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Systematic Review and Life Cycle Analysis of biomass derived fuels for Solid Oxide Fuel Cells

FCH2 2017
TECHNICAL CONFERENCE

Sophie Archer saa329@bham.ac.uk

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Sustainable Hydrogen → Hydrogen from Biomass → Pathway Investigation → Life Cycle Analysis

Focus: Identification of sustainable hydrogen and gaseous fuel sources, from biomass feedstocks, for use in fuel cells.

Stage 1: Identification of biomass pathways, analysis of fuel gases, and ranking of sustainable & high yielding pathways with potential for fuel cells.

Stage 2: Utilisation of Life Cycle Analysis (LCA) to assess and investigate the environmental impact of key pathways, and re-ranking of fuel gases.

Research Overview

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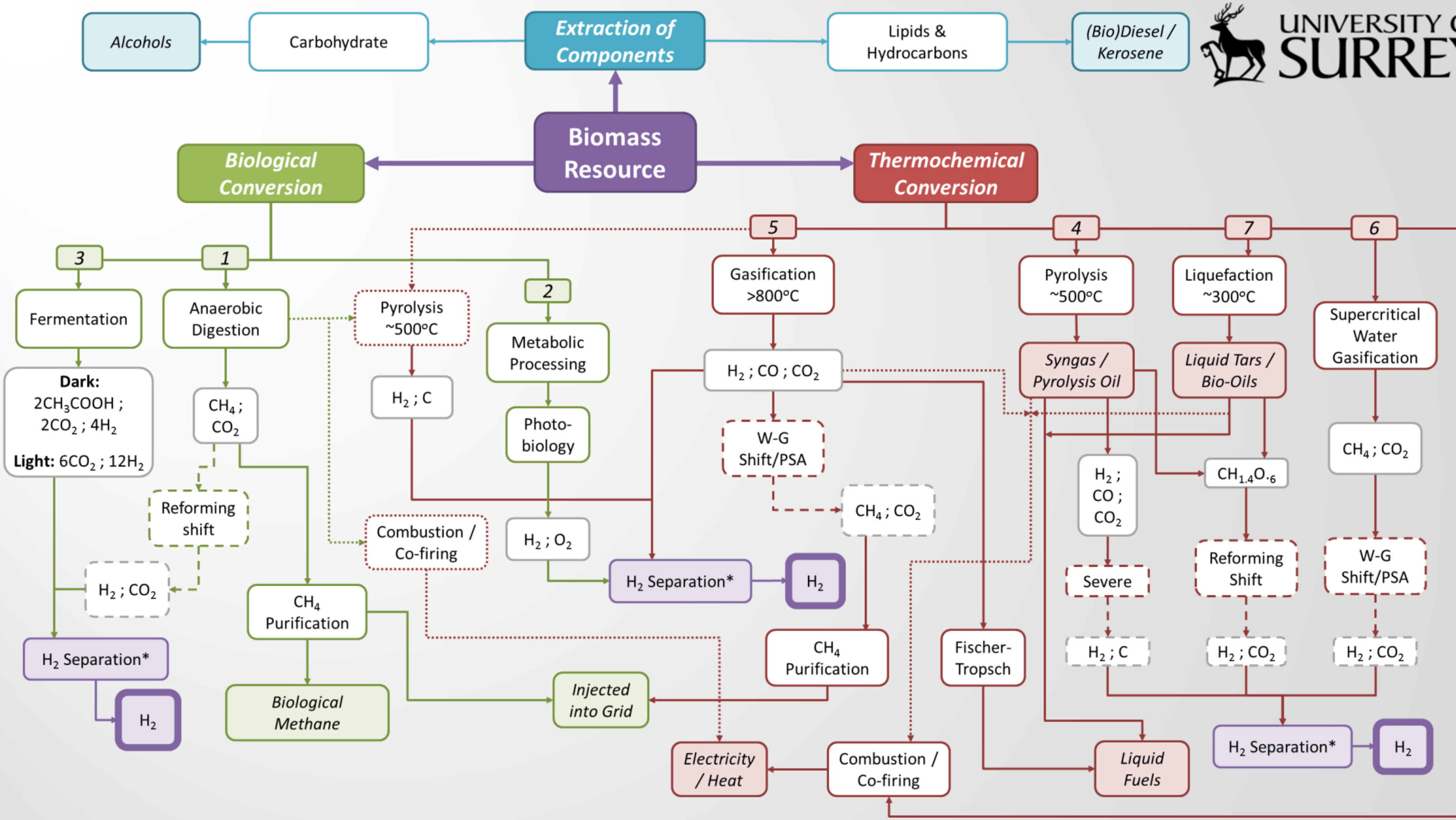
- Issue of hydrogen coming from fossil sources.

- Abundance of different types of waste biomass:

  - Lignocellulosic (*woody biomass/ forestry residues*)
  - Agricultural residues (*corn stover, rice straw, etc., /animal slurries*)

- Most can be exploited to extract hydrogen and hydrogen rich gases.

- Developments in sustainable biological produced hydrogen (biohydrogen) are advancing.



* '*Hydrogen Separation*' stage is where additional gases are removed to produce pure hydrogen, typically via pressure swing absorption.

NB: 'Reforming Shift' and *'Bio-shift'* in *Figure 2* refer to steam methane reforming and biological water-gas shift reaction.

Figure 1
Hydrogen pathways from biomass
Adapted from: Schlarb-Ridley (2013) and Milne (2002)

Table 1
Biomass pathways and respective fuel gas production

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	Pathway	Inputs	Outputs	Potential Fuel Gas
1	**Anaerobic Digestion**	Plant Biomass / Animal Slurry / Wastes.	Biogas.	Biogas* Biomethane.
2	**Metabolic Processing**	Carbon Dioxide + Water + Nutrients.	Biohydrogen.	Biohydrogen.
3	**Fermentation**	Algal Biodigester Sludge / Anaerobic Digestate / Organic Waste Biomass.	Biohydrogen.	Biohydrogen.
4	**Pyrolysis**	Dry Biomass.	Syngas (32.6%).	Syngas^. Hydrogen.
			Bio-Oil (36%).	Hydrogen.
5	**Gasification**	Dry Biomass.	Syngas.	Syngas^. Hydrogen.
6	**Supercritical Water Gasification**	Wet or Dry Biomass.	Syngas.	Syngas^. Hydrogen.
7	**Liquefaction**	Wet Biomass.	Bio-Oil.	Hydrogen.
RC	**Natural Gas**	Grid Source	Fossil Natural Gas~.	De-sulphured Natural Gas.

* Biogas (~60% CH_4, ~39% CO_2, ~1% N_2, trace SO_2, trace SiO_2)
^ Syngas (~50% H_2, ~25% CO, ~10% CO_2, ~10% H_2O, ~5% CH_4, trace H_2S)
~ Fossil Natural Gas (~95% CH_4, ~2.5% C_2H_6, ~1.5% N_2, <1% CO_2, trace SO_2)

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Table 2
Biomass pathways summary table ranking order – Stage 1

	Pathway	Fuel Gas	Fuel Gas LHV	Fuel Cell	Total Chain Efficiency	Fuel Cell Output	Stack Fuel Demand	Biomass Feedstock Demand
1	**Anaerobic Digestion**	Biomethane.	13.89 kWh_e/kg	SOFC	32.4%	4.50 kWh/kg	222.20 kg/MWh	0.00045 kg/MWh
RC	**Natural Gas**	De-sulphured Natural Gas.	11.95 kWh_e/kg	SOFC	28.7%	3.43 kWh/kg	291.81 kg/MWh	364.77 kg/MWh
2	**Metabolic Processing**	Biohydrogen.	33.34 kWh_e/kg	SOFC	5.4%	1.80 kWh/kg	555.51 kg/MWh	811.02 kg/MWh
6	**Supercritical Water Gasification**	Hydrogen.	33.34 kWh_e/kg	SOFC	35.7%	10.42 kWh/kg	96.00 kg/MWh	3692.19 kg/MWh

S1

Biomethane from Biogas via PSA

Goal and Scope: Assessment of four 1MWh SOFC systems, each with a different fuel gas, including production of fuel gas from biomass/source materials/biological processes.

Inventory: The quantity of biomass and fuel gas needed for each system was calculated. Processes, inputs and outputs were also defined. Investigatory research data was used and topped up with database data.

ISO 14040 & 14044

2006 Standards

Environmental Management

LCA & LCI Principles & Framework

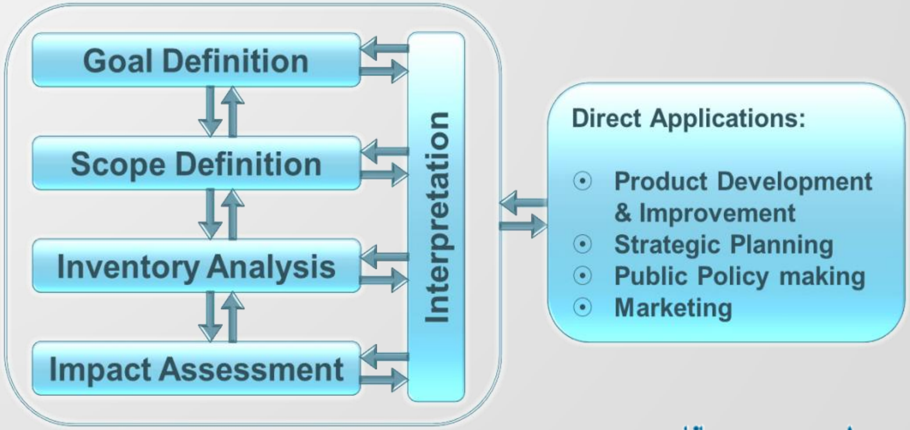

Figure 2
LCA methodology

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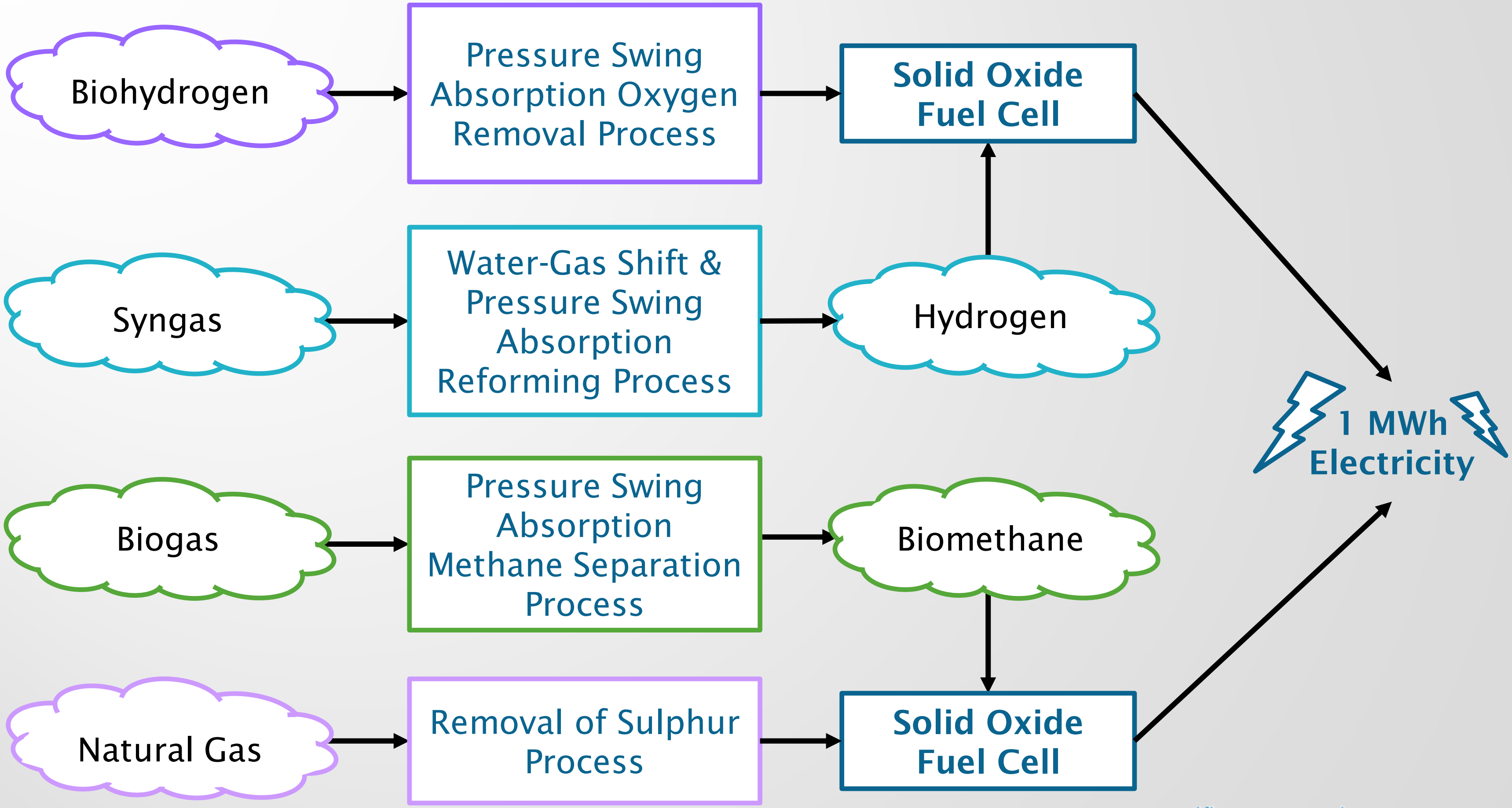

Figure 3
1MWh electrical output SOFC pathway with different fuel gases

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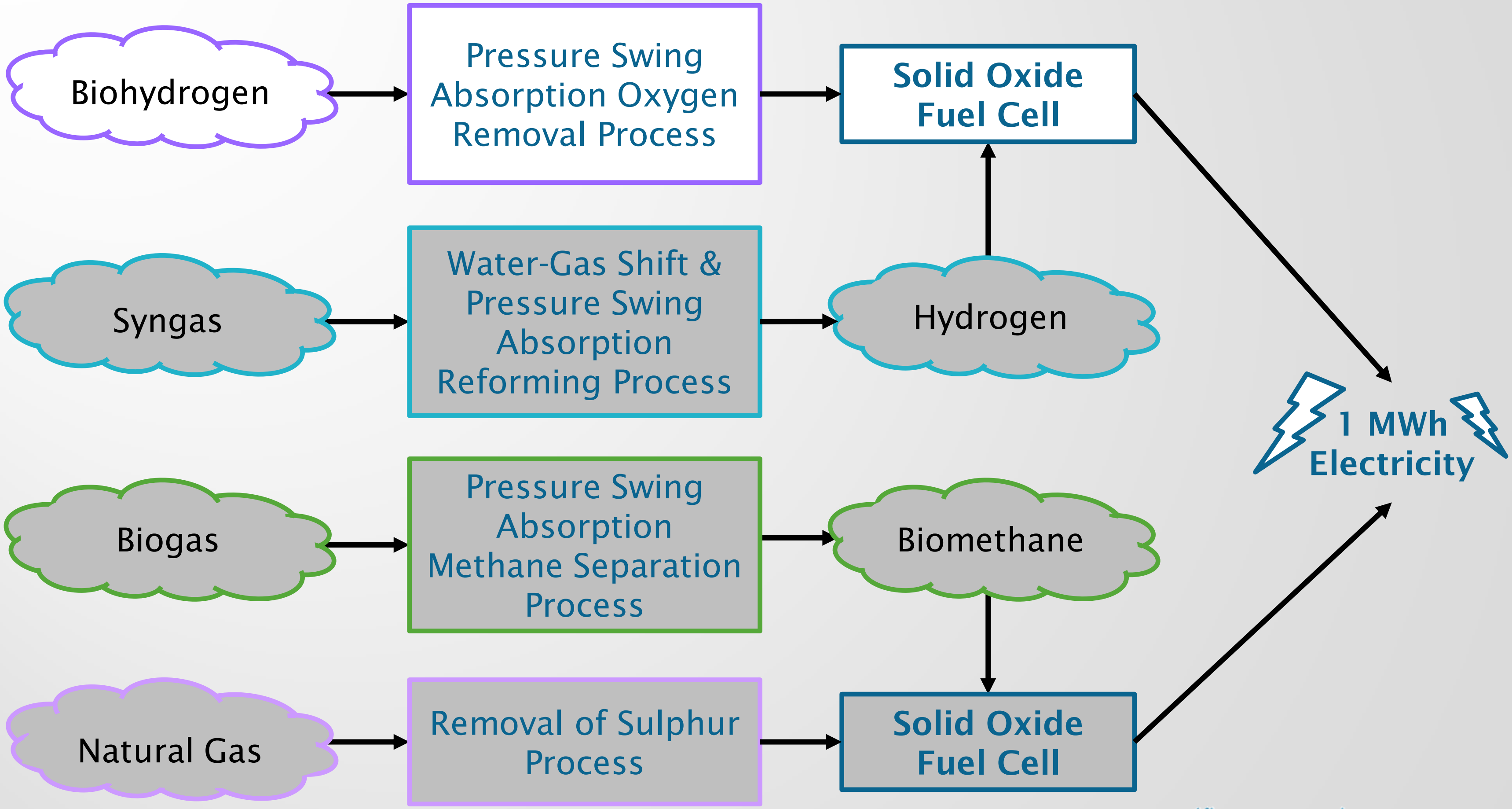
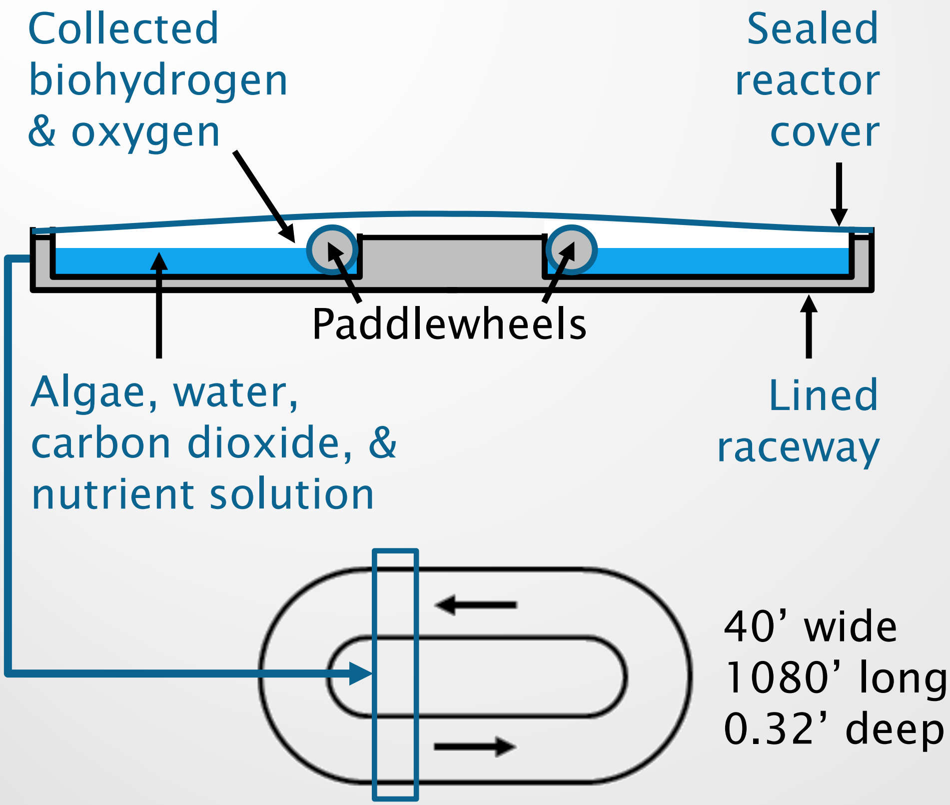


Figure 3
1MWh electrical output SOFC pathway with different fuel gases

Metabolic Processing - Algal Biohydrogen



1 tonne biohydrogen requires 20 raceways

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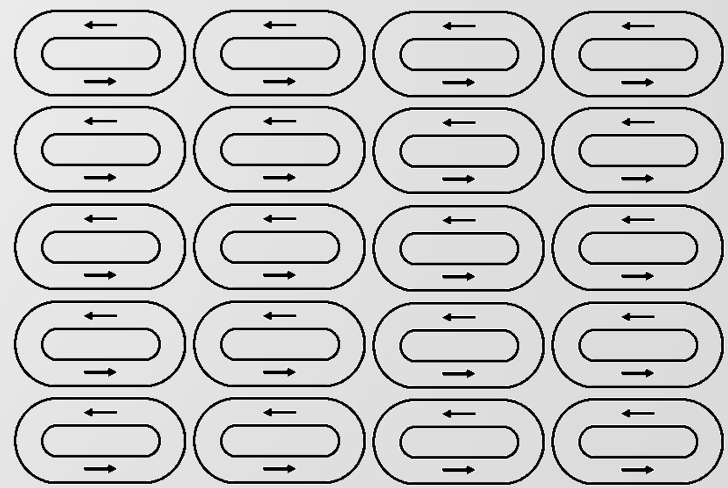

Figure 4
Metabolic Processing Photobiolysis Bioreactor
Adapted from: NREL (2015)

Metabolic Processing – Biohydrogen via PSA

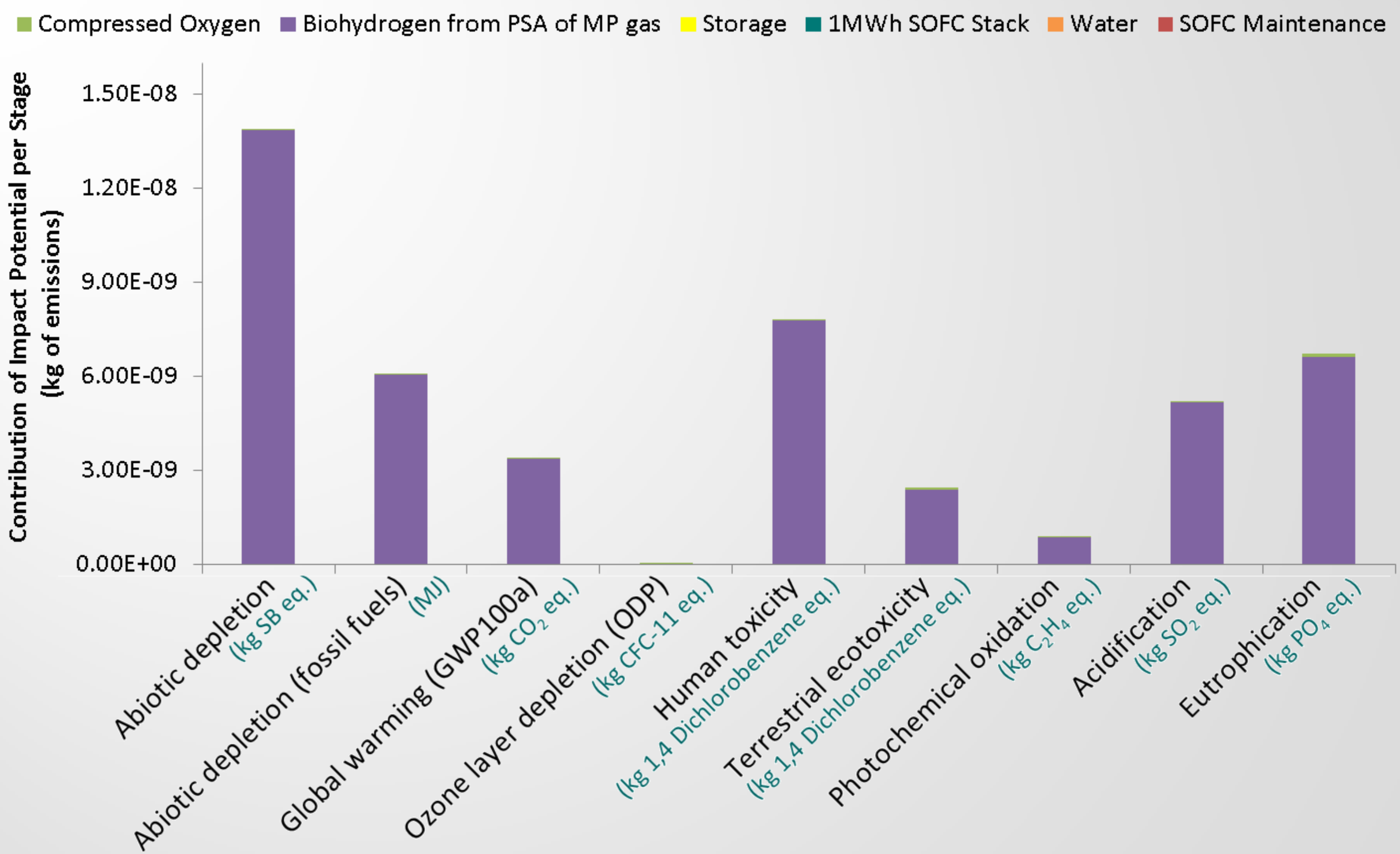

Figure 5
Biohydrogen via PSA Impact Assessment

Metabolic Processing – Biohydrogen via PSA

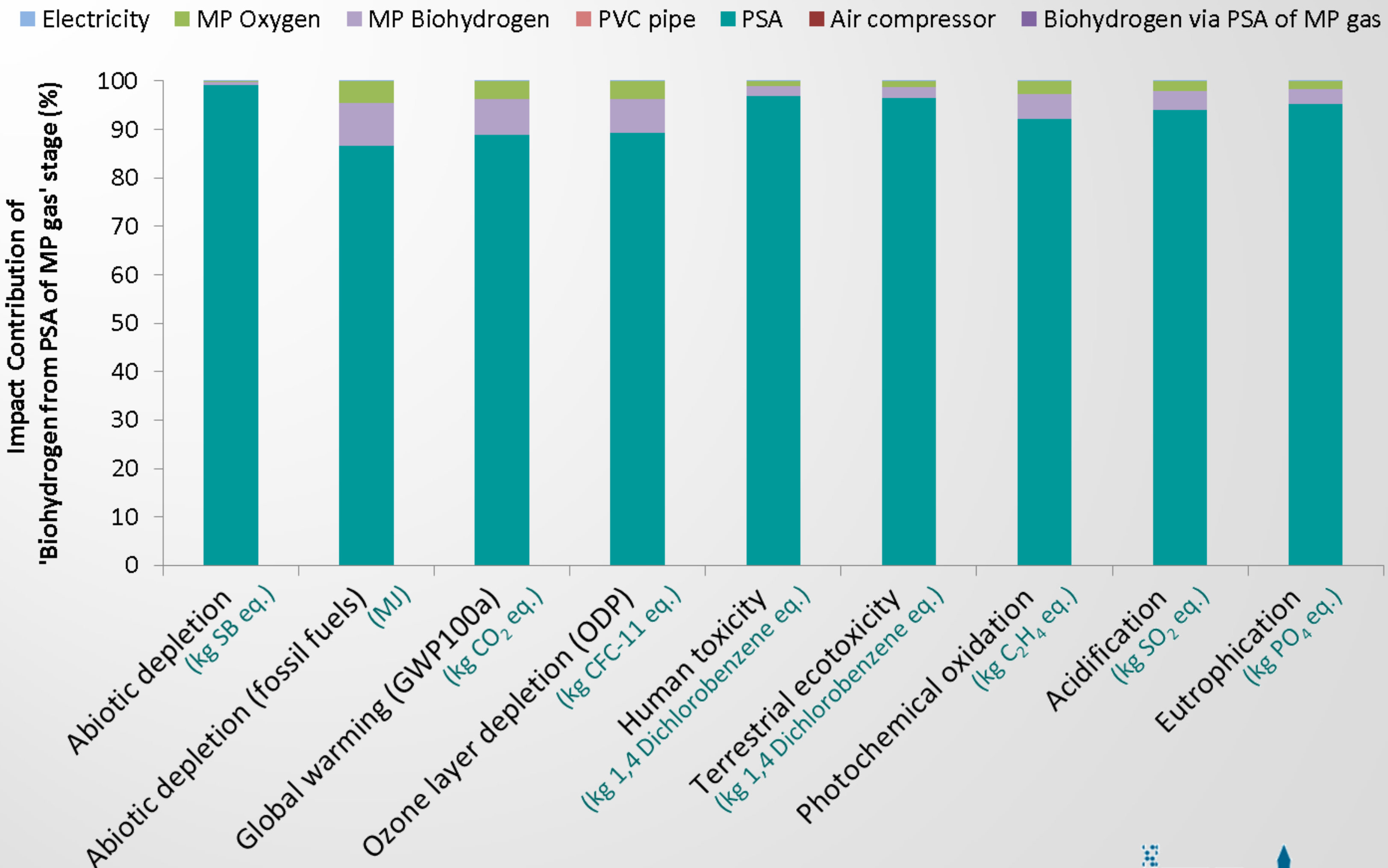

Figure 6
Biohydrogen via PSA Impact Assessment (Biohydrogen percentile)

Metabolic Processing – Pre-PSA Biohydrogen

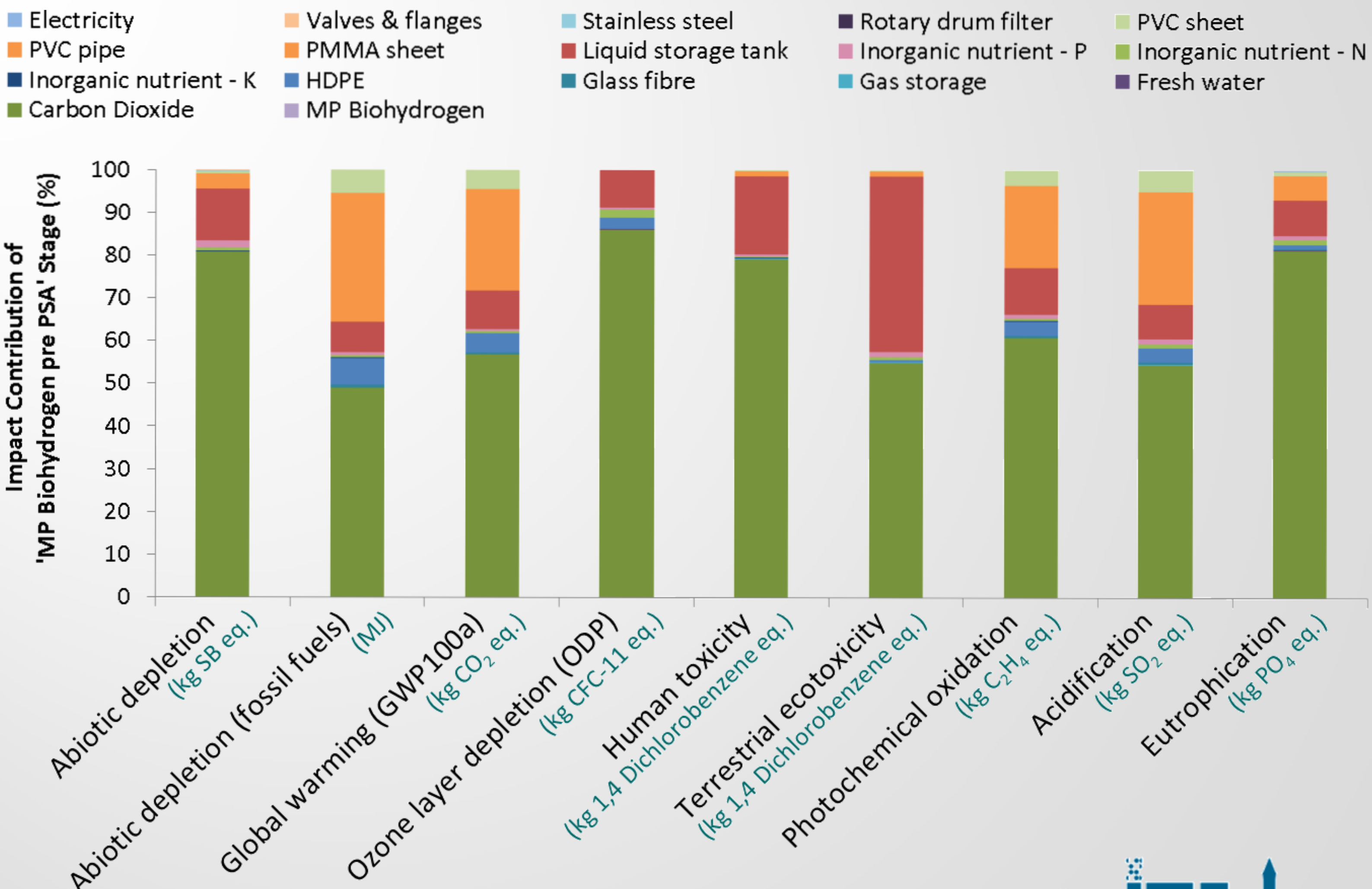

Figure 7
MP Biohydrogen pre PSA Impact Assessment (percentile)

Sustainable Hydrogen → Hydrogen from Biomass → Life Cycle Analysis → **Pathway Investigation**

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Anaerobic Digestion:

High impact fuel.

Natural Gas:

Low impact fuel, but fossil sourced – to be avoided.

SCWG:

Second highest Impact.

Metabolic Processing:

Lowest impact!

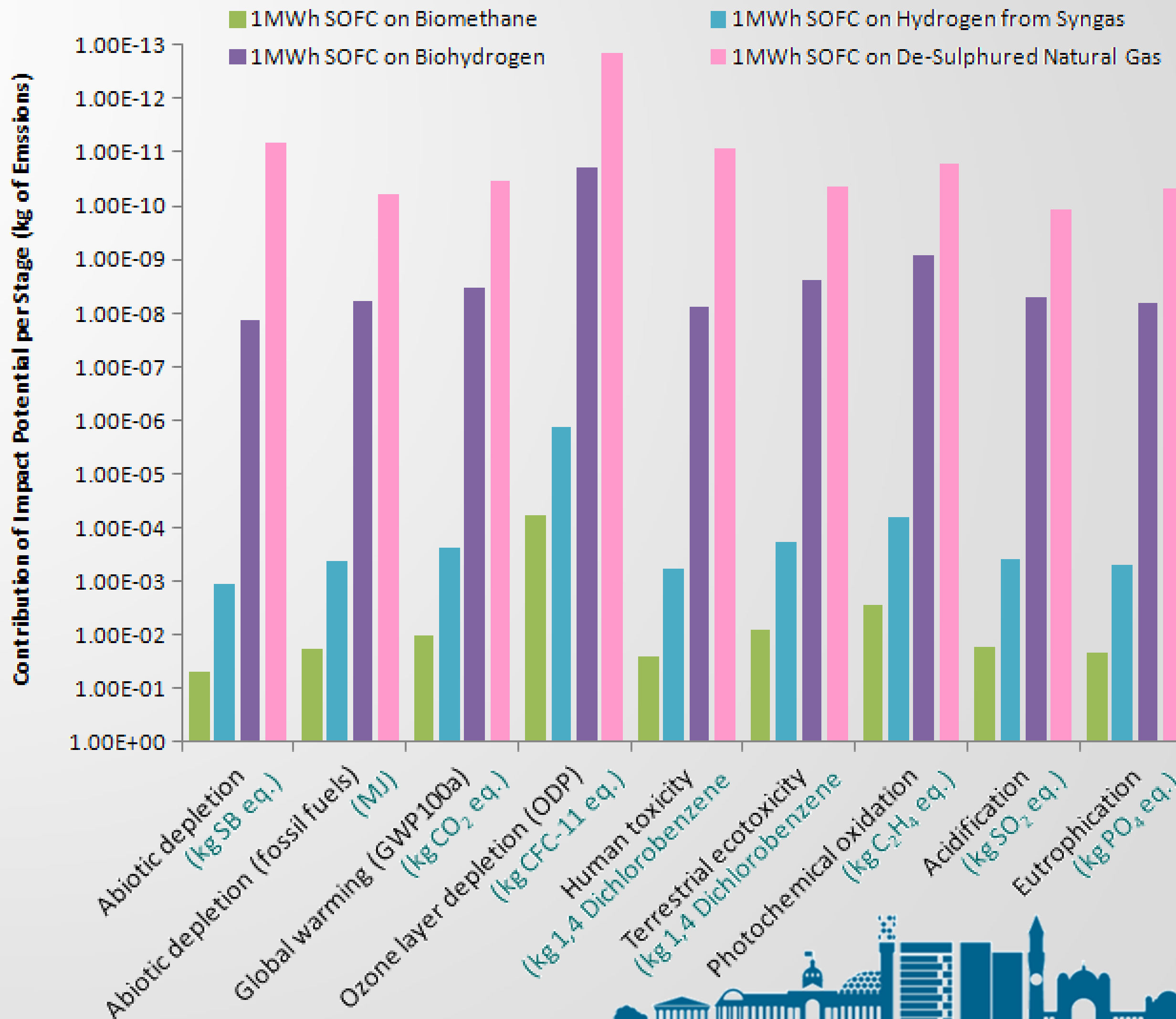

Figure 8
1MWh SOFC fuel comparison
Impact Assessment (normalised)

Table 3
Biomass pathways summary table ranking order – Stage 2

	Pathway	Fuel Gas	Environmental Impact Rank
2	**Metabolic Processing**	Biohydrogen.	Lowest impact per 1MWh worth of biohydrogen
RC	**Natural Gas**	De-sulphured Natural Gas.	Good environmental performance, but fossil source with high demands.
6	**Supercritical Water Gasification**	Hydrogen.	High impact fuel, with high demands for 1MWh SOFC.
1	**Anaerobic Digestion**	Biomethane.	Highest impact fuel, but low demands for 1MWh SOFC.

S2

Biohydrogen via PSA of MP gas

Focus: Identification of sustainable hydrogen and gaseous fuel sources, from biomass feedstocks, for use in fuel cells.

Stage 1: Anaerobic Digestion and SCWG identified as potential biomass pathways for sustainable, high yielding fuel gases for SOFCs. Better performance seen from external reforming than internal reforming, unlike Gasification Syngas.

Stage 2: LCA results showed environmental impacts of Algal Metabolic Processing biohydrogen had excellent fuel gas potential. SCWG was also found to have a lower impact than Anaerobic Digestion, but higher than Natural Gas.

Stage 3: Preliminary assessment of impact burdens shows potential allocation to sub-processes, not fuel gas.

Research Summary

1) **Are the Impact Assessment emissions really burdens?**

Are burdens associated only with the primary produce, not the waste?

If true, can burdens be allocated to a deeper sub-process?

i.e. Are emissions truly associated with the fuel gas, or with a sub-process?

2) **Potential for 'free' fuel gas**

Comparison of results to original emissions from waste pathway and calculating the associated 'free' fuel gas that has come from using a waste product.

i.e. What impacts does leaving the waste biomass to naturally decompose and/or be disposed of have?

3) **Stage 3 Rankings**

Biomethane from AD Biogas **VS** Biohydrogen from Algal MP gas

Final identification of sustainable fuel gases for SOFCs!

Further Work – Stage 3

Thank You

Any Questions?

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saa329@bham.ac.uk

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Appendix 1
Biomass pathways and respective coverage in literature across ‘biomass’ and ‘biomass LCA’ filters

Literature Statistics	**Unfiltered**	**Biomass Filter**	**Biomass Life Cycle Filter**	**Whole Pathway Potential**	**Biomass LCA Potential**	**Research Ranking**
Anaerobic Digestion	7,012 (100%)	806 (11.5%)	107 (1.5%)	7.8%	**6.9%**	**3rd**
Metabolic Processing	11,010 (100%)	784 (7.1%)	41 (0.4%)	12.3%	**2.6%**	**1st**
Fermentation	14,184 (100%)	1,654 (11.7%)	193 (1.4%)	15.8%	*12.4%*	*5th*
Pyrolysis	14,047 (100%)	1,407 (10%)	230 (1.6%)	15.7%	*14.8%*	*6th*
Gasification	14,239 (100%)	1,774 (12.5%)	379 (1.7%)	15.9%	*24.4%*	*7th*
Combustion/Co-Firing	22,307 (100%)	2,689 (12.1%)	375 (1.7%)	24.9%	24.1%	n/a
Liquefaction	4,650 (100%)	553 (11.9%)	149 (3.2%)	5.2%	9.6%	*4th*
Supercritical Water Gasification	2,152 (100%)	334 (15.5%)	82 (3.8%)	2.4%	**5.3%**	**2nd**

Appendix 2
Biomass pathway efficiencies and total chain efficiencies

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	Pathway	Process Efficiency	Gas Clean-up / Reforming Efficiency	Fuel Gas	Fuel Gas LHV	Fuel Cell Efficiency	Total Chain Efficiency	Ref.
1	**Anaerobic Digestion**	75%	n/a 90%	Biogas*. Biomethane.	5.28 kWh_e/kg → 13.89 kWh_e/kg →	SOFC ~60% SOFC ~60%	**36%** 32.4%	Charles (2011) Rasi (2009)
2	**Metabolic Processing**	< 10%	90%	Biohydrogen.	33.33 kWh_e/kg →	SOFC ~60% PEFC ~45%	**5.4%** 4.05%	Lee (2012) Benemann (1997)
3a	**Dark Fermentation**	~ 9%	90%	Biohydrogen.	33.33 kWh_e/kg →	SOFC ~60% PEFC ~45%	**4.89 %** 3.65%	Kotay (2008) Das (2001)
3b	**Light Fermentation**	~ 6%	90%	Biohydrogen.	33.33 kWh_e/kg →	SOFC ~60% PEFC ~45%	**2.97%** 2.23%	Kotay (2008) Das (2001)
4	**Pyrolysis**	75%	n/a 74.4% < 60%	Syngas^. Hydrogen. Hydrogen.	3.61 kWh_e/kg → 33.33 kWh_e/kg → 33.33 kWh_e/kg →	SOFC ~60% SOFC ~60% PEFC ~45% SOFC ~60% PEFC ~45%	11.74% **12.05%** 9.04% 9.72% 7.29%	Hanif (2016) Zafar (2015) Keachagiopoulos (2006)
5	**Gasification**	50 – 80% (65%)	n/a 74.4%	Syngas^. Hydrogen.	3.61 kWh_e/kg → 33.33 kWh_e/kg →	SOFC ~60% SOFC ~60% PEFC ~45%	**31.2%** 29.02% 21.76%	Ernsting (2015) Sikarwar (2016) Braga (2016)
6	**Supercritical Water Gasification**	< 80%	n/a 74.4%	Syngas^. Hydrogen.	3.61 kWh_e/kg → 33.33 kWh_e/kg →	SOFC ~60% SOFC ~60% PEFC ~45%	**33.6%** 31.25% 23.44%	Sikarwar (2016) Braga (2016)
7	**Liquefaction**	70%	< 60%	Hydrogen.	33.33 kWh_e/kg →	SOFC ~60% PEFC ~45%	**25.2%** 18.9%	Yokoyama (2008) Keachagiopoulos (2006)
RC	**Natural Gas**	80 – 90% (85%)	50 – 100% (75%)	De-sulphured Natural Gas.	11.94 kWh_e/kg →	SOFC ~60%	**28.69%**	Muggeridge (2014) Shimeskit (2012)

* Biogas (~60% CH_4, ~39% CO_2, ~1% N_2, trace SO_2, trace SiO_2)
^ Syngas (~50% H_2, ~25% CO, ~10% CO_2, ~10% H_2O, ~5% CH_4, trace H_2S)
~ Fossil Natural Gas (~95% CH_4, ~2.5% C_2H_6, ~1.5% N_2, <1% CO_2, trace SO_2)

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Appendix 3
Biomass pathways and their respective fuel cell and biomass demands

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	Pathway	Fuel Gas	Fuel Gas LHV		Fuel Cell Efficiency	Total Chain Efficiency	Fuel Cell Output	Stack Fuel Demand	Biomass Feedstock Input	Ref.
1	**Anaerobic Digestion**	Biogas*.	5.28 kWh_e/kg	→	SOFC ~60%	36%	1.90 kWh/kg	526.27 kg/MW	0.0013 kg/MW	CROPGEN (2011) Anaerobic Digestion (2017) Stucki (2011)
		Biomethane.	13.89 kWh_e/kg	→	SOFC ~60%	32.4%	4.50 kWh/kg	222.20 kg/MW	**0.00045 kg/MW**	
2	**Metabolic Processing**	Biohydrogen.	33.33 kWh_e/kg	→	SOFC ~60%	5.4%	1.80 kWh/kg	555.51 kg/MW	**811.02 kg/MW**	NREL (2015)
					PEFC ~45%	4.05%	1.35 kWh/kg	740.68 kg/MW	1081.35 kg/MW	
3a	**Dark Fermentation**	Biohydrogen.	33.33 kWh_e/kg	→	SOFC ~60%	4.89 %	1.62 kWh/kg	617.23 kg/MW	**12.06 kg/MW**	Kim (2006)
					PEFC ~45%	3.65%	1.22 kWh/kg	822.98 kg/MW	16.07 kg/MW	
3b	**Light Fermentation**	Biohydrogen.	33.33 kWh_e/kg	→	SOFC ~60%	2.97%	0.99 kWh/kg	1010.02 kg/MW	**20.08 kg/MW**	Kim (2006)
					PEFC ~45%	2.23%	0.74 kWh/kg	1346.69 kg/MW	26.77 kg/MW	
4	**Pyrolysis**	Syngas^.	3.61 kWh_e/kg	→	SOFC ~60%	11.74%	0.42 kWh/kg	2359.41 kg/MW	6590.54 kg/MW	Ayalur Chattanatha (2012) Capareda (2013)
		Hydrogen.	33.33 kWh_e/kg	→	SOFC ~60%	12.05%	4.02 kWh/kg	248.90 kg/MW	**2262.77 kg/MW**	
					PEFC ~45%	9.04%	3.01 kWh/kg	331.87 kg/MW	3017.03 kg/MW	
		Hydrogen.	33.33 kWh_e/kg	→	SOFC ~60%	9.72%	3.24 kWh/kg	308.62 kg/MW	2805.61 kg/MW	
					PEFC ~45%	7.29%	2.43 kWh/kg	411.49 kg/MW	3740.82 kg/MW	
5	**Gasification**	Syngas^.	3.61 kWh_e/kg	→	SOFC ~60%	31.2%	1.13 kWh/kg	887.50 kg/MW	546.16 kg/MW	Capareda (2013) Kumar (2009)
		Hydrogen.	33.33 kWh_e/kg	→	SOFC ~60%	29.02%	9.67 kWh/kg	103.38 kg/MW	**1602.83 kg/MW**	
					PEFC ~45%	21.76%	7.25 kWh/kg	137.84 kg/MW	2137.11 kg/MW	
6	**Supercritical Water Gasification**	Syngas^.	3.61 kWh_e/kg	→	SOFC ~60%	33.6%	1.21 kWh/kg	824.11 kg/MW	54940.66 kg/MW	Kelly-Yong (2011) Convert Units (2017)
		Hydrogen.	33.33 kWh_e/kg	→	SOFC ~60%	31.25%	10.42 kWh/kg	96.00 kg/MW	**3692.19 kg/MW**	
					PEFC ~45%	23.44%	7.81 kWh/kg	137.84 kg/MW	4922.92 kg/MW	
7	**Liquefaction**	Hydrogen.	33.33 kWh_e/kg	→	SOFC ~60%	25.2%	8.40 kWh/kg	119.04 kg/MW	**59.52 kg/MW**	Ayalur Chattanatha (2012)
					PEFC ~45%	18.9%	6.30 kWh/kg	158.72 kg/MW	79.36 kg/MW	
RC	**Natural Gas**	De-sulphured Natural Gas.	11.94 kWh_e/kg	→	SOFC ~60%	28.69%	3.43 kWh/kg	291.81 kg/MW	**364.77 kg/MW**	

* Biogas (~60% CH_4, ~39% CO_2, ~1% N_2, trace SO_2, trace SiO_2)
^ Syngas (~50% H_2, ~25% CO, ~10% CO_2, ~10% H_2O, ~5% CH_4, trace H_2S)
~ Fossil Natural Gas (~95% CH_4, ~2.5% C_2H_6, ~1.5% N_2, <1% CO_2, trace SO_2)

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