Industrial Decarbonisation Frontiers Report

Industrial Heat and Energy Efficiency

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 Industrial Heat and Energy Efficiency.

Published April 2025

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Executive summary

With industrial processes currently representing 23% of the UK's total heating demand, pathways to improve energy efficiency and to decarbonise heating and cooling processes are critical to achieving the UK's net zero targets by 2050. This report explores advancements in industrial heat and energy efficiency through research carried out by the Industrial Decarbonisation Research & Innovation Centre (IDRIC), focusing particularly on decarbonisation strategies within the UK's industrial clusters.

The report highlights IDRIC's research on energy systems modelling and optimisation, waste heat recovery and energy storage, fuel switching, and infrastructure and systems integration, alongside emerging workforce considerations.

Key findings

Energy systems modelling and optimisation for industrial clusters
Through integration of optimised energy configurations, electrified heating, and renewable energy generation, dramatic reductions in costs, emissions, and heat losses can be achieved.

Waste heat recovery and energy storage
Technologies such as mobile thermal energy storage (MTES) and enhanced compressed air systems have shown significant potential to reduce industrial energy waste and lower operational costs.

Sustainable fuels
Hydrogen, ammonia, and biomass all show significant promise as alternative fuels for industrial process, but challenges in integration into existing systems, safety considerations and regulatory frameworks need to be addressed.

Infrastructure development
Viable fuel switching options are highly dependent on place. Dispersed industrial sites may not have access to increased power, hydrogen production facilities, or CO2 transport, and therefore require targeted infrastructure planning to enable fuel switching.

Workforce and training
A continuing professional development (CPD) module has been developed and deployed to upskill industry professionals on low-carbon heating and cooling technologies. Additional CPD modules will further enhance workforce's expertise and better prepare them for the challenges of decarbonising the industry.

Recommendations for industry

Enhance waste heat recovery and utilisation through synergistic processes and on-site energy storage solutions.

Invest in alternative fuels, such as low- and net zero carbon hydrogen and ammonia, as key decarbonisation vectors.

Adopt integrated decarbonisation systems using a whole-system approach and integrating synergistic technologies.

Develop predictive analytics and advanced control systems to optimise resource use and minimise emissions.

Recommendations for policymakers

Support diverse heating technologies, beyond heat pumps, enabling industries to adopt solutions tailored to their specific requirements.

Introduce incentives to promote the adoption of sustainable fuels and accelerate the development of regulatory frameworks to promote their safe and effective use.

Foster cross-sector collaboration to leverage synergies between sectors and support the development of shared infrastructure.

Expand funding to support the rapid testing and scaling of innovative green technologies in industrial contexts.

Address skills gaps to ensure the workforce is adequately trained to deploy and maintain new technologies.

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Introduction

In 2019, UK industry sectors released approximately 61 million tonnes of carbon dioxide equivalent ($MtCO_{2e}$) from production processes and fuel combustion alone[1]. This figure would be significantly higher if emissions from electricity generation and fuel supply were included.

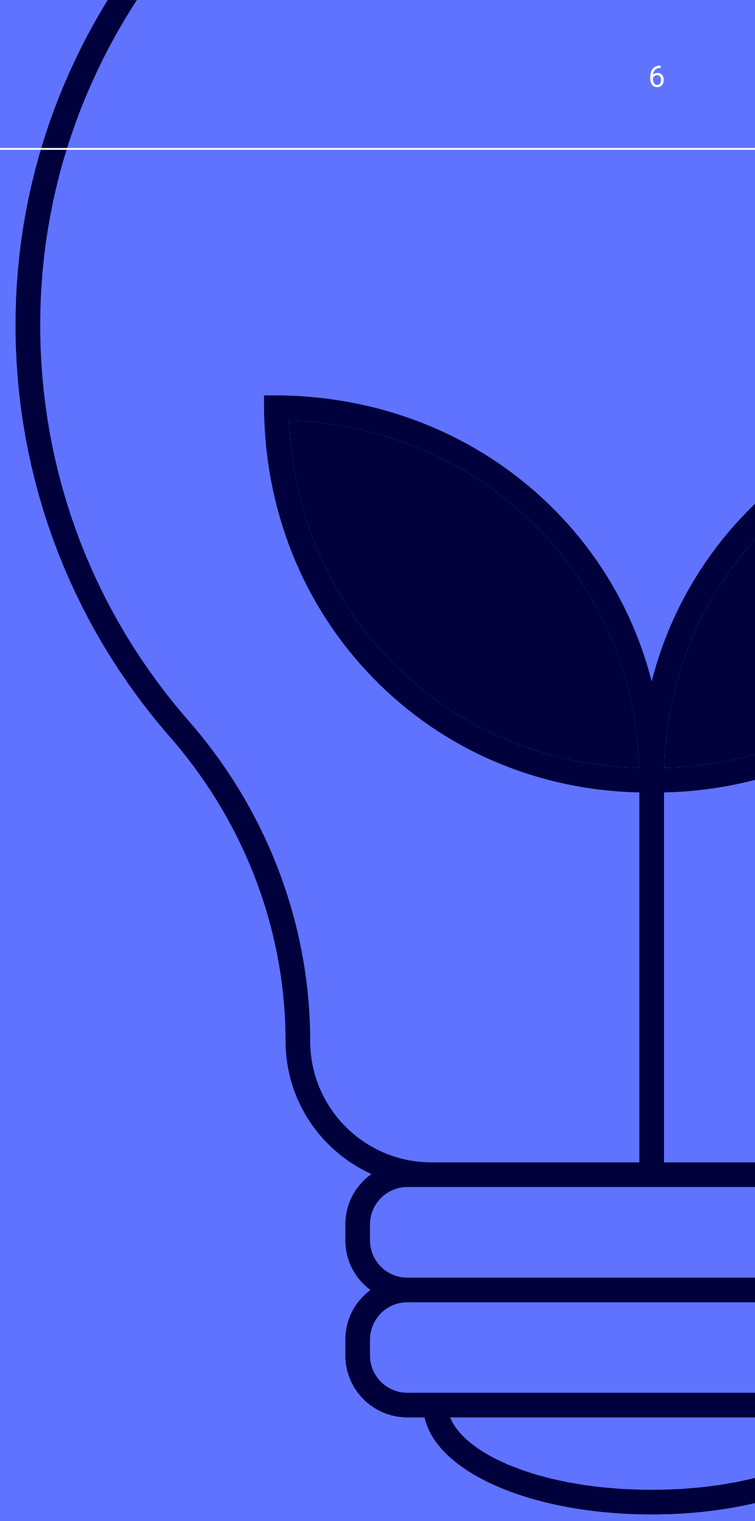


Figure 1 illustrates the greenhouse gas emissions released by individual industrial sectors, which are energy intensive and heavily reliant on fossil fuels.

In the UK, these industry sectors account for approximately 18% of the nation's total annual energy consumption. Of the 270 TWh consumed in 2019 (down from 314 TWh in 2010),[3] 54.1% and 4.1% of energy were used to meet heating and cooling demand (146 TWh and 11 TWh) respectively.[4] The heating demand – representing 23.2% of the UK's total heating demand – is currently met by a combination of gas (49.7%), electricity (25.9%), solid fuel (5.4%), oil (4.1%), bioenergy and waste (9.5%), and direct heat (5.4%). This energy is used for low- and high-temperature processes (37.7% and 22.6%, respectively), drying and separation processes (12.3%), space heating (12%), and other industrial uses (14.4%) whilst the cooling demand is supplied entirely by electricity (Figure 2).[4] These industrial processes collectively release approximately 62 TWh waste heat per year through exhaust, cooling liquid, and radiant heat.[4]

In line with the national commitment to net zero by 2050, the UK's industrial clusters in Teesside, Humberside, South Wales, Merseyside, Grangemouth, Southampton, and Black Country, have been collaborating with academics to explore decarbonisation strategies through research and innovation, as evidenced by significant governmental backing through IDRIC projects. These research and innovation projects, as highlighted in this section, can drive the development of low- and zero-carbon industries, attract investment, and create jobs, while also reducing emissions, altogether positioning the UK as a key player in the global shift towards a green economy.

1 Accredited official statistics — Final UK greenhouse gas emissions national statistics: 1990 to 2022. Final estimates of UK territorial greenhouse gas emissions; Department for Energy Security and Net Zero
2 C. Ogwumike et al., "Transitioning or tinkering at a net-zero economy? Introducing an assessment framework for industrial cluster decarbonisation in the United Kingdom," (2024) Energy Research & Social Science, 110: 103459
3 UK Energy in Brief; Department for Business, Energy & Industrial Strategy
4 Opportunity areas for district heating networks in the UK — National Comprehensive Assessment of the potential for efficient heating and cooling", Department for Business, Energy & Industrial Strategy, London, 2021; Department for Business, Energy & Industrial Strategy

Figure 1

Greenhouse gas emissions by industrial sectors in the UK.[2]

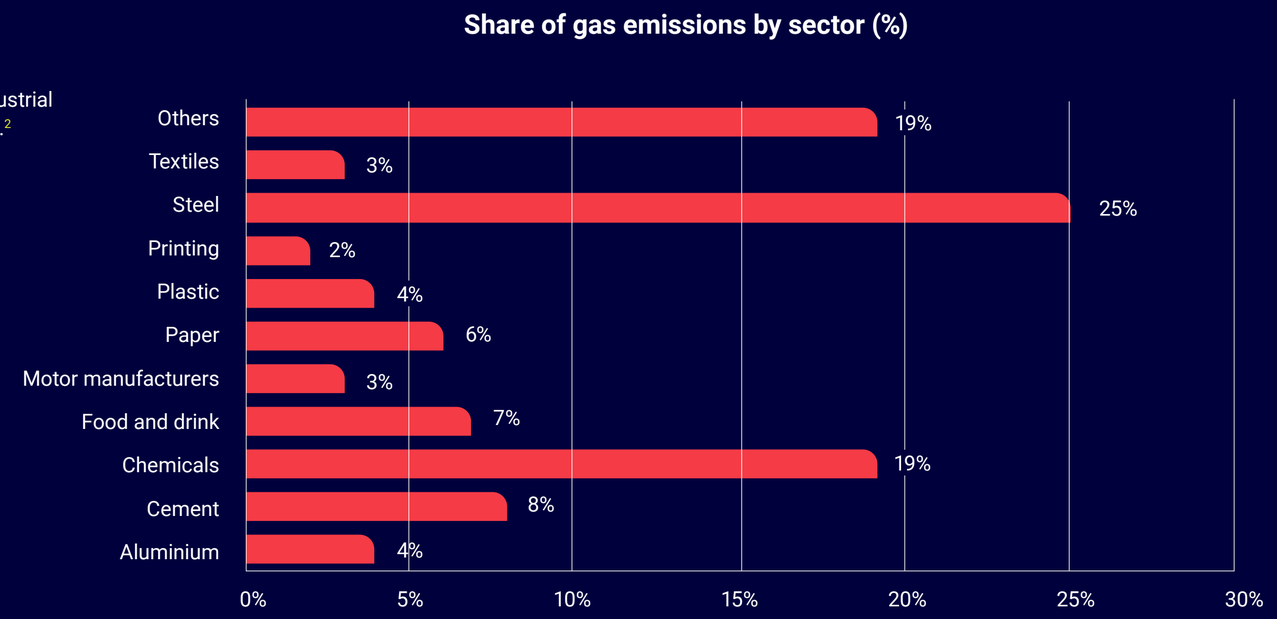
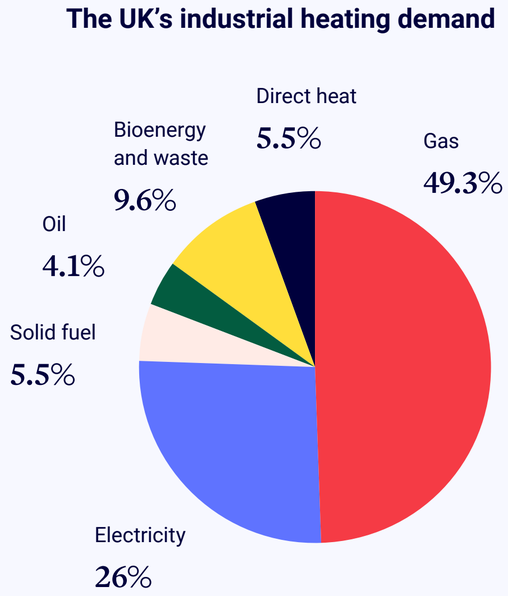
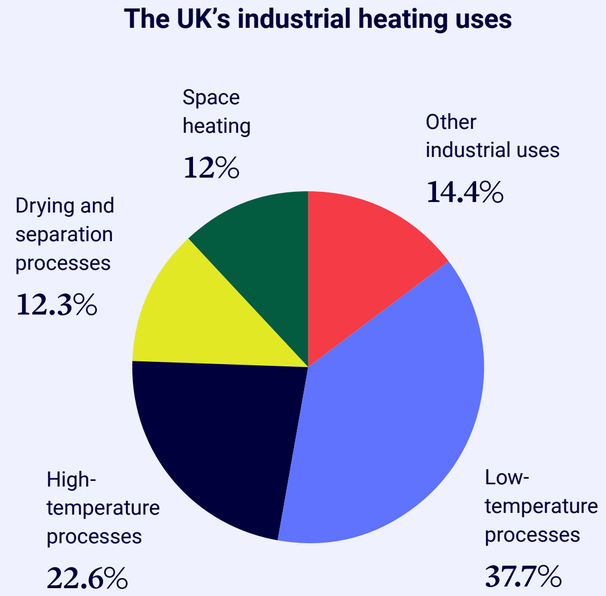


Figure 2

Breakdown of energy sources meeting the UK's industrial heating demand, and of the UK's industrial heating uses.





Research findings

Various aspects of industrial decarbonisation have been explored by IDRIC to address innovative solutions for reducing emissions, improving energy efficiency, and promoting sustainable practices. The research findings showcase advancements in energy systems, energy management, sustainable fuels and training resources – forging a path to a sustainable, low-carbon industrial future as summarised below.

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

Project ID	Project name
MIP 1.1	An integrated energy system planning tool for net-zero industrial clusters
MIP 2.3	Systems, infrastructure and technologies for providing low-carbon fuels to industry in the UK
MIP 3.1	A smart decision modelling (SDM) tool for industrial cluster decarbonisation
MIP 4.1	Mobile energy stored as heat (MESH)
MIP 4.2	A flexibly integrated solution for gas compression and industrial thermal processing decarbonisation
MIP 4.5	CPD module development on industrial heating and cooling
MIP 5.1	Ammonia and hydrogen use for industrial heat and power generation — Part I
MIP 5.1	Ammonia and hydrogen use for industrial heat and power generation — Part II
MIP 7.7	Enabling low carbon fuel technology deployment for power and high-temperature heat across the clusters
FF 1-1	High-efficiency green hydrogen production and compression for industrial decarbonisation
FF 1-12	Synergistic process for carbon capture, waste heat recovery and hydrogen production
FF 2-2	Determining optimum pyrolysis condition 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 4-2	Hydrogen: v of the future
FF 4-16	Enabling sustainable cooling and heating across the Tees Valley industrial cluster
IA 2-1	Decarbonising UK industrial clusters with a mobile thermal energy storage system

Optimised energy configurations within a cluster could cut industrial costs by 80%, emissions by 49%, and heat losses by 72%.

Energy systems modelling and optimisation

Modelling cluster configurations offers better understanding for strategic planning and investment. For instance, through optimised energy configurations developed for a case study cluster, IDRIC project MIP 1.1 demonstrated significant reductions in costs (37%), heat losses (95%), and emissions (21%), alongside a 12% increase in energy efficiency. When electrified heating and renewable generation were integrated in grid mode, reductions were even more dramatic—costs, emissions, and heat losses fell by 80%, 49%, and 72%, respectively.

IDRIC project MIP 2.3 modelling estimates an increase in electricity demand in all regions by 50-70% compared to current gas demand (Figure 3). Hydrogen demand would range from 8-37% of existing gas levels, predominantly near Merseyside, Humberside, and other major industrial conurbations (West Midlands, West Yorkshire). Additionally, demand for carbon capture, utilisation, and storage (CCUS) would remain steady, especially for cement and brick sectors.

The framework developed in project MIP 3.1 emphasised stakeholder perspectives in assessing energy transition feasibility within industrial clusters.

Figure 3

Fuel demand model based on preliminary results: Baseline scenario is technology agnostic and allows the model to progress in default manner.

Enhanced Hydrogen scenario models positive frameworks and policies allowing faster hydrogen deployment (MIP 2.3).

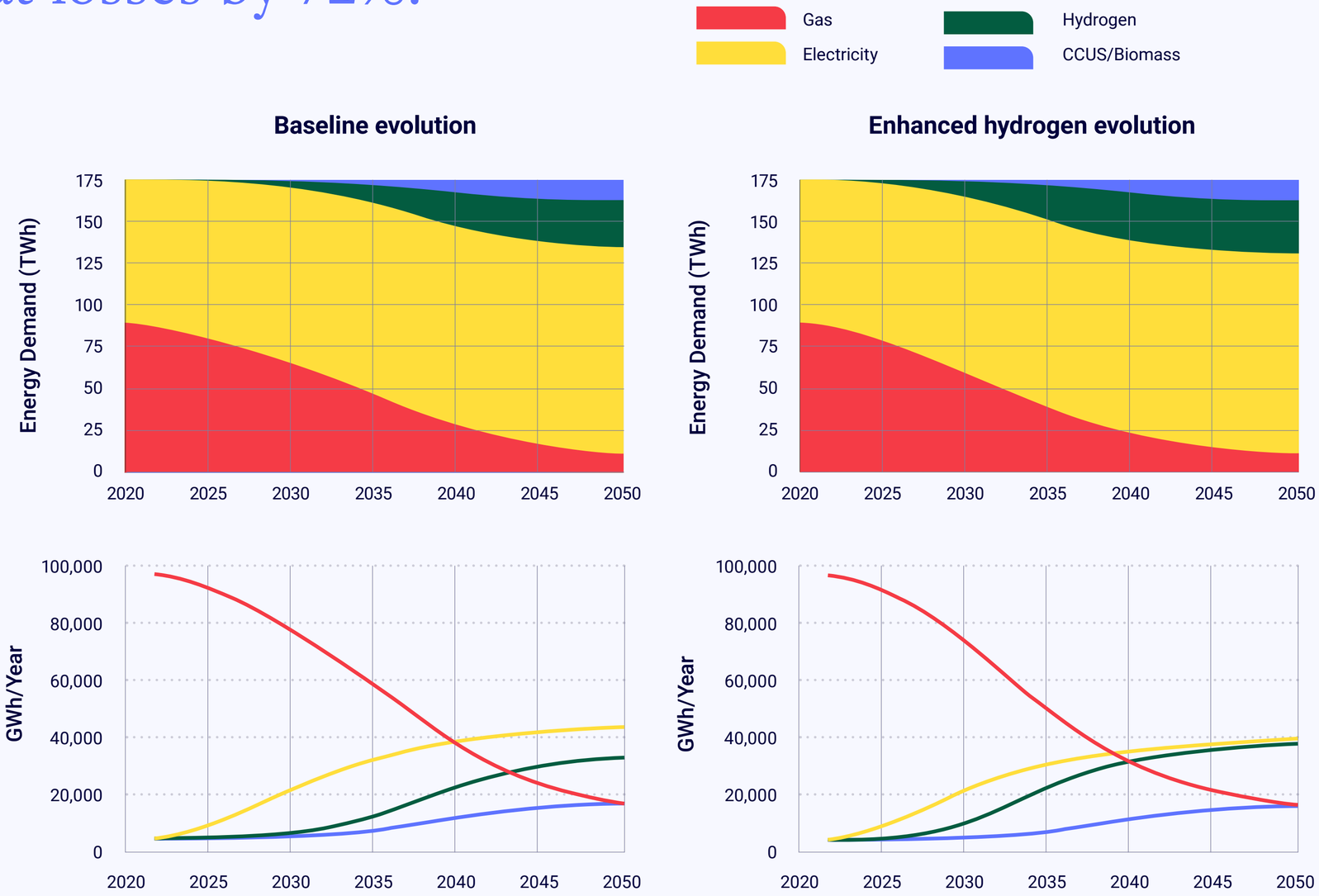
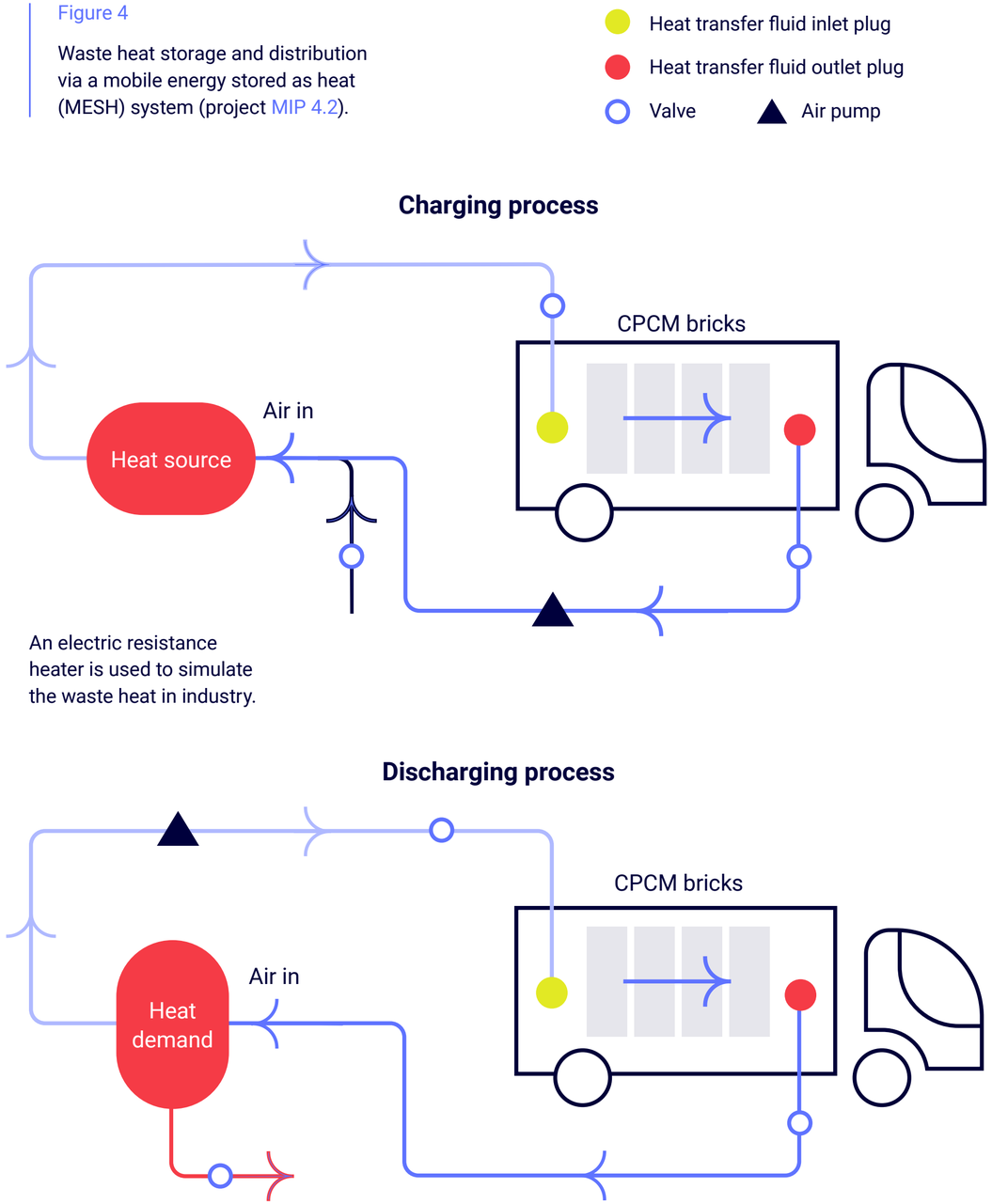


Figure 4

Waste heat storage and distribution via a mobile energy stored as heat (MESH) system (project MIP 4.2).



An electric resistance heater is used to simulate the waste heat in industry.

Capturing low-grade waste heat from industrial sites like Tata Steel's plant in Port Talbot could supply heating for 33,000 homes annually.

Waste heat recovery and advanced energy storage

The potential for capturing, utilising and storing low-grade waste heat from gaseous waste streams was explored for efficient energy recovery. For example, using thermochemical materials, IDRIC project MIP 4.1 demonstrated that low-grade waste heat from industrial sites like Tata Steel's plant in Port Talbot could supply heating for approximately 33,000 homes annually where the transport of this waste heat within a 30-mile radius would be feasible.

Given the typically low energy efficiency of industrial air compression (around 10%, which accounts for approximately 10% of the total industrial energy use), an enhanced air compression system could offer significant improvements. The system developed in project MIP 4.2 integrating compressed air and heat storage could boost efficiency to 35% and reduce cost by up to 40%. The mobile thermal energy storage (MTES) technology, also developed in project MIP 4.2 utilising composite phase change materials (CPCM) to store and transport waste heat could further support decarbonisation of industrial heat (Figure 4).

The waste heat recovery case study carried out in project FF 4-16 demonstrated that using heat pump systems for crisp frying could heat vegetable oil to 160°C, achieving a payback period of 8.5 months.

These advancements all present a practical path to utilising industrial waste heat.

Biochar offers the potential for carbon-negative steel production — but only if supply chains are developed now.

Sustainable fuels: Hydrogen, ammonia and biomass

Research into sustainable fuels highlights the potential for ammonia, hydrogen, and biomass as clean alternatives across various industrial applications.

Exploring ammonia's feasibility as a combustion fuel, IDRIC project MIP 5.1 Part I identified strategies for reducing NOx emissions by controlling the air/fuel ratio at varying pressures, proposing diverse injection systems tailored to specific applications and underscoring the need for adaptable, scenario-specific solutions.

Project MIP 5.1 Part II converted internal combustion engines to operate on hydrogen fuel, developed a novel method for early detection of impending thermoacoustic oscillations in gas turbines (which pose a limiting factor on the introduction of hydrogen fuel), and proposed a new approach to controlling the ignition of lean mixtures using a zero-carbon additive, hydrogen peroxide (H_2O_2). Complementing this, project MIP 7.7 examined the transition from natural gas to hydrogen, showing that heat transfer in hydrogen flames would rely more on convection than radiation, a factor potentially impacting certain industrial processes, and concluding that training for operators, proof-of-concept testing, and dedicated R&D facilities as essential resources to support the fuel-switching transition. The model developed in project FF 1-1 for a metal hydride compressor integrated with a PEM electrolyser demonstrated potential for green hydrogen generation with increased efficiency through heat recovery, another key step in decarbonising energy-intensive sectors.

Biochar is a sustainable alternative to metallurgical coal, with the potential to achieve carbon negativity by utilising biogenic carbon from biomass cultivated on rewetted peatlands through land-use change. Project FF 2-2 demonstrated that optimising the pyrolysis process can develop biochar with coal-like properties, offering a viable decarbonisation pathway for hard-to-abate industries, such as iron and steel, and enabling the possibility of carbon-negative steel production. The study on fuel type interoperability in project FF 4-2 showed uniform combustion across the pilot chamber, thus validating the practicality of shifting to cleaner fuel sources without major modifications to existing systems.

Together, these projects showcase the diverse applications of ammonia, hydrogen, and biomass, supporting a sustainable transition across industrial sectors.

For dispersed industries, access to hydrogen, power, or CO_2 transport is not guaranteed — targeted planning is essential.

Infrastructure and systems integration

For different fuel switching options to be viable, appropriate infrastructure needs to be in place, which will depend on location. This is especially important for dispersed industries responsible for 55% of emissions that may not have access to increased power, hydrogen production facilities, or CO_2 transport. Analysis of technology and demand scenarios, as demonstrated in IDRIC project MIP 2.3, can help identify where future infrastructure could enable fuel switching across the UK. By integrating carbon capture and waste heat recovery from flue gases in steel and chemical sectors as well as producing hydrogen, the system investigated in project FF 1-12 not only achieved a 40% energy efficiency gain and lowered emissions – it also demonstrated scalability through a study of a pilot system.

The CPD module developed by IDRIC features is designed to upskill professionals in low-carbon heating and cooling technologies. It uses real-world industrial case studies and covers a range of existing and emerging technologies.

Supported by

Durham University

TETRA TECH RPS ENERGY

IDRIC Decarbonisation of Heating and Cooling eLearning Course

Modules covered by the course

1. **The importance of heating and cooling for decarbonisation**
2. **Space heating and cooling fundamentals**
3. **From thermal demand reduction to net-zero**
4. **Heat from gas — Toward hydrogen, carbon capture and storage**
5. **Heat pump — Vapour compression heat pump**
6. **Heat pump — Adsorption heat pump (AHP)**
7. **Techno economics of heating/cooling systems**
8. **Solar collectors and solar driven heating systems**
9. **Thermal energy storage**
10. **Integrated energy systems, heating and cooling networks**

A CPD module has been created to upskill industry professionals in low-carbon heating and cooling — building the workforce of the future.

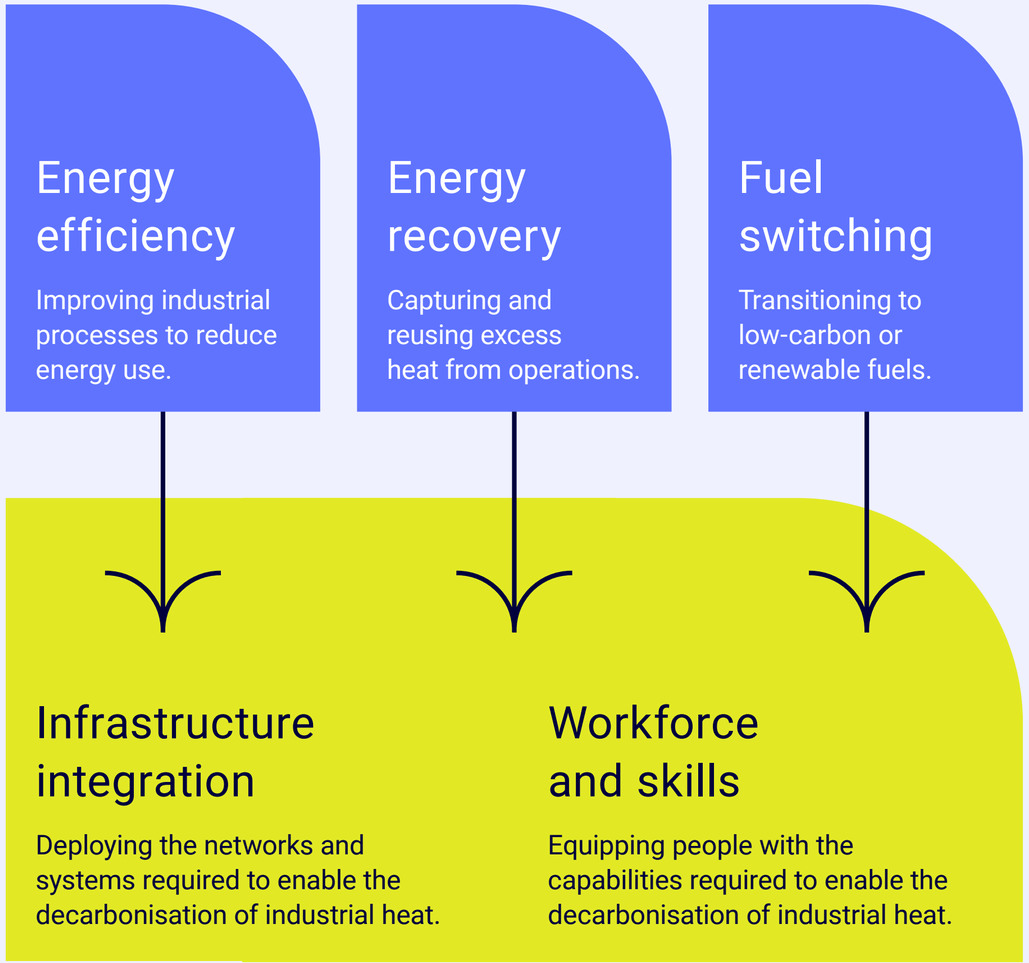
Training and development for decarbonisation technologies

The industry-focused continuing professional development (CPD) module developed in IDRIC project MIP 4.5 featured real-world industrial case studies, upskilling industry professionals whilst enhancing their awareness and understanding of low-carbon heating and cooling technologies to bolster the decarbonisation agenda. The Decarbonisation of Heating and Cooling eLearning Course is available through the RPS Learning Hub.

The findings described so far in this report reveal the transformative potential achievable in the UK, with implications spanning multiple domains, as summarised in Figure 5.

Figure 5

Key industrial heat decarbonisation pathways and enablers addressed across IDRIC's research portfolio.



Resource use and energy recovery

The UK steel industry's transition to electric arc furnaces presents an ideal opportunity to adopt biochar as a carbon-negative coal alternative, which has lower contamination levels such as sulphur content, but achieving this integration successfully will require a well-developed biomass/biochar supply chain to avoid costly retrofits in the future (project FF 2-2). Space heating, gas consumption, as well as the carbon footprint of buildings can be significantly reduced if the waste heat from industries such as steel–which is currently vented to the atmosphere–is utilised with correct investment (project MIP 4.1).

As the UK's industrial clusters produce around 48 TWh of waste heat annually,[5] the CPCM-based mobile thermal energy storage system, proposed by project MIP 4.2, could capture this heat, transport it to end users, and release it for heating. Broad industrial adoption across temperature ranges could be achieved through scalable CPCM fabrication and adaptable formulations, further reducing fossil fuel dependence and emissions. The demonstration of heat pumps achieving high coefficient of performances (COPs) also offer scalable applications for wider industry sectors, particularly those involving high-temperature processes (project FF 4-16). For hydrogen combustion systems, it is worth noting that existing high-temperature industrial processes may not require any substantial change in the physical structure of the plant. The total radiative exchange is a key factor for high temperature processes (project FF 4-2).

5 The potential for recovering and using surplus heat from industry. Department of Energy & Climate Change. 2014

Energy efficiency and emissions reduction

IDRIC project MIP 1.1 modelled heat and power demands of a dynamic hybrid cluster, assessing heat electrification, renewables, and fuel switching in both grid-connected and island modes. The results underscore substantial energy efficiency and emissions reductions through optimised generator operations (achieving up to 95% savings in steam losses and a 25% reduction in primary energy demand) and electric steam boiler integration (reducing costs by 75% and emissions by 50%) while using green hydrogen further cuts emissions but significantly increased costs.

Fuel switching

Metal hydride compressors can achieve high hydrogen compression using low-grade waste heat, which would reduce energy consumption and costs in hydrogen production and delivery when integrated with Proton Exchange Membrane (PEM) electrolysers (project FF 1-1). Integrating hydrogen production and carbon capture not only reduces greenhouse gas emissions and energy waste, but also lowers the cost per tonne of CO_2 captured and optimises heat management, while generating value-added products that provide economic benefits for industries and, particularly in sectors that are difficult to electrify, supporting the broader transition to cleaner energy systems (project FF 1-12). The early detection of thermoacoustic oscillations in gas turbines enables the use of hydrogen. The use of H2O2 as a zero-carbon additive can improve internal combustion engine performance (project MIP 5.1 Part II).

As the UK's industrial sector transitions to hydrogen for process heating, there is a risk of product quality being affected due to changes in heat release location, necessitating a broader strategy beyond simply retrofitting 'hydrogen-ready' burners and requiring specialised expertise delivered through fuel switching centres integrated into clean growth hubs across industrial clusters (project MIP 7.7). Using ammonia to store energy could decrease hydrogen delivery needs, but significant safety considerations are necessary for large-scale ammonia storage – and regulatory frameworks are still evolving to support its use in fuelling applications (project MIP 5.1 Part II).

Infrastructure and regional planning

Whilst key performance indicators (KPIs) for decarbonisation projects vary widely between industrial clusters, a framework that is applicable and adaptable to different industrial settings for industrial clusters worldwide could foster a standard approach to industrial decarbonisation (project MIP 3.1). With hydrogen infrastructure becoming essential on a national scale by the early 2030s, urgent electricity infrastructure upgrades are recommended whereas regional and local planning laws must support the establishment of hydrogen hubs. CCUS and biomass applications should be prioritised in rural and geographically constrained sites (project MIP 2.3).

Workforce empowerment

To implement advanced low-carbon technologies effectively, there is a need for in-depth, specialised content and reliable information to equip industry professionals with skills and the awareness of industrial decarbonisation options, a culture of professional development as well as greater financial support from industry and government to ensure the workforce can address decarbonisation challenges (project MIP 4.5).

Recommendations to industry

Based on IDRIC’s research findings in industrial heat and energy efficiency, we make the following recommendations to industry to facilitate the transition towards a more sustainable industrial sector, as well as highlighting areas requiring further exploration.

Key recommendations

1. Enhance waste heat recovery and utilisation through synergistic processes and on-site energy storage solutions.
2. Invest in alternative fuels, such as low- and net zero carbon hydrogen and ammonia, as key decarbonisation vectors.
3. Adopt integrated decarbonisation systems using a whole-system approach and integrating synergistic technologies.
4. Develop predictive analytics and advanced control systems to optimise resource use and minimise emissions.

Harnessing waste heat can reduce total energy consumption in industrial sectors, thereby improving energy efficiency without compromising production, and significantly lowering greenhouse gas emissions. However, this poses a substantial challenge due to the complexity of bespoke industrial processes employed by different sectors, as well as the high costs associated with energy-efficient equipment and innovative technologies, in addition to the significant knowledge and skills gaps faced by the sectors.

Other measures to decarbonise industrial sectors include integrating energy storage, transitioning to net zero or low-carbon fuels, increasing the share of renewable energy, electrifying industrial heat, and adopting CCUS. Since conventional systems are largely reliant on fossil fuels, these strategies will require better understanding through a whole-system approach, predictive analytics, and advanced control, retrofitting production plants and redesigning operational systems (as described below). Thus, achieving net zero will demand not only technological innovation, but also cross-sector collaboration, policy support, and significant financial investment.

The following insights highlight actionable strategies and potential areas for development to drive progress in decarbonisation, particularly within the UK, while also considering international best practices.

Enhance waste heat recovery and utilisation

The re-evaluation of waste heat capture and utilisation is crucial for reducing energy waste and may create alternative revenue streams for large-scale operations. Industries should focus on optimising waste heat recovery systems and adopting on-site energy storage solutions, such as thermal energy and compressed air storage, to achieve more flexible and cost-effective operations.

By leveraging waste heat recovery, industries can not only reduce their carbon footprint but also enhance operational efficiency, thus aligning with broader sustainability goals. The use of synergistic systems that combine waste heat recovery with other low-carbon technologies can further optimise energy use across industrial processes.

Piloting small-scale demonstration projects – as previously supported by the Industrial Energy Transformation Fund in the UK – is recommended as a starting point, allowing industries to assess feasibility and scalability before fully committing to large-scale capital investments and applications.

Industries should invest in synergistic technologies that integrate carbon capture, waste heat recovery, and hydrogen production.

Invest in alternative fuels as a key decarbonisation vector

Hydrogen-based fuels offer significant potential as zero-carbon vectors, especially in process heating applications; however, the transition requires careful consideration of how changes in heat release impact existing industrial processes, as highlighted in IDRIC project MIP 7.7.

Industrial collaboration is recommended to develop testing and proving resources for hydrogen infrastructure, which will reduce uncertainties and foster a more widespread adoption of hydrogen-based solutions. This collaborative approach could help industries identify optimal strategies for fuel switching, which is critical for hard-to-abate sectors like heavy industry and transportation.

To further facilitate this transition, industries should consider investing in hydrogen compression technologies, such as metal hydride systems, which can enhance the efficiency and sustainability of hydrogen production and delivery. Research and development into integrating PEM electrolysis with metal hydride compression, as noted in project FF 1-1, could provide a more cost-effective and efficient method of producing pressurised hydrogen for industrial use.

Ammonia also presents a viable alternative as a hydrogen energy carrier, particularly in industries reliant on energy-intensive combustion processes where hydrogen infrastructure is underdeveloped, and hydrogen combustion poses challenges. Assessing the feasibility of using ammonia as a working fluid or fuel (in applications like steelmaking or power generation) could unlock new pathways for decarbonisation. Industries are encouraged to conduct pilot studies to evaluate the practical use of ammonia in their operations, particularly in settings where conventional hydrogen use may not be feasible.

Adopt integrated decarbonisation systems through a whole-system approach

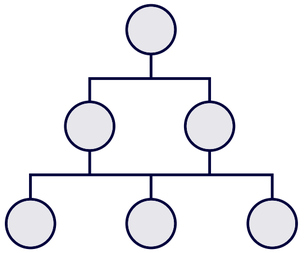
Industries should invest in synergistic technologies that integrate carbon capture, waste heat recovery, and hydrogen production. The combination of these systems can maximise resource efficiency and reduce overall emissions, as demonstrated in projects such as FF 1-12, where integrated approaches have shown significant potential in enhancing both energy efficiency and environmental performance.

By fostering cross-sector collaborations, for instance between hydrogen production and power generation, industries can optimise shared infrastructure for carbon management and energy recovery, thereby reducing costs and achieving more sustainable operations.

Additionally, industries should explore adopting scalable energy solutions, such as the transcritical CO_2 heat pumps tested in IDRIC project FF 4-16, which have demonstrated substantial CO_2 savings while offering relatively short payback periods.

Partnering with research institutions to develop customised energy models can further tailor these solutions to specific industrial needs, ensuring that technological advancements translate effectively into practical applications.

A holistic, whole-system approach to reducing emissions is essential for achieving long-term sustainability. Industries should carefully evaluate the long-term impacts of their decarbonisation initiatives, considering both environmental and economic factors before implementation.



Develop predictive analytics and advanced control systems

There is a critical need to enhance data collection and predictive analytics to help industries quantify benefits, optimise investments, and reduce risks and uncertainties associated with new technology deployments. Industries are recommended to leverage these capabilities to make more informed decisions during their planning, design, and implementation of decarbonisation strategies, particularly in complex projects.

The integration of advanced control systems into multi-vector energy systems offers promising applications for managing interconnected industrial components, as suggested in IDRIC project MIP 1.1. Industries should also explore the development of integrated cluster models that incorporate storage technologies to improve system resilience and efficiency, further optimising resource use and minimising emissions.

Address gaps and future areas of focus

While the recommendations above outline clear pathways for industries to advance their decarbonisation efforts, several gaps still need addressing.

For example, industries should embed CPD into their corporate culture, encouraging ongoing training and tracking individual progress to align employee skills with business strategies.

Additionally, there is a need for standardised specification and design procedures to ensure that retrofitting existing process plants with greener technologies deliver the process capability required. This general observation, based upon experience of retrofitting combustion systems for different fuels, would ensure consistency and efficiency of equipment supply across sectors.

Future research and development should expand the integration of predictive analytics into industrial systems to optimise technology pathways and minimise risks.

By addressing these gaps, industries can accelerate their journey towards achieving net zero targets while maintaining competitive advantage.

Developing predictive analytics and advanced control systems can unlock efficiency and emissions reductions across industrial clusters.

Recommendations to policymakers

Drawing on insights gained from these projects, the following recommendations are made for policymakers, highlighting the critical areas where government intervention is needed to drive decarbonisation.

Key recommendations

1. Support diverse heating technologies, beyond heat pumps, enabling industries to adopt solutions tailored to their specific requirements.
2. Introduce incentives to promote the adoption of sustainable fuels and accelerate the development of regulatory frameworks to promote their safe and effective use.
3. Foster cross-sector collaboration to leverage synergies between sectors and support the development of shared infrastructure.
4. Expand funding to support the rapid testing and scaling of innovative green technologies in industrial contexts.
5. Address skills gaps to ensure the workforce is adequately trained to deploy and maintain new technologies.

Diversify heating technologies

As decarbonising heating systems is crucial, policymakers should consider a range of future heating scenarios to ensure flexibility and resilience in achieving sustainability targets. This means that the transition must explore alternative technologies that could be equally effective as heat pumps and not solely rely on them. This can help industries adopt solutions tailored to their specific requirements, ultimately reducing carbon emissions while maintaining operational efficiency.

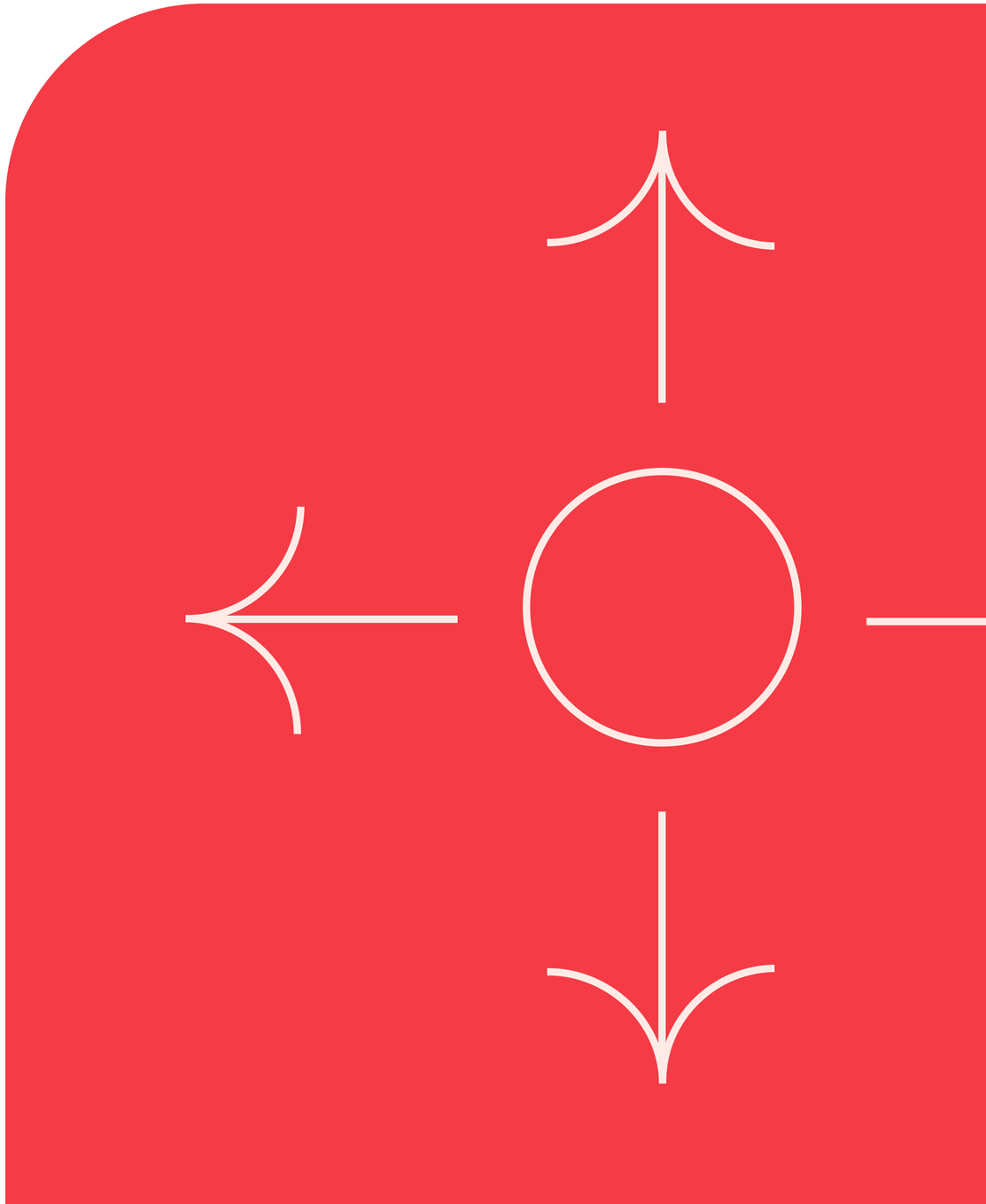
For industries reliant on process heating, fuel switching to low-carbon alternatives remains a significant challenge. Policymakers should allocate resources to support collaborative efforts among industry groups, enabling the testing of hydrogen-based fuels in process heaters over extended periods.

Diversify fuel sources

To foster the adoption of green hydrogen for industrial processes, policymakers should introduce incentives that encourage industries to embrace these solutions. Support for research into innovative methods, such as metal hydride technology for hydrogen compression, will further accelerate this transition. Policies that promote the use of renewable energy sources for hydrogen production are equally critical to ensuring that hydrogen remains a truly sustainable option.

Ammonia's potential as a direct fuel source in combustion systems should be explored, alongside the development of appropriate regulatory frameworks to guide its safe and effective use. This is because ammonia presents a promising opportunity in sectors where hydrogen infrastructure (e.g., pipelines) is currently lacking or where electrification proves prohibitively expensive. As a hydrogen carrier, ammonia should only be considered where it is economically and technically advantageous.

Policymakers should consider the performance of zero-carbon fuels in applications such as gas turbines and internal combustion engines, which are essential for power and heat generation, as well as in the transportation of CO_2 to sequestration sites. By gathering data on operational ranges and efficiencies, government can develop evidence-based policies that support the adoption of zero-carbon energy sources across multiple sectors.



A whole-system approach is essential: energy efficiency, fuel switching, waste heat recovery, and workforce development must all work together.

Promote cross-sector collaboration and whole-systems approaches

The decarbonisation of hard-to-abate industries can be supported by leveraging synergies between different sectors, such as those demonstrated in project FF 2-2 between agri-food and industrial manufacturing. Policymakers should facilitate dialogue among industrial clusters to align policies with sustainable development goals and drive collaborative solutions. Adopting a whole-systems approach that considers the interconnectedness of sectors can yield more efficient and effective outcomes.

Developing shared infrastructure (for hydrogen distribution, carbon storage, and heat recovery in energy-intensive industries, for instance) can significantly ease adoption across multiple sectors. Clear regulatory frameworks are needed to drive the adoption of synergistic processes. Financial and regulatory incentives should be offered to industries that implement these technologies, promoting innovation and cost reduction. To enhance these efforts, cross-sector collaboration between industries, researchers, and government bodies should be encouraged to share knowledge and accelerate the deployment of these technologies.

Enhance grid flexibility

Improving grid flexibility and demand response is essential for a sustainable energy transition, as it will optimise resource efficiency, balance renewable energy variability, and enhance energy security — ultimately supporting a more reliable low-carbon energy system. Financial incentives are key to promoting the adoption of energy-efficient technologies, supporting research and development initiatives, and facilitating pilot programmes to test these innovations. Whilst these measures collectively drive the uptake of flexible grid technologies, robust standards and certification systems ensure their safety, reliability, and performance, thereby encouraging industries to scale up deployment and accelerate the energy transition.

Expand funding for green technologies and research partnerships

To align with the UK's net zero targets, increased funding and grants are needed to support industries in adopting greener technologies – for instance, heat pumps and waste heat recovery systems. Policymakers should simplify access to small funding grants to test seed ideas, to undertake quick wins/fails and move to the next stage quickly. Developing pipelines of projects that retain unfunded submissions for future consideration can ensure that promising research is not overlooked, at the same time as supporting rapid testing and scaling of innovative concepts, thereby fostering continuous progress in decarbonisation.

Encouraging partnerships between academia and industry can enhance research and development of innovative energy solutions, accelerating progress toward sustainability. By fostering collaboration between research institutions and the private sector, policymakers can drive the development of technologies that contribute to long-term environmental goals.

Address skills gaps and workforce development

While significant progress has been made in promoting low-carbon technologies, addressing the practical challenges that industries face in adopting these innovations remains crucial, through equipping industries with the necessary tools and knowledge to overcome barriers, including engineering, financial, and the awareness of technologies. This will ensure that workers are equipped with the technical expertise and knowledge to support a green transition effectively, therefore addressing the skills gap in the workforce.

Ensuring that the workforce is adequately trained to deploy and maintain new technologies is essential for translating research advancements into real-world applications, reducing emissions while maintaining operational integrity. Policymakers should incentivise companies to invest in upskilling their employees through continuous professional development (CPD) training, certifications, and accreditations. This could include tax breaks, grants, or recognition schemes for businesses demonstrating commitment to skills development. By bridging the skills gap, the government can help industries to ensure that technological innovations are deployed efficiently, driving progress towards national decarbonisation goals.

Moving forward

Driving innovation and technology deployment

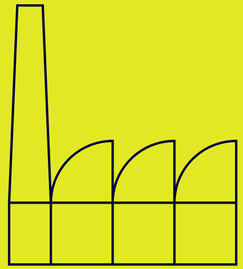
To remain competitive globally, the UK must invest in innovation that can reduce reliance on fossil fuels, and meet its net zero targets efficiently and economically. Research is critical in developing innovative solutions to provide sustainable industrial heating and improved energy efficiency. In addition to the innovation areas recommended in previous sections, understanding how different sectors can adapt their processes to improve efficiency is key to providing tailored solutions.

Low-carbon solutions are still in developmental stages or are not cost-effective for widespread adoption. Advancing these technologies to make them commercially viable and scalable for industrial use is essential. Retrofitting existing industrial systems poses another challenge. For small-scale industrial processes, key challenges also include identifying current and future energy demands, in terms of not only scale but also speed of deployment and understanding inherent uncertainties. Whilst upscaling and demonstrating technologies in low-risk industrial arenas should be prioritised, scenario analysis and machine learning algorithms should be used to explore options and cluster similar regions. This can enable best practice from one area to benefit others, streamlining development plans.

Strengthening collaboration and policy support

Collaboration between the energy sector and industry should consider infrastructure implications, grid upgrade roadmaps, and pathways for implementing CCUS demand and infrastructure. Without case studies demonstrating technical benefits, research and innovation activities are unlikely to be adopted in risk-averse industries. Programmes that foster collaboration between academics and industry are essential in bridging knowledge gaps and aligning innovations with practical needs. The benefits from this come from knowledge and experience — the industrial partners may not be aware of ongoing academic research that could be directly relevant, and conversely, the researchers are not aware of potential limitations and impacts their potential solutions.

It is very challenging for the foundation industries and commodity material suppliers to make investments in new technologies and plants, particularly given the long lifespans of assets (typically many decades). Clarity in national and international policy on decarbonisation, along with increased support covering a higher proportion of capital outlay, is needed to encourage the replacement of older technologies with processes that have lower energy or carbon intensity.



Without case studies demonstrating technical benefits, research and innovation activities are unlikely to be adopted in risk-averse industries.

Ensuring safety, sustainability and social acceptance

Research should also prioritise materials science to assess the impacts of ammonia/hydrogen blends on composites and other materials operating at high temperatures. This will build on existing knowledge of the interaction between hot gases from fossil fuels and materials and extend to use of sustainable low-carbon fuels. Methods to establish the lifespan of materials used in combustor components (e.g., control valves, metering devices, fuel injection and ignition systems, combustor walls, and lubricants) must be developed. This includes evaluating how combustion conditions affect component lifespan, exploring the impact on process operation, productivity, and product quality. Also, demonstrating that the change of fuel type can be managed successfully for energy-intensive processes, establishing guidelines for maintenance and repair, and supporting industrial planning and adoption.

Procedures for economically viable solutions to safely transport hydrogen and ammonia to sites, addressing connections, storage locations, and maintenance are necessary. Using hydrogen and ammonia as fuels poses unique challenges beyond their conventional applications. Ammonia used as fuel will redistribute nitrogen geographically, potentially affecting the nitrogen cycle. The impact on the global nitrogen cycle warrants attention, and further studies are needed to understand the environmental consequences. Existing data from conventional applications will provide the foundation for this research but access to this is very limited, particularly regarding bespoke procedures for plant operations. While safety regulations exist for conventional uses, new regulations are needed to address explosion and toxicity risks. This is important operational health and safety, but also to gain social acceptance, since accidents could lead to public rejection. Operational acceptance is particularly difficult in urban areas, where health and safety concerns are heightened, whereas rural locations provide reduced risk. To ensure environmental compliance and sustainability, NOx emissions released during hydrogen and ammonia combustion must be mitigated through conducting advanced modelling and technology advancement.

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 1.1	An integrated energy system planning tool for net-zero industrial clusters	Janie Ling-Chin ◢, Anthony Paul Roskilly, Yousaf Khalid, Andrew Smallbone, Ugochukwu Ngwaka	Durham University
		Huda Dawood, Nashwan Dawood, Faisal Siddiqui, Ruben Pinedo-Cuenca	Teesside University
MIP 2.3	Systems, infrastructure and technologies for providing low-carbon fuels to industry in the UK	Jonathan Radcliffe ◢, Thomas Fender	University of Birmingham
MIP 3.1	A smart decision modelling (SDM) tool for industrial cluster decarbonisation	Nashwan Dawood ◢, Huda Dawood, Ruben Pinedo-Cuenca, Fathi Abugchem, Chris Ogwumike, Faisal Siddiqui, Adepeju Oyewole	Teesside University
		Sumit Roy, Janie Ling-Chin, Anthony Paul Roskilly, Andew Smallbone	Durham University
MIP 4.1	Mobile energy stored as heat (MESH)	David Worsley ◢, Sahand Hosouli, Jonathon Elvins	Swansea University
MIP 4.2	A flexibly integrated solution for gas compression and industrial thermal processing decarbonisation	Yulong Ding ◢, Yongliang Li, Adriano Sciacovelli, Jonathan Radcliffe, Grant Wilson, Tontong Zhang, Song Yang, Mengqu Bai, Benjamin Gregoire, Hongkun Ma, Robin Fisher	University of Birmingham
		David Worsley, Jonathon Elvins	Swansea University
		Anthony Paul Roskilly, Zhiwei Ma, Ruiqi Wang	Durham University

Project ID	Project name	Researchers	
MIP 4.5	CPD module development on industrial heating and cooling	Huashan Bao, Richard Williams, Andrew Smallbone, Zhiwei Ma, Anthony Paul Roskilly	Durham University
		Joseph Howe	University of Lincoln
MIP 5.1	Ammonia and hydrogen use for industrial heat and power generation — Part I	Philip Bowen, Augustin Valera-Medina, Burak F Goktepe, Steve Morris	University of Cardiff
MIP 5.1	Ammonia and hydrogen use for industrial heat and power generation — Part II	Yannis Hardalupas, Chaoxu Chen, Alex Taylor	Imperial College London
MIP 7.7	Enabling low carbon fuel technology deployment for power and high-temperature heat across the clusters	Richard Marsh, Philip Bowen, Steve Morris	Cardiff University
		Yannis Hardalupas, Alex Taylor	Imperial College London
FF 1-1	High-efficiency green hydrogen production and compression for industrial decarbonisation	Sumit Roy, Andrew Smallbone, Anthony Paul Roskilly	Durham University
FF 1-12	Synergistic process for carbon capture, waste heat recovery and hydrogen production	Binjian Nie, Aidong Yang, Guokun Liu, Zi Huang	University of Oxford
FF 2-2	Determining optimum pyrolysis condition 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, Souvik Roy, Louis Mitchell, Aliyu Aliyu, Joe Howe	University of Lincoln
FF 4-2	Hydrogen: Industrial furnace fuel of the future	Andy Heeley, Abdulaziz Gheit, Kris Milkowski, Janos Szuhanzski, Karen Finney, Karim Elamawy, Ihab Ahmed	University of Sheffield
FF 4-16	Enabling sustainable cooling and heating across the Tees Valley industrial cluster	Kumar Patchigolla, Nashwan Dawood, Gari Harris	Teesside University
IA 2-1	Decarbonising UK industrial clusters with a mobile thermal energy storage system	Yulong Ding, Tongtong Zhang, Megnqi Bai, Song Yang, Benjamin Gregoire	University of Birmingham

Project ID	Project name	Outputs	
MIP 1.1	An integrated energy system planning tool for net-zero industrial clusters	Industrial cluster energy systems integration and management tool	Journal
MIP 2.3	Systems, infrastructure and technologies for providing low-carbon fuels to industry in the UK	Industrial energy infrastructure for a decarbonising Britain	Webinar
MIP 3.1	A smart decision modelling (SDM) tool for industrial cluster decarbonisation	Transitioning or tinkering at a net-zero economy? Introducing an assessment framework for industrial cluster decarbonisation in the United Kingdom	Journal
MIP 4.1	Mobile energy stored as heat (MESH)	A Multi-Criteria Decision Making (MCDM) methodology for high temperature thermochemical storage material selection using graph theory and matrix approach	Journal
		Development and characterisation of an alginate and expanded graphite based composite for thermochemical heat storage	
MIP 4.2	A flexibly integrated solution for gas compression and industrial thermal processing decarbonisation	Cost effective decarbonisation of blast furnace: Basic oxygen furnace steel production through thermochemical sector coupling	Journal
		Mobile energy recovery and storage: Multiple energy-powered EVs and refuelling stations	
		Liquid air energy storage technology: A comprehensive review of research, development and deployment	
		Hydrogen liquefaction and storage: Recent progress and perspectives	
		Mapping and distributing GC and ITP waste heat within ICs and local regions	Report
MIP 4.5	CPD module development on industrial heating and cooling	The decarbonisation of heating and cooling eLearning course	Training
MIP 5.1	Ammonia and hydrogen use for industrial heat and power generation	‘Ammonia’ in renewable fuels: Sources, Conversion, and utilization	Book chapter
		Multiscale analysis of turbulence-flame interaction based on measurements in premixed flames	Journal
		A detailed CO_2 ($^1B_2$) chemiluminescence chemical kinetics model for carbon monoxide and hydrocarbon oxidation	
		Laser-induced breakdown spectroscopy for local equivalence ratio measurement in opposed jet methane-air flames	
MIP 7.7	Enabling low carbon fuel technology deployment for power and high-temperature heat across the clusters	Enabling low carbon fuel technology deployment for power and high-temperature heat across the clusters	Webinar
FF 2-2	Determining optimum pyrolysis condition 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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Published by
The UK Industrial Decarbonisation Research and Innovation Centre (IDRIC)

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This work was supported by the UK Industrial Research and Innovation Centre (IDRIC), through awards EP/V027050/1 under the UKRI ISCF Industrial Challenge/ Industrial Decarbonisation Challenge (IDC) and also EPSRC award EP/Z53125X/1.