Flue2CHEM

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FINAL REPORT

JUNE 2025

KEY POINTS

1 The chemical industry must transition to alternative carbon sources to achieve net zero.
Fossil-derived carbon is unsustainable; future supply chains must incorporate recycled, biogenic, or captured carbon dioxide.

2 Flue2Chem has demonstrated that a circular carbon supply chain is technically feasible.
The project successfully captured carbon dioxide, converted it into platform chemicals, and showed that consumer products could be formulated from such materials without compromising performance.

3. However, the current system is not yet economically viable.
High costs – especially for green hydrogen – mean that without policy support or incentives, commercial deployment is not feasible.

4. Collaborative, cross-sector R&D is essential to accelerate innovation.
The project's success was driven by collaboration across academia, industry, and government, enabling rapid problem-solving and knowledge sharing.

5. Infrastructure and scale-up capabilities are critical enablers.
The UK lacks sufficient pilot and commercial-scale facilities, which limits domestic development and forces reliance on overseas assets.

6. Policy and regulatory alignment is needed to unlock investment.
A supportive fiscal and regulatory environment – similar to the SAF mandate – could catalyse market development for renewable chemicals.

7. Public and market recognition of renewable chemicals must grow.
Consumer demand and policy incentives are both needed to drive adoption and reduce the green premium.

EXECUTIVE SUMMARY

Flue2Chem is a 4.4 million GBP collaborative R&D project involving 12 commercial organisations, two universities, a part of the High Value Manufacturing Catapult, a trade association and a charity, all supported by the UK government, to evaluate the components of a supply chain for the chemical industry utilising carbon dioxide (CO_2) emissions as a feedstock for producing chemicals, instead of fossil carbon.

The project captured CO_2 from industrial sources, in this case paper mills, and investigated its conversion to the important platform chemicals, ethylene oxide and long chain fatty alcohols, through biological and thermo-catalytic processes before verifying that these could be converted into surfactants that can be formulated into consumer products without affecting specification and performance.

The project highlights the importance of renewable energy and hydrogen as inputs into any circular carbon supply chain, as well as the carbon capture technologies and the necessary chemical process technologies including conversion and separation. It identified significant gaps around logistical and technical landscape that are not easily available in the UK but could position the UK favourably if addressed.

The project has demonstrated that chemical feedstocks derived from captured carbon dioxide have the technical potential to significantly reduce the carbon footprint of the chemical industry, but it is still in an early stage of commercial development with much support needed in technology demonstration, infrastructure and policy development to enable the transition.

Flue2Chem has unlocked the drive and capabilities of industrial partners across the value chain to move at pace, leveraging the creativity of the UK academic network and SMEs, and supported by the far-sighted view of the UKs innovation agency. It should be considered as an exemplar for collaborative, challenge-led R&D.

There are opportunities for the UK Government to work with the companies in the sector to develop and implement the new science and technology to build a renewable chemicals industry in the UK.

1 BIG PICTURE

WHY WE NEED CARBON

Historically, we used naturally occurring materials for everything – but a combination of market volumes outstripping easily available sources and the growing availability of "synthetic" materials led to the rapid growth of materials derived from the petrochemicals supply chain. It is difficult to say exactly when the "synthetic" materials world started, but the huge expansion came with the use of fractions of the oil and gas, that we were already extracting from the ground as a fuel, as material feedstocks about 170 years ago. In 2019, the petrochemicals supply chain accounted for about 2.6 billion tonnes of carbon dioxide equivalent a year (about 5.7% of the fossil carbon extracted that year) and is growing at about 5-8% a year – meaning that, without intervention, it could roughly double every 10 years and lead to an estimated use between 10 and 15 billion tonnes a year by 2050. Over 80% of this carbon is contained in the products. We can "decarbonise" the energy used to affect the transitions from raw materials to products, but we cannot take the carbon out of products made of carbon! And the products at the end of the many supply chains that start with these fossil feedstocks range from things we cannot do without (such as disinfectants, soaps, textiles for clothes and so on) to things we "like" to have but would probably fight to keep (such as cosmetics, electronics and toys)!

The focus is often on single use plastic packaging, which makes up about 30% of that 2.6 billion tonnes. But there are many other products that depend on the same source – products for use in the home (insulation, carpets, upholstery, paint and adhesives) at about 16%, textiles (mostly for clothes) at about 15%, pharmaceuticals, agrochemicals and fertilisers at about 11%, cleaning products and cosmetics at about 10%, the interiors of cars and their tyres at about 7% and the use in electrical and electronic products (both insulation and enclosures) at about 4%. Such is society's use of these products, that we cannot simply stop using them, or make them from something other than carbon. We need a source of carbon – and at the same scale.

There are three sources of carbon which are talked about.

1 Recycling of the carbon already in use. This can mean simple mechanical recycling, where the material is reused in the same chemical state. For most this means recycling plastics, primarily from packaging, toys, cases of many electrical goods, storage boxes and so on. The challenges are well rehearsed – mixing polymers (often even different variants of the same chemical type) can cause loss of properties, collecting the end of life products, additives used to add colour affecting appearance, and so on.

   Beyond this comes chemical recycling, where the products are thermally "cracked" back into smaller building blocks – usually a mixture – and then separated in a way similar to how oil is made into its usable fractions. The supply chain is used to this type pf input – we currently start with oil (which is a complex mixture of hydrocarbons) and gas – so this has the least impact on the rest of the downstream supply chains.

   However, if you think about the products that are made of carbon, they cannot all be collected and recycled. Most plastics (in all uses) could be, but there are social and logistics problems to tackle. Many of the uses in the automotive sector can be more easily collected but often required separation into very different types of materials that need different processing. And many uses of carbon based products end up highly dispersed into the environment – cleaning products at 10%, pharmaceuticals, agrochemicals and fertilisers at 11% and who is going to strip the paint off walls to recycle it? Overall, it might be difficult to chemically recycle more than 30-40% of the end uses.

2 The second source of carbon is usually termed "biomass". Carbon is the basis of plants and animals (and humans!) but this source is mainly about using plants. Something around 100 billion tonnes of biomass are produced every year – just over half on land and the rest in the oceans. Of that about 14 billion tonnes is cultivated by humans – about 6 billion to feed animals, about 4 billion for grazing, about 0.5 billion for energy uses and about 3.2 billion for human consumption. Estimates vary, but about 1 billion of that is not used for its primary purpose and so might be considered "waste" and is therefore available for its carbon content without compromising the primary use as food (for both humans and animals).

   Another source of biomass is wood. The annual global harvest is a little under 3 billion tonnes, with its use split between manufactured wood/paper products and energy generation. There is an established hierarchy of use for wood fibres (with high levels of recycling) intended to deliver the maximum value from harvested materials. Higher qualities of timber are used for higher value uses such as construction, furniture, wood flooring and the like, while lower grade timber and the wood from the removal of partially grown trees from thinning managed forests are used for applications such as pulp and particle board manufacture.

3 The third source of carbon is the carbon dioxide we have been, and are still, adding to the ecosphere over the past 150 years.

   It can be measured that we have added about 1.1 trillion tonnes of carbon dioxide to the atmosphere, but we know carbon dioxide is also absorbed into the oceans (the amount absorbed depends on temperature and salinity) and there is estimated to be an additional 400 billion tonnes of carbon dioxide in the oceans worldwide.

   The concentration in the atmosphere – about 0.04% – makes direct air capture of the carbon dioxide a technical challenge. But we are still emitting flue gases from factories and power stations (although some are from burning biomass, and hence biogenic, most are created either by using fossil carbon as a fuel, using carbon as a reducing agent to turn ores into metals, or produced as a by-product of the manufacturing process itself), and here the concentration is about 20% – making capture easier. So we could mitigate the amount of carbon dioxide we add to the atmosphere and develop a sustainable source of carbon for the chemicals industry. And if we develop the capture technology sufficiently, at some point in the future, we might be able to remediate the damage we have done to the atmosphere by our use of fossil carbon as a fuel.

The principal reason fossil carbon (coal, oil and gas) has been as heavily used as it has is that it is a very efficient and easily available way to make heat. Put simply, burning carbon or hydrocarbons releases a lot of energy as heat, and using that heat to power transportation or industrial processes has driven the industrial revolution and answered the needs of society for long enough that we find it difficult to imagine an alternative.

$C + O2 \rightarrow CO_2$ -393.5 kJ/mole

1 mole = 12 g 1 tonne = 83,333 moles 32.8 GJ

$CH4 + 3O2 \rightarrow CO_2 + H2O$ -890.3 kJ/mole

1 mole = 16 g 1 tonne = 62,500 moles 55.6 GJ

This equates to between 9 and 15 MWh of energy released when we burn 1 tonne of fossil fuel. The processes for turning that into "useful" energy (for example, an internal combustion engine maxes out at 45%) often means that a lot of energy is wasted.

The downside of this is that to take carbon dioxide and turn it back into a hydrocarbon requires the same amount of energy.

And since we are talking about an oxidation-reduction cycle, we are going to need a lot of hydrogen to drive the reaction – about 6 atoms of hydrogen for every 1 carbon dioxide molecule – so 136 kg for every tonne of carbon dioxide. Since we are currently using about 3 billion tonnes of carbon dioxide equivalent a year (which will rise, according to conservative estimates to over 5.5 billion tonnes by 2025), we are going to need between 400 and 750 million tonnes of hydrogen (if all the carbon is sourced from carbon dioxide). Given that hydrogen is often quoted in energy terms, that is equivalent to 13,500TWh to 25,000TWh.

A more accurate future might have 1/3 biomass (which also needs hydrogen, but less of it) and 1/3 captured carbon, which would halve these numbers. Given that the total projected production of hydrogen in 2050 is between 16,500 and 20,000 TWh, there might be issues.

2 PROJECT ACTIVITY (FLUE2CHEM)

2.1 CHOOSING THE TARGET MOLECULE

Early on, we agreed that the project would attempt to cover an entire supply chain – from captured carbon dioxide to final product(s). We would not, with the resources and time available cover off all the options, so we needed to agree a target molecule to produce. It needed to be industrially relevant (i.e. produced at scale and used in a variety of products) but also moderately simple in structure.

The surfactant chosen is widely used in cleaning products, but also as a stabiliser in coatings. It is produced at a scale of around 6 million tonnes per year.

The hydrophobic end is made as dodecanol (also known as lauryl alcohol) – a linear aliphatic alcohol with 12 carbon atoms. Traditionally it is produced from palm kernel oil – which actually contains a distribution of carbon chain lengths (about 50% C12, 16% C14, 8% C16 and 20% C18 (with various levels of unsaturation). However, the scale of the market needs drove over-production, and has led to a drive for "sustainably farmed palm kernel oil" and a search for alternatives. It can also be produced from ethylene by the oxo/hydroformylation process.

The hydrophilic end contains 5-7 ethylene oxide units. Ethylene oxide is usually made from ethylene by oxidation, and the ethylene either comes from fractionating fossil oil in a refinery or from ethanol produced by fermentation of carbohydrates.

2.2 SOURCES OF CARBON DIOXIDE

The concept of extracting carbon dioxide (CO_2) from flue gases has been around since the 1950s. Initially, the focus was on capturing CO_2 for economic purposes, such as enhanced oil recovery

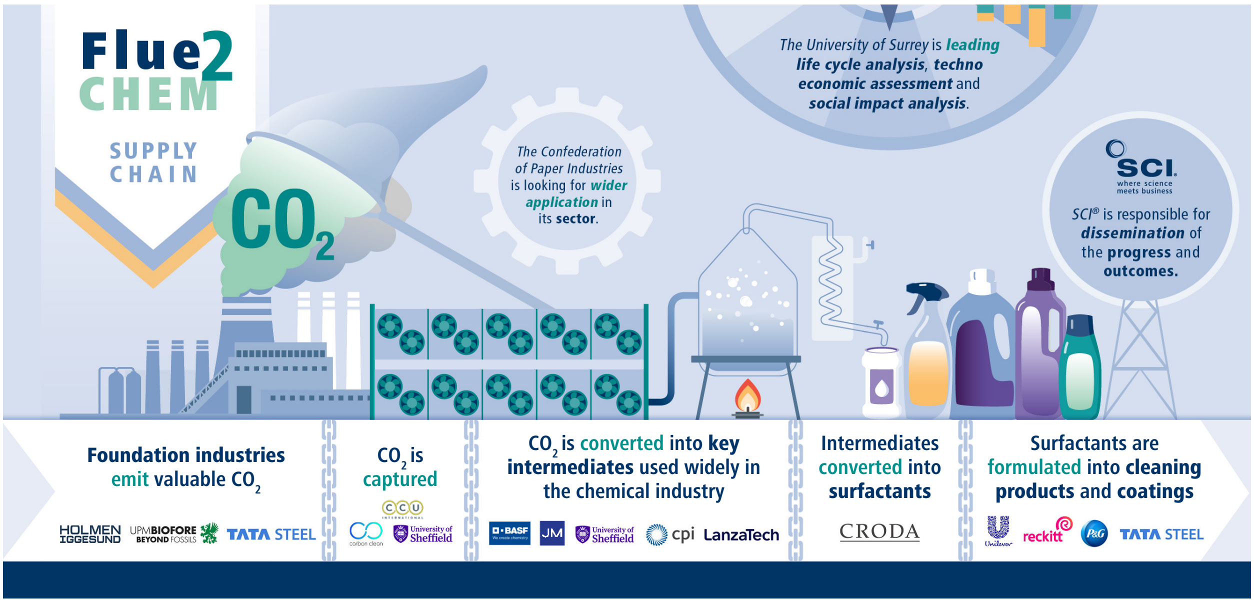


Figure 1
The Journey of carbon through the supply chain
WP1: Foundation industries emit carbon dioxide, which is captured
WP2: Biological conversion to key intermediates
WP3: Thermo-catalytic chemical conversion to key intermediates
WP4: Chemical conversion of key intermediates to surfactant
WP5: The surfactant is formulated into cleaning products and coatings
WP6: Impact: how much it costs, the environmental and social impacts

(EOR), where CO_2 is injected into oil reservoirs to increase oil mobility and productivity. Over time, the motivation shifted towards environmental concerns, specifically the reduction of greenhouse gas emissions to mitigate climate change.

Carbon capture and storage (CCS) technologies have evolved to capture CO_2 emissions from fossil fuel combustion and store them underground, thus preventing their release into the atmosphere. Nowadays, at Carbon Capture Utilisation and Storage (CCUS) conferences, discussions on utilisation often focus on the direct use of CO_2 in applications such as carbonating beverages and enhancing plant growth in greenhouses. However, there is ongoing research and development aimed at finding more innovative and impactful ways to utilise captured CO_2.

We are aiming for something different.

When we were putting together the Flue2Chem consortium we understood that different sources would have different chemical compositions, so we sought out different types of sources to maximise the spread of data for both the techno-economic and life cycle analyses. We started off the project with 3 sources of carbon dioxide – two paper mills with biomass boilers and a steel blast furnace.

The two paper companies in the consortium are Holmen in Workington and UPM in Irvine. Their carbon dioxide emissions are almost all "biogenic" as they arise from sustainable biomass, though they can also contain small fractions of fossil CO_2 arising from fossil carbon included in feedstock. Emissions are monitored, independently verified and reported to regulators. Both mills have biomass powered combined heat and power plants, using a combination of low grade forest residues, wood industry co-products and wood-derived wastes. The sustainability of the biomass has to be justified and meet the criteria set through the Renewable Obligation contracts held by the mills. This proof of sustainability is independently verified and must be in place for the generated electricity to be supported through the Renewable Obligation scheme. Accordingly, for carbon accounting purposes, the biomass emissions from these mills are counted as zero carbon, because at national level, this carbon is accounted for in the forestry sector. Emitted carbon is reabsorbed by new growth through a shallow carbon cycle. The mills emit around 2000-2500 tonnes of biogenic carbon dioxide a day.

We also started with the Port Talbot site of Tata Steel as part of the project. You could classify the carbon here as "used fossil carbon". Coal is used both as a source of heat and as a reducing agent to turn the iron ore into iron. It is a complex process and so there are many sources of carbon dioxide on the Port Talbot site, some mixed with carbon monoxide. In total Port Talbot used to generate about 15000-20000 tonnes of carbon dioxide a day and was responsible for 1.5% of the UK territorial emissions in 2023.

Although the goal of Net Zero is often stated as avoiding greenhouse gas emissions, it primarily targets those emissions resulting from the combustion of fossil fuels, which alter the balance of carbon dioxide between the geosphere and the biosphere and contribute significantly to climate change. However, there are also industrial processes, such as cement manufacturing, which at the scale they operate generate carbon dioxide at rates faster than natural processes can absorb, exacerbating the impact of fossil fuel combustion. While emissions from burning fossil fuels are expected to decrease as we transition to alternative energy sources, emissions from these industrial processes will persist longer and will require ongoing carbon capture and abatement efforts.

And finally, figures that cover the coal, oil and gas industries indicate that we have added about 2.2 trillion tonnes of carbon dioxide to the biosphere over the last 150 years. Although this is at a much lower concentration than found in flue gases, its capture and utilisation can still be included in any future plans for atmospheric remediation to minimise the damage to our (human) environmental niche on this planet.

2.3 CARBON CAPTURE TECHNOLOGIES

The basic requirement for a process to capture carbon dioxide is easy to state – you need a system that will reversibly absorb carbon dioxide, and some good engineering!

The liquid amine route for capturing carbon dioxide uses a mixture of amines to react with the carbon dioxide to form a mixture of carbamates, bicarbonates and carbonates. The absorption is usually carried out in a vertical column where the amine trickles down in a packed column and the carbon dioxide flows up. The resulting carbamate is then moved into another column where it is heated to decompose the carbamate to reform the amine and release the carbon dioxide. The energy efficiency of the process is largely determined by the energy required to decompose the carbamate.

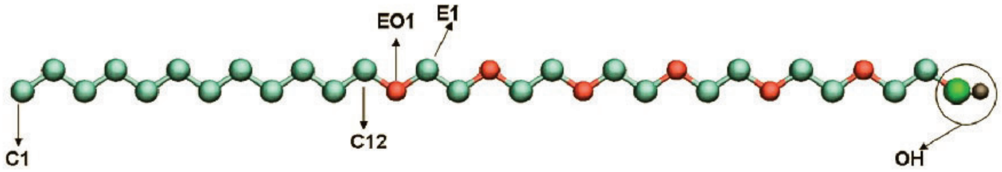


Figure 2
The selected target molecule

Over the years, different companies have developed innovative solvents to minimise the energy cost and often keep those formulations as trade secret due to the competitive advantage they provide.

Solid state absorption systems rely on physisorption. They used to be based on zeolites, but many recent ones use metal-organic frameworks. The early ones used a similar temperature driven process to control the absorption and desorption, but there are now systems based on pressure swing, where the absorption is driven by higher pressure and the desorption by much lower pressures. These are suggested to use lower energy than the more conventional temperature driven systems.

Early on in the project, one of the two companies providing the capture systems we wanted to include in the project – Carbon Clean – ran into an issue with the Environment Agency's policy regarding disclosure of the solvent they use in their process. They use an amine based solvent and, as mentioned above, they want to protect the confidentiality of their intellectual property from this major commercial risk. However, the Environment Agency requires disclosure of any chemicals that might be emitted in any process, and most amines have a measurable partial pressure at the temperature used in the carbon capture process, so although they might have been able to get an exemption for a research or test use, once they go commercial in the UK with their system, they will currently have to disclose to the Environment Agency. However, the Environment Agency is subject to Freedom of Information requests and would have to disclose Carbon Clean's proprietary information. This is why Carbon Clean chose to withdraw its technology from the project, while continuing to provide data for the techno-economic analysis.

There was another decision – this time by Tata Steel. Early in the project lifetime, they announced the closure of the blast furnaces at Port Talbot and a move to use electric arc furnaces. Depending on the exact implementation route they chose, there might be minimal emission of carbon dioxide, so they withdrew from the work package to collect carbon dioxide.

Key Learnings Regulations which make sense on their own can combine to cause a barrier to business.

Key Recommendations If you are building an interdependent project team, always have a Plan B!

Fortunately, in addition to Carbon Clean, we had also included a solid-state capture technology, albeit at a much lower state of technology development, in the project. FluRefin had been developed at the University of Sheffield and was being commercialised by Carbon Capture and Utilisation International (CCUI). This had been operated at the small scale, but as part of the project, would be scaled up to 1 tonne/day capture. This required wholly new equipment, some of which had to be imported from India, some from Germany, but was assembled in the UK. It was planned to be installed at the first collection site (Holmen) at the end of November 2023, but was delivered to site in mid-January, and commissioning issues delayed the first real carbon capture until late April. We have learnt a lot about fast-tracking process development – and the challenges it causes, partners working off different versions of the Process and Instrumentation Diagrams, the design experts being in Sheffield and the equipment being in Workington and so on but, as anyone who has done this before will tell you, this is all quite normal and we were very optimistic in our initial plans! Once on site in Workington, we had the support of some excellent engineers, and the various problems were overcome.

For example, one aspect of using a pressure swing process is the need to compress the input gas. This required the use of a number of compressors, but when they arrived, we discovered that they had been designed for compressing air to be used as "compressed air" and were a bit "leaky" on the input side. We knew this because the output carbon dioxide concentration was lower than the input and not as we needed and thought we would get. This required more engineering to adapt the compressors for our use.

Another requirement of using the pressure based system is that the input flue gases need to be cooled (from about 150°C to around 30°C) – this recovers a fair amount of heat. To fix the problem in the short term required more engineering, but this was also recognised as a substantial opportunity to generate heat for a local heating system.

Over the next few months, we started to capture enough carbon dioxide to supply the chemical conversion work packages. But this led to another "challenge". We were aiming to capture about 1 tonne per day. This is below the level where we could engage one of the major gas product companies to provide bottling technology, and we were initially not planning to liquefy the gas (so did not have the required equipment). This meant we were using a fairly basic "put gas in a pressurised gas bottle" process. The University of Sheffield team were also involved in another UK Research & Innovation (UKRI) project – called SUSTAIN Steel – where they were making use of a small carbon dioxide liquefaction kit. We "borrowed" this equipment for evaluation but realised that the rate of liquefaction was too slow for our needs and so we had to develop our own bottling liquefaction plant in-situ at Holmen!

Key Learnings Scaling up new process technologies always takes longer than hoped!

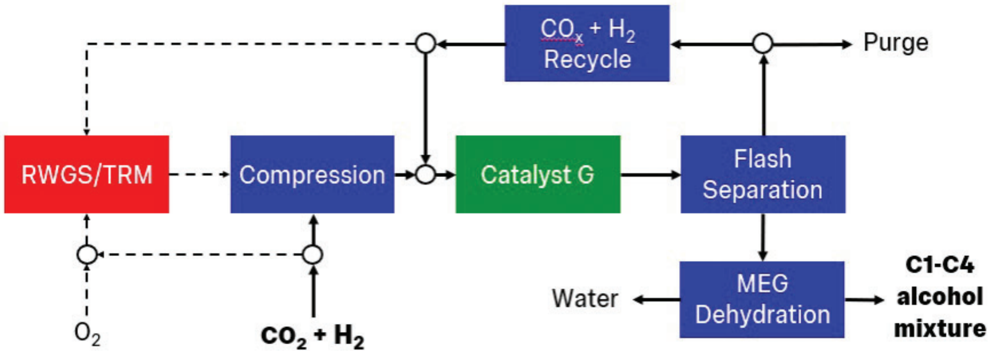


Figure 3 *Block flow diagram of an industrial-scale CO_2-to-Alcohols plant. Catalyst G was developed by BASF as part of Flue2Chem for a one-step conversion of flue-gas CO_2 to ethanol and other alcohols.*

Key Recommendations Planners need to balance optimism with realism. And site engineers are (often) gods!

2.4 TURNING CARBON DIOXIDE INTO A FEEDSTOCK

The project required that we turned the captured carbon dioxide into two chemical building blocks for the target surfactant – ethylene oxide and dodecanol. We also decided, to give us the widest possible set of options, to evaluate both biological and thermo-catalytic routes to both of these intermediates.

Ethylene Oxide

2.4.1 BASF

In addition to fermentation-based routes for the production of ethanol, thermo-catalytic routes for converting carbon dioxide and green hydrogen to ethanol and water are possible. As they are carried out at much higher temperatures than fermentation, the exothermic reaction can generate valuable steam for heat integration with other processes rather than dissipating the heat into the environment. Moreover, the concentration of the ethanol product is expected to be considerably higher for the thermo-catalytic than for the bioprocessing routes, with benefits for cost and environmental impact of the required ethanol separation.

BASF has investigated the one-step thermo-catalytic conversion of CO_2 into ethanol in the framework of Flue2Chem. BASF took an interdisciplinary and holistic approach that involved more than 40 scientists in six different organisations to provide the required expertise. These were co-ordinated as a cluster activity under the umbrella of Flue2Chem.

BUILDING A BETTER CATALYST

THE CHALLENGE

There are two primary challenges:

1. Existing catalysts were designed to work with carbon monoxide (CO) rather than carbon dioxide (CO_2)
2. The catalysts contained expensive precious metals that would make the process too costly

THE SOLUTION APPROACH

BASF assembled a team highly specialized researchers (20 scientists from three entities) to tackle these challenges. They used an innovative combination of digital and experimental techniques:

- Computer simulations and machine learning to predict promising catalyst candidates (BASF SE)
- High-throughput experimentation to test many catalyst variations quickly (hte-company, Heidelberg)
- Detailed analysis of reaction mechanisms to understand how to improve performance (BASCAT, TU-Berlin)

This integrated approach allowed them to:

- Reduce the amount of precious metals in the catalyst by approximately 50%
- Develop catalysts that tolerate CO_2 (as opposed to state-of-the-art catalysts)
- Optimize the catalysts to reduce unwanted side reactions that produced methane (an unwanted byproduct)

Note that catalysts not containing precious metals were tested within Flue2Chem, but not considered in detail due to their low performance.

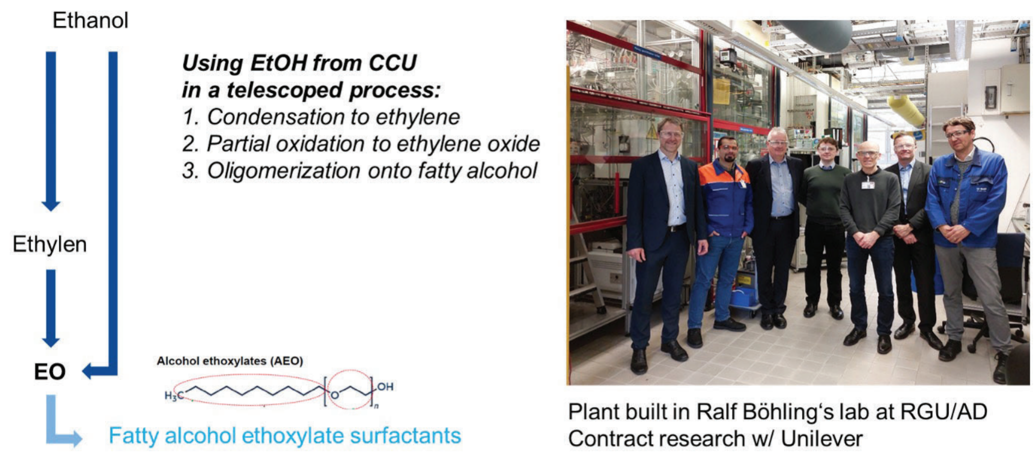
REAL-WORLD TESTING

The most promising catalyst was installed in a mini-pilot facility where, using carbon dioxide captured at Holmen, it successfully operated for over 100 hours, producing a sample of ethanol that was 87% pure. This demonstrated that the technology could work beyond laboratory conditions. A purified demonstrator sample was delivered.

FROM ETHANOL TO CONSUMER PRODUCTS

The project also explored how the ethanol produced from captured CO_2 could be further processed into ingredients for consumer products. BASF set up a three-stage pilot plant to convert ethanol into ethylene oxide and then combine it with fatty alcohols to create surfactants (key ingredients in many cleaning products).

While each individual step of this process worked successfully when tested separately, the team



Plant built in Ralf Böhling's lab at RGU/AD
Contract research w/ Unilever

Figure 4 *Concept and laboratory photograph of the telescoped, continuous process for grafting oligo ethylene oxide headgroups onto the fatty alcohol tails.*

encountered challenges when attempting to run the entire process continuously. Specifically, a side-product from the first reaction contaminated the catalyst in the second stage. This highlighted the complexity of integrating new sustainable processes into existing manufacturing systems. BASF plans future trials with an alternative catalyst in the second half of 2025.

TECHNOECONOMIC REALITY CHECK: IS IT COMMERCIALLY VIABLE?

A crucial part of the project was evaluating whether the technology could compete economically with existing methods. Experts from BASF and Imperial College London conducted detailed analyses of:

- Production costs
- Energy requirements
- Environmental impacts
- Comparison with alternative technologies

TECHNOLOGICAL CONCEPT OF INDUSTRIAL-SCALE PRODUCTION (SARGENT CENTRE AT IMPERIAL COLLEGE LONDON)

Flow sheets of the most reasonable industrial processes were generated in-silico. They are the basis for techno-economic assessment, life-cycle assessment, and cost-of-goods estimation. Three different process configurations were analysed:

1. A basic setup that focused on direct conversion
2. A more complex setup that included additional processing to handle methane byproducts
3. A configuration that used an alternative approach to deal with methane formation

KEY ECONOMIC LEARNINGS

The analysis was done in close collaboration with BASF's life-cycle assessment and economic forecast specialists. It revealed several important insights:

1. *Hydrogen Cost is Dominant*: The cost of green hydrogen (produced using renewable electricity) accounted for 60-80% of the total production cost
2. *Methane Formation is Problematic*: The unwanted production of methane significantly reduced efficiency and increased costs
3. *Comparison with Alternatives*: The process was 50-80% more expensive than the current industry standard methods for producing similar chemicals
4. *Green Premium*: The chemicals produced would need to be sold at 2-5 times the current market price to be profitable

ENVIRONMENTAL ASSESSMENT

Despite the higher costs, the process showed environmental benefits compared to fossil-based methods when using green hydrogen and renewable electricity. However, traditional bioethanol production (fermentation) currently offers a better balance of cost and environmental performance.

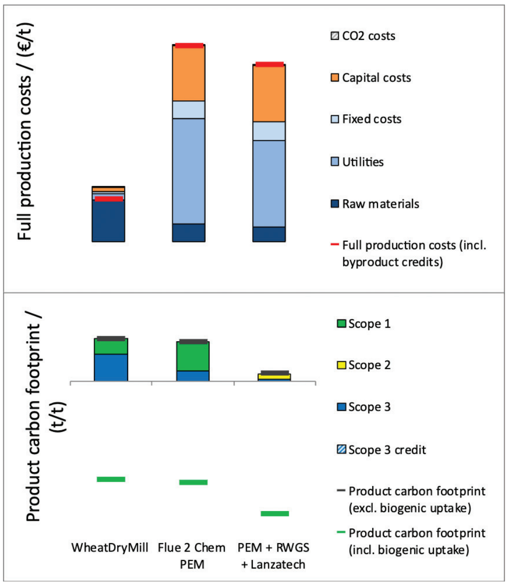


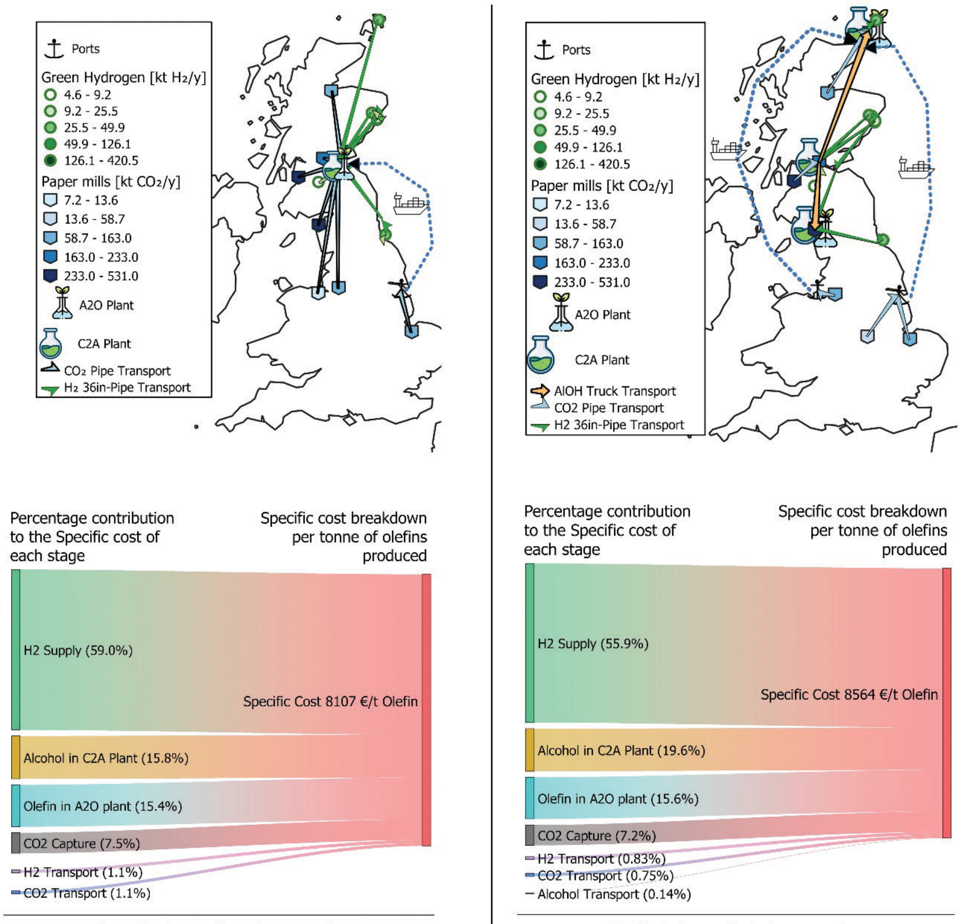
Figure 5 *Life cycle assessment and economic benchmarking of different competing technologies for the production of ethanol from flue gas CO_2: CCU is economically not attractive compared to fermentation-based ethanol given the current economic boundary conditions.*

SUPPLY CHAIN CONSIDERATIONS: WHERE TO BUILD IN THE UK?

The project also examined the optimal locations in the UK for implementing this technology. This analysis considered:

- The locations of paper mills that could provide biogenic CO_2
- Planned green hydrogen production sites

Figure 6
Centralised vs. distributed manufacturing scenario: supply chain configuration and corresponding specific cost analysis.



Centralised manufacturing scenario

Distributed manufacturing scenario

- Transportation infrastructure
- Economies of scale in production

CENTRALIZED VS. DISTRIBUTED MANUFACTURING

Two approaches were compared:

1. Centralized Manufacturing: Building one large facility to process CO_2 from multiple sources
2. Distributed Manufacturing: Building several smaller facilities located closer to CO_2 sources

The analysis found that a centralized approach would be slightly more cost-effective (about 5.6% cheaper) due to economies of scale, despite higher transportation costs. The optimal location would be in northern UK, close to major sources of both biogenic CO_2 and green hydrogen.

KEY LEARNINGS

1. Technical Success: BASF successfully developed a catalyst that can convert CO_2 to ethanol with improved efficiency and reduced precious metal content
2. Methane Formation: Future catalyst development needs to focus on reducing methane production as an unwanted side-product
3. Economic Challenges: Current costs remain too high for commercial deployment without policy support or incentives
4. Hydrogen Cost: The high price of green hydrogen is the main economic barrier

FUTURE OPPORTUNITIES

Based on and inspired by the project's findings, BASF is having in-depth discussions on promising directions for future research:

- Development of improved reverse water gas shift (RWGS) catalysts that can operate at lower temperatures (600°C instead of 900°C), which would reduce energy requirements and could be powered by electricity rather than methane
- Exploration of alternative target molecules that might offer better economic viability
- Internal discussions with BASF divisions that could potentially deploy this technology to meet the company's net-zero targets

BASF is planning to carry out a future project in a consortium similar to Flue2Chem, under the condition that it promises to lead to an economically viable technology.

ACADEMIC AND COMMERCIAL OUTPUTS

The project is expected to result in:

- Two scientific publications on value chains and supply chains
- One patent application for the catalyst technology
- Valuable cross-fertilization between academic and industrial research

KEY POLICY IMPLICATIONS

The findings from this project highlight that while technologically feasible, carbon capture

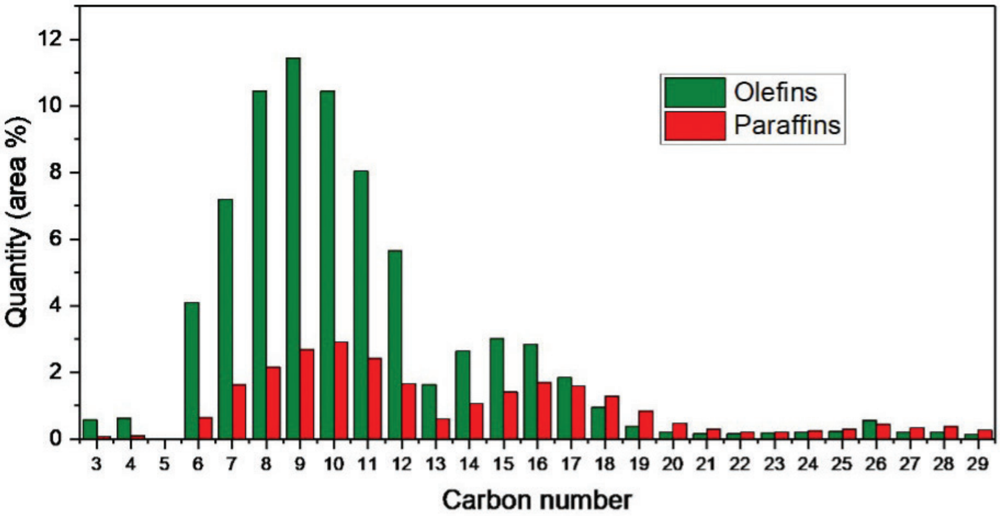


Figure 7
Catalyst: Fe-Metal Oxide direct to alcohol, scaled-up production (greater structural heterogeneity than small batch); Feedstock: Captured CO_2 (Holmen) at 20 barg

and utilization for chemical production faces economic challenges that require policy support to overcome:

1. Incentives for green hydrogen production to reduce costs
2. Carbon pricing mechanisms to make sustainable alternatives more competitive
3. Investment in shared transport infrastructure for CO_2 and hydrogen

With appropriate support, technologies like those developed in the Flue2Chem project could play a significant role in the transition to a more sustainable chemical industry and help achieve net-zero emissions targets.

2.4.2 LANZATECH

Given that the delays in carbon capture meant that BASF would not be able to produce ethanol with enough time to deliver the later stages of the project, we decided to source ethanol from another, already commercial, source.

So, LanzaTech provided ethanol from a LanzaTech facility in China. This ethanol was produced using biological gas fermentation of steel mill emissions (primarily CO gas).

Industrial activity generates waste gases that are either flared or combusted for power and emitted as CO_2 emissions. In the steel industry, CO rich gases are produced due to the chemistry of steel making. This gas is captured and piped into LanzaTech's specialised fermentation vessels filled with naturally occurring microorganisms that consume the carbon in the gas stream and grow, producing ethanol in the process. LanzaTech's proprietary technology platform integrates gas fermentation with upstream processes, such as gasification and gas conditioning, and downstream processes, such as product separations and catalytic conversions. Gas fermentation uses specialised biocatalysts that consume waste carbon gases to make desired carbon containing end products. Because the system is biological, it is inherently more tolerant of variability in feedstock composition and supply than systems based on catalytic chemistry and is therefore highly customisable.

Step 1: The process begins by receiving off-gas or waste gas streams comprising gases that contain various mixtures of CO, CO_2 and H_2, such as from steelmaking emissions.

Step 2: These gases are subsequently compressed, conditioned, and transferred into bioreactors containing LanzaTech's proprietary biocatalysts (microbes) and a liquid media,

Step 3: The microbes ferment the gases in proprietary bioreactors and as part of their natural biology they produce ethanol and other chemicals as a product of this fermentation. This is a continuous process that can run without shutting down for extended periods.

Dodecanol

Most medium length carbon chains are currently produced by the Fischer-Tropsch reaction. In this a mixture of hydrogen and carbon monoxide is catalytically converted to a distribution of carbon chains between 10 and 20 carbon atoms long. They are mainly saturated and straight chain, although there are side reactions that give alkenes and alcohols. It produces a distribution of chain lengths, but since the main use of the output is as a fuel, this is not an issue.

2.4.3 SHEFFIELD

The original plan was to convert the captured CO_2 to long-chain olefins (terminal alkenes) which would then be hydroformylated using catalytic a reaction with carbon monoxide to give the required long-chain fatty alcohols (FAs).

Active catalysts for the process have been designed, synthesised, tested and scaled up (this activity was not in the original workplan). Capacity for larger-scale reaction testing has been constructed and will be implemented by the end of May 2025. This and the other reactor in final development will provide online capacity for future larger-scale studies. The catalyst is an iron-based mixed metal oxide which produces a narrow carbon chain distribution similar to that obtained during the refining of crude oil hydrocarbons. The majority products are olefins with a smaller alkane distribution mirroring the main target product. This is shown in Figure 6.

The output was fractionally distilled to separate the fractions, with the C10-14 being the lengths of interest for AEO7 synthesis. In addition, the light and heavy distillates were also collected as these have a secondary use as synthetic transport fuels. The synthetic diesel fraction is shown in Figure 7 and was prepared from captured biogenic flue gas.

Testing of the conversion of the produced olefins to alcohols is on-going. Separation from small volumes yielded from bench-scale studies is challenging cf. larger scale processes. Conversion of produced olefin to required alcohols is scheduled for summer 2025, continuing in the SUSTAIN Hub.

A second iron-based catalyst was developed that was able to convert CO_2 directly to the fatty alcohol. This is yet to be optimised and the yield of the fatty alcohol is low when compared to the alkane/alkene fractions. However, it is a novel contribution to the carbon dioxide utilisation portfolio and has the novelty to be considered for IP protection or publication. The first steps have been taken to evaluate the system as the basis for a university commercialisation investigation.

Interaction between experimental (University of Sheffield) and modelling (Johnson Matthey) work has identified a clear output, a peer-reviewed journal publication. As part of this additional analysis and characterisation work is on-going at the University of Sheffield, including structural and physico-chemical characterisation of the catalyst; identification of possible structure-performance relationships; more precise quantification of the product distribution, e.g. through the use of an additional GC-MS column to quantify low(er) molecular weight products.

Studies were also carried out to determine if ethanol could be produced effectively directly from carbon dioxide. A copper oxide based catalyst was developed that was able to produce ethanol from captured flue gas in a conversion of 67%. The 1H NMR of the product is shown in Figure 9 and indicates a clean product free from by-products and impurities.

Sheffield will continue work on larger-scale synthesis of olefins (and their conversion to alcohols) beyond the end of the Flue2Chem in March. The Mezzanine pilot plant has insurance sign-off but still needs the hydrogen safety monitors to be fully commissioned. Full operation will commence in May and will be rolled over into the SUSTAIN Hub workplan to ensure continued operation, testing and validation. The iron metal

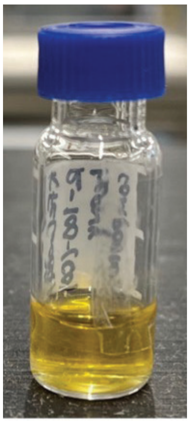


Figure 8 *Synthetic diesel fraction isolated from the output of using the iron metal oxide complex*

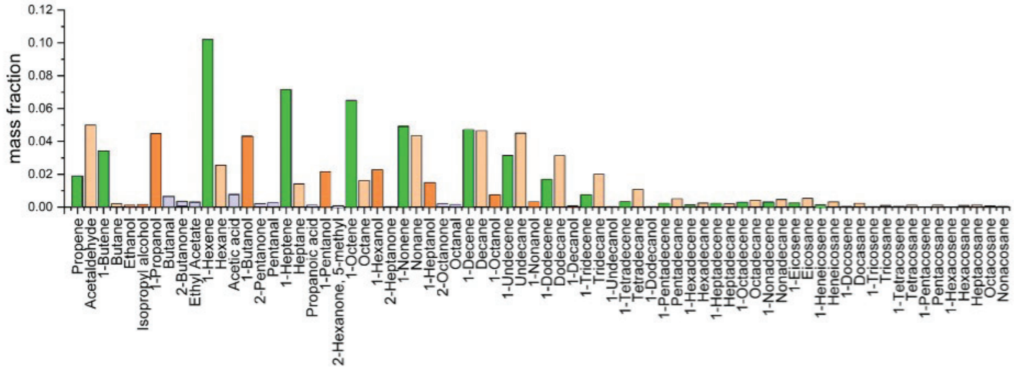
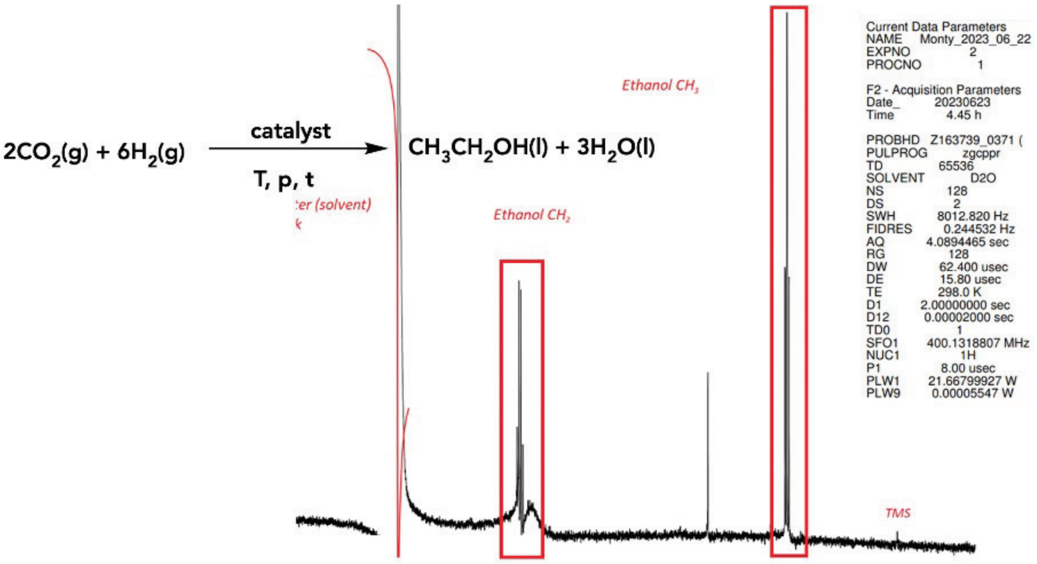


Figure 9 *Catalyst: Fe-Metal Oxide II, direct to alcohol, scaled-up production (greater structural heterogeneity than small batch); Feedstock: Captured CO_2 (Holmen) at 20 barg*



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PROCNO               1

F2 - Acquisition Parameters
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Time              4.45 h

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SOLVENT             D2O
NS               128
DS                 2
SWH         8012.820 Hz
FIDRES      0.244532 Hz
AQ        4.0894465 sec
RG               128
DW          62.400 usec
DE           15.80 usec
TE             298.0 K
D1        2.00000000 sec
D12       0.00002000 sec
TD0                1
SFO1     400.1318807 MHz
NUC1              1H
P1            8.00 usec
PLW1       21.66799927 W
PLW9        0.00005547 W
```

Figure 10 *Catalyst: Cu-Metal Oxide, CO_2 direct to alcohol, ; Feedstock: Captured CO_2 (Holmen)* oxide catalyst, as tested on the bench-scale system with captured CO_2 from WP1, has been prepared and has been loaded into the reactor in advance of insurance sign-off. Longer-term, provisional funding has been identified for completion of a dedicated gas-to-liquid pilot plant (0.5 L catalyst working volume). There have been discussions with potential users who see the value of a flexible reactor of this sort for demonstration studies and process testing.

2.4.4 JOHNSON MATTHEY

A techno economic analysis by Johnson Matthey showed that commercial technology aimed at SAF produced very small amounts of the C12-14 of alcohols or alkenes that were not economically viable to separate from the remaining components.

Developmental Fe based Fischer Tropsch (FT) catalysts reported in the literature and investigated by Sheffield had higher selectivity to alkenes and a higher fraction of product in the C12-14 range.

A paper study evaluated the separation and conversion of this part of the product to alcohols via hydroformylation of the alkene. Though this analysis suggest the Fe based FT catalysis route may potentially generate higher yields of C12-14 alcohols the process would still require several extra separation steps, and the yields are likely low. Any commercial use of this route would therefore require it to be carried out at large scale to generate significant C12-14 alcohol and incorporate valorisation of all the other components of the FT conversion process.

In addition, significant cost is added by the use of large amounts of green hydrogen required to reduce the CO_2 which makes all products significantly more expensive than those currently produced for example from fossil sources or palm oil. Therefore the overall process was found to be uneconomic in the absence of incentives, subsidies, or other significant measures that would affect the relative cost of the alcohol produced from CO_2

Key Learnings Flexibility in planning it always necessary. And the thermo-catalytic routes all produce co-products which have value, we need a holistic approach to designing processes.

Key Recommendations The UK needs suitable scale-up facilities, from universities, through pilot scale to semi-commercial.

2.4.5 CENTRE FOR PROCESS INNOVATION, HIGH VALUE MANUFACTURING CATAPULT

There is, potentially, an alternative route. Biological systems often store energy as triglyceride of fatty acids. Most commonly, these have 16 or 18 carbon atoms (C16-C18) in a straight chain. There are organisms that produce fatty acids with 12 carbon atoms (C12, our target), for example coconut and palm, but they are not common, and we also needed a system that could use carbon dioxide as a substrate.

Given the promise of specificity and low energy usage, we decided to see if a bacterium that could use carbon dioxide as a substrate could be genetically engineered to produce a C12 fatty acid chain instead of a C18.

To address the problem and to produce the target surfactants using a carbon negative process we started with bacteria that can naturally utilise carbon dioxide and that can accumulate fatty acids. To make the process more economically viable we focused on improvements of two aspects:

- Increasing fatty acid production
- Shifting the fatty acid carbon chain length from the naturally occurring 16-18 to 12-14

To improve the strains, we developed strategies involving genetic modification of the bacteria to alter fatty acid metabolism. For targeting the fatty acid chain length, a total of 11 genes from organisms with innate capability to produce C12 fatty acids were identified. Increases in fatty acid production were targeted by introducing genes affecting supply of fatty acid precursors and regulation of fatty acid pathways. These genes were then cloned and expressed in Rhodococcus strains that can use CO_2 directly as a carbon source.

The genetically modified bacteria were then grown under a continuous gas feed of carbon dioxide and hydrogen with monitoring of fatty acid content. Initial data, from shake flask cultures, showed that introduction of additional copies of the nitrogen regulatory gene, nlpR, resulted in an increase in fatty acid production. However, when this was repeated in continuous culture in stirred tank bioreactors (i.e. conditions more relevant for scale-up), no increase in fatty acid production was observed. Limiting nitrogen availability is a strategy known to increase production of lipids in some bacteria, in this instance the introduction of extra copies of nlpR was intended to 'trick' the cells into higher lipid production under non-limiting nitrogen levels. This worked in shake flasks growth, but further studies are needed to transfer this improvement to scale-up production by continuous culture in bioreactors.

In fatty acid synthesis in microorganisms, the final carbon chain lengths are tightly controlled by several factors including thioesterase enzymes and acyl-CoA-binding proteins. Thioesterase activity affects fatty acid chain length by releasing the growing chain from the fatty acid biosynthesis machinery once it reaches a defined chain length. A range of thioesterase genes, from different biological sources were selected based on literature precedence and reported fatty acid chain length specificity at C12-C14. The selected genes were synthesised and cloned into the Rhodococcus bacteria to generate genetically modified strains, that expressed these foreign thioesterases. These strains were then assessed for fatty acid production upon growth on CO_2 and H_2. Ultimately, we were able to achieve a 20% increase in fatty acid production upon growth on CO_2 compared to the wild type. However, the fatty acid chain length remained predominantly in the natural C16-C18 range, although small increases in C12-C15 fatty acids were observed, indicating that further development work would be required to get close to a commercially viable process.

Fatty acid biosynthesis is carried out by complex enzymes and enzyme complexes that typically produce a narrow range of fatty acid chain lengths. Producing C12-C14 fatty acid chains requires premature termination of the typical microbial fatty acid carbon chain. Use of foreign thioesterases has been successful in changing chain length in some instances reported in the literature, but success has been species specific and unpredictable, thought to be due to how well the foreign thioesterase can access and interact with the growing carbon chain. Alternative approaches are possible, for example in one report, medium chain fatty acids were overproduced when a thioesterase gene was fused to a fatty acid synthase gene and co-expressed as a single enzyme in a recombinant yeast. Up to 40 % of the total fatty acids produced were C12 and C14 chain length.

As part of our work, we also improved the tools and methods available for introducing genetic changes to the CO_2 utilising bacteria. Introduction of foreign DNA was found to be slow and inefficient, but during the course of this project we developed a novel method that achieved > 50-fold improvement in foreign DNA uptake efficiency, which would expedite the strain engineering process in follow-on projects using the same strain.

During the project we also considered other approaches for sustainable production of medium chain fatty acids from CO_2. In addition to the direct microbial conversion of CO_2 to fatty acids, that was experimentally explored, we also considered a two-stage fermentation process, and the use of CO_2 derived methanol as a microbial feedstock.

For the two-stage fermentation process to produce C12/C14 fatty acids from CO_2, the first stage utilises a natural acetogenic bacteria that can produce acetic acid from CO_2 and hydrogen. The acetic acid produced from the first stage fermentation is then used as a feedstock for the second stage fermentation which employs an engineered yeast to produce medium chain fatty acids. This approach decouples CO_2 fixation from fatty acid production and takes advantages of natural characteristics of two distinctive groups of microorganisms. Acetogenic bacteria are known for their energy efficiency for CO_2 fixation and particular yeast species that can metabolise acetic acid and naturally accumulate fatty acids at high levels.

Sustainable methanol is currently produced at commercial scale from CO_2 and H_2 feedstocks, with additional plants currently being built to expand production capacity. Microbial utilisation of methanol is well understood, and large-scale methanol fermentation processes have previously been developed for the production of single cell protein. As a microbial feedstock methanol presents fewer technical challenges than flammable gas feedstocks. Sustainable methanol is thus an attractive feedstock for developing microbial fermentation routes for fatty acid production.

Key Learnings Biological process development outcomes can be unpredictable and requires more time and money than we allowed for in the project.

Key Recommendations This work should be followed up. Further work should widen the scope to conduct parallel microbial strain engineering strategies and two-stage fermentation process development.

2.5 TURNING THE FEEDSTOCKS INTO A SURFACTANT

About 18 months into the project, we realised that delays in capturing the carbon dioxide meant our goal of having “line of sight” between captured carbon dioxide and the final products would not be achievable. We could not get enough ethanol/ethylene oxide or dodecanol to turn into a surfactant – which we planned to do at Croda’s Atlas Point facility. We therefore decided to use ethanol supplied by LanzaTech (see above) as the source of ethylene oxide (Croda use ethanol as a feedstock and turn it into ethylene oxide in situ) and sustainably farmed Palm Kernel Oil as the source of dodecanol.

This was produced in November 2024 and sent to the companies that would turn it into products.

2.5.1 FLUE2CHEM - ATLAS POINT TRIALS

Ethanol charging to bulk storage

- CarbonSmart Ethanol sample (25L) was received from LanzaTech at the end of September 2024.
- The ethanol (25L) was fed into the site bulk ethanol storage tank on 17/10/24 via the strainer housing of the ethanol unloading pumps. The strainer was then returned to normal condition and a railcar unloaded to pull the LanzaTech ethanol through the pump and into the storage tank.

Conversion to mass balance ethylene oxide (EO)

- Ethanol from the site bulk storage, which included the LanzaTech material, was fed into the production scale EO plant on 17/10/24.
- The ethanol was converted to EO by dehydration to ethylene and subsequent oxidation. After purification, three 1.5 kg cylinders of mass balanced EO were sampled from the EO bulk storage tank on 18/10/24. Quality analysis showed the EO met specification.

Synthesis of mass balance surfactant

- The cylinders of EO were transferred to the Atlas Point R&D labs, along with a sample of commercial "No Deforestation, Peat and Exploitation" (NDPE) palm fatty alcohol.
- The EO and fatty alcohol were reacted together using an alkali metal hydroxide catalyst in the lab-scale ethoxylation reactor. Batch size of 1 kg, targeting the commercial Brij L7 specification.
- The product was stripped post-reaction to remove unreacted EO and the base catalyst was neutralised using weak acid. Product yield was quantitative.
- Analysis by the Atlas Point Quality Control department showed that the mass balance surfactant met the targeted specification.
- The mass balance surfactant was sent to Croda in the UK, where FTIR spectroscopy and MALDI-TOF mass spectrometry confirmed its equivalence to commercial Brij L7 surfactant.

2.6 MAKING AND EVALUATING THE FINAL PRODUCTS

P&G – CLEANING PRODUCTS

With the non-ionic sample from WP4 in hand, P&G proceeded to assess the sample for performance and alignment with required material specifications, compared to the grade of non-ionic surfactant used in their Ariel powder laundry detergent. The assessment to check whether the sample met material specifications was carried out using industry standard methods such as mass-spectroscopy. The performance assessment was done using industry standard methods for surfactant performance such as surface tension. No differences were observed between the batch created using the captured CO_2 and the regular batch.

UNILEVER – CLEANING PRODUCTS

With the AE7 sample delivered through the Flue2Chem project, we conducted several tests to compare the new alcohol ethoxylate to our standard raw material. Firstly, we tested the raw material to compare dynamic air/water surface tension using maximum bubble pressure and dynamic oil/water interfacial tension against olive oil using a drop volume tensiometer. The two AE7 samples were compared at 0.5gpl in demineralised water over a range of surface ages, and no significant difference between the two surfactants was observed. An anionic/non-ionic surfactant mixture was also tested using both methods at 0.5gpl and 24°FH. Again, no significant difference between the curves was observed.

We also formulated Persil Nonbio with the Flue2Chem sample. The Flue2Chem AE7 was used as a 1:1 replacement for our current AE7, with no other adjustments to the Persil Nonbio formulation. All product specifications, such as pH, viscosity, and colour, were met with this alternative surfactant.

The cleaning performance of the current Persil Nonbio surfactant system and the Flue2Chem sample was compared on a small scale using a lintiest protocol: 30-minute wash at 40°C with 24°FH water (2:1Ca:Mg), followed by two rinses with a range of stains. No evidence was found that the Flue2Chem sample performed any differently from our current raw material.

RECKITT – CLEANING PRODUCTS

Reckitt currently use surfactants in a range of household products that they sell commercially, the purpose of the work that Reckitt carried out was to identify if the surfactant produced in the Flue2Chem project was comparable to similar surfactants currently included in Reckitt products.

The work carried out included laboratory scale feasibility replacing current surfactants in formulation with the Flue2Chem material. Stability testing of the generated batch, and various quality checks to confirm this formulation performed to the same standard as the product that is currently produced.

Manufacture of this test product used the same method of manufacture as currently used, when at lab scale. The material was included in the formulation in a like for like replacement of Flue2Chem surfactant with current surfactant. The formulated product was then placed under the standard testing that would be use at initial pilot stage when assessing the inclusion of an alternative raw material.

Micro Testing – The Flue2Chem inclusive batch was tested for micro capabilities. When tested, the formulation led to the successful reduction of colonies for various bacterial strains.

Cleaning Tests – The Flue2Chem inclusive batch was tested alongside current formulation for cleaning capabilities and demonstrated on par performance with current product.

6 Week Stability – The Flue2Chem inclusive batch was placed in various conditions and temperatures for a 6 week period to monitor the inclusion of the surfactant. Testing of appearance, odour, pH & density – All retained the same as current formula during the 6 week period.

Conclusions of this work is that in early feasibility stage testing the Flue2Chem material is comparable to current ingredients used.

TATA STEEL – COATINGS

A recent academic study from the University of California and Stanford University (published in Science, January 2025) has estimated that over 16 billion tonnes of CO_2 could be stored each year in building materials. That's about 50% of the CO_2 emissions caused by human activities in 2021. The researchers looked at how different materials

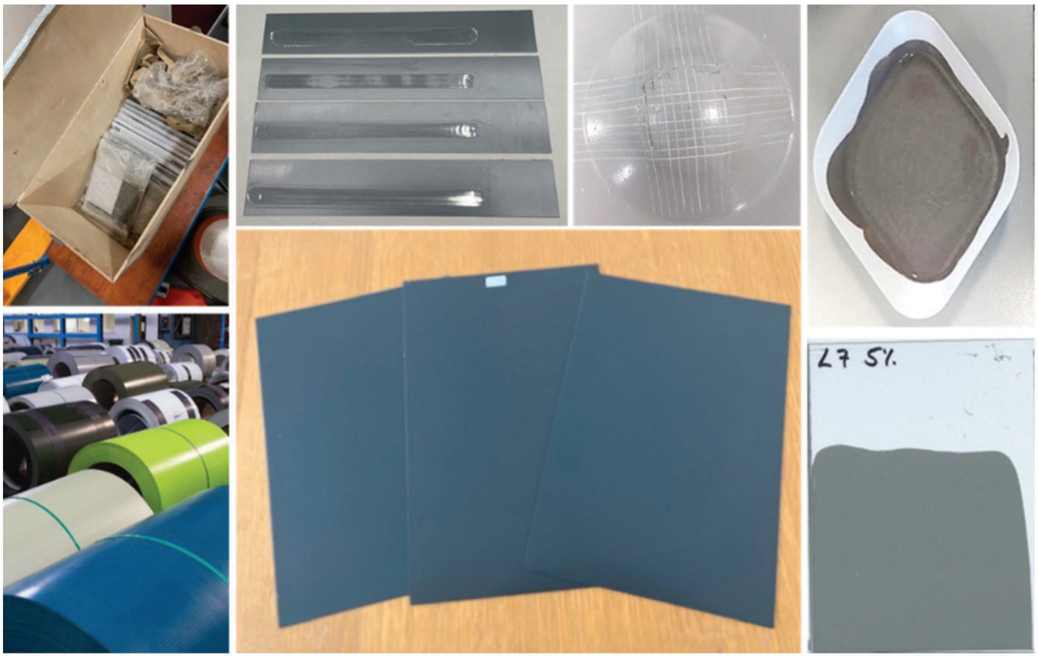

Figure 11 *(Bottom centre) Project demonstrator samples of Tata Steel construction materials: from left to right, control (Shotton's normal product - goosewing grey), incorporating 5 weight % Croda commercial surfactant, and incorporating 5 weight % Flue-2-Chem surfactant. (Clockwise from bottom left) example Tata Steel painted steel coils for construction applications; Beckers produced samples incorporating Croda commercial surfactants; chemical durability test (MEK rubs); physical cohesion test (Erichsen Dome); liquid paint incorporating Croda commercial surfactants; and Tata Steel R&D produced sample panel incorporating Croda commercial surfactant (ECO BRIJ L7).*

could hold or "store" carbon and found that bio-based plastic had the highest capacity for this type of carbon storage.

However, the study did not include coatings – like paints – used widely in construction. For example, at Tata Steel UK's Shotton site the Colorcoat® lines, up to 11 million litres of paint are used each year on construction products such as steel panels used in warehouses. These painted steel products are designed to last for decades; in fact some of them come with a Confidex® guarantee for up to 40 years, depending on the environment they are used in.

As part of the Flue2Chem project, Tata Steel, in collaboration with one of its industrial paint suppliers, Beckers, explored whether paints used on construction steel could include Flue2Chem surfactants made from captured carbon emissions. The surfactants could replace the existing surfactant in the paint or could be included in larger amounts – up to the point that the added surfactant affected the paint properties – in order to store more carbon. There is also the potential in future to incorporate recycled carbon directly into the molecules of the paints themselves, further increasing the amount of recycled carbon used in these construction products.

The work in Flue2Chem involved three iterations of testing. Initially, Tata Steel UK R&D researchers assessed the effect of adding commercial alkoxylated surfactants, provided by our project partner Croda, to a paint coating system. Five different surfactants, potentially manufacturable from captured flue gasses, were assessed at additions of 1, 2, 5 and 10 weight %. The five surfactants varied in their molar concentrations of ethylene oxide (EO). At lower molar concentrations of EO (3, 4, 7) there was no noticeable effect on physical properties or sample production. At higher molar concentrations of EO (9, 23) heating was needed to mix the surfactants into the coating and at the highest EO concentration (23) de-wetting was seen on application.

To ensure that the lab-based experiments completed at Tata Steel were indicative, repeat experiments on the commercially available surfactants were subcontracted through one of Tata Steel's paint suppliers, Beckers. Beckers repeated the experiments using their lab-based production and testing facilities in Liverpool. Results showed that all the commercial surfactants could be incorporated into the paints at concentrations of 1, 2, 5, and 10 weight %, with only one failure of cure (200 MEK dry rubs of ECO BRIJ J4 at 10 weight %) and some variation in surface gloss. It was noted however, that some of the 10 weight % additions appeared to be on the edge of failure, and it may be that this is the upper limit of surfactant incorporation.

Finally, the project derived surfactant, thought to most closely resemble Croda's commercial ECO BRIJ L7, was delivered to Beckers for incorporation into the paint and subsequent testing. Samples were again produced at 1, 2, 5 and 10 weight %. In this case however, the 10 weight % sample was found not to cure fully and produced a tacky surface unsuitable for subsequent testing. The 1, 2 and 5 weight % samples were cured and evaluated, but MEK rubs (200) suggest that the 5 weight % surfactant addition is also borderline with respect to chemical resistance, although all physical results look promising. Subsequent discussions with Croda researchers suggest there may be traces of unreacted polyethylene glycol (PEG) in the project surfactant which may be disrupting the paint curing.

In conclusion, Flue2Chem project produced surfactant, containing recycled carbon, was successfully incorporated into Tata Steel construction products as a replacement for paint surfactants normally used in the product.

2.7 LIFE CYCLE ASSESSMENT, TECHNO-ECONOMIC APPRAISAL AND SOCIAL IMPACT ASSESSMENT

The objective of Work Package 6 (WP6) was to evaluate the economic, environmental, and social impacts of products (such as alkoxylated surfactants and paper) within the Flue2Chem system under conditions of industrial symbiosis through Carbon Capture and Utilisation (CCU), in comparison to separate industries.

This study is concentrated on the current UK supply chain, with the entire Flue2Chem process operating on wind electricity, including electrolytic hydrogen production. The goal of WP6 was to utilise primary data from within the Flue2Chem system wherever possible. However, due to varying Technology Readiness Levels (TRLs) of the process steps in the Flue2Chem system, challenges inevitably arose in conducting the Life Cycle Assessment (LCA) and Techno-Economic Assessment (TEA).

The Flue2Chem system is multi-functional, producing various co-products and by-products. These include paper, steel, hydrocarbons, and in several process steps, co-products exceed the target product. Experts in WP6 discussed methods to account for multifunctionality, but there were limitations due to unknowns regarding volumes, purity, further processing requirements, and market values. As a result, it is not advisable to draw numerical conclusions from the LCA and TEA. As a result, it is not advisable to draw numerical conclusions from the LCA and TEA, although an initial LCA/TEA has been conducted within the constraint of data uncertainties and availability. As a result, the following directional conclusions can be made:

1 The Flue2Chem process is not currently economically feasible.
2 The highest cost contributor is hydrogen.
3 The surfactant yield is small in respect to the carbon dioxide in the flue gas due to co-products produced.
4 The surfactant yield must increase to result in more favourable economics. This could be achievable by syngas conversion through the FT synthesis process, following a reverse water gas shift reaction of the carbon dioxide present in the flue gas.
5 The Flue2Chem process's total site energy integration and recovery must be studied in-depth for economic feasibility and to decrease environmental impacts. To enable this deployment location scenarios are needed.
6 Reducing the coproduct with no increase in surfactant yield lowers the discounted cash flow.
7 Electricity needed to generate the hydrogen as a reactant incurs the largest Global Warming Potential (GWP).
8 The Flue2Chem process is better-performing than fossil-based surfactant production systems in climate change mitigation.

Future work should focus on further development of the LCA and TEA. Steps that could be included are streamlining, detailed process modelling and process integration study for more detailed energy data and a more detailed inventory data collected from the partners as the various process stages increase in TRL.

Key Learnings Applying standard Life-Cycle Assessment and Techno-Economic Assessment tools on a "jigsaw piece" supply chain is fraught with issues.

Key Recommendations All projects that promise to impact achievement of Net Zero or Circular Economy goals need to include a thorough discussion of how the LCA, TEA and SIA tools can be used to validate their claims.

3 WHAT WE LEARNED

3.1 ACTION

Probably the most important thing we learned from the Flue2Chem project was the importance of trying to do it! Bringing together the companies was a herculean effort that took 3 years before we submitted the application to Innovate UK. We need a many more projects like Flue2Chem where paper based studies are extended into small scale validation across a whole supply chain. And it will take time and coordination to do this efficiently.

3.2 OPTIONS

Next came the importance of evaluating options – at every step. If we had not decided to include two alternative carbon capture technologies, the project would have died in the first few months. If we had not gone for both thermo-catalytic and biological routes to make the two feedstocks, then we might not have produced any final products. And although Unilever, Reckitt and P&G are all demonstrating the resultant surfactants in their products, they have all chosen different applications – and Tata Steel are evaluating the surfactant in the coatings used to protect their sheet steel products. Pushing one technology would have been a waste of time and money – the world is complex and inter-related.

3.3 HYDROGEN

Chemistry from renewable carbon sources, especially sourced from carbon dioxide, needs significant amounts of hydrogen. Although carbon recycled from existing use is at about the right state of oxidation/reduction for direct replacement of current feedstocks, carbon from biomass requires about 20% the mass of the source biomass to get it to the right level of oxidation/reduction and carbon sourced from carbon dioxide needs about 50% of the source mass of carbon dioxide – it we sourced carbon entirely from captured carbon dioxide, we would need about 2 billion tonnes of hydrogen by 2040 (about 65 TWh). The current projected output is for about 240 million tonnes by 2024!

3.4 RENEWABLE ENERGY

With more green hydrogen needs and both carbon capture and chemically turning carbon dioxide into ethanol or ethylene being an energy consuming process, we will require a lot of renewable energy.

3.5 INTEGRATED LOGISTICS

Current CCS pipeline systems will need to be adapted to enable offtake of captured carbon for industry, in cases of smaller emitters distributed manufacturing hubs may need to be established.

3.6 MANUFACTURING ASSETS

There is a lack of both pilot scale and commercial manufacturing capability in the UK. Croda had to use manufacturing assets in the USA, and BASF had to use their capabilities in Germany due to lack of suitable manufacturing assets in the UK.

3.7 MANUFACTURING ASSETS

There is no UK manufacturing capability to convert ethanol into ethylene oxide. We recommend government support to incentivise this.

4 SUMMARY OF NEEDS

4.1 THE NEED TO CHANGE

Currently the petrochemical supply chain starts with about 6% of all the fossil carbon extracted from the planet. Although some products can last for a long time, many degrade quickly to carbon dioxide. If the various plans for “decarbonising” electricity generation, industry and transport are successful, then this will rise to about 40% of extracted carbon by 2050. Even if governments are largely ignoring the challenge of “defossilising” their products, many in the chemicals industry are evaluating their options for alternative sources of carbon as a feedstock.

4.2 THE NEED FOR COLLABORATION

The supply chains in the chemicals industry are complex and interlinked. It is more of a supply web! This means that any plans for change (towards a less fossil carbon intensive feedstock) will need coordination across many steps. Flue2Chem has demonstrated both that many companies within the supply web are willing to make a commitment to work together and that when they do so, things can happen faster than they would without that collaboration.

4.3 THE NEED FOR NEW SCIENCE

Much of the industrial chemistry developed over the last 150 years has been based on the cheap and easily available feedstocks derived from coal, oil and natural gas. Here, carbon is found in a highly reduced state, where every carbon is linked to either another carbon atom or hydrogen. We extract the energy in these molecules by “oxidising” them – mostly by burning them to make heat.

If we start with carbon dioxide as the feedstock, we need to “reduce” it back to this state – it makes all the subsequent processing much easier. And that requires a large amount of hydrogen – every carbon atom requires at least 6 hydrogen atoms

$$xCO_2 + 3xH_2 \rightarrow (CH_2)_x + 2xH_2O$$

There are several routes to start with carbon dioxide and make ethanol. That ethanol can be made into ethylene and then ethylene oxide. We tried to test a biological route to make the dodecanol but could not do it in the time available. Subsequent discussions have indicated that there is still potential in this area. We explored the carbon chain building reactions based around Fischer-Tropsch catalysis, where it is clear that wide product distributions are a issue when the target is a single chain length, but integrated chemicals hubs (similar to those today based on petrochemical refining) could be a viable option to valorising multiple products from the ‘soup’.

4.4 THE NEED FOR SCALE-UP FACILITIES

From the scaling of new chemical catalysts to that of most biological processes, we constantly ran into stories about companies having to take their development and early stage commercial activities overseas because no suitable assets were available in the UK. This was identified by the House of Lords Select Committee as part of their analysis of Engineering Biology, but it is true in most areas of chemistry.

5 NEXT STEPS?

During the project the team identified key learning points and two main areas where further activity is needed if the UK is to transition to carbon capture and utilisation (CCU) derived chemicals: ensuring commercial viability of the technology and generating market pull for these sustainable products.

5.1 GETTING THE TECHNOLOGY TO COMMERCIAL VIABILITY

While it was not expected that the Flue2Chem process, in its current form, would be commercially viable, the progress made over just two years, and with a relatively modest investment, of around £5 million, is encouraging. None of the individual steps in the process have yet been optimised or scaled, and this is typical for emerging technologies. By contrast, incumbent processes have benefited from over a century of refinement and investment.

What this project has shown is that there is real potential. With coordinated effort, the UK could build on this foundation to develop a more sustainable chemical industry. A logical next step might be to explore the creation of a national programme – one that supports applied research, technology optimisation, and scale-up. This could take inspiration from successful models in other sectors, such as the Faraday Challenge/Advanced Propulsion Centre in automotive or the Aerospace Technology Institute.

Such a programme could benefit from a coordinating body that brings together government, industry, and academia to:

- Support the development of core industrial capabilities based on renewable carbon.
- Enable access to integrated scale-up facilities, potentially co-located to maximise efficiency.
- Act as a focal point for aligning regulatory and legislative frameworks with innovation needs.
- Help safeguard and grow jobs across the UK's industrial clusters.

A key learning from Flue2Chem is how the project itself came into being. It emerged not from a funding call explicitly designed for this kind of supply chain transformation, but from a shared recognition – between industry and government – that the Transforming Foundation Industries programme could be shaped to meet a broader need. This was only possible through close collaboration and a willingness to align strategic goals with available mechanisms.

Maintaining this kind of flexibility – where funding opportunities can be adapted to support emerging industrial challenges – will be essential as we continue to build momentum. We believe there is an opportunity to work with government departments – such as DBT, DESNZ, and DSIT – and relevant agencies to explore how such a programme might be shaped. The idea has already been raised within the UK Government's Chemical Innovation Forum, and we would welcome the chance to develop it further in partnership.

5.2 INFLUENCING THE MARKET

The current routes that supply carbon as a material and energy have been in place for many decades. They are optimised for production efficiency and often supported by sympathetic fiscal and regulatory regimes. By contrast, while the supply chains necessary for a circular carbon economy have been shown to be scientifically feasible, they are unproven at commercial scale. Flue2Chem has made a little progress, but it has mostly shown the type and scale of the challenges we will face if we want to move our chemistry-based industries to be part of the move to net zero and not the remnant problem!

Flue2Chem has shown that the technologies are now available to produce the type of chemicals that the FMCG industry and paints industry need from carbon dioxide. However, like most new technologies the price of production needs both development and scale to bring down the cost which currently sits somewhere in the region of 5-10 times the cost of fossil carbon equivalent chemicals. This requires investment by industry – and this can be encouraged by support from governments.

However, the markets appetite for more sustainable chemicals and materials is also part of the equation. The current interpretation of marketing data is that most customers will not pay a premium for sustainable products but expect it to be embedded in what they buy.

As has been seen in other sectors such as tailpipe emissions and renewable energy, it is possible to balance the cost/price equation with policy support and move towards a market where these technologies become competitive.

One big opportunity arises from the current integration and complementarity between the fuels sector and the chemical industry. They are historically linked through the extraction and refining of fossil carbon as a common feedstock. In addition, end user application chemicals are produced from platform chemicals that are produced alongside the fuels.

Although significant sections of the fuels industry are under pressure from alternative energy sources (in power generation, many forms of transport and industrial processes), the aviation sector is moving towards "sustainable aviation fuel" – where the chemicals currently used as fuel and produced from fossil carbon can be replaced by identical chemicals made in a manner directly analogous to the first stages of the supply chains needed to supply the chemicals industry. This addresses the goal of not adding to the overall amount of carbon dioxide in the atmosphere. It is worth noting that the current size of the aviation fuel industry is about 50% the size of the petrochemicals industry – in terms of the amount of carbon!

The market for sustainable aviation fuel is being "encouraged" by many governments through escalating mandated use e.g. ReFuelEU, where Europe is aiming for 70% SAF use in all European airports by 2050

There may be lessons here for the chemicals sector. One potential approach could be to explore a phased policy framework that encourages the use of sustainably sourced carbon in chemical supply chains. This might include:

- Mandated targets for renewable carbon content in specific product categories over time. Where such mandates would sit—whether with consumer goods manufacturers, chemical producers, or other actors in the value chain—would need careful consideration and consultation to ensure they are effective and proportionate.

- Market pull mechanisms, such as VAT reductions, green public procurement, or labelling schemes for products containing certified sustainable carbon, to help stimulate demand and reward early adopters.
- Recognition of renewable chemicals as a key enabler of net zero, ensuring they are integrated into broader decarbonisation strategies and industrial policy.

We believe there is value in continuing to work closely with government to explore these options. Flue2Chem has shown what is possible when industry and government collaborate to align funding with strategic need. A similar spirit of partnership could help shape the policy and market environment needed to support the next phase of development – culminating in a fully defossilised chemicals industry by 2050.

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