Advanced Thermochemical Conversion of Various Waste Feedstock with CCS for Hydrogen Production – A Life Cycle Assessment

Suviti Chari, Alex Sebastiani, Andrea Paulillo, Paola Lettieri, Massimiliano Materazzi
University College London

Solid Waste Management, Chania 2023
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Context: Waste, Hydrogen & Carbon Capture & Storage

Feedstocks
- Energy crops
- Short rotation forestry
- Marine crops
- MSW/RDF

Pre-processing

Conversion
- Gasification
- Pyrolysis
- Combustion
- Anaerobic digestion
- Fermentation
- Esterification

Energy vector
- Biomethane
- Biodiesel
- Biohydrogen
- Electricity
- Aviation fuels

CCUS
- Pre-combustion capture
- Post-combustion capture
- Direct air capture
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(1) BEIS. UK Hydrogen Strategy; 2021; Vol. 85
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BECCS, DAC

(1) IPCC. Mitigation of climate change Summary for policymakers; 2022
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(1) Committee on Climate Change. *The Sixth Carbon Budget The UK's path to Net Zero*. 2020
Research Objectives

Understand the environmental value of $H_2$ with BECCS and the effect of composition of waste on carbon sequestration potentials

- Feasibility of using Waste (MSW/Waste Wood) to produce grid-quality $H_2$ with Carbon capture and storage

- Identify **environmental hotspots** of industrially validated Bio-$H_2$ – BECCS process

- Understand how **changing biomass content** of waste affects environmental impact results

- Compare with other alternative low-carbon hydrogen production technologies
- Will convert 8,000 tonnes of waste per annum into 22 GWh of substitute natural gas (SNG).
- Will be first plant in the world to produce BioSNG from waste (RDF/WW)
- Work is ongoing to demonstrate production of Bio-H₂ for heat and transport.
Process Overview: Waste-to-H₂ with CCS

- Detailed mass-and-energy balances using ASPEN Plus, validated by demo & pilot plant operation
- Modelled commercial facility converts 110,000 tonnes per annum of waste to approximately 50 MWh of fuel-cell quality hydrogen (99.9% purity)
- Atmospheric steam-oxygen gasification as core conversion technology (2 stage – FBR & plasma tar reforming)
- Amine-based solvent CO₂ removal technology employed (at 90% removal efficiency, 99% CO₂ purity)
- CO₂ transported to one of UK’s CCUS clusters and injected into a saline aquifer
LCA Methodology: Assumptions

- **Functional unit:** 1 MW of fuel-cell quality H₂ produced
- **System Boundary** includes: waste transportation (50km), CO₂ transportation by lorry, ship & pipeline, CO₂ injection and fugitive H₂ emissions. Plant construction is also included in hotspot analysis.
- **Zero-burden approach** for waste. Counterfactual cases not considered
- **Multifunctionality & substitution:**
  - Electricity from tail gas (via gas engine) replaces UK grid mix
  - Recovery of metals from MSW for RDF preparation

EF 3.0 Method.
Ecoinvent datasets

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Complete system boundary: Blue-H$_2$ and Green-H$_2$
LCA Hotspot Results: MSW & Waste Wood – Climate Change Impact

Climate Change Impact (kg CO₂ eq. / MW H₂)

MSW

-88

Waste wood

-261

LCA Comparative analysis: Low-carbon H₂ production routes


LCA Comparative analysis: Low-carbon H$_2$ production routes

- Acidification [Mole of H$^+$ eq.]
- Ecotoxicity, freshwater - total [CTUeq]
- Eutrophication, freshwater [kg P eq.]
- Eutrophication, marine [kg N eq.]
- Eutrophication, terrestrial [Mole of N eq.]
- Human toxicity, cancer - total [CTUh]
- Human toxicity, non-cancer - total [CTUh]

<table>
<thead>
<tr>
<th>Normalised input [PE/FU]</th>
<th>Normalised input [PE/FU]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>0.4</td>
<td>0.4</td>
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<tr>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

- Ionising radiation, human health [kBq U235 eq.]
- Land Use [Pt]
- Ozone depletion [kg CFC-11 eq.]
- Particulate matter [Disease incidences]
- Photochemical ozone formation, human health [kg NMVOC eq.]
- Resource use, fossils [MJ]
- Resource use, mineral and metals [kg Sb eq.]
- Water use [m$^3$ world equiv.]
LCA Comparative analysis: Low-carbon H₂ production routes

- Pre-combustion CCS plays a crucial role for GHG mitigation \(\rightarrow\) carbon negative technology

- Boundary conditions reveal that biogenic content carries the greatest weight in climate change impact result. However, trade-offs exist (contributions to all other categories)

- BECCS capability may change based on waste composition feedstock

- For H\(_2\) production, low-carbon technologies will likely complement not compete

**Acknowledgements**
Suviti Chari
suviti.chari.20@ucl.ac.uk

https://www.linkedin.com/in/suvitichari/

Bioenergy Technology Research Lab
Department of Chemical Engineering, UCL

Acknowledgements
Appendix

**Conventional System**
- Slipstream of hydrogen rich syngas taken after water gas shift reactor.
- Transferred to Xebec PSA which produces high purity hydrogen stream and hydrogen rich tail gas.
- Tail gas recycled into the process.
- Hydrogen metered into gas bottles for use in transport.

**SEWGS System**
- UCL to host SEWGS system at Manufacturing Futures Lab.
- Simulated syngas based on experience from Swindon plant will be injected into system.
- Absorber operated at 300-400°C, 5 bar. Desorber operated at 600-700°C, 1 bar.
- SEWGS offers significant advantages over conventional WGS coupled with carbon advantage. Far lower GHG emissions associated with process.

**Project Timelines**
- Installation through 2023, commissioning in H1 2024, operational in H2 2024.
BioH₂ purity for transportation

- H₂ and oxidant air supplied to the polymer electrolyte fuel cell (PEFC)
- Contaminants CO₂ and CH₄ fed through the H₂ supply to PEFC.

- Considerable impact on PEFC performance observed only beyond 20% (vol.) CH₄.
- PEFC performance recovered to normal after the removal of CH₄ (pure-H₂ repeat case).
  - CH₄ acts mainly as diluent.

- 0.5% CO₂ resulted in significant performance reduction (equivalent to 20%CH₄ dilution).
- PEFC performance not recovered after the removal of CO₂ (pure-H₂ repeat case).
  - CO₂ contamination results in permanent performance reduction due to chemical reaction.
### Changing Feedstock: Key Data

<table>
<thead>
<tr>
<th>Key flows</th>
<th>Units</th>
<th>Biohydrogen (MSW)</th>
<th>Biohydrogen (Waste wood)</th>
<th>Blue Hydrogen SMR</th>
<th>Blue Hydrogen ATR</th>
<th>Green Hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feedstock type</td>
<td></td>
<td>MSW/RDF</td>
<td>Waste wood</td>
<td>Natural gas</td>
<td>Water</td>
<td></td>
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<tr>
<td>Feedstock kg</td>
<td>kg</td>
<td>442.2/283.6</td>
<td>372.2</td>
<td></td>
<td></td>
<td>226.8</td>
</tr>
<tr>
<td></td>
<td>m³</td>
<td></td>
<td>116.4</td>
<td>117.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen kg</td>
<td>kg</td>
<td>89.4</td>
<td>101</td>
<td></td>
<td></td>
<td>n.a.</td>
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<tr>
<td>Electricity MJ</td>
<td>MJ</td>
<td>514</td>
<td>617</td>
<td>27.7</td>
<td>115.7</td>
<td>4974</td>
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<tr>
<td>Thermal energy MJ</td>
<td>MJ</td>
<td>1550</td>
<td>1657</td>
<td></td>
<td></td>
<td>n.a.</td>
</tr>
<tr>
<td><strong>Output</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen MJ</td>
<td>MJ</td>
<td>3600</td>
<td>3600</td>
<td>3600</td>
<td>3600</td>
<td></td>
</tr>
<tr>
<td>Materials recovered kg</td>
<td>kg</td>
<td>17.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CO₂ released kg</td>
<td>kg</td>
<td>46.5</td>
<td>53.5</td>
<td>120.63</td>
<td>38.1</td>
<td>0</td>
</tr>
<tr>
<td>Sequestered CO₂ kg</td>
<td>kg</td>
<td>414.4</td>
<td>484.1</td>
<td></td>
<td></td>
<td>n.a.</td>
</tr>
</tbody>
</table>
### Waste fractions [wt% as received]

<table>
<thead>
<tr>
<th>Waste fractions</th>
<th>MSW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper and cardboard</td>
<td>22.7</td>
</tr>
<tr>
<td>Wood</td>
<td>3.7</td>
</tr>
<tr>
<td>Metals</td>
<td>4.3</td>
</tr>
<tr>
<td>Glass</td>
<td>6.6</td>
</tr>
<tr>
<td>Textile</td>
<td>2.8</td>
</tr>
<tr>
<td>WEEE</td>
<td>2.2</td>
</tr>
<tr>
<td>Plastics</td>
<td>10</td>
</tr>
<tr>
<td>Inert/aggregates/solid</td>
<td>5.3</td>
</tr>
<tr>
<td>Organic fines</td>
<td>35.5</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>7.1</td>
</tr>
</tbody>
</table>
Process Environmental Performance

- Biogenic Carbon 65%
- H₂ purity >99.97%, P=46 bar
- CO₂ purity >95%, P=35 bar

* MEA: Monoehanolamine solution (30% wt)
** SEWGS: Sorption enhanced water gas shift
Demo-plant for BioSNG/BioH₂ production

~22 ton/day RDF (GCV:22.1 MJ/kg)
T: 830 °C (1S) – 1150 °C (2S)
ER: 0.3-0.38
S/O mol: 2.5-3

Energy conversion η: 73-76%
H₂/CO = 1.0-1.2
Tar reforming η: +99%
Ash in slag product: 56-63% wt.

Syngas to BioSNG η: 70-75%
CO₂ removal η: +99%

Benfield process

CH₄ bulk production

Gas cleaning
Demo-plant for BioSNG/BioH$_2$ production (flowsheet)

~22 ton/day RDF (GCV: 22.1 MJ/kg)
T: 830 °C (1S) – 1150 °C (2S)
ER: 0.3-0.38
S/O mol: 2.5-3

Syngas in: 10-20 kg/h
BioH$_2$ out: 0.6-1.2 kg/h
Syn to BioH$_2$ energy η: 67%

Syngas to BioSNG η: 70-75%
CO$_2$ removal η: +99%
Feasibility for BioH$_2$ from waste feedstock

<table>
<thead>
<tr>
<th>Stream</th>
<th>Mass flow [kg/h]</th>
<th>Energy [MW$_{HHV}$]</th>
<th>H$_2$ purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>RDF input</td>
<td>361.5</td>
<td>1.66</td>
<td></td>
</tr>
<tr>
<td>BioH$_2$ from PSA</td>
<td>25.5</td>
<td>1</td>
<td>&gt;99.97%</td>
</tr>
<tr>
<td>Tail gas from PSA</td>
<td>488.6</td>
<td>0.32</td>
<td>~14%</td>
</tr>
</tbody>
</table>

- Absence of acid contaminants and impurities after the gas cleaning stage;
- Increased H$_2$ fraction after the WGS stage upto 56% dry; CO reduction to 6% dry
- CO$_2$ removal efficiency > 99% with the PSA
- Approximately 40% H$_2$ is lost with tail gas
Process optimization: tail gas recirculation
Hotspot Analysis

- Credits for **net electricity production** – from grid-quality hydrogen produced from gas engine

- Credits from **ferrous & non-ferrous metal recovery** during MSW preparation

- Burdens for **reforming process, CO₂ liquefaction and H₂ compression** to climate change and photochemical ozone formation

- Burdens for **gas cleaning process, primarily alkali scrubber**, to most categories