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Beyond carbon emissions reductions: Examining the co-benefits of industrial decarbonisation in the United Kingdom

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ABSTRACT

Industrial decarbonisation reduces greenhouse gases emissions and also deliver broader economic and social gains. We synthesise co-benefits of decarbonising energy-intensive industries in the United Kingdom by combining a scoping review with evidence from over 60 Industrial Decarbonisation Research and Innovation Centre (IDRIC) projects. We asked where, how and for whom co-benefits arise at R&D and early deployment stages, and what technology-policy pairing unlock them. Using a reproducible coding framework, we classify co-benefits into four clusters, i) environmental and health; ii) energy cost and productivity; iii) innovation, skills, and jobs; and iv) energy security and system resilience. Across our classification, frequently reported benefits include improve local air quality, reduced energy intensity and operating expenses volatility, workforce upskilling and new roles in emerging value chains, and reduced exposure to imported fuels via electrification, hydrogen, and CCUS. Because the evidence base is R&D-weighted, many benefits are anticipated rather than realised and are contingent on enabling infrastructure, market design, and standards. We propose a short reporting system to standardise co-benefits documentation and improve comparability. Our study reveals where targeted policy and investment can most effectively convert potential co-benefits into tangible outcomes at cluster scale.

1. Introduction

The interconnection between climate change and decarbonisation of energy intensive industries is crucial to comprehend the future of the planet. Industries and production facilities such as manufacturing and energy generation are major sources of emissions that contribute to carbon emission. Studies show that decarbonisation measures in industries can greatly decrease emissions which can drive the stabilisation of climate patterns that comes with other co-benefits. Therefore, industrial decarbonisation is pivotal to the UK's net-zero pathway and public acceptance improves when co-benefits are material and visible (e.g., air-quality, competitiveness, skills). In 2023, United Kingdon (UK) territorial emissions were 383 $MtCO_2e$, industry accounted for 13–14 % of this total (52 $MtCO_2e$), continuing a 60 % decline from 1990 levels [1]. However, within industry, the largest emitting subsectors in 2023 were chemicals (8.2 $MtCO_2e$; 16 %) of Industry, and iron and steel (8.1 $MtCO_2e$; 16 %), cement and concreate were (6.6 $MtCO_2e$; 13 %, reflecting a faster than economy decarbonisation since 2018 [2] Studies shows that decarbonisation of energy intensive industries (EIIs) can greatly decrease emissions which can drive the stabilisation of climate patterns [3]. Yet existing studies are sector- or technology-siloed and seldom comparable, leaving a fragmented picture of UK co-benefits and little guidance on how to measure them at research and development (R&D) or early deployment. This paper synthesises co-benefits evidenced within the industrial decarbonisation research and innovation centre (IDRIC) funded research and innovation projects, and other related literature, making three contributions. i) a UK-specific mapping of co-benefits across over 60 projects, ii) a technology–policy interface clarifying the mechanisms that unlock benefits, and iii) a reporting template to improve comparability in future projects. We focus on R&D and early-deployment evidence and explicitly distinguish anticipated from realised benefits. In the context of carbon emissions reduction from

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EIIs activities also known as decarbonisation, plays a vital role in addressing climate change mitigation [4].

We synthesise over 60 IDRIC projects and triangulate with recent literature to map co-benefits across sectors/technologies using a directed coding scheme and portfolio-level clustering. Industrial sectors contribute significantly to greenhouse gas emissions, accounting for approximately 21–27 % [5]. Another study reveals that to meet climate goals and limiting temperature rise to well below 1.5 degrees Celsius it is critical to decarbonise EIIs [6,7]. Apart from lowering emissions, it is important to consider the other impacts of industrial decarbonisation, such as better air quality, increased energy security and sustainable economic growth [8,9]. Against this backdrop, this study focuses on exploring these co-benefits and highlights the importance of deepening our understanding to inform political and societal readiness necessary for effective policy in achieving the next phase of energy transition. While the overall advantages of reducing carbon emissions are widely known this study aims to delve into the additional benefits associated with industrial decarbonisation. The goal is to offer a rationale, for implementing targeted policies within the UK's largest industrial clusters. This is important to grasp and measure these benefits to guide policy, investment choices and technology deployment. In some ways studies outlines benefits beyond just lowering emissions and organises them into categories and evaluates how they vary across different regions and industries [10,11].

Nevertheless, industry is most framed as hard-to-abate given its heterogeneity of requirements, such as skills, supply chains, and technologies, many of which are unique to particular sectors. For example, the food and beverages industry utilises large amounts of low-temperature heat and refrigeration but must offer an extremely large diversity of food and drink products while also maintaining special considerations about health, safety and waste [12]. Glass, by contrast, uses high temperature heating and blast furnaces which account for 75–85 % of total energy requirements [13,14].

In this paper, we draw from the outcomes of the UKs Industrial Decarbonisation Research and Innovation Centre (IDRIC) funded research projects to examine how decarbonisation of these energy-intensive industries shares other co-benefits such as new jobs and skills for low-carbon transitions and industrial sustainability. Specifically, our focus on the six steps towards achieving zero industry [8], a study that explores the wider implications of decarbonisation with a view to highlighting the potential other opportunities that can emerge from strategic projects funded by IDRIC [15,16]. Ultimately, these objectives seek to contribute to our understanding of industrial decarbonisation impacts beyond carbon emission reduction, thus aiding in making evidence-based policy decisions and promoting sustainable industrial growth. In this study, we firstly provide an overview of co-benefits of industrial decarbonisation literature; secondly examine how this literature addresses the issue around research and development (R&D) and technological deployment and lastly, review the over 65 funded research projects that is funded by IDRIC.

Our analysis of co-benefits is framed within technological transformations with a focus on how communities perceive and interact with changes brought about by technology shifts and sustainable growth [17]. Assessing the synthesis results, we placed importance on considering options such as carbon capture, utilisation, and storage (CCUS) and shifting to hydrogen in industrial clusters where multiple industries are closely interconnected due, to their practicality [18]. The focus ison examining the strategies adopted in the UK in this area which include policy shifts, funding for decarbonisation of energy intensive industries. For instance, Fan et al. (2024) reveal the potential of technologies to meet energy needs without adding more carbon dioxide (CO_2) and other greenhouse gases to the atmosphere [19]. Davis et al. (2018) stressed the importance of cost efficiency and coordinated implementation across energy industries [20]. As Wan et al., (2022) discussed decarbonisation within developing economies pointing out its significance in industrialisation [21]. Additionally, Zhao et al. (2022) outline the status, challenges, opportunities and strategies for reducing carbon emissions in the automotive sector reflecting diverse research efforts in this area [22].

However, exploring the challenges and prospects in achieving decarbonisation in EIIs such as electricity, chemicals, iron and steel, cement and aluminium offers the richness and deepness into how new technologies, policy frameworks, market influences and socio-economic issues shape the transition, towards a low-carbon economy [23] Even though, other studies emphasise on the significance of decarbonising EIIs in combating effects posed by climate change, they recognised challenges and concerns of potential job losses, and competitiveness in the process of decarbonisation [24,25]. Therefore, transition processes must address implications of decarbonising EIIs beyond emission reduction and identify emerging issues such co-benefits for further research [26]. Against this background, there is need to deep our understanding of the intersection of energy transformation within environmental and climate mitigation [27–29]. Even though, studies underscore the need for place-based research strategies in decarbonisation, suggesting inquiries into concepts, place attachment and community identity. It argues the integrating social science theories into decarbonisation policies while communities' experiences is crucial, for achieving fair and inclusive decarbonisation goals [30].

The rest of this study is organised as follows; Section 2 provides account on emerging discourse in technology and policy on industrial decarbonisation, Section 3 outlines the methodology used in the study while, Section 4 discusses the results of co-benefit cluster and mechanisms. Section 5 presents the challenges and limitation of this study. Finally, Section 6 provides the conclusions and policy implication aimed at providing insights for policymakers, industry players and future topics for researchers navigating the shift, towards a low carbon industrial economy.

2. Background: emerging research on industrial decarbonisation technology and policy

Recent studies have discussed the challenges and opportunities linked to reducing carbon emissions in energy intensive industry. For example, Veselov et al. (2022) stressed the significance of evaluating the viability and technological self-sufficiency requirements for reducing carbon emissions, in Russian electric power sector emphasising the necessity for domestically manufactured power and electrical equipment that do not contribute to emissions during production [31]. Similarly, Ju et al. (2021) writes on the challenges in reducing carbon emissions in energy industries like steel and cement due to rising demand and time needed to update existing infrastructure and the presence of process related emissions that points out the sector's hurdles in decarbonisation [32].

Research into co-benefits plays a role in understanding how societal views reducing carbon emissions within industrial sectors and showcased an instance on how research supports decarbonising shipping by offering insights into resolving controversies surrounding lifespan of cargo ships decarbonisation [33–35]. Again, Pultar & Ferrier (2022) identified areas, for policies aimed at decarbonisation including establishing a common understanding of decarbonisation opportunities addressing technical and non-technical challenges, as well as strengthening public involvement and trust [36]. Robertson (2022) also emphasised the need, for increased support for energy intensive industry research and understand the co-benefits of decarbonisation [37]. These discussions touch aspects such as research, funding strategies and policy implications within renewable, sustainable energy and low-carbon technology development and deployments [38,39].

A visual representation in Fig. 1 reveals the distribution of projects initiated by IDRIC across focus areas providing scope on priorities of industrial decarbonisation and associated policy landscape. Notably, carbon dioxide storage emerges as the addressed area with 22 projects under IDRICs Wave 1 and Wave 2 flex funding programs. Wave 1 and

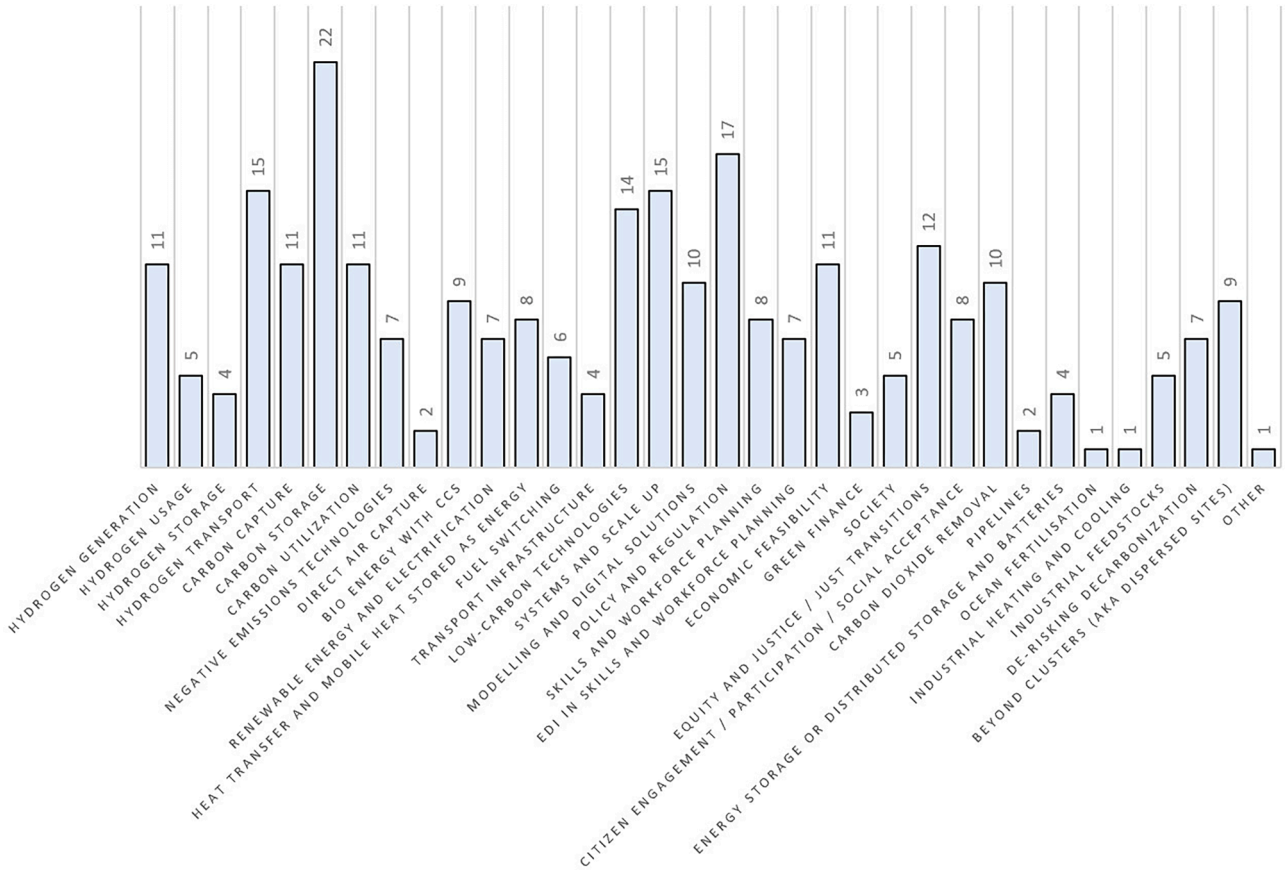

Fig. 1. IDRIC: evidence coverage by co-benefit cluster and technology domain.
Source: IDRIC.org.

Wave 2 signify phases of funding cycles targeting facets of decarbonisation projects. Flex funding offers added financial flexibility to cater to evolving needs and opportunities within these funding. These projects encompass exploration of technologies related to carbon capture, utilisation and storage essential for decarbonisation efforts. Additionally, policy and regulation account for 17 projects either as secondary focuses indicating a concentration, on formulating and enforcing policies to tackle sustainability challenges. In total there are 15 projects dedicated to scaling up systems aiming to improve and extend technologies or systems, for reach and acceptance. Similarly, another 15 projects are centered around hydrogen transportation focusing on ideas and approaches for the transport and delivery of hydrogen as a crucial component, in clean energy advancements.

Industrial decarbonisation literature has been increasingly acknowledging the significance of exploring co-benefits which refers to the economic and environmental consequences in UK steel industry [40]. Our analysis also reveals how co-benefits linked to stakeholders' views on decarbonisation processes is important especially in industrial clusters, stressing the importance of considering the broader economic implications when shifting towards low carbon industrial practices [41, 42] see also, [43]. Ultimately, our study underscores the potentials of environmental co-benefits of decarbonisation particularly in terms of enhancing air quality improving public health, creating new jobs and addressing climate change concerns [44]. However, the economic co-benefits of transitioning industries to low carbon practices have garnered little attention in research [45]. Even though, other advantages such as cost savings, job opportunities, resilience communities and fostering local innovation practices [46].

Notably, incorporating energy technologies and energy efficiency measures plays a role in reaping these economic co-benefits by cutting down on energy costs and bolstering energy security [47]. Moreover, literature emphasises the positive impacts on society and the environment from moving towards decarbonisation, in industries including enhancing renewables energy and energy efficiency policies [48]. There is potential to decrease air pollutants, improve air quality and lessen the health effects of activities by strengthening decarbonisation efforts [49, 50]. Although there are insightful reviews that co-benefits of decarbonisation are not limited to reducing emissions but also extend to climate action that can result in positive outcomes [51]. These proves into the implications of decarbonisation, within the literature of sustainable development and climate resilience. Because of the iron and steel industry's energy-intensive nature, and economic advantage it has on local communities, but it is importance of considering it effects of reducing carbon emissions, on environmental fairness and long-term sustainability [52]. These has shown how economic, social and environmental co-benefits are closely linked [53,54]. Also, our review results identify that many effective decarbonisation options across, involves multi-stakeholders, and having policies to maximise co-benefits and minimise drawbacks related to coherent policies is still lacking [55, 56].

Therefore, while studies have provided evidence into the impacts of industrial decarbonisation, the area of co-benefits still need more investigation and examination [57]. Our review covers the in-depth studies that encompass the co-benefits of social and environmental consequences of industrial decarbonisation. Despite the few studies that have investigated co-benefits there is a need for comprehensive analyses that take into account the interconnected relationships among economic, social and environmental effects [58,59]. It's crucial to understand how these dimensions interact and affect each other to develop decarbonisation strategies that benefit multiple sectors and stakeholders [60]. However, existing literature has mainly concentrated on the effects of decarbonisation in sectors, countries or regions overlooking the need,

for broader clusters and communities' assessments [61]. This entails examining how supply chains, trade dynamics and global cooperation intersect and influence each other [62].

One study reported that deploying decarbonisation technology at scale is essential to grasp its wide-ranging effects on industrialisation which requires international to mitigate climate change and achieve low-carbon transitions effectively [63]. Moreso, there are gaps in existing literature concerning the lasting effects decarbonising US natural gas, especially on technology development and deployment [64, 65]. Several studies have briefly discussed the impacts of decarbonisation, however, there is a call for more, in depth examinations to delve into how decarbonisation of oil and gas sector brings industrial innovation, job trends and economic strength [66]. It is essential to comprehend the impacts of decarbonisation, on society and the economy over the long term to create sustainable and inclusive transition strategies [67]. While a few studies have touched upon the significance of ensuring consistency, in policies and involving stakeholders there remains a call for analyses delving into the policy landscape and the institutional dynamics that influence efforts, for decarbonising industries [68].

3. Research design, conceptual approach and limitations

IDRIC coordinates UK academic–industry research across nine Multidisciplinary Integrated Programmes (MIPs) aligned to major industrial pathways. We analyse IDRIC outputs as an R&D-weighted evidence base for potential co-benefits, distinguishing anticipated from realised outcomes. Fig. 2 depicts the coding frame linking MIPs to four co-benefit clusters. We examined co-benefits beyond GHG reductions associated with UK industrial decarbonisation R&D within the IDRIC scope, we asked: what potential co-benefits are evidenced at R&D or early deployment stage; how do they map to economic, social, environmental and energy systems outcomes; and what enabling policies and technologies recur across projects? In doing so, we combine, i) IDRIC projects outputs (reports, datasets, journal papers) relevant to the seven UK industrial clusters; ii) peer-reviewed syntheses on industrial decarbonisation (hydrogen, natural-gas transitions, iron and steel, refining), used only to triangulate co-benefits, not to over-generalise beyond the UK context.

Our inclusion centred on the outputs that a) relate to UK energy-intensive industries (chemicals, iron and steel, cement, refining, and allied process industries); b) plausibly co-benefit indicators (e.g., air-quality proxies, energy cost reduction, skills and jobs, energy security); c) are dated 2019 – 2024. We excluded information that are unrelated to the UK. We applied a two-level coding; (L1) co-benefit domain (e.g., environmental, health, economic/productivity, skills/jobs, energy-security/resilience); (L2) mechanism (e.g., fuel switch, hydrogen, CCUS, process integration, demand-side and resource efficiency, innovation ecosystems/policy). We then performed a directed analysis to i) extract indicators, ii) map clusters, and iii) synthesise recurring mechanisms and conditions for deployment (infrastructure, regulations, finance, policy). We do not present systematic review, rather a structured, reproducible scoping synthesis anchored in the UK context.

This method allowed us to assess the strengths and weaknesses of the nine Multidisciplinary Integrated Programmes (MIPs) created each to address a key challenge or pathway for United Kingdom's industrial decarbonisation. The nine core MIPs of IDRIC in Fig. 2, served as our coding frame aligned to four co-benefit clusters and a technology–policy interface map used for extracting the relevant inputs that were reviewed. As showed in Fig. 2, Table 1, we independently coded an 86 % sample, disagreements were resolved by discussion and the codebook refined. We then summarised portfolio composition (Fig. 2) and reported results as frequencies and illustrative cases (IDRIC outputs), with discussion linking to broader literature. Because IDRIC funds R&D, we explicitly distinguish potential or anticipated benefits from realised outcomes.

Lastly, in terms of limitations, our study offers a structured evidence synthesis rather than a systematic review on the co-benefits of industrial decarbonisation mainly based on research conducted in the UK's industrial decarbonisation research and innovation centre (IDRIC) has certain these limitations should be taken into account [69]. It draws primarily on R&D and early-deployment outputs from IDRIC-funded projects, supported by recent peer-reviewed literature. As such, many co-benefits are anticipated (modelled or proxied) and only a minority are ex-post at plant or cluster scale. Baselines and context are UK-specific for 2024, and quantitative comparisons is not generalised to other years or jurisdictions [70,71]. Project documentation varies in depth; where methods or indicators were incomplete, we reported qualitative signals only. Finally, the technology is weighted towards supply-side options (electrification, hydrogen, CCUS). Even though, the demand-side measures (material efficiency, circularity, product design) are under-represented and merit further empirical assessment.

The Table 1 pairs each technology domain with the primary policy

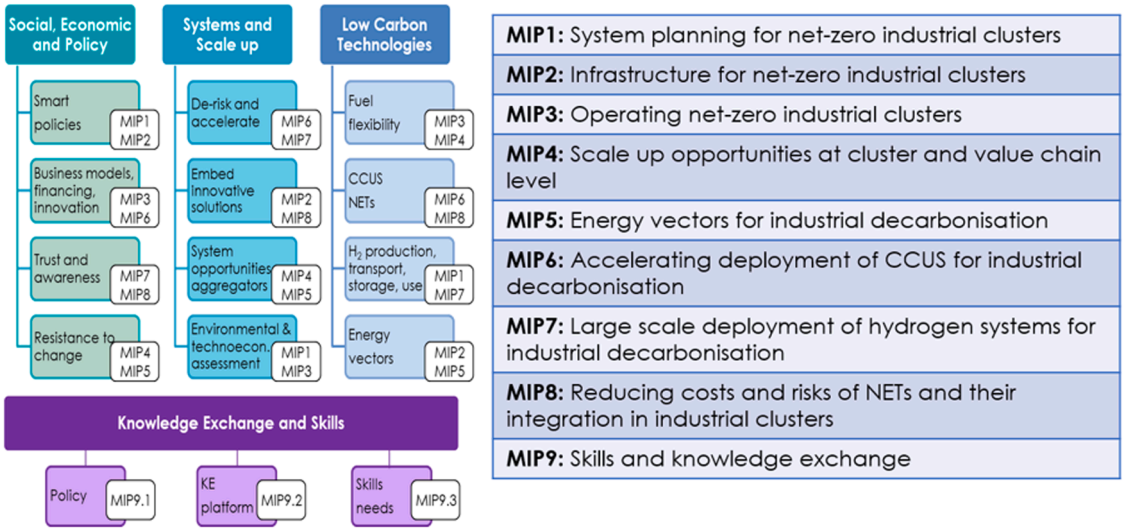

Fig. 2. Logic model and coding frame for co-benefit mapping: Research and Innovation Themes and Multidisciplinary Integrated Programmes of IDRIC. MIP = Multidisciplinary Integrated Programme.
Source: IDRIC.org.

Table 1
IDRIC coding schema for technology domains, policy instruments, and mechanisms.

Technology domain	Enabling policy instruments	Mechanism (how the policy lever accelerates deployment and co-benefits)
High-temperature electrified process heat (e.g., EAF steel, electric kilns/ furnaces)	**Infrastructure**: distribution, transmission capacity, connections; Market/finance: time-of-use/peak-avoidance tariffs, targeted electricity price support for industry, capex grants; Standards: power-quality and reliability; Skills: high-voltage safety & controls	Lowers OPEX exposure to peak prices, reduces connection delays, and de-risks capex; enables air-quality and health gains (less on-site combustion), and productivity (process control, thermal stability).
Hydrogen fuel-switching and H_2-DRI (process heat; ironmaking route)	**Infrastructure**: hydrogen backbone/phased offtake; Market/ finance: H_2 support (CfD/production credits), offtake contracts; Standards: safety codes, purity specs; Skills: H_2 handling and maintenance; Social licence: community safety engagement	Creates bankable offtake and safe access to gas, reducing technology and demand risk; supports air-quality, security (fuel diversity) and jobs/skills in new value chains.
CCUS (capture integrated with process units)	**Infrastructure**: CO_2 Transport and Storage (T&S) access; Market/ finance: capture and T&S business models, liability clarity; Standards: monitoring/verification; Skills: capture operations; Governance: permitting	Provides route-to-sink and predictable revenue/cost recovery, so capture can run at high load; delivers large GHG cuts with co-capture of acid gases/particulates, conditional on solvent/plant management; enables cluster economies.
Process integration and waste-heat recovery (heat exchangers, heat pumps, pinch integration)	**Market and finance**: efficiency grants/accelerated depreciation; Standards: metering and performance reporting; Infrastructure: low-temp heat networks; Skills: thermal systems design	Improves energy intensity and throughput/quality; short payback when finance and metering transparency reduce internal competition for capital; local air-quality improves when combustion hours fall.
Digital controls and optimisation (sensoring, APC, predictive maintenance)	**Market and finance**: digital adoption incentives; Standards: interoperability or data; Skills: data/OT-IT; Governance: cyber-security guidance	Reduces unplanned downtime and energy use per tonne; creates O&M jobs and strengthens productivity, enabling smoother integration of electrified/H_2 equipment.
Lower-carbon process chemistries and materials (e.g., low-clinker cements, solvent management)	**Standards**: product specs, performance certification, public procurement; Market/finance: scale-up grants; Skills: QA/QC; Social licence: stakeholder acceptance	Standards and procurement create demand confidence for new materials, enabling GHG and air-quality gains without performance penalties; reduces process emissions per unit output.
Fuel-switching to sustainable bio-derived streams (where appropriate)	**Standards**: sustainability criteria; Market/finance: credits/ guarantees of origin; Regulation: emissions factors; Skills: combustion handling	Clarifies sustainability and emissions accounting, enabling limited, targeted substitution that delivers air-quality and security benefits in suitable processes.
Demand-side and resource efficiency (material efficiency, reuse, recycled content)	**Standards and procurement**: recycled-content and durability criteria; Market/finance: circular economy incentives; Governance: reporting; Skills: design for circularity	Shifts demand to less resource-intensive products and inputs, reducing energy use and process emissions upstream; co-benefits in cost, air-quality, and jobs in remanufacture/recycling.
On-site renewables and storage for process loads	**Infrastructure**: connection and permits; Market and finance: on-site PPAs, storage support; Standards: safety or grid-codes; Skills: O&M	Reduces exposure to wholesale volatility, supports flexible electrification, and lowers local pollutant emissions by cutting fired hours.
Shared cluster infrastructure (multi-user H_2, CO_2 T&S, heat)	**Governance**: anchor-tenant/third-party access; Market/finance: regulated asset models/tariffs; Standards: access & measurement; Social licence: regional engagement	Achieves economies of scale and lowers unit transport/capacity costs, making first-mover projects viable; co-benefits in jobs, security, and environmental performance at cluster scale.

Source: IDRIC outputs (2019–2024) for UK EIIs.

instruments that unlock its co-benefits, pairings are intentional (row-wise), and mechanisms specify how instruments accelerate deployment and benefits [72]. The table reveals the elements shared between technology innovation and policy considerations within each technology policy domain. This was created by linking each technology to its innovation, including R&D advancements, engineering progress, patents and processes or products [73]. Additionally, it identifies policy measures such as viability, regulatory structures, community involvement, fairness and justice, workforce skills planning and societal views. Analysis of these intersections play a role in understanding the challenges and potential co-benefits of decarbonising energy intensive sectors [74]. Through this overview the table provide insight, into how technological progress and policy frameworks should harmonise to effectively promote industrial decarbonisation. Each row pairs a technology (left column) domain left-hand side technology with enabling policies (right column). These pairing mechanisms indicate how instruments reduce risk and costs (e.g., market creation, infrastructure provision, standards, skills), thereby converting anticipated benefits into realised outcomes. Rows can be many-to-many, e.g., how skills policies support both hydrogen and CCUS.

Sectorally, our reviews and UK-focused analyses show ex-ante modelling of low-carbon steel options where cost competitiveness depends on electricity pricing and carbon policy these studies quantify levelised costs and emissions and test policy scenarios [75,76]. In parallel, critical reviews in process industries (e.g., glass) compile ex-post and ex-ante evidence for furnace upgrades, waste-heat recovery and preheating, linking energy savings to throughput and quality outcomes [14]. Meanwhile, most productivity benefits are modelled under assumed power and carbon prices, real-world outcomes hinge on industrial electricity tariffs, connection capacity, and downtime for retrofit [77]. These shows that the evidence outside pilot lines remains sparse for continuous, high-temperature processes in UK clusters.

4. Results: five prominent co-benefits to industrial decarbonisation

In this section, we provide the analysis our results, arranged inductively around five prominent themes found within our data from IDRIC projects synthesis. We identify four robust co-benefit clusters across the sectors- C1) environmental and health; C2) energy cost and productivity; C3) innovation, skills and jobs; C4) energy security and resilience. Exemplars include anticipated local air-quality improvements from fuel-switch and electrification pilots (C1), reduced energy intensity from process integration and controls (C2), emerging training, and operations and maintenance roles around hydrogen/CCUS assets (C3), and reduced import exposure via flexible electrified loads and shared CO_2 transport and storage (C4). We differentiate anticipated (ex-ante) from realised (ex-post) cases throughout.

These cut across technical, economic, political, and socio-environmental dimensions [78]. To guide presentation our results, we relied on two distinct sets of search terms (shown in Table 1) technology and policy that encompass our focus on co-benefit of industrial decarbonisation [79]. We executed these search permutations on over 60 projects supported by IDRIC -on our synthesised data repositories to capture the state-of-the-art across both scholarly and grey literature. The analysis focuses on the outcomes highlighted in the synthesis report on IDRIC's industrial decarbonisation research [80], which underscores the importance of other advantages such as cost reductions, job creation, new skills, market prospects and innovation. We examine these co-benefits as research activities that may lead to savings through

enhanced energy efficiency, costs and better resource utilisation. These effects are seen to drive socio-technical changes according to studies [81].

Our analysis affirms that adopting low carbon technologies and practices can spur job growth in areas, like chemical, cements, iron and steel, through energy efficient manufacturing processes [82]. This shift contributes to both expansion and increased employment opportunities based on our study and findings [83]. The shift, towards decarbonisation of energy intensive industries has the potential to create opportunities in the market, by promoting economic growth through R&D investment, adoption and commercialisation of clean technologies and sustainable products in chemical industry [84,85]. The economic effects of hydrogen production in decarbonisation are broad ranging encompassing cost savings as well as long term economic strength, thus supporting sustainable economic growth and long-term prosperity [86]. For example, co-benefits of decarbonisation of oil refinery could also result in other advantages that enhance public health, quality of life and justice due to reduced environmental pollution levels, improve air quality thereby reducing health risks associated with pollution [87].

4.1. Environmental and health co-benefits

Across IDRIC domain studies, our analysis reveals that pilots on hydrogen, electrification, and CCUS are ongoing and expected to reduce on-site combustion emissions (NO_x, SO_2, PM) and process fugitives relative to incumbent fuel use, with benefits concentrated around cluster communities, these effects are most visible where projects target high-temperature heat or switch from coal to hydrogen in energy intensive industries (EIIs) [88]. The conceptual mapping in Table 1 shows repeated policy–technology pairings (e.g., standards, networks, finance) intended to convert these anticipated air-quality and exposure reductions into realised outcomes at scale.

Energy intensive industries involve substantial consumption is driven by demand for various products. Especially primary products such as glass, cements, paper, chemicals, oil and gas which its demand has increased enormously in recent years, accounting for two-thirds of the industry's total energy consumption [89]. As Fig. 3 - indicates, the total energy consumed mainly consists of electricity, heat, oil and gas, and petroleum products, these excludes biofuel. However, renewables such as biofuels account for the least amount of fuel consumed in those industries. Interestingly, the idea of technology phase-out is important as it involves the process of phasing out a specific technology or system over time [90]. We suggest embracing clean technologies and sustainable practices by EIIs in the UK cluster not only reduce cost and efficiency but also improves the quality of life, creates healthier and more sustainable living environments, for both communities and individuals [91]. Moreover, technology phase-out in industrial decarbonisation can play a prominent role in promoting equity by supporting sustainable practices, which helps address social inequalities and enhance community resilience [92]. We view the technology phase-out, and the social implications of decarbonising industrial clusters has been crucial for building fairer and more resilient natural gas based communities, ultimately contributing to the overall economy, well-being and development of the United Kingdom [78].

Our systematic and sector syntheses indicate that switching fuels and optimising furnaces processes in EIIs (e.g., glass, steel) reduces both GHGs and local pollutants, evidence is largely ex-ante (techno-economic modelling; scenario analysis) with some ex-post plant-level KPIs for specific retrofits [3]. Recent reviews of the glass industry identify combustion phase dominance (75–85 % of energy in furnaces) and consistent policy levers (carbon pricing, R&D incentives) that would lower both CO_2 and criteria pollutants when coupled with electrification and efficiency upgrades [14,93]. However, the limitation underpin IDRIC evidence base is R&D assessment, observed local air-quality improvements are anticipated from pilots rather than measured ex-post at deployment scale [94]. Achieving co-benefits in this regard depend on

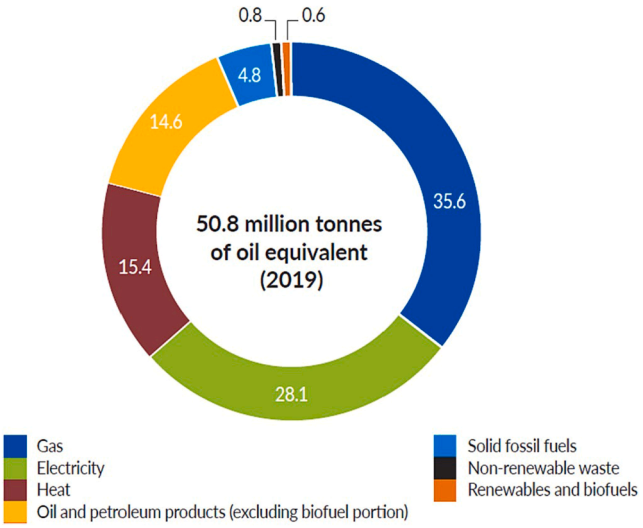

Fig. 3. Total energy consumption in the UK chemical industry by source (%). *Source*: Chung et al., 2023.

fuel quality, upstream electricity mix, and enabling policy (e.g., standards, network capacity). Transferability across clusters is constrained by site-specific baselines and process configurations [95].

4.2. Energy cost and productivity co-benefits

IDRIC-linked projects assess emerging decarbonisation to increase productivity from electrified process heat and process integration (e.g., heat recovery, controls), with anticipated reductions in energy intensity and operating expenses (OPEX) volatility where power-price risk is mitigated [96]. Our mapping foregrounds mechanisms such as network investment, market design and finance, and skills to reduce adoption risk and convert energy savings into productivity gains [97]. This can add to co-benefits such as conserving resources across the UK's seven industrial clusters. For some, the current decarbonisation strategies such as the UK's Just Transition plan can contribute to the co-benefits to historically underrepresented groups, that is creating a more equitable industrial transformation [98,99]. On the other side adoption of cleaner technologies aid in conserving resources and cost, through optimisation of their utilisation for better water stewardship and promoting principles of a circular economy and less environmental degradation around cluster sites [100].

Moreover, decarbonisation of energy intensive industries can enhance ecosystem health by lessening harm, safeguarding land and water management in industrial communities [101]. The environmental outcomes of decarbonisation play a role, in upholding ecological balance advancing responsible resource management practices, combating climate change and ultimately fostering overall environmental sustainability and resilience [68]. Interestingly, the progress in industrial clusters decarbonisation bolsters the UK's position in international climate just energy transition dialogues, underscoring its leadership in policy design and implementation [102].

4.3. Innovation, skills and jobs co-benefits

The UK's ambition for net-zero has set out on a path to reduce carbon emissions aiming to reach net zero by 2050 which has created an opportunity to reskill and upskills. Our analysis suggests that hydrogen, CCUS and electrification create demand for engineering, operations, and digital skills adjacent to existing UK industrial capabilities [41]. Anticipated effects include retraining of incumbent workforces and new roles in project development, operation and maintenance, and supply chains across cluster geographies, conditional on project progression from

pilots to early deployment [103]. Again, there are opportunities for the existing employees to benefit from advanced training programs, learning to operate or maintain innovative equipment. This boosts the overall skill level in local labour markets, helping mitigate workforce displacement from technology phase-outs [48]. Notably, the UK's steel industry has seen strides in decarbonisation with the integration of methods such as hydrogen-based steel production and CCUS [24]. This progress has not only reduced carbon footprints, but also paved the way for new job openings, in clean energy sectors and spurred technological innovation within the steel industry [63].

The UK has made strides in transitioning to low carbon steel production placing it alongside Sweden as a leader, in sustainable manufacturing. This shift has not only opened up market opportunities but has also boosted the country's competitiveness on the world stage [104]. According to our systematic analysis, Fig. 4 below shows that 8 % of projects are focusing on technologies like BECCS (Bioenergy with Carbon Capture and Storage) to capture carbon dioxide emissions from biomass energy production. This indicates a growing interest in utilizing methods to reduce greenhouse gas emissions in processes. Additionally, there is attention on hydrogen storage technologies with 20 % of the projects dedicated to exploring ways of storing hydrogen gas [105]. Moreover, CCUS technology – focused on capturing and storing carbon emissions – make up a portion of the projects at 28 %. Another notable area of focus is hydrogen ammonia that is 8 % of the projects, which involve both the production and utilisation of these elements [72]. Within the CCUS specific emphasis with 8 % projects placed on design aspects aimed at developing systems, for capturing and storing carbon emissions [89]. Lastly there are 12 % of projects categorised under "Others " covering diverse technologies related to industrial decarbonisation and clean energy.

Our reviews on sociotechnical systems of steel and refining identify skill complementarities and institutional conditions needed for low-carbon transitions (standards, infrastructure, finance) [3,4]. These studies are predominantly ex-ante (qualitative synthesis; scenario/roadmap analysis) with case-based ex-post insights on diffusion barriers and enabling institutions [18]. However, employment estimates are not yet derived from ex-post deployment in UK EIIs; outcomes depend on supply-chain localisation, procurement, and policy stability. Our findings reals that without investment and infrastructure decisions, training pipelines risk running ahead of demand [106].

4.4. Energy security and system resilience co-benefits

To further foreground the everyday implications of sociotechnical change that may be overlooked in more abstracted discussions of energy systems and infrastructure change in industrial decarbonisation. Some IDRIC projects assess routes that diversify process energy (hydrogen, electrification) and develop shared CO_2 transport and storage, anticipated co-benefits include reduced exposure to imported fuels and improved system flexibility if electrified loads can provide demand response [60]. Realisation requires coordinated infrastructure and market design, as signposted in the policy–technology pairings [107]. The UK-focused modelling in steel shows policy and pricing conditions under which based direct-reduced iron feeding an electric-arc furnace routes outperform CCS pathways on cost and emissions, implying security gains when electricity is decarbonised and priced competitively [3]. Systems review in process industries outline governance and investment prerequisites (carbon pricing, R&D incentives, networks) for resilient transitions. The energy security benefits the study reveals are contingent on timely network build-out (power; CO_2 transport and storage) and currently there are still possibilities of the wholesale that industrial price pass through. Without these, fuel-switching can shift risk rather than reduce it, even though many of this evidence are still at R&D -stage ex-post resilience metrics are not yet available.

4.5. Demand-side and resources efficiency co-benefits

While our analysis emphasises supply-side R&D, several strands touch demand-side and circularity measures (e.g., process integration, waste-heat use, cullet/batch preheating analogues in high-temperature sectors), indicating potential to lower energy use and costs while improving quality and yield [11]. These benefits are anticipated where design-for-longevity, reuse and recycling can be embedded in cluster value chains. Early analytic insights emerged during our synthesis that process industries (e.g., food and drink, glass and ceramic) and cross-industry syntheses document analyses shows material and energy savings from efficiency, circular inputs, and waste minimisation, with associated economic and sometimes health co-benefits [3]. Our analysis reveals that the demand-side management remain under-represented across UK industrial clusters relative to supply-side options. The benefits depend on standards, procurement, and market acceptance (e.g., recycled content), and on data availability for ex-post verification. The co-benefits also arise from demand-side strategies (material efficiency, circularity, product or service redesign) that can curb industrial energy and process emissions while improving air quality, affordability, and competitiveness [108]. Although the IDRIC projects coverage is weighted toward supply-side technologies, integrating demand-side measures broadens co-benefits and reduces lock-in. Ultimately, the current evidence in UK EIIs is emergent rather than comprehensive, because there are still ongoing perceptions of underinvestment. Our

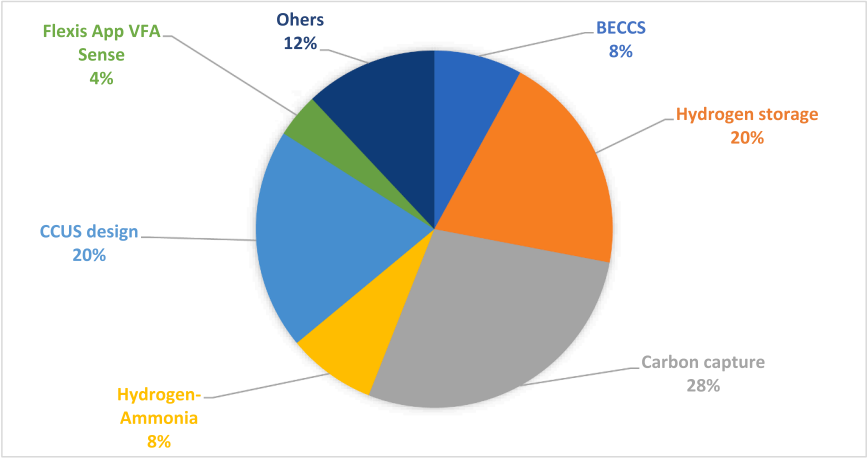

Fig. 4. Anticipated co-benefits across IDRIC technology domains at the R&D stage.
Source: Authors.

analysis thus illustrates the multiple temporalities at play in technology-policy interface that will drive over future decarbonisation strategies.

5. Discussion: challenges and opportunities to capturing co-benefits

Our review identified four practical challenges to realise co-benefits in the UK's industrial decarbonisation. First, investment and price signals to electrified heat and hydrogen routes are sensitive to industrial electricity prices, network charges and carbon policy [109]. Where electricity is costly or grid connections are constrained, anticipated gains in air quality, energy costs and productivity are difficult to capture. Second, enabling infrastructure to support co-benefits from CCUS and hydrogen depend on timely networks and, for CCUS, access to transport and storage, without these, technology deployment remains at pilot scale [105]. Third, organisations require capabilities and skills in process control, safety and digital operations, in several cases training pipelines are in place but demand remains uncertain until technology move beyond pilots. Fourth, consistent standards and markets co-benefits linked to product quality, recycled content or lower emissions intensity need standards, procurement and certification to translate into market value [106]. Ultimately, these conditions shape whether R&D-stage benefits progress from potential to realised outcomes within UK clusters.

Even though sectors that are hard-to-abate such as iron and steel production, present challenges along with evident opportunities for transitioning to zero emissions requiring further exploration and innovative approaches [100]. The is lack of coordination in deployment strategies and integration of operations across discrete energy intensive sectors, these need to be addressed to enhance cost reductions.

Lastly, the transformation of the energy system presents opportunities for reducing air pollution globally, resulting in substantial public health benefits [107,108]. Despite the challenges involved in realising co-benefits beyond emission reductions, advancements in technology, policy implications and potential prospects provide avenues, for maximising co-benefits within the framework of industrial decarbonisation [110]. Addressing the identified challenges, and capitalising on the opportunities of co-benefits such as energy reduction and carbon savings, cost and financial savings can create a sustainable and resilient industrial sector with significant economic, social and environmental advantages.

6. Conclusion and policy implications

This study indicates that UK industrial decarbonisation can deliver multiple co-benefits alongside emission reductions. Four clusters recur across our synthesis, i) environmental and health gains from lower combustion and process emissions; ii) energy cost and productivity improvements from efficiency and process integration; iii) skills, jobs and supply chains associated with emerging low-carbon technologies; and iv) energy security and resilience through fuel diversification and flexible electrification. Because the underlying evidence is R&D or early-deployment, most benefits are potential and contingent on enabling conditions.

The UK's drive toward decarbonisation have positioned it as a leader in manufacturing globally fostering economic growth and boosting competitiveness in the international market. Policy should therefore focus on pairing technologies with the specific instruments that unlock their co-benefits. For instance, electrified heat, this means network capacity, tariff design and capital support that reduce operating risk. For CCUS, CO_2 transport and storage access and clear liability frameworks are decisive. For hydrogen, safety standards, infrastructure sequencing and market creation are central. Across all domains, skills, standards and public procurement can translate technical performance into market value. Incorporating demand-side and resource-efficiency in clusters would broaden and accelerate co-benefits while reducing infrastructure lock-in. A short, common reporting template for co-benefits would improve comparability across projects and enable tracking as pilots scale.

Finally, although industrial decarbonisation poses challenges it also presents pathways for achieving socio-economic growth and environmental co-benefits. Addressing these challenges can provide benefits such as creating new jobs, energy and carbon savings in the industrial products value chain, cost and financial saving, safety, health and sustainability, all these are co-benefits happening in the UK's industrial clusters.

CRediT authorship contribution statement

Abbas AbdulRafiu: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Benjamin K. Sovacool:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition. **Marc Hudson:** Writing – review & editing, Visualization, Validation, Formal analysis, Data curation. **M. Mercedes Maroto-Valer:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition. **Clare Howard:** Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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