Industrial Decarbonisation Frontiers Report

Circular Economy

Since its launch in 2021, the Industrial Decarbonisation Research and Innovation Centre (IDRIC) has funded 100 projects, investigating and addressing the key dimensions of the whole system of industrial decarbonisation. This work has generated a vast body of knowledge, offering critical insights into the challenges we face in decarbonising and into the solutions – technical, economic and social – that are emerging. The *Frontiers Reports* series brings together all these insights to share with our industry and policy stakeholders.

Each report synthesises key findings from multiple projects conducted on a closely related theme, providing a comprehensive perspective on a specific aspect of industrial decarbonisation. Far more than simply research summaries, these reports translate academic insights into practical, evidence-based recommendations for our stakeholders. These recommendations are shaped by the expertise and evidence gathered by our research teams and are designed to support decision-makers in advancing their net-zero goals.

The *Frontiers Reports* are anticipated to serve as catalysts for meaningful discussions between academia, industry, and policymakers on the most viable paths forward. We welcome constructive debate and are eager to support the implementation of recommendations that best align with our stakeholders' priorities and goals towards net zero.

This report brings together all IDRIC's research on Circular Economy.

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Executive summary

The circular economy offers a transformative pathway for UK industry – turning emissions and waste into financial opportunity, whilst accelerating net zero ambitions. This report synthesises IDRIC's research on the circular economy and its critical role in accelerating industrial decarbonisation. The circular economy strategies explored in the report – focused particularly on resource efficiency, waste valorisation and carbon capture and use (CCU) – offer opportunities to reduce reliance on fossil inputs, minimise waste, and create new value chains across industries.

Key findings

Redefining waste as a resource
Research highlights the huge potential for waste materials, CO_2 emissions, and other by-products from industrial processes to be repurposed into valuable fuels, chemicals, and materials. Industrial clusters are uniquely positioned to support circular systems by co-locating processes, enabling industrial symbiosis, and sharing infrastructure.

Technological innovation and systems integration
Projects explored a wide variety of scalable technologies such as microbial fermentation, electrolysis, and catalytic conversions to produce chemicals and energy carriers from waste streams. Many innovations are nearing pilot scale, but deployment requires further testing under real-world industrial conditions.

Barriers to adoption
Uncertainty in definitions of circularity itself, fragmented supply chains, limited financial incentives, and insufficient demonstration projects are slowing progress to adopting circular systems. Small & medium enterprises (SMEs), despite their key role in supply chains, often face resource and policy challenges in adopting circular practices.

Life cycle assessment (LCA)
Accurate and transparent carbon modelling, accounting LCA frameworks are essential to evaluate the true impact of circular systems.

Recommendations to industry

Maximise resource efficiency through systems integration
Identify opportunities to use industrial by-products and waste streams – such as waste heat, CO_2 and co-produced chemicals – as inputs for other processes, creating value chains within industrial clusters.

Invest in pilot-scale demonstrators
Support long-term projects that validate circular technologies such as algae systems, e-fuels and e-chemicals, biorefineries, and low-carbon cement under operational conditions.

Plan for longevity and scalability
Invest in circular projects with long-term value potential, recognising that scalable impact may require extended timeframes beyond typical commercial payback periods.

Foster collaboration across sectors
Build partnerships between large industries, SMEs and agriculture to unlock new value chains between sectors and accelerate the adoption of circular practices.

Support improvement of LCA frameworks
Advocate for the development of robust carbon accounting and LCA frameworks to evaluate circular systems, ensuring cost-effectiveness, reduced emissions, and maximised environmental benefits.

Recommendations to policymakers

Strengthen regulatory and policy support
Redefine waste as a resource and update regulations to enable the use of byproducts and unconventional feedstocks, removing current barriers to the development of circular supply chains.

Enhance carbon accounting and pricing frameworks
Align carbon pricing frameworks and develop transparent and standardised carbon accounting systems tailored for circular processes to ensure circular outputs are competitive with conventional products.

Support SMEs and supply chain development
Create de-risking mechanisms and targeting funding streams to enable SMEs to participate in circular supply chains. Consider establishing regional hubs for SMEs to access shared resources and collaboration opportunities.

Enable long-term investment and industrial transformation
Extend funding cycles to 7–10 years to match the timescales needed for infrastructure and technology development, and align industrial and research timelines to support systemic change.

Enhance financial incentives and infrastructure development
Create financial mechanisms that encourage industry to integrate circular economy practices at scale and invest in the infrastructure needed to connect emitters with users of industrial by-products.

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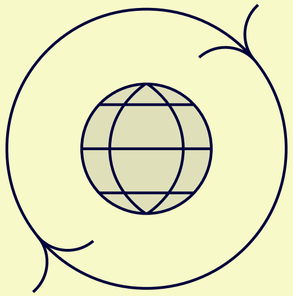
Introduction

Resources are finite and the release of greenhouse gasses (GHG) into the atmosphere is driving catastrophic climate change. We need new ways of doing business, creating materials, dealing with waste, and creating meaningful employment and resilient societies. Traditional linear models of “take-make-dispose” cannot continue as they exacerbate emissions by relying on energy-intensive resource extraction, production, and waste generation. As we defossilise and decarbonise, it is essential to develop alternative approaches for material and fuel production.



Transitioning to a circular economy is vital for reducing industrial emissions, as it focuses on resource efficiency, reuse, and closed-loop systems that minimise waste, energy consumption and environmental impact. There is ambiguity in defining ‘circular economy’, which in itself leads to challenges with its successful adoption. The European Parliament describes the circular economy as a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products for as long as possible. Other definitions, such as the one used by the Ellen MacArthur Foundation, bring in tackling biodiversity loss and restoring nature more explicitly. IDRIC’s focus is on decarbonisation, therefore the focus of circularity in this report is on carbon and associated greenhouse gases. This means, within this report, the definition of a circular economy is principally focused on the use and re-use of carbon.

Addressing the root causes of carbon emissions in industry is critical to success. A circular approach reduces the demand for virgin raw materials, which often requires energy-intensive extraction and processing. The UK currently has a “Circularity Metric” of just 7.5%, leaving a significant “Circularity Gap” of 92.5%. This means over 90% of the UK’s material use comes from virgin sources, and within that 80% of these materials are extracted abroad.1 This highlights that we are not using our valuable resources efficiently or sustainably.

The industrial clusters are critical areas for testing and rolling out circular systems. Their locality can facilitate local waste valorisation – i.e. the process of taking materials that would otherwise be discarded and converting them into something valuable, like materials, chemicals, fuels, or energy. There are opportunities to build on local communication and infrastructure networks, and link business together to create innovative industrial symbiosis opportunities. Industrial clusters can showcase the circular economy through sharing by-products, waste heat, or materials to create value chains that mimic natural ecosystems. For example, the waste gases from one plant can serve as raw materials for another, or alkali mineral wastes from the foundation industries and/or demolition waste from the construction industry, can be used as raw materials for carbon capture and utilisation (CCU) via mineral carbonation. Such symbiotic relationships enhance resource efficiency and significantly cut emissions. CCU in these types of systems can lead to short term carbon storage in materials and products.

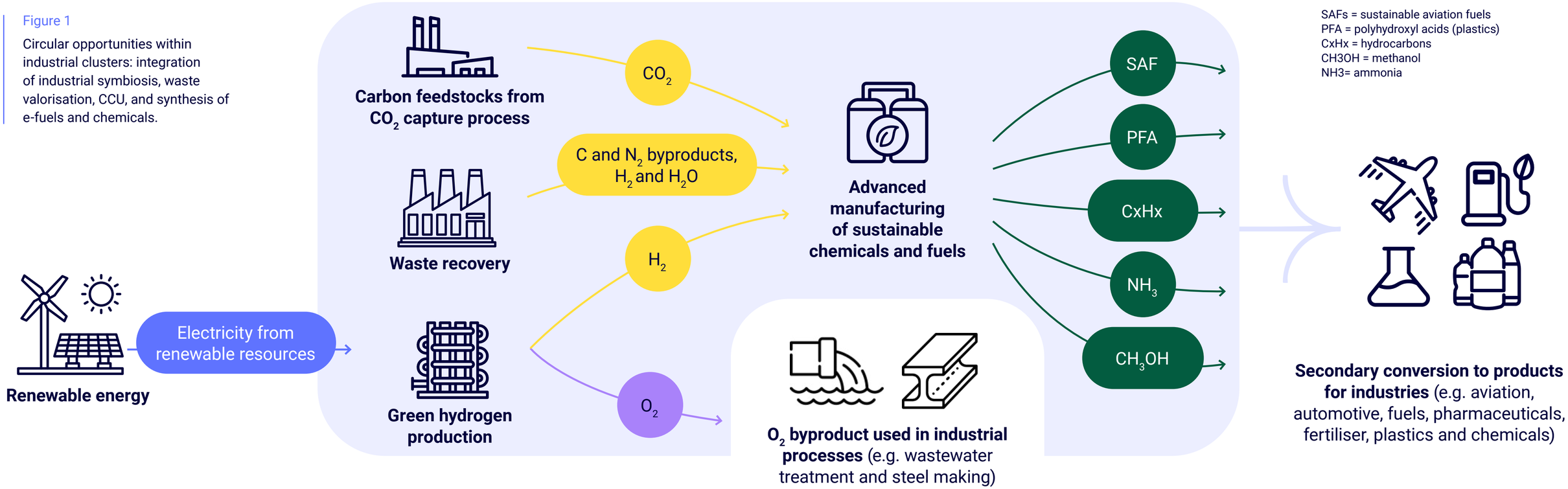
IDRIC’s work has had a strong focus on the creation of value from emissions – reducing waste output, and material input. However, to maximise impact, we need to understand and create better mechanisms to achieve this. IDRIC’s focus on the circular economy will reduce (and long term remove) our dependency on fossil fuels by creating new systems and materials. Many circular practices, such as recycling and localising supply chains, use less energy than traditional practices, enabling industries to transition more effectively to low-carbon energy sources. However, identifying which systems are most effective and optimising them for real value creation remains a key challenge.

In the context of global climate goals, the circular economy also aligns with carbon neutrality targets by promoting carbon capture and (re)use (CCU) – a key topic for IDRIC’s research. Waste carbon – often treated as a pollutant – can become a valuable input in circular systems, such as being converted into building materials or alternative fuels (Figure 1).

Transitioning to a circular economy is vital for reducing industrial emissions, as it focuses on resource efficiency, reuse, and closed-loop systems that minimise waste, energy consumption and environmental impact.

Figure 1

Circular opportunities within industrial clusters: integration of industrial symbiosis, waste valorisation, CCU, and synthesis of e-fuels and chemicals.



SAFs = sustainable aviation fuels
PFA = polyhydroxyl acids (plastics)
CxHx = hydrocarbons
CH3OH = methanol
NH3= ammonia

Much of IDRIC's work on circularity has focused on the synthesis of electro-fuels and electro-chemicals, also known as e-fuels and e-chemicals. These are produced using hydrogen generated through electrolysis (green hydrogen), where the electricity used comes from renewable sources. Utilising co-electrolysers, this hydrogen can react with sustainable sources of carbon and nitrogen to produce a wide range of e-chemicals and e-fuels, such as sustainable aviation fuels (SAFs), methanol or ammonia. If required, these substances can be further converted into more complex chemical products.

When CO_2 and other carbon and nitrogen containing by-products are captured from industrial processes – rather than going to waste or being released into the atmosphere – they can instead be used in the production of e-chem and e-fuels, and the process can be made circular (Figure 1).

There is growing momentum behind the shift to a more circular economy, including a nascent UK government strategy,[2] as well as specific research and industrial consultancy from actors such as the Ellen MacArthur Foundation and Deloitte (via Circle Economy[1]) who highlight both the potential economic and environmental benefits.

Nevertheless, in order to adopt a circular approach, industry needs to be supported in several critical areas:

- The development and scale up of technologies that enable industry to deploy novel circular systems.
- Integrating supply chains and creating infrastructure to connect industry and circular systems.
- Clear policy, technical guidance, and definitions of what circularity means* (for example, over what timescale would or should a system be circular?).
- Consistent measurement methods and success criteria.

Although most agree that a circular economy feels appropriate and beneficial, there is ambiguity in defining the term "circular economy" itself. This is a critical barrier to success as the term can mean different things in different industries, causing confusion across a complex web of interconnected supply chains.

Research findings

24 of IDRIC's projects have contributed to the advancement of circularity, with a strong emphasis on "waste" material use and re-use to create new materials (waste valorisation). Many of these projects focused on technological innovation, carbon capture and utilisation (CCU), and creating novel systems – all leading to material and resource efficiencies and decarbonisation of emissions-intensive and hard-to-abate sectors.

24 IDRIC projects contributed to this report. They are referred to by their project IDs throughout.
→ See further information.

Project ID	Project name
MIP 1.3	Life cycle analysis framework for industrial decarbonisation
MIP 5.2	The VFA factory for decarbonisation
MIP 5.3	Solid oxide electrolysis for CO_2 utilisation
MIP 5.4	Integration of sustainable production of chemical energy vectors in industrial clusters
MIP 5.6	VFA to PHA: decarbonisation as a route to sustainable plastics
MIP 5.7	Accelerating the scale-up of next-generation fuels from CO_2
MIP 6.2	Thermodynamic models for application in industrial decarbonisation
MIP 6.7	Algae-based carbon capture and utilisation for UK cluster decarbonisation
MIP 7.2	Electrolysis for green hydrogen and co-produced chemicals at scale
MIP 7.3	Utilisation of co-produced oxygen from electrolysis to enable deep decarbonisation
MIP 8.1	To transform bio CCU from low volume conversion to speciality products into a Mtonne process
MIP 8.3	BECCS-to-sustainable aviation fuels (SAF)
MIP 8.5	Bio-balance
MIP 8.7	Up-scaling on-site CO_2 utilisation for decarbonisation of dispersed cement sector: A novel route to reliable net-zero concretes
MIP 8.8	Creating a carbon framework for a decarbonised circular economy
FF 1-8	Novel chemical strategies for the conversion of industrial derived CO_2 to value chemicals
FF 1-9	Towards a sustainable phase change material (TASPCM)
FF 2-2	Determining optimum pyrolysis conditions for biochar to be used as metallurgical coal replacement – In support of deep decarbonisation of large UK industrial emitters based within the Humber cluster
FF 2-3	CapCon — Conversion of captured carbon dioxide
FF 2-4	On site trail of OXYHYWATER — A novel net zero wastewater treatment process
FF 2-7	Valorising incineration bottom ash into cement rich in ternesite (VIBACT)
FF 3-2	Utilisation of industrial waste ammonia form steelmaking in solid oxide electrolysis cell technology for efficient and clean hydrogen production
FF 4-1	Assessing the feasibility of implementing CO_2 capture and utilisation in Quorn mycoprotein process
IA 4.2 (FF 2-1)	Accelerating the scale-up mechanism of e-chemicals

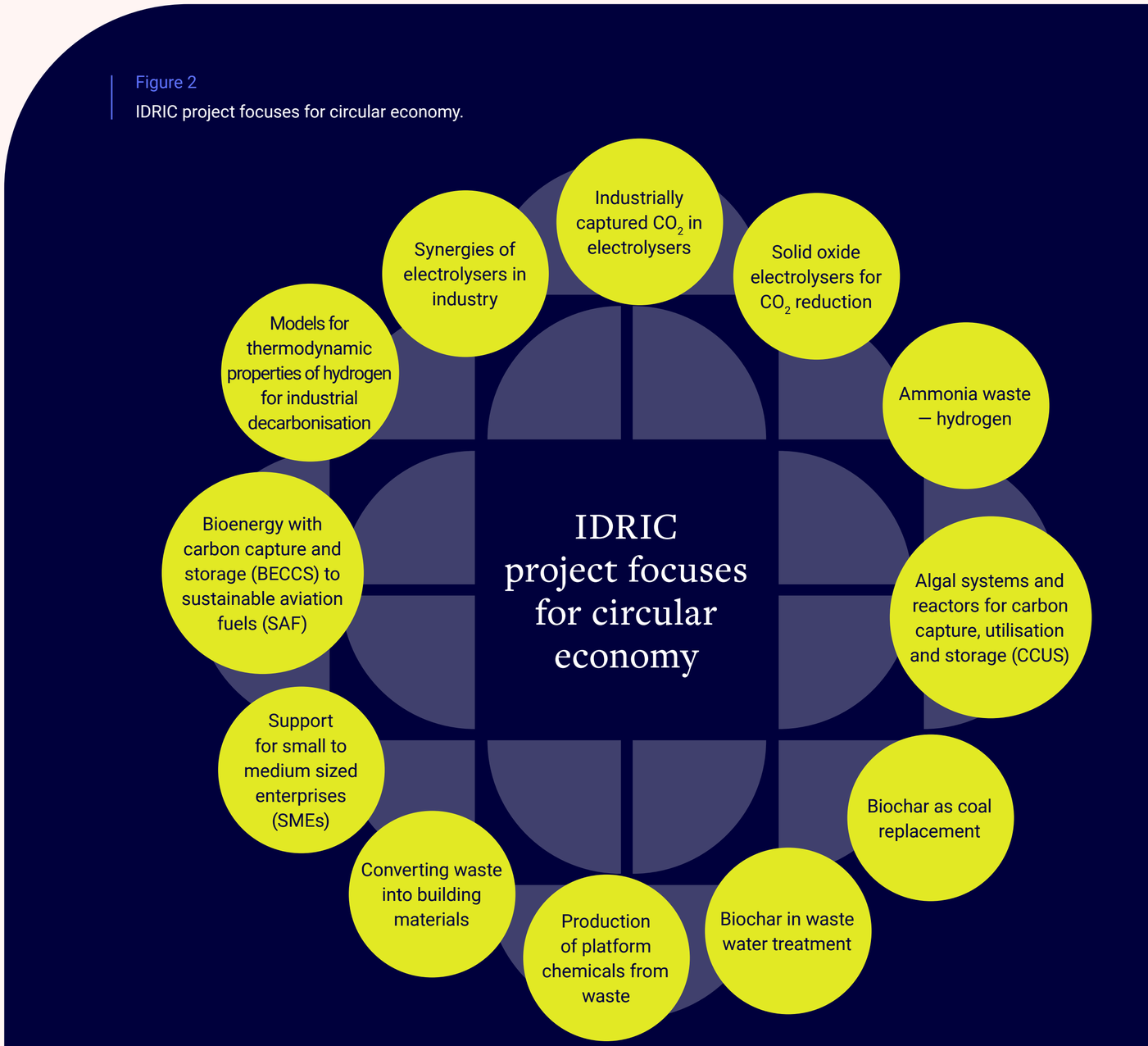
Whilst the research topics were highly diverse, there were several key themes, particularly in the use and valorisation of waste materials for CCU and platform chemical production, the use of algae in CCU, and the use of bioenergy with carbon capture and storage (BECCS) for CCU. Additionally, several of the projects focused on electrolyser research to develop novel and more efficient routes to the synthesis of e-fuels and e-chemicals, integrating the use of green hydrogen.

Although some projects were very focused on specific technical requirements within parts of a circular system, there was a reoccurring theme: in order to create a circular economy, we need to focus on “real system” research with the associated impurities and challenges (for example, using CO_2 with associated impurities rather than pure CO_2). Additionally, there is a requirement for industry and business to communicate and understand the mutual benefits that working together in a circular system can bring.

The key findings were focused in five key areas which are explored in detail in this section of the report.

Figure 2

IDRIC project focuses for circular economy.



Innovative technologies to enable resource efficiency

Focused research identified and developed innovative technologies that are required to create and capture the resources needed for a circular economy. Projects showcased advances in microbial fermentation, electrolysis, and catalytic conversions to produce chemicals and energy carriers from waste streams.

For example, research into low- and high-temperature electrolysis and solid oxide electrolyser cells (SOEC) demonstrated the potential for co-producing chemicals and hydrogen, whilst optimising energy use. Being able to use these techniques in a wide variety of industrial situations is critical to their success – enabling efficient production of, for example, valuable oxidants such as hydrogen peroxide (project MIP 7.2). Robustness of high temperature electrolysers, which can enhance efficiency through waste heat utilisation is similarly critical for the valorisation of materials for a circular economy (project MIP 7.2).

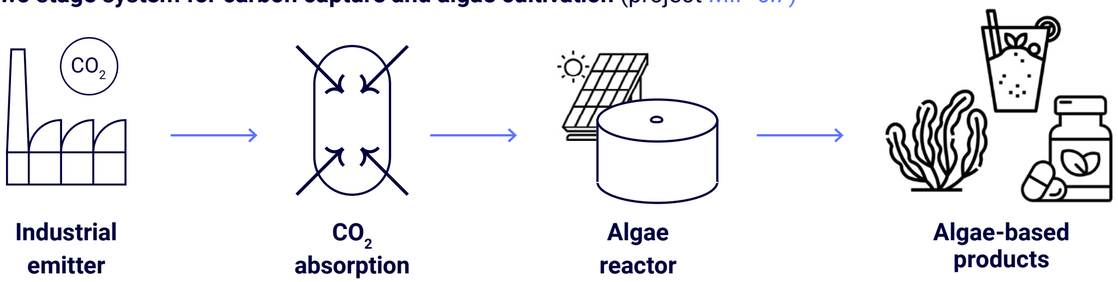
Research into mechanisms to convert industrial and municipal wastes into high-value chemicals through, for example, microbial processes underscored the need for pilot studies to enhance our understanding of what is required for the scale-up of researched processes.

The integration of novel reactor designs, such as continuous flow electrolysers and submerged LED photobioreactors to produce chemicals and fuels, improves scalability and efficiency that is critical to a successful circular economy. Fundamental research in SOECs for CO_2 reduction showed methods for improving catalytic activity – but further work is required to create better durability at scale and under differing conditions (project MIP 5.3).

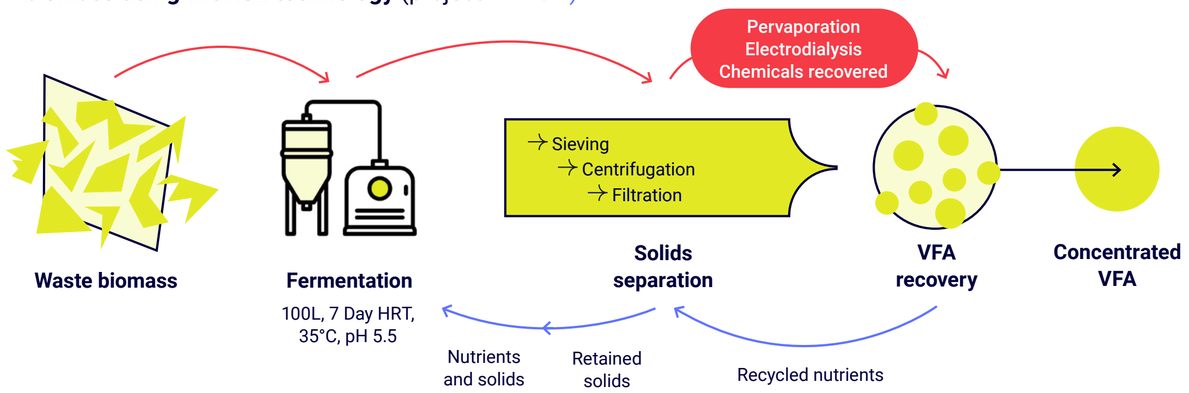
Moving towards a circular economy will take many actors. Our research shows that the building blocks are critical to everyone's success and that fundamental science and engineering still requires work and adaptation to real life situations.

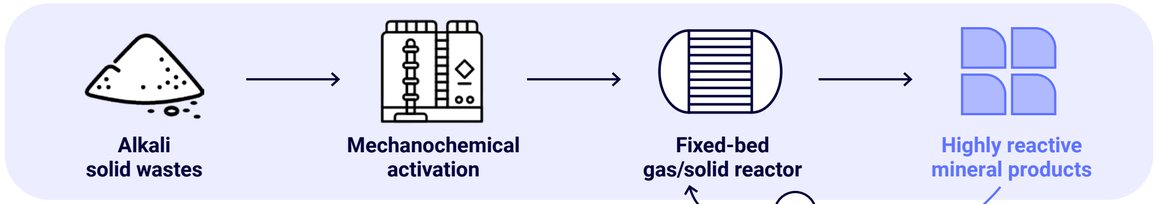
Figure 3
Examples of IDRIC's novel waste valorisation and carbon utilisation processes.

Two stage system for carbon capture and algae cultivation (project MIP 6.7)



Production of volatile fatty acids (VFAs) from waste biomass using BIOACE technology (project MIP 5.2)





Novel route to integrate mineral carbonation with cement production at industrial scale (project MIP 8.7)

Waste valorisation and carbon utilisation strategies

The conversion of industrial waste streams (e.g. biosolids, CO_2, and other emissions) into valuable chemicals or fuels demonstrates a circular approach to emissions management. IDRIC's research has driven innovation in this space, including the development of pilot scale studies; however, further scale-up is still required to test and deliver for industry.

Several of IDRIC's projects are close to scale-up phase, particularly in the area of carbon capture and utilisation (CCU) systems across sectors, including: algae-based carbon capture (project MIP 6.7 and MIP 8.1); cement-based CO_2 utilisation (project MIP 8.7); the production of volatile fatty acids (VFAs) from waste (projects MIP 5.2 and MIP 5.6); bioenergy with carbon capture to produce sustainable aviation fuels (project MIP 8.3); steel production using biochar as a coal substitute (project FF 2-2); methanol synthesis from CO_2 for maritime fuels (project MIP 5.7); and oxygen-enhanced waste water treatment to recover carbon-containing materials (project FF 2-4). Innovations such as Mn-doped perovskites for CO_2 electrolysis (project MIP 5.3) or ternesite-rich clinkers for low-carbon cement (project MIP 8.7) illustrate efforts to redesign materials to improve performance and enable circularity. Valorisation of "waste" materials has been a particular strength for IDRIC, with focus on wastewater, large industrial GHG emissions, and the repurposing of ammonia waste for hydrogen production (project FF 3-2). Projects have also focused on integrating renewable resources and circular strategies to decarbonise emissions-intensive (and hard-to-abate) industries, for example using CO_2 and heat from steel production (or any other industry use to produce high value platform chemicals (project MIP 5.2 and MIP 5.6). IDRIC's work on carbon utilisation extends to agriculture through greenhouse emissions capture, crop production, and integrating circular practices in food production (e.g. project MIP 8.5), reducing costs and environmental burdens. This shows the whole system approaches required to link industrial clusters with wider societal needs within a truly circular economy.

The use of waste materials and CO_2 as alternative raw materials in the cement sector demonstrates a cost-effective and scalable circular solution to pursue net zero targets. Project MIP 8.7 evaluated of CO_2 utilisation in alkali solid waste materials, achieved production of nearly net zero cement products, and demonstrated a scalable processes for industrial adoption. Addressing challenges such as energy-intensive pre-treatment processes is critical for refining the technology and maximising its contribution to a sustainable, net zero future.

IDRIC's work highlights scalable opportunities for developing the methods and circular systems required in the short, medium and longer term to deal with waste, enabling the creation of valuable materials ready for a fossil fuel and petrochemical free future.

Scaling and integration in industrial clusters

By the nature of its funding, IDRIC research has focused on the lower end of the Technology Readiness Level (TRL) scale. Pilot plants are therefore critical to help develop these technologies for practical deployment. What works well in a laboratory setting might not work so well in a scaled system, without further investigation.

For example, our research has shown that when, using industrially captured CO_2, rather than pure CO_2, we see highly significant reductions in electrolyser life spans (from 5000 hours to 4-5 hours) (project FF 2-3). It is therefore critical to understand how to address and overcome these issues in order to ensure successful scale up. Similarly, hydrogen purity is important factor in understanding its thermodynamic properties, which are particularly poorly understood when hydrogen is mixed with other molecules (e.g. alcohols). Current models lack validation due to limited experimental data and this needs to be addressed at scale in order to understand how we can utilise and create a hydrogen economy (project MIP 6.2).

Modelling techniques, such as Computational Fluid Dynamic (CFD) models can play a vital role in optimising industrial-scale processes and in IDRIC we have developed and used techniques to help us recreate industrial conditions (project MIP 5.7). Further research must prioritise modelling industrial conditions to ensure we have the right systems in the right place and that we can calculate and measure the correct costs and environmental impacts of proposed systems.

Creating circular systems

We have seen that industrial clusters play a central role in circular economy initiatives, enabling shared infrastructure and resource flows (e.g. heat, hydrogen, oxygen, CO_2). Furthermore, cross-sector collaboration and integration of co-produced resources, such as using oxygen from electrolytically produced hydrogen in wastewater treatment or steelmaking (project MIP 7.3), improve efficiency and cost-effectiveness (Figure 4).

While much of IDRIC's research focused on specific technological innovations, some projects addressed integration within the whole system. For example, the integration of agriculture and steel production to create circular systems, through the use of waste heat for glass house growing (projects MIP 1.3 and MIP 8.5) and the use of biochar as coal replacements and in within agriculture as a soil improver (project FF 2-2). As well as the technical challenges here, critical to success is the buy in from all stakeholders.

Much focus is traditionally on the large industrial sector, but Small & Medium Enterprises (SMEs) play a significant part in all systems and contribute substantially to GHG emissions, as well as providing opportunities to help with their reduction. However, SMEs often struggle to access resources for sustainable models (project FF 1-9). This is particularly problematic as they underpin many large businesses through supply chains, as well as being direct emitters themselves. Mechanisms for incentivising collaboration between upstream and downstream stakeholders remains limited (project FF 1-9) and when businesses do collaborate, methods for crediting where carbon savings are made are highly complex in terms of carbon accounting (project MIP 8.8).

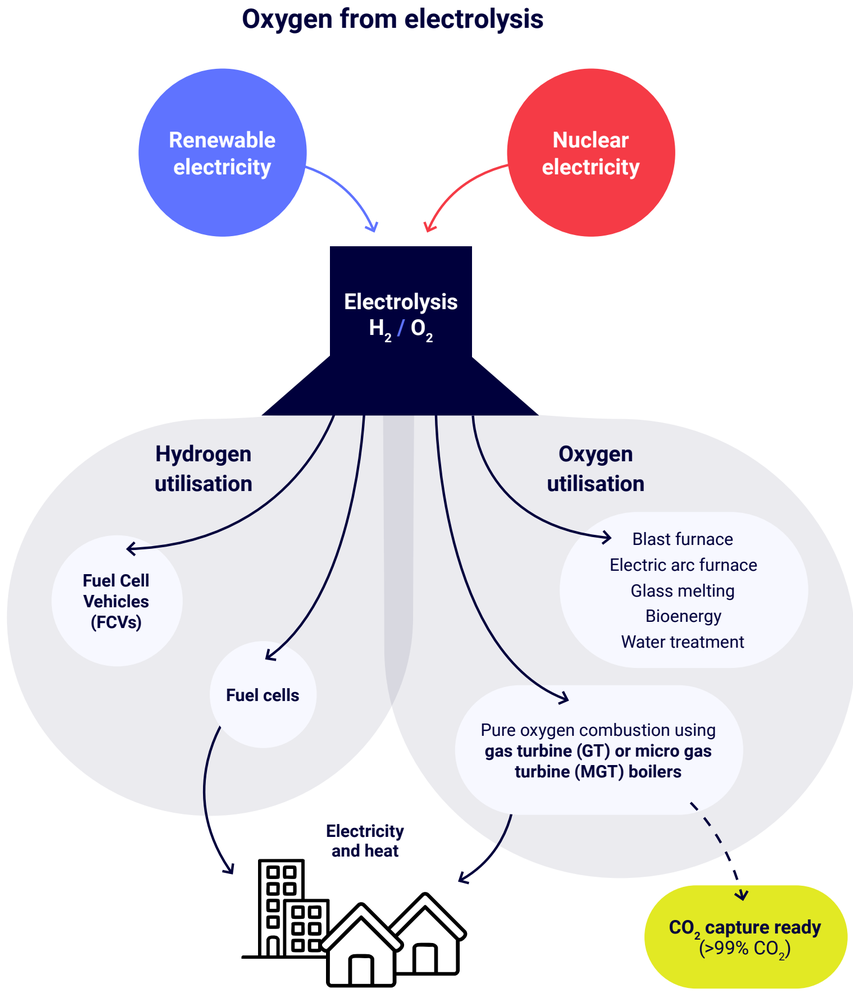


Figure 4

Example of how co-produced resources, such as oxygen from electrolytically produced hydrogen, can be used by other sectors like steelmaking and wastewater treatment (project MIP 7.3).

Life Cycle Assessment (LCA) and Techno-Economic Assessment (TEA), and challenges for measurement and uncertainty

Environmental and economic assessments underpin the transition to circular systems, focusing on emissions reduction, resource efficiency, and economic viability. Comparative analyses show that circular systems, such as biochar in steelmaking or microbial production of VFAs, significantly lower environmental impacts compared to conventional processes (projects MIP 1.3 and MIP 5.2). Accurate carbon modelling and transparent accounting frameworks are critical but challenging for novel and circular systems due to variability in spatial, temporal, and methodological factors (projects MIP 1.3 and MIP 8.8). Therefore, the research emphasises the development of robust frameworks to ensure that local and global decarbonisation goals align without unintended environmental consequences (project MIP 8.8).

See IDRIC Frontiers Report on Life Cycle Assessment for much more information.

Reducing costs and environmental impact is critical to any system's success. Although levels of uncertainty are higher at system design stage, understanding and designing in cost and environmental improvements at an early stage is critical to creating long lasting and robust value, based on environmental gain and cost minimisation. Anticipatory LCA (or emerging tech LCA) is a growing area of research, and critical to the success of this field. Neither LCA nor TEA should be bolted on to research, but should be used to help influence and design – creating environmental and value net gain for the longer term.

Recommendations to industry

The UK industrial clusters can lead the transition to net zero by integrating circular economy principles into their operations, pioneering sustainable practices to become global exemplars. Based on IDRIC's work in this area, we make the following recommendations to industry to support them in adopting circular systems.

Key recommendations

1 **Maximise resource efficiency through systems integration**
Identify opportunities to use industrial by-products and waste streams – such as waste heat, CO_2 and co-produced chemicals – as inputs for other processes, creating value chains within industrial clusters.

2 **Invest in pilot-scale demonstrators**
Support long-term projects that validate circular technologies such as algae systems, e-fuels and e-chemicals, biorefineries, and low-carbon cement under operational conditions.

3 **Plan for longevity and scalability**
Invest in circular projects with long-term value potential, recognising that scalable impact may require extended timeframes beyond typical commercial payback periods.

4 **Foster collaboration across sectors**
Build partnerships between large industries, SMEs and agriculture to unlock new value chains between sectors and accelerate the adoption of circular practices.

5 **Support improvement of LCA frameworks**
Advocate for the development of robust carbon accounting and life cycle assessment (LCA) frameworks to evaluate circular systems, ensuring cost-effectiveness, reduced emissions, and maximised environmental benefits.

Systems integration and valorisation: A pathway to decarbonisation

The creation of value from waste (until there is no “waste”) within industrial clusters will create novel areas for research and innovation. Integration of renewable energy sources, such as wind and solar, into operations to reduce emissions and operational costs can help alleviate ongoing energy price increases, and can map onto waste valorisation, but does require capital investment.

IDRIC’s research has highlighted key areas where industry could focus its efforts to drive circular economy adoption and enhance resource efficiency. These include:

Enhancing industrial integration for resource efficiency

- Identify and exploit opportunities to integrate byproducts, such as waste heat and excess oxygen from electrolysis, into industrial processes to create more energy-efficient and cost-effective systems.
- Encourage co-location of emitters and resource users, such as pairing CO_2-emitting facilities with algae cultivation systems, to maximise resource utilisation and reduce energy wastage.

Addressing research gaps to support waste valorisation

To unlock the potential of valorisation of “waste” materials, industry could prioritise support for research and development in the following key areas:

- Improving electrolyser tolerance under industrial conditions to enhance durability and efficiency.
- Integrating solid oxide electrolyser cells (SOECs) with waste heat sources for higher system efficiency.
- Developing scalable systems, such as algae-based CO_2 capture, to utilise diverse CO_2 streams.
- Increasing the energy efficiency of the electrified clean production process, such as the mechanochemical activation, which have the potential to reduce the use of traditional manufacturing process that relies on fossil fuels.
- Converting biorefining waste carbon emissions into valuable platform chemicals such as VFAs and convert further to materials such as bioplastics.

Overcoming challenges in adoption

Several challenges hinder the widespread adoption of circular practices. These include a lack of successful case studies demonstrating the benefits, industry resistance due to unfamiliarity, as well as financial and logistical barriers, and regulatory complexities. Addressing these issues is critical to accelerating the transition to a more circular economy. Some areas for industry to consider include:

Expanding case studies and demonstration projects

- Increase the availability of case studies to raise awareness and encourage the adoption of unconventional circular systems.
- Industrial clusters should take a leading role in publishing results from demonstrators to showcase tangible benefits.
- Expand and extend current pilot projects to provide clear evidence of both operational and financial advantages of circular technologies and systems.

Longevity and scalability of projects

Many industries understandably prioritise rapid payback periods. However, this short-term outlook can hinder investment in scalable and long-term circular economy solutions. Whilst the climate crisis requires immediate action and results, it is clear that for longer-term truly sustainable change, projects must focus on delivering value over 7–10 years and beyond. Industry must adopt a balanced approach, investing in both short-term and long-term initiatives to drive the transition to a circular economy. Recommendations in this space include:

Investing in long-term pilot projects for industrial scalability

- Expand long-term pilot projects to test the industrial feasibility of technologies such as:
  - Algae-based CO_2 capture;
  - Biochar as a sustainable alternative to coal in steel making;
  - Sustainable aviation fuels (SAFs).
- Support research that ensures technologies remain viable at scale beyond initial pilot phases.

Strengthening SME and industry partnerships for sustainable growth

- Recognise the role SMEs can play as enablers of scalability within circular supply chains and industrial ecosystems.
- Foster collaboration between SMEs and large industries create resilient supply chains and social systems that support circular practices at scale.

Cross-sector collaborations: Unlocking new opportunities

Collaboration between industries, academia, and agriculture can create innovative solutions for industrial clusters. For example:

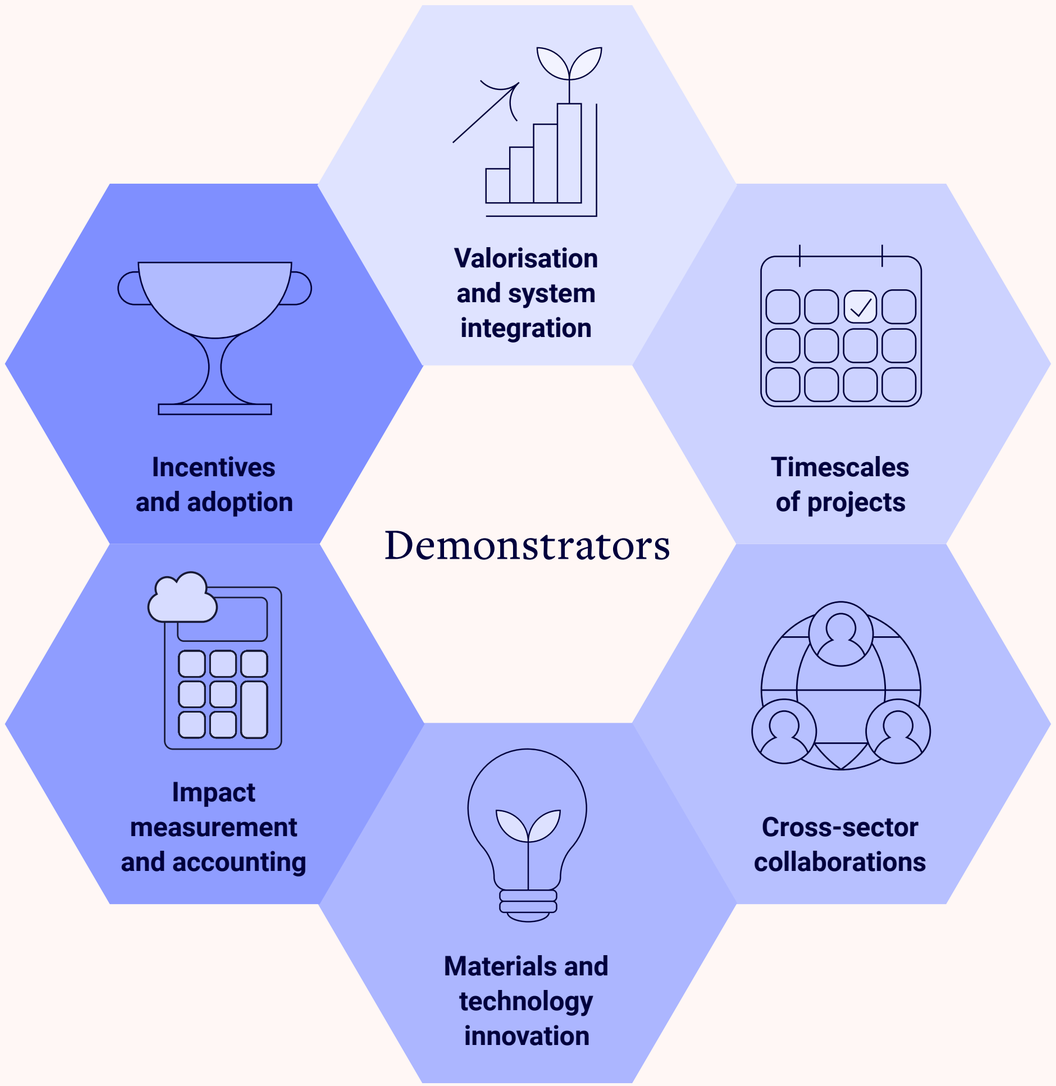
- Agricultural-industrial partnerships could utilise industrial CO_2 emissions for algae cultivation or pyrolysis of biochar to improve soil health.
- Cross-sector partnerships and agricultural-industrial collaborations can be encouraged in order to explore sustainable systems which promote healthy living as well as sustainable energy, green chemicals and materials, and food security.

Innovation in materials and technology

Several areas have been identified by IDRIC researchers to prioritise investment in innovation in materials and technology. These include:

- Investing in advanced materials to improve durability, efficiency, and cost-effectiveness in circular economy processes.
- Scaling key technologies such as gas cleaning systems and solid oxide electrolysis cells (SOECs) to enhance industrial cluster viability.
- Developing low-impact carbon capture materials to reduce ecotoxicity concerns.
- Enhancing gas cleaning technologies to support the competitiveness of sustainable aviation fuel (SAF) production at scale.

Figure 5
Key areas identified for industry focus.



Demonstration projects are critical to success as they are essential to de-risk investments and showcase the operational feasibility of circular economy technologies. Expanding pilots across industries will strengthen confidence in adopting these solutions.

The role of demonstration projects

Demonstration projects (Figure 5) are critical to success as they are essential to de-risk investments and showcase the operational feasibility of circular economy technologies. Expanding pilots across industries will strengthen confidence in adopting these solutions. For example, industry could:

- Fund pilot projects that demonstrate scalable algae systems, biorefining of waste carbon into sustainable chemicals and materials, biochar processes, and SAF pathways.
- Expand existing operational trials for integrating waste heat and renewable energy sources into industrial systems.

Impact measurement and accounting

To be successful, circular systems need to enhance the environment, minimise carbon emissions and be cost effective. In order to demonstrate this, we need to be able to measure carbon and costs effectively, transparently and efficiently. To enable this, industry could:

- Encourage greater transparency and the enhancement of incentives for businesses to adopt sustainable practices.
- Foster cross-sector collaboration to create robust and effective frameworks for carbon accounting at cluster, industry, national and international level.

Recommendations to policymakers

The circular economy requires a complete overhaul of existing systems, eventually removing one of the biggest inputs to our industry and materials creation – fossil fuels and petrochemicals. In order to do this new markets, legislation and regulation is required.

Key recommendations

1 **Strengthen regulatory and policy support**
Redefine waste as a resource and update regulations to enable the use of byproducts and unconventional feedstocks, removing current barriers to the development of circular supply chains.

2 **Enhance carbon accounting and pricing frameworks**
Align carbon pricing frameworks and develop transparent and standardised carbon accounting systems tailored for circular processes to ensure circular outputs are competitive with conventional products.

3 **Support SMEs and supply chain development**
Create de-risking mechanisms and targeting funding streams to enable SMEs to participate in circular supply chains. Consider establishing regional hubs for SMEs to access shared resources and collaboration opportunities.

4 **Enable long-term investment and industrial transformation**
Extend funding cycles to 7–10 years to match the timescales needed for infrastructure and technology development, and align industrial and research timelines to support systemic change.

5 **Enhance financial incentives and infrastructure development**
Create financial mechanisms that encourage industry to integrate circular economy practices at scale and invest in the infrastructure needed to connect emitters with users of industrial by-products.

With innovative thinking, this is a significant opportunity for industry, industrial clusters and the UK. However, support from governments will be required in the short term to help industry make the required changes. Based on IDRIC's research into the circular economy, we make the following recommendations to policymakers (Figure 6).

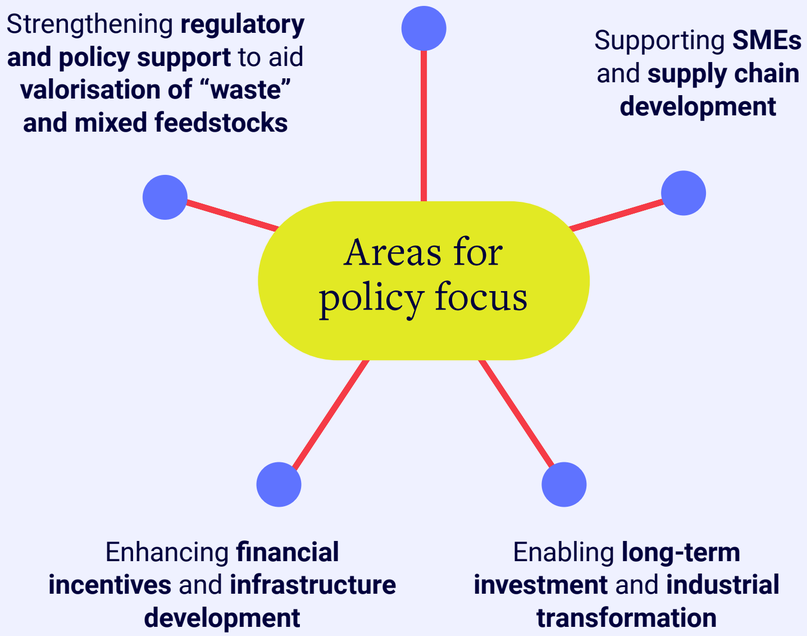


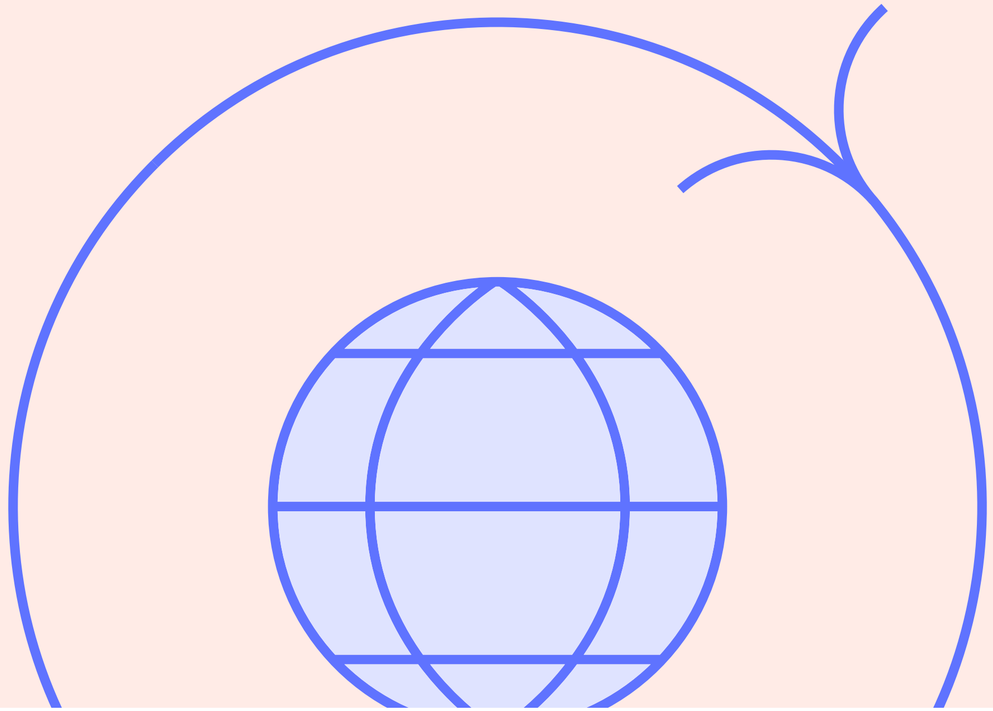
Figure 6
Key areas for policy focus to strengthen the UK's circular economy.

Strengthening regulatory and policy support to aid valorisation of "waste" and mixed feedstocks

- Redefine waste as a resource and streamline regulations to facilitate the valorisation of waste and mixed feedstocks, removing barriers that prevent industries from using byproducts as resources. Examples of this include the use of sewage as an input to systems, the cultivation of algae with mixed feedstocks, biorefining strategies to circularise carbon in chemicals and materials, waste processing (particularly ammonia) and the use of mixed materials for SAF production.
- Create financial incentives and align subsidy frameworks that support novel systems, supply chains and circular pathways that use waste as a resource.
- Explore how regulations and logistics need to change to support novel systems and supply chains.

Enhancing carbon accounting and pricing frameworks

- Develop robust and transparent carbon accounting frameworks for the circular economy.
- Consider flexible targets for industrial clusters, which are linked to global impact and negate the counterproductive impact of companies deciding not to onshore because of the resultant carbon impact to their region, despite a potential global carbon reduction.
- Align carbon pricing frameworks to ensure that circular economy outputs remain competitive with conventional products.



Supporting SMEs and supply chain development

- Recognise the role SMEs can play as enablers of scalability within circular supply chains and industrial ecosystems.
- Develop de-risking mechanisms for SMEs. Large corporations often dominate funding streams, sidelining smaller, innovative players who face higher risks.
- Establish regional hubs to support SMEs through shared resources and cross-sector collaborations, as well as specific policy and regulatory support. Foster collaboration between SMEs and large industries create resilient supply chains and social systems that support circular practices at scale.

Enabling long-term investment and industrial transformation

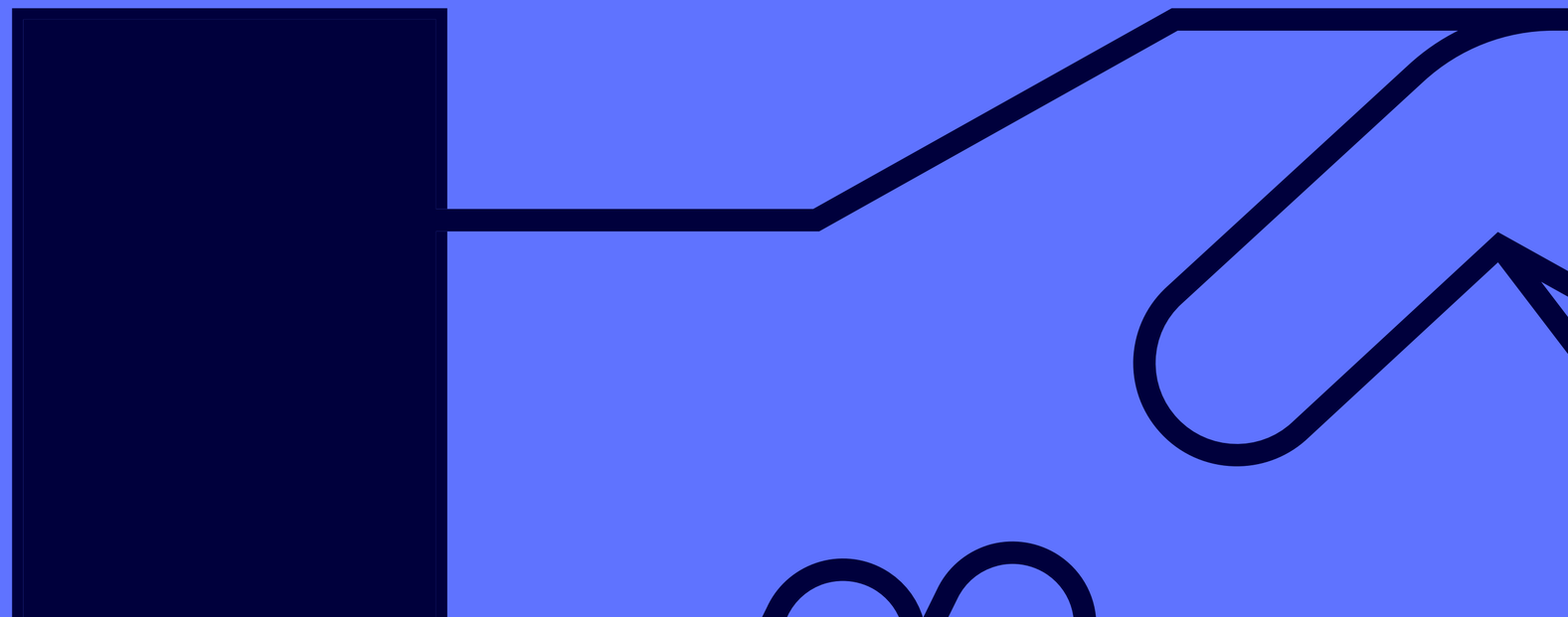
- Extend funding cycles to 7–10 years to support industrial transformation and infrastructure development.
- Encourage long-term investment strategies that align research and industrial timelines, bridging the disconnect between rapid industry payback expectations (typically 18 months) and the longer development cycles required for systemic change (7–10 years).
- Develop training and skills programs to equip the workforce for emerging circular economy industries.

Enhancing financial incentives and infrastructure development

- Support concerted efforts to develop of financial mechanisms to incentivise industries to integrate circular economy practices.
- Invest in infrastructure to connect emitters with users of industrial byproducts (e.g. CO_2, waste heat) to enable efficient resource valorisation.

Moving forward

There are critical areas within the circular economy which require further work, with particular focus on academic research and the need for innovative demonstration projects, alongside policy and regulation support.



Circular economy definition

Perhaps most fundamentally, there is ambiguity in defining “circular economy” and this is a critical barrier to success. We need a clear and actionable definition which includes incorporating energy and carbon loops, as well as broader sustainability metrics alongside material reuse. Scalability and economic feasibility should be included as integral components.

Technology and scientific research requirements

Alongside the more general requirements for demonstrators and policy changes, there are particular technical areas that require further research in order to aid the capture of carbon and other “wastes” and turn these into valuable materials. This includes:

- Scale up from lab to field through pilot-scale hydrogen injection trials and long-duration experiments to validate storage behaviour under realistic operational conditions.
- Develop predictive modelling tools to simulate hydrogen injection, withdrawal and retention in porous media, supporting better design and operational decision-making.
- Refine site selection methodologies by incorporating small-scale structural features, overburden integrity and depth thresholds based on technical and economic feasibility.

Cross-sector collaboration

Collaborative approaches are essential for circular economy success. It is therefore important to incentivise sectors that may not already work together to do so. Critical integration is required in sectors such as energy, chemicals and agriculture. Formal mechanisms to foster dialogue between traditionally siloed industries will help identify synergies and optimise resource use.

Creating demonstrators and high value product case studies

Creating lasting economic feasibility could be initiated by targeting high-value products which would improve economic feasibility. Examples that could be explored include algae-derived pigments and Omega-3s as exemplars of circular products that command premium prices, supporting financial viability. Similarly, aligning sustainable aviation fuel (SAF) production with subsidy frameworks to improve market competitiveness would aid the creation of supply chains, markets and infrastructure required for SAF and other associated products. Conversion of waste carbon into sustainable alternatives to petrochemically derived plastics would also generate additional revenue opportunities, as well as delivering significant environmental benefits

Public engagement and social considerations

The circular economy cannot be developed by industry alone and needs to be placed in a wider social framework. The need for public awareness and desire for change is crucial to achieve alongside technical innovation. As part of this, a wider conversation about how industry, supply chains and systems will need to change is required. Integrating social sciences into circular economy strategies is critical as public adoption is critical for long-term success. Framing for adopting circularity could include intensity indices to help identify how circular a product or system is.

Industrial clusters and the UK have a critical role to play here – with the opportunity to build on the industrial clusters to create global demonstrators of circular systems – showcasing not just industrial decarbonisation but real resource longevity and efficiency coupled with societal and environmental benefit.

Contributing projects

IDRIC projects included in this report

IDRIC ran three complementary strands of projects:

1 In-depth research projects embedded within nine Multidisciplinary Integrated Programmes (MIPs), each programme tackling a key challenge or pathway for industrial decarbonisation;

2 Shorter-term Flexible Fund (FF) projects designed to rapidly address emerging or urgent opportunities identified directly by industrial clusters;

3 Impact Accelerator (IA) projects aimed at maximising the impact of existing IDRIC projects.

Projects discussed within the report are referred to by their project ID.

◣ – Principal investigator

Project ID	Project name	Researchers	
MIP 1.3	Life cycle analysis framework for industrial decarbonisation	Marcelle McManus ◣, Linda Newnes, Ariane Pinto, Lewis McDonald, Sam Cooper	University of Bath
MIP 5.2	The VFA factory for decarbonisation	Alan Guwy ◣, Rhys Jones, Jaime Massanet-Nicolau	University of South Wales
		Marcelle McManus, Ariane Pinto, Lewis McDonald	University of Bath
MIP 5.3	Solid oxide electrolysis for CO_2 utilisation	John Irvine ◣, Nuoxi Zhang	University of St Andrews
MIP 5.4	Integration of sustainable production of chemical energy vectors in industrial clusters	Mercedes Maroto-Valer ◣, John Andresen, Jeannie Tan	Heriot-Watt University
MIP 5.6	VFA to PHA: decarbonisation as a route to sustainable plastics	Alan Guwy ◣, Rhys Jones, Jaime Massanet-Nicolau, Lucy Oram, Rodrigo Fernandez Feito	University of South Wales
		Marcelle McManus, Lewis McDonald	University of Bath
MIP 5.7	Accelerating the scale-up of next-generation fuels from CO_2	Lindsay-Marie Armstrong ◣, Robert Raja, Stylianos Kyrimis	University of Southampton
MIP 6.2	Thermodynamic models for application in industrial decarbonisation	Martin Trusler ◣, Xuehui Wang	Imperial College London
		Jon Maddy	University of South Wales
MIP 6.7	Algae-based carbon capture and utilisation for UK cluster decarbonisation	Jonathan Wagner ◣, Tanja Radu	Loughborough University
		Dongda Zhang	University of Manchester
		Rossen Kazakov, Bing Zhu	Heriot Watt University

Project ID	Project name	Researchers	
MIP 7.2	Electrolysis for green hydrogen and co-produced chemicals at scale	Nigel Brandon, Anthony Kucernak, Paul Boldrin, Colleen Jackson	Imperial College London
MIP 7.3	Utilisation of co-produced oxygen from electrolysis to enable deep decarbonisation	John Andresen, Susana Garcia, Manuel Ojeda	Heriot-Watt University
MIP 8.1	To transform bio CCU from low volume conversion to speciality products into a Mtonne process	Andrew Barron, Darren Oatley-Radcliffe, Andrius Stanulis, Alla Silkina, Jose Gayo	Swansea University
MIP 8.3	BECCS-to-sustainable aviation fuels (SAF)	Mohamed Pourkashanian, Mohammed Akram, Maria Rojas Michaga, Andy Heeley, Kris Milkowski, Solomon Brown	University of Sheffield
MIP 8.5	Bio-balance	Marcelle McManus, Ariane Pinto, Lewis McDonald, Rebecca Rowe, Iain Donnison	University of Bath
MIP 8.7	Up-scaling on-site CO_2 utilisation for decarbonisation of dispersed cement sector: a novel route to reliable net-zero concretes	Xinyuan Ke, Mohamed Katish, Vahiddin Alperen Baki, Brian Ding	University of Bath
		Susan Bernal, Alice Macente	University of Leeds
		Phil Renforth	Heriot-Watt University
MIP 8.8	Creating a carbon framework for a decarbonised circular economy	Marcelle McManus, Linda Newnes, Ariane Pinto, Lewis McDonald, Jose Luis Hernandez Galvan	University of Bath
		Jonathan Radcliffe, Alok Choudhary, Taofeed Ilb Mohammed, Neha Metha, Thomas Fender	University of Birmingham
FF 1-8	Novel chemical strategies for the conversion of industrial derived CO_2 to value chemicals	Gareth Owen	University of South Wales
FF 1-9	Towards a sustainable phase change material (TASPCM)	Jeannie Ziang Yie Tan, John Andresen	Heriot-Watt University
FF 2-2	Determining optimum pyrolysis conditions for biochar to be used as metallurgical coal replacement — In support of deep decarbonisation of large UK industrial emitters based within the Humber cluster	Amir Badiee, Louis Mitchell, Souvik Roy, Aliyu Aliyu, Joe Howe	University of Lincoln
FF 2-3	Capcon - conversion of captured carbon dioxide	Alex Cowan, Bhavin Siritanaratkul	University of Liverpool

Project ID	Project name	Researchers	
FF 2-4	On site trail of OXYHYWATER — A novel net zero wastewater treatment process	Alan Guwy, Jaime Massanet-Nicolau	University of South Wales
FF 2-7	Valorising incineration bottom ash into cement rich in ternesite (VIBACT)	Aniruddha Baral	University of Sheffield
FF 3-2	Utilisation of industrial waste ammonia form steelmaking in solid oxide electrolysis cell technology for efficient and clean hydrogen production	Michal Czachor, Christian Laycock, Alan Guwy, Kleitos Panagi	University of South Wales
FF 4-1	Assessing the feasibility of implementing CO_2 capture and utilisation in Quorn mycoprotein process	Dawid Hanak, Nashwan Dawood, Gari Harris, Kumar Patchigolla, Diana Feliciano, Ellis Marshall	Teesside University
IA 4.2 (FF 2-1)	Accelerating the scale-up mechanism of e-chemicals	Jeannie Ziang Yie Tan	Heriot-Watt University

Project ID	Project name	Outputs	
MIP 1.3	Life cycle analysis framework for industrial decarbonisation	Synergy between industry and agriculture	Journal
		Improving life cycle assessment for carbon capture and circular product systems	
MIP 5.2	The VFA factory for decarbonisation	A review of carboxylate production and recovery from organic wastes	Journal
		Production of volatile fatty acids by anaerobic digestion of biowastes	
		Improving life cycle assessment for carbon capture and circular product systems	
		VFA factory for decarbonisation and VFA to PH	Webinar
MIP 5.4	Integration of sustainable production of chemical energy vectors in industrial clusters	Core-shell nanostructured cu-based bi-metallic electrocatalysts for co-production of ethylene and acetate	Journal
		3D direct ink printed materials for chemical conversion and environmental remediation applications	
		Investigation of process parameters for solar fuel production using earth-abundant materials	
		Electrosynthesis of ethylene from carbon dioxide-derived syngas using nanostructure Cu-based catalysts	
		From brew to clean fuel: harnessing distillery wastewater for electrolysis H_2 generation using nano scale nickle selenide water oxidation catalysts	

Project ID	Project name	Outputs	
MIP 5.6	VFA to PHA: decarbonisation as a route to sustainable plastics	A review of carboxylate production and recovery from organic wastes	Journal
		VFA factory for decarbonisation and VFA to PHA	Webinar
MIP 5.7	Accelerating the scale-up of next-generation fuels from CO_2	Image processing of computed tomography scanned poly-dispersed beds for computational fluid dynamic studies	Journal
		Impact of particle size on the selection of a representative bed section for poly-dispersed fixed bed reactors	
		Hydrodynamic profiles of computed tomography-scanned polydispersed beds produced by sieving	Conference paper
		Accelerating the scale-up of next-generation fuels from CO_2	Webinar
MIP 8.3	BECCS-to-sustainable aviation fuels (SAF)	Bioenergy with carbon capture and storage (BECCS) potential in jet fuel production from forestry residues	Journal
		Sustainable aviation fuel (SAF) production through power-to-liquid (PtL)	
MIP 8.5	Bio-balance	Synergy between industry and agriculture	Journal
MIP 8.7	Up-scaling on-site CO_2 utilisation for decarbonisation of dispersed cement sector: A novel route to reliable net-zero concretes	Comparative life cycle assessments of laboratory and Pilot-scale Mechanochemical processes for producing carbonated mineral products as cement substitutes	Journal
MIP 8.8	Creating a carbon framework for a decarbonised circular economy	Carbon accounting	Policy brief
		Towards a unified carbon accounting landscape	Journal
		Creating a carbon framework for a decarbonised circular economy	Webinar
FF 1-8	Novel chemical strategies for the conversion of industrial derived CO_2 to value chemicals	An air and moisture stable boat shaped hydroxo-bridged ruthenium(II) binuclear complex for the catalytic hydrogenation of CO_2	Journal
FF 1-9	Towards a sustainable phase change material (TASPCM)	From brew to clean fuel	Journal
		Promoting e-chemical production by optimising the cathode–anode pair	
FF 2-2	Determining optimum pyrolysis conditions for biochar to be used as metallurgical coal replacement — In support of deep decarbonisation of large UK industrial emitters based within the Humber cluster	Determining optimum pyrolysis temperature for biochar to be used as metallurgical coal replacement	Webinar

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