UK Catalysis Market Study Summary

Prepared for KTN

Dr Michelle K. Lynch CChem FRSC

26 June 2020

Enabled Future Limited

TABLE OF CONTENTS

GLOSSARY

AWE	Alkaline Water Electrolysis
Bio-SA	Biosuccinic Acid
BDO	Butanediol
bpd	Barrels Per Day
Bn	Billion (1×10^9 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
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
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

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

exploit the content. Nor may you transmit it or store it in any other website or other form of electronic retrieval system.

DISCLAIMER

The information contained in this report has been provided by Enabled Future Limited for information purposes only. This information does not constitute legal, professional or commercial advice. While every care has been taken to ensure that the content is useful and accurate, Enabled Future Limited gives no guarantees, undertakings or warranties in this regard, and does not accept any legal liability or responsibility for the content or the accuracy of the information so provided, or, for any loss or damage caused arising directly or indirectly in connection with reliance on the use of such information.

Enabled Future Limited does not make any warranty, express or implied, including warranties of merchantability and fitness for a particular purpose, nor does it assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed within this report, nor does it represent that its use would not infringe privately owned rights.

Reference in this report to any specific commercial products, process or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favouring by Enabled Future Limited. The views and opinions of authors expressed herein do not necessarily state or reflect those of Enabled Future Limited and shall not be used for advertising or product endorsement purposes.

1. EXECUTIVE SUMMARY

1.1. Key Highlights from the Study

- The global catalyst industry is a **$34 bn market**; almost **$50 bn** if catalytic process licensing is included. [1] By 2025 the market for catalysts will have increased to **$44 bn**.
- Catalysis is a sector growing faster than global GDP with the 2019-2025 CAGR forecast at **4.3%** per annum. The value created by catalyst products is put at some **$15 trillion**.
- Key areas of growth for catalysis include **petrochemical carbon efficiency, clean fuels, biorenewables, hydrogen generation, biomass and waste utilisation and carbon capture utilisation and storage (CCUS)**.
- The UK catalyst exports were worth **$920 m** in 2019[2] and in total the UK produced at least **$1 bn** worth of catalyst **– 3%** of the global total.
- Domestic UK consumption of catalyst is estimated to be worth **$433 m** in 2019 and is growing at a **CAGR of 3.0%** per annum from 2019-2025 to reach **$517 m**.[3]
- The catalyst consumed in the UK enables around **$190 bn** worth of domestic revenue across different catalyst end-use applications. By 2025 this will have risen to **$227 bn.**
- There is potential for the **UK to expand its catalysis sector** even further given its **expert skill base** and growing number of **catalysis-related SME's**.
- Investment is needed to nurture new technologies aimed at **clean growth** and to meet the objectives for a **green recovery** in the aftermath of the COVID-19 pandemic.

1.2. Catalyst Market Trends

Global chemical market revenue is set to reach $3.9 trillion (tn) in 2020. The CAGR for the period 2020-2035 is forecast at 3.8% per annum such that the total chemicals market reaches $6.8 tn in 2035.[4] The largest market is China with $1.4 trillion market – 36.4% of the total. The top performing product groups globally are in fine chemicals areas – agrochemicals, consumer chemicals and other specialty fine chemicals. Increased wealth, population growth and migration to city dwelling are the main drivers for most of the growth in the chemical industry.

Demand for refined products surpassed the 100 million bpd level in 2019 and will continue to grow during the study forecast period (2019-2025). Catalyst revenue is benefiting in the short term from continuing growth for transportation fuels demand, tightening emissions regulations in markets which require cleaner fuels and the need to maximize product yield and value from petrochemical feedstocks, including utilisation of the heavy ends (carbon efficiency). The move to production of chemicals as the main growth driver for refineries will also see catalyst revenue shift into those businesses, this is not necessarily an additional demand, but it will displace smaller less integrated chemicals producers at the laggard part of the cost curve.

Motor vehicle demand will break the 100 million-unit mark in 2021. There is diversification in the market, both in terms of the catalysts which need to go on conventional internal combustion engine (ICE) vehicles and those for new electric vehicle powertrains e.g. plug-in hybrids (PHEV) and fuel cells

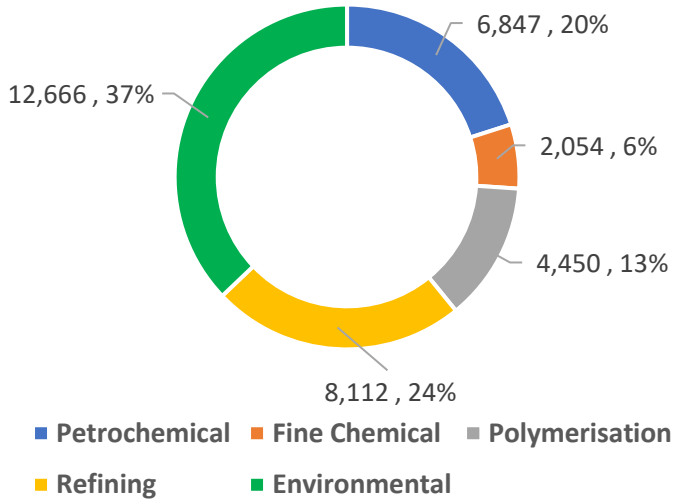
[1] The Catalyst Group Resources (TCGR), (2018); "The Intelligence Report: Business Shifts in the Global Catalytic Process Industries 2017-2023."
[2] Comtrade SITC Rev 4 Data (accessed June 2020)
[3] Enabled Future Limited (2020) "Catalysis Forecast Model 2019-2025" (all national catalyst revenue figures in the report are from this source)
[4] Roland Berger, (2018); "Chemicals 2035 – Gearing Up for Growth"

(FCEV). In future, this will have a sizeable impact on overall catalyst market revenue. Traditional environmental autocatalysts will eventually see a downturn in demand as the number of battery electric vehicles (BEV) which do not employ catalysts are sold. However, for now as car ownership increases and legislation tightens, the market will remain in growth. In the short-term, electrification will focus on PHEV which require catalysts. The aftertreatment system on a typical FCEV i.e. the Toyota Mirai, is also based on a cobalt-platinum coated membrane catalyst, and so, adoption of this powertrain will help to bolster environmental catalyst demand. Concurrently the need for PEM-based water electrolysers and other methods of producing low-carbon hydrogen will also have a net positive effect on catalyst revenue, especially considering the continued application in stationary power and signs of adoption for industrial hydrogen production – although here there will be a replacement in traditional hydrogen production catalysts and the net effect on revenue will depend on the relative volume and value of the new electrocatalysts vs. heterogeneous catalysts.

1.3. Global Catalyst Market

The global catalyst market was worth $34.1 bn in 2019 and is forecast to reach $44 bn in 2025. It is a sector growing faster than global GDP with the 2019-2025 CAGR forecast at 4.3% per annum. The value created by catalyst products is put at some $15 trillion.[Error! Bookmark not defined.] Even so, the catalyst industry is generally unrecognised as the technology has low visibility compared with the end-use applications.

Fig 1.3.1 Global Catalyst Market by Sector 2019



The global catalyst market is essentially made up of the environmental market, petroleum refining and chemical value chains. The latter consists of petrochemicals and fine chemicals making up 26% of the global catalyst market revenue. The polymerisation catalyst market makes up another 13% bringing the total for all chemicals, elastomers and polymers, primary plastic resins and synthetic rubbers to almost 40%. By 2025, these three markets will account for almost $18 bn in global catalyst market revenue. Catalysts for petroleum refining applications make up 24%. The largest single market sector is environmental with 37% of the market. Any significant changes in the environmental market can therefore have a major impact on the catalyst industry in particular as there are backward effects on the other two sectors. Cleaner fuels for vehicles for instance need more intense purification stages in petroleum refineries. The introduction of full battery electric vehicles (BEV) will lower automotive catalyst demand and refined products, however it has a positive

effect on the chemicals market, because EV require significantly higher volumes of chemicals compared with existing internal combustion engine (ICE) vehicles.

Most materials sold into the commodity petrochemicals sector are heterogeneous (solid catalysts) and a smaller amount are homogeneous (liquid phase) catalysts. Homogeneous catalysts are used for chemicals such as acetic acid, oxo-alcohols, and silicones. Heterogeneous catalysts will continue to be the largest sector, and although mature, they are being innovated with more complex designs, better robustness, higher performance, and lower toxicities. The petrochemicals catalyst market is still set to grow at a healthy CAGR of 4.4% in 2019-2025 to reach $8.85 bn.

In the fine chemicals sector, the most common type of catalysts are heterogeneous, however there is more use of liquid phase homogeneous catalysts and biocatalysts. Biotechnological approaches in the fine chemicals sector are growing rapidly and this is very positive for biocatalysts. The fine chemicals sector is the fastest growing catalyst market with a CAGR in 2019-2025 of 9.3% per annum, boosted by population growth and wealth.

Polymerisation catalyst revenue reached $4.45 bn in 2019 and is set to increase to $5.6 bn in 2025, growing at a CAGR of 3.9% per annum. Polyolefins dominate the market along with polyethylene terephthalate (PET) and other engineering plastics such as acrylonitrile butadiene styrene (ABS) and polyamides (nylons). Growing demand for polymers with higher functionality has led to very strong catalyst innovation. This trend will continue with opportunities for new materials and chemically recycled plastics to enter the market. These will also require continued catalyst innovation.

Refinery catalysts made up 24% of catalyst market revenue in 2019. This sector is set to increase from $8.1 bn in 2019 to $9.2 bn in 2025, a CAGR of 2.1% making it the slowest growth sector of the catalyst market. Fluid Catalytic Cracking (FCC) and hydroprocessing have equal splits in this market and reforming has around 10% of the market. The remainder includes alkylation and a range of smaller special duties catalysts. [5] The most significant types of catalysts in the refinery market are solid acids with porous, high surface area structures i.e. zeolites as used in FCC processes, typically ZSM-5 and Zeolite Y, a wide range of base metal and precious metals supported catalysts in hydroprocessing and reforming. Other types of catalysts include zirconium-based superacids and tungstate formulations.

The refinery sector is suffering from lower crude oil prices and demand growth, set to slow as electrification becomes more significant in the automotive industry. However, it is buoyed by increasing demand for vehicles in Asia. The overall contribution in terms of market size is large and there is growing demand for more efficient and high-performance catalyst materials which makes it an attractive area for catalyst manufacturers and process licensors.

The environmental catalyst market, with revenue of $12.67 bn in 2019 and is forecast to rise to $16.85 bn in 2025. It is almost entirely based on catalysts for automotive engines, other transportation engines, off-road engines and stationary-source emissions control in the power sector. As more complex pollutants enter our waterways, for instance from the production of lithium-ion batteries for electric vehicles, other metals and mining activities and increasing amounts of pharmaceutical residues, more catalysts and higher functionality sorbents will be required to provide clean water.

There is coalescence in the process schemes for the production of chemicals and refinery fuels and deeper sector-coupling through the use of Power-To-X modalities. Hydrogen will be required not just

[5] Adapted from IHS-Markit, TCGR and Grace public domain figures

as a chemical and a refinery feedstock, but also as a source of heat, power, and transportation fuel. For now, hydrogen catalysts are all included in petrochemical catalyst revenue but as the market forecasts extend beyond 2025, they will begin to appear both in the environmental and a new energy transition category.

1.4. Catalyst revenue Country Comparison

The catalyst market revenue by country is summarised in Tables 1.4.1 and Figure 1.4.1. Collectively the catalyst markets covered in the study accounted for 61.5% of the total in 2019. The UK is the smallest of the six geographic markets studied and considering its expertise in catalysis and population relative to other countries, its home market is perhaps under-exploited. On an international level the UK provides a large proportion of the catalyst materials and technology and enables $100's bn in product sales. The UK is home to Johnson Matthey and INEOS who between them, cover a large part of the catalyst market outside of crude oil refinery catalyst. The UK also has a range of SME's with focused catalyst toolkits which contribute to the revenue for catalytic processes and licensing (which is outside of the scope of this study).

The UK is also well placed to serve clean growth with its skills in production of conventional hydrogen catalysts and process technologies, as well as hydrogen fuel cells and water electrolysers. Many SME's from the UK are proving themselves on an international level in the catalysis sector and have either been acquired by overseas companies or are seeing considerable levels of investment from them. Likewise, for fine chemicals development, the UK already has a thriving export market and its SME's are finding great success with growing their businesses to meet these needs.

Table 1.4.1 Country Comparison of Catalyst Revenue 2019

Values in $ million

Product Group	UK	France	Germany	USA	China	Japan	World
Petrochemicals	93.7	194.8	497.7	1,078.8	2,522.5	434.3	6,850
Fine Chemicals	18.0	42.8	60.6	178.2	697.8	122.2	2,050
Polymerisation	40.1	44.9	288.2	972.3	1,861.7	386.1	4,450
Refining	99.7	120.9	172.7	1,524.0	1,394.3	283.7	8,110
Environmental	181.4	292.9	700.5	2,190.3	3,339.9	1,235.1	12,670
TOTAL	433.0	696.3	1,719.7	5,943.6	9,816.2	2,461.5	34,129
CAGR 2019-2025 %	3.0%	5.3%	2.9%	1.8%	6.3%	1.5%	4.3%

The major trend in the catalyst market over next five years is a rapid increase in revenue in China as its domestic market grows organically and overseas manufacturing industries continue to migrate there. The USA is the second largest growth driver in the catalyst industry, enabled by shale gas which lowers the cost of production to competitive levels with other regions. However, the USA is set to lose some of its end-use export markets as China ramps up its own industries and this is expected to be compounded by increased manufacturing activity in other low-cost production bases in South America and the Middle East.

France is growing at the fastest rate, boosted by its fine chemicals and environmental catalysis sectors. France is home to several large automotive OEMs including PSA, Renault and Citroen. It is also a top global producer of fine chemicals for fragrances, as well as agrochemicals and pharmaceuticals. Germany is the main industrial powerhouse in Europe. All of its domestic catalyst demand sectors are worth more than the UK and France combined. It has a strong and growing fine chemicals sector. The only domestic catalyst market where the UK is expecting a higher CAGR than Germany is in environmental catalysts.

In spite of the high level of R&D and innovation that takes place in Europe, the catalyst market is increasingly being concentrated in China. As of 2019, China's domestic consumption of catalyst in revenue terms accounted for 29% of the global total and by 2025, this will have risen to 32%. It has an increasing desire to have more catalyst production housed domestically as well as to increase its catalyst export. Growth in China, the USA and other developing markets are key for UK catalyst exports, however at the same time there is scope to think about growing the domestic end-use application markets, enabled by high-quality catalyst technologies.

Japan is a small catalyst market compared with China and the USA, although it is an important catalyst producer on a global level with over 7% of the total market revenue. According to data from the Catalyst Manufacturers Association of Japan (CMAJ), Japan exports about half of its 100,000-ton catalyst production and imports 30,000 tons from other regions.[6]

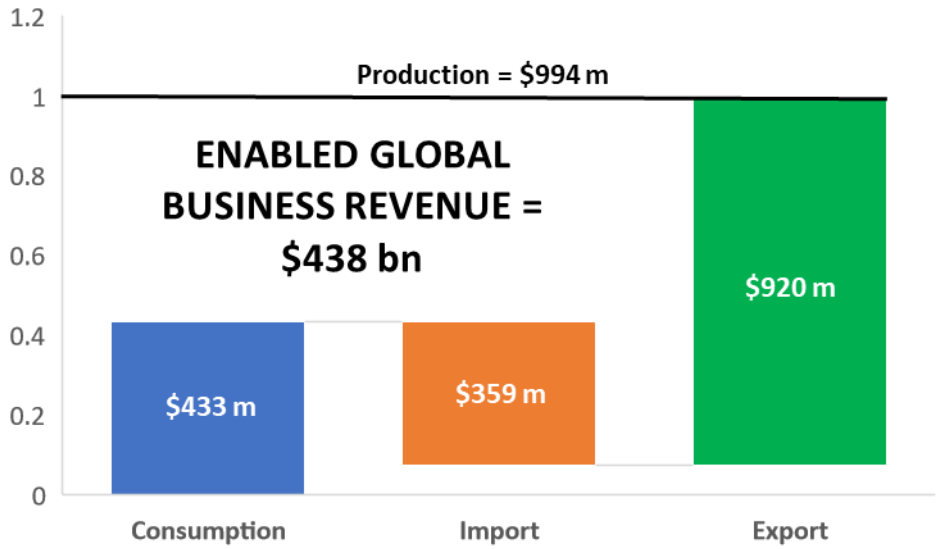
Japan has been investing for decades in development of electric vehicles, with Toyota having already sold millions of mild and plug-in hybrids and having developed the world's first fuel cell vehicle (including its fuel cell catalyst) sold under the Toyota Mirai brand. Longer term, therefore, the environmental market in Japan is set for growth. It is also looking to boost its fine chemicals sector and is investing in biotechnology companies to raise the capabilities, competitiveness and value of its fine chemicals and pharmaceuticals industries. Technology licenses can then be sold globally, including to China and other growth regions.

1.5. The UK Catalyst Market

The consumption of catalyst in the UK accounts for $433 m of revenue. This is relatively small at 1.27% of the global total. However, as shown in Figure 1.5.1, the total amount of catalyst produced and exported is at least $ 994 m (2.9% of the global total catalyst market revenue). The value created by the $34.1 bn catalysts market globally in downstream sectors (e.g. sales of chemicals, polymers, fuels and vehicles) is $15 tn. On this basis, the UK catalyst revenue of $433 m, which is based on the amount we consume domestically enables around $190 bn of domestic UK business. The amount of catalyst produced and sold by UK manufactures, including for domestic consumption and exports, ($994 m) enables around $438 bn of end-use industry revenue globally. Catalyst process licensing and aftermarket services are additional revenue sources not included in these figures. On a global basis this adds another $16 bn to the $34.1 bn catalyst market – the UK's contribution will be significant, but the valuation is not part of the scope of this report.

Figure 1.5.1 UK Catalyst Market, 2019

[6] https://cmaj.jp/



Environmental catalysts make up the largest segment in the UK with 42% of the total revenue. This largely consists of vehicle production. Nissan and Jaguar Land Rover were the two largest OEM's manufacturing the 1.3 million vehicles made in the UK in 2019, with BMW, Honda and Toyota making up the remainder. The environmental catalyst market revenue in the UK is growing at a CAGR of 4.4% per year in 2019-2025 to reach $235.6 m by the end of the forecast period.

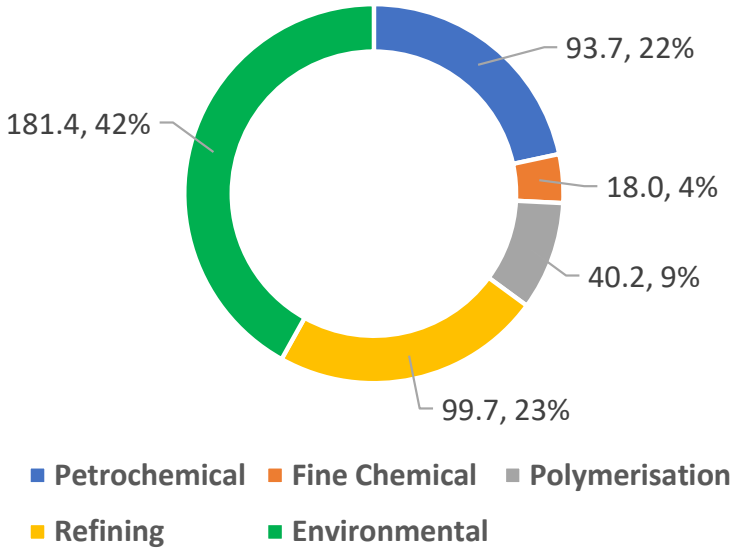
Chemical catalyst markets including petrochemical and fine chemical make up a further 26% of the UK's consumption and if catalysts for primary plastics and rubbers are included, the figure comes to 35% ($151.8 m in total). The UK's chemical catalyst consumers are made up of a number of large multi-national companies (MNC's) as well as many thousands of small-to-medium enterprises (SME). The larger companies tend to sit in chemical clusters. There are three chemical clusters in the UK: Grangemouth, Scotland; Wilton International/Teesside, England and Saltend, Hull, England. The Grangemouth industrial cluster is focused around the INEOS refinery complex, with a crude oil refinery and 2 million metric tons per annum (2 mtpa) of chemical products. There are also plans to build the Summit Power Caledonia Clean Energy Project at this location.[7]

The Wilton site houses manufacture of light olefins, polyethylene, and a range of intermediate chemicals. Biffa Polymers, Huntsman, INEOS, Lucite, SABIC and others are present on this site. This site forms the UK's ethylene hub called Wilton Ethylene Control (WEC) and from here ethylene is moved around by pipeline to the Sabic Olefins 6 plant, the Sabic LDPE plant on site, the INEOS Grangemouth site and the Inovyn site at Runcorn. Saltend in Hull, North East England is a large chemical park housing the activities of Air Products, BP European Acetyls, INEOS, Yara and several others. [8] It is owned by an infrastructure management company called pX who bought the site from BP in March 2018.[9] Dow Corning and Synthomer are two of the largest polymer producers in the UK situated outside of the main three chemical cluster parks.

Figure 1.5.2 UK Catalyst Market by End-Use Applications, 2019

[7] https://www.alignccus.eu/industry-clusters
[8] https://www.saltendchemicalspark.com/companies/
[9] https://www.pxlimited.com/what-we-do/saltend-chemicals-park/

Value $ m, % of total



The UK's fine chemicals sector is one with an excellent skill base. Major producers include – Croda, Syngenta, Unilever, GSK and Astra Zeneca are at the larger end, and there are in the order of thousands of smaller companies. While the total catalyst revenue is only $18 m as of 2019, it is growing faster than any other catalyst market at a CAGR of 5.6% in 2019-2025. This is still somewhat short of the global fine chemicals' catalyst revenue CAGR of 9.3% over the same time period. A deeper investigation of the reasons for the small size and slower growth in this sector may be warranted as it is a large area of opportunity for catalyst revenue and enabled revenue in end-use applications.

The UK is home to six petroleum refineries which are significant end-users for catalyst, and these make up the remaining 23% of the market. Catalyst revenue for refining applications is growing at a CAGR of 1.1% in 2019-2025 in the UK. There are no refinery capacity increases anticipated in the UK and any growth is down to the increased value of catalysts employed per unit capacity in the refinery. This increase is to be expected in line with demand growth for cleaner fuels mandated by tightening in fuel specifications. There is also potential to convert some of this capacity to renewables for instance by feeding in hydrogenated vegetable oil (HVO) to make a synthetic crude product. TOTAL has converted some of its refining capacity in France to HVO fuels which are covered under the European Renewable Energy Directive – Recast to 2030 (Red II) as recognised green fuels.[10] This would also increase the amount of catalyst required at the refinery at the front end.

1.6. UK Catalysis Companies

The major company in the UK producing catalysts is Johnson Matthey, headquartered in Royston, Hertfordshire. The company has a leading position in supply of environmental catalysts for clean air. This is mainly transportation and other engine-out and stationary power emissions control as well as gas scrubbing and purification. It is also a leading supplier of catalysts and process technologies for

[10] https://ec.europa.eu/jrc/en/jec/renewable-energy-recast-2030-red-ii

hydrogen, syngas and derivatives, clean fuels, chiral molecules, commodity, and fine chemicals. JM's catalyst accounts for the majority of catalyst material exported from the UK globally.

In addition to JM, INEOS, headquartered in London and with plants in the Wilton and Grangemouth chemical clusters is also a large developer and producer of catalysts. These are mainly used captively for production of its range of intermediates and polymers, with licenses sold to selected third parties. Much of INEOS' catalyst is produced outside of the UK and will account for some of the imports to be used at its UK chemicals and polymers production sites.

Thereafter the UK has a number of SME's with catalyst manufacturing and catalyst technology toolkits in niche areas. Many of these companies also offer technology for catalytic steps. These SME's are promising companies for growing UK catalysis and require investment to allow them to reach their full potential.

Table 1.6.1 UK Catalysis Technology Providers & Producers

Company Name	HQ/UK Location	Key Products & Services
Johnson Matthey	Royston, Herts	Manufacture of catalysts for chemicals and pollution abatement, precious metal chemicals, battery materials and pharmaceutical ingredients.
INEOS	London	Manufacturing petrochemicals, speciality chemicals and oil products. Catalysts for oxidation, ammoxidation and polyolefins
Luxfer MEL	Clifton, Greater Manchester	Environmental catalysts; zirconia catalysts and additives
Catalyst Technologies Ltd	Stockton-On-Tees, Teeside	Titanium polymerisation catalysts, zirconium cross-linker catalyst
Molecular Products	Harlow, Essex	Sodalime sorbent, CO oxidation catalyst, chlorate candles, ethylene absorbers
Cat-Sci	Wentloog, Cardiff	Contract research, catalytic processes, lead optimisation, route design and development
Biocatalysts Limited	Nantgarw, Cardiff	Specialty enzymes for food and fine chemicals
Biosynth Carbosynth	Compton, Berks	CDMO services, technologies for of enzyme substrates, carbohydrate and nucleoside chemistries, specialty silicas, catalogue chemicals, homogeneous catalysts
PQ Corporation	Warrington, Cheshire	Silica gel
Cleansorb	Guildford, Surrey	In-situ acid generation technologies for oil reservoirs.
Ames Goldsmith - Ceimig	Dundee, Scotland	Catalysts for gas sensors, bio-sensors, PEM hydrogen fuel cells, precious metals compounds
Eurocats	Denmead, Hampshire	Pollution control catalysts and Diesel Particulate Filters (DPF) for the vehicle aftermarket
Stoli Catalysts Ltd,	Wellesbourne, Coventry	Stoliflow precious metals coated tubes for hydrogenation reactions, coated monoliths, fuel cell components
Sterling Pharma	Cramlington, Northumberland	Technologies for hazardous reactions, chiral molecules, and controlled substances

Centre for Process Innovation (CPI)	Wilton, Middlesborough	Six UK locations and has technologies for biotechnology, pharmaceuticals and printed electronics.
Drochaid Research Services	St Andrews, Scotland	Contract catalyst design and synthesis
Finden	Harwell, Oxfordshire	Advanced catalyst characterisation and analysis.
C-Tech	Chester, Cheshire	Electro-heating and electrochemical processes

1.7. UK SWOT Analysis

The UK has a very strong catalysis industry and wider community including a catalyst major (Johnson Matthey) with strengths in catalysts for chemicals and environmental applications; INEOS which also has a strong set of catalysis technologies for chemical intermediates and certain polymer groups and many SME with niche catalysis toolkits.

Catalysts for carbon efficiency using petrochemical feedstocks is a mature area for UK catalysis producers and one where much of their revenue growth will continue to be derived. These UK companies supply catalysts and catalytic process technologies from across the different categories – including heterogeneous, homogeneous, electrocatalysis (catalyst coated membranes and biocatalysis). The UK is home to several companies with fuel cell and hydrogen generation technology including Johnson Matthey, ITM Power and others and is ideally placed to become a global leader in supplying hydrogen solutions for the growing hydrogen economies around the world as well as at home. This is an area which is gathering pace with the UK government having funded the development of low-carbon hydrogen over the last couple of years.

The UK has been relatively slow to exploit its skills in hydrogen until quite recently and now is the time for it to accelerate this area and to ramp up funding to levels seen for the battery industry. This is not an area that should be delayed – because other countries are looking to accelerate here too. Air Liquide in France for instance has enhanced its technology offerings by partnering with Hydrogenics in Canada, in which it owns a 19% stake.[11] Air Liquide constructs PEMEL plants and owns over 40 electrolysers. Germany is pushing ahead and has published a national hydrogen strategy white paper.[12] ITM Power in the UK has also been part-purchased by Linde, Germany and the two companies subsequently created a JV subsidiary – ITM Linde Electrolysis GmBH.[13] Russia meanwhile is developing its own electrolysis technology and Gazprom has its methane adiabatic conversion (MAC) technology as well as methane pyrolysis and water electrolysis in development. Gazprom has announced its intention to supply green hydrogen to Australia and to become the largest supplier globally by 2030.[14] China has led the way on fuel cell adoption and the majority of fuel cell demand is housed there – mainly for fuel cell buses and trucks. It has relied in part on overseas fuel cell catalyst technology but is now looking to accelerate development of fuel cells and

[11] https://energies.airliquide.com/air-liquide-makes-strategic-investment-production-decarbonated-hydrogen-electrolysis
[12] https://www.cleanenergywire.org/factsheets/germanys-national-hydrogen-strategy
[13] https://www.itm-power.com/news/incorporation-of-itm-linde-electrolysis-gmbh-and-appointment-of-managing-director
[14] https://www.renewableenergyworld.com/2019/11/18/momentum-for-green-hydrogen-picking-up-in-europe/#gref

electrolysers. It already has a handful of companies working in this area. Beijing Yihuatong has recently launched a high-power 100 kW fuel cell engine which has been approved by the state.[15]

There is an increasing focus on carbon capture, utilisation and storage (CCUS) with more revenue being derived from technologies which use CO_2 as a feedstock – in particular for methanol, dimethyl ether (DME), methane, ethanol and some types of polymers – polyethercarbonate polyols (PECP) and polyhydroxyalkanoates (PHA). CCUS goes together with hydrogen technologies as part of "Power-To-X" processes which use electricity or other energy sources in the direct production of chemicals. The UK is much further behind on CCUS than other countries, and much of the expertise in this area for sorbents and conversion technologies is not based within the UK. However, it would be possible to make improvements here if funding is provided. There are already SME's with important CCUS skill sets. Econic Technologies has a process to make PECP from CO_2 rivalling those of larger companies including Saudi Aramco (who purchased Novomer) and Covestro. Several other SME's in the CCUS area include Carbon Clean Solutions in Reading Berkshire making CO_2 capture solvents and capture technologies, Carbon8 Systems in Gillingham with technology for carbonation aggregates and CCM Technologies in Swindon making fertilisers.

However, many more of these innovations are required. The UK needs to collaborate with companies which have such technologies and to combine its skills in hydrogen to fully exploit its opportunities in the Power-To-X sector. As a country, the UK has much to benefit from its increasing proportion of renewable energy, strong academic network and CO_2 catalysis skillsets. There are opportunities which have perhaps come and gone unnoticed. Companies in the catalysis sector have accepted foreign investment and have been bought up and relocated to the US and other regions. Molecular Products Limited, based in Harlow, Essex is a good example. This company has an interesting product area, including CO_2 sorbents and CO oxidation catalysts which it was exporting to over 60 countries from the UK. It is now owned by US-based Arlington Capital and most of its production is overseas. Monitoring of SME's with catalysis capabilities would be a good activity on a regular basis.

In the area of fine chemicals, the UK has a large number of contract research organisations (CRO) and SME's with strong skills in organic synthesis and process innovation centres set up to support catalysis. There is however, need for more expertise in scale-up. In the patent subsets, some of the top codes relate to the production of fine chemicals for pharmaceuticals as well as for food and industrial products. Several SME's in the UK are active here and again, they have been under the radar, but are now attracting foreign investment. The UK has a very strong trading relationship with Japan, and this can continue to be exploited. As the chemical industry moves further towards higher-value chemicals and specialties, this is another skillset which the UK can exploit to grow its catalysis sector and wider chemical synthesis services industry revenue.

Figure 1.7.1 UK Catalysis SWOT Analysis

UK SWOT ANALYSIS	
STRENGTHS	**WEAKNESSES**
• Hydrogen technology & supply chain • Renewable energy • Fuel cell technology	• High cost manufacturing • Lack of government-led laboratories

[15] https://fuelcellsworks.com/news/chinas-successful-development-of-high-power-hydrogen-fuel-cells-100kw-power-can-be-used-for-passenger-cars-heavy-trucks/

• Catalyst design & manufacture • Contract research • All types of catalysis • Fine chemicals synthesis • Academic catalysis network • Strong patenting by SME's • International reach of patents	• Underdeveloped national catalysis strategy • Scale-up capabilities • Exploitation of innovations • Insufficient focus and cohesive strategies for hydrogen c.f. battery technologies • Lack of CCUS experience
OPPORTUNITIES	**THREATS**
• Renewable electricity • Asian market growth • North America market growth • Fine chemicals market growth • Hydrogen economy • Biogas and waste feedstocks • CO_2 Capture & Utilisation (CCUS)	• Asian self-sufficiency • COVID-19 fuelled • Global recession • Insufficient funding • Acquisition and relocation of catalyst businesses to overseas • Building green hydrogen technologies by competitors

1.8. Intellectual Property

The IP analysis for the six countries in the study is summarised in Table 1.8.1. The data shows total patent families, the percentage with a granted member and the global reach (average number of patents per family, indicating in how many countries each invention has been filed). The UK has the lowest number of patents of the six countries in the study. It has a moderate level of granted patents at 61% and a high global reach ratio of 11.1. It has a relatively high number of clean growth patents at around 1,000 families and similarly for healthcare with 1,900. Each of these has a moderate level of patent grants at 66% each.

France has a higher level of patenting and its grants are considerably higher by a margin of around 20% for the whole patent set and the subsets compared with the UK. Germany's patenting is higher than both the UK and France together, however its % grants are similar to the UK. China has the highest number of patents of all six countries although it has the lowest level of grants ranging from between 43% for the whole patent set to just 32% in healthcare. Asian countries typically file many more patents than are ever granted and, China files utility patents which are weaker than full patents and only last 10 years. Japan's rate of patenting is as high as the US and it has a relatively high number of grants, and a global reach on a par with Germany. Its clean growth subset is particularly impressive, with over 26,000 documents and a 60% rate of grants. Japan exploits its innovations outside of its own country and has chemical technologies and automotive catalyst business with a reasonable global reach (GR) of 7.1.

Table 1.8.1 IP Comparison by Country Including Clean Growth and Healthcare Subsets

Patent Set	GB		FR		DE		US		CN		JP	
Families	*'000s*		*'000s*		*'000s*		*'000s*		*'000s*		*'000s*	
All Patents												
Families	8.1		11.1		30.0		47.9		227.1		47.5	
Grants	4.9	61%	9.2	83%	18.0	60%	30.5	64%	97.8	43%	26.1	55%
GR	11.1		9.1		7.3		8.1		1.2		7.1	

CG												
Families	1.0		1.4		2.9		7.8		12.0		7.6	
Grants	0.7	66%	1.2	88%	1.8	63%	387.7	72%	5.2	44%	4.6	60%
HC												
Families	1.9		2.0		3.9		8.3		10.7		4.3	
Grants	1.3	66%	1.7	86%	2.7	68%	5.3	64%	3.5	32%	1.6	37%

CG = Clean Growth HC = Healthcare GR = Global Reach

Table 1.8.2 shows the IP analysis in more detail for the key topics. These reflect the strong skills in the UK of catalyst preparation, exhaust gas catalysis and fine chemicals. Specifically, in clean growth fuel cells appears as a top area as well as Fischer-Tropsch chemistry. The other countries have nuanced differences – pyrolysis oil in France is an important topic and in Germany process efficiency for conventional fossil fuels as well as lignocellulosic (LC) biomass feature strongly. This is also the case in the USA and Japan. There are some specific areas of therapeutic interest which appear in the fine chemical's subset for the UK – i.e. heterocycles for protein kinase inhibitors for anti-inflammatory disorders and cancers.

Table 1.8.2 Key Topics Comparison by Country

	Key Topics		
	All Patents	Clean Growth	Fine Chemicals
UK	Cat Prep Exhaust Gas Fine Chem	CO_2, Syngas, Fischer-Tropsch MEA, Fuel Cells	Heterocycles Protein Kinase Disorders Microcapsules
France	Exhaust Gas Cat Prep & Colloids Personal Care	CO_2, Syngas Pyrolysis Oil Catalyst Prep	Catalyst Features Acrylic Acid - Absorbent Deodorising catalysts
Germany	Exhaust Gas Cat Prep & Colloids Polymers	CO_2, Syngas LC Biomass Process Efficiency	Personal Care Detergents Superabsorbents
USA	Catalysts, sorbents, FBR catalysts Nanotechnology Exhaust Gas	CO_2, Syngas Transportation Fuel, LC Biomass, Bio-Oil	Personal Care Protein Kinase Anti-Cancer Drugs
China	Air & Water Purification Catalyst Preparation Specialty materials	CO_2, Syngas Catalyst Prep Water splitting	Food preservatives Animal feed Antimicrobials Soybean products
Japan	Exhaust Gas Fuel Cells Catalyst Preparation	CO_2, Syngas LC Biomass Metal Recycling	Personal Care AA/SAP CO_2 Absorbents

The other countries have nuanced differences – pyrolysis oil in France is an important topic and in Germany process efficiency for conventional fossil fuels as well as lignocellulosic (LC) biomass feature strongly. This is also the case in the USA and Japan.

Outside the UK, the fine chemicals subsets are more geared towards personal care and cosmetics, and in China there is focus on food production. Both France and Japan have technology for making acrylic acid (AA) and superabsorbent polymer (SAP) which can account for these topics appearing in the patent search.

1.9. Opportunities for Growth

During the study, several opportunities emerged where the UK could grow its catalysis industry. These are summarised in table 1.9.1. For each opportunity, a comparison has been made to the other five countries in the study as well as "Other Europe" where several key catalyst producers are based (e.g. Clariant, Haldor-Topsoe). Comments on the ability of the UK to compete with existing innovations have been summarised. There are many areas where the UK could grow its catalysis industry. In the area of carbon efficiency, the UK has a very strong position on natural gas and coal conversions. It has less technology for refinery catalysts relative to its competitors in other regions besides some niche products. However, there may be research groups and SME's with interesting technologies that could be supported.

Of the technologies in the list, hydrogen is the largest opportunity for creating new catalyst revenue in the chemicals and environmental sectors. The UK has picked up the pace on supporting this area with the Hydrogen Supply Competition being run by the Department for Business Energy & Industrial Strategy (BEIS). The UK has two main options in development – water electrolysis and novel reformer concepts. There may be scope to look as well at methane pyrolysis which does not require carbon capture, although it requires more work to improve selectivity.

There has been very little achieved on CO_2 capture in the UK to date. Only now has a CCS project been agreed and it will be supported by several European partners including Total and Shell. CO_2 utilisation projects hold much promise with Econic Technologies advancing its CO_2 to polyols and several companies advancing CO_2 mineralisation processes. Tata is reportedly setting up to turn 40,000 tpa of CO_2 into bicarbonate.[16] There are likely many other CO_2 processes in development and a scan of promising SME's would be worthwhile. Power-To-X projects have a high impact on reducing carbon footprints, as well as increasing catalyst demand - the possibility of developing a CO_2 methanation catalyst is one example of an application which would increase overall catalyst demand. Thyssenkrupp has a process but there are relatively few similar on the market today.

Renewables tend to have mixed fortunes and targets must be carefully chosen. Promising platform molecules which have functional benefits can more often justify a green premium over those of simple drop-in equivalents. Biofuels are still the largest opportunity. Total in France has opted to convert one of its refineries from crude oil to hydrogenated vegetable oil (HVO) and as the UK has six refineries this could be an area to consider which would create catalyst revenue and help to decarbonise the refining network. The UK also has access to large quantities of biogas and there is potential to upgrade this for fuel and to convert it into green methanol and other derivatives. To make the most of biogas, new C1 chemistries are needed and this is also an area which could be further developed in the UK.

In the environmental sector, the market for automotive catalysts is highly developed and JM has a large market share. However, in other environmental applications there is potential for novel sorbents and solutions to clean up increasingly complex waste streams. DuPont in the USA has developed a strong portfolio for water treatment and has a strategy to expand in order to meet the needs of battery producers and recyclers as well as the upstream production of strategic metals. There may be interesting SME's in the UK with technology that would be worth supporting.

The area of polymerisation has many catalyst producers with vast experience, however the UK has already one SME which has performed well with a focused portfolio for PET catalysts – Catalyst Technologies Ltd. There are likely other SME's which would be worth supporting with focused or niche innovations and this is worth further investigation.

[16] https://www.ft.com/content/b45d94b6-97fc-11e9-8cfb-30c211dcd229

In fine chemicals the UK has many SMEs with technology and services for process design. In addition, there are a growing number with biocatalysis portfolios serving the food industry as well as industrial and pharmaceutical sectors. The pharmaceutical industry has been adopting biotechnology as a strong area to bolster design of new molecules and the UK patent analysis showed that this is an area of strength in the UK. It is possible that there are SME's with skillsets to be further exploited and perhaps even as a collective to help each other's businesses. This is a model already adopted by BRAIN Group in Germany and it is helping UK SME's to grow their businesses.

Lastly the UK has immense skills in the design of advanced materials and additive manufacturing. The desire to move away from pellet and shaped extrudate catalysts to a more simple and robust packed structure is an area where 3D modelling, design and printing could be exploited. This may be area where collaboration between the two communities could result in more innovation.

Table 1.9.1 IP Comparison by Country Including Clean Growth and Healthcare Subsets

Theme		Analysis & Growth Strategy
Carbon Efficiency	*UK Position*	Well-developed position on fossil fuels to petrochemicals. Novel concepts on hydrocarbon reforming.
	Competitor Positions	Stronger on COTC in France (Axens), Germany (Evonik FCC), USA leaders on COTC (ExxonMobil, KBR and others)
	Opportunities	Investigate integration with UK refineries. Exploit novel reformers for natural gas carbon efficiency.
Hydrogen	*UK Position*	World leader on petrochemical hydrogen catalysis. Electrolysis technology available. Novel reformers in development. World class conventional technology. Fuel cell catalysis
	Competitor Positions	France in strong position, Other Europe world class conventional technology (e.g. Clariant, Haldor-Topsoe). Japan, China hydrogen users but need technology. Methane pyrolysis in Russia, Germany.
	Opportunities	Support electrolysers, look at other low-carbon opportunities e.g. methane pyrolysis and reforming with CCS
CO_2 Capture	*UK Position*	Very little technology for CO_2 capture at large scale. First UK project now underway.
	Competitor Positions	North America and Japan have technology and projects China and France (Total), 1 plant, Germany is behind. Other Europe (Shell) has vast experience and technology.
	Opportunities	Small-scale capture to facilitate CCUS. Need to develop or acquire technology for CO_2 sorbents. Opportunities for a direct air capture (DAC) plant and to improve the sorbent.
CO_2 Utilisation	*UK Position*	SME's with technology in a couple of applications. Likely more technologies which could be nurtured. Playing catch-up.
	Competitor Positions	Mostly Power-To-X projects in Northern Europe German technology (e.g. Thyssenkrupp), USA has innovative SME's, Japan weak, China has the most large-scale commercial projects. E.g. CRI (Iceland) methanol, PHA's production
	Opportunities	Identify and support further UK technologies. Use CO_2 as a feedstock for biodegradable polymers and carbon-neutral fuels
Polymerisation	*UK Position*	INEOS strong on polyolefins; SME's with successful innovations.
	Competitor Positions	China has the largest share followed by the USA. Germany strong and technology for chemical recycling, circular polymers

	Opportunities	Catalysts for functional materials and novel materials. Look at green innovations for converting waste food and other waste streams.
Renewables	*UK Position*	JM technology for platform biobased chemicals, SME processes, much more feedstock which could be exploited.
	Competitor Positions	Other Europe, USA, strong on biobased platform chemicals, Japan low, China low. France strong – HVO use
	Opportunities	HVO for UK refineries. Combine heterogeneous catalysis with biocatalysis for bulk specialties. Utilise biogas, MSW and other waste for feedstocks
Fine Chemicals	*UK Position*	Strong IP position on small molecules. Large number of CRO/CMO providing and exporting technology
	Competitor Positions	China has largest share, Japan moving to increase biotech skills, USA weaker position, France and Germany strong positions.
	Opportunities	Identify and exploit CRO's with catalyst expertise. Link in with renewables and biocatalysis
Water Treatment	*UK Position*	Not strong on innovative water treatment. Need will grow, in particular for battery production plants
	Competitor Positions	USA – DuPont large portfolio of sorbents and additives
	Opportunities	Identify and support SME's working in this area in the UK.
Catalyst Formulations	*UK Position*	New developments on polymer catalysts, structured reforming catalysts, interest in 3D printing designs
	Competitor Positions	US strong on developing new formulations, same in Other Europe (e.g. Clariant, Haldor-Topsoe).
	Opportunities	Look at more opportunities for use of 3D modelling/printing and continue to support novel catalyst structures and reactor types.

1.10. Conclusions

The catalyst market is constantly evolving and requiring ever more complex catalyst solutions. It is growing above GDP in all sectors except for petrochemicals. Fine chemicals are growing much faster and constitute a rich area for new catalysts and processes. The total market will also be boosted if new processes are introduced to replace ones which were previously non-catalytic, i.e. production of synthetic natural gas from CO_2 methanation, and replacement of crude oil with HVO and Fischer-Tropsch fuels. While the UK has a smaller domestic catalyst market than other countries, it is still set to exceed $500 m by 2025 which will add $227 bn to the UK economy in downstream market sectors. In addition, it has a No.1 global market share in environmental catalysis. The UK exports over $900 m of catalyst each year and produces in the region of $1 bn.

Innovations will be concentrated inside large companies, but equally SME's continue to emerge from obscurity to lead on specific technologies. There are many opportunities to help them and to ensure that the UK makes the most out of these companies for increasing its own catalyst industry and GDP. Short domestic supply chains can also be developed which increase the UK's self-sufficiency, supply-chain security and create new areas of employment. This will also contribute towards net-zero targets by reducing the need to import high carbon footprint products from other regions.