Co-production of Hydrogen and Electricity from Lignocellulosic Biomass: 

*Process Design and Thermo-economic Optimization*

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Context

- Climate change mitigation & sustainable energy supply
  - H₂ as an alternative energy carrier

H₂ production & Power plants
- Natural gas reforming & coal gasification
  - Fossil fuel usage & CO₂ emissions

Alternative:
Thermo-chemical biomass-based processes for H₂ & É production
Objective

- Thermo-chemical biomass conversion
  - Renewable resources usage
  - CO₂ emissions reduction

**Diagram**

Biomass → Biomass decomposition (200-1200°C) → Syngas (CO+H₂) → Water gas shift → (CO₂+H₂) → H₂ purification → H₂ → GT

**Objectives**

- Development of a comprehensive comparison framework
  - Consistent comparison & optimization with regard to energetic, economic & environmental considerations
- Assess the competition between H₂ and electricity only generation processes and polygeneration processes with/without CO₂ capture

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<th>H₂ prod.</th>
<th>ε [%]</th>
<th>kg₃CO₂/MWh₃H₂</th>
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- Potential process improvement by energy recovery and heat valorization for the polygeneration of H₂, captured CO₂, heat & power

IPCC 2005
Methodology

- Systematic framework: Thermo-environomic modeling and optimization
  - Flowsheeting
  - Energy integration techniques
  - Performance evaluation: Costing & Life cycle assessment
  - Multi-objective optimization

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Biomass conversion process

- Without/with CO₂ capture (compression to 110bar)
- H₂ production: É import or energy self-sustained conditions (selfsufficient)
- É generation by burning H₂-rich fuel or pure H₂

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Process Performance - Indicators

- Performance indicators
  - Overall energy efficiency $\varepsilon_{tot}$
    - Expressed on the basis of the lower heating value of dry substance
      \[
      \varepsilon_{tot} = \frac{\Delta h_{H_2, out}^0 \cdot \dot{m}_{H_2}^- + \dot{E}^-}{\Delta h_{biomass}^0 \cdot \dot{m}_{biomass}^+ + \dot{E}^+}
      \]
  - Natural gas equivalent efficiency $\varepsilon_{eq}$
    - $\dot{E}$ substituted by a natural gas fuel equivalent: NGCC/HP
      \[
      \varepsilon_{eq} = \frac{\Delta h_{H_2, out}^0 \cdot \dot{m}_{H_2}^- + \frac{1}{\eta_{NGCC}} \frac{\Delta h_{NG}^0}{\Delta k_{NG}} \dot{E}^-}{\Delta h_{biomass}^0 \cdot \dot{m}_{biomass}^+}
      \]
  - $H_2$ productivity
    - $H_2$ yield
      \[
      Y_{H_2} = \frac{g_{H_2}}{kg_{biomass}}
      \]
    - Conversion efficiency
      \[
      \varepsilon_{tot} = \frac{\Delta h_{H_2, fuel}^0 \cdot \dot{m}_{H_2, fuel}^-}{\Delta h_{biomass}^0 \cdot \dot{m}_{biomass}^+}
      \]
• Energy Integration – H₂ production (Ê import)
  - Without / with CO₂ capture

- CO₂ capture: Energy consumption for solvent regeneration

- Study influence of heat recovery and cogeneration systems including steam network, gas turbines and heat pump
Multi-objective optimization

- **Objectives**
  - Max $\varepsilon_{tot}$
  - Min investment
  - Decision variables: $T_{syn}$, $P_{syn}$, $T_{HTS}$, $T_{LTS}$, $P_{WGS}$, $S/C$
  - Constraints: Thermo-economic model

- **Optimization improves performance**
  - $\varepsilon_{tot}$ ↑ , investment ↑
  - $\varepsilon_{tot}$ ↑ , $CO_2$ capture rate ↓
  - Compromise $\varepsilon_{tot}$ & capture

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ECOS 2011 – Co-production of $H_2$ & $\dot{E}$ from wood  
L. Tock / EPFL-LENI
Process Performance

- Energy Integration – Compromise configurations
  - H₂ production: È import
  - H₂ production: self-sufficient

- Energy integration improved by modification operating conditions
- CO₂ capture integration improved by introduction of heat pump transferring heat to higher T for valorization in steam cycle
Energy Integration – Compromise configurations

- **H₂ production: È import**
  - $\varepsilon_{\text{tot}}$ 60%
  - $\varepsilon_{\text{eq}}$ 38%
  - 65% capt.

- **H₂ production: self-sufficient**
  - $\varepsilon_{\text{tot}}$ 40%
  - $\varepsilon_{\text{eq}}$ 40%
  - 75% capt.

- $\varepsilon_{\text{tot}} \downarrow$: lower H₂ yield since part is burnt (50g$_{\text{H}_2}$/kg$_{\text{BM}}$ (44%))
- $\varepsilon_{\text{eq}} \uparrow$: internal electricity production more efficient than NGCC
Electricity generation
- Pure H₂ burnt in GT

Steam network integration optimized
- Maximal cogeneration
- $\varepsilon_{\text{tot}}$ competitive with coal IGCC with CO₂ capture
Electricity generation

Production cost

Contributions:

- Resource purchase (>50%)
  - 50$/MWh_{wood}
- Gasifier purchase

* Economic assumptions: Operation: 8000h/y; lifetime 15 y; interest rate 6%, Wood price 50$/MWh_{BM}
Process Performance

- Production cost – influence of resource price
  - Wood price: 10-70$/MWh_BM

*É* generation

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- H₂ production

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- COE: 89-362$/MWh_{\text{e}}
  - competitive if high CO₂ taxes

- CO₂ capture: production cost
  - $\epsilon_{\text{tot}} \downarrow$ up to 10%-points

- Production cost: 65-262 $/MWh_{\text{H}_2}$

* Economic assumptions: Operation: 8000h/y; lifetime 15 y; interest rate 6%, *É* price 270$/MWhe
Environmental impact: \( \dot{E} \) generation

- IPCC method with GWP 100 years, FU 1kJ of biomass

Environmental benefit of capturing CO\(_2\)
Conclusions

- Systematic methodology
  - Thermo-economic & LCA models
  - Multi-objective optimization
    - Conceptual design, optimization & comparison of H₂ and electricity production from wood

- Potential of polygeneration of H₂, captured CO₂, heat & power
  - Appropriate energy integration improving performance

- Process performance
  - H₂: $\varepsilon_{\text{tot}} = 60\%, \ 65\text{-}262$/MWh$_{\text{H₂}}$
  - $\dot{E}$: $\varepsilon_{\text{tot}} = 39\%, \ 89\text{-}362$/MWh$_{\text{e}}$
  - LCA analysis: benefit using renewable resources and capturing CO₂

| H₂ prod. | $\varepsilon$ [%] | kg$_{\text{CO₂}}$/MWh$_{\text{H₂}}$ | $\$/MWh$_{\text{H₂}}$
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| Coal IGCC | $\varepsilon$ [%] | kg$_{\text{CO₂}}$/MWh$_{\text{e}}$ | $\$/MWh$_{\text{e}}$
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*IPCC 2005

*Competitiveness on energy market depends strongly on resource price and imposed CO₂ taxes and technologies!*
Thank you for your attention!