Assessing the performance of future integrated biorefinery concepts based on biomass gasification

Methodology and tools

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Special Thanks to Erik Axelsson from Profu AB
**Biorefinery - definition**

”A wide range of technologies able to separate biomass resources (wood, grasses, corn, etc.) into their building blocks (carbohydrates, proteins, fats, etc.) which can be converted into value-added products such as biofuels and bio-chemicals”.

*F Cherubini and A Strømman, ”Principles of Biorefining”, Elsevier 2011.*

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**Example of biofuels and conversion processes**

- **Biomass**
  - Cellulose & Lignin
    - wood, black liquor, grass
  - Starch
    - wheat, corn, potatoes
  - Sugar
  - Oil
    - rapeseed, palm oil, soy
  - Rest flows
    - from agriculture, forestry, industries, societal waste etc, e.g. straw, sawdust, manure, sludge, food waste.

- **Conversion Process**
  - Combustion
  - Gasification to syngas (CO and H2)
  - Fischer-Tropsch Diesel
  - DME (Dimehtyleter)
  - Methanol
  - Methane
  - Ethanol
  - FAME
  - HVO

- **Energy Carrier**
  - Electricity
  - Hydrogen
  - Fischer-Tropsch Diesel
  - DME (Dimehtyleter)
  - Methanol
  - Methane
  - Ethanol
  - FAME
  - HVO

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**Fuels / chemicals**

- El. Power
- Heat
- Waste / By-products
Limited resource

Fast-growing demand

Biorefineries must be as efficient as possible
- Optimal mix of products
- Maximize heat cascading within and between processes
Co-location with an industrial process can create significant integration opportunities

- Biomass
- Biorefinery
- Waste/By-products
- Fuels / chemicals
- El. Power
- Heating / cooling at 1000°C
- Heating / cooling at 500°C
- Heating / cooling at 200°C
- Heating / cooling at 100°C
- Heating / cooling at 10°C
- Heating / cooling at -50°C
Integrate Biorefinery concepts

Gasification to H₂
Gasification to Fischer-Tropsch Fuel

Switch crude feedstock
Switch fuel

Cogenerate Electricity
Export excess heat for district heating

Example
Possible carbon mitigation options for the oil refining industry

Enhance energy efficiency

Implement CCS

Example Possible carbon mitigation options for the oil refining industry

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Drivers behind the current interest in gasification-based biorefineries

Oil refineries, petro-chemical plants, ...

- Handle large volumes of fuels or chemicals
- Consume large quantities of fossil fuels
- Core processes are often based on high temperature synthesis routes
- Are constrained by strict safety regulations regarding chemical hazards and pressurized equipment

Pulp and paper plants:

- Large quantities of by-products than can be converted to high-value products: Black liquor, bark, etc.

Gasification constitutes an interesting initial common core process path, that can be followed by a multitude of downstream conversion operations
Methodology and tools to support strategic decision-making for future integrated biorefinery concepts

- Systematic screening and optimal synthesis of biorefinery concepts
- Value and supply chain management and evaluation
- LCA-based evaluation of biorefinery concepts
- Future energy market scenarios for evaluation of biorefinery concepts
- Decision-making under uncertainty regarding future market conditions
- Quantifying the benefits of heat integrated vs stand-alone biorefinery concepts
Maximizing biorefinery efficiency using process integration tools

1. Understand the process
   - Raw material → Products → Heat supply → Cooling
   - Map energy flows and temperature levels in process. Establish targets for utility usage

2. Process modelling & validation
   - Integrated biorefinery
   - Refined biomass
   - EI
   - Cooling

3. Pinch analysis
   - Process modifications
   - Evaluation
     - Energy efficiency
     - Profitability
     - CO₂ Footprint
     - Primary energy savings

4. Example: heat integrate a biomass conversion process, adjust key process stages for enhanced integration performance, etc

- Use Energy market scenarios to define conditions in surrounding system

System and Integration Aspects of Biomass-based Gasification, November 19-20 2013, Göteborg, Sweden
Assessing primary energy savings, profitability and carbon balances of biorefinery investments in industry

Fossil fuel prices on the European commodity market

Policy instruments

Different optional energy projects

The ENPAC tool (for constructing energy market scenarios)

Electricity price

Fuel prices

$\text{CO}_2$ emissions associated with marginal energy

Energy intensive industry

Robust investment options

Consequences for global $\text{CO}_2$ emissions

Construction of...

...consistent energy market scenarios for...

...evaluation of energy projects in industry...

...to identify robust solutions with low $\text{CO}_2$ emissions.

Figure 1: Overview of the purpose of energy market scenarios for evaluation of energy efficiency investments in energy intensive industry where the ENPAC tool is used to construct the scenarios.
Why do we need Energy market scenarios?

Possible energy export options resulting from implementation of Energy saving measures

Electricity export 126 GWh/year INV: 28 M€

Biomass fuel export 500 GWh/year INV: 22 M€

Which option is most profitable and has greatest potential for CO₂ emissions abatement in the medium-term future?

To answer this we need

Future energy prices and description of the future energy market - Not available!

Next best option: Possible future energy prices and energy market description i.e. scenarios
## Energy market scenarios

### Electricity market

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base load build margin</td>
<td>NGCC</td>
<td>Coal</td>
<td>Coal</td>
<td>Coal</td>
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<tr>
<td>Coal CCS</td>
<td>Coal CCS</td>
<td>Coal CCS</td>
<td>Coal CCS</td>
<td></td>
</tr>
<tr>
<td>El. price (€/MWh)</td>
<td>54</td>
<td>57</td>
<td>62</td>
<td></td>
</tr>
<tr>
<td>CO₂ (kg/MWh&lt;sub&gt;el&lt;/sub&gt;)</td>
<td>374</td>
<td>136</td>
<td>723</td>
<td>136</td>
</tr>
</tbody>
</table>

### Biofuel market

<table>
<thead>
<tr>
<th>Scenario</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marginal biofuel user</td>
<td>Coal power</td>
<td>Coal power</td>
<td>DME Prod.</td>
</tr>
<tr>
<td>Biofuel price (€/MWh)</td>
<td>14</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>CO₂ (kg/MWh&lt;sub&gt;biofuel&lt;/sub&gt;)</td>
<td>329</td>
<td>329</td>
<td>122</td>
</tr>
</tbody>
</table>
Constructing consistent energy market scenarios with ENPAC tool

IEA WEO

Fossil fuel prices on the N.European commodity market

Macro ES models + WEO

Policy instruments associated with specific IPCC targets

Based on statistical data for Swedish end product market

Based on base-load build margin (i.e. power plant tech that achieves minimum levelized COE

WTP for biomass as fossil fuel substitute
• Power plants
• Transportation fuels
• Bulk chemicals

WTP for heat based on alternative production cost

Fossil fuel market model

Fuel prices and well-to-gate CO₂ emissions

Electricity market model

Electricity price and associated CO₂ emissions

Biomass energy market model

Biomass fuel prices and CO₂ emission consequences of marginal use of biomass fuel

Heat market model

Price and reduction of CO₂ emissions for heat delivery

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Scenario construction in practice

High and low fossil fuel prices are combined with different cost levels for CO₂ emissions and used as input to ENPAC tool. Consistent energy market scenarios are generated.

Fossil fuel prices

<table>
<thead>
<tr>
<th>High</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sc 1</td>
<td>Sc 2</td>
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</tbody>
</table>

Indicative price levels for el, biomass fuel and excess heat & related CO₂ emissions for Scenario 1
Sample input data: CO$_2$ emissions costs, €/ton
Sample input data: Fossil fuel prices, €/MWh (low/high)
- European Energy and Transport 2006, baseline (low) and soaring prices (high)
Sample results: base-load electricity price (excl transmission charges and taxes)

![Graph showing electricity price and fossil fuel price - CO₂ charge over time]

- **Electricity price**
- **Fossil fuel price - CO₂ charge**
  - Broken lines = High fossil fuel prices
  - Continuous lines = Low fossil fuel prices

The graph illustrates the base-load electricity price and fossil fuel price - CO₂ charge from 2010 to 2050. The prices are categorized by high and low levels, with high and low fossil fuel charges indicated by broken and continuous lines, respectively.
Carbon dioxide emissions associated with base load marginal electricity generation (kg/MWh)

Fossil fuel price - CO₂ charge

- Black: High - level 4
- Gray: Low - level 4
- Red: High - level 3
- Pink: Low - level 3
- Blue: High - level 2
- Green: Low - level 2
- Brown: High - level 1
- Olive: Low - level 1

Years: 2010, 2020, 2030, 2040, 2050
Unprocessed wood fuel prices for 2 different assumptions

- CO$_2$ charge component dominates
- Easy to understand
- Good match with current prices

- Oil price dominates
- Transport sector assumed to have the same CO$_2$-charge as other sectors, which favours biofuel
Comparative study of Fischer–Tropsch production and post-combustion CO₂ capture at an oil refinery: Economic evaluation and GHG (greenhouse gas emissions) balances

Daniella Johansson a,*, Per-Åke Franck b, Karin Pettersson a, Thore Berntsson a

a Division of Heat and Power Technology, Department of Energy and Environment, Chalmers University of Technology, SE-412 96 Göteborg, Sweden
b CIT Industriell Energi AB, Chalmers teknikpark, SE-412 88 Göteborg, Sweden
Integration of a biomass-to-Fr syncrude unit at an oil refinery site
Profitability and CO₂ balances for Fischer-Tropsch fuels production (integrated and stand-alone) as well as CCS

ΔNet Annual Profit [M€/y]

Δglobal GHG emissions [kt/y]

Scenarios:
(Fossil fuels price/CO₂ charge)

CO₂ capture
- Scenario: (Low/Low)
- Scenario: (Low/High)
- Scenario: (High/Low)
- Scenario: (High/High)

HI FT fuel production
- Scenario: (Low/Low)
- Scenario: (Low/High)
- Scenario: (High/Low)
- Scenario: (High/High)

SA FT fuel production
- Scenario: (Low/Low)
- Scenario: (Low/High)
- Scenario: (High/Low)
- Scenario: (High/High)
Integration of a biomass-to-hydrogen process in an oil refinery

Jean-Florian Brau*, Matteo Morandin, Thore Berntsson

Department of Energy and Environment
Division for Heat and Power Technology
Hydrogen Production Unit

HPU:

Switch to biomass feed

System and Integration Aspects of Biomass-based Gasification, November 19-20 2013, Göteborg, Sweden
Comparison of 4 different cases:

- **Case A.** 35 % substitution, internal drying, HP steam export
- **Case B.** 100 % substitution, internal drying, HP steam export
- **Case C.** 100 % substitution, external drying, HP steam export
- **Case D.** 100 % substitution, external drying, electricity production
Results: excess energy export and efficiency

- **Case A**: energy demand drying = excess heat from HPU
- **Case B**: internal drying = penalty on efficiency
- **Case C**: external drying = gain of 9 p.p. in efficiency
- **Case D**: 21.8 MW electricity produced
Results: reduction of carbon footprint

ΔCO₂ (kt/y)

Case A  Case B  Case C  Case D

0  -100  -200  -300  -400  -500  -600  -700  -800

Refinery’s total CO₂ emissions: 1,67 Mt in 2010
Integration of biomass gasification with a Scandinavian mechanical pulp and paper mill – Consequences for mass and energy balances and global CO₂ emissions

Johan Isaksson a, b, Karin Pettersson a, Maryam Mahmoudkhani a, Anders Åsblad b, Thore Berntsson a

a Division of Heat and Power Technology, Department of Energy and Environment, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden
b GT Industriell Energi, Chalmers Teknikpark, SE-412 88 Gothenburg, Sweden
Host site: TMP mill and co-located Sawmill

- Biomass residues corresponding to 94 MW\textsubscript{LHV}
- In addition, about 1.55 TWh (177 MW\textsubscript{LHV}) of forest residues is available within a 100 km radius.

3 gasification based biorefinery concepts were considered
Carbon balances incl comparison with stand-alone concepts

Grey-shade: if CCS is applied to process off-gases

Graph showing CO₂ emissions reduction in kg CO₂/ΔMWh for different marginal electricity production technologies and substitution of coal in coal PP (co-firing).
SNG production process integrated with Bio-CHP plant

Thermal integration

Power

Heat

Biomass CHP (existing)

Biomass SNG (extension)

Boiler

Gasifier

Fuel

Fuel

Steam

Gas processing

SNG

Excess heat

Char

Heat

Char
Case study – SNG production

Case SNG standalone
- existing CHP plant
- Stand-alone SNG process with steam dryer

Cases SNG integrated

Case 1
- steam drying
- Balancing integration
- integrated SNG production (8000 h/y)
- existing CHP plant

Case 2
- low T air drying
- Balancing integration
- integrated SNG production (8000 h/y)
- existing CHP plant

Initial state
- \( \dot{Q}_{\text{wood fuel}} \) (5000 h/y)

Stand-alone SNG production
- \( \dot{Q}_{\text{wood fuel}} \) (5000 h/y)
- heat discharged (3000 h/y)

Integrated SNG production
- \( \dot{Q}_{\text{wood fuel}} \) (5000 h/y)
- \( P_{el} \) (5000 h/y)

System and Integration Aspects of Biomass-based Gasification, November 29-30, 2013, Göteborg, Sweden
Results - $\eta_{sys}$

Results - $\Delta CO_2$

Results - biomass use CO$_2$ neutral

Results - Investment opportunity
Integration of biomass gasification to incumbent industry – energy balances and greenhouse gas emission consequences

Kristina Holmgren, PhD student, IVL Swedish Environmental Research Institute Ltd /Chalmers, Div. Heat & Power Technology
Thore Berntsson, Supervisor; Professor, Chalmers; Div. Energy & Environment, Dep. Heat & Power Technology
Eva Andersson, Co-supervisor; PhD, CIT Industriell Energi AB
Tomas Rydberg, Co-supervisor, PhD, IVL Swedish Environmental Research Institute Ltd

Financially supported by:
Process integrated cases analysed

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<tr>
<th>Case</th>
<th>Action</th>
<th>Energy Requirements</th>
<th>Fuel Savings</th>
<th>Product Replacement</th>
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<tbody>
<tr>
<td>1</td>
<td>Steam at three levels</td>
<td>Chemical cluster (current energy balance)</td>
<td>Fuel savings</td>
<td>Product replacement.</td>
</tr>
<tr>
<td></td>
<td>Gasification &amp; MeOH synthesis</td>
<td>Low temperature heat for biomass drying (106 MW)</td>
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<tr>
<td>2a</td>
<td>Steam at two levels</td>
<td>Chemical cluster (cat. A measures introduced)</td>
<td>Fuel savings</td>
<td>Product replacement.</td>
</tr>
<tr>
<td></td>
<td>Gasification &amp; MeOH synthesis</td>
<td>Low temperature heat for biomass drying (43 MW)</td>
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</tr>
<tr>
<td>2b</td>
<td>Steam at three levels</td>
<td>Chemical cluster (cat. A measures + new LP steam lines introduced)</td>
<td>Fuel savings</td>
<td>Product replacement.</td>
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<td>Product replacement.</td>
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<td></td>
<td>Gasification, MeOH &amp; MTO process</td>
<td>Low temperature heat for biomass drying (106 MW), H₂ for increasing MeOH prod.</td>
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<td>Steam to central boiler in cluster</td>
<td>Chemical cluster (cat. A measures introduced)</td>
<td>Fuel savings</td>
<td>Product replacement.</td>
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Introduction – Objective - Background – Method

Papers – I – II – III

Conclusions – Future work
Conclusions

- Process integrated cases have higher GHG reduction potential than SA cases
- The GHG impact of replacing DH can be negative or positive
- The use of excess H$_2$ increase GHG emission reductions
- Production of olefins and biofuels result in GHG emissions reductions of similar magnitude
- Directly replacing coal is still better than all the investigated cases
General conclusions from recent studies in our group

• Hard to compete with coal substitution if climate change mitigation is the main objective for biomass usage…
• Electric power generation in high-efficiency biomass-fired power plants is a climate-friendly option, as long as coal power plants are the marginal power generation technology
• For future power grid generation mixes, the situation is significantly different. Use of biomass as feedstock for production of vehicle fuels, materials and chemicals is most attractive from a climate-change perspective
• Integration of biomass gasification biorefinery concepts at an industrial process plant site can achieve significant synergy effects compared to stand-alone operation
• Carbon atoms are not strictly necessary for energy purposes whereas they are necessary for production of "green" materials and chemicals