Biofuel production via thermal gasification of biomass

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Who am I?

- Assistant Professor at the Section of Thermal Energy

- Expertise in thermodynamic modeling and energy/exergy optimization of complex energy systems
  - Focus on biofuel production via thermal gasification

- Other research interests:
  - Exergy analysis of energy systems
  - Thermoeconomics
  - Integration of agriculture in the energy system – nutrient recycling

- Recent projects at the Section of Thermal Energy
  - High temperature heat pumps
  - Low temperature heat to power (ORC, Kalina, other mixtures of working fluids, solar thermal power)
Biofuel production via thermal gasification

An overview

Biomass → Gasifier → Syngas (synthesis gas)
- Consist of CO and H₂
  (the building blocks for chemical synthesis)

Syngas → Synthesis reactor → Liquid fuel
Agenda

• Gasification of biomass
  – Gasifiers developed at DTU

• Biofuel production plants
  – Proposed designs
    • Biofuel plants based on entrained flow gasification of torrefied biomass
    • Biofuel plants based on the Two-Stage Gasifier
    • Biofuel plants integrating electrolysis of water
  – Future work
    • Biofuel plants based on an oxygen-blown Two-Stage Gasifier
    • Biofuel plants based on an entrained flow gasifier with integrated torrefaction of biomass
Gasifiers developed at DTU:

The Two-Stage Gasifier

- Downdraft fixed bed
- High energy efficiency (~93%)
- No tar and low CH₄ in gas
- Temperature out: 730°C
- Small-scale plant (max 5 MWth)

[Diagram of the Two-Stage Gasifier]
Gasifiers developed at DTU:

The Two-Stage Gasifier (The Viking Gasifier)

- The Viking gasifier (picture) is 15-20 kWe
- It has been successfully upscaled to 100 kWe
- A 500 kWe plant is being built at the moment.
- The Technology is now owned by the Danish company Weiss.
Gasifiers developed at DTU:

The Pyroneer gasifier

- 2 fluidized beds
- High tar and CH₄ in gas
- Temperature out: ~650°C
- Can convert almost any kind of biomass
  - Straw
  - Biogas residue
- The ash can be used as fertilizer because temperatures are below 730°C
Gasifiers developed at DTU:

The Pyroneer gasifier

- The Technology is now owned by the Danish power company DONG Energy

- A 6 MWth demonstration plant is under operation at the moment (picture).
Gasifiers developed at DTU:

The Pyroneer gasifier

- Straw
- Manure
- Biogas residue
- Wood
- Sewage sludge
- Industrial waste
- Household waste
- Other agricult. waste
- Meat-and-bone meal
- Etc.

Pyroneer gasifier, or LT-CFB plant

- Cofiring with coal, oil or gas into existing powerplant boilers
- Indirectly fired gasturbines
- Large Stirling engines
- Directly fired gasturbines, combustion engines or fuel cells (with gas cleaning)
- Production of liquid fuels or more valuable chemicals

Reforming of the tar and CH₄ in the gas is required

Suitable plant sizes: ~5-150 MWth (depending on the fuel and the application)
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Biofuel production via thermal gasification

An overview

Biomass $\rightarrow$ Gasifier $\rightarrow$ Synthesis reactor $\rightarrow$ Liquid fuel

Syngas (synthesis gas)
- Consist of CO and H$_2$
  (the building blocks for chemical synthesis)
Biofuel plants: Proposed designs

1. Biofuel plants based on entrained flow gasification of torrefied biomass
   - Shows the potential of state of the art within biofuel plants

2. Biofuel plants based on the Two-Stage Gasifier
   - Shows the potential of small-scale biofuel plants
   - Economy at this scale is a great challenge – this must be outweighed by the advantages of small-scale (high-efficiency gasifier, co-production of heat).

3. Biofuel plants integrating electrolysis of water
   - Enables full conversion of the carbon in the biomass to biofuel
   - Enables conversion of electricity from fluctuating renewables (wind, solar) to biofuel for the transportation sector.
Biofuel plants based on entrained flow gasification of torrefied biomass

- Very large scale is possible by using torrefied wood pellets as fuel.
- Torrefied wood has increased energy density (~20 MJ/kg), which increases gasifier energy efficiency.
- Almost all the syngas can be converted to fuel because the syngas contains few inerts (CH₄, N₂) – oxygen-blown gasification is used.

- Modeling shows potential of energy efficiencies up to 59% (LHV) from untreated wood to DME – 64% including net-electricity.
Biofuel plants: Proposed designs (2/3)

Biofuel plants based on the Two-Stage Gasifier

- Small-scale due to the Two-Stage Gasifier
- High energy efficiency due to high energy efficiency of gasifier
- Modeling shows potential of energy efficiencies up to 58% (LHV) from untreated wood to DME – no net-electricity.
Biofuel plants: Proposed designs (3/3)

Biofuel plants integrating electrolysis of water

- All the carbon in the biomass ends up in the biofuel – therefore no CO₂ emission.
- Potential for storing surplus electricity from renewables (wind, solar, etc.)
- Modeling shows potential of energy efficiencies up to 115% from untreated wood to methanol – with electricity consumption the efficiency drops to 58%.

**Typical gas composition from gasifier (mol%):**
- 29% H₂
- 51% CO
- 7% CO₂
- 13% H₂O.

**Diagram:**
- Water
- Electrolyser
- O₂
- O₂
- H₂
- Biomass
- Gasifier
- Gas
- Syngas
- Chemical energy
- Heat
- MeOH
- Electricity
- 99%
- 69%
- 45%
- 115%
- Wood
- 100%
- 90%
- 96%
- Torrefaction
- 10%
- 18%
- 22%
- 4%
- Off-gas boiler
- Gasification
- Synthesis
- 24%
- 30%
Why integrate electrolysis of H$_2$O/CO$_2$ in a biofuel plant?

- If great amounts of fluctuating renewables (wind, solar, etc.) needs to be integrated in the electricity grid. This is the case of Denmark:
  - In 2011 28% of the Danish electricity consumption was provided by wind.
  - In 2020 the official goal is 50%
  - In 2050 the official goal is a fossil free energy system.

- If the biomass resource shows to be very limited and expensive.

In a recent Danish Study (CEESA), Biofuel plants with integrated electrolysis supplies 44% of the fuel for the Danish transportation sector in the 2050 Scenario (see next slide).
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Biofuel plants: Future work

The planned future work continues to explore the integration of electrolysis in biofuel plants

1. Biofuel plants based on an oxygen-blown Two-Stage Gasifier + SOEC/SOFC
   - Can reach unprecedented energy efficiencies
     (biomass + electricity $\Rightarrow$ biofuel)

2. Biofuel plants based on an entrained flow gasifier with integrated torrefaction of biomass + electrolysis
   - The loss of chemical energy due to torrefaction is eliminated
   - High energy efficiency
Biofuel plants: Future work

Biofuel plants based on an oxygen-blown Two-Stage Gasifier + SOEC/SOFC

- Work based on the proposed designs: 2 and 3
- Higher energy efficiency due to greater conversion of syngas to biofuel (no N₂)
- Integration of a SOEC/SOFC. Used as SOEC when electricity is cheap – used as SOFC when electricity is expensive.

- The project will include both theoretical and experimental work.
- Partners:
  - The Gasification group at DTU
  - Haldor Topsoe
  - Danish Gas Technology Centre (DGC)
Biofuel plants based on an entrained flow gasifier with integrated torrefaction of biomass + electrolysis

- Work based on the proposed designs: 1 and 3
- The volatiles released during torrefaction is used as a chemical quench in the gasifier. This increases gasifier efficiency, and ensures that no biomass is lost in the torrefaction.
Biofuel production via thermal gasification

Biomass $\rightarrow$ Gasifier $\rightarrow$ Liquid fuel

Thank you for your attention
extra slides
Hurdles to overcome before biofuel plants are commercial

- **Cost**
  - An incentive to use biomass instead of coal is needed
    - Subsidy on biomass
    - Tax on coal
    - Tax on CO₂ emission (best option, and also the main hurdle!!)

- **Technical**
  - Up scaling the demonstrated small-scale gasifiers
  - Using biomass on existing large-scale coal gasifiers

- **Environmental**
  - The biomass used must be sustainable (not replace food/feed production, net greenhouse gas emissions from land use change, etc.)
The total energy efficiency of the biofuel plant can be increased by co-production of:
- Electricity
- Heat

Biofuel plants
Polygeneration

Biomass → Gasifier → Synthesis reactor

Liquid fuel ← Fuel
← Electricity
← Heat
### Important aspects in the design of BTL plants

<table>
<thead>
<tr>
<th></th>
<th><strong>Pros</strong></th>
<th><strong>Cons</strong></th>
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<tbody>
<tr>
<td><strong>Gasification</strong></td>
<td></td>
<td></td>
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<tr>
<td>Air</td>
<td>Low cost, simple design</td>
<td>$N_2$ in syngas $\Rightarrow$ lower conversion of syngas to fuel</td>
</tr>
<tr>
<td>Oxygen</td>
<td>No $N_2$ in syngas $\Rightarrow$ higher conversion of syngas to fuel</td>
<td>Cost and electricity consumption of oxygen plant</td>
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<tr>
<td><strong>Atmospheric</strong></td>
<td>Cost of gasifier, simple design</td>
<td>High electricity consumption for pressurization of syngas</td>
</tr>
<tr>
<td>Pressurized</td>
<td>Low electricity consumption for pressurization of syngas</td>
<td>Cost of gasifier</td>
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<tr>
<td><strong>Synthesis</strong></td>
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<td>Recycle of unconverted syngas (RC)</td>
<td>Higher conversion of syngas to fuel</td>
<td>Lower electricity co-production</td>
</tr>
<tr>
<td>Once through synthesis (OT)</td>
<td>Higher electricity co-production</td>
<td>Lower conversion of syngas to fuel</td>
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</tbody>
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The processes in a biofuel plant

Generic biofuel plant (DME) showing the important processes

Adjusting the H₂/CO-ratio:

$$CO + H_2O \rightarrow CO_2 + H_2$$

DME: $$3CO + 3H_2 \rightarrow CH_3OCH_3 + CO_2$$

Methanol: $$CO + 2H_2 \rightarrow CH_3OH$$
Gasifier types

Fixed bed gasifier
- Updraft
- Downdraft

Fluidized bed gasifier

Entrained flow gasifier