Industrial Decarbonisation Frontiers Report

Carbon Dioxide Removal Technologies

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* series 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 Carbon Dioxide Removal Technologies.

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Lead author

Lindsay-Marie Armstrong — University of Southampton

Contributing authors

Muhammad Akram — University of Sheffield

Amir Badiee — University of Lincoln

Caspar Donnison — Lawrence Livermore National Laboratory

Diarmaid Clery, Clair Gough — University of Manchester

Isobel Marr, Phil Renforth — Heriot-Watt University

Ronny Pini — Imperial College London

Executive summary

This report examines the role of carbon dioxide removal (CDR) technologies in both advancing industrial decarbonisation, and moving towards ‘negative emissions’ scenarios. It focuses on IDRIC-funded projects that explore innovative solutions such as biochar, bioenergy with carbon capture and storage (BECCS), geochemical CDR and direct air capture (DAC). The report highlights key findings and offers recommendations for industry and policymakers to support a sustainable transition toward net zero.

Key findings

BECCS and industrial decarbonisation
BECCS offers significant potential to support renewable energy generation while enabling negative emissions. However, challenges include biomass supply chain constraints, regulatory uncertainties, and cost barriers. Studies show that BECCS can achieve up to 88% CO_2 capture efficiency, but economic feasibility depends on government incentives and carbon pricing mechanisms.

Steel industry decarbonisation
The use of biochar as both metallurgical coal replacement and slag carbonation presents viable pathways for reducing CO_2 emissions in steel production and enabling negative emissions. Research indicates that biochar from pyrolysis at 800°C can achieve calorific values comparable to coal, while slag carbonation could capture up to 5-8% of emissions. However, financial incentives such as CO_2 credits will be essential for scaling these technologies.

Direct Air Capture (DAC)
DAC is a complementary CDR strategy with the potential to remove residual industrial emissions. While it requires significant energy and land resources, cluster-based integration with existing infrastructure can improve efficiency. Studies suggest DAC's land footprint is lower than biomass-based approaches but requires high energy input and optimised siting strategies for cost-effective deployment.

Broader systems thinking
Effective deployment of CDR technologies requires a holistic approach that integrates technological advancements, economic feasibility, regulatory support, and social acceptance. A whole-systems approach ensures that industrial clusters can strategically align CDR technologies with national net zero goals.

Recommendations for industry

Adopt a whole-systems approach
Integrate CDR technologies within broader decarbonisation strategies to maximise impact.

Ensure sustainable biomass sourcing
Develop resilient supply chains to avoid resource competition and ensure long-term sustainability.

Enhance cross-sector collaboration
Strengthen communication among industries, policymakers and researchers to align roadmaps for industrial decarbonisation.

Foster community engagement
Engage local communities early in project planning to ensure transparency and social acceptance.

Recommendations for policymakers

Establish clear frameworks
Develop Monitoring, Reporting, and Verification (MRV) standards to build market confidence in CDR technologies.

Incentivise investment
Provide financial mechanisms, such as carbon pricing, tax credits, and supply chain incentives, to accelerate CDR adoption.

Support research and international collaboration
Promote funding for next-generation carbon removal solutions and facilitate knowledge-sharing to maintain the UK's leadership in industrial decarbonisation.

Moving forward

To scale CDR technologies effectively, the UK must address supply chain resilience, market demand, social acceptance, and regulatory clarity. Policymakers and industries should prioritise integrated approaches that balance economic viability, environmental sustainability, and social equity. Continued investment in innovative research, infrastructure, and policy support will be critical to achieving the UK's net zero commitments.

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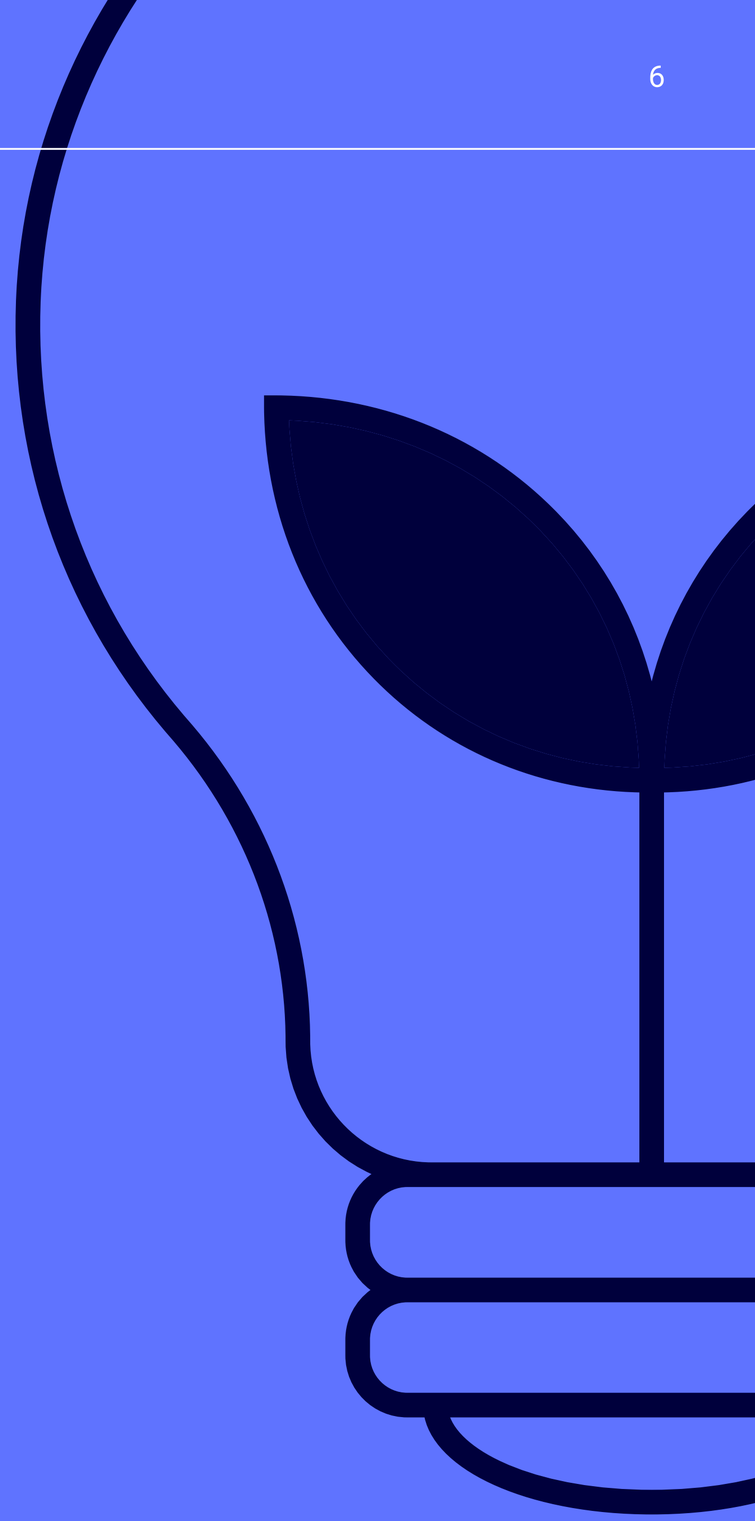
Introduction

Climate change mitigation necessitates the urgent and effective implementation of strategies within a comprehensive carbon dioxide removal (CDR) portfolio to reduce greenhouse gas emissions, support atmospheric CO_2 removal, and potentially move towards a ‘negative emissions’ scenario. Almost all CDR technologies require dedicated efforts to make them economically appealing and less energy demanding.[1,2,3]



As industrial decarbonisation progresses, and CCS infrastructure comes online, the wider role of the industrial clusters – i.e. concentrated areas of energy-intensive industries - in delivering net zero will come into sharper focus, including the potential to deliver negative emissions. Bioenergy with Carbon Capture and Storage (BECCS) systems are a promising CDR technology in supporting renewable energy generation, whilst potentially offering a route to negative emissions.[4,5,6] Direct air carbon capture and sequestration, DACCS or simply DAC, is acquiring further interest due to its capturing potential of both direct and indirect emissions thus offering another route towards net negative emissions.[1,3,7]

Achieving net zero emissions through the deployment of BECCS requires an unprecedented scale of operation, targeting the sequestration globally of 3–7 $GtCO_2$/yr by 2050.[8,9] Whilst BECCS could support the Paris Agreement targets and climate thresholds, there are concerns that the scale of future biomass feedstock and land-use demand may also have negative societal impacts and breach planetary ecological boundaries.[10,11] There needs to be a coordinated effort that shifts from a point-to-point supply chain to a more comprehensive and multi-disciplinary hub-and-spoke supply chain model. However, this brings additional challenges, including the interactions between proximal supply chains, increased biomass competition and bottlenecks for the deployable scale of BECCS facilities.[12,13]

BECCS and DAC will become key pillars of the UK net zero strategy – but there are many challenges and uncertainties that require a holistic, whole-systems approach that encompasses the technological advancements alongside economic feasibility, socio-cultural acceptance, and robust political and regulatory frameworks to their deployment.[10]

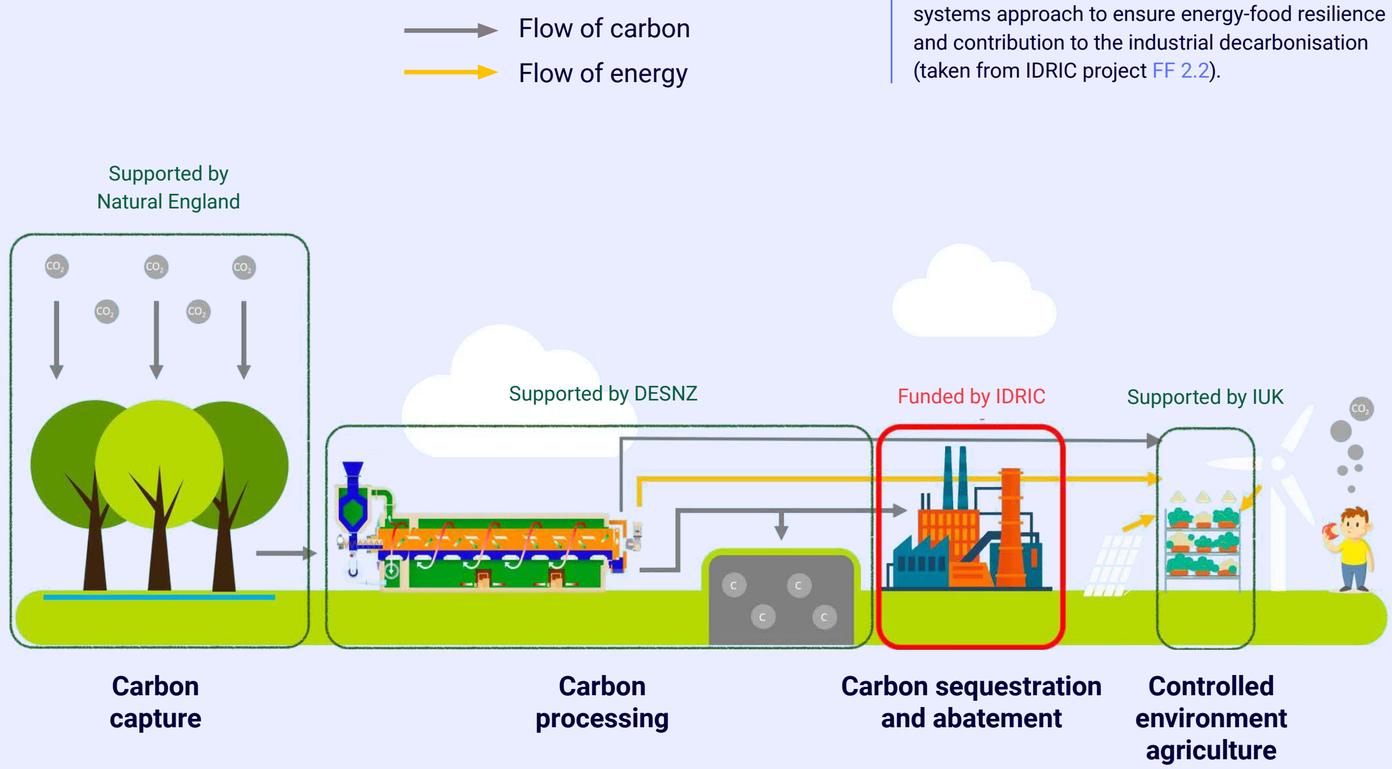


Figure 1
Example of an interlinked project with whole-systems approach to ensure energy-food resilience and contribution to the industrial decarbonisation (taken from IDRIC project FF 2.2).

1 IEAGHG: Assessing the Techno-Economic Performance, Opportunities and Challenges of Mature and Nearly-mature Negative Emissions Technologies (NETs) (2024)
2 Lezaun et al. (2021), Governing Carbon Dioxide Removal in the UK: Lessons Learned and Challenges Ahead. Front. Clim. 3:673859
3 Strefler et al. (2018), Environ. Res. Lett. 13:044015
4 DESNZ: Biomass Strategy (2023)
5 Krause et al. (2020), A regional assessment of land-based carbon mitigation potentials: Bioenergy, BECCS, reforestation, and forest management, GCB Bioenergy. 12: 346
6 Clery et al. (2021), Bringing greenhouse gas removal down to earth: Stakeholder supply chain appraisals reveal complex challenges Global Environmental Change. 71:102369
7 House et al. (2011), Economic and energetic analysis of capturing CO_2 from ambient air, Proc. Natl. Acad. Sci. 108:20428
8 Butnar et al (2020), A deep dive into the modelling assumptions for biomass with carbon capture and storage (BECCS): a transparency exercise, Environ. Res. Lett.15:084008
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12 Bai et al. (2015). Biofuel Supply Chain Design and the Impacts on Transportation Systems and Infrastructure. In: Eksioglu, S., Rebennack, S., Pardalos, P. (eds) Handbook of Bioenergy. Energy Systems. Springer, Cham.
13 Da Silva et al. (2018), CO_2 capture in ethanol distilleries in Brazil: Designing the optimum carbon transportation network by integrating hubs, pipelines and trucks, International Journal of Greenhouse Gas Control. 71: 168

Research findings

Carbon dioxide removal (CDR) technologies play a crucial role in supporting the transition of heavy industries toward a decarbonised future and may potentially facilitate net-negative emissions scenarios. IDRIC projects have explored the current status, opportunities and challenges for a range of technical scenarios including biochar, bioenergy with carbon capture and storage (BECCS), geochemical CDR and direct air capture (DAC) technologies.

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

Project ID	Project name
MIP 2.6	Integrated assessment of BECCS in context: environmental, policy, regulatory and social factors
MIP 6.6	Process intensification of CO_2 capture with bioenergy using rotating packed bed (PICCABU)
MIP 8.2	Industrial NETs using alkaline materials
MIP 8.3	BECCS-to-sustainable aviation fuels (SAF)
MIP 8.4/ IA 4.4	Where to locate new bioenergy with carbon capture and storage? A natural capital approach
MIP 8.6	Integrated design and optimisation for nationwide deployment of direct air capture units
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

The research highlights the importance of considering technological advancements through a holistic and systemic integrated approach.

The projects contribute to a growing body of research exploring the practical and scalable pathways to decarbonise industries, ranging from using biochar in steelmaking, biofuels in sustainable aviation fuel (SAF) production, DAC as a complementary solution, and solid biomass in BECCS power to reduce industrial emissions. They address challenges that hold back the potential of BECCS and DAC, including feedstock impurities, biomass supply chain development, and land-use sustainability. The research further highlights the importance of considering technological advancements through a holistic and systemic integrated approach; as well as regulatory certainty and funding mechanisms, communication and collaboration between industry, policymakers and financial markets, and the scale-up of projects which are seen as critical for fostering confidence in CDR markets.

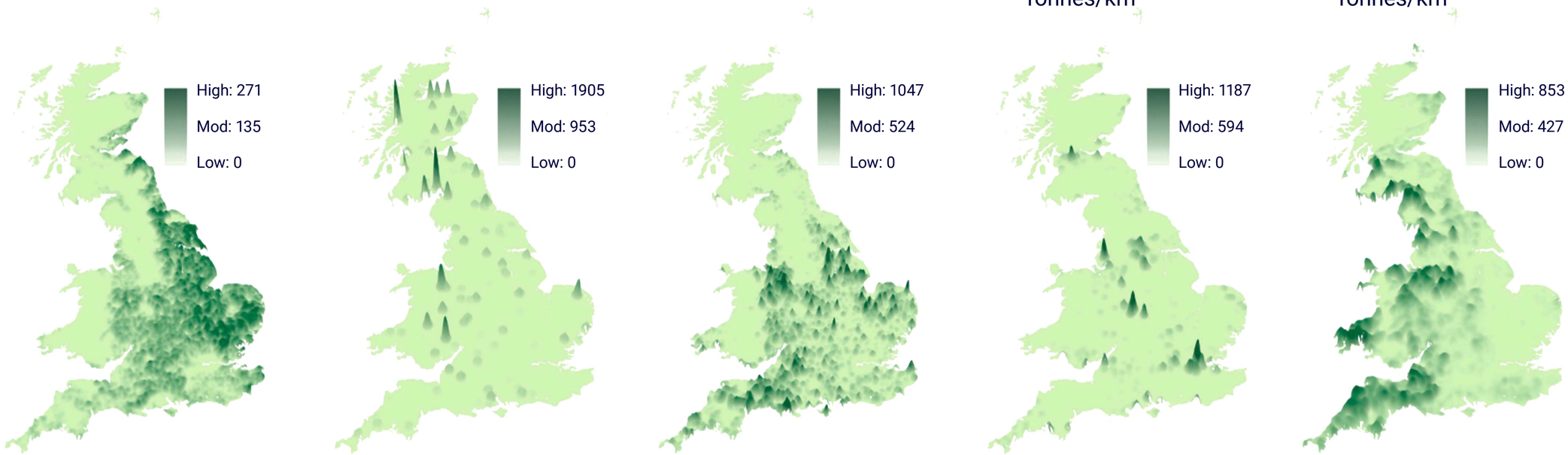


Figure 2
Spatial distribution of selected biomass types for the BECCS supply chains in the UK (taken from IDRIC project MIP 2.6, Freer et al.)

The role of BECCS for the energy sector

Several IDRIC projects focused on BECCS as a technology for decarbonising the energy and chemical sectors. The efficiency of CO_2 removal and challenges surrounding its deployment was explored by IDRIC project MIP 6.6, who presented the capability of BECCS technologies for effectively achieving up to 88% of CO_2 capture from biomass flue gas using a rotating packed bed absorber. The successful system used a blend of APBS-CDRMax® solvent and up to 83% monoethanolamine (MEA) (35% weight/weight), respectively. Impurities in biomass flue gases, such as potassium, sodium, and sulphur still present operational challenges and cost implications for such systems.

The potential for producing SAF through Fischer-Tropsch synthesis coupled with BECCS was investigated using a combined techno-economic and life-cycle assessment approach in IDRIC project MIP 8.3. The study found that the inclusion of carbon capture and storage (CCS) managed to achieve net negative emissions for the system, whilst increasing the minimum selling price of SAF by 7.9%. However, they identified that the financial feasibility of a BECCS process configuration can only be attained through the implementation of existing policy schemes for CDR and the formulation of new strategies that would reward negative emissions.

Project MIP 2.6 evaluated the systemic and policy challenges facing BECCS implementation, such as the need for regulatory certainty and public support with particular focus on the North-West industrial cluster. The study used an advanced digital twin model via the Carbon Navigation System and detailed biomass mapping to investigate five distinct BECCS supply chains at the Protos site, each using feedstocks from waste or residue and reflecting novel configurations that closely align with upcoming BECCS projects within the UK (Figure 2).

However, they highlighted potential gridlock scenarios with challenges around securing enough biomass to fuel these systems. They concluded that competition over biomass resources could hinder the UK's efforts to reach net zero greenhouse gas emissions.

IDRIC project MIP 8.4 applied a holistic approach to determine the land-use scenarios and environmental impacts of domestically grown bioenergy crops used for BECCS power. The technology can be used sustainably to perform a limited role in delivering CDR, with minimal impact to UK food production. The findings also supported previous conclusions that larger deployments, requiring high UK land-use, would increase environmental pressures, including for food production and biodiversity (Figure 3). The project also highlighted that collaborative frameworks and robust Monitoring, Reporting, and Verification (MRV) systems are essential for the market confidence and investments needed to scale these BECCS projects.

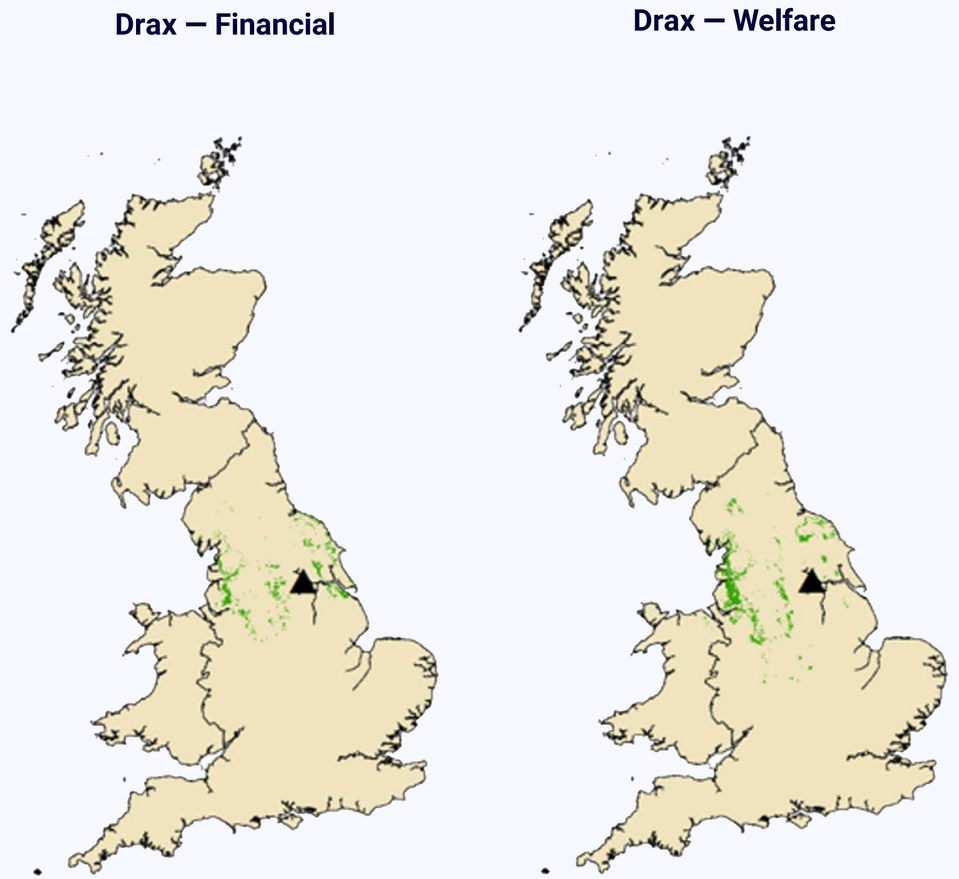


Figure 3

Modelling results for the land-use scenario providing biomass supply to BECCS projects at Drax Biomass, Humber Cluster UK (taken from IDRIC project MIP 8.4).

Pathway	Drax Biomass
No. BECCS units	2 x 620MW
Biomass imports	80%
Biomass domestic	20% (1.0 Mt)
CO_2 injected annually	7 Mt

Land-use (100 miles)	74,772 ha	83,783 ha
UK arable land-use	1%	1%
Net societal value	£1.9bn	£1.9bn

At 800°C the biochar achieved calorific values comparable to, or higher than, coal.

Decarbonisation of the steel industry

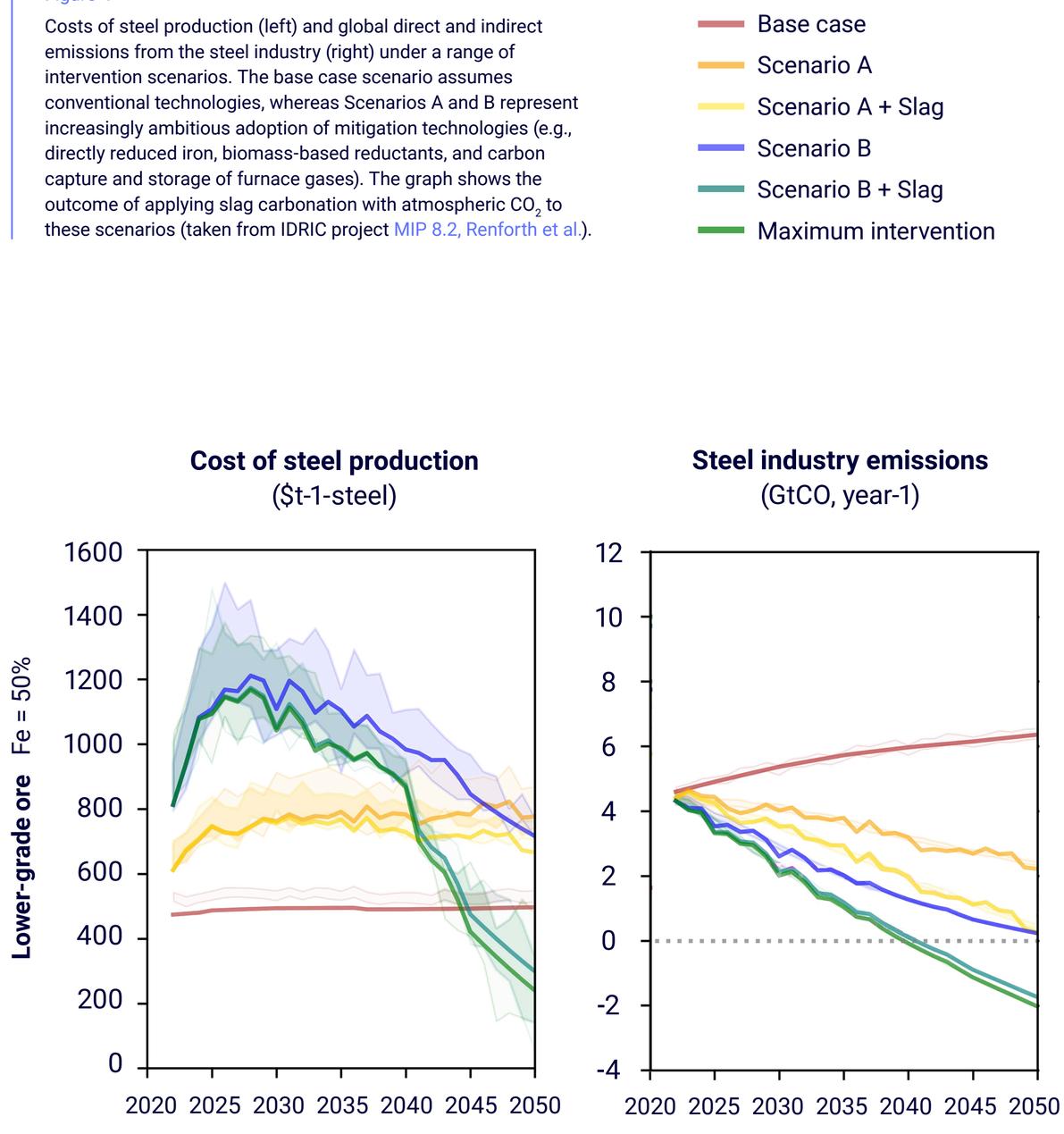
A couple of projects focused on decarbonising steel production through both the application of biochar, and innovative CDR methods. The findings collectively demonstrate the potential of biochar and slag carbonation as complementary strategies, achieving decarbonisation and even the possibility of net-negative emissions in the steelmaking sector.

The suitability of biochar produced from debarked biomass as a sustainable alternative to metallurgical coal, with particular focus on the impact of pyrolysis temperature on biochar properties was investigated by IDRIC project FF 2.2. They demonstrated that at 800°C the biochar achieved calorific values comparable to, or higher than, coal. Additionally, biochar demonstrated lower contamination levels compared to coal, making it a more favourable option for steelmaking. This is particularly advantageous for electric arc furnace (EAF) technology, which the UK steel industry is showing some movement towards.

Project MIP 8.2 focused on identifying and implementing strategies for achieving carbon-negative emissions in the steel industry through innovative CDR approaches. The study applied a techno-economic model to explore the viability of various climate intervention scenarios, such as biomass-based reductants, direct reduction of iron (DRI) using hydrogen, carbon capture and storage (CCS), and specifically, the reaction of CO_2 with slag. The study suggested that the steel industry could potentially be decarbonised by 2050 if it captured up to 5–8% of emissions through slag carbonation and adopting CDR technologies (Figure 4). However, the model reinforced the need for economic incentives, such as a CO_2 credit price, to potentially offset costs and promote the use of lower-grade iron ores, a novel outcome with substantial industrial implications.

Figure 4

Costs of steel production (left) and global direct and indirect emissions from the steel industry (right) under a range of intervention scenarios. The base case scenario assumes conventional technologies, whereas Scenarios A and B represent increasingly ambitious adoption of mitigation technologies (e.g., directly reduced iron, biomass-based reductants, and carbon capture and storage of furnace gases). The graph shows the outcome of applying slag carbonation with atmospheric CO_2 to these scenarios (taken from IDRIC project MIP 8.2, Renforth et al.).



Direct Air Capture (DAC) as a complementary strategy

DAC is an emerging complementary solution, particularly in settings with constrained point-source emissions or high-quality renewable energy. However, its land and energy demands limit its standalone viability. IDRIC Project MIP 8.6 studied how the integration of DACs within industrial clusters offers specific strategic benefits through access to key shared resources and infrastructure, such as electricity, waste heat, water and transport & storage networks (Figure 5). The project developed a model-based tool to design sorbent-based DAC units and used it to quantify the performance limits in terms of energy consumption and the amount of CO_2 captured per day. They found that specific energy usage of the sorbent-based DAC was comparable to other sorbent-based CO_2 capture applications, such as point-source CO_2 capture. The study further suggests that maximum productivity of the system was low, requiring a large land footprint should the technology be deployed to climate-relevant scales; however, it could be argued that this is still comparatively small compared to the land-use requirement for biomass-based approaches. Furthermore, they found a strong degree of synergy needed to be achieved between geographical siting, adsorbent selection, contactor design, and process operating conditions in order to achieve environmentally efficient DAC processes with low energy usage and low land footprint.

Broader implications and systems thinking

All of the IDRIC projects within the theme of CDR technologies reinforced the crucial need for a holistic approach, whole systems perspective, and proposed synergistic achievable benefits. Policymakers and industry must prioritise collaboration across sectors, incentivise innovation, and implement robust verification frameworks to drive adoption. While the findings highlight promising pathways, several critical gaps remain, including additional data on biomass feedstock availability, long-term economic impacts, and societal support.

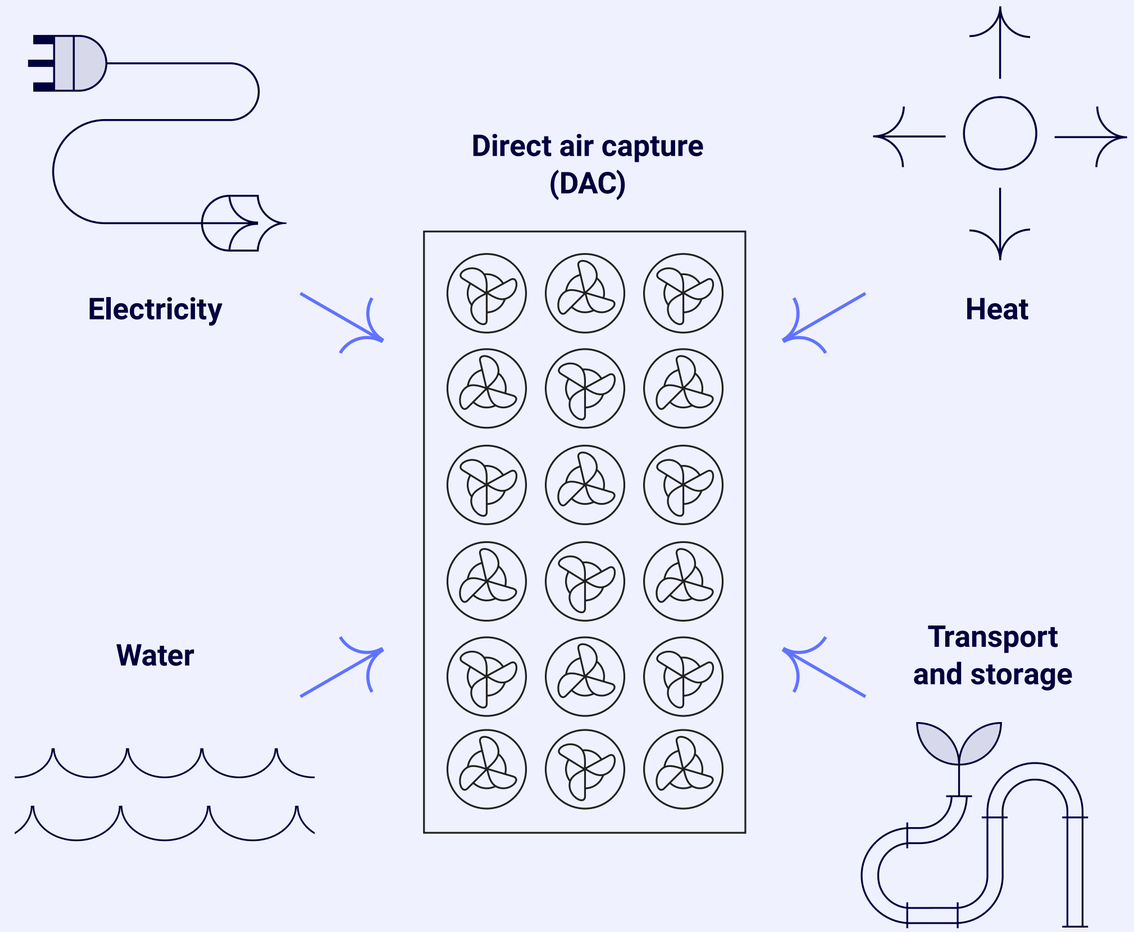


Figure 5

Integrated approach accounting for the full scope of emissions associated with the CO_2 capture, transport, and storage chain for DAC (taken from IDRIC project MIP 8.6)

Recommendations to industry

Based on IDRIC's findings from the research carried out into CDR technologies, we make the following recommendations to industry to facilitate effective industrial decarbonisation.

Adopt a whole-systems approach

A comprehensive whole-systems approach must consider emission reduction strategies that address sustainable practices, providing an increase in environmental, social, and economic benefits. This approach prioritises adaptive, evidence-based planning and considers the evolving needs of industries.
A systems approach further advances actionable insights and identifiable areas for deeper collaboration and policy innovation to support UK industries in reaching net zero emissions.

Employ CDR technologies as part of a comprehensive decarbonisation strategy

To mitigate emissions effectively, cluster-based industries should employ CDR technologies as part of a comprehensive decarbonisation strategy. Industry stakeholders should consider:

1. Employing hydrogen-based direct reduction and BECCS to further offset emissions costs.
2. Integrating DAC into clusters to address the very hard-to-abate residual emissions while leveraging shared infrastructure.
3. Implementing carbon capture and utilisation practices within the steel industry, including adopting CDR via slag carbonation, which the research identifies as a promising approach for achieving net-negative emissions (Figure 6).

Regardless of the decarbonisation strategy, the industrial clusters need to explore how the integration of these technologies can mitigate emissions without sacrificing profitability.

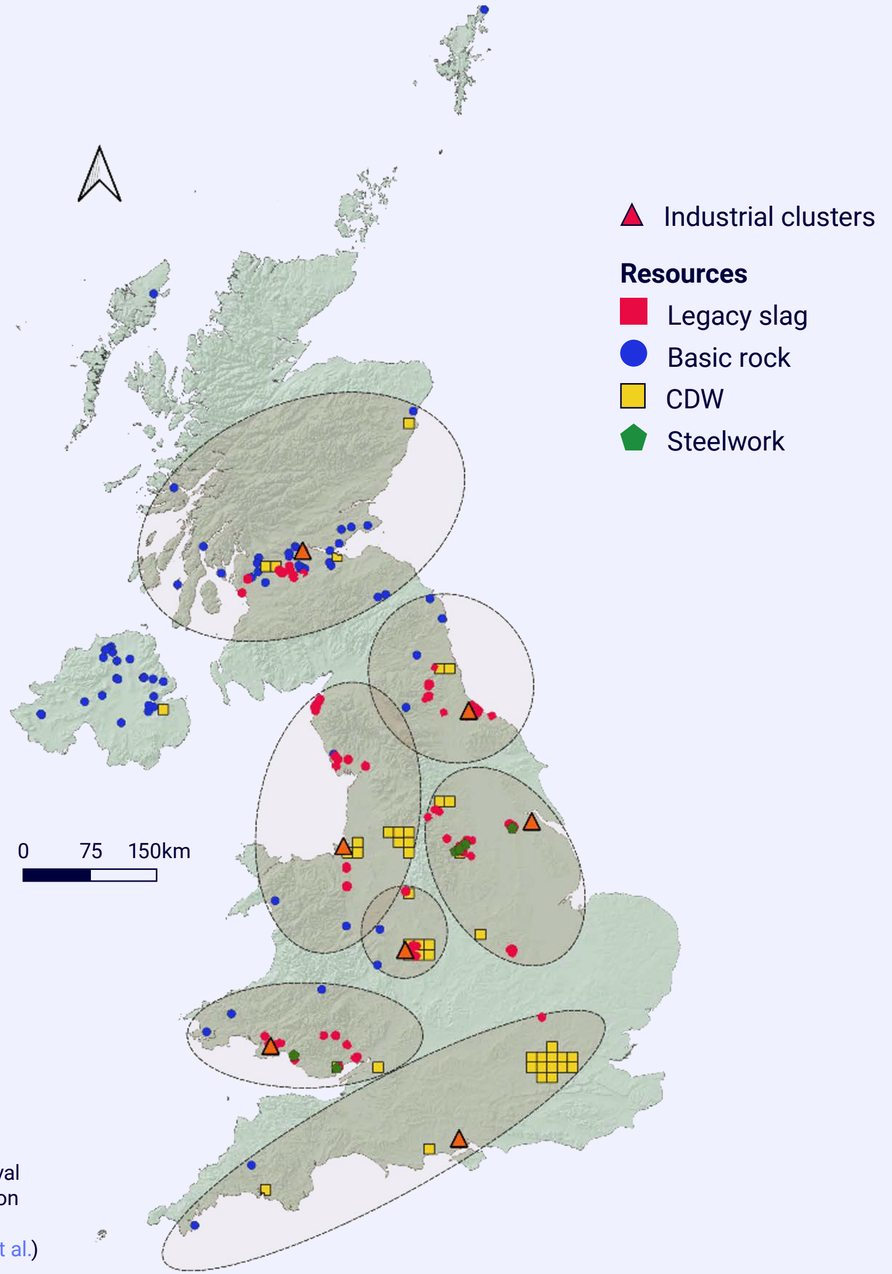


Figure 6

Geochemical carbon dioxide removal resources in the UK and their relation to industrial clusters. (Taken from IDRIC project MIP 8.2, Madankan et al.)

Ensure sustainable biomass sourcing

Sustainable biomass sourcing must follow collaborative frameworks to optimise biomass supply chains, preserve the natural environment and ensure sustainable provision of services. By initiating collaboration across sectors, particularly the agriculture sector, and emphasising a systems perspective, industries can transition toward decarbonised operations while maintaining economic competitiveness and environmental integrity.

Addressing potential competition for biomass requires coordinated resource allocation as multiple BECCS facilities may seek similar feedstocks, leading to risks of supply shortages and cost increase. Decisions on resource allocation will depend on factors such as contractual flexibility, existing fuel demand, and relationships with suppliers, so clarity on project details is recommended to prevent delays associated with permitting.

Strengthen cross-sector communication to develop clear net zero roadmaps

Clear communication across all sectors is recommended, including the need for clear roadmaps of the net zero plans to aid the visualisation of synergies between CDR technologies, to illustrate the interactions between industrial decarbonisation and sustainable practices (e.g., agriculture, land use), to present pathways from biomass sourcing to CO_2 capture and utilisation and address in collaboration the complex challenges to subsequently create clear policy roadmaps.

Foster transparent and long-term community engagement

Transparent, long-term and on-going engagement strategies are critical for building trust and gaining community support for decarbonisation projects and to foster transparency and facilitate feasibility and environmental benefits. Industries are recommended to develop relationships with local communities affected by their projects as early as possible to allow meaningful input on project design and understanding the opportunities and risks for the community.

For more information, read IDRIC's Frontiers Report: Public Perceptions and Just Transitions.

Recommendations to policymakers

Based on IDRIC's findings from the research carried out into CDR technologies, we make the following recommendations to policymakers to facilitate effective industrial decarbonisation.

There is a critical need for clarity and leadership on the role of carbon dioxide removal in the net zero goal, and funding mechanisms for these approaches. Without clear policies, the UK risks losing its competitive edge internationally.

Policy support and funding mechanisms to support a diversified mix of CDR technologies, aligning incentives across sectors, and the integration of industrial decarbonisation into broader energy security strategy, could be addressed at future cross-sector workshops.

National government level

At the national government level, the broad recommendation is that policymakers adopt a whole-systems approach to industrial decarbonisation, aligning regulations with Sustainable Development Goals (SDGs) to ensure co-benefits across economic growth, environmental sustainability, and social equity.

Initiating interdisciplinary collaborations across sectors, e.g., agriculture and industrial clusters, could enable synergies and co-benefits for potential carbon-negative biomass production and waste valorisation, and advance policies through adaptive planning principles and transparent inter-sectoral cooperation.

Government support is necessary for setting clear Monitoring, Reporting, and Verification (MRV) standards for CO_2 removal, necessary for trust in CDR markets, and for implementing financial de-risking mechanisms to attract investments in large-scale decarbonisation projects.

Local governments and authorities

Local governments and authorities can perform an important role in identifying which CDR approaches align with their local resources and opportunities; facilitating their development through leveraging existing resources and expertise and through engagement with the communities where these projects could be deployed.

Priority actions

Develop and implement a robust framework for CDR technologies, including MRV standards, supply chain incentives, and community engagement strategies.

There remains a significant need for the **establishment of clear and stable business models for CDR technologies** for application across all sectors. Policymakers play a critical role in preventing piecemeal approaches through coordinating supply chain support and clarifying the MRV requirements.

Governments must **implement robust sustainability criteria for biomass supply chains**, informed by scientific modelling and stakeholder input. Clear policies should ensure that biomass resource use aligns with environmental and social sustainability goals.

Policymakers need to **incentivise the deployment of diverse pathways scenarios** and could consider the **introduction of cost-stabilisation mechanisms for CO_2 transport and storage** to provide predictability in carbon offset pricing, enabling investment confidence in CDR-related infrastructure.

Policymakers play a role in ensuring meaningful early engagement with communities affected by industrial decarbonisation projects. Transparent communication about the benefits, risks, and sustainability of technologies like BECCS and DAC is essential to build trust and avoid project delays. Policies should **mandate community consultation as a prerequisite for project approvals** and incentivise projects that deliver social co-benefits like improved local transport infrastructure, reduced energy bills and local job creation.

For more information, read IDRIC's Frontiers Report: Public Perceptions & Just Transitions.

Promote research funding and international cooperation to advance innovative solutions and maintain competitiveness.

For the decarbonisation of the steel industry, policies should **incentivise the adoption of low-carbon production methods, such as hydrogen-based direct reduction and BECCS**. Carbon taxes or emissions trading schemes with substantial pricing could make CDR technologies like slag carbonation more viable. **Policies should also promote the use of biomass for renewable chemicals and fuels**, contributing to decarbonisation in industrial sectors and displacing virgin fossil fuels. Funding mechanisms for R&D should be established to address challenges in biomass gasification, such as high levels of impurities and the cost of Fischer-Tropsch (FT) processes.

There should be **increased government investment into research and development of scalable decarbonisation technologies**, focusing on reducing capital costs, enhancing energy efficiency, and enabling the commercial viability of emerging solutions, for example slag carbonation and biomass gasification.

Co-locating DAC within industrial clusters could exploit shared infrastructure, reduce carbon intensity, and provide scalable solutions for residual emissions from hard-to-abate sectors. The US have introduced and provided funded programmes to explore the concept of "DAC hubs", where DAC technologies can be demonstrated at commercial scale removing 1 million metric tons of CO_2 annually from the atmosphere. Undertaking research at scale into the feasibility of DAC technologies will offer insights into the potential synergies and trade-offs between different policy objectives, such as promoting economic growth, reducing emissions, and enhancing energy security.

By engaging with different stakeholders, future research will contribute to the development of informed and evidence-based energy policies that facilitate the transition to a sustainable and low-carbon future. This would be further enhanced through international collaboration to share knowledge, accelerate best practice, harmonise emissions standards and advance technology development to accelerate sector-wide adoption.

Moving forward

Integrating CDR technologies

Integrating CDR technologies faces further challenges with regards to ensuring resilient supply chains, ensuring a stable market demand and commercial viability, as well as societal support. Specific findings identified through the projects include:

- **Supply chain development**
  Establishing resilient supply chains for biochar, biomass, and BECCS feedstocks is crucial to meeting demand. This includes addressing logistical challenges and fostering cross-sector collaboration.
- **Market demand and commercial viability**
  Stable demand for carbon removal technologies is essential. Policies to ensure consistent demand – including government acting as an initial buyer – can accelerate market maturity.
- **Social support**
  Building trust amongst local communities, policymakers and stakeholders from industrial and farming sectors is critical to achieve a “social licence to operate” for CDR technologies. Transparent communication, sensitivity to the local context and collaborative planning are key.

Political and systemic challenges

A number of projects highlighted the political and systemic challenges facing the integration of different CDR technologies, including:

- **Regulatory and economic incentives**
  Carbon pricing, clear carbon accounting standards, greater clarity on business models and incentives for negative emissions technologies are required to ensure these processes are economically viable. Furthermore, building capacity in regulatory and permitting frameworks and reliable CO_2 verification mechanisms are also essential.
- **Integration of DAC and BECCS**
  Supporting the development of DAC hubs and integrating these technologies within existing industrial clusters can provide strategic co-benefits and economies of scale.
- **Environmental and economic alignment**
  Policies must ensure that BECCS and other CDR technologies align with broader environmental and social goals, supporting just transitions for affected communities while fostering international collaboration.
- **Circular economy approaches**
  Technologies must align with sustainability principles, ensuring waste valorisation, resource efficiency, and minimisation of environmental footprints.
- **Tailored solutions**
  A soft-systems approach, addressing the interconnections between sectors and regions, is necessary to ensure that decarbonisation strategies do not have unintended consequences or the transfer of challenges, such as economic, social, or environmental impacts, to other areas.

Technical areas

Our researchers also identified a number of technical areas where research should be prioritised to accelerate a range of CDR technologies across different sectors:

- **Biochar development and applications**
  Research must refine biochar production processes to ensure scalability, cost efficiency, and minimal environmental impact. Additionally, studies should explore the integration of biochar with sustainable agricultural practices and peatland restoration if we are to achieve carbon-negative outcomes in the UK steel industry.

- **Solvent behaviour in BECCS**
  Long-term tests with real biomass flue gas are needed to better understand the impacts of contaminants on solvent behaviour. Endurance testing of steady operations with regular sample collection for solvent and particulates is recommended, as well as frequent biomass analysis, followed by investigation of solvent degradation chemistry by techniques such as quantum chemistry.

- **Reaction of slag with atmospheric CO_2 in steelmaking**
  Further technical and economic feasibility studies into the use of lower-grade iron ores would provide a more abundant source of slag for CO_2 capture through carbonation. Extending these studies to consider alternative low-carbon reductants, including hydrogen and biomass, will help determine the most effective methods to reduce reliance on fossil fuels in steel production.

- **DAC development**
  Benchmarking DAC technologies through experimental benchmarking with demonstration units, starting from the laboratory scale. High-fidelity modelling and optimisation tools are needed to enable accurate process performance characterisation and identification of optimal process design whilst enhancing energy efficiency and integration into wider systems. More extensive data collection on sorbent properties is critical for improving process energy costs.

Collaborative approach and effective data sharing

A collaborative approach is crucial to weaving together the technical, societal, environmental and political efforts through targeted research, policy adjustments, and stakeholder engagement. To achieve this requires effective data sharing among industries, researchers, and policymakers and this will be essential to guide long-term strategies and foster innovation.

Interdisciplinary collaboration forums, and equitable and just transitions

Sharing outcomes from long-term experimental operations and developing robust datasets on material properties will improve decision-making and accelerate technology readiness.

Establishing interdisciplinary collaboration forums for co-creation among experts and stakeholders will help address complex challenges and create clear policy roadmaps. Efforts must prioritise equitable and just transitions for rural and industrial communities, ensuring social acceptance and economic benefits.

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 number.

◗ — Principal investigator

Project ID	Project name	Researchers	
MIP 2.6	Integrated assessment of BECCS in context: environmental, policy, regulatory and social factors	Clair Gough ◗, Sarah Mander, Diarmaid Clery, Muir Freer, Abhilasha Fullonton, Lisa Bell	University of Manchester
MIP 6.6	Process intensification of CO_2 capture with bioenergy using rotating packed bed (PICCABU)	Muhammad Akram ◗, Mohamed Pourkashanian, Lin Ma, Kris Milkowski, Maria Fernanda Rojas-Michaga, Janos Szuhanszki	University of Sheffield
		Jonathan Lee	Newcastle University
MIP 8.2	Industrial NETs using alkaline materials	Phil Renforth ◗, James Campbell, Mijndert Van der Spek, Mohammad Madankan	Heriot-Watt 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 8.4/ IA 4.4	Where to locate new bioenergy with carbon capture and storage? A natural capital approach	Lindsay-Marie Armstrong ◗, Gail Taylor ◗	University of Southampton
		Brett Day	University of Exeter
		Caspar Donnison	UC Davis
MIP 8.6	Integrated design and optimisation for nationwide deployment of direct air capture units	Ronny Pini ◗, Maria Papathanasiou, Adam Ward	Imperial College London
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

Project ID	Project Name	Outputs	
MIP 2.6	Integrated assessment of BECCS in context: environmental, policy, regulatory and social factors	Integrated assessment of BECCS in context: environmental, policy, regulatory and social factors	Webinar
		Co-deployment of bioenergy with carbon capture and storage in the UK: Growth or gridlock?	Journal
MIP 8.2	Process intensification of CO_2 capture with bioenergy using rotating packed bed (PICCABU)	Measurements in geochemical carbon dioxide removal	Guidance
		Remediating the sky: the role of geoenvironmental engineers and applied geoscientists in geochemical carbon dioxide removal	Journal
		CO_2 removal could result in the use of lower-grade iron ore in a decarbonised net-negative emission steel industry	
		Quantifying CO_2 removal at enhanced weathering sites: A multiproxy approach	
		An inventory of UK mineral resources suitable for enhanced rock weathering	
		Geochemical negative emissions technologies	
MIP 8.3	BECCS-to-sustainable aviation fuels (SAF)	Bioenergy with carbon capture and storage (BECCS) potential in jet fuel production from forestry residues: A combined Techno-Economic and Life Cycle Assessment approach	Journal
		Sustainable aviation fuel (SAF) production through power-to-liquid (PtL): A combined techno-economic and life cycle assessment	
MIP 8.4/ IA 4.4	Where to locate new bioenergy with carbon capture and storage? A natural capital approach	Sustainable land-use delivery of bioenergy with carbon capture and storage (BECCS)	Webinar
		Land-use change from food to energy: Meta-analysis unravels effects of bioenergy on biodiversity and cultural ecosystem services	Journal
		Expert workshop gives a reality check on bioenergy with carbon capture and storage (BECCS): trust, demand, and collaboration are critical	Report & video
MIP 8.6	Integrated design and optimisation for nationwide deployment of direct air capture units	Embedding flexibility to the design of pressure-vacuum swing adsorption processes for CO_2 capture	Journal
		Operability-economics trade-offs in adsorption-based CO_2 capture processes	
		The impact of design and operational parameters on the optimal performance of direct air capture units using solid sorbents	
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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