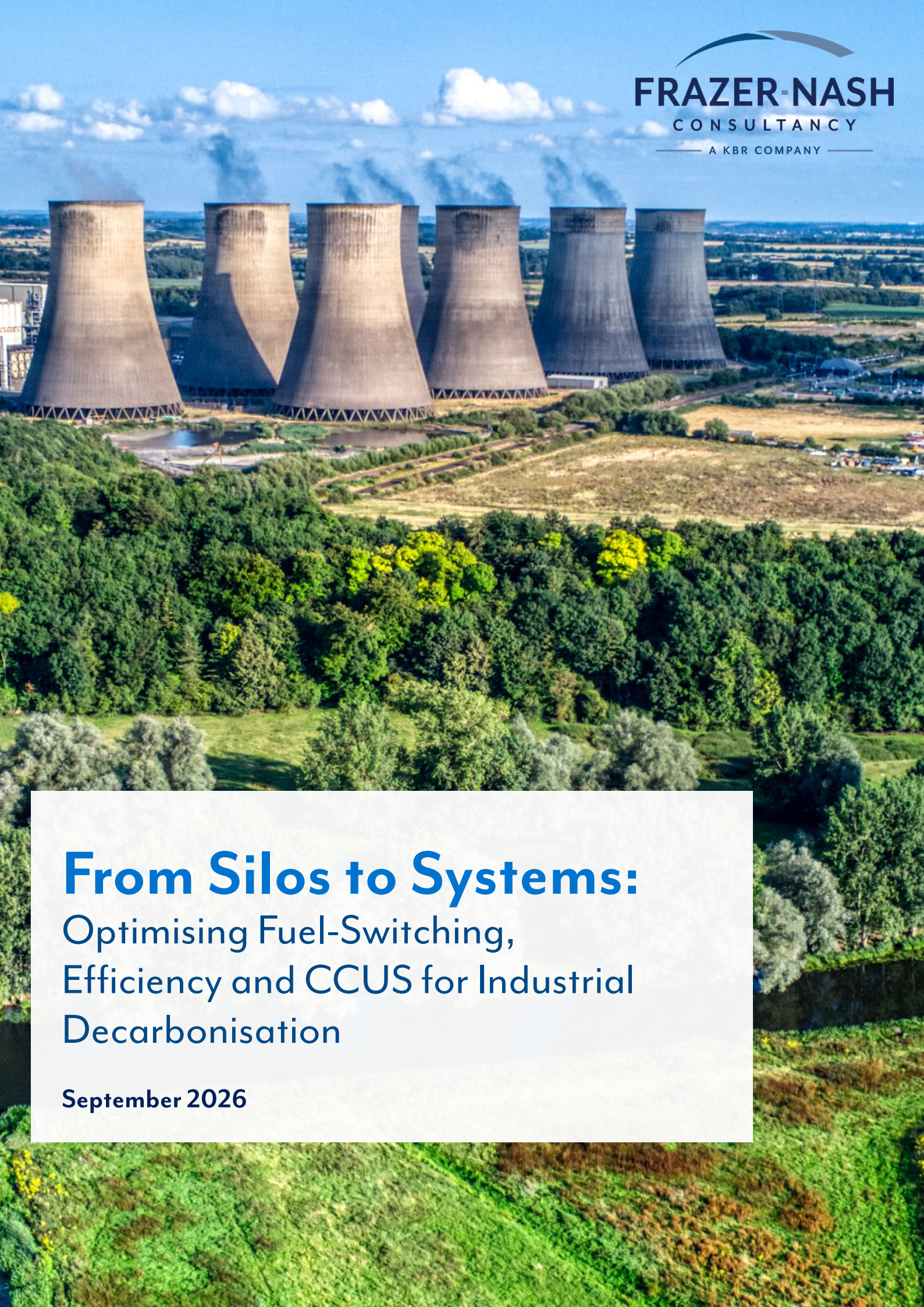




From Silos to Systems:

Optimising Fuel-Switching,
Efficiency and CCUS for Industrial
Decarbonisation

September 2026

01. Executive Summary

The UK's industrial decarbonisation challenge is increasingly one of system coordination rather than technology deployment. While significant progress has been made in developing low-carbon technologies and supporting policy frameworks, the greatest opportunity now lies in optimising how fuel-switching, energy and resource efficiency, and carbon capture, utilisation and storage (CCUS) interact as part of a single integrated system. A whole-system approach can help balance affordability, decarbonisation, resilience and resource efficiency, while avoiding fragmented investment decisions, infrastructure bottlenecks and unnecessary costs.

Key points covered in this report:



Fuel-switching will be critical for industrial decarbonisation, particularly through electrification and low-emissions fuels such as hydrogen. However, large-scale deployment will increase pressure on electricity networks, critical material supply chains and supporting infrastructure, highlighting the need for careful system planning.



Energy and resource efficiency should be treated as the starting point of industrial decarbonisation pathways. Reducing demand through efficiency measures, industrial symbiosis and circular economy approaches lowers the scale of generation, network and carbon management infrastructure required across the system.



CCUS remains essential for managing residual and process emissions, particularly in sectors such as cement, chemicals and heavy industry where emissions cannot be eliminated through fuel-switching alone. However, CCUS should complement rather than substitute wider decarbonisation efforts.



The greatest value is delivered when all three pillars are deployed together. Hybrid pathways that combine efficiency, fuel-switching and targeted CCUS deployment are likely to deliver lower system costs, improved resilience and reduced unnecessary build-out than approaches centred on a single technology pathway.



Flexibility is a critical enabler of system optimisation. Demand-side response, energy storage, digital technologies and flexible infrastructure will be essential to integrate growing electricity demand, support hydrogen deployment and maximise the value of low-carbon energy systems.



Industrial decarbonisation requires stronger system governance and coordination. Existing institutions provide many of the foundations needed, but greater alignment of infrastructure planning, market design, supply chain development, workforce planning and investment decisions will be required to optimise outcomes across the whole system.

To realise these benefits, the recommendation is to adopt a whole-system decision framework that assesses interventions against affordability, decarbonisation, resilience and efficiency, while considering interactions across infrastructure, market policy, digital systems, and supply chains and skills. Applying this framework can help identify the shape that key policy levers should take to enable system integration, including coordinated infrastructure planning, integrated market design, innovation support, and regulation and standards. The report also highlights the need for stronger institutional coordination across government and delivery bodies, alongside the development of a clearer system-orchestrator function to improve investment sequencing and trade-off management. Finally, it emphasises that successful implementation will depend on building the delivery capabilities needed to translate system thinking into action, including systems analysis, pathway modelling, techno-economic assessment, infrastructure planning, stakeholder coordination and programme delivery expertise. Together, these measures can create the conditions for a more coordinated, cost-effective and resilient industrial decarbonisation pathway.

02. Introduction: Why a System Perspective is Needed

The UK has made significant progress in developing the policies, institutions and infrastructure needed to deliver industrial decarbonisation. However, the greatest opportunity now lies not in accelerating individual technologies in isolation, but in advancing coordination across fuel-switching¹ strategies, efficiency initiatives, CCUS deployment, as well as improving the prioritisation and planning of industrial decarbonisation pathways.^{2/3} Optimising the planning and delivery of fuel-switching, energy and resource efficiency, and CCUS as an integrated system is essential to effectively address the UK's decarbonisation challenges.

A systems approach is already beginning to emerge in UK energy policy. For example, the Office of Gas and Electricity Markets (Ofgem) and the Department for Energy Security and Net Zero's (DESNZ) approval of the Network Energy System Operator's (NESO) Strategic Spatial Energy Plan (SSEP) methodology represents an important step towards whole-system infrastructure planning.^{4/5} However, further progress is needed to ensure that decisions relating to fuel-switching, efficiency and CCUS are prioritised and sequenced in a coordinated manner to deliver the best overall outcomes for industry, consumers and government.

System optimisation in the current context refers to making decisions that maximise value across the whole industrial decarbonisation system rather than maximising the deployment of any individual technology. In contrast, a siloed approach can create a range of financial and delivery inefficiencies. Infrastructure may be developed ahead of demand, investment may be duplicated across overlapping programmes, and technology choices may be made without considering wider system impacts. For industrial decarbonisation, these risks are particularly important because decisions made today regarding electricity networks, carbon transport and storage systems, and efficiency prioritisation will shape the cost and feasibility of decarbonisation pathways for decades.

Effective industrial decarbonisation therefore requires decisions on infrastructure, market design, innovation and supply chain to be considered through a common systems lens rather than as separate workstreams. This systems perspective reframes industrial decarbonisation as a coordination challenge as much as a technology challenge. The key question is not how to maximise the transition to low-carbon energy sources, efficiency or CCUS individually, but how to combine them in a way that optimises outcomes across the whole system.

When planned together, each of the three pillars performs a distinct role. Efficiency reduces the overall scale of energy demand. Fuel-switching decarbonises energy demand where it represents the most cost-effective solution. CCUS addresses residual emissions that cannot be eliminated through efficiency improvements or fuel switching.

Coordinating these pathways enables policy-makers to balance four objectives simultaneously:

 **Affordability**
 **Decarbonisation**
 **Resilience**
 **Resource Efficiency**

When estimating this balance, it is also important to include in this assessment the trends and future shifts in policy, economic and technology conditions that will have an impact on the resilience of industrial decarbonisation strategies. For example, the International Energy Agency (IEA)'s Energy Technology Perspective's report indicates that energy technology manufacturing is showing resilience to recent industrial and trade policy changes, but that the high concentration of supply chains in countries like China remains a source of vulnerability.⁶

Moving from technology-specific delivery towards system optimisation is therefore essential if the UK is to decarbonise industry at the pace, scale and cost required. The challenge is determining how technologies should interact within a coordinated industrial decarbonisation system.

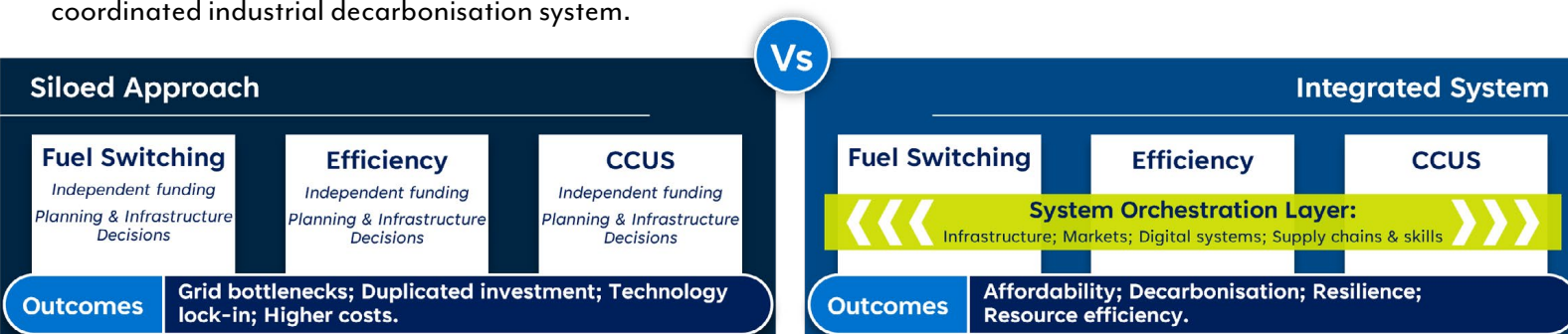


Fig. 1 – From silos to systems to deliver industrial decarbonisation.

1. The definition of fuel-switching used in this document is the replacement of fossil-fuel with lower-carbon energy sources, including electrification, hydrogen and bioenergy.

03. Three Pillars of Industrial Decarbonisation

3.1 Fuel-Switching



Electrification is a central pillar of decarbonisation, spanning heat, transport, and industrial processes. Deployment is already accelerating, driven by the rollout of electric vehicles, heat pumps, and electrified industrial technologies. This trend is expected to continue as the power system becomes increasingly decarbonised.

Electrification offers clear advantages. It enables zero-emissions energy use at the point of consumption and supports system flexibility, particularly when combined with digital and demand-side response technologies.

There are some sectors where electrification cannot be used, such as industrial processes requiring high-temperature heat, which will continue to require fuels. In these cases, sustainable fuels such as low-emissions hydrogen (hydrogen produced from renewable electricity, nuclear electricity, biomass, or fossil fuels with carbon capture), hydrogen-based fuels (ammonia, methanol or synthetic hydrocarbons) and biofuels (fuel derived from biomass feedstock) will be required.⁷

The International Energy Agency's Net Zero Emissions by 2025 scenario estimates that low-emissions fuels will supply around 20% of total final energy consumption by 2050.

However, electrification and low-emissions fuels also introduce significant challenges. Scaling electrification places substantial pressure on the electricity system, requiring major improvement of transmission networks and distribution infrastructure. The intermittency of renewable power sources further complicates supply-demand balancing, particularly during periods of peak demand.^{8/9} Infrastructure is also a barrier to deploy electrolytic hydrogen at scale.¹⁰

Furthermore, adoption of biofuels is influenced by costs as well as supply limitations. The main cost driver for existing commercial biofuels is feedstock, which accounts for more than **80% of the total cost of production**. Biofuels depend on land use for their production and this is constrained by competition with other initiatives like forest restoration.¹¹

In addition, electrification and clean energy are highly dependent on critical minerals and their supply chains. For example, with a low reserve of naturally occurring minerals in the UK, the supply chain of solar photovoltaics, rare earth elements (REEs) for wind turbine motors, and lithium-ion batteries for storage is heavily dominated by China.^{12/13} Furthermore, China also dominates in the production of major clean energy components / enablers such as nacelles and turbine blades. The hydrogen required for hard-to-electrify industrial applications like industrial heating and pyrometallurgy for metal manufacturing comes with its own complex material and infrastructure challenges, particularly in relation to storage and transport, while also relying on platinum group metals (PGMs) for catalysis.¹⁴

Case Study | Critical Minerals Recycling and Midstream Processing Capability Assessment

Our materials, techno-economic and policy experts collaborated with policymakers from the UK Government's Department for Business and Trade's Critical Minerals team, alongside the Critical Minerals Association and Materials Processing Institute, to inform the recently published Vision 2035: Critical Minerals Strategy. The assessment highlighted the demand for critical minerals in the UK as the energy transition is delivered and decarbonisation pathways are realised. While several barriers to accessing these materials exist, with investment in infrastructure, innovation, skills and international partnering, the UK is in a position to build on its manufacturing and industrial heritage to capitalise on opportunities in midstream processing and recycling to secure a domestic supply of critical minerals.



Case Study | International Benchmarking of Advanced Materials

We were commissioned by the then Department for Science, Innovation and Technology (DSIT) to undertake an international benchmarking study of advanced materials ecosystems, comparing the UK's capabilities against leading international competitors and identifying the factors that enable successful translation of research into industrial and commercial outcomes. The study combined quantitative and qualitative analysis across eight analytical pillars, covering innovation, skills, infrastructure, investment and industrial capability. A key finding was that while the UK maintains a world-class research base, competitor nations often outperform the UK in the commercialisation and industrialisation of new technologies. International examples demonstrated the importance of coordinated support across the innovation lifecycle, including pilot-scale facilities, scale-up infrastructure, strategic supply chains and long-term market signals.

The findings from this work have informed the development of the recently announced National Materials Innovation Programme which places a strong emphasis on accelerating the transition from laboratory research to commercial deployment and manufacturing scale-up.



The lessons learned through this case study are equally relevant to industrial decarbonisation. Many decarbonisation technologies, including electrified industrial processes, advanced materials, hydrogen systems, CCUS and circular economy solutions, face similar scale-up challenges. Achieving a system-optimised decarbonisation pathway therefore requires not only investment in innovation, but also coordinated action to commercialise and deploy emerging technologies at industrial scale. Without effective industrialisation pathways, promising low-carbon technologies risk remaining confined to demonstration projects rather than delivering meaningful emissions reductions across the UK industrial base.

3.2 Energy Efficiency & Resource Efficiency



Energy and resource efficiency reduce demand across industry including sectors such as chemicals, materials manufacturing and buildings. These are not necessarily new concepts for industry. Sectors such as steel have been using efficiency principles for many years. For example, excess heat from coke ovens and blast furnaces is often used to re-heat cast steel slabs in readiness for hot working. Furthermore, the sector champions resource efficiency through examples such as steel making by-products, slag in particular, being readily used in the other adjacent foundation industries for cement, aggregate and insulation. While the steel industry is undergoing major transformation, these are exemplary principles on which to build.¹⁵

Efficiency is widely recognised as the “first line of defence” to reduce energy costs and emissions as it helps to reduce the need for energy use.¹⁶ For example, technologies such as battery energy storage systems (BESS) can reduce the scale of electrification and CCUS required by storing energy and reducing the need for additional generation during peak periods.

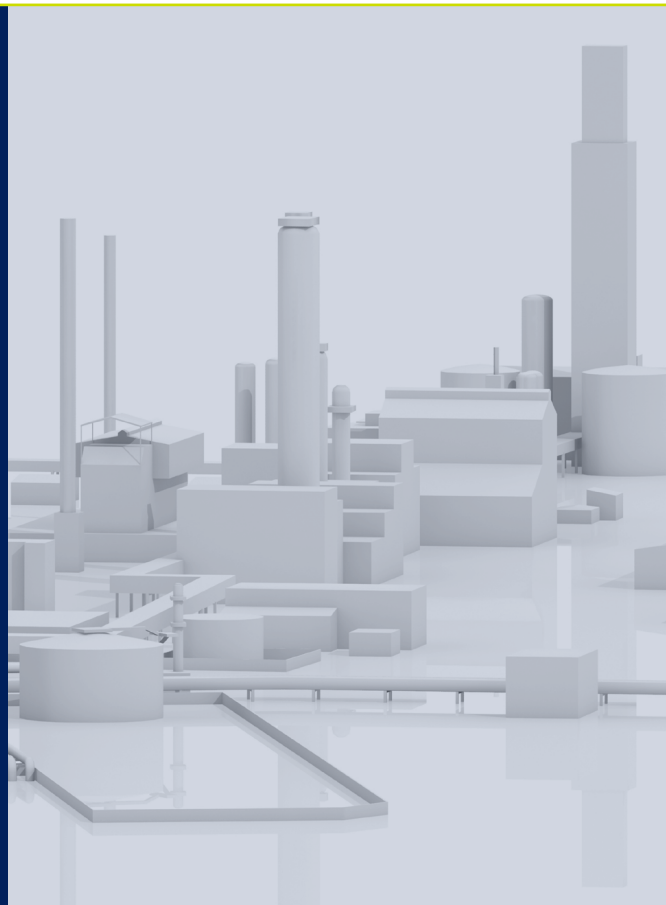
Energy efficiency actions in the past 15 years avoided emissions equivalent to 20% of today's global total. However, the average annual progress of energy efficiency has slowed down since 2019 – annual improvement plummeted to 1.3% on average, which is well below the COP28 target of a 4% by 2030.¹⁷

Efficiency faces a number of challenges. Global energy demand in sectors like industry has grown fast since 2019, which has contributed to the watering-down of efficiency progress. This progress is further undermined by the disconnect between the pace of technology improvements and the speed at which regulatory standards change to support the scale and use of those improvements. Higher material costs and labour shortages are also important challenges impacting efficiency.¹⁸

Case Study | Energy Audit of a Manufacturing Facility

A leading engine manufacturer engaged us to assess and improve the sustainability of its plant operations. The site comprised a diverse range of energy-intensive processes, with large volumes of fragmented and inconsistent energy data making it difficult to understand overall energy performance. To address this challenge, Frazer-Nash conducted a comprehensive energy audit to quantify energy flows across the facility and establish a clear baseline of energy consumption.

A key element of the study was a detailed temporal and spatial analysis of energy use, examining when and where energy was consumed throughout the manufacturing process. This enabled the team to identify inefficiencies, uncover opportunities for energy recovery and reuse between processes, and assess the feasibility of targeted improvements. The analysis informed a series of energy efficiency recommendations, highlighting areas where operational changes and energy integration could reduce consumption and improve sustainability performance. Implementation of the identified opportunities had the potential to deliver significant fuel, energy and cost savings across the business, while supporting wider decarbonisation objectives. These findings formed the basis of collaborative workshops with the client, leading to the development of practical, sustainable solutions aligned with environmental and operational targets.



The potential of resource and energy efficiency needs to be fully exploited and for that to happen the sector needs increased support. An example of such support is the Transforming Foundation Industries (TFI) Challenge, funded through UK Research and Innovation (UKRI). This initiative aims to address some of the most complex challenges faced by Foundation Industries, ie: glass, ceramics, steels, cements, chemicals and paper, such as reducing/removing their reliance on fossil fuels, the need for innovation in reducing energy usage, and greater inter- and intra-sector industrial symbiosis to minimise waste that often ends up in landfill.

The TFI Challenge does this by allocating funds of ~£1.4M to enable the development of small projects for the benefit of the Foundation Industries on key topics, including: energy efficiency, resource efficiency & industrial symbiosis, digitisation, next-generation processes.¹⁹

3.3 CCUS



CCUS plays a critical role in decarbonising sectors where emissions are difficult or impossible to eliminate through fuel-switching alone, such as cement, chemicals, and heavy industry. It also enables carbon removal, which is essential for addressing residual emissions and achieving net-zero targets. CCUS technologies are gaining traction, with growing policy support and the development of industrial clusters and CO₂ transport and storage networks.

In addition to reducing emissions, captured carbon can be reused as a feedstock in industrial processes, such as in the production of synthetic fuels or low-carbon cement. Research indicates that the need for carbon will persist even in a net-zero world. In sectors like aviation, steel and chemicals, ie those using carbon for feedstock or industrial processes, carbon is difficult to substitute due to fundamental constraints like energy density and process chemistry. Planning must therefore focus on building a sustainable system to source, (re)use and dispose of carbon in perpetuity.²⁰

However, CCUS faces significant barriers to scale. The capital intensity and high costs of the technology are a limitation to investors, and the industry is dependent on sustained policy support to create a viable route to market.²¹ Carbon removal technologies require substantial amounts of clean electricity, further linking CCUS to the wider energy system.²²

There are also strategic risks. Over-reliance on CCUS can delay emissions reduction elsewhere, creating lock-in to fossil-based systems and increasing long-term costs.²³ CCUS is therefore not a substitute for electrification or efficiency, but a critical complementary pillar within a coordinated system.

Case Study | Carbon Capture as a Service (CCaaS)

As part of the Industrial Decarbonisation Challenge, UK Research and Innovation (UKRI) commissioned a study from us to achieve better understanding of the current carbon capture as a service landscape and explore pathways for developing a thriving market. Through review of existing studies and targeted engagement with industrial cluster representatives, the study has identified seven insights from which corresponding recommendations have been drawn:

1. **Complex cross chain integration requires direct support.**
2. **Consistent guidance across the CCUS value chain to ensure wider system awareness of CCaaS.**
3. **Emitter location impacts ease of participation.**
4. **Small emitters require additional incentives.**
5. **Interactions with the international CCaaS market should be considered.**
6. **Considering risk allocation between stakeholders is important.**
7. **Investors need to understand the CCaaS business case in order to commit investment.**



04. How the Three Pillars Interact as a System



4.1 System Interactions

Fuel-switching, efficiency, and CCUS are not independent levers – they are deeply interconnected, and their interactions ultimately determine system performance.

Efficiency plays a foundational role by reducing overall energy demand. This lowers the scale of electrification and energy required, which in turn reduces grid stress, infrastructure investment, and system costs. Efficiency can also be achieved via industrial symbiosis - the exchange of waste and by-products between companies and industries to create mutual benefits, reduce waste, and keep resources in productive use for longer.²⁴

Fuel-switching reduces reliance on fossil fuels and enables the transition to clean energy. At the same time, it provides the low-carbon energy needed to power CCUS systems, particularly for energy-intensive processes such as direct air capture.

CCUS complements these levers by addressing emissions that cannot be reduced through efficiency or fuel-switching alone, particularly in hard-to-abate sectors. It can also supply industry with a sustainable source of carbon.

Together, these interactions determine the overall cost, efficiency, and resilience of the system, so understanding them is essential.

4.2 Trade-offs and Tensions

While these pillars are complementary, they also create a range of trade-offs and tensions that must be carefully managed.

At a fundamental level, decision-makers face key questions when looking at the decarbonisation of different areas of industry:

- **Should energy demand be reduced** first via, for example, the pursuit of symbiotic networks, or supplied as-is?
- **What is the tipping point** at which it is too costly or ineffective to reduce demand, and fuel-switching would make more sense?
- Is it more effective to **switch away from fossil fuels, or to capture emissions from existing systems?**
- Should carbon be **captured at source, or removed from the atmosphere later?**
- To what extent do efficiency and fuel-switching **increase demand for critical materials** and how can the UK **harness this growing demand** to build competitive domestic manufacturing, processing and recycling industries?

These trade-offs are not purely technical – they are economic, infrastructural, and strategic. Poorly managed decisions can lead to:

- **Grid saturation and infrastructure bottlenecks**
- **Over-reliance on CCUS** undermining the shift away from fossil fuel-dependence
- **Rebound effects**, reducing the impact of efficiency measures
- **Technology lock-in**, limiting future flexibility

Managing these tensions requires a clear system-level perspective, supported by robust analysis and coordinated decision-making.

4.3 Defining “Optimal System Outcomes” (what a UK system needs to solve)

To navigate these trade-offs effectively, it is essential to define what an optimal system is trying to achieve.

In the UK context, system design should aim to balance:

- **Affordability:** minimising total system cost, including infrastructure, operations and impact on consumers
- **Resource efficiency:** avoiding overbuild and maximising utilisation; and optimising the reliance on materials and supply chains (including the utilisation of by-products and waste streams)
- **Decarbonisation:** delivering emissions reductions at pace
- **Resilience:** ensuring reliability and adaptability over time

These objectives provide a framework against which different system pathways can be assessed. Rather than optimising for any single goal, the challenge is to balance competing priorities. This balance ultimately defines the difference between a siloed system that is technically feasible and a system-optimised pathway that is deliverable in practice.

4.4. Pathways: What Different System Strategies Look Like

System pathways vary depending on how fuel-switching, efficiency, and CCUS are sequenced. Each pathway reflects a different balance between the outcomes outlined above.

Low-emissions energy and electrification-led pathways centre on rapidly switching energy demand to clean electricity across sectors. While this approach focuses on delivering decarbonisation, it places significant pressure on the power system, requiring extensive grid expansion, increased generation capacity, and substantial material inputs.

Efficiency-first approaches prioritise demand reduction through energy and resource efficiency measures. These pathways reduce the need for new infrastructure. However, it is clear that efficiency alone will not achieve the desired levels of decarbonisation required in line with the Paris Agreement, particularly in hard-to-abate sectors, where the use of renewables and CCUS will also be required.²⁵

CCUS-enabled pathways emphasise carbon capture and storage to reduce emissions from existing industrial processes. These can deliver progress in the near term -particularly for sectors where electrification is difficult – but risk locking in fossil-based systems and require significant infrastructure investment.

In contrast, a hybrid optimised pathway integrates the strengths of all three approaches. It prioritises efficiency and incentivises industrial symbiosis to reduce demand at source, deploys fuel-switching where it is most cost-effective and technically viable, and uses CCUS strategically to address residual emissions and enable hard-to-abate sectors. **This coordinated approach minimises overall system cost, avoids unnecessary infrastructure build-out, and delivers a more resilient and flexible pathway to net zero.**

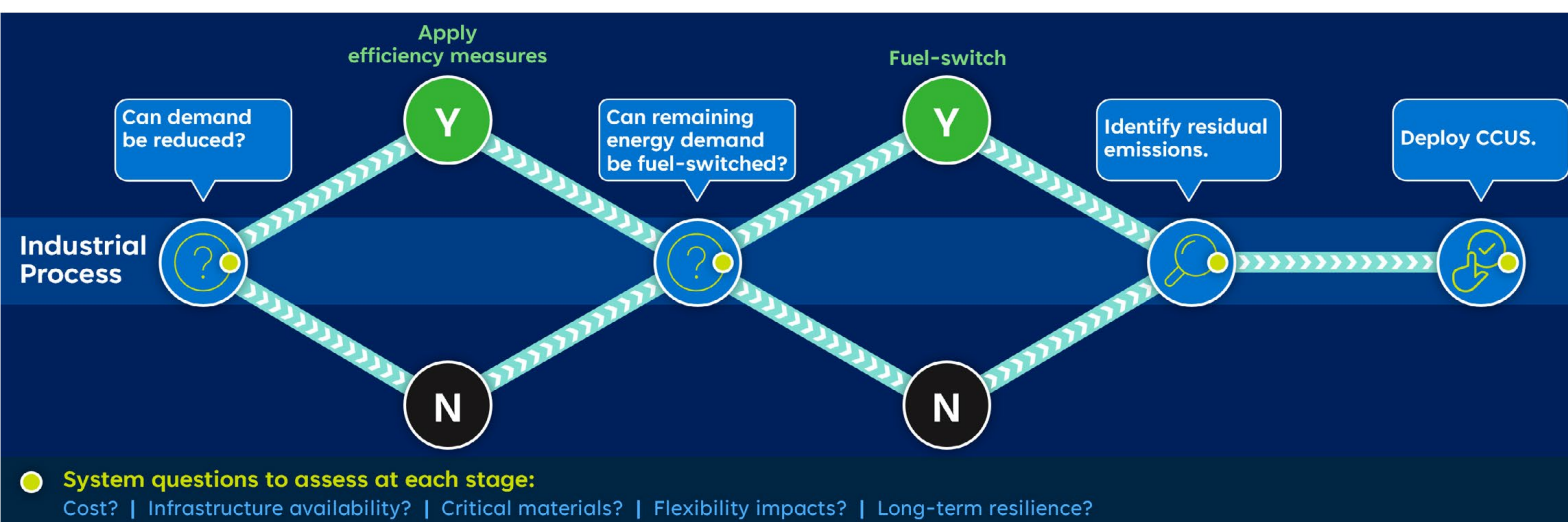


Fig. 2 – High-level representation of the decision flow across pillars.

05. Deep Dive on Industry as a Sector

Industrial combustion and processes account for around 24% of global CO₂ greenhouse gas (GHG) emissions according to the European Commission's 2025 GHG emissions dataset and is one of the hardest sectors to decarbonise.²⁶ Unlike power or transport, many industrial processes involve both energy-related and process emissions, where CO₂ is a direct by-product of chemical reactions rather than just combustion. This means no single lever is sufficient. A hybrid optimised pathway, leveraging the opportunities across efficiency, electrification and CCUS, reflects the technical and economic realities of the sector.

5.1 Energy & Resource Efficiency: Reducing the Problem

In industry, reducing demand means addressing waste heat, inefficient processes, and material output.

Globally, the annual rate of improvements in energy intensity – the amount of primary energy needed to produce a dollar of economic output – will average 4.1% by 2030 according to the International Energy Agency. One result of achieving this rate of improvement is that energy demand in 2030 would be nearly 10% lower than in 2022, even as the economy continues to grow. Technical efficiency measures and avoided energy demand through material and resource efficiency improvements each contribute roughly a third of the gains.²⁷

In the UK, the Industrial Energy Transformation Fund (IETF) has supported businesses with high energy use across manufacturing, chemicals, ceramics, and food and drink to invest in energy efficiency and low-carbon technologies. Launched in 2020, the IETF has held three competition phases to support projects and has £163 million of funding allocated to support them. Unfortunately, as a result of the Spending Review, the IETF will not be extended to include any further projects.²⁸

Resource efficiency adds a further dimension. In steel making, increasing scrap recycling rates and transitioning to electric arc furnaces cuts energy use substantially compared to primary blast furnace production. **Recycling scrap steel is significantly more efficient, consuming around 72% less energy per tonne produced and reducing CO₂ emissions by 58%.**²⁹ The Ellen MacArthur Foundation has documented similar leverage points of reusing and recycling resources, noting that in the construction sector, **up to 70% of CO₂ emissions can be removed by using recycled instead of virgin materials.**³⁰

5.2 Fuel-Switching: Shifting Where Technically and Economically Viable

Innovation to adopt fuel-switching as a credible near-term pathway in industry has demonstrated significant use cases.

The steel sector provides the clearest real-world example. SSAB in Sweden is deploying the HYBRIT process, replacing coking coal with green hydrogen and electric arc furnaces technology. With HYBRIT technology, SSAB aims to be the first steel company in the world to bring fossil-free steel to market in 2026.³¹

In the UK, Tata Steel has committed to a major transition at Port Talbot. Tata Steel has signed a £500 million Grant Funding Agreement with the UK Government as part of a £1.25 billion project to install a state-of-the-art electric arc furnace at its Port Talbot steelworks in Wales. The transformation of Port Talbot's steel making is expected to be completed by late 2027.³²

For lower-temperature industrial heat, industrial heat pumps are an increasingly important technology, with the EU's Heat Pump Accelerator Platform launched in January 2025 to drive uptake - though the broader European market saw a 22% sales decline in 2024, indicating that deployment at scale remains a work in progress.³³

High-temperature processes - above 800-1,000°C in sectors like cement, lime, and glass - remain more technically constrained, though plasma torch technologies are now entering early industrial demonstration. Heidelberg Materials operated a 300kW plasma-heated cement kiln at its Slite plant in February 2025 as part of the ELECTRA project - which explores new technologies to replace traditional combustion processes with electricity-based solutions in the long-term - achieving simplified carbon dioxide capture, lower carbon dioxide emissions, no fuel ash and higher quality clinker.³⁴

Case Study | Ammonia technologies carbon intensity analysis

Green ammonia is being increasingly recognised as a vector to enable green hydrogen, as a means of decarbonising fossil-fuel produced ammonia and as a carbon-free fuel in its own right.

In partnership with the Science and Technology Facilities Council (STFC), the ASPIRE (Ammonia Synthesis Plant powered by Intermittent Renewable Energy) project has been developed, starting in April 2023 and running for two years. The project initially investigated the conceptual design of a novel Haber-Bosch reactor, to technically and cost-effectively produce green ammonia using only water, air and an intermittent renewable energy source. After a successful feasibility study, the project was further developed to the demonstration phase, which was funded through £4.3m support from DESNZ' Net Zero Innovation Portfolio (NZIP) Hy-Supply 2 competition. This enabled a small-scale (137 kW or 300 kg/day) green ammonia synthesis demonstrator plant to be designed and built

We closely collaborated with STFC on this project and was responsible for delivering four workstreams using a multi-disciplinary approach: i. independent design review and process governance, ii. HAZOP and DSEAR safety assessments, iii. control system development and design, iv. business case and routes to market.

This proof-of-concept demonstrator plant could form the basis for large-scale off-grid green ammonia supply, as well as a low carbon, economically viable hydrogen supply solution.



5.3 CCUS: Managing Residual and Process Emissions

For sectors where fuel-switching cannot reach, CCUS is effectively the only viable deep decarbonisation route. Cement is the clearest case: calcination - the chemical decomposition of limestone - accounts for almost two-thirds of the total CO₂ emissions from cement production, with the remainder coming from energy used to heat the kiln.³⁵ These process emissions cannot be eliminated by switching fuels; only carbon capture can address them.

In the UK, HyNet and the East Coast Cluster are the two most advanced industrial CCUS projects. In October 2024, the government announced up to £21.7 billion of funding over 25 years for the two Track-1 clusters. HyNet's industrial partners include Heidelberg Materials and Viridor. HyNet is expected to store 4.5 Mt CO₂ per year initially, expanding to 10 Mt per year by 2030. The East Coast Cluster is expected to capture and store 23 Mt CO₂ per year by the mid-2030s and its industrial partners include CF Fertilisers among others.³⁶ In addition to this, in July 2025, the UK government announced the investment of £28.6 million in the Peak Cluster project via the National Wealth Fund. This investment forms part of the overall equity investment in the project which also includes £31 million from the private sector. The Peak Cluster includes four major cement and lime producers and it will build the infrastructure to capture, transport and permanently store the CO₂ of these emitters.³⁷

Globally, demand-side signals for hard-to-abate sectors are strengthening through initiatives like the First Movers Coalition. From over 30 members at its launch at COP26 in 2021, the coalition has grown to 100+ members with commitments for breakthrough industrial decarbonisation technologies covering steel, cement and concrete, aluminium, and other hard-to-abate sectors. **By 2030, the commitments made to date will represent an annual demand of more than \$16 billion for near-zero-emission products and services, and over 30 Mt CO₂e in annual emissions reductions.**³⁸

Case Study | Carbon mapping the Tees Valley cluster

The Tees Valley is home to the largest chemical complex in the UK and the second largest in Europe in terms of manufacturing capacity. We developed a carbon mapping methodology to capture and report the carbon footprint, and the pathways of carbon transferred within and out of the cluster to understand the opportunities to calculate Net Zero and outline how carbon is avoided and used as a commercial product.

A carbon transfer dashboard was developed to summarise data collected from all the sources with graphical representation to provide clearly visible carbon input, use and output. A cluster mapping data collection workbook was provided with the methodology to enable annual data collection and tracking of carbon management and progress to Net Zero.

The Cluster Carbon Mapping Methodology was presented to UKRI as demonstration of industrial sector progress in carbon management. This allowed the client to have a greater understanding of the transfers of carbon both within and externally to the cluster and highlight development opportunities.



5.4 Integration: Why it Matters

The three levers are most powerful when applied in combination. Efficiency reduces the total volume of emissions that electrification, low-emissions fuels and CCUS must address - lowering both capital requirements and operating costs. Fuel-switching decarbonises what can be electrified or transition to low-emissions energy sources, reducing reliance on CCUS for energy-related emissions and reserving it for where it is truly needed: unavoidable process emissions. This sequencing is reflected increasingly in sector-specific roadmaps developed by trade bodies including Make UK and the Mineral Products Association.³⁹

06. The Role of Flexibility



Flexibility is the critical enabler of a system-based decarbonisation pathway. It acts as the “glue” connecting fuel-switching, efficiency, and CCUS, allowing them to operate as a coordinated system rather than as isolated levers. Without flexibility, even well-designed decarbonisation strategies risk reverting to a siloed approach - resulting in inefficiencies, higher costs, and system imbalances.

At its core, flexibility enables the system to dynamically balance supply of energy, demand, and emissions management. As renewable energy becomes the dominant source of electricity, its inherently variable nature requires demand to be more adaptive. Flexibility allows demand of energy use to shift across time, aligning consumption with periods of high renewable generation.

In this context, flexibility optimises:

- **Electrification** by aligning new electrical demand with periods of abundant low-carbon generation. It also optimises the use of low-emissions fuels like hydrogen by balancing where supply networks will need to be built as well as where can they be integrated to support electricity systems
- **Efficiency** by focusing on the effective use of energy infrastructure and reducing the need for excess generation, storage and network capacity
- **CCUS** by identifying where system conditions are most favourable for carbon capture and storage and carbon removal processes to operate

As industrial processes, heating and transport become increasingly electrified, the reliability and resilience requirements of the power system become even more important. The UK Energy Research Centre (UKERC) notes that increasing dependence on electricity raises the economic and social impacts of supply interruptions.⁴⁰ This has important implications for electrification strategies: widespread electrification cannot simply focus on replacing fossil fuel technologies with electric alternatives. It must also ensure that flexible demand, storage and system balancing capabilities are available to maintain resilience. Without these capabilities, electrification risks transferring pressure from fuel networks to the electricity system rather than reducing overall system costs and emissions.

The geographic and temporal variability of renewable generation further reinforces the need for flexibility.⁴¹ Large renewable resources are often located far from centres of industrial demand, while output can fluctuate significantly over time. Reducing congestion and improving utilisation of existing assets is needed to mitigate this problem. This allows the energy system to extract greater value from existing infrastructure before investing in additional network capacity.

This is particularly important given the long lead times associated with network expansion. New transmission infrastructure can take 12-14 years to deliver, creating a gap between decarbonisation ambitions and infrastructure availability.⁴² Flexibility therefore acts as a bridge that allows electrification programmes to progress while network upgrades are completed. It also ensures that efficiency improvements translate into lower infrastructure requirements by managing energy flows more effectively across existing assets. In practical terms, flexibility reduces the risk that decarbonisation pathways become constrained by infrastructure bottlenecks.

The interaction between flexibility and CCUS is equally important. UKERC highlights that some low-carbon generation sources such as gas generation with CCS, are not typically expected to provide significant operational flexibility because operators seek to maximise utilisation of these capital-intensive assets.⁴³ This creates an important system challenge: decarbonisation cannot rely solely on CCUS. A portfolio of flexible resources, including demand-side response, storage and interconnection, is required to ensure that these assets can operate efficiently within a highly renewable power system. In this context, flexibility enhances the value of CCUS by integrating it more effectively into the wider energy system.

The growing role of hydrogen further strengthens the links between flexibility, electrification and CCUS. UKERC identifies future hydrogen infrastructure and electrolyzers as potentially important sources of system flexibility.⁴⁴ For industrial decarbonisation, hydrogen can act as both a decarbonisation vector and a flexibility resource. Electrolyzers can absorb excess renewable generation during periods of high output, while hydrogen storage can provide longer-duration balancing services. Where hydrogen is produced from natural gas with carbon capture, this also creates a direct link between flexibility and CCUS, demonstrating how these decarbonisation pillars can become mutually reinforcing.

Similarly, flexibility opportunities across buildings, heating systems and data centres illustrate how efficiency can be optimised to support the energy system. Thermal inertia in buildings allows heat pump demand to be shifted while maintaining consumer comfort,⁴⁵ while data centres can use workload shifting, storage and cooling flexibility to optimise electricity consumption.⁴⁶ These approaches do not simply reduce consumption; they improve the timing of consumption, increasing the effective utilisation of low-carbon generation and reducing the need for additional infrastructure. In this sense, flexibility can be viewed as a multiplier of efficiency benefits rather than a separate intervention.

Delivering these outcomes at scale requires appropriate market and policy frameworks. UKERC highlights challenges relating to flexibility markets, digitalisation of the energy system, consumer participation, allocation of network costs, barriers to electricity storage and interconnection, and changes to the existing Contract for Difference (CfD) and Capacity Market mechanisms.⁴⁷ These reforms are essential because the value of flexibility arises from its ability to coordinate electrification and low-emissions fuels, efficiency and CCUS across the whole system. Without market incentives that reflect whole-system value, organisations may optimise individual assets rather than optimise overall system performance.

Flexibility is therefore not an optional enhancement but the mechanism through which fuel-switching, efficiency and CCUS deliver maximum value. Flexibility ensures these three levers work together, reducing infrastructure costs, improving system resilience, accelerating renewable integration and enabling a more cost-effective pathway to net zero.

Case Study | Hydrogen Transportation and Storage Infrastructure Requirements to 2035

The applications for which hydrogen will play a role to enable the decarbonisation of the UK's energy system are becoming more certain. However, despite this increasing certainty over the role of hydrogen, there has been a degree of uncertainty around the required supporting infrastructure. Frazer-Nash Consultancy was therefore tasked by the Department for Energy Security and Net Zero (DESNZ) to investigate the Transport and Storage infrastructure required to support the emerging hydrogen economy out to 2035.

Frazer-Nash Consultancy and Cornwall Insight delivered a report to DESNZ looking at the following:

- How much hydrogen transportation and storage infrastructure will be required up to 2035?
- What is this transportation and storage infrastructure likely to cost?
- What commercial arrangements could be used to develop this infrastructure?
- What short term steps should be taken by government to enable the development of this infrastructure to support the emerging hydrogen energy system?

We leveraged our extensive network of UK energy sector connections to engage with multiple future hydrogen economy stakeholders, including producers, consumers, and potential storage operators. We asked stakeholders targeted questions which allowed us to develop the key components of the hydrogen economy and to combine these to form archetype units. We combined these archetype units to form scenarios for the hydrogen economy's future development.

We assessed the transportation and storage infrastructure requirements to produce estimated costs for each scenario. Cornwall Insight investigated the potential commercial arrangements that would be required to enable each scenario, identifying potential commercial blockers.



07. Governance and Policy Architecture

7.1 A System-Oriented Policy Framework

Delivering a system-based approach to decarbonisation requires a continued evolution in how policy is designed and implemented. DESNZ have already taken important steps towards a more integrated approach through initiatives such as the Carbon Budget Delivery Plan and Clean Power 2030 Action Plan, which recognise the interdependencies between power, industry, buildings, transport, hydrogen and carbon capture, and seek to coordinate delivery across multiple parts of the energy system.

In parallel, DESNZ, alongside the Scottish and Welsh Governments, have commissioned NESO to develop Great Britain's first Strategic Spatial Energy Plan (SSEP), providing a long-term, whole-system approach to planning the location, timing and scale of future electricity and hydrogen infrastructure.

Nevertheless, progress is still needed to move away from sector-specific or technology-specific frameworks. There remains an opportunity to strengthen coordination to prioritise and sequence industrial decarbonisation pathways.⁴⁸ Building on the foundations already established by DESNZ and NESO, a more system-oriented policy framework would place greater emphasis on optimising outcomes across the whole set of technologies that form part of the energy system. A framework like this would act as a blueprint for decision-making so decisions address whole-system considerations and deliver optimisation.

There are four components that could underpin such a framework:

- **Integrated infrastructure planning:** Infrastructure deployment must be coordinated across electricity networks, CO₂ transport and storage infrastructure, hydrogen and biofuels systems, energy storage infrastructure, flexibility infrastructure and industrial sites. This ensures that infrastructure is developed in a strategic and efficient sequence, avoiding overbuild and enabling different system components to evolve together
- **Cohesive incentives management through integrated market policy:** Incentives across the value-chain of different technologies should be managed through an integrated market policy strategy. This will enable to balance behaviours to incentivise desired system outcomes and address market failures without impacting other parts of the system. Adopting this lens will also allow to identify where interventions are most effective by having a system-wide view of the economic and financial barriers of different technologies
- **Leveraging digital tools and technologies for system optimisation:** Working on integrating digital systems and data sharing and using AI and other technological innovations is key to take advantage of the information across the system and identify where optimisation is required
- **Fully understanding and planning for supply chain and workforce needs:** Government efforts in incentivising the development of supply chain and skills needed for decarbonising industry will be more efficient if the needs and opportunities across the system are considered instead of focusing separately on what specific sectors or technologies need. Strategies, technical upskilling plans and international collaboration opportunities will be better informed if dependencies and needs across the system are mapped

Basing policy decision-making on a framework with these characteristics is essential to unlock the full benefits of system optimisation.

7.2 Policy Levers to Enable System Integration

Using a system-oriented policy framework when assessing the direction policy should take provides increased confidence that chosen policy levers are explicitly designed to align incentives across fuel-switching, efficiency, and CCUS, rather than supporting them in isolation.

Several key levers are particularly important:

- **Market design for flexibility and for transitioning to self-sustaining markets:** Enabling flexibility requires market mechanisms that reward demand-side response and dynamic system participation. This includes time-of-use pricing, flexibility markets, and incentives for industrial load shifting and energy storage. Market design can also reduce investment uncertainty, create predictable revenue streams and stimulate private capital investment to transition from government-led market creation to self-sustaining markets. Mechanisms to achieve this include business models and revenue support mechanisms, carbon pricing, carbon credits and removals markets, contracts-for-difference-style arrangements, market access rules, infrastructure access and charging frameworks, and risk-sharing mechanisms
- **Infrastructure planning and investment frameworks:** Coordinated frameworks shape the physical systems that enable industrial decarbonisation. They are needed to align the development of energy networks and CO₂ transport and storage infrastructure, energy storage systems and flexibility infrastructure. A coordinated framework that signals what infrastructure will be built, when and how creates the enabling conditions for coordinated infrastructure deployment
- **Innovation levers:** these levers can help bring new technologies from research and development through demonstration to commercial deployment. These include innovation funding, demonstration programmes, pilot projects, technology validation initiatives and commercialisation support. When deployed strategically, these levers can accelerate technology maturation, reduce uncertainty for investors and industry, shorten the time required for technologies to reach market, and strengthen the UK's position as a leader in industrial decarbonisation innovation
- **Regulation and standards:** rules, standards and obligations shape decision-making across industrial systems. These include technical standards, reporting requirements, emissions accounting rules, product standards, planning frameworks and compliance mechanisms. Well-designed regulation can provide long-term certainty for investors, encourage adoption of low-carbon solutions, create consistent market conditions, improve transparency and accountability, and ensure that industrial decarbonisation progresses in a way that aligns with wider environmental and economic objectives

Together, these levers can form the foundation of a policy environment that enables system integration. Without them, market signals remain fragmented, and system-level optimisation cannot be achieved.

7.3 Institutional Coordination

The importance of system coordination is increasingly recognised across the UK energy transition, and significant progress has been made in establishing institutions with complementary roles across policy development, system planning, regulation and investment.

Different organisations play important but distinct roles across the system:

- **DESNZ** sets policy, provides strategic direction and oversees delivery of the UK's energy security and net zero objectives
- **NESO** is responsible for electricity system planning and operation
- **Ofgem** regulates energy markets and infrastructure investment
- **Great British Energy** has emerged as a public investment vehicle to support deployment of clean energy infrastructure
- **The Low Carbon Contracts Company** provides revenue certainty by managing contractual schemes and business models for renewable energy generators and CCUS projects

Collectively, these institutions provide many of the capabilities needed to deliver decarbonisation. However, as the transition becomes increasingly interconnected, there is an opportunity to further strengthen the mechanisms through which decisions are coordinated across fuel-switching, energy efficiency and CCUS pathways. While strategic oversight already exists, many decisions continue to be developed within separate policy, regulatory and delivery processes, which can make it more challenging to optimise outcomes across the whole system. This can create risks around the sequencing of investments, alignment of infrastructure development and management of trade-offs between competing pathways.

Addressing this challenge requires the continued development of a stronger system orchestrator function, building on DESNZ's existing strategic leadership role and supported by enhanced coordination arrangements across government, regulators and system planners. Such a function would focus on aligning decisions on market policy, infrastructure, investment, the use of digital tools and system, supply chain and workforce over time, ensuring that fuel-switching, efficiency and CCUS pathways are assessed and prioritised within a coherent whole-system framework.

7.4 Bridging the Gap: Where Delivery Capabilities are Needed

Realising the benefits of system optimisation depends on having the delivery capabilities required to understand system interconnections and translating that into practical decisions, investments and implementation programmes. Government, industry and the private sector need to work together to build and leverage those capabilities across the board.

- **Integrating efficiency, fuel-switching and CCUS requires end-to-end systems thinking.** Decisions that appear optimal for a single technology can create unintended consequences elsewhere in the system. Delivery teams therefore need the capability to assess interactions between technologies, identify dependencies, and evaluate how decisions affect affordability, decarbonisation, resilience and resource efficiency across the whole system
- **Designing optimal decarbonisation pathways requires robust strategy development, pathway modelling and scenario analysis.** Different sectors, sites and industrial clusters face different technical and economic constraints, meaning there is no single decarbonisation pathway that can be applied universally. Decision-makers require evidence-based tools that can assess alternative pathways, quantify trade-offs and identify no-regrets actions that deliver value under multiple future scenarios
- **Translating systems thinking into investment decisions requires techno-economic analysis that combines engineering, commercial and policy considerations.** Governments, investors and industrial operators need to understand not only whether a technology is technically feasible, but also whether it is economically viable within the wider system. This includes assessing capital requirements, operating costs, infrastructure dependencies, policy support mechanisms and system-wide impacts
- **Navigating infrastructure dependencies requires advanced planning and coordination capabilities.** Electrification, hydrogen, CO₂ transport and storage, energy storage and digital infrastructure are all interconnected. Delays or constraints in one area can affect the viability of investments elsewhere. Effective infrastructure planning therefore requires supply chain and resource planning, integration and management, stakeholder engagement and coordinated sequencing of investments across multiple organisations and delivery bodies
- **Delivering complex, multi-stakeholder programmes requires programme management and transformation expertise.** Industrial decarbonisation involves government departments, regulators, network operators, infrastructure developers, industrial sites, investors and local communities. Successful delivery depends on aligning incentives, managing risks, maintaining stakeholder commitment and ensuring that strategic objectives remain connected to implementation decisions over time

Together, these capabilities form the foundation required to move from strategy to delivery. Organisations that can combine deep technical expertise with systems thinking, economic analysis and programme delivery are best placed to support government and industry in implementing a coordinated industrial decarbonisation pathway.

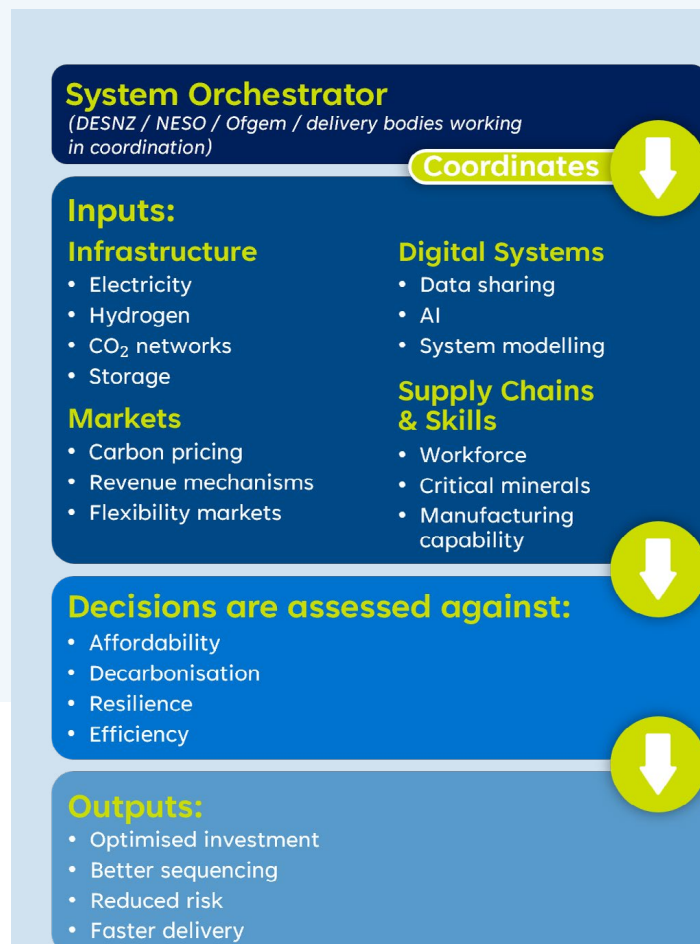


Fig. 3 - A system-oriented framework for decision making.

08. Our top 10 Recommendations

- 01** **Establish a clear whole-system decision framework** that looks at the interactions of four main system components – infrastructure, markets, digital and supply chain and skills, and evaluates interventions against four objectives: affordability, decarbonisation, resilience and resource efficiency.
- 02** **Identify where in industry efficiency and resource productivity can be prioritised**, reducing the scale of infrastructure and energy supply required across the system.
- 03** **Deploy fuel-switching where it is technically viable and economically advantageous**, while explicitly considering impacts on networks, flexibility requirements and critical material demand.
- 04** **Target CCUS towards residual and process emissions** where alternative decarbonisation routes are limited, rather than treating CCUS as a substitute for wider system transformation.
- 05** **Embed flexibility as a core design principle** across industrial decarbonisation programmes through market design, digitalisation, storage and demand-side response capabilities.
- 06** **Strengthen integrated infrastructure planning** across electricity, hydrogen, CO2 transport and storage, energy storage and industrial clusters to avoid fragmented investment decisions.
- 07** **Develop a stronger system-orchestration capability** across government, regulators and system planners to improve coordination, sequencing and management of trade-offs.
- 08** **Use scenario modelling and pathway analysis** to identify no-regrets actions that remain beneficial under multiple future technology, policy and demand scenarios.
- 09** **Align supply-chain, workforce and innovation strategies** across the full decarbonisation system rather than developing sector-specific interventions in isolation.
- 10** **Focus delivery support on translating strategy into implementation** through programme delivery, techno-economic analysis, stakeholder coordination and investment decision support.



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