR}$

Nitrogen oxides - $3\text{ kW}_\text{el}$

- $100\text{WC}$
- $75\text{WC25FR}$
- $50\text{WC50FR}$
- $25\text{WC75FR}$
Particulate matter - $2kW_{el}$

- [mg/m$^3$]
- [mg/Nm$^3$]

Particulate matter - $3kW_{el}$

- [mg/m$^3$]
- [mg/Nm$^3$]

Aşağıdaki grafikler, farklı güç seviyelerindeki particulate matter miktarlarını göstermektedir:

- **$2kW_{el}$**: 100WC, 75WC25FR, 50WC50FR, 25WC75FR
- **$3kW_{el}$**: 100WC, 75WC25FR, 50WC50FR, 25WC75FR

**DSR [%]**:
- **$2kW_{el}$**: 10.0 - 70.0
- **$3kW_{el}$**: 10.0 - 70.0

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Conclusions

- A small-scale open-top gasifier coupled with an engine-generator set was operated with various mixtures of forest residues (FR) and standard wood chips (WC).

- Different plant operation conditions were observed for different FR fractions. Larger ER deviations were observed with increasing fraction of FR in the feedstock mixture (75% of FR).

- The variation of ER involved some differences in performance indicators such as LHV of PG, Ychar, SGE, CGE, etc.

- This variability was also evident in the engine output. However, some trends were observed: an increase in terms of CO emission and a decrease for NOx and PM in relation to the growth of DSR.

- In conclusion, biomass residues from forests could be valorized by using them as inexpensive feedstock in CHP processes, thereby reducing plants’ operational costs.

- However, due to the inherent variability in their physical and chemical composition predictability and reproducibility of results might be a challenge.
Acknowledgments

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Thank you for your attention

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