UK Net Zero carbon reduction in the areas of catalysis innovation

Summary Report

Prepared for Innovate UK

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Enabled Future Limited

TABLE OF CONTENTS

GLOSSARY

AWE	Alkaline Water Electrolysis
Bio-SA	Biosuccinic Acid
BDO	Butanediol
bpd	Barrels Per Day
Bn	Billion (1 x 10^9 or one thousand million)
BTX	Benzene, Toluene Xylene
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CASE	Coatings, Adhesives, Sealants and Elastomers
CCUS	Carbon Capture, Utilisation and Storage
CFD	Compression Force Deflection
CO2U	Carbon Dioxide Utilisation
COTC	Crude Oil to Chemicals
CRM	Critical Raw Material
CPC	Cooperative Patent Classification
CS	Compression Strength
CEXD	Cumulative exergy demand
DMC	Dimethyl Carbonate
DME	Dimethyl Ether
DOE	United States Department of Energy
EC	European Commission
EET	Ecological, Economic and Technological
EO	Ethylene Oxide
EOL	End of Life
ESG	Environmental, Social and Governance
ESS	Energy Storage System
EU	European Union
FTR	Flake to Resin
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GlyC	Glycerol Carbonate
Gt	Gigaton (10^12 tons)
GWP	Global Warming Potential
HDPE	High Density Polyethylene
HMDI	Hexamethylene Di-Isocyanate
HMG	Her Majesty’s Government
HVAC	Heating Ventilation Air Cooling
HVO	Hydrogenated Vegetable Oil
IP	Intellectual Property
IPC	International Patent Classification
IPCC	Intergovernmental Panel on Climate Change
LCA	Lifecycle Analysis/Assessment
LCOE	Levelised Cost of Electricity
LCOH	Levelised Cost of Hydrogen
LLDPE	Linear Low-Density Polyethylene
LDPE	Low Density Polyethylene
LIB	Lithium-Ion Battery
LPG	Liquefied Petroleum Gas
MDA	Methylene Dianiline
MDI	Methylene Diphenyl Diisocyanate

MEG	Monoethylene Glycol
MMO	Methyl Monooxygenase
MNC	Multi-National Company
NASA	National Aeronautics and Space Administration
NDC	Nationally Determined Contributions
NET	Negative Emissions Technology
NGFS	Network for Greening the Financial System
NGL	Natural Gas Liquids
NOAA	National Oceanic and Atmospheric Administration (NOAA).
NOP	Natural Oil Polyols
NOx	Nitrogen Oxides
NREL	National Renewable Energy Laboratory
NWE	North West Europe
OPEX	Operating Expenditure
PCD	Polycarbonate Diols
PCLP	Polycaprolactone polyols
PDI	Pentamethylene Diisocyanate
PE	Polyethylene
PEC	Polyether Carbonate
PECP	Polyether Carbonate Polyols
PEF	Polyethylene furanoate
PESP	Polyester Polyols
PET	Polyethylene Terephthalate
PETP	Polyether Polyols
PGM	Platinum Group Metal
PO	Propylene Oxide
PP	Polypropylene
PPC	Polypropylene Carbonate
PHA	Polyhydroxyalkanoate
PHB	Polyhydroxybutyrate
PHV	Polyhydroxyvalerate
PHB/V	Polyhydroxybutyrate-covalerate (PHB/V),
PHH	Polyhydroxyhexanoate
PO	Propylene Oxide
POCP	Polycarbonate Polyol
PTMEG	Polytetramethylene ether glycol
PU	Polyurethanes
PTA	Purified Terephthalic Acid
PtG	Power-To-Gas
PtL	Power-To-Liquids
P2X	Power-To-X
PVC	Polyvinyl Chloride
PX	Paraxylene
RED	Renewable Energy Directive
RFS	Renewable Fuels Standard
ROCOP	Ring-Opening Copolymerisation
RPET	Recycled Polyethylene Terephthalate
SAP	Superabsorbent polymer
SME	Small-to-Medium Enterprise
TCA	Tricarboxylic Acid

TDA Toluene Diamine
TDI Toluene Di-Isocyanate
Tn Trillion (1 x10^{12} or million x million)
TOC Table of Content
Ton Metric Ton
TPO Thermoplastic Polyolefins
TPU Thermoplastic Polyurethanes
TRL Technology Readiness Level
UN United Nations
UNFCCC United Nations Framework Convention on Climate Change
VOC Volatile Organic Chemical
XDI Xylylene Di-Isocyanate

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1. EXECUTIVE SUMMARY

1.1. Key Highlights from the Study

- Catalysis plays a major role in mitigating 123.6 million tCO_2eq of carbon savings – 21.4% of the UK's production emissions or 15.5% of the 800 million tCO_2eq consumption emissions.
- Blue hydrogen plays the largest role in terms of total carbon savings (88 million tCO_2eq). Catalytic innovations are mainly focused on the reactor with new sorbents also playing a role in continuing to bring down the price of blue hydrogen production.
- The benefits of blue hydrogen are clear; however, it will require a vast amount of carbon to be sequestered and necessitate the extraction of fresh fossil fuel which creates both CO_2 and methane emissions during exploration, production and transport and results in loss of biodiversity. Diversion of this carbon back into the system for utilisation would be beneficial for the environment. The possibility of new chemistries to convert CO_2 or CO (which is actually made in the blue hydrogen process but then converted to CO_2) could facilitate a three-fold environmental and commercial benefit (providing the hydrogen, avoiding fossil fuel and avoiding sequestration).
- Green hydrogen via water electrolysis is one of the single most important future transformations in the chemicals industry, underpinning a whole host of downstream power-to-x (P2X) value chains. These span larger bulk chemicals and so-called "e-fuels" including ammonia, methanol and synthetic liquid transportation fuels. Industrial biotechnology combined with green hydrogen has the propensity to allow a wide range of other bulk, specialty, fine chemicals, proteins and polymers to be manufactured at scale. Investment in biocatalysis, electrocatalysis as well as more conventional chemocatalysis is essential to allow these growth areas to flourish.
- The UK needs to go much further in mitigating solid wastes which create greenhouse gas emissions when they are incinerated or landfilled. This report has highlighted several techniques which can be employed, with improved catalysis, to allow for reuse of food, municipal solid waste (MSW), valuable polymers and residual, unrecyclable mixed plastic waste (PSW). The UK has many companies active in this area, including overseas companies with UK locations, domestic UK SME's and many active university departments. Specific chemical transformations that were studied are:
    - Hydrogenated vegetable oil (HVO) from catalytic processing of used cooking oil (UCO)
    - Some methods for production of novel materials from specific types of food waste e.g., beer from waste bread and synthetic leather from pineapple peels
    - Production of recycled polyethylene terephthalate (RPET) from waste PET streams
    - Production of fuels or olefinic monomers from waste unrecyclable PSW via a number of catalytic methods including pyrolysis and gasification
- The NetZero roadmap is highly dependent upon catalysis – this is not a technique which improves the pathway a little or saves a few % on operating costs – it is a "stop/go" scenario – without the catalyst and associated reactor technologies, it is impossible to proceed at all.
- Non-catalytic technologies are not common – even if there is a non-catalytic step, such as thermal pyrolysis, catalysts are usually required somewhere else within the process.
- As of now, there are no technology ready solutions for reaching NetZero in the manufacturing industries with the exception of biofuels. Much more urgency is required and

specific focus on catalysis for decarbonisation, if the governments NetZero targets are to be achieved.

1.1.1. Summary of Contributions

The individual contributions from the different areas studied are summarised in Table 1.1.1.1. Hydrogen is the major way that the UK is considering decarbonising sectors which cannot be addressed via electrification. For the purposes of the report, blue and green hydrogen are seen as complementary rather than competing – i.e., green hydrogen for heat and power has not been considered, nor has hydrogen use in fuel cell vehicles. Only power-to-x (P2X) conversions to liquid transportation fuels and chemicals have been included.

For blue hydrogen, the data comes from the H21 gas industry projects study. The lower end (88 million tCO_2eq) considers the use of hydrogen in home heating for a proportion of UK residences, 31% of power and 61% of UK combined heat and power (CHP) including high pressure industrial clusters and whereas the upper value (117 million tCO_2eq) considers complete decarbonisation of heat and transport. This is considered unlikely, and therefore the lower value has been used in the total.

The same H21 studies detailed the amount of CO_2 which would need to be stored or sequestered to meet Net Zero (75-175 million tonnes). In order to be more circular, and to avoid the extraction of virgin fossil fuel, it will be necessary either to move to green hydrogen, or to reutilise the CO_2. In this study the reuse of CO_2 is considered a better option than sequestration because of the large additional environmental benefits including prevention of methane emissions and loss of biodiversity. Various options for reusing CO_2 are possible (see section 1.2) including the production of chemicals and polymers. Another possibility considered is the use of CO instead of CO_2 for green carbonylations which are an important class of reactions for the chemical industry.

Several Power-To-X applications are included in the report. All of these utilise green hydrogen as a feedstock. Those processes profiled use chemocatalytic methods to convert green hydrogen to products. However, fermentative approaches are also possible. Ingenza Ltd also has a biocatalytic process for converting CO_2 to formic acid. They estimate being able to save 4 million tCO_2eq and while a full chapter has not been devoted to this topic, it is included in the table. The figure given for power-to-liquids (PtL) is the lower end of the 2-8 million tCO_2eq provided in published data. Collectively the Power-To-X and CCU approaches would mitigate 12.9 million tCO_2eq emissions based on the technology and market assumptions used in the case studies.

The remaining areas covered in the study are the conversion of solid wastes, namely plastic waste, plastic waste combined with municipal solid waste (MSW), and options for converting used cooking oil (UCO) to hydrogenated vegetable oil (HVO). For conversion of waste plastics, the scenarios considered are, separation of PET and a depolymerisation route followed by repolymerisation to recycled PET (RPET) and pyrolysis of the remaining mixed plastic waste (PSW) to fuels. The gasification of PSW/MSW to methanol is an alternative route and it is not included in the total.

A number of options were detailed for conversion of food to novel materials (NM) however, these are not considered to be high impact on decarbonisation – and in fact because of the number of stages involved in the processes, they might very limited if any impact on overall carbon emissions. Therefore, only HVO has been counted for conversion of waste food.

In total, these technologies can provide 123.6 million tCO_2eq carbon savings. This amounts to 20% of the entire UK carbon footprint based on production, and 15% based on consumption. It is vastly higher than the 33 million tCO_2eq emitted by manufacturing industries. If additional suitable CO_2 utilisation options can be identified, this could be increased much further.

Table 1.1.1.1 Summary of Data for Catalytic Technologies for Reaching UK NetZero

Product	Million tCO2eq abated	Applications	Comments
Blue Hydrogen	88-117.4	Residential Heat, Power, CHP	Uses the H21 North of England scenarios H21 XL and H21 MAX
Green Hydrogen		Power-To-X	
Power-To-Ammonia	8.4	Shipping	Based on Haldor-Topsoe's analysis of green ammonia
Power-To-Gas	n/a	Residential Heat	Assume that hydrogen blending included in blue hydrogen would be preferable
Power-To-Methanol	4.2	Transport Fuel	Based on blending methanol into gasoline passenger cars
Power-To-Formic Acid	4.0	Energy Carrier	Based on Ingenza fermentation technology
Power-To-Liquids	2.0	Transport fuel	Based on blending into diesel passenger cars
CO_2 to Polyols	0.2	Polyurethanes, polycarbonates	Using Econic Technologies scenarios
CO_2 to Polyhydroxyalkanoates	2.5	Packaging, various other applications	This technology fits well with the UK's industrial biotechnology focus
CCUS/P2X	12.9		
Other CCUS/P2X	87.1	Various broad applications	Based on avoided CCS and development of processes
Waste Food Conversion			
Avoided disposal, novel materials	4.0	Clothes, shoes, accessories	Based on meeting the Courtauld's commitment
Conversion to HVO	5.5	Diesel fuel replacement	Assumes 10% of diesel is replaced with HVO from UCO. This could be much higher if 50% of the UK diesel was replaced with HVO.
Plastic Solid Waste Conversion			
Pyrolysis to fuels	3.3	Fuels	Based on avoiding the incineration of PSW as well as carbon displacement.
Gasification to methanol	1.65 (alternative to pyrolysis)	Chemicals, fuels	Alternative to pyrolysis. Does not account for the carbon saving in the application
Use in PET	1.5	Drinking bottles and textile fibres	Chemical recycling of PET which is additional to PSW
Grand Total	**123.6**		

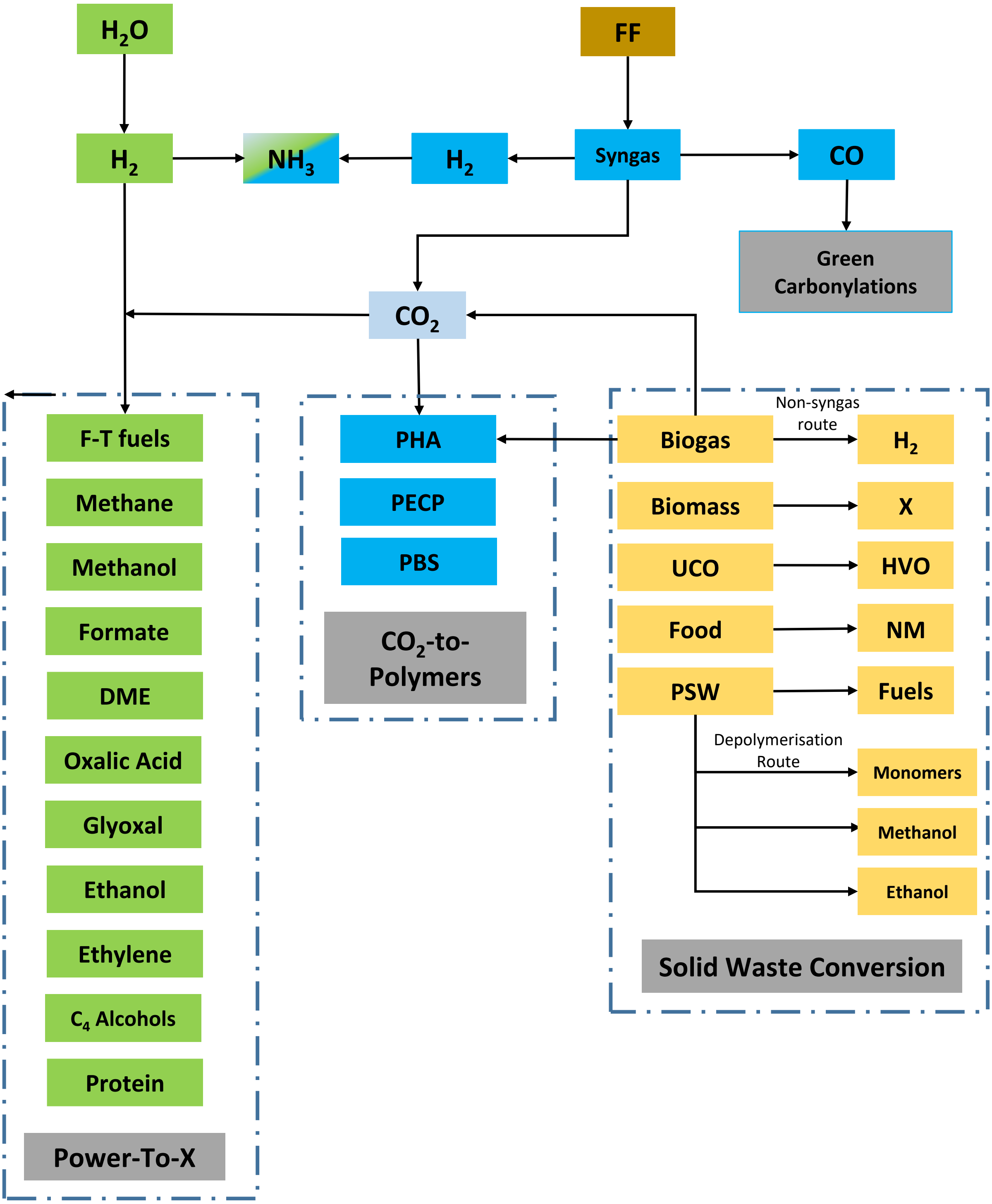
1.2. Scope of Chemicals Covered

There are a vast number of catalytic routes which could have been included in this report. However, it is limited to the most topical and current areas. The starting materials covered are mainly blue hydrogen, green hydrogen, CO_2 and solid waste and the main transformation areas are Power-To-X, CCUS and chemical transformations of solid wastes. There is a high-level summary provided for biobased chemicals and plastics, but a more detailed view is outside the scope. Equally any non-catalytic transformations and CO_2 capture are also outside of the scope. The routes of interest for the report are shown in figure 1.2.1 below. The majority of the focus is on hydrogen production, Power-To-X transformations for CCUS and chemical transformations of solid waste.

There are many possibilities for chemicals from Power-To-X, much of the initial focus has been on production of commodity chemical projects mainly methanol, dimethyl ether (DME), ethanol and synthetic natural gas (SNG) and Fischer-Tropsch projects and some of these are reaching higher TRLs. Over time approaches and the type of target molecules has diversified; increasingly fermentation and biotechnology approaches have been utilised with more specialty and fine chemicals possible as a result.

The main polymers which are directly made with CO_2 in the polymerisation reaction which have had any commercial progress are polyhydroxyalkanoates (PHA) and polyethercarbonate polyols (PECP). Polymers can also be made CO_2-derived monomers. Commercially polybutylene succinate (PBS) is the only notable example, but with improvements in Power-To-X technology, many others would be possible. Reduction of solid waste is an important tool for lowering the carbon footprint of the chemical industry because of the two-fold benefit of avoiding landfill and displacing virgin fossil feedstocks. While much of the focus for plastic waste has been on production of fuels it is important to find circular routes via chemical recycling, because this is the only way to compensate for the already have high carbon footprint of these materials.

Figure 1.2.1 Scope of Catalytic Routes Included in the Report



Source: Enabled Future Limited

1.3. Contributions to NetZero by Group

1.3.1. Blue Hydrogen

Table 1.3.1.1 Blue Hydrogen Product & Technology Summary and Recommendations

Product Group/Technology		**Reaction Chemistry**
Blue Hydrogen		Fossil Fuel → Syngas → $H_2 + CO_2$
		Technology Description
		Blue hydrogen is produced from fossil fuel derived syngas combined with CO_2 capture and storage (CCS). The technology development has mostly focused around optimising the hydrogen yield and flowsheet for integration with CCS. Catalytic reactor innovation has been key, more so than the catalysts themselves although sorbents for some variants form an integral part of the technology. The Johnson Matthey low carbon hydrogen (LCH) technology is expected to be widely deployed although newer variants claim to be able to improve the techno-economics.
		Technology Developers
Cadent/Johnson Matthey/Progressive Energy		Low carbon hydrogen (LCH) flowsheet.
Cranfield University		Hydrogen via sorbent enhanced steam reforming (HyPER). The Compact Hydrogen Generator (CHG) technology
Teeside University		Catalytic Membrane Reactor (CMR)
		Carbon Reduction Potential in the UK
		Decarbonised hydrogen is likely to have the highest single impact on reaching UK NetZero than any other of the product groups. The decarbonisation potential of blue hydrogen as a method for providing heating in homes and as transportation fuel has been estimated at **88-117 million tCO_2eq**. The amount of hydrogen required in the chemical and manufacturing industries is hard to ascertain as much of it will be generated and used captively. However, the merchant hydrogen requirement would be relatively small compared to the amount needed for heat and transport.
		Techno-Economic Factors
		The CAPEX for blue hydrogen via the LCH was estimated at **£8.5** bn for nine units providing 12.15 GW of hydrogen for home heating. These would provide 50 million tCO_2eq savings.

	Cranfield can achieve a 20% reduction in LCOH compared to SMR/ATR+CCS: a 40% CAPEX reduction relative to ATR+CCS and 50% CAPEX reduction relative to SMR+CCS.
	Comments on Funding
	Cost reduction is imperative for hydrogen production in terms of CAPEX and OPEX. Even a 1% reduction in these figures has a major impact. Continue to look at novel reactor and sorbent technologies and to support those in earlier stages of development from Cranfield University and Teeside University which have the potential to lower costs. The need for new catalysts is not so high for blue hydrogen, however, as refineries increasingly look for other ways to survive the downturn in transportation fuel demand, they could look to produce hydrogen, especially from the heavy cuts. This is not an area with much UK innovation – this could be discussed with the Catalysis Hub and with other catalysis stakeholders to see if there is interest. The LCH technology and the HyPER/CHG process from Cranfield have already received funding via BEIS to develop the process. The Teeside University CMR may be more in need currently to scale up its concept.
	Summary & Recommendations
	High growth area with v. high impact on decarbonisation. Relatively lower need for new catalyst innovation. Worth funding reactor variants and new sorbent technologies. Consider looking at new processes for gasification of heavy refinery feeds where more catalysts might be needed.

1.3.2. Green Hydrogen

Product Group/Technology	Reaction Chemistry
Green Hydrogen	Water Electrolysis: H2O → H_2 + 1/2O_2
Technology Description	
Green hydrogen is manufactured via water electrolysis with the most likely technology for widespread adoption being proton exchange (polymer electrolyte) membrane (PEMEL). The membranes form the backbone of the PEMEL's electrodes and are coated with platinum group metal (PGM) catalysts for both the anode and the cathode. It is the key feedstock in the entire Power-To-X value chain which is broadening to include not just bulk hydrogen and derivatives, but also specialty and fine chemicals.	
Technology Developers	
ITM Power	PEMEL with catalyst coated membranes (CCM)
PV3 Technologies	Electrocatalyst powders, coated electrodes, VRB electrolyte
Imperial College	
Carbon Reduction Potential in the UK	
The carbon reduction potential of green hydrogen for the purposes of this report is being considered for its downstream derivatives and not for its direct use in heat, power and industry.	
Techno-Economic Factors	
For the system cost, ITM Power is targeting 5 MW PEMEL with a CAPEX of £400/kW compared with the value of £1,090 kW in 2017. The levelized cost of hydrogen (LCOH) target is £2-3/kg and this depends very much on the electricity price. This is expected to be achievable by 2030 as wind energy price decreases continue.	
Comments on Funding	
As with blue hydrogen, there is considerable work to do in order to bring down the cost and improve the performance of green hydrogen at scale. ITM Power is well advanced in its technology deployment, and it may be more appropriate to look an earlier stage company in the UK such as PV3 Technologies.	
Summary & Recommendations	
Green hydrogen is an essential tool underpinning the entire Power-To-X chemicals platform. Considerable progress has been made in its commercialisation; however, it is worth considering funding SME's with potentially disruptive technologies and thrifting PGM catalyst systems.	

1.3.3. Green Ammonia

Product Group/Technology	**Reaction Chemistry**
Green Ammonia (Use)	Haber Bosch: $H_2 + N_2 \rightarrow NH_3$ Ammonia Cracking: $NH_3 \rightarrow H_2 + N_2$
Technology Description	
Green ammonia is manufactured from green hydrogen and nitrogen using standard Haber-Bosch process. While this will not require any additional catalyst innovation, the ability to utilise green ammonia as a fuel, for instance onboard requires either ammonia cracking or ammonia fuel cells. Siemens has developed a novel lithium amide ammonia cracking catalyst which is being demonstrated at the Rutherford Appleton laboratory. Meanwhile, Surrey-based AFC Energy, has successfully demonstrated an ammonia cracker integrated to its alkaline fuel cell to provide hydrogen for marine shipping.	
Technology Developers	
Siemens/Engie/STFC	Green Ammonia Demonstrator at Rutherford Appleton
AFC Energy	Integrated ammonia cracker-fuel cell system for off-grid energy
Carbon Reduction Potential in the UK	
Based on a 90% reduction with wind ammonia, savings of **8.4 million tCO2eq per annum** by switching VLSFO to green ammonia**.** In addition, using the same data, a saving of **1.7 million tCO2eq** could be made if all the UK ammonia production were switched to green ammonia.	
Techno-Economic Factors	
Green ammonia cost is in the range ($400-850/ton) and is currently far more expensive than either conventional ammonia ($250/ton) or blue ammonia ($350-400/ton), however it can compete with the high price of Very Low Sulphur Fuel Oil (VLSFO) which is ($500-600/ton). As the cost of renewable energy decreases it is expected to become more competitive with blue hydrogen.	
Comments on Funding	
The current players in this sector within the UK are already quite advanced however, there are relatively few ammonia cracking catalyst concepts, and there may be scope for more groups to work on this technology.	
Summary & Recommendations	
Green ammonia offers considerable decarbonisation potential, not just for fertiliser production, but also as a green shipping fuel. It might be useful to seek out more university groups to work on ammonia cracking catalysts as there are relatively few players in this area.	

1.3.4. Power-To-Gas

Product Group/Technology	**Reaction Chemistry**
Power-To-Gas (PtG)	CO_2 methanation: $CO_2 + 4H_2 + \rightarrow 2CH_4 + 2H_2O$
Technology Description	
PtG describes green methane made from the catalytic methanation of waste CO_2 with green hydrogen according to the Sabatier reaction as shown above. It is a major area in the Power-To-X area with several major companies globally developing technology including Thyssenkrupp Industrial Solutions (TKIS), Germany. The technology has been demonstrated in Germany and Italy as part of the EU2020 Store&Go project.	
UK Technology Developers	
University of Bath	Catalyst developed - ruthenium promoter on a nitrogen-doped carbon nanotube support (Ru-Fe@NCNT)
Carbon Reduction Potential in the UK	
The carbon footprint of a future PtG process has been calculated at 0.4 kg CO_2eq/Nm^3 of PtG SNG compared with natural gas at 2.4 kg CO_2 eq/Nm^3. This was for the 200-kW unit at Troja, Italy. The method is considered unlikely to compete with upgraded biogas for vehicles, and hydrogen for heat. Therefore, its carbon footprint for the UK has not been considered in this report.	
Techno-Economic Factors	
The techno-economics were not disclosed for the Store&Go project. Further analysis on other projects has not been performed.	
Comments on Funding	
There is scant research being carried out on PtG in the UK. Other than the University of Bath, there seem to be few opportunities for funding.	
Summary & Recommendations	
PtG technology is a popular Power-To-X project area however it is not a focus for the UK, and it is. For now, it is a lower priority for the UK than other P2X projects.	

1.3.5. Power-To-Methanol

Product Group/Technology	**Reaction Chemistry**
Power-To-Methanol	Methanol Synthesis: $CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$
Technology Description	
Power-to-methanol refers to the conversion of green hydrogen and waste CO_2 into methanol. This is one of the most common types of power-To-X projects, it also opens up the ability to produce a wide range of green fuels and chemicals through standard chemistries and as such is highly enabling for NetZero in the chemicals industry. Carbon Recycling International (CRI) Emissions-To-Liquids (ETL) is the most developed. Other companies include Air Liquide in partnership with Clariant and- Breathe Sciences in India.	
UK Technology Developers	
Cardiff Catalysis Institute (CCI)	Bimetallic palladium on zinc oxide (Pd/ZnO).
Carbon Reduction Potential in the UK	
CRI's technology is having a small demonstration in UK vehicles. If methanol were used at a 15% blend for gasoline in 20 million vehicles, **4.2 million tCO2eq** savings could be made.	
Techno-Economics	
The CAPEX for the new CRI project in China has been valued at £67 million and will convert 150,000 tpa of CO_2 to produce 110,000 tpa of methanol and 70,000 tpa LNG annually.	
Comments on Funding	
The UK is also very far behind on Power-To-Methanol compared with overseas countries. Compared with PtG there is more interest and in particular Cardiff Catalysis Institute (CCI) have looked at non-copper catalyst systems. Oxford University also have an interest in developing non-copper systems. The topic is worth exploring further considering that it can leverage decarbonisation of several chemical value chains and alternative fuels.	
Summary & Recommendations	
Power-To-Methanol is an important enabling technology for NetZero and although the UK is far behind on technology development, it may be able to innovate novel catalyst systems.	

1.3.6. Power-To-Ethanol

Product Group/Technology	**Reaction Chemistry**
Power-To-Ethanol	Ethanol Synthesis: $2CO_2 + 6H_2 \rightarrow CH_3OH + 3H_2O$
Technology Description	
Several groups around the world have been working on eletrocatalyst systems for Power-to-Ethanol and most recently Argonne National Laboratory (ANL) in the USA has reported on a copper-based catalyst for converting CO_2 to ethanol. Herriott-Watt university has studied the reaction mechanism and reported on nickel on titania nanoparticle catalysts which convert CO_2 into ethanol, acetahdehyde and acetic acid.[1]	
UK Technology Developers	
Herriott-Watt University	Nickel on titania nanoparticle catalysts
Carbon Reduction Potential in the UK	
The change from E5 to E10 in UK vehicles is predicted to lower carbon emissions using bioethanol by 750,000 tCO_2eq. There is insufficient data on Power-To-Ethanol as yet, but the carbon saving would be expected to be in this order of magnitude if used in the same quantities in UK vehicles.	
Techno-Economics	
The technology is embryonic, and it is too early to provide techno-economics. The electricity price would be a large determinant. Worth noting that half of the hydrogen generated ends up back as water and this would be mean only 50% of the hydrogen generated would end up as product.	
Comments on Funding	
This is an interesting area in that it would not suffer the same issues as bioethanol in terms of land usage, competition with food crops, fertilizer use and ozone emissions or product stability. However, it has no identified SME's and funding would need to be for very early-stage projects.	
Summary & Recommendations	
Power-To-Ethanol is an interesting concept which could delink transportation fuel from biomass but challenging to find suitable UK entities with expertise and interest in taking it further.	

[1] Ola O et al. (2013) "Turning CO2 into valuable chemicals"; Energy Procedia 37 (2013) 6704 – 6709

1.3.7. Power-To-Liquids

Product Group/Technology	**Reaction Chemistry**
Power-To-Liquids (PtL)	Fischer-Tropsch conversion of CO_2 and H_2
Technology Description	
Power-To-Liquids (PtL) generally refers to the conversion of CO_2 to any transportation fuel that can be liquefied including methanol, ethanol, DME, OME or F-T liquids. Only the latter is in the project scope. The concept lends itself to small scale mini-GTL reactors. In the UK CompactGTL and Velocys have processes starting with natural gas and Johnson Matthey has provided them with catalysts. However, none of these companies has disclosed any move towards a PtL process although it would seem to be theoretically possible. A PtL variant using biogas containing CO_2 is a possibility being considered in the UK.	
UK Technology Developers	
CompactGTL/Johnson Matthey	Natural gas and biomass feedstocks
Velocys	Natural gas and biomass feedstocks
CDUUK	Process simulation for PtL using MEA solvent for CO_2 capture
Carbon Reduction Potential in the UK	
Based on the CDUUK simulation, PtL technology is estimated to have the potential to lower the UK's transportation carbon footprint by 2-8 million tCO_2eq per year. This assumes a hypothetical replacement of 9.75–12.4% of diesel by FT fuels as a blend and technology based on monoethanolamine (MEA) absorption of CO_2. At face value, there does not seem to be any reason why a higher blend could not be used, although biogas is also being used for CNG, so the amount of available raw material needs to be better understood.	
Techno-Economics	
The process simulation from CDUUK puts the total CAPEX for a biogas/CO_2 feedstock for a large scale 1,670 tpd PtL plant at £2.53 bn and the OPEX at £758 million per year. The fuel price achievable is £1.85 per litre and the GWP was 70% lower than that of diesel.	
Comments on Funding	
A PtL variant using biogas provides an interesting possibility of leveraging the UK's biogas feedstocks for liquid transportation fuels. Techniques such as these are needed to manage the energy transition in the next 20 years while ICE are still on the road. This is a good area to fund and there is considerable expertise in the UK on PtL technology which could be leveraged to form a consortium.	
Summary & Recommendations	
A biogas-based PtL variant could be a powerful tool for decarbonisation of the remaining ICE fleet in the UK. A consortium of UK companies with expertise could be formed and the area further developed.	

1.3.8. CO_2-To-Polyhydroxyalkanoates (PHA)

Product Group/Technology	**Reaction Chemistry**
CO_2 to polyhydroxyalkanoates	Fermentation of methane, biomethane or green H_2 and CO_2
Technology Description	
PHA and variants are a group of biodegradable polymers with widespread potential applications. They are made via microbial activation of methane and synthesis of PHA. $8\ CH_4 + 12O_2 + FP \rightarrow C4H_6O_2$(PHB monomer) $+4CO_2$ +12ATP +FPH2 Oxidation occurs when methyl monooxygenase (MMO) dissociates oxygen molecules which react with methane to make methanol and water. Methanol is then oxidised using methanol dehydrogenase to make formaldehyde which undergoes subsequent biochemical conversions to Acetyl-Co-A via serine. Acetyl-Co-A then undergoes further transformations to form PHB. Some methane is sacrificially converted through the tricarboxylic acid (TCA) cycle to CO_2 in order to regenerate the energy required within the fermentation cycles. Only a few companies have technology globally – Newlight Technologies, USA is one of the highest profile.	
UK Technology Developers	
None identified	
Carbon Reduction Potential in the UK	
Because the technology mitigates methane emissions, it is regarded as carbon negative. However, without conclusive data it has been assumed to be carbon neutral. The potential applications of PHA are extensive, even if it were used just to replace UK PE packaging, the overall carbon saving would be 2.5 million tCO_2eq savings.	
Techno-Economics	
Newlight Technologies estimate a 100,000 tpa PHB have production costs were estimated at $4.1-$6.8/kg PHA. Use of methane in place of sugar reduced the raw material component from 30-50% of production costs to 22%. The study reported that replacement of refrigerant with cooling water would reduce costs further to $3.2-5.4/kg but for this further development of MMO is needed. Cambridge Consultants UK estimate PHA to have reached price parity with typical packaging materials.	
Comments on Funding	
PHA are potentially a highly versatile product which have applications across many sectors including packaging, medical, automotive, energy and others. Also, this is a technology which lends itself to the UK's industrial biotechnology skillset and access to biogas feedstock. It has the propensity to provide biodegradable plastic to be used in appropriate applications.	
Summary & Recommendations	
PHA are an underexploited technology which could contribute well to UK NetZero. Liaison with the industrial biotechnology hubs and stakeholders to see how it could be funded is advised.	

1.3.9. CO_2-to-Polyethercarbonate polyols (PECP)

Product Group/Technology	**Reaction Chemistry**
CO_2 to polyethercarbonate polyols (PECP)	Ring Opening Copolymerisation of Epoxides with CO_2
Technology Description	
A ring opening copolymerisation of epoxides with CO_2 (ROCOP) technology can be used to replace the petrochemical source of the CO_2 linkage in polyurethanes (such as dimethyl carbonate – DMC), with CO_2 itself. The CO_2, obtained from waste power plant flue gas, is inserted at intervals along the polymer chain, replacing a percentage of the conventional units and linking up with those that remain. The theoretical maximum is 50% (alternating units). Several companies have developed systems including Novomer, Repsol and Econic Technologies UK.	
UK Technology Developers	
Econic Technologies	Bimetallic metallorganic complexes
Carbon Reduction Potential in the UK	
It is estimated that a total of 200,000 tCO_2eq per year could be offset using Econic Technologies.	
Techno-Economics	
Econic Technologies reported that for a plant with a capacity of 50,000 tpa the use of CO_2 feedstock would save £36 million pounds on the cost of production (£720 per tonne).	
Comments on Funding	
The ROCOP technology from Econic Technologies is an excellent example of a successfully developed CCU reaction and it seems to be an ideal technology to fund. Potential for further catalyst development in UK universities may also be an option.	
Summary & Recommendations	
Award-winning technology developed in the UK with the potential to decarbonise products in the UK and overseas through product licensing. Further funding would likely be productive and would counterbalance investment in earlier TRL technologies.	

1.3.10. Conversion of Used Cooking Oil

Product Group/Technology	**Reaction Chemistry**
Hydrogenated Vegetable Oil (HVO)	Decarboxylation, deoxygenation and hydrodeoxygenation of triglycerides to paraffinic hydrocarbons.
Technology Description	
Oxygenated species in used cooking oil (UCO) are removed via three reactions, two of the three reactions convert the triglyceride feedstocks into paraffins (decarbonylation and decarboxylation) remove oxygen as CO or CO_2 respectively, thus there is a loss of carbon. Hydrodeoxygenation (HDO) removes oxygen as water, retaining all of the carbon in the product fuel. Decarboxylation Cnf COOR + H_2 → C„H2„+2+ CO_2+ RH Decarbonylation Cnf COOR + $2H_2$ → CnH2n+2+ CO + H20+ RH Hydrodeoxygenation CnH2n-HCOOR + $4H_2$ → Cti+iH_2(n+2) + $2H_2O$ + RH Catalyst innovations which result in selectivity towards hydrodeoxygenation pathways are still an area of development.	
UK Technology Developers	
UOP	Water tolerant cobalt-molybdenum/silica-alumina HDO catalyst.
Cardiff Catalysis Institute	Nickel-substrate interactions study
Carbon Reduction Potential in the UK	
If 10% of the UK diesel consumption were met from HVO this would amount to a saving of **5.5 million tCO_2eq per annum**.	
Techno-Economics	
Neste Oil's 800 mtpa plant in Singapore is estimated to have cost ~€550m (around £480 m using 2011 currency rates). A decision has been taken to expand the plant capacity by 1.3 mtpa at a cost of €1.4 bn (£1.25 bn).	
Comments on Funding	
This would be an interesting area to fund because of the level of interest in HVO as a near-term option for decarbonising diesel vehicles. It is favoured strongly by OEMs because of its ease to blend into existing diesel engines and superior burn characteristics. It is a matter of finding suitable UK entities to fund – they would almost certainly win backing from industry partners to work as part of consortium projects.	
Summary & Recommendations	
Acknowledge as a near term option for decarbonisation of transport fuels, with distinct needs for improvements in the catalyst. More effort is needed to identify UK entities to fund.	

1.3.11. Conversion of Plastic Solid Waste

Product Group/Technology	Reaction Chemistry
Mixed Plastic Waste (PSW)	Several routes including pyrolysis, depolymerisation, cracking, gasification and hydrotreating methods
Technology Description	
There are a number of ways to treat plastic waste – mechanical, thermochemical and catalytic routes via cracking, depolymerisation, thermal pyrolysis, catalytic pyrolysis, catalytic fast pyrolysis, hydrotreating and combinations thereof. Products include heat, power, hydrogen, liquid fuels, syngas and chemicals, in particular monomers. Plastic pyrolysis oil (PPO) can be fed into a petroleum refinery at various point to be made into chemicals including olefins and fuels, or into a steam cracker to make olefins. These options are being considered by UK SME's.	
UK Technology Developers	
He3 Ltd	Proprietary pyrolysis process for chemicals and fuels
Enerkem	Gasification process for chemicals and fuels
INEOS	Thermal depolymerisation
Klean Industries	Catalytic clean-up and thermal pyrolysis
Licella/Armstrong Chemicals	Hydrothermal upgrading
Plastic Energy	Thermal Anaerobic Conversion (TAC)
QMRE Ltd	Thermal pyrolysis
Recycling Technologies Ltd	RT7000 thermal cracking
Carbon Reduction Potential in the UK	
Three options were assessed based on information available at the time of writing. • The Klean Industries SPR process was estimated to be able to offset 3.3 million tons CO_2eq from the same weight of UK PSW. • The Enerkem process which can produce methanol from PSW and offset 1.65 million tons of CO_2eq from the conversion of 3.3 million tons of PSW single-use and non-recyclable plastic waste in the UK. • Catalytic depolymerisation of PET using methanolysis via a process such as LOOP/Indorama for 683,000 tons of UK PET waste arising would result in a carbon reduction of 1.5 mtCO2eq based on a PET carbon footprint of 2.19tCO2eq/t of PET.	
Techno-Economics	
• The Klean Industries SPR process runs at the 15,000 tpa scale (CAPEX not disclosed). The tyre pyrolysis projects at 120 tpd are slated to cost \$150 million. • Enerkem gasification plants. Enerkem's original MSW facility in Edmonton, Canada - a 100 ktpa plant cost \$100 million. Newer plants are planned at 350 ktpa which is a scale that can start to compete with fossil fuel processes. • QMRE have prices 50 stand-alone thermal pyrolysis production facilities for the UK market with each requiring an investment of £6.482 million and annual running costs of £900k. • Indorama is investing \$1.5 billion for a 750 ktpa RPET facility.	
Comments on Funding	
Plastics recycling is a large and complex area with several different technical approaches. The future focus is likely to be on circularity, rather than burning for fuel which effectively adds to an already very high carbon footprint. He3 Ltd is actively looking for funding to scale up its process and is looking to focus on production of olefins rather than fuels.	
Summary & Recommendations	
This is a strong area of focus for UK universities, existing companies either UK located, or owned and a range of SMEs. The latter are actively looking for funding and need more support than more established industry participants.	

1.3.12. Areas for further study

There are many other opportunities for decarbonisation which could be considered in addition to those enabled by the technologies covered in this report. Recommendations for further research include:

- Biobased chemical platforms in particular those beginning with carbohydrates extracted from biomass. There are many biobased chemicals which have been developed, but most of these are outside of the UK. More effort is needed to understand why there has not been more success within the UK and to see if there is a business case for funding innovation.
- Scotland has developed considerable expertise in the area of industrial biotechnology, and a variety of companies and stakeholders are developing ways of fermenting CO_2, and low carbon methane e.g., biogas into chemical products. This is an area where funding is much needed to grow SMEs, but it requires a dedicated focus to understand these opportunities in more detail.
- Plastics recycling is a complex topic with multiple approaches that can be employed. It interfaces with operations at both chemical plants and petroleum refineries. A full report on this area expanding on what has been included here could be of benefit.
- More advanced investigations of CCU including green carbonylations as a method of rebalancing the CO and H_2 supply/demand situation, as capacity for blue hydrogen increases. These would include the development of more advanced Power-To-X approaches as well as traditional chemocatalytic and biocatalytic approaches.