UKRI Interdisciplinary Centre for Circular Chemical Economy

# CircularChem Explained

## A Circular Future for the Chemicals Industry

NICER PROGRAMME

UK Research and Innovation

UKRI Interdisciplinary Centre for Circular Chemical Economy

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**PROF JIN XUAN**
PI AND DIRECTOR OF THE CENTRE
UNIVERSITY OF SURREY

Our Centre started in January 2021 and completed in March 2025. This final report is a testament to the incredible four-year journey we have undertaken together, and highlights our shared commitment to transforming the chemical industry into a model of sustainability and circularity.

When we began, the challenges were immense. The chemical industry's reliance on fossil fuels and the environmental impacts demanded urgent and transformative solutions. Thanks to the dedication and hard work of our talented team, industry partners, and stakeholders, we have made remarkable progress toward addressing these issues.

These efforts earned us the 2023 IChemE Global Award for Sustainability, a recognition of the impact of our work. However, challenges remain. In this report, we reflect on what has been achieved, identify persistent barriers, and outline the critical steps needed to scale innovations and drive systemic change.

This report is both a celebration of our achievements and a roadmap for the future. It reflects the dedication of our researchers, industry partners, and stakeholders who have worked tirelessly to advance the vision of a circular chemical economy. As you explore this report, I encourage you to consider not only the progress made but also how you can contribute to this vital mission.

Together, we have demonstrated that a sustainable future for the chemical industry is not only possible but within reach. Let us continue to build on this momentum, striving for a world where circularity is the norm, and innovation serves as a bridge to a better tomorrow.

**55** CENTRE MEMBERS

**3** PATENTS

**200+** INDUSTRIAL PARTNERS

**30+** POLICY SUBMISSIONS & WHITE PAPER

**70+** PEER-REVIEWED PUBLICATIONS

**100+** EVENTS

**£10M+** FOLLOW-ON FUNDING

**1** SPIN OUT


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## THE IMPORTANCE OF THE CHEMICAL INDUSTRY

### Chemicals play a crucial role in everyday life, as an essential component of products including food, healthcare, textiles, electronics, and many more.

The chemical sector feeds and supports many other sectors of the UK economy, creating thousands of jobs and billions in export revenues. As such, the industry is uniquely placed to drive the UK's Net Zero transition, securing sustainable access to resources and stimulating long-term economic growth. However, this requires a concerted national effort to move away from fossil fuel inputs towards a fully circular chemical economy.

#### KEY STATISTICS OF THE UK CHEMICALS INDUSTRY

- **96% manufactured products in the UK contain synthetic chemicals**
- **4,400 companies**
- **151,000 employees**
- **£31 billion of added GDP**
- **£50 billion of export goods**
- **90% chemicals are derived from fossil fuel sources**
- **6-8% greenhouse gas contribution**

## CHALLENGES & OPPORTUNITIES

### NET-ZERO FUTURE

Low-carbon technologies depend on high-performance chemical products, from lightweight composites to insulation. However, current manufacturing routes are heavily reliant on fossil fuel inputs, both as a source of energy, and as the building blocks for chemicals themselves. While it is not possible to 'decarbonise' the chemical sector, we can move towards non-fossil sources of carbon, driven by renewable electricity, to create a circular chemical industry.

### STIMULATE GROWTH

Continued investment in a sustainable chemicals industry in the UK with accompanied increases in green energy will secure a healthier economic future for the UK. As well as retaining large-scale chemical manufacture, more flexible, small-scale technologies can create high-value products from dispersed resources, offering the UK an opportunity to upscale and adapt new technologies to retain jobs and establish itself as a sustainable chemical exporter.

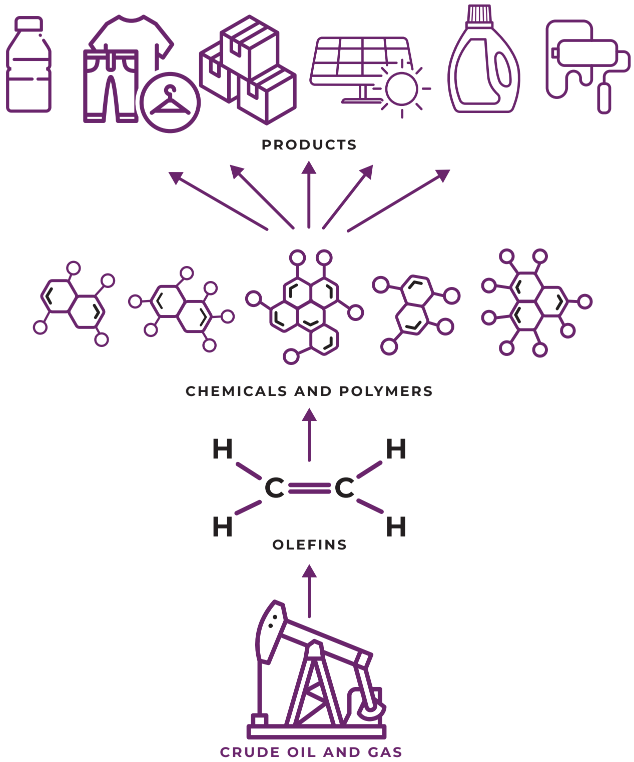
### RESOURCE SECURITY

Significant changes in the social and political landscape over the course of the project have emphasised the importance of a strong domestic chemical sector. Investment in the upscaling of the technologies outlined in this report now will provide a more secure and resilient supply chain, helping to maintain affordable products in the long-term.

## FINDING A SECTOR WIDE SOLUTION

### The chemical value chain is highly diverse, encompassing a multitude of production lines that produce a vast array of products essential to modern life.

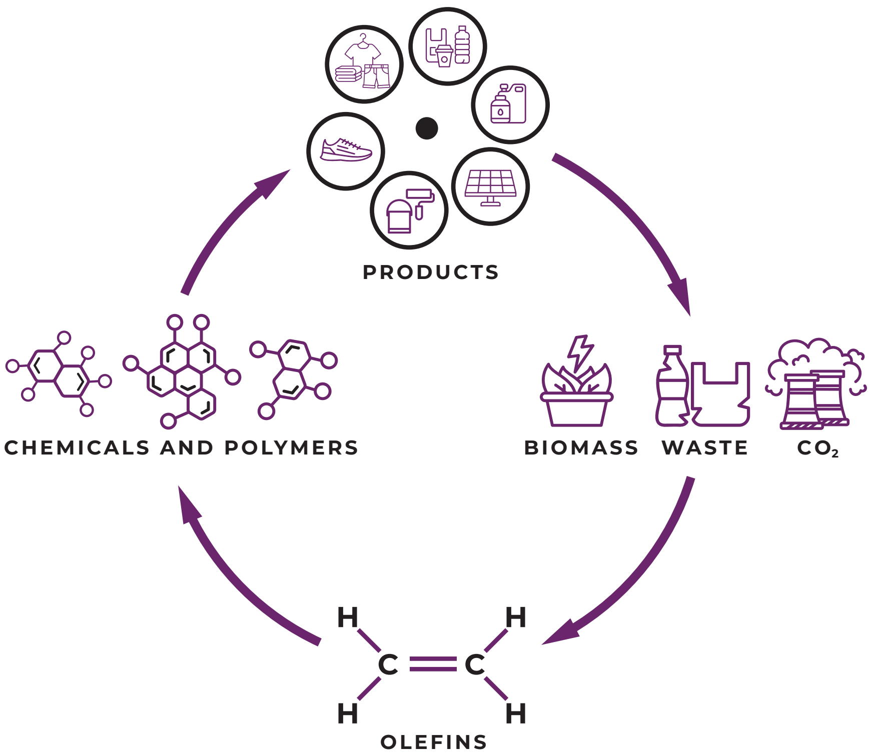
This complexity poses a significant challenge to systemic change, as focusing on individual production lines offers limited impact and scalability. However, at the core of this vast network lies a handful of platform chemicals, such as olefins, which serve as the foundational building blocks for countless downstream products. Currently, these platform chemicals are predominantly derived from fossil resources, perpetuating environmental and resource challenges.




## ALTERNATIVE CARBON SOURCES

### If we can make the resource flows of these platform chemicals, such as olefins, circular - using direct or indirect recycling of chemical carbon - we have the potential to transform the entire chemical sector.

This approach would allow us to achieve systemic change without requiring widespread alterations to the majority of existing infrastructure. By targeting these critical nodes within the value chain, we can unlock a more sustainable and resilient future for the chemical industry as a whole.

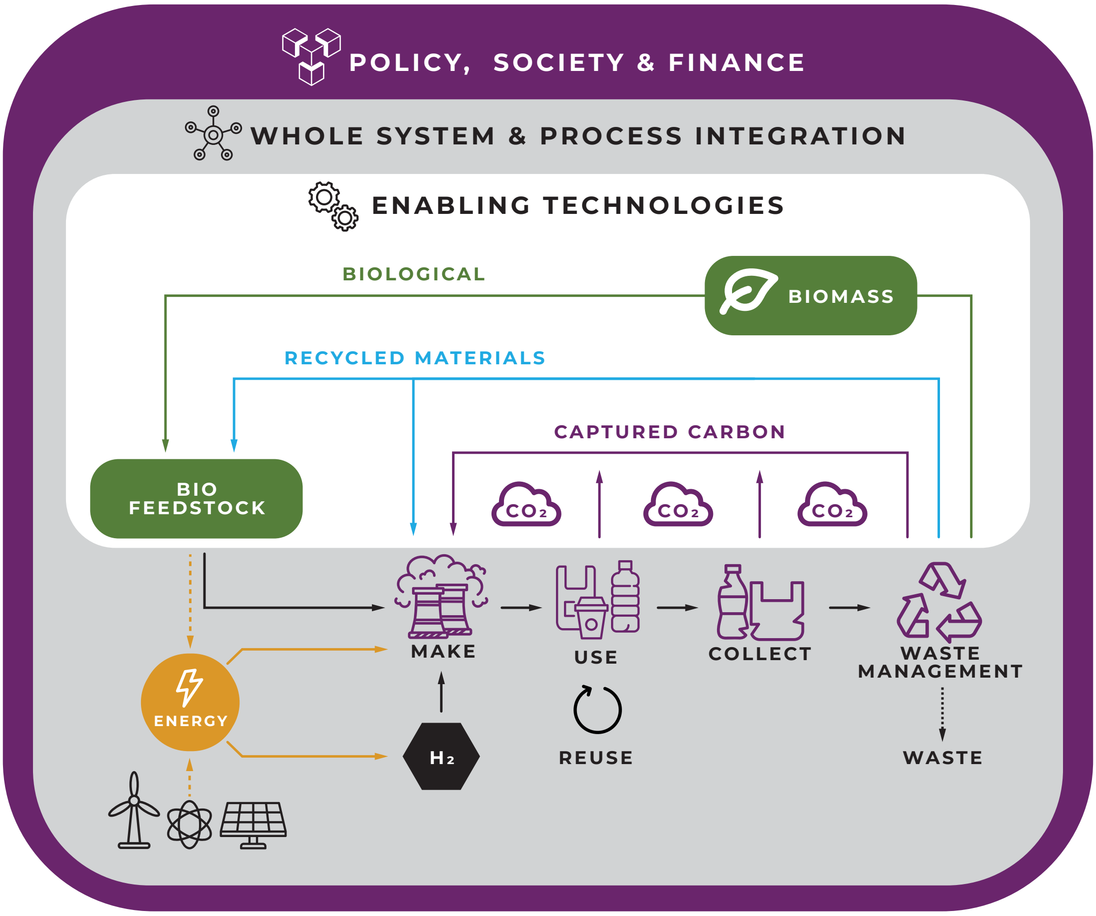


## Our Centre has been pioneering in the proposed use of biomass, solid waste carbon, and carbon dioxide as three alternative feedstocks for the chemical industry, to reduce reliance on fossil fuels and mitigate greenhouse gas emissions.

Through cutting-edge science and innovation, we have developed enabling technologies and systems understanding for these feedstocks while actively advocating for a paradigm shift within the field. This advocacy has reshaped industry understanding, with these feedstocks now recognised as critical alternatives in various reports such as the ones from the **Royal Society**[1] and **KTN**[2], establishing them as a consensus and joint voice for a sustainable future.

Our approach is the development of a sector-wide solution rooted in circularity and focusing on the resources flow of olefin—the raw material for 70% of all organic chemical production. It represents a fundamental paradigm shift away from the current make-use dispose model, requiring scientific innovations at all levels. Starting from the development of new disruptive technologies, their integration into existing processes and evaluation of whole system impacts, to the identification of non-technical barriers and opportunities and how they can be overcome/realised.

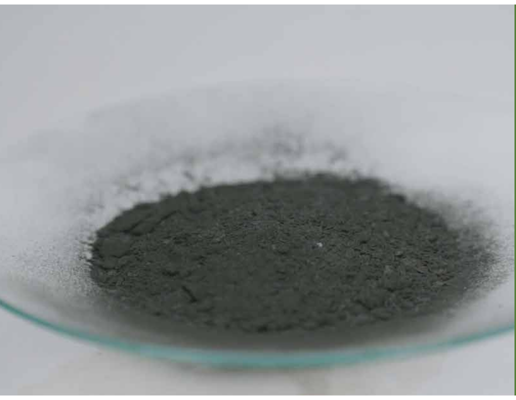
To address these challenges, CircularChem was formed to explore, develop and evaluate three alternative sources of non-fossil carbon – **biomass**, **plastic waste** and **$CO_2$** – to produce olefins and methanol, some of the most important chemical building blocks, which account for around 70% of all organic chemical production.




1. Royal Society https://royalsociety.org/-/media/policy/projects/defossilising-chemicals/defossilising-chemical-industry-report.pdf
2. KTN https://iuk-business-connect.org.uk/wp-content/uploads/2024/08/IUK-Sustainable-Carbon-Report.pdf

## Enabling a circular carbon chemicals industry is dependent on the availability and competitiveness of technologies for the conversion of non-fossil carbon into either the products of, or the feedstocks for the chemicals industry.

Recognising that there is no one-size-fits-all approach the centre has identified, and advanced the understanding and state-of-the-art, of conversion technologies across all three of our target non-fossil resources (**biomass**, **plastic waste** and **$CO_2$**).



### BIOMASS

**Hydrothermal Liquefaction | TECHNOLOGY READINESS LEVEL: 3**

We have produced a low-cost, magnetically-recyclable iron-based catalyst that improves bio-oil yield and quality[3], enabling further upgrading into olefins. have also explored the potential of co-converting biomass with plastic wastes to complement and enhance chemical recycling.

### PLASTIC WASTE

**Hydrogenolysis of waste polymers | TECHNOLOGY READINESS LEVEL: 3**

The team developed new catalysts which could be used to convert household plastic waste into useful liquid (alkane) chemicals[4]. They also looked at the effect of catalyst supports on activity to progress fundamental understanding. We have contributed to a rapid increase in awareness of the challenges at the fundamental chemistry, device and systems levels.

### $CO_2$

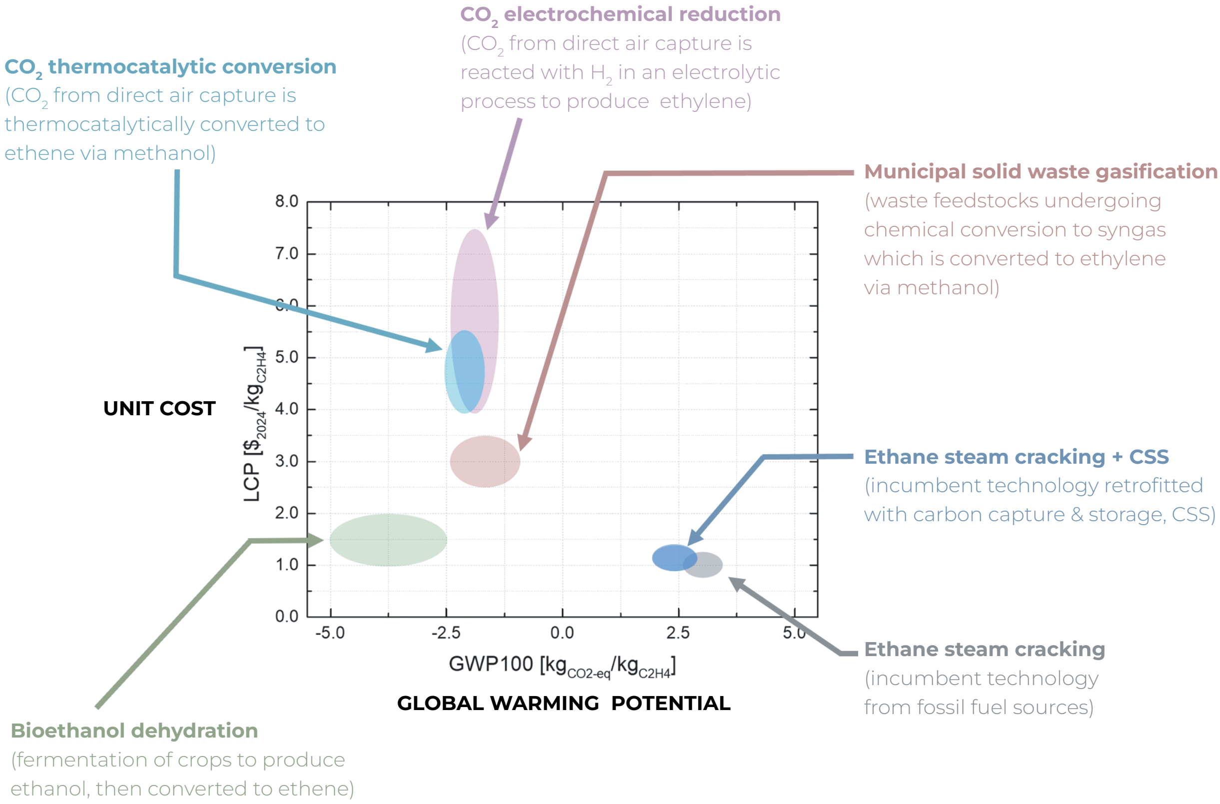
**$CO_2$ electrolysis | TECHNOLOGY READINESS LEVEL: 4/5**

We have developed molecular catalysts with a reverse biased bipolar membrane electrolysers[5]. Two Patents have been filed around electrode compositions and device structures. Devices were tested with real-world captured gases from industry partners. $CO_2$ is increasingly understood to be a resource, not just waste.

3. Mukundan S *et al*, Bioresource Tech., (2023), **369**, 128479
4. Mazharul M. Islam *et al*, J. Phys. Chem. C., (2024), **128**(46), 19621
5. Siritanaratkul B *et al*, Phil. Trans. R. Soc. A., (2024), **382**, 20230268

## Guiding the deployment of a circular carbon chemicals industry requires quantifying the environmental impacts of early-stage technologies for chemical recycling, along with the projected costs of these circular chemicals, and benchmarking against existing technologies.

Our results have shed light on the trade-offs between production cost, carbon intensity, and resource efficiency for producing organic chemicals from the three main circular carbon feedstocks: **biomass**, **plastic waste** and **$CO_2$**.




The figure above shows how the cost of producing ethylene (a critical olefin) compares to the global warming potential (amount of carbon emissions) for different carbon sources in the UK. The predictions are based on advanced computer models that simulate and optimise the chemical processes from 'cradle to gate', i.e. carbon source to ethylene. These models also include data on costs and environmental impacts to estimate how well the recycling technology would work on a large scale.[6] Compared to the cradle-to-gate emissions of ethane steam cracking, these clearly show the benefits of green ethylene.

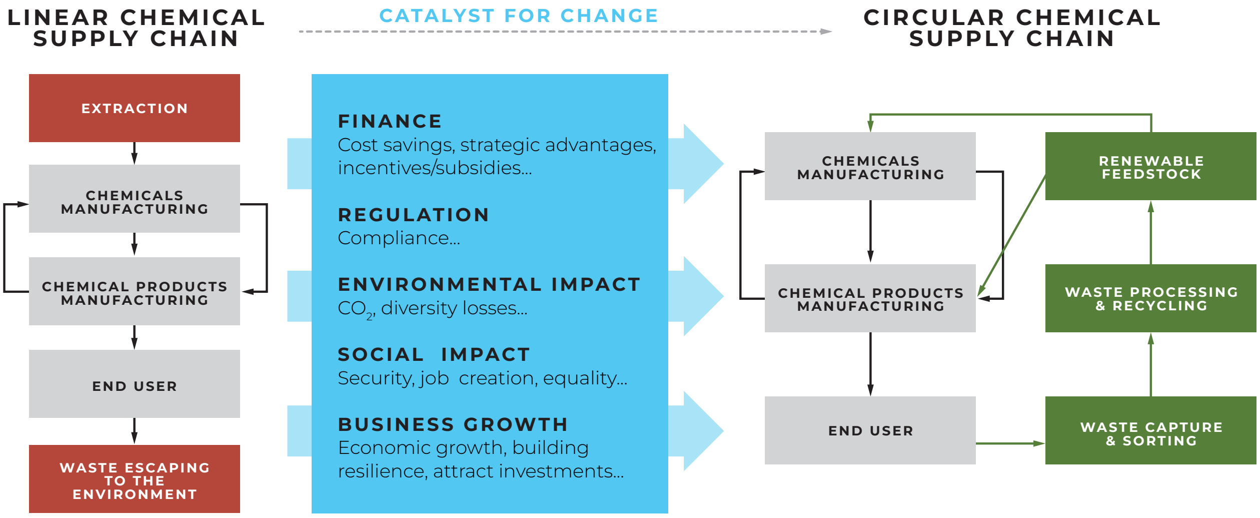
### KEY TAKEAWAYS:

- CCS could abate a cracker's direct emissions subject to a modest cost premium, but reducing upstream emissions to reach net-zero would require carbon dioxide removal (CDR) technologies
- Except for the bioethanol pathway, producing defossilised ethylene comes at a significant cost premium of 3-times or more its current market price
- After bioethanol which is in limited supply in UK and has competing uses (e.g., fuels), MSW gasification could be prioritized in medium-term, while continuing research & development on CCU and chemical recycling

6. a. Nyhus *et al*, Energy Environ. Sci. (2024), **17**, 1931
   b. Lyons *et al*, Comput. Aided Chem. Eng. (2024), **53**, 763

## ADDRESSING THE NON-TECHNICAL CHALLENGES

Transitioning to a circular economy requires a comprehensive, system-wide approach that brings together businesses, policymakers, consumers, financiers, and innovators to drive the transformative changes. Through a range of activities, we have employed a systematic and integrated strategy to CE practices, delivering significant benefits for businesses and the public, while providing policymakers with practical, evidence-based recommendations.




## HOW CIRCULARCHEM HAS MADE PROGRESS

### SHARED UNDERSTANDING

Improve alignment across stakeholders by promoting a systematic, whole-system perspective. Examples include the **NICER Insight Reports**.

### PROACTIVE & EFFECTIVE FINANCING MECHANISMS

Transfer insights from financiers to businesses equips them with financial strategies to enhance resilience and ensure long-term success.

### SUPPLY CHAIN INTEGRATION

Collaboration across the supply chain involving communication among stakeholders. Exemplified in the **BASF ChemCycling™ case study**.

### EDUCATE CONSUMERS

CircularChem engaged over 3,000 citizens via surveys, focus groups, school visits & science festivals.

### TECHNOLOGY DEVELOPMENT

The **LanzaTech-India Glycols-Unilever case study** highlights tangible progress in technology-driven CE solutions.

### IMPLEMENTATION

CircularChem enabled sustainability improvements by collaborating with SMEs, such as **Banner**, to co-create tailored roadmaps and metrics.

## ACCELERATING CIRCULAR ECONOMY IMPLEMENTATION ACROSS SECTORS AND VALUE CHAINS

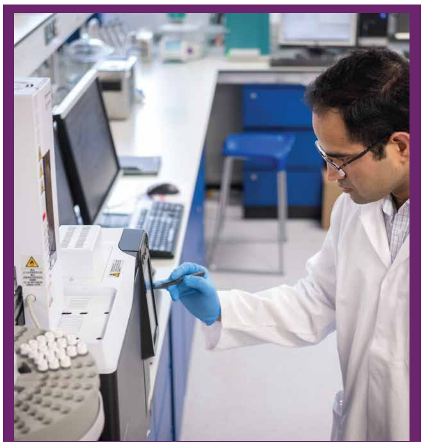
Innovate UK, along with the UKRI National Interdisciplinary Circular Economy Research (NICER) programme ran two rounds of Feasibility Studies. This funding enabled SMEs to engage with and benefit from access to expertise at the five NICER research centres via collaborative research and development (CR&D) activities. CircularChem was delighted to collaborate with the following six successful projects:

CASE STUDY 1:

## HOW CAN WE PRODUCE GREEN PLATFORM CHEMICALS FROM $CO_2$?

**$CO_2$ emissions from hard to abate industries such as glass, steel and cement manufacture offer the opportunity of $CO_2$ capture at point of emission, due to the high concentration of carbon.**

This offers an opportunity for the development of sustainable and circular pathways for chemical manufacture. $CO_2$ electrolysers that can use renewable electricity to convert the waste gas stream to useful products such as ethylene or CO offer a promising solution.



### IN THE LAB

We have developed new electrolysers that achieve high $CO_2$ utilisation efficiencies. Our bipolar membrane (BPM) electrolyser prevents $CO_2$ loss and the need for $O_2$ removal. In this way we have achieved > 50% single pass conversion efficiencies for CO production.

In 2022 we reported a breakthrough class of Ni catalysts in these devices. We have since developed new electrodes which have improved the selectivity towards the desired syngas products and device stability. The work has received significant academic attention, including being highlighted by Nature Catalysis.

### REAL WORLD ANALYSIS

Our **life cycle assessment** confirmed that net emissions per tonne of green ethylene produced could be as low as −3.3 $tCO_2$-eq, evidencing a negative carbon balance from cradle-to-gate.

Our **techno-economic analysis** predicted that green ethylene production could be three times more expensive than its current market price, providing a clear incentive for intensifying R&D efforts on catalyst and process innovation.

Our **social risk screening** also identifies important social impact and supply chain risks (such as renewable energy) for green ethylene production that need to be considered for future planning.


### IMPACT & INFLUENCE

**R3V Tech Ltd:** A spin off company from the Centre, using electrochemical approach to create new circular chemicals value chains, has secured more than £500k grants and loans to support its efforts to demonstrate the circular technology at scale.

**New IP developed** around electrode structures and electrolyser designs for $CO_2$ conversion to syngas has been filed and led to early stage projects to explore commercialisation and follow-on funding for scale up.

**www.r3vtech.com**

CASE STUDY 2:
**THE ROLE OF CHEMICAL RECYCLING WITHIN A CIRCULAR CHEMICAL ECONOMY**

## CircularChem has made important technical advances to improve the efficiency of chemical recycling technologies and evaluated the environmental and economic potential of selected chemical synthesis routes. Through extensive industry consultation we have influenced UK recycling policy, to improve business drivers for investing in chemical recycling technologies.

**Advanced catalysis:**
New fundamental understanding of the selective hydrogenolyis of plastic wastes into liquid hydrocarbons will drive the development of cheaper and more active catalysts [7,8].

**Thermoconversion of municipal waste:**
Demonstrated the potential of hydrothermal processing to selectively fractionate waste processing residues into value-adding products[9].

**Magnetically recoverable catalysts:**
Developed low-cost, recyclable catalysts for bio-oil production from distillery wastes, improving process efficiency and scalability[10].

### SCALE UP POTENTIAL AND SYSTEM DRIVERS

In-depth enviro-economic analysis demonstrated that the negative environmental impacts from three selected chemical recycling routes could significantly outweigh their slight increase in processing costs compared to landfill or energy-from-waste. Findings are key to inform targeted policies for costing environmental impacts and increase investor confidence.

### ADVANCING POLICY

Extensive engagement with industry experts and other system stakeholders through focus groups and case studies revealed the need for:

- **Reclassification of chemical recycling as energy from waste**
- **Acceptability of mass balance for allocating recycled content**
- **Need for increased transparency and better reporting mechanisms**
- **Findings were summarised in a joint publication with WRAP at the start of 2022[11]**

Following a consultation in 2023, legislation has been updated to establish the mass balancing approach to exempt chemically recycled plastics from the UK plastic packaging tax.

This significantly increases the financial incentive for investing in these technologies[12].

7. Tomer *et al*, Appl. Cat. A, Gen., (2023), **666**, 119431.
8. Inns *et al,* J. Mater. Chem. A., (2025), **13**, 2032-2046.
9. Okoligwe, O *et al*, *Waste Management*, (2022), **140**, 133
10. Mukundan, S *et al,* Bioresource Tech, (2023), **369**, 128479
11. https://www.wrap.ngo/sites/default/files/2022-08/Non-Technical%20Challenges%20to%20Non-Mechanical%20Recycling.pdf
12. https://www.gov.uk/government/consultations/plastic-packaging-tax-chemical-recycling-and-adoption-of-a-mass-balance-approach/plastic-packaging-tax-chemical-recycling-and-adoption-of-a-mass-balance-approach

Our vibrant engagement programme was designed to guide the research, receive feedback and transfer discoveries from the lab to commercial applications. Partners in CircularChem have been key to ensuring research is embedded with stakeholders, involving businesses, policymakers, consumers and society, the third sector and other affected groups and communities at every part of the programme.

***“Owing to the diverse nature of the chemical sector, it struggles to communicate to external stakeholders where are the opportunities for the future. CircularChem has provided a means to collate the views of top academics working in different technology areas but also to ensure those views are informed by the industry.”***

Dr Peter Clark,
Head of Chemistry & Industrial Biotechnology, Innovate UK

**Industry & SME engagement**
Three industry/SME focused workshops have led to follow-on funding and policy publications. Approximately 20 interviews conducted with academic and industrial experts, to explore business models and finance, were complemented by the development of over 10 case studies.

**Wider engagement & networking**
Circularchem ran external workshops and roundtables targeting specific industrial engagement events. We hosted over 28 webinars and two summer schools alongside the other NICER programmes. In 2024, we hosted a three-day international symposia ***‘A circular economy for the chemical sector’*** with Cell Press in Cardiff.

***“We especially value the fact that the Centre has brought together key stakeholders from academia, industry, government and NGOs to understand how we, together, can transform the UK’s chemical industry.”***

Professor Jeremy Shears, Chief Scientist, Shell Research Ltd

## SUPPORTING CAREERS









***"At CircularChem, we know that the research environment and culture we created today will shape the leaders of the circular economy tomorrow.***

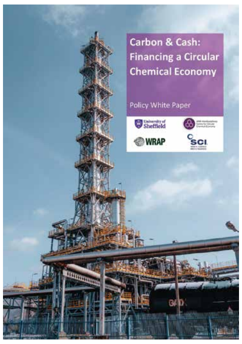
***That’s why we’ve built a supportive, collaborative space where early career researchers can thrive - gaining the skills, experience, and networks needed to drive real change.***

***It is incredibly rewarding to witness the achievements and career progression of our ECRs as they contribute to a more sustainable future."***

Professor Jin Xuan

## INFORMING POLICY

Our members have contributed to government calls for evidence in England, Scotland, Wales & Northern Ireland. By raising awareness of the challenges and opportunities for circular economy principles to be applied in the chemicals sector, the language of government is changing from carbon capture and storage to carbon capture and re-use. We welcome the opportunity to continue working with the government's circular economy taskforce, supporting the creation of a circular economy strategy.



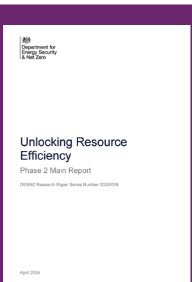

In October 2024 we published a Policy White Paper, "**Carbon & Cash: Financing a Circular Chemical Economy**"[13] (ISBN: 9 780957 258891) and accompanying **Executive Summary**[14] that provided recommendations on how more sustainable chemicals manufacture could be accelerated in the United Kingdom. The report was the synthesis of opinion and evidence gathered through two interdisciplinary online workshops and a final face to face event at the SCI in London. The report highlights the possibilities for action but also recognises the financial investment and incentives needed if this is to be implemented over a reasonable timescale going forwards.

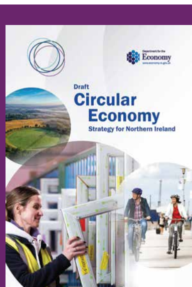
***"I would call out the work that CircularChem has completed on policy development for a circular chemical economy. The extent of effort on this topic and the quality of engagement with influential stakeholders has been excellent and such advocacy is hugely appreciated by Johnson Matthey".***

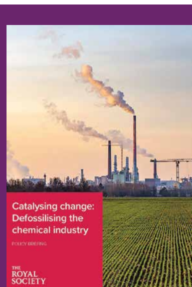
Raymond Hadden, Business Development Manager, Catalyst Technologies, Johnson Matthey

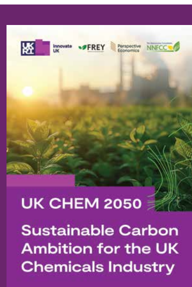
## KEY POLICY RECOMMENDATIONS

- **Recognise that the chemical industry is at the heart of the net zero transition**
- **Focus on de-fossilisation rather than decarbonisation of chemical feedstocks**
- **Strengthen the investment case for industry to implement circular chemical solutions**










Our experts at CircularChem have also been invited to contribute to a number of high-profile reports (above).

13. https://www.circular-chemical.org/wp-content/uploads/2024/11/Financing-a-Circular-Chemical-Economy-Policy-White-Paper-November-2024.pdf
14. https://www.circular-chemical.org/wp-content/uploads/2025/03/Circular-Economy-of-Olefins-Roadmap-Executive-Summary.pdf

ROADMAP FOR THE UK'S CIRCULAR ECONOMY OF CHEMICALS

# Achieving net zero in the UK chemical industry will require a balanced approach, leveraging immediate emissions reduction potential while planning for long-term integration of sustainable practices across the sector.

### GLOSSARY OF ACRONYMS & KEY

**pEPR** = Extended Producer Responsibility
**DRS** = Deposit return scheme
**MS** = Municipal solid waste
**MTO** = Methanol to olefins
**DAC** = Direct air capture
**CCU** = Carbon capture and utilisation
**CCUS** = Carbon capture, utilisation and storage

- **Carbon**
- **Biomass**
- **Plastic**
- **Municipal Solid Waste**
- **Fossil**

## EXISTING POLICY DRIVERS

Timeline showing existing policy drivers and milestones for reduction of waste and $CO_2$ emissions.

- **2025** – Waste packaging fees; Digital waste tracking; pEPR; DRS
- **2026** – "Simpler Recycling" plan; EU Carbon Border Adjustment Mechanism (CBAM)
- **2027** – Kerbside film Collection
- **2028** – Zero biodegradable municipal waste to landfill
- **2030** – 4 x Carbon capture, utilisation and storage (CCUS) clusters
  ↓63% GHG Wales; ↓55% GHG EU
  5 GW $H_2$ capacity
  Power 50g $CO_2$e/kWh
  ≥70% Recycling for packaging UK/EU
- **2035** – 6th Carbon Budget
  50 $MtCO_2$/year captured
  78% reduction in GHG - UK
  345 TWh renewable electricity
  MSW: >65% recycled, >10% landfill
- **2040** – World's 1st Net Zero cluster
  440 TWh renewable electricity
- **2042** – Zero plastic waste
- **2045** – Scotland NET ZERO
  562 TWh renewable electricity
- **2050** – NET ZERO
  712 TWh renewable electricity
  Zero avoidable waste

## TECHNOLOGY DEVELOPMENT MILESTONES

Technology development milestones for advanced recycling and carbon capture and utilisation to support reduction of waste and de-fossilisation of the ethylene supply chain.

- Pilot Scale e-methanol (e-MeOH)
- Commercial Scale Mechanical Recycling

- Pilot Scale Gasification, MS, & MTO
- Pilot Scale DAC
- Commercial Scale Thermochemical
- Pilot Scale Advanced Fermentation & DHE

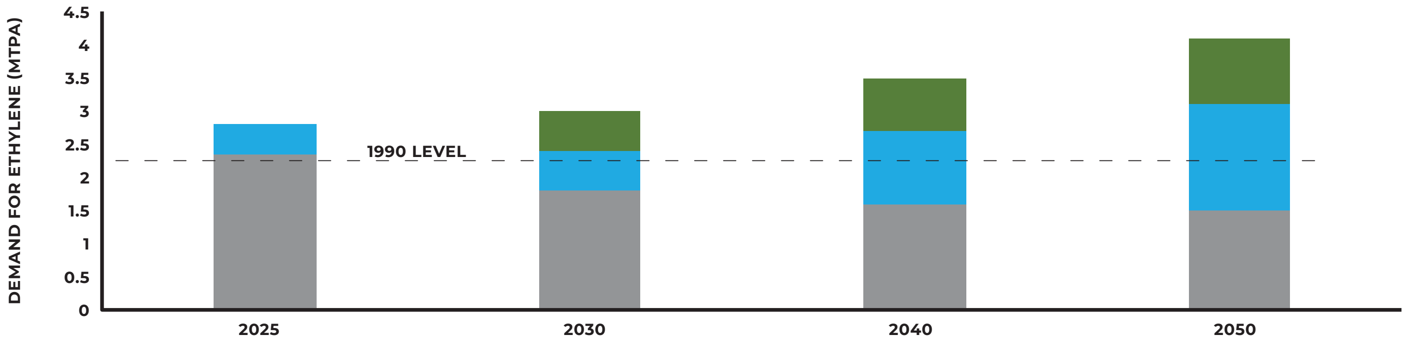
- Pilot Scale Thermochemical
- Pilot Scale Solvent-based

- Commercial Scale Gasification, MS, & MTO
- Commercial scale DAC & CCU
- Pilot Scale Enzymatic
- Pilot scale Advanced Fermentation & DHE

- Commercial scale $CO_2$ to olefins
- Commercial Scale Solvent & Enzymatic

## THE DEMAND FOR ETHYLENE

Increasing demand for ethylene can be met with recycled carbon, initially from biomass and "visible polymers" (plastic waste) diverted from landfill and incineration.




*Plastic waste is projected to grow from 5.59 Mt in 2022 to 6.24 Mt by 2035 (BPF desired scenario), potentially exceeding 7 Mt by 2050. Increasing reuse and collection, and recirculating carbon from visible polymers will reduce fossil demand and associated scope 1 emissions.*

*30% of available residual biomass (non-energy crops) will go to chemicals from 2030, increasing to 50% by 2050 at a CAGR of 2.5%.*

*Not all polymers can be recovered, and some scope 3 product emissions will still need to be mitigated. Deeper reduction of fossil ethylene demand requires incentives for CCU including cheaper, fully renewable power and H2 and/or CO2 credits or a disruptive technology.*

*Electrification of steam cracking could reduce process emissions by 90%. This will require a reliable supply of renewable electricity and green hydrogen.*

CircularChem Roadmap Executive Summary Report:
https://www.circular-chemical.org/wp-content/uploads/2025/03/Circular-Economy-of-Olefins-Roadmap-Executive-Summary.pdf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**The CircularChem team would like to thank everyone who has engaged with the programme over the last four years and helped contribute to the successes and advancements of a circular chemical economy.**

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