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

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University College London

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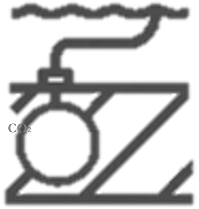
Context: Waste, Hydrogen & Carbon Capture & Storage



CCUS

- Pre-combustion capture
- Post-combustion capture
- Direct air capture

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

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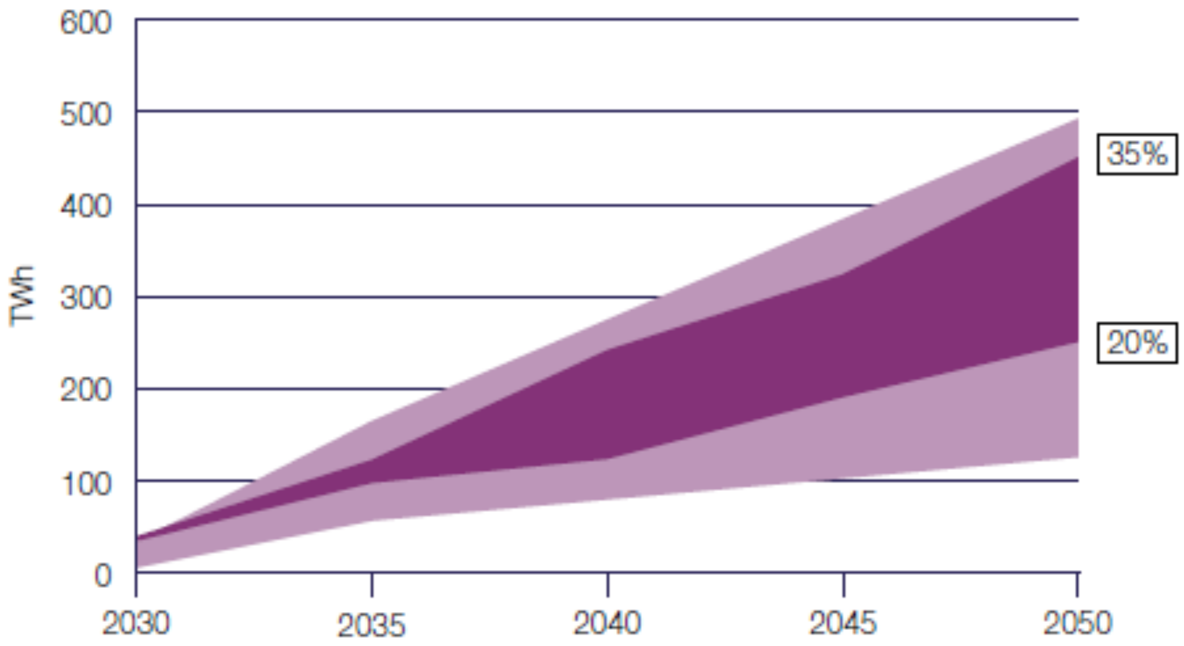
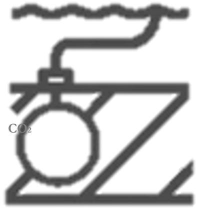


% = hydrogen as proportion of total energy consumption in 2050



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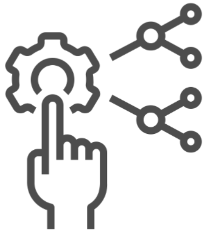

Feedstocks → Pre-processing → Conversion → Energy vector

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(1) BEIS. *UK Hydrogen Strategy*; 2021; Vol. 85

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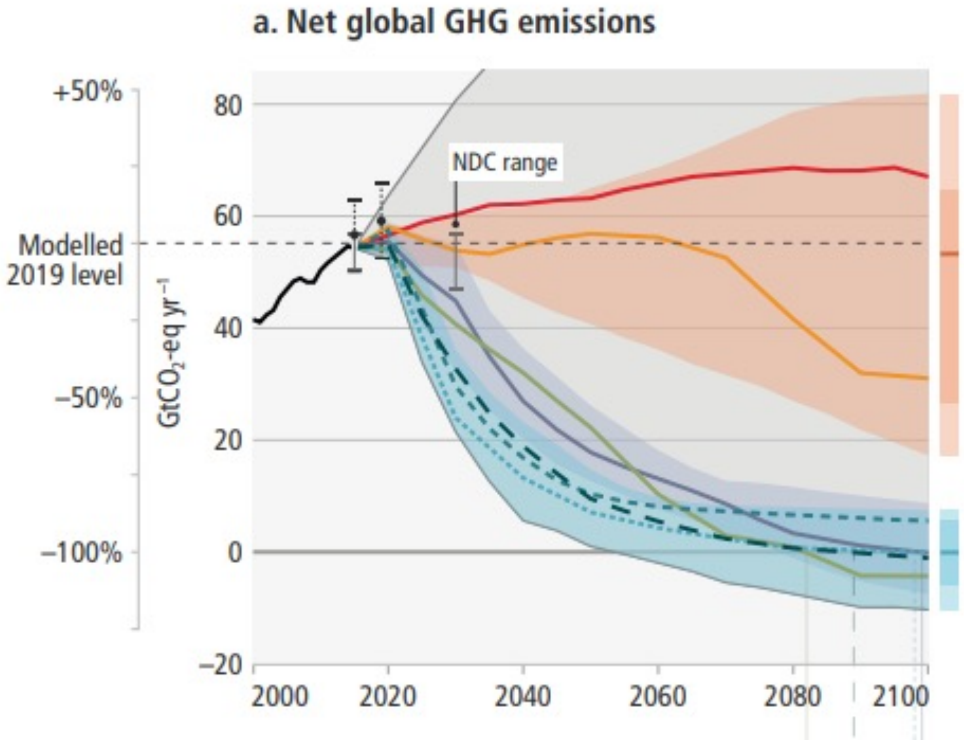
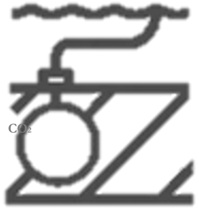


BECCS, DAC



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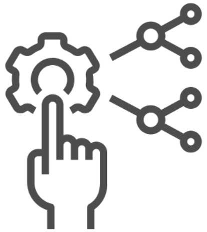

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(1) IPCC. *Mitigation of climate change Summary for policymakers*; 2022

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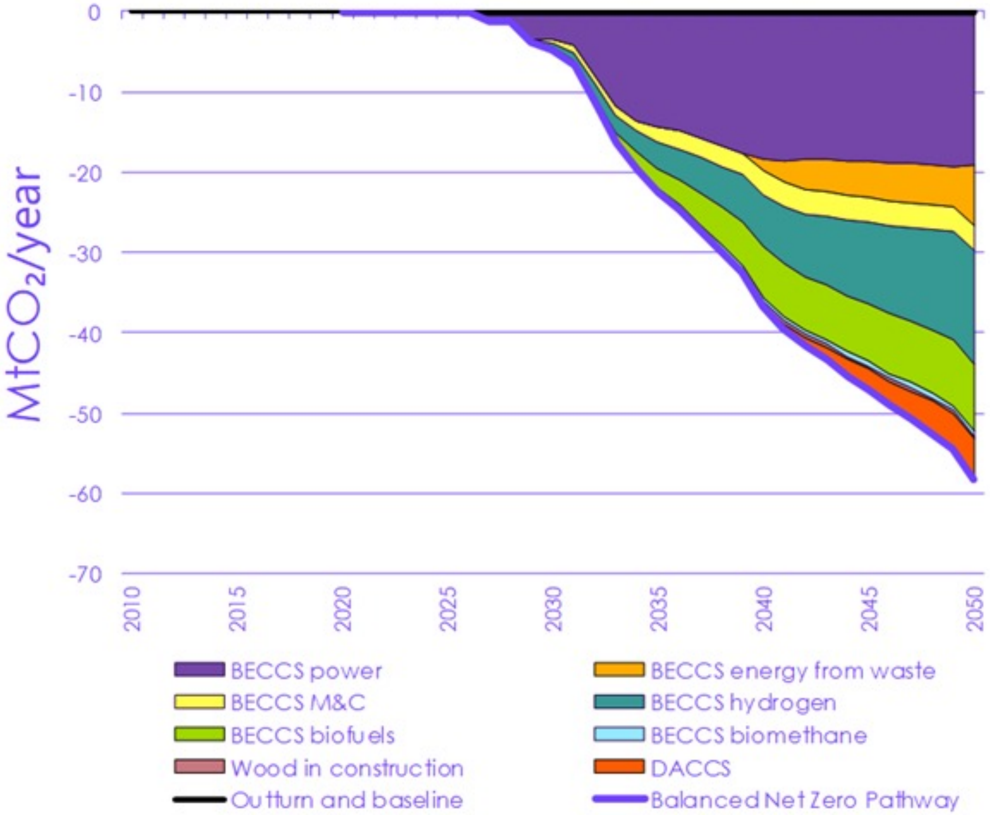

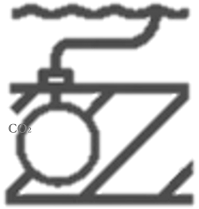

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(1) Committee on Climate Change. *The Sixth Carbon Budget The UK's path to Net Zero.* 2020

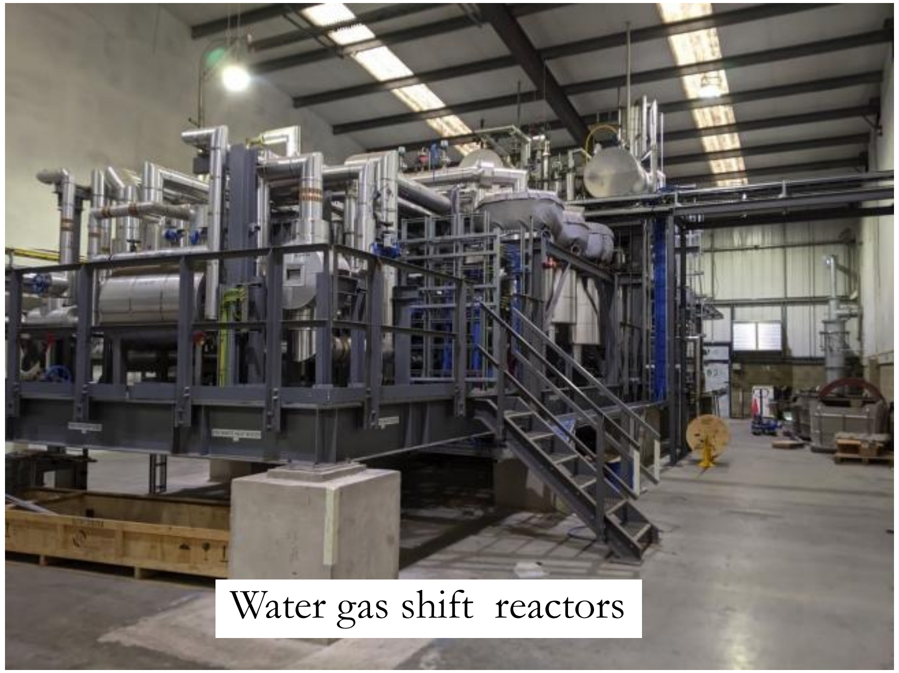
Research Objectives

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

Process Overview: Demonstration Plant (Advanced Biofuels Solutions)

- 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-H_2 for heat and transport.

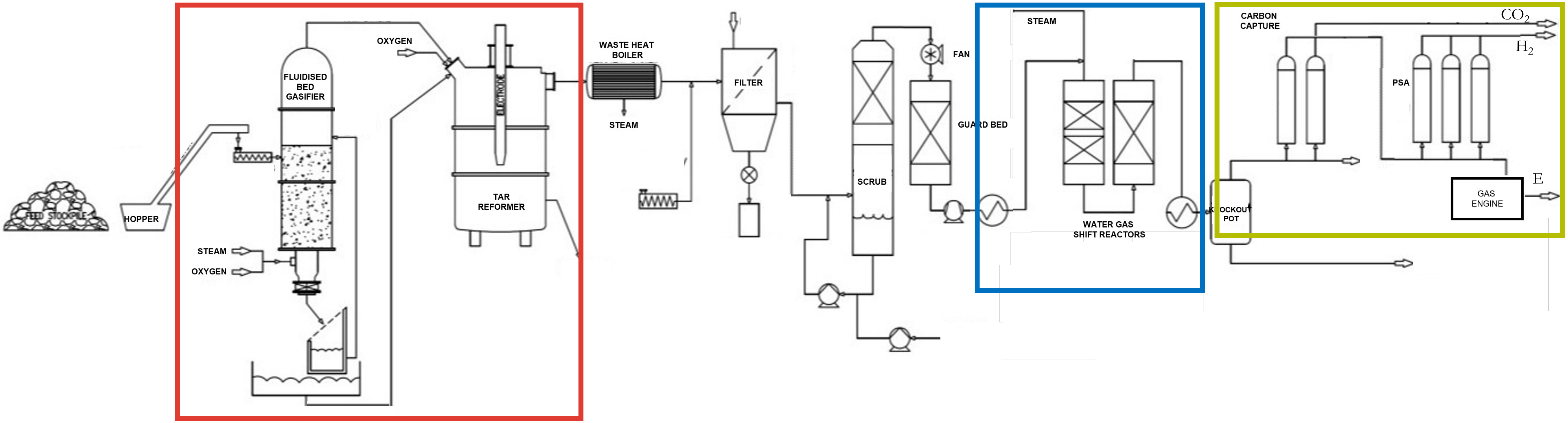


Water gas shift reactors

CCS unit

Demonstration plant gasifier

Process Overview: Waste-to-H_2 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** CO_2 removal technology employed (at 90% removal efficiency, 99% CO_2 purity)
- CO_2 transported to one of UK's CCUS clusters and injected into a saline aquifer

LCA Methodology: Assumptions

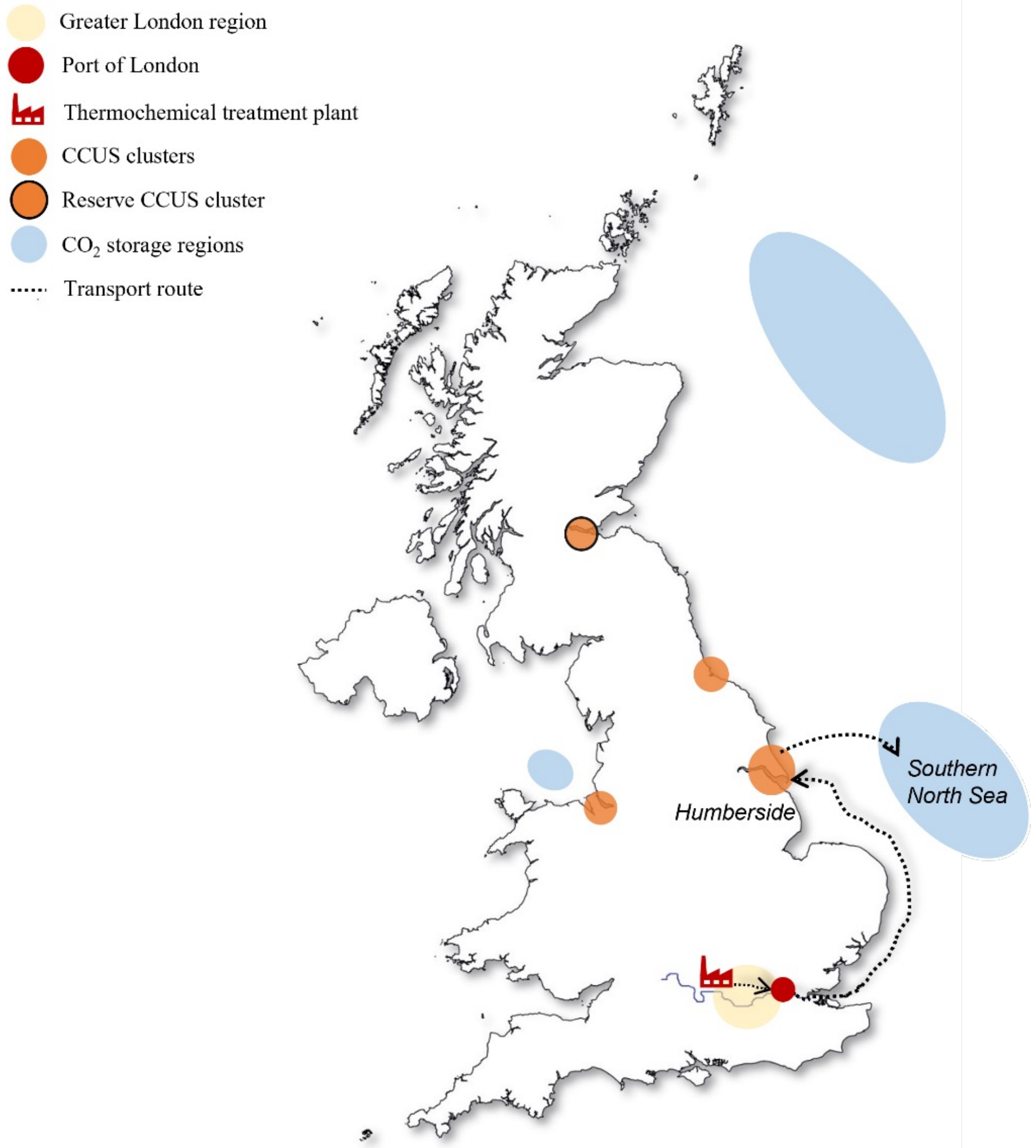
- **Functional unit:** 1 MW of fuel-cell quality H_2 produced
- **System Boundary** includes: waste transportation (50km), CO_2 transportation by lorry, ship & pipeline, CO_2 injection and fugitive H_2 emissions.

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

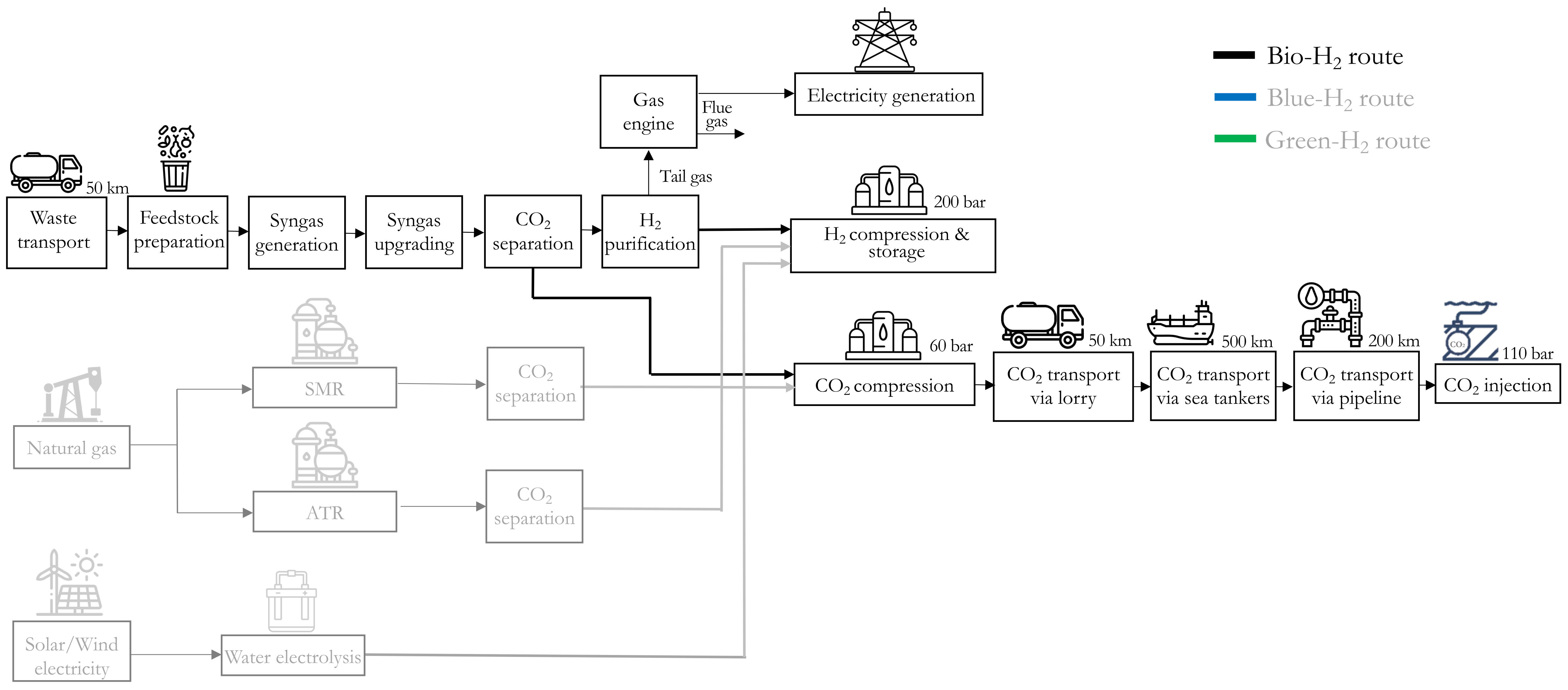
EF 3.0 Method.

Ecoinvent datasets

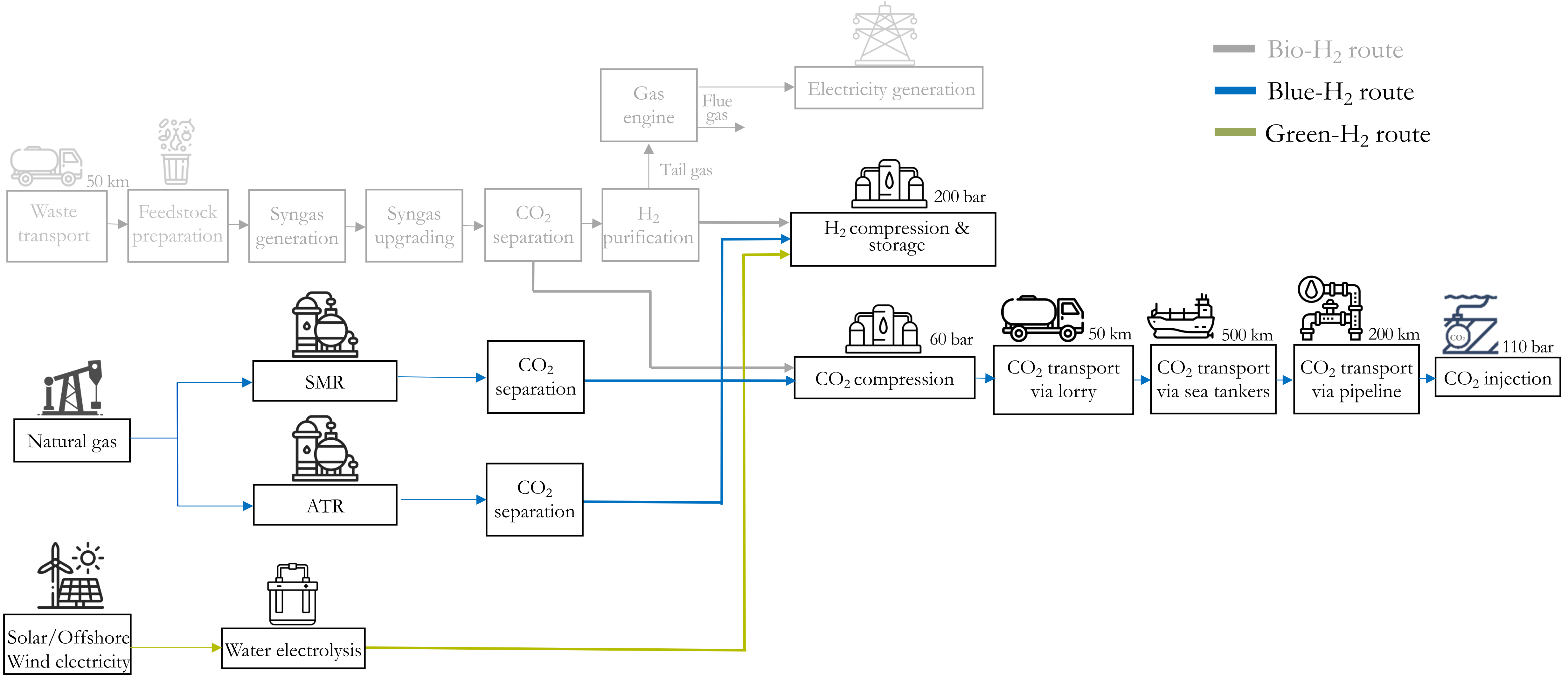


(1) Chari, S.; Sebastiani, A.; Paulillo, A.; Materazzi, M. The Environmental Performance of Mixed Plastic Waste Gasification with Carbon Capture and Storage to Produce Hydrogen in the U.K. *ACS Sustain. Chem. Eng.* **2022**.

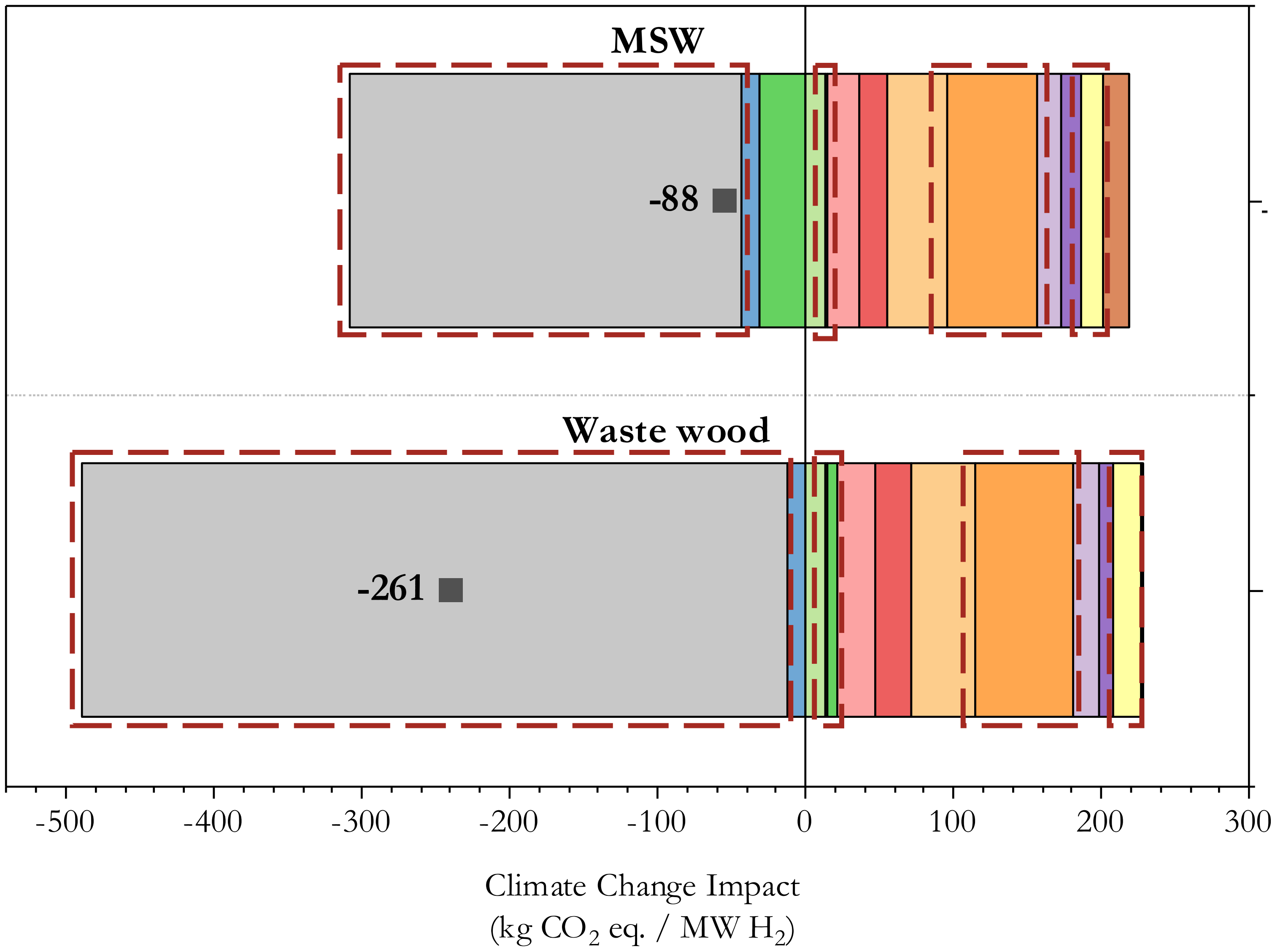
Complete system boundary: Waste-to-H_2 with CCS

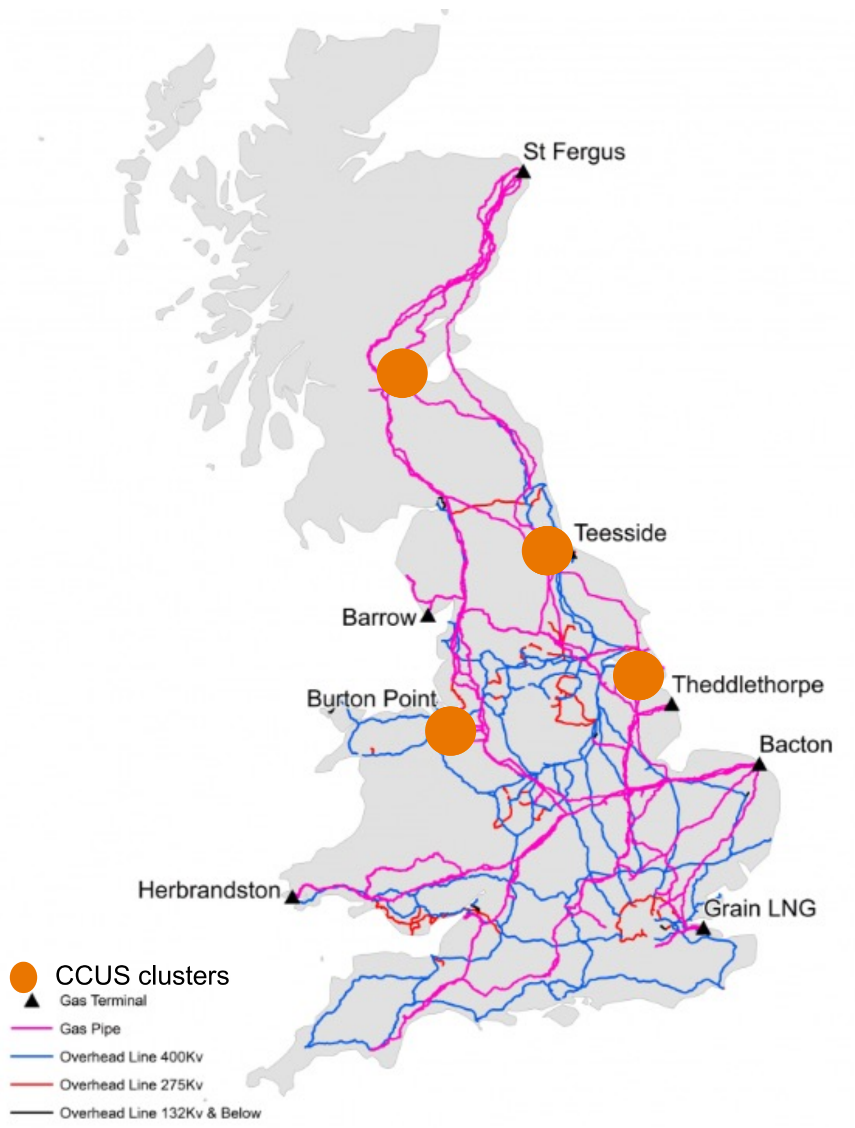


Complete system boundary: Blue-H_2 and Green-H_2



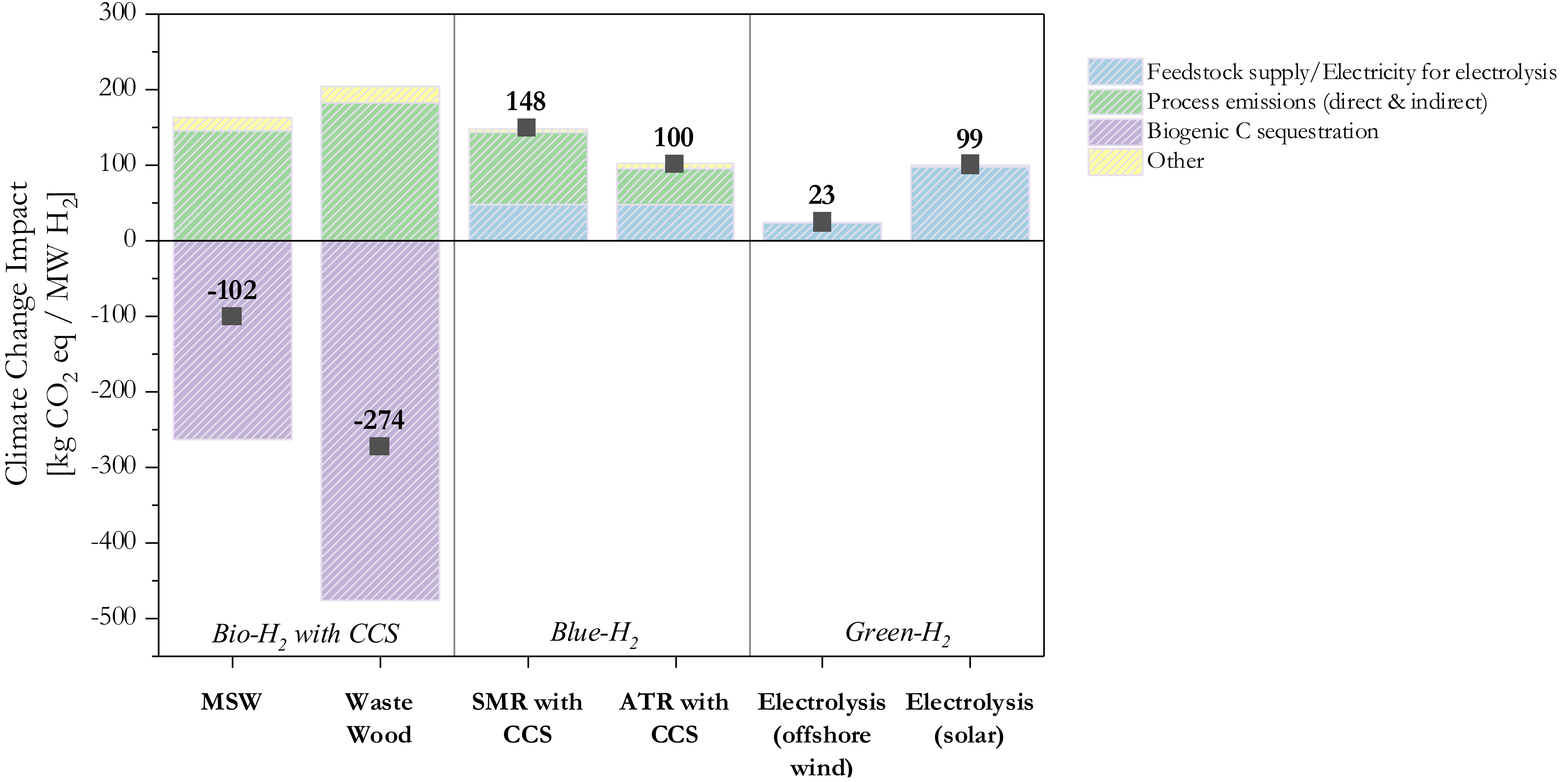
LCA Hotspot Results: MSW & Waste Wood – Climate Change Impact





(1) Amaya-Santos, G.; Chari, S.; Sebastiani, A.; Grimaldi, F.; Lettieri, P.; Materazzi, M. Biohydrogen: A Life Cycle Assessment and Comparison with Alternative Low-Carbon Production Routes in UK. *J. Clean. Prod.* **2021**, *319*, 128886

LCA Comparative analysis: Low-carbon H_2 production routes



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(2) Antonini, C.; Treyer, K.; Streb, A.; van der Spek, M.; Bauer, C.; Mazzotti, M. Hydrogen Production from Natural Gas and Biomethane with Carbon Capture and Storage - A Techno-Environmental Analysis. *Sustain. Energy Fuels* **2020**, *4* (6), 2967–2986. https://doi.org/10.1039/d0se00222d.

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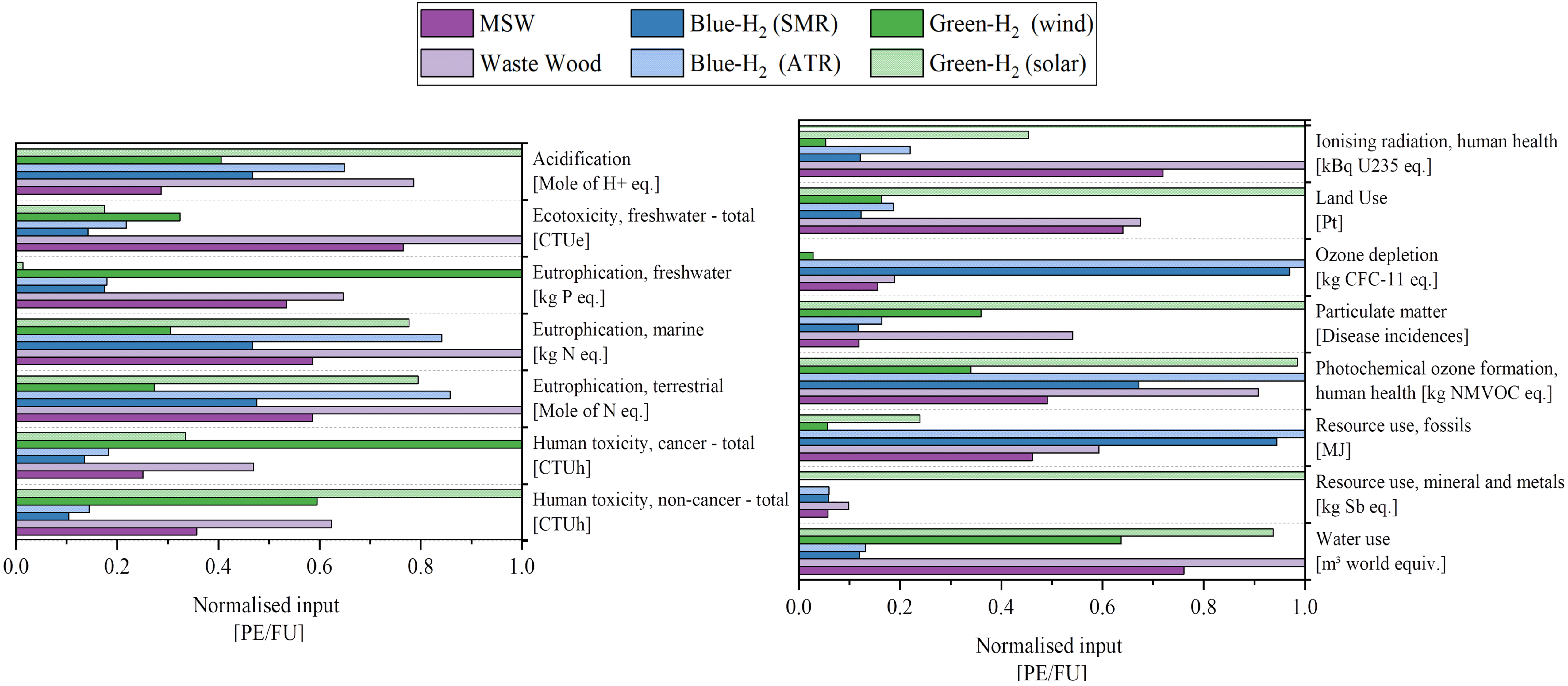

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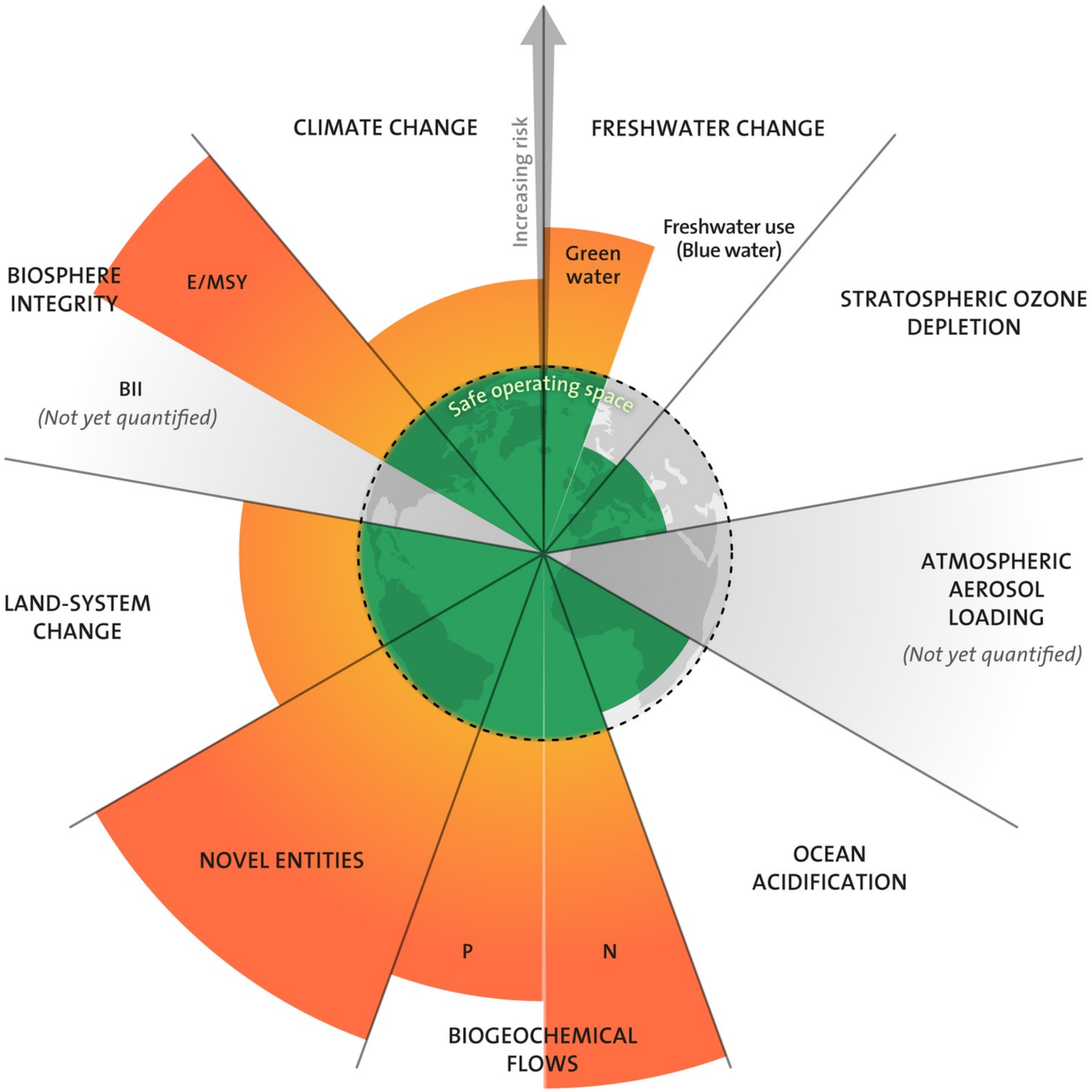
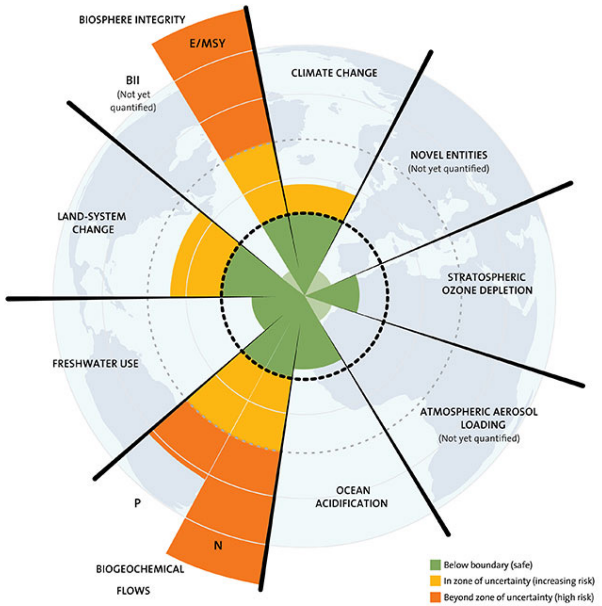


(1) Wang-Erlandsson, L., Tobian, A., van der Ent, R.J. *et al.* A planetary boundary for green water. *Nat Rev Earth Environ* **3**, 380–392 (2022). https://doi.org/10.1038/s43017-022-00287-8

Conclusion - Summary

- Pre-combustion CCS plays a crucial role for GHG mitigation → 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

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UKRI Innovate UK

Department for Business, Energy & Industrial Strategy

Get in touch!

UCL

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Acknowledgements

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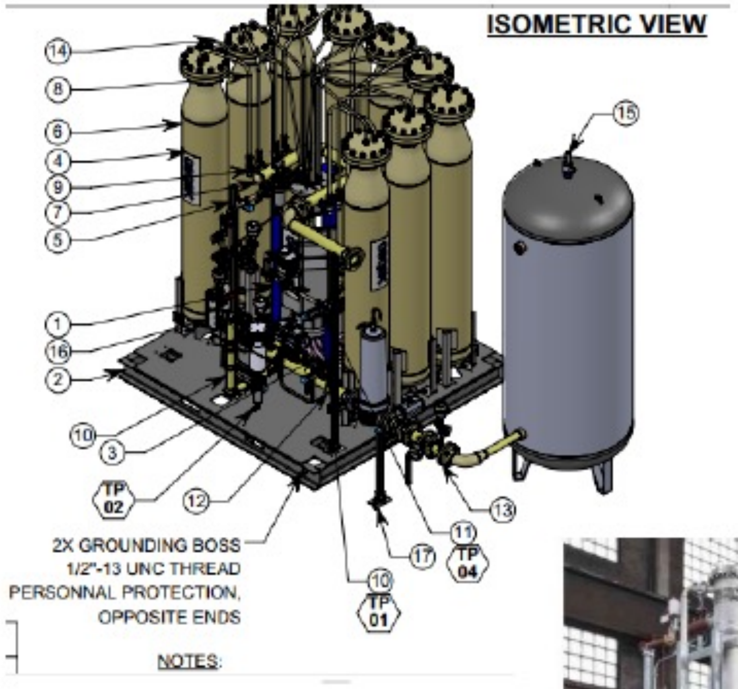


Source: ABSL

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.

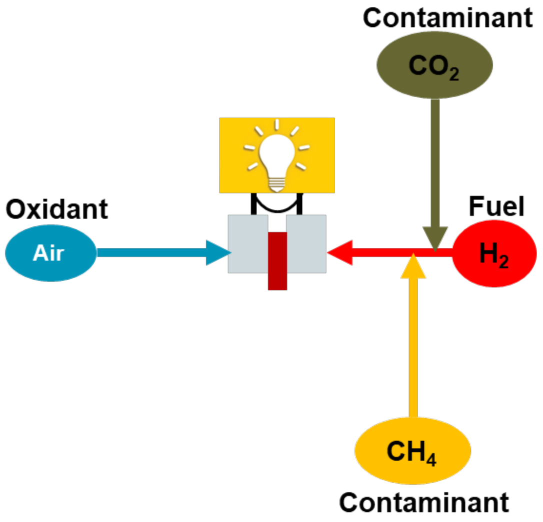
SEWGS System

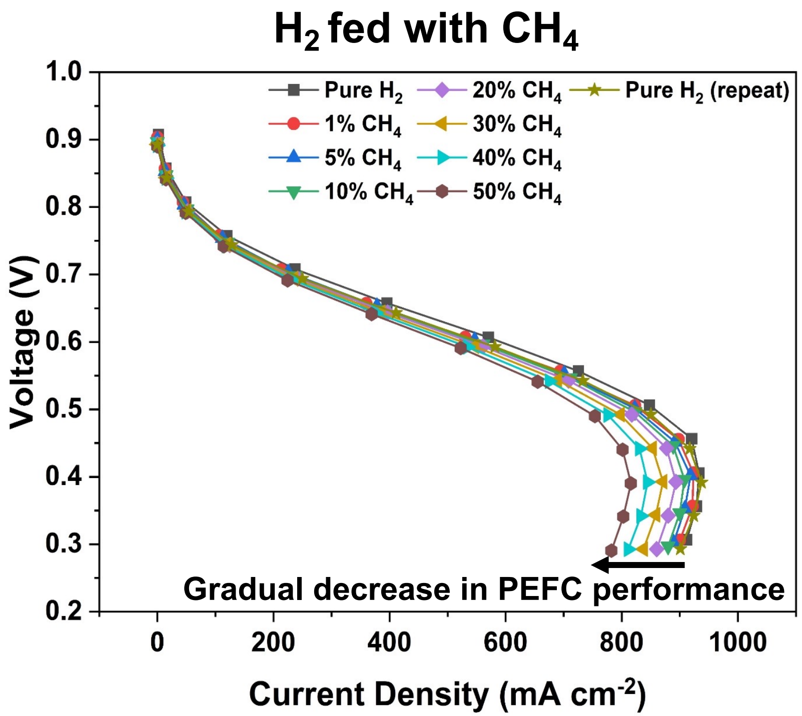
- UCL to host SEWGS system at Manufacturing Futures Lab.
- Simulated syngas based on experience from Swindon plant will be injected into system.
- Absorber operated at 300-400C, 5 bar. Desorber operated at 600-700C, 1 bar.
- SEWGS offers significant advantages over conventional WGS coupled with carbon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

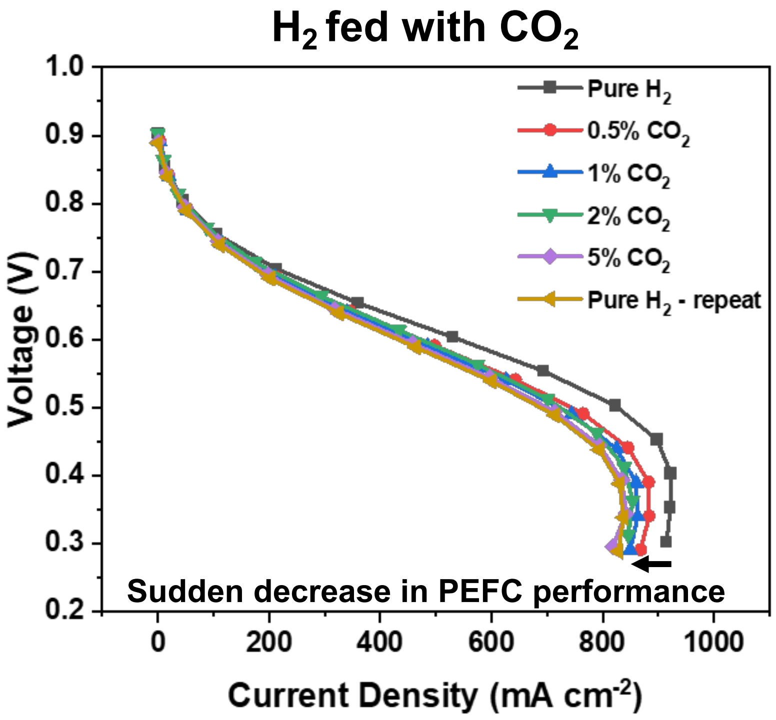
Project Timelines

- Installation through 2023, commissioning in H1 2024, operational in H2 2024.

BioH$_2$ purity for transportation







- H_2 and oxidant air supplied to the polymer electrolyte fuel cell (PEFC)
- Contaminants CO_2 and CH_4 fed through the H_2 supply to PEFC.

- Considerable impact on PEFC performance observed only beyond 20% (vol.) CH_4.
- PEFC performance recovered to normal after the removal of CH_4 (pure-H_2 repeat case).

✓ CH_4 acts mainly as ***diluent***.

- 0.5% CO_2 resulted in significant performance reduction (equivalent to 20%CH_4 dilution).
- PEFC performance not recovered after the removal of CO_2 (pure-H_2 repeat case).

❖ CO_2 contamination results in ***permanent*** performance reduction due to chemical reaction.

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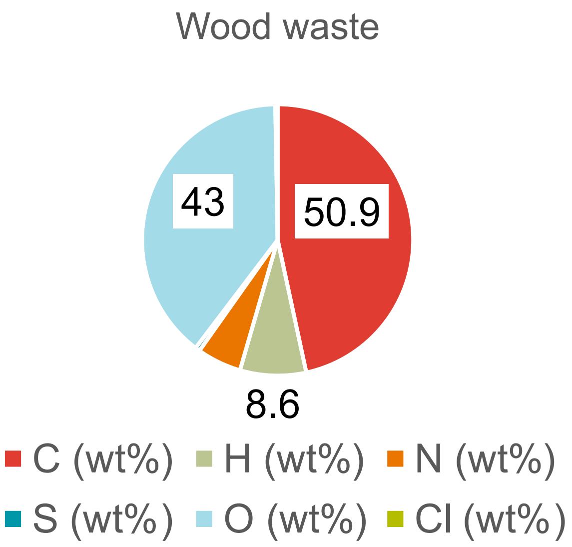
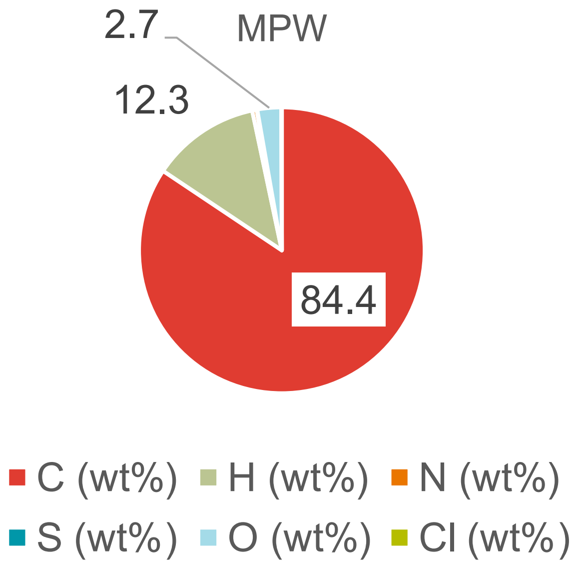
Changing Feedstock: Key Data

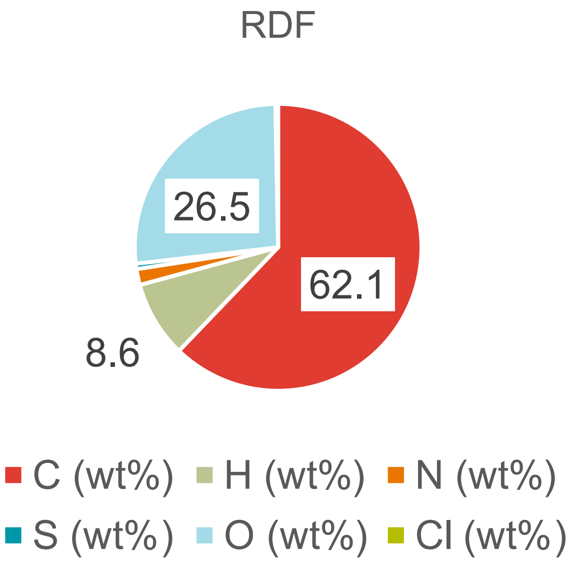
Key flows	Units	Biohydrogen (MSW)	Biohydrogen (Waste wood)	Blue Hydrogen SMR	Blue Hydrogen ATR	Green Hydrogen
<u>**Input**</u>						
Feedstock type		MSW/RDF	Waste wood	Natural gas		Water
Feedstock	kg	442.2/283.6	372.2			226.8
	m^3			116.4	117.6	
Oxygen	kg	89.4	101			n.a.
Electricity	MJ	514	617	27.7	115.7	4974
Thermal energy	MJ	1550	1657	-	-	n.a.
<u>**Output**</u>						
Hydrogen	MJ	3600	3600	3600		3600
Materials recovered	kg	17.1	-	-	-	-
CO_2 released	kg	46.5	53.5	120.63	38.1	0
Sequestered CO_2	kg	414.4	484.1			n.a.

Appendix



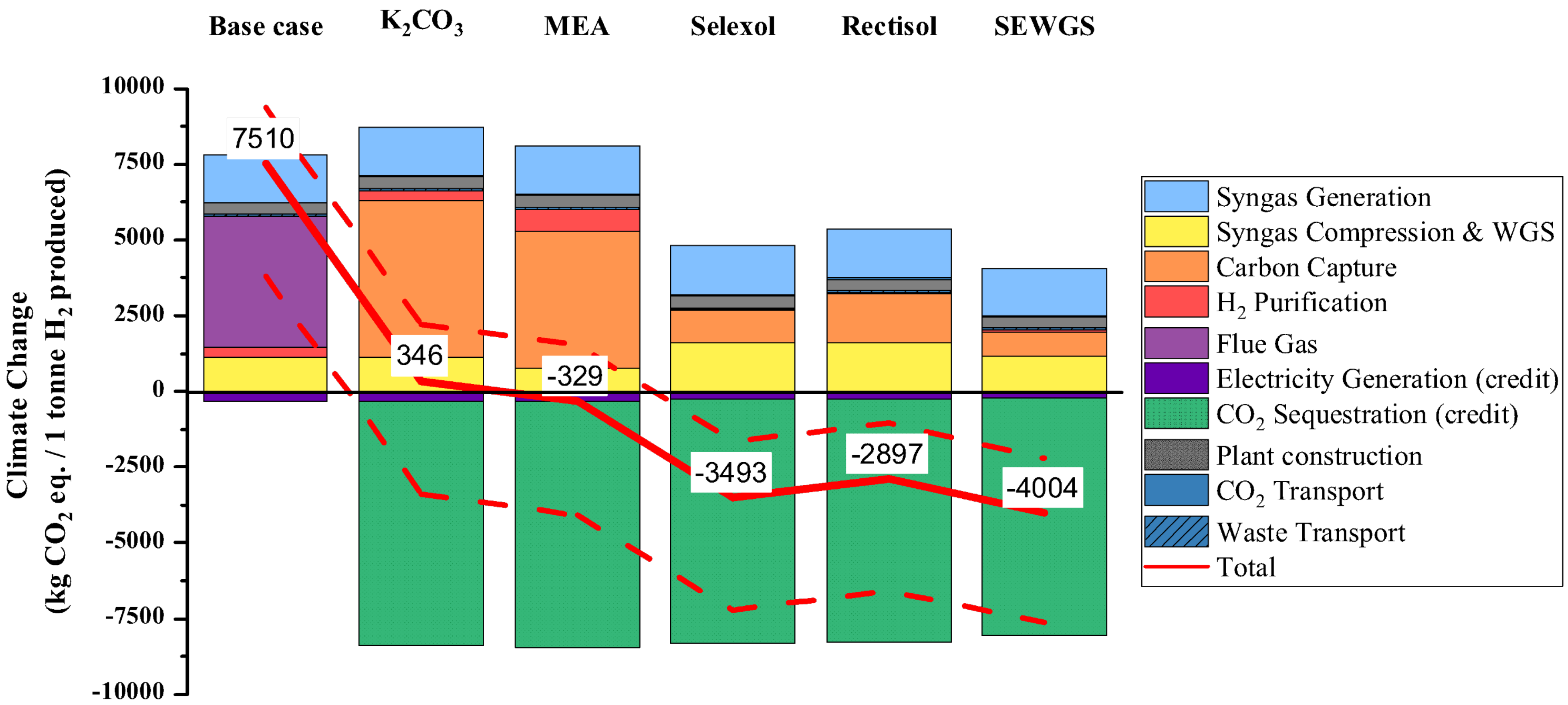


45% PP, 27% HDPE, 27% LDPE



Waste fractions [wt% as received]	MSW
Paper and cardboard	22.7
Wood	3.7
Metals	4.3
Glass	6.6
Textile	2.8
WEEE	2.2
Plastics	10
Inert/aggregates/solid	5.3
Organic fines	35.5
Miscellaneous	7.1

Process Environmental Performance

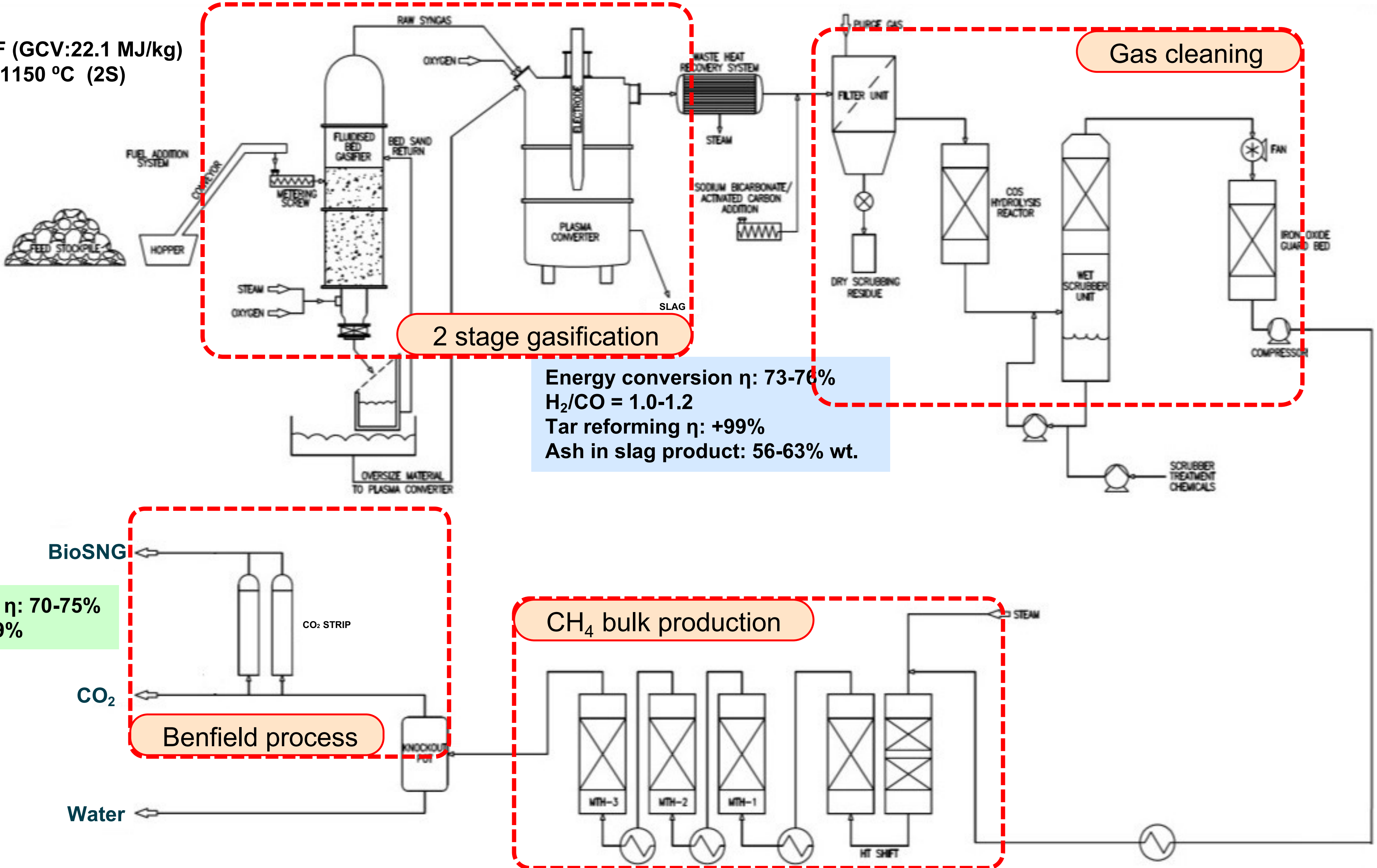


- Biogenic Carbon 65%
- H_2 purity >99.97%, P=46 bar
- CO_2 purity >95%, P=35 bar

* MEA: Monoehanolamine solution (30% wt)
** SEWGS: Sorption enhanced water gas shift

Demo-plant for BioSNG/BioH_2 production

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



Energy conversion η: 73-76%
H_2/CO = 1.0-1.2
Tar reforming η: +99%
Ash in slag product: 56-63% wt.

Syngas to BioSNG η: 70-75%
CO_2 removal η: +99%

Demo-plant for BioSNG/BioH_2 production (flowsheet)

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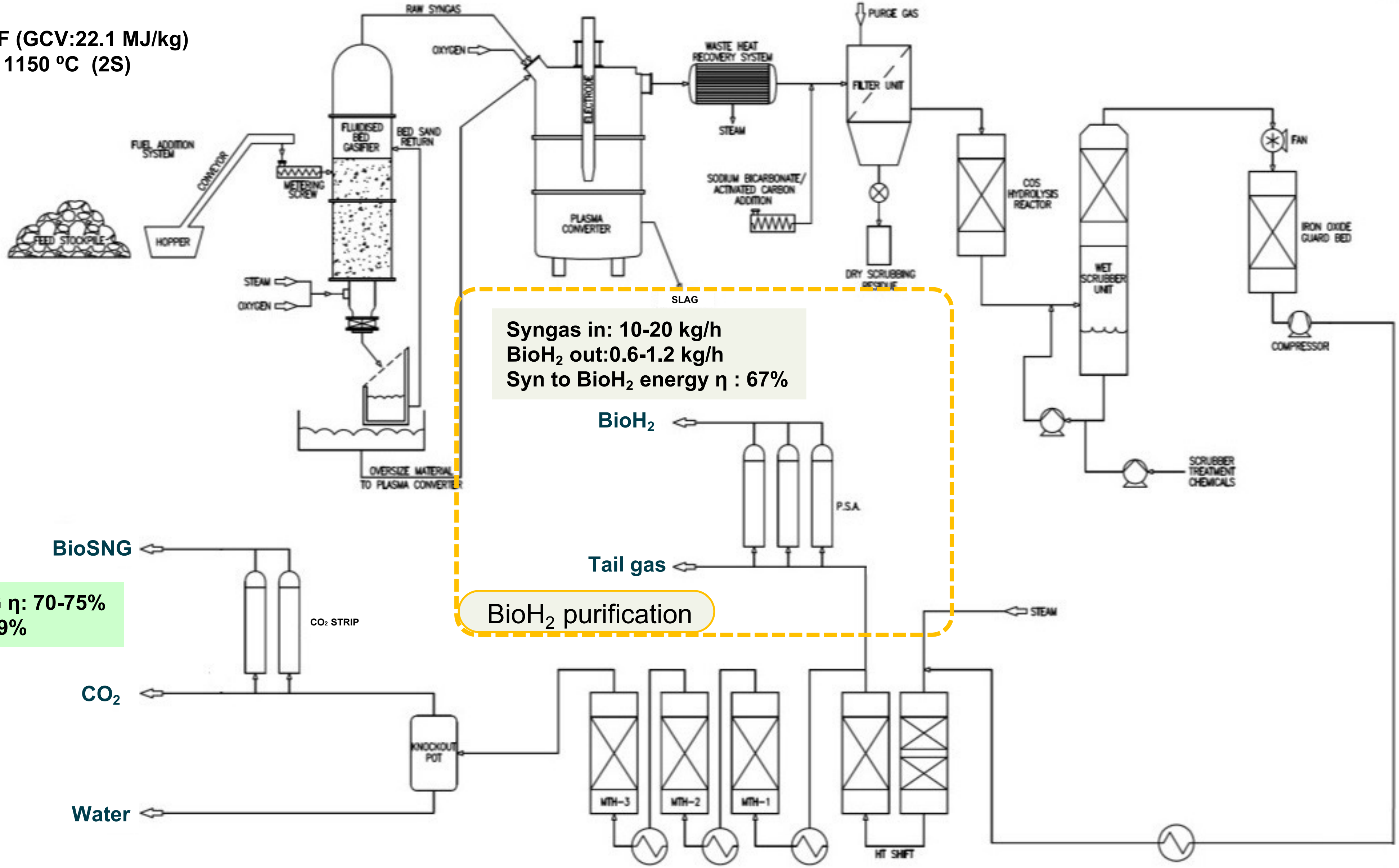

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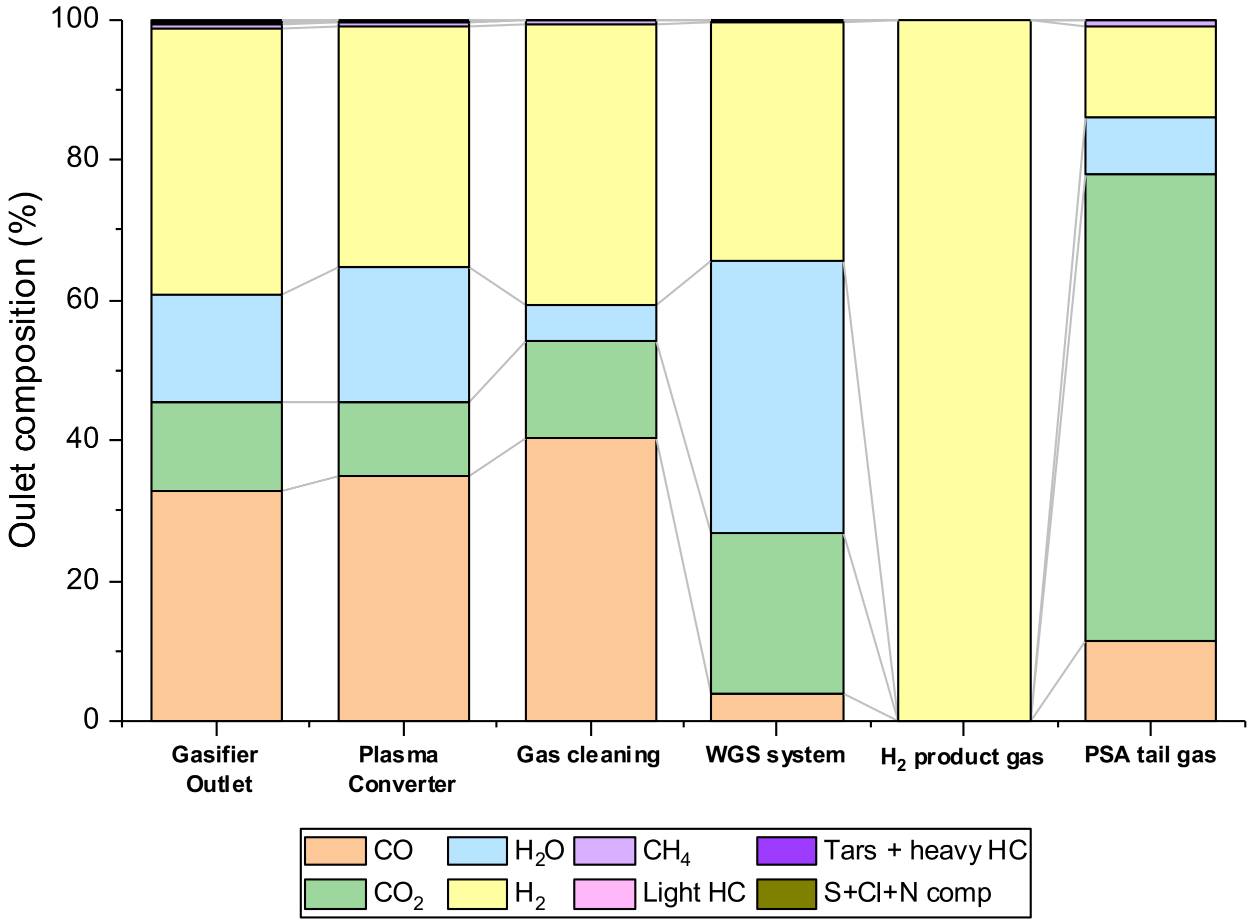
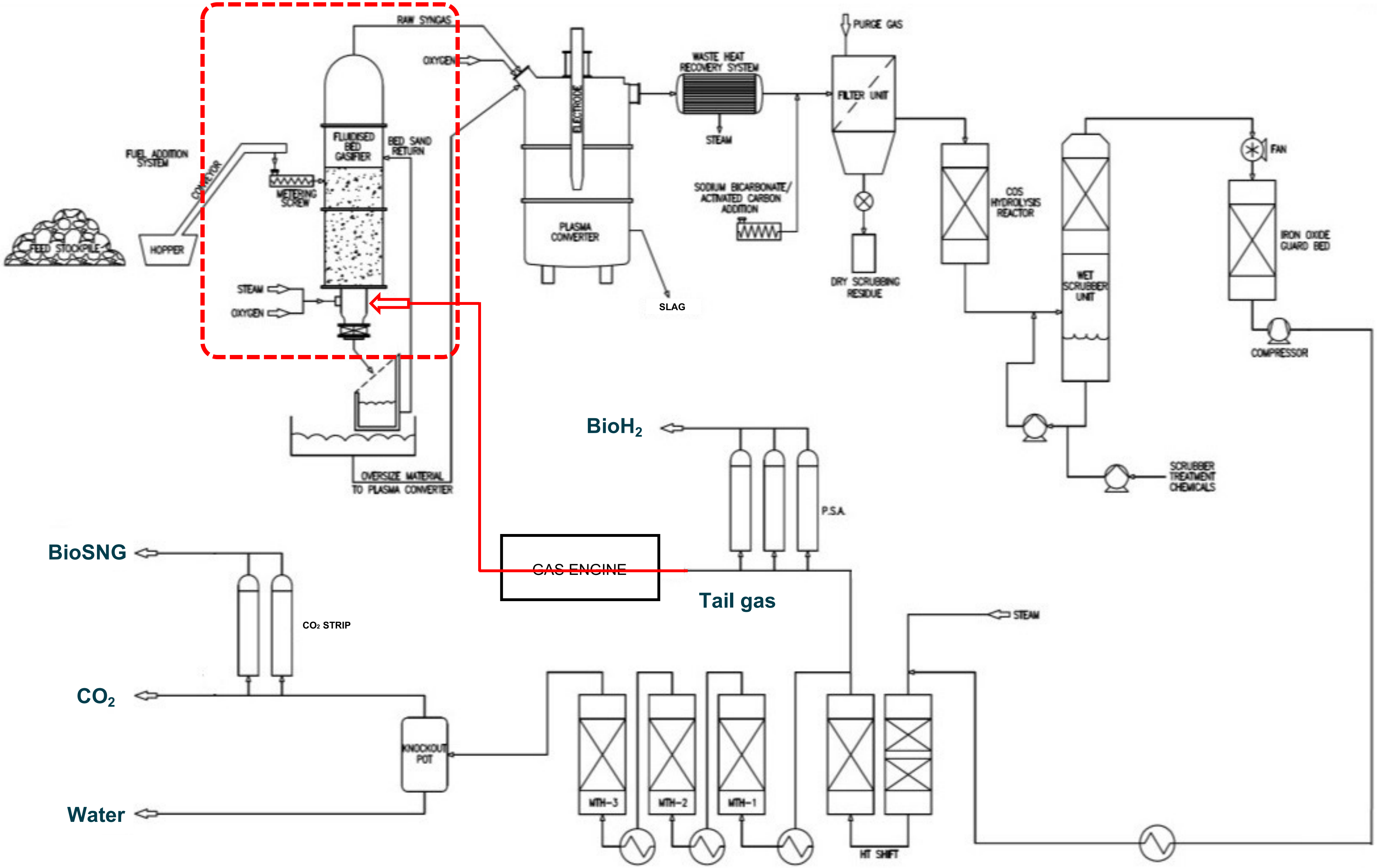
Feasibility for BioH_2 from waste feedstock



Stream	Mass flow [kg/h]	Energy [MW_{HHV}]	H_2 purity
RDF input	361.5	1.66	
BioH_2 from PSA	25.5	1	>99.97%
Tail gas from PSA	488.6	0.32	~14%

- 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



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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, CO_2 liquefaction and H_2 compression** to climate change and photochemical ozone formation
- Burdens for **gas cleaning process, primarily alkali scrubber**, to most categories