Final Report

Modeling the decarbonisation of carbon-intensive industries through the integration of CO2 biomethanation: assessment of carbon savings and production costs

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Executive Summary

CO_2 Biomethanation is the biological conversion of carbon dioxide and hydrogen to biomethane via the action of hydrogenotrophic methanogens. In this work biomethanation is integrated into carbon intensive industries using carbon capture technologies which isolate carbon dioxide from industrial flue- and off-gasses, with the hydrogen supplied through the electrolysis of water (Figure S1). The produced biomethane can be used as a drop-in fuel to replace natural gas in industrial processes or can be exported using the natural gas grid and used elsewhere.

In this project, five industries were considered: Cement, steel, distillery (for potable distilled spirits), pulp and paper and ammonia, although biomethanation integration with current commercial ammonia was found to be illogical relative to direct application of electrolysis, so this was not considered further. Although each industry is diverse with a range of processes variants or different technologies, an exemplar **baseline** process for each industry, representing a realistic and/or common version of the industrial process, was developed using data from literature.

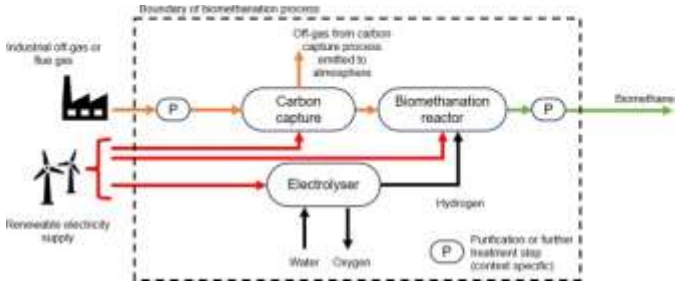

Figure S1. The biomethanation process.

Each **baseline** process was extended to produce a high-level design of the integration of biomethanation (the **decarbonised** process) by identifying CO_2 containing flue- and off-gasses and opportunities for replacement of natural gas with biomethane. Integration was done whilst making minimal changes to the baseline process such that biomethanation could be considered a potential retrofit upgrade to existing industrial infrastructure. Relevant mass and energy flows were quantified based on reaction stoichiometry and literature data. Subsequently this data used to estimate the carbon footprint (Figure S2) and additional costs associated with the process integration only considering the differences between the **baseline** and **decarbonised** processes.

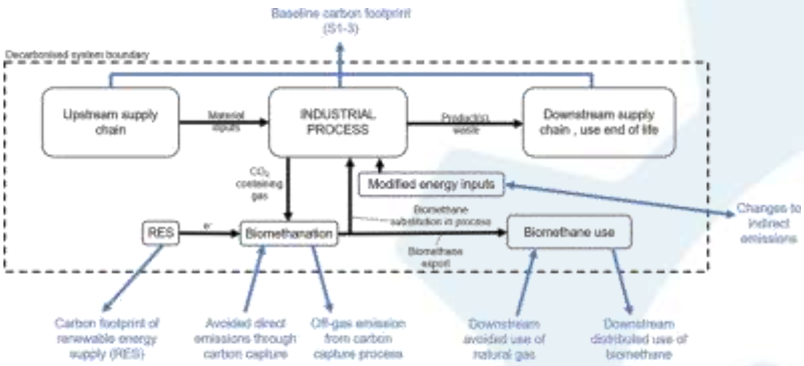

Figure S2. Generalised methodology for carbon footprint calculation.

For the other four industries considered, it was found that biomethanation can result in substantial decarbonisation, ranging from 0.70-2.87 $tCO_{2e}/t_{product}$ which could lead to potential global decarbonisation of 4249 $MtCO_{2e}/a$. The **baseline** and **decarbonised** carbon footprints of the four industries were 870 $kgCO_{2e}/t_{Clinker}$ and 166 $kgCO_{2e}/t_{Clinker}$, 2200 $kgCO_{2e}/t_{Liquid\_Steel}$ and 1455 $kgCO_{2e}/t_{Liquid\_Steel}$, 2.03 $kgCO_{2e}/L_{Alcohol}$ and 0.50 $kgCO_{2e}/ L_{Alcohol}$, 950 $kgCO_{2e}/t_{Air\_Dried}$ and -1915 $kgCO_{2e}/t_{Air\_dried}$ for cement, steel, distillery and pulp and paper respectively. Other important results are summarised in table S1. Where the carbon source was biogenic (pulp and paper, distillery) the decarbonisation replaced all direct fossil emissions with equivalent biogenic emissions. It was found to be critical to achieve decarbonisation that electricity be renewable and ideally to be from the lowest carbon options e.g. wind, solar.

The decarbonisation was mainly driven by the substitution of natural gas with biomethane, both in the industrial process and exported to downstream applications. For industries where the carbon source was biogenic (distillery, pulp and paper) this effect was more pronounced such that decarbonisation via biomethanation could be more effective than direct electrification (i.e. removal of direct fossil GHG emissions). Despite substantial gains in terms of decarbonisation potential, these rely strongly on the substitution of fossil fuels, and net-zero emissions cannot be reached by using biomethanation alone unless a biogenic carbon source is used, since the downstream combustion of biomethane results in the emission of the carbon captured as part of the biomethanation process.

Economic assessment predicted increases in production cost for cement (1070%), pulp and paper (561%), steel (182%) and distillery (37%). These were based on nominal estimates of additional costs and revenues after the integration. As for any economic prediction these are subject to large uncertainties and should be treated as indicative. 'Best case' calculations, based on minimum cost and maximum revenues predicted more modest increases in production cost, and are shown in table S1. Additional costs are dominated by hydrogen production cost which is predicted to remain high into the future even where curtailed electricity is targeted, but producing alternative higher value products (compared to methane) could offset high additional net-costs by increasing additional revenue generation.

Overall performance metrics were defined to facilitate external comparison of the **decarbonised** scenarios consider with other decarbonisation options. The **decarbonisation intensity**, defined as the fossil GHG avoided per unit of renewable energy consumed was 0.084-0.096 tCO_{2e}/MWh with the industries with biogenic carbon sources being slightly higher. **Cost of decarbonisation**, defined as the additional costs of avoiding GHG emissions s was £773-837/tCO_{2e} for the processes considered.

Table S1. Summary of results of the biomethanation study (LS – liquid steel, LA – litre of alcohol, ADt – Air dried ton).

Industry	**Baseline or Decarbonised**	**Carbon footprint**	**Fossil (F) or Biogenic (B) direct emissions (F:B)**	**Biomethane export (%)**	**Additional (renewable) electricity requirement**	**Production cost Nominal case (best case)**
Cement	Baseline	870 $kgCO_{2e}/t_{Clinker}$	Fossil	-	-	£55/ $t_{clinker}$
	Decarbonised	166 $kgCO_{2e}/t_{Clinker}$	Fossil	69%	1070 MW for 125 $t_{clinker}$/hr	£644/ $t_{clinker}$ (£237/ $t_{clinker}$)
Steel	Baseline	2200 $kgCO_{2e}$/tLS	Fossil	-	-	£326/tLS
	Decarbonised	1455 $kgCO_{2e}$/tLS	Fossil	78%	5200 MW for 5.3 MtLS/a	£919/tLS (£469/tLS)
Distillery	Baseline	2.03 $kgCO_{2e}$/LA	Mixed (52:48)	-	-	£3.44/LA
	Decarbonised	0.50 $kgCO_{2e}$/LA	Biogenic	45%	113 MW for 61 MLA/a	£4.69/LA (£3.93/LA)
Pulp and paper	Baseline	950 $kgCO_{2e}$/ADt	Mixed (3:97)	-	-	£395/ADt
	Decarbonised	-1915 $kgCO_{2e}$/ADt	Biogenic	97%	5410 MW for 4000 ADt/d	£2609/ADt (£863/ADt)