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Research article

"Oh Yes! Net-Zero": Sociotechnical capabilities and regional innovation systems for British industrial decarbonization

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ABSTRACT

Few sectors in the global economy need deep decarbonization as much as heavy industry, which is currently the largest and fastest growing source of global carbon emissions. Based on an original dataset of 111 expert interviews and 52 site visits, this paper asks: what sociotechnical pathways, capabilities, and regional innovation systems are emerging to support industrial decarbonization? It combines and applies insights from evolutionary economic geography and transitions studies, such as sociotechnical capabilities and learning, as well as spatial frameworks such as challenge-oriented regional innovation systems (CoRIS) and green industrial restructuring. It utilizes these collective concepts of pathways, capabilities and CoRIS to explore the organizational and technological, individual, and systems level dimensions of industrial decarbonization efforts ongoing across Great Britain. We find that *within* industrial net-zero clusters, spatial and technological proximities are being effectively leveraged, especially through new forms of networking, collaboration, and partnerships. CoRIS provides the basis for greater reflection on perennial transitions issues, both *within* and *across* clusters, related to incumbency and innovation, in addition to spotlighting emergent issues such as light versus deep green restructuring and incremental versus transformative change. In simpler terms, industrial decarbonization unfolds as a multi-scalar process. Industrial decarbonization exhibits both incremental and transformative patterns of change. Industrial decarbonization lastly involves dynamic processes that coevolve across a spectrum of sociotechnical attributes.

1. Introduction

Perhaps no part of the global economy needs deep decarbonization as much as heavy industry, which accounted for 38 % of total final energy use in 2020 (International Energy Agency, 2022). Industrial emissions are directly tied to energy usage. The emissions of energy-intensive sectors such as chemicals, iron and steel, cement, and aluminum, correlate to industrial output, the latter continuing to grow, especially in newly industrializing countries. For example, China accounted for over half of the world's industrial energy usage increase over the last decade (International Energy Agency, 2022). Industrial emissions have, consequently, risen with energy usage since much of industry remains tethered to fossil fuels, especially coal. Underscoring the importance for industrial

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decarbonization, the latest IPCC report (2022) confirms that industry is the fastest growing sector of carbon dioxide emissions, as well as the single largest source of global greenhouse emissions (34 %), including both direct and indirect emissions from electricity consumption and heat generation. This precipitous rise in industrial emissions is driven by both increased materials and minerals extraction as well as higher rates of manufacturing and production.

Against this background, this paper asks: what sociotechnical pathways, capabilities, and regional innovation systems are emerging to support industrial decarbonization? To provide an answer, it uses a mixed methods research design drawing on an original expert interview corpus ($N = 111$) coupled with ethnographic research through extensive field research via site visits ($N = 52$). It draws on insights from regional innovation systems (RIS) theory to explore the organizational and technological, individual and systems level dimensions of industrial decarbonization. Going further, CoRIS (challenge-oriented regional innovation systems) enables us to uncover spatial patterns of proximity, concentration, and networking, as well as deeper issues of light versus deep green restructuring and incremental versus transformative change.

In doing so, we aim to make empirical and conceptual contributions. Empirically, we present rich, original data covering five industrial clusters in the UK. This empirical data can inform ongoing debates about implementation of industrial decarbonization policies, projects, and strategies in other parts of the world. Conceptually, we respond to calls from the RIS and transitions literatures to broaden investigations to consider policy innovations, trace the role of nontraditional actors (such as local governments and civil society groups), and center the analysis on possible failures, risks, and externalities (see especially Tödtling et al., 2022 but also Uyarra et al., 2019; Shearmur et al., 2016).

2. Background and conceptual approach: regional innovation systems and capabilities for net-zero industry

This Section introduces our primary conceptual framework of regional innovation systems (RIS) before discussing its application in the context of net-zero industry, and its connection to core aspects of capabilities and learning.

2.1. Regional innovation systems

While the socio-technical transitions literature has been effective at defining problems and potential pathways associated with industrial decarbonization, it risks remaining an academic exercise without understanding the pressures, constraints and incentives of industrial clusters. Taking such a regional and cluster approach, RIS grew from work on National Innovation Systems (Lundvall, 1992). The RIS involves five key pieces: (1) a region; (2) innovations; (3) networks; (4) learning; and (5) interactions (Cooke et al., 1997). Regions are conceptually composed of "a knowledge infrastructure system […], an industrial system […], and a governance system" (Fløysand et al., 2022: 16). Cooke (2008) adds that part of RIS's success as a theory is that it also avoids 'one-size-fits-all' thinking by looking at specific dynamics and differing instruments, at regional scale. Moreover, it is capable of revealing "network regions" that share similar attributes such as innovation structures. Cooke (2010) further notes that RIS is applicable to "platform industries" and regional clusters that are useful for crossing industry borders, given that they can facilitate knowledge flows across a variety of subnational actors including universities and governments.

Hence, RIS theory is suitable to analyze industrial clusters because it can provide a more pragmatic explanation for innovation, renewal, and rejuvenation (MacKinnon et al., 2019; Gancarczyk et al., 2023). Since it is a "territorially-focused perspective" that consists of a "network of actors and institutions in the public and private sectors," RIS helps to unpack how regional systems "import, modify and diffuse new technologies inside and outside the region" (Iammarino, 2005: 505). The position and authority of knowledge brokers, bridging institutions, and intermediaries are consequential, as they can enable firms and knowledge brokers, which in turn can instantiate a locus of innovation (Powell et al., 1996). Coenen and Morgan (2020) add that RIS is useful at revealing how firms, supply chains, government actors, and even knowledge institutions such as universities can become networked and generate "place-based" structures of innovation.

RIS has also been successfully applied to investigate regions that adopt "green innovations" or reorient themselves towards more sustainable processes (Isaksen et al., 2022). The basic argument is that, given the existence of agglomeration economies, area-level institutions and networks substantially influence firms' capabilities (Balland et al., 2022). These insights rest on much earlier work by Storper (1997), who suggests that regional outcomes are governed by three 'spaces'—territory, organizations and technologies—and the local 'untraded interdependencies' that regulate agents' behavior (Nathan and Overman, 2013: 394).

Andreason and Sovacool (2015) have suggested that a RIS is analytically distinct from both national innovation systems and technological innovation systems. According to Hajek et al. (2011: 202), in contrast to NIS, RIS involves the intricate "interplay between organization capabilities, evolving market structure and technological development, within the context of broader developments in the political, scientific, environmental, legal, economic and social spheres." Since industrial clusters are naturally confined by locational constraints, firms must leverage synergies "because of their geographical proximity and interdependence" (Rosenfeld, 1997: 4). Along these lines, Asheim and Gertler (2005) add that RIS place geography, rather than technology or national culture, at the center. The geographical focus of RIS is thus another added benefit (in contrast to, for instance, national innovation systems).

In aggregate, RIS reveals the dynamic nature of innovation subsystems—paying attention to uneven evolution at subnational scales—drawing attention to the key locational aspects of innovative activities. More importantly, proximity is fundamental, and not incidental to the innovation process itself: "that one simply cannot understand innovation properly if one does not appreciate the central role of spatial proximity and concentration in this process" (Asheim and Gertler, 2005: 292). Indeed, as industrial clusters involve firms in close proximity to each other (Martin and Sunley, 2003), their business activities depend on pooling knowledge and local resources (Boschma et al., 2017; Iammarino, 2005).

These ideas are advanced in recent interventions that focus on green transitions in industrial clusters and regions. In this research domain, RIS informs the “greening of industrial clusters” and “green industrial restructuring” (Trippl et al., 2018; Isaksen et al., 2018; Tödtling et al., 2022; Fløysand et al., 2022). Within this strand of literature, the innovation capacity of regions is viewed as an outcome of the relational and dynamic interdependencies between actors, their actions, the networks they create, and the institutions they support (Tödtling et al., 2022: 2142). Redirecting industrial regions in a low-carbon, or green direction, marks a radical departure from earlier RIS literature “since it implies the emergence of entirely new industries or business models based on scientific discoveries, radical new technologies or forms of organization, user-driven innovation or social innovation (Tödtling and Trippl, 2021: 1780).

One recent conceptual development arising from RIS theory is a framework presented by Jakobsen et al. (2022) based on the specific dynamics of RIS aiming for green transformation. As visualized in Fig. 1, RIS for green restructuring must involve policy experimentation, given that there is no quick fix or established blueprint for success: as green industrial transformation is novel, trial and error and ongoing experimentation are needed. The nurturing of entirely new markets is also required, given the difficulties for new green products to compete with incumbent products, particularly in the earliest phases of market development. Since industrial development has significant degrees of path dependence (Tödtling and Trippl, 2021; Steinböck and Trippl, 2023), a reconfiguration of resources is necessary to stimulate change (Njøs and Jakobsen, 2016; Jakobsen et al., 2022).

The notion of a challenge-oriented RIS (CoRIS) is a promising new development in conceptual thinking. CoRIS refers to a RIS dedicated towards addressing some form of grand societal challenge (Isaksen et al., 2022; Tödtling et al., 2022; Steinböck and Trippl, 2023), such as poverty reduction, sustainability or species loss. It is apt for our study because industrial decarbonization involves multiple societal challenges, including climate change as well as local economic development and growth. Isaksen et al. (2022) add that CoRIS’ can develop along two different routes: strategic reorientation (building or reusing existing actors, competencies, assets, and policies), and strategic transformation (challenging or disrupting existing actors, competencies, assets, and policies).

The CoRIS approach helps hedge some of the following concerns. A central feature of RIS thinking is the focus on agglomeration economies that stimulate trust through common conventions, norms, and flows of tacit and codified knowledge (Storper and Venables, 2004), with emphasis on inter-organizational and technological capabilities development (Hajek et al., 2011). It also recognizes industrial idiosyncrasy (Pavitt, 1984) by focusing on specific industrial dynamics, differing policy instruments and regional scale issues (Cooke, 2008). However, the overarching assumptions within the RIS and clusters literature is that they provide efficiencies and competitiveness under a well-understood business models, but pay scant attention to externalities like climate change.

In addition, economic concerns, i.e. national competitiveness, jobs and inflation, have, until very recently, overshadowed climate concerns in industrial clusters. These economic concerns were very much the original drivers behind the RIS and clusters discourse, which in turn played a role in how the UK clusters were established. and evolved into CoRIS. Such societal concerns draw parallels with the recent and dominant theoretical approach to decarbonation, the socio-technical transitions literature (Bauer, 2020; Victor et al., 2019; Sovacool et al., 2023)

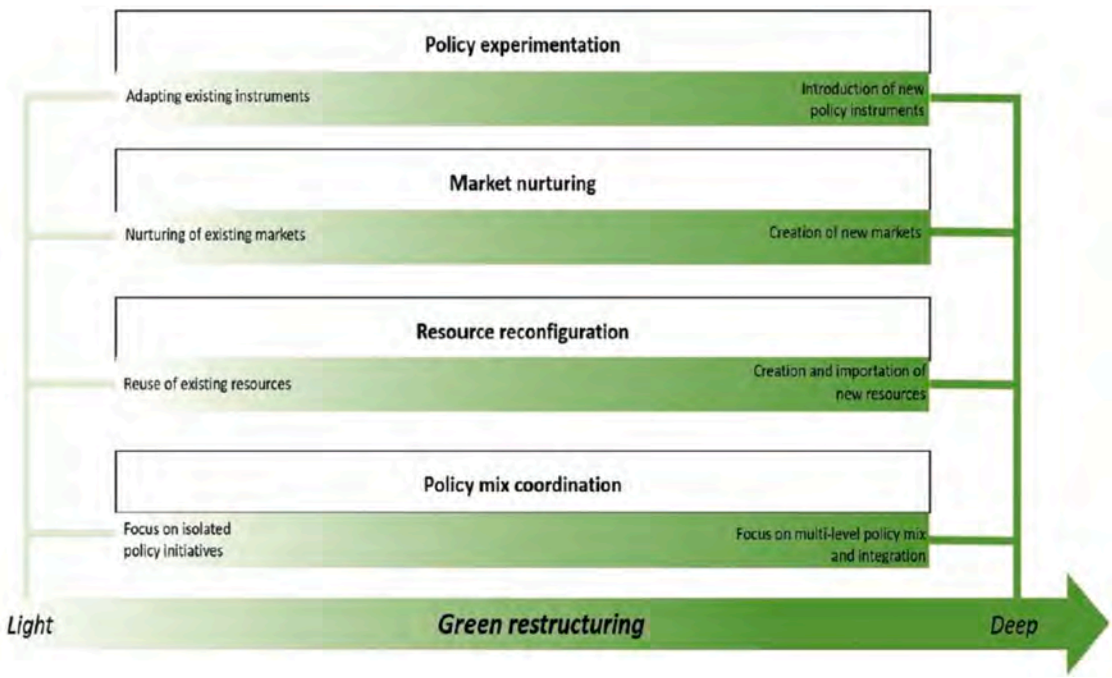

Fig. 1. Visualizing regional innovation systems for green restructuring.
Source: Jakobsen et al. 2022.

2.2. Net-zero industry, incumbency and deep decarbonization

Given the specific CoRIS in the United Kingdom (UK) is centered on net-zero industry, it faces challenges relating to the materiality of greening innovation systems (Zhou et al., 2023), a challenge augmented by strong degrees of incumbency and previous failures in decarbonization policy. Despite the large quantity of emissions stemming from industry, it has until recently been sheltered from stringent regulation owing to economic concerns about job losses, inflation and national competitiveness, overshadowing climate concerns. Decarbonizing industry, moreover, is not straightforward, given that there are legitimate concerns of carbon 'leakage', which occurs when firms relocate to less-stringent countries resulting in little overall benefit to global GHG reductions. Since a global "price on carbon" has yet to come to fruition, there are legitimate worries about carbon leakage—regulating heavy industry can lead to offshoring of carbon emissions (Löfgren and Rootzen, 2021).

Industrial decarbonization also faces a set of pernicious barriers, with some sectors having few low-carbon alternatives (Nidheesh and Kumar, 2019; Geels and Gregory, 2023), and different industrial processes require entirely unique decarbonization solutions (Markusson et al., 2011; Meckling et al., 2021). For example, the food and beverages industry utilize large amounts of low-temperature heat and refrigeration, with surprisingly high emissions, but it also uses carbon in fizzy drinks, which might be one avenue for decarbonization (Sovacool et al., 2021). Glass by contrast uses high temperature heat and blast furnaces which account for 75–85 % of total energy requirements (Furszyfer Del Rio et al., 2022). Remarkably, 90 % of pharmaceutical, agricultural chemicals, petrochemicals and plastics production require petroleum inputs, each with their own distinct supply chains that demand unique decarbonization solutions (Griffiths et al., 2022). In addition, the iron and steel industry is the largest user of coal and the most greenhouse gas intensive in terms of emissions per weight of product (Kim et al., 2022).

It remains an open question whether net-zero policies, based on the "burn now and pay later" principle, are doing more harm than good, especially when they promote the power of incumbents to maintain resources and capabilities. Dyke et al. (2021) write that such framing "helps perpetuate a belief in technological salvation and diminishes the sense of urgency surrounding the need to curb emissions now." At the heart, green industrial transformation implies significant reorientation of industry in a low-carbon direction (Njøs et al., 2020). Restructuring and reorientation of industry can take the form of greening existing industries and processes from the bottom-up, e.g. driven at the corporate level through firm processes, or through a top-down approach of government policy and regulation (Sjøtun and Njøs, 2019). In the UK, specifically, industrial decarbonization policy has emphasized action at both levels, with bottom-up advancements made within clusters on technical innovations such as hydrogen and CCUS, coupled with top-down coordination among policy and planning at the level of the Prime Minister's office and ministerial departments such as BEIS (renamed the Department for Energy Security and Net Zero in 2023) (Sovacool et al., 2024).

The potential for green industrial transformation and reorientation via CoRIS has recently grabbed the attention of policymakers, as it shapes specific net-zero pathways. They can enlist two levers to stimulate the net-zero transition: *phasing-out* fossil fuels or converting existing industrial plants, or alternatively *phasing-in* new systems or practices such as electrification, hydrogen, recycling, carbon capture and resource efficiency. This reflects the political desire to balance industrial effectiveness and economic benefits with environmental and sustainability goals (Fløysand et al., 2022; Tödtling et al., 2022; Steinböck and Trippl, 2023), but also create resilience against future shocks such as Covid-19 or the Russia-Ukraine war (Trippl et al., 2023). Haus-Reve and Asheim (2023) and Hassink and Gong (2021) add that green industrial policy must now balance attempts to manage environmental challenges with promoting diversified or "smart" specialization of skills and the reshoring or regionalization of value chains to secure economic prosperity.

2.3. Sociotechnical capabilities and learning

To help conceptualize the complexities embedded in low carbon industrial transitions, there are numerous sociotechnical approaches, but one of the most significant in terms of its popularity among scholars as well as its explanatory power is the Multi-Level Perspective, or the MLP (Sovacool et al., 2023; Sovacool and Hess, 2017). In an industrial context, the MLP has been utilized to frame different processes with transitions, notably across the phases of emergence, diffusion and reconfiguration. These processes are applicable and can be applied to a range of industrial sectors such as plastics, cement, steel, shipping, aviation, agriculture and automobiles (Bauer, 2020; Victor et al., 2019). Emergence captures technologies or transitions at their early stages, with more emphasis on learning, problematization, scaling, and alignment of actors, interests, and resources. Diffusion relates to more established innovations such as traditional buildings, cars, or conventional power plants, which demand broader attention on coordination, market expansion, and pragmatic actions towards reconfiguration of collective interests. Reconfiguration is a phase that challenges mature technologies, especially those confronted by selection pressures, compliance or monitoring burdens.

The application of the core tenets of co-evolutionary dynamics of the MLP is helpful in the industrial decarbonization setting (Victor et al., 2019), such as the policy imperative to bend and "facilitate transformative innovation (articulating guiding visions and experimenting with options and pathways)" (Voß et al., 2009: 285). From this perspective, guidance and nurturing "rather than planning and controlling long-term societal change" marks an important feature of transition governance (Voß et al., 2009). Relinquishing some control enables ongoing evaluation and policy experimentation (Voß et al., 2009). These renditions of sociotechnical transition theory are, in parallel, developed in related bodies of literature where innovation policies encourage "transition to new fields and trajectories and stimulating product and process innovations for new markets" (Todtling and Trippl, 2005: 1214).

Gruchmann et al. (2021) expand on the MLP, arguing that transition pathways are influenced by not only the dynamic capabilities of actors, but also the timing and space pressures. Innovation from the bottom-up occurs through the interaction of multiple agents, interlocking organizational practices, and structural processes that all shape strategy and courses of action. What this means is that

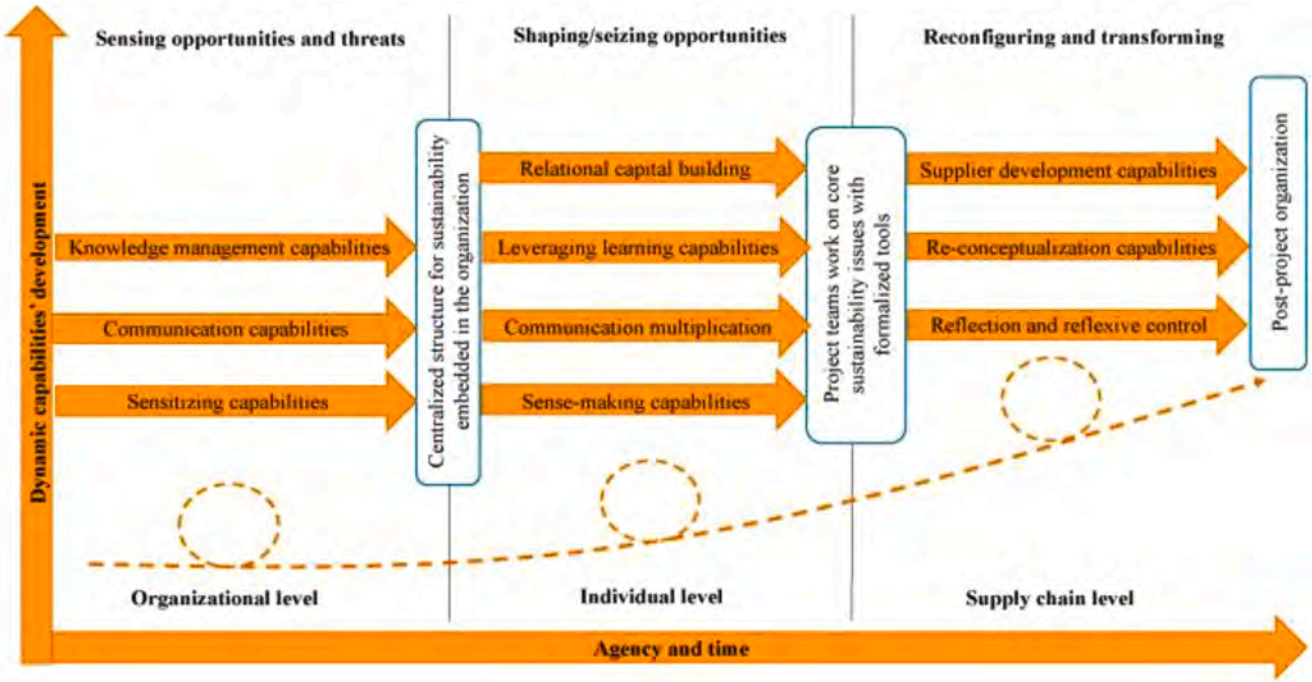

Fig. 2. Envisioning three sociotechnical pathways for net-zero industry.
Source: Gruchmann et al. (2021).

business strategies in industry are partly determined by managerial decisions, yet they are also embedded in wider organizational systems, systems of promotion, as well as broader pressures from the business environment. Nevertheless, scholarship still struggles to identify and delineate between bottom-up and top-down elements from the RIS perspective (Njøs and Fosse, 2019).

As shown in Fig. 2, the eventual success of lower-carbon transitions depends, to a large extent, on the alignment across three different scales: the organizational level (where the incumbent firm can seize new opportunities and avoid threats), the individual level (where managers can build capital and leverage capabilities), and the supply chain level (where suppliers can reflect and enhance their control).

As Fig. 2 also depicts, Gruchmann et al. (2021) propose that more substantial change can be found within multi-scalar and temporal dimensions. These ideas are also reflected by Njøs et al. (2020), arguing that "multi-scalar dynamics and agency" are important features of "new industries in a region" (pg. 269). This suggests that, within a particular industrial sector, for example, managers can foresee opportunities and develop a vision. From a more granular level, this managerial vision is communicated to work floor staff, which engages in its own sense-making of the sociotechnical transition, borne out in capacity building and the delivery of new projects. If these processes are positive, they lay foundations for deeper structural changes inside the organization (through "reflection" and "reconceptualization") and outside the organization (through changes to supply chains). These views are commensurate with a more bottom-up focus, similar to the classic work of Burgelman (1983), with emphasis placed on organizational, individual and systems level mechanisms for sociotechnical change.

When applied to net-zero industrial transitions, a final feature from this approach is that strategic change within industry possesses different depths and, consequently, can be driven by variegated processes. Within the context of industrial decarbonization, this means that new innovations such as hydrogen or carbon capture and storage demand that firms incorporate new capabilities and strategies (Nightingale, 2004; Ning and Guo, 2022). Such technologies might be attractive to incumbent firms because they are mostly modular add-ons (as carbon capture, for instance, does not alter fossil fuel inputs), and as a result might avert jeopardizing core operational processes of many incumbent firms (Geels, 2022). The approach also enables us to capture different material and immaterial assets that firms may use to both innovate or reconfigure as they decarbonize. This could involve reconfigurations in for example: natural assets such as biomass or natural gas; infrastructural and material assets such as buildings; machines, networks and pipeline infrastructure; industrial assets such as technology and firm competencies; human assets such as labor skills and knowledge; and even institutional endowments such as rules, routines, norms, values and culture (Bugge et al., 2022).

Haus-Reve and Asheim (2023) demonstrate that industrial clusters can also lead to the creation and maintenance of new sets of skills especially, those related to the digital economy or "Smart Specialization Strategy" within the European Union, which seeks to promote more inclusive economic development. In this way, industrial decarbonization goals can intersect with innovation policies that are both more place-based and equitable as well better integrated with the introduction of new digital technologies and platforms (Trippl, 2023).

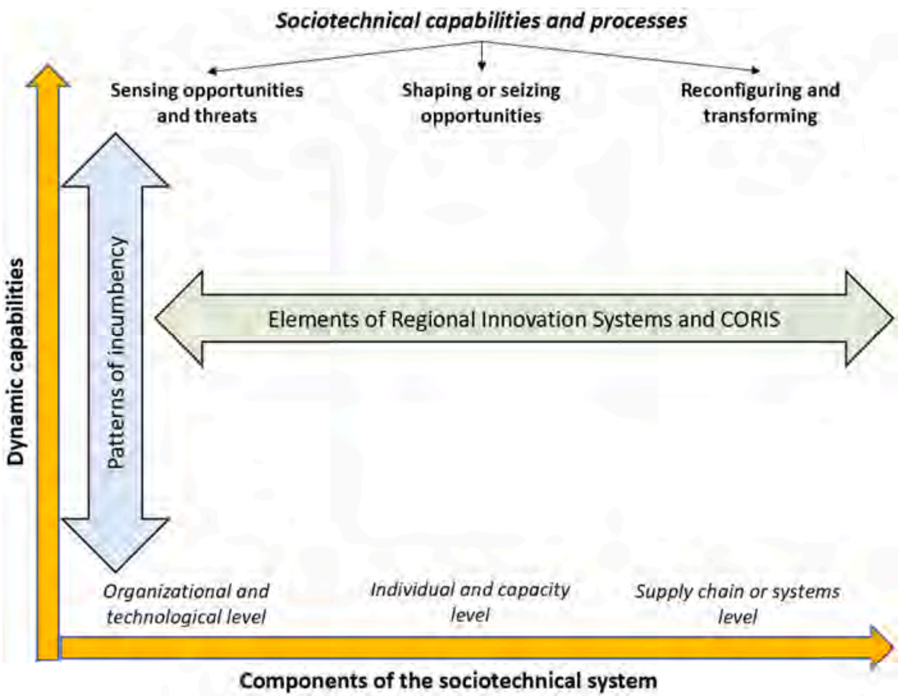

Fig. 3. Conceptualizing interactions between CoRIS, incumbency and capabilities.
Source: Author, based on Sections 2.1–2.4.

2.4. Connecting CoRIS, incumbency and capabilities: a synthesis

Although the concepts of RIS and CoRIS have been mostly developed in a non-net-zero or industrial decarbonization context, and isolated from specific connections to capabilities and learning, we seek to connect them in this paper. As Fig. 3 attempts to illustrate, the spatial elements of RIS and CoRIS permeate all three levels of organizations and technology, individual capacity, and supply chains and systems. Moreover, patterns of incumbency—and the priorities and agendas of incumbent firms and technologies—exert multi-scalar pressures across all levels of dynamic capabilities. Industrial decarbonization therefore becomes a multi-scalar, multi-technological, dynamic process that simultaneously involves sensing threats, shaping opportunities, and responding via incremental vs. transformative change or tactics.

We will return to these three core aspects of RIS and CoRIS, incumbency, and capabilities and learning to structure our results in Section 4.

3. Case study selection and research design

In this study, the United Kingdom (UK) is taken as qualitative case study of industrial decarbonization because it is one of the first major economies to begin industrial decarbonization at scale, and also because it represents a nation-state committed to socio-ecological and spatial "fixes" to energy and climate problems (Angel, 2022). The UK government formally catalogued the top five industrial clusters in terms of their total volume of carbon dioxide emissions (see Fig. 4). We then conducted original research across these top five industrial greenhouse gas emitters, including (1) the Humber (10.03 million tons of carbon dioxide emissions per year); (2) South Wales (8.98 million tons); (3) Merseyside (5.04); (4) Grangemouth (5.01); and (5) Teesside (3.82).

Data-collection across these five clusters centered on semi-structured research interviews conducted with 111 expert respondents over the course of February 2022 to January 2023 (see Table 1). Semi-structured interviews enable researchers to proceed with an open line of questioning, unpacking expert knowledge on important concepts, narratives, and perspectives (Bryman, 2016). Furthermore, they provide "guidance and flexibility […] [to enhance] information-gathering […] allowing space for spontaneous responses" (Noel et al., 2018: 131). We intentionally sought to include a diverse range of perspectives from industry (who dominate our sample, given the topic), as well as national government and policymakers, local authorities, start-up companies, NGOs, and members of academia to ensure triangulation. Within industry, we were able to secure interviews with some of the most prominent actors in each cluster.

Appendix I shows our interview guide and list of questions asked across the interviews, which focused on technology implementation and experimentation; policy and governance; benefits and risks; business strategy; and equity and vulnerability. Interviews lasted between 30 and 180 min, were recorded, and then fully transcribed. They were then coded by the authors inductively to identify recurring themes and topics. Our interviews were semi-structured, enabling the research team to gauge different topics that emerged in

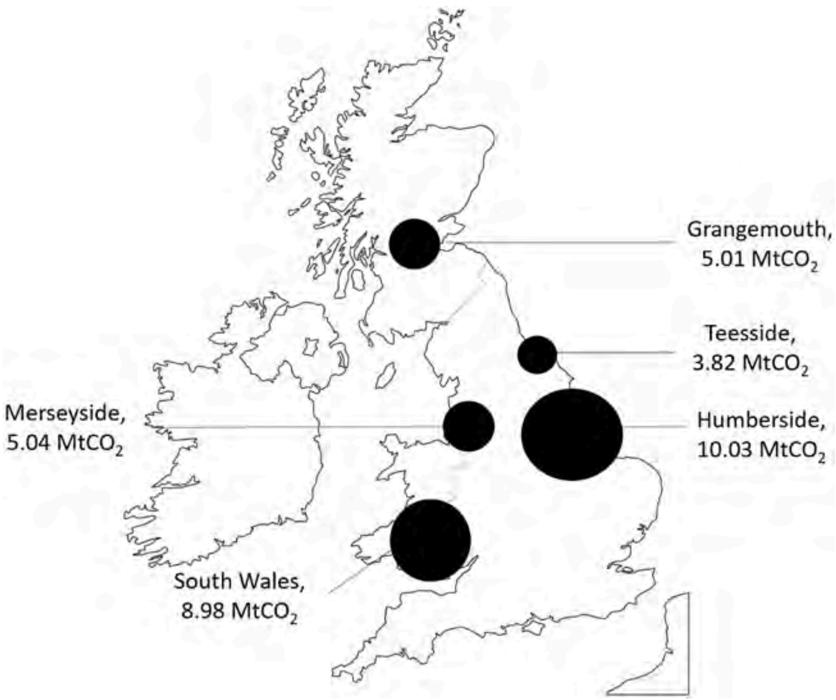

Fig. 4. Visualizing the top five industrial clusters in the United Kingdom by their volume of carbon emissions.
Source: Emissions data plotted from HM Government (2021).

Table 1
Overview of semi-structured expert interview respondents ($N = 111$).

Code	Institution	Type	Date
R01	BEIS	Policy	10.02.22
R02	University of Manchester, the Tyndall Centre for Climate Change Research	Academia	16.02.22
R03	Equinor ASA	Industry	25.02.22
R04	Wood	Industry; provides technical and industry expertise	28.02.2022
R05	University of Oxford	Academia	2.03.22
R06	Centrica	Industry	3.03.22
R07	VPI Immingham	Industry	4.03.22
R08	ITM Power	Industry	4.03.22
R09	Phillips66	Industry	7.03.22
R10	SSE	Industry	10.03.22
R11*	Triton Power	Industry	16.03.22
R12*	Triton Power	Industry	16.03.22
R13	Humber LEP	Local authorities	17.03.22
R14	Centrica	Industry	18.03.22
R15	VPI Immingham	Industry	18.03.22
R16	Cadent	Industry	8.03.22
R17	University of Sussex	Academia	20.03.22
R18	University of Chester	Academia	21.03.22
R19	Progressive Energy	Industry	21.03.22
R20	University of Chester	Academia	21.03.22
R21	Progressive Energy	Industry	22.03.22
R22	Peel	Industry	22.03.22
R23	North West Business Leadership Team	Industry/Business	23.03.22
R24	BEIS (ET&CG, Industrial Energy)	Policy	25.03.22
R25	Phillips66	Industry	28.03.22
R26	Progressive Energy	Industry	29.03.22
R27	North Lincolnshire Council	Local authorities	4.04.22
R28	British Steel	Industry	12.04.22
R29	Imperial College London	Academia	12.04.22
R30	Element Energy	Industry	13.04.22
R31	Offshore Renewable Energy Catapult	Industry/Academia (research)	13.04.22
R32*	BEIS	Policy	14.04.22
R33*	BEIS	Policy	14.04.22
R34	Inovyn	Industry	15.04.22
R35	Pilkington	Industry	19.04.22
R36	Encirc	Industry	20.04.22
R37	National Grid	Industry	21.04.22
R38	Hull city council	Local authorities	22.04.22
R39*	SSE	Industry	25.04.22
R40*	SSE	Industry	25.04.22
R41*	SSE	Industry	25.04.22
R42	Mitsubishi Power Europe	Industry	27.04.22
R43	EssarOil	Industry	29.04.22
R44	University of Sheffield, UK CCS Research Centre	Academia	1.04.22
R45	Norwegian British Chamber of Commerce	Industry	26.05.22
R46	Drax	Industry	13.06.22
R47	Manchester University	Academia	17.09.22
R48*	NECCUS	Industry: trade group	22.09.22
R49*	NECCUS	Industry: trade group	22.09.22
R50	Energy Transition Advisor Limited, Storegga	Industry	06.10.22
R51	Herriot-Watt University	Academia	05.10.22
R52	Kellas Midstream	Industry	05.10.22
R53	British Geological Survey (BGS)	Policy-Research-Academia	10.10.22
R54	Lanzatech	Industry	10.10.22
R55	Stanford University	Academia	05.10.22
R56	North Sea Transition Authority	Policy	14.10.22
R57	Wales West Utilities	Industry	21.0.22
R58	SBH4	Industry	24.10.22
R59	ECITB	Trade	24.10.22
R60	Carbon8	Industry	24.10.22
R61	Aker Solutions	Industry	25.10.22
R62	TuvSud	Policy-Research	25.10.22
R63	UCL	Academia	28.10.22
R64	British Geological Survey (BGS)	Policy-Research	27.10.22
R65	Imperial College London, Just Transition Scotland	Academia	26.10.22
R66	SWIC, Industry Wales, Baxter360	Industry	27.10.22
R67	Wales Hydrogen Centre, Uni. of South Wales	Academia	28.10.22

(*continued on next page*)

Table 1 (*continued*)

Code	Institution	Type	Date
R68	CT Energy, Southeast Water UK, CPH2, Nuclear Decommissioning Authority, Cadent Gas Ltd.	Industry	27.10.22
R69	Tarmac	Industry	28.10.22
R70	University of Strathclyde	Academia	28.10.22
R71	University of Strathclyde	Academia	31.10.22
R72	Plansea	Industry	31.10.22
R73	Manchester Uni.	Academia	31.10.22
R74	Aker Solutions	Industry	24.10.22
R75	Carbon Trust	Policy	03.11.22
R76	Storegga	Industry	03.11.22
R77	Renewables hydrogen alliance	Policy	09.11.22
R78	Just Transitions Committee, Uni. of Bath	Academia	09.11.22
R79	Airhive	Industry	10.11.22
R80	Engaging Next Gen. Industry, Fuel Change	Trade	10.11.22
R81	University of Aberdeen	Academia	28.10.22
R82	Reliagen, Association of Renewable Energy and Clean Technology, BioSci	Industry	10.11.22
R83	Suez Group	Industry	11.11.22
R84	Shell	Industry	11.11.22
R85	green alliance	Policy	09.11.22
R86	SCCS	Policy	14.11.22
R87	Vale	Industry	31.01.23
R88	Storegga (Pale Blue Dot)	Industry	14.11.22
R89	Tees Valley CA, CER Technologies, Ltd.	Local authorities	08.11.22
R90	ENSUS UK Ltd., NEPIC	Trade	15.11.22
R91	Innovate UK (Enterprise Services at Heriot-Watt)	Policy-Research	16.11.22
R92	VNZS, VItaBio Group	Industry	07.11.22
R93	Oxford	Academia	16.11.22
R94	British Geological Survey (BGS)	Policy-Research	18.11.22
R95	Edinburgh University	Academia	18.11.22
R96	Honeywell	Industry	18.11.22
R97	Sheffield University	Academia	18.11.22
R98	BEIS (NZBI - Clean Heat)	Policy	15.11.22
R99	Low Carbon Contracts Company	Policy-Industry	24.11.22
R100	Shell	Industry	25.11.22
R101	Intercontinental Energy, Everything About Hydrogen, Hydrogen Council, Sustainable Energy Council	Industry	25.11.22
R102	Scottish Parliament	Policy	02.12.22
R103	British Geological Survey	Academic/Research/Industry	06.12.22
R104	Durham University	Academia	09.12.22
R105	retired British Steel	Industry	16.12.22
R106	Helmholtz Centre, RIFS-Potsdam	Academia	
R107	BEIS	Policy	07.12.22
R108	Kellas Midstream (NEPIC)	Industry	22.12.22
R109	Sembcorp Energy UK (Wilton Int.)	Industry	11.01.23
R110	RWE	Industry	15.12.22
R111	Protium Green Solutions, Everything About Hydrogen (UK Hydrogen & Fuel Cell Association)	Industry	19.01.23

Source: Authors. Note: * refers to a group interview with more than one respondent present.

more flexibility and depth. To protect the anonymity of respondents, all specific qualitative data are referred to only by a generic respondent number. Ethics approval for the project was granted by the Social Sciences & Arts C-REC board at the University of Sussex with reference number ER/BS289/6.

To complement the interviews, improve triangulation and match stated preferences with observed preferences, members of the research team also conducted a total of 52 site visits, with a sample of visits shown in Fig. 5. This included seven visits to the Humber cluster, with accompanying visits of the cities and villages of Easington, Hull, Immingham, and Drax:

1. Saltend Chemicals Park (March 2022).
2. Centrica Gas Compression and Storage Terminal (March 2022).
3. Langeled Pipeline Entry Terminus (March 2022).
4. VPI Immingham Combined Heat and Power Plant (March 2022).
5. Humber Oil Refinery (owned by Philips 66) (March 2022).
6. Lindsay Oil Refinery (owned by Prax, formerly Total) (March 2022).
7. Drax power station (March 2022).

These visits were complimented by another 13 visits to the Northwest, Merseyside and HyNet cluster, accompanied by visits to the cities and villages of Liverpool, Manchester, Runcorn, Chester, Ellesmere Port, and Daresbury, as well as Flint in North Wales:

Fig. 5. Depicting the largest five industrial clusters across England, Scotland and Wales.
Source: Authors. Panel A shows the Site of Hydrogen Blending with Gas at the Triton Power Facility and Saltend Chemicals Park in the Humber. Panel B the Essar Oil Refinery where Hydrogen Boilers are Being Installed in Merseyside. Panel C the Acorn Hydrogen Facility at St. Fergus. Panel D the Tata Steel Ironworks in South Wales. Panel E the chemicals park at Teesside.

8. Rocksavage Power Plant (March 2022).
9. Viridor Runcorn Energy Recovery Facility (waste to energy) (March 2022).
10. Thorton Science Park (March 2022).
11. Cadent gas compressor station at Northwich (March 2022).
12. Essar refinery at Stanlow (March 2022).
13. Ineos salt and chemicals plant at Weston Point (March 2022).
14. Ineos/Inovyn salt cavern and brinefield at Northwich (March 2022).
15. Storengy salt cavern gas storage at Stublach (March 2022).
16. Uniper Gas Storage at Holford (March 2022).
17. Tata Europe Chemicals facilities at Lostock and Winnington (March 2022).
18. The Protos Energy Facility (which included CF Fertilizers Billingham, ENCRIC Glass, a biomass power plant, an energy from waste facility, and the Frodsham Wind Farm) (March 2022).
19. ENI's Point of Ayr Terminal in North Wales (March 2022).
20. Uniper's Connah's Quay Power Station in North Wales. (March 2022).

The research team conducted 6 visits to the Teesside cluster, with accompanying visits of the cities of Redcar, Middlesborough, Billingham and High Clarence:

21. Teesworks: Sea-Ah Turbine Manufacturer Site (October 2022).
22. Teesworks: British Steel Corp (October 2022).
23. Teesworks: BOC (October 2022).
24. Teesworks Freeport / Harbour (October 2022).
25. Wilton International (October 2022).
26. Teesside (Towns (October 2022).

The research team conducted 11 visits to the Grangemouth and Scottish Cluster, with accompanying visits of St. Fergus, Peterhead, Aberdeen, Iverness and Nairn:

27. INEOS, Grangemouth (October 2022).
28. Acorn CCS, St. Fergus Gas Terminal (January 2023).
29. Acorn Hydrogen, St. Fergus (January 2023).
30. Peterhead Carbon Capture, Peterhead (January 2023).
31. HyWind Floating offshore wind, Peterhead (January 2023).
32. Peterhead Port (Project Cavendish) (January 2023).
33. NSMP, St. Fergus gas terminal (January 2023).
34. SEGAL/FLAGA, Shell, St. Fergus gas plant (January 2023).
35. H2 Green Hydrogen, SGN, Iverness (January 2023).
36. Green Freeport Firth of Forth and Iverness (January 2023).
37. Iverness Distilleries Project (many sites) (January 2023).

Finally, the team conducted 15 site visits to the South Wales Industrial Cluster, with accompanying visits to Port Talbot, Milford Haven, Swansea and Cardiff:

38. Tata Steel Ironworks, Port Talbot (January 2023).
39. Tata Steel Steelworks, Port Talbot (January 2023).
40. Tata Steel Morfa Coke Oven Plant, Port Talbot (January 2023).
41. Vale Europe, Swansea (January 2023).
42. Tarmac Cement, Briton Ferry, Port Talbot (January 2023).
43. Welch Water, Llanigon (January 2023).
44. Associated British Ports (ABP), Port Talbot (January 2023).
45. Pembroke Power Station, RWE (January 2023).
46. Pembroke Oil Refinery, Valero (January 2023).
47. Milford Haven Energy Kingdom (January 2023).
48. Dragon LNG, Milford Haven (January 2023).
49. South Hook LNG Terminal, Milford Haven (January 2023).
50. BP Lightsource Solar Farm, Pembroke (January 2023).
51. Western Wood Energy Plant, Port Talbot (February 2023).
52. BOC Gases, Port Talbot (February 2023).

Finally, to triangulate the data from the interviews and site visits, our study is supplemented with an analysis of externally–oriented presentations and reports, internal planning documents, trade-journals and other sector-specific publications.

All interviews, notes from the site visits, and documents collected were recorded, fully transcribed, and then coded by the research team. Given that the interviews were completed over a five-month period and the site visits over a slightly longer period, blocks of interviews and notes were sent to a professional transcription service as they were completed. Upon being returned, all transcripts were then cleaned by authors. New nodes (and sub-nodes) were iteratively created to capture the diverse perspectives within the material. Data collection commenced separately from thematic analysis. That is, all data were collected first, and then cleaned and transcribed, and only after that fact did thematic analysis commence. This was intentional, and intended to avoid any possible bias in results towards (or away from) any particular theory or conceptual framework. Only after we completed data collection did the authoring team then undertake a deep, thematic analysis of interview data to connect interview responses, field research notes and findings from the documents to the specific concepts of RIS and CoRIS, incumbency, and/or capabilities and learning.

4. Results: regional innovation systems and capabilities in a net-zero UK

This Section presents our results, organized around the three core elements of Section 2, as follows: Section 4.1 focuses on regional innovation systems and CoRIS, 4.2 on incumbency and decarbonization pathways and 4.3 on capabilities and learning.

4.1. Regional innovation systems and CoRIS

As described in Section 2.1, net-zero industry is not only a sociotechnical affair, but also a spatial process. Spatial considerations bring regional innovation systems to the fore, with implications for concentration of interests but also the potential for a range of networking and learning opportunities.

In terms of *spatial proximity and concentration*, our data revealed strong connections to space and place with multiple emergent dimensions. R75 spoke about proximity to knowledge bases, as well as to local authorities and policymakers, saying that:

> "The deployment of end-to-end projects is a spatial affair, one that requires project managers to work with a local authority but also regionally active stakeholders, to get them all around the table, and again starting the process of developing a trustworthy evidence base, spatial analysis, taking into consideration things like the resources available in a region, the sectors active that are important to the local economy, but also the sectors that are contributing most to emissions. Then, perhaps, understanding where those bits overlap and, therefore, where there could be potential for hydrogen deployment. Only then, based off of that evidence generation and the results of that piece of work, we'll scope out a program of projects, making sure all regional actors engage with each other, so that development and deployment occurs regionally."

R75 added that this may mean, in some regions, the matchmaking exercise will result in hydrogen not being widely deployed, whereas it is in other regions. Moreover, deployment will be regionally specific and will have to match the spatial flows of energy, capital, and labor unique to each region. R98 affirmed this viewpoint and recognized the value of the UK's approach by stating that "only the UK has this spatial cluster approach to decarbonization that ties it all together geographically based on clusters, this puts the UK decades ahead of others, such as the United States, and it creates spatial economies of scale, and economies of knowledge. This place-based approach is really helpful, and effective." This response highlights the RIS aspects of the UK's net-zero cluster approach and leads to our next subject – networking.

In terms of *vertical and horizontal networking*, R20 spoke about its importance in pushing net-zero plans forward: "net-zero wouldn't happen in clusters without networking, the clusters work very closely together across regions in terms of getting the industrial clusters mission across the line." R26 framed net-zero pathways as a complex network of physical technologies and infrastructures, adding weight to networking and collaboration:

> "hydrogen production sites and carbon storage networks are literally layers of different systems stacked on top of each other, where we can take refinery off gasses from the refinery as a feedstock into hydrogen production and return hydrogen back into the refinery as well as supplying hydrogen to offsite industry as well. That's why it starts there. That's also where our CO2 pipeline starts, because we have the fertilizer plant and the cracker at the refinery will be two large carbon capture sites, so it all starts in that area in Cheshire [the starting point for the HyNet Northwest project] and then basically grows out from there."

Furthermore, they added that such technological networks are critically dependent on actor-networks to make them work, noting that:

> "none of this would happen without the involvement of a very large number of industries, many of which are in the public domain, that's already on our website with names and logos of companies who have signed memoranda of understanding with us to either offtake hydrogen or connect to the carbon capture and storage system. Of course, we have our big delivery partners who are building this, so Vertex Hydrogen building the hydrogen production, ENI who are developing the CO2 transport and storage system, Cadent for the hydrogen networking, Inovyn for the hydrogen storage, and then we have carbon capture plants, and then a large number of hydrogen off takers."

R90 also spoke about the criticality of corporate networks supporting the projects, stating that "Essentially net-zero industry is all focused around the very overt companies within clusters growing faster than companies outside of clusters. That's the real crux of it. And it's especially true for integrated industries such as the chemical industry, where you have complex elements such as ammonia supply chains, where CF Fertilisers produce ammonia and then that goes to other companies that then add value to that material and manufacture components. So yeah, a hugely integrated industry. A lot of these industries are only viable because of the existing industrial assets within the region. So, integration and networking are really essential for the chemical industry and will be essential part of industries as well. It is actor-networks that will determine the members' needs, whatever interests, builds relationships, identifies opportunities, promote collaboration, and enable growth. So, it's very different compared to other industries such as the automotive industry, where you say, 'Here are a few manufacturers that produce cars" (R42).

Another element of networking concerns international partnerships and engagement well beyond the UK. R88 drew consideration to international climate change events that have shaped, and might in turn be shaped by, the UK's industrial decarbonization efforts. As they clarified:

> "In the last year we've been very much building up our Acorn [Project] involvement experience via conferences and other networking business development opportunities. And now a number of MOUs internationally working with different government and private enterprises in the US, North America, other countries in Europe, the Middle East and Southeast Asia, and Australia, working to further there, both commercial regulatory frameworks as well as a bit on the development planning aspects of how you bring the whole chain and components of a CCS infrastructure supply chain together."

To the same point on cross-border outreach and collaboration, R101 spoke about embedding UK clusters into global networks, noting that "we've been engaging with Japanese, American, Norwegian companies about our net-zero plans" and working with "a lot of different groups, like the Getting to Zero Coalition or Global Maritime Forum, the Aspen Group, and the WEF."

Crang et al. (2013) emphasize the multiple spatial domains within decarbonization—key components include dominant logics of supply and multi-directional flows of goods; value capture and materiality; inter-firm governance including the role of intermediary firms in intermediary places; and the embeddedness of carbon or fossil fuels in relational networks, with their example of the embodied carbon within recycling and waste flows for clothing. Differential capabilities enable actors to capitalize and exploit global networks to sustain their own agendas, which can at times also taking advantage of gaps or inconsistencies in regulation there they can concentrate environmental hazards. This is consistent with Uyarra et al. (2016: 270): "As a result of an increasingly crowded policy landscape, concerns emerge in relation to the coherence and consistency of the policy mix. We find that coherence and consistency in UK low-carbon innovation policy is however lacking, which is creating uncertainty and hampering private sector investment."

Our findings also largely agree with Hildingsson et al. (2019) who note, in a study of Sweden's industrial decarbonization transition, that there are many "governance challenges." Nevertheless, the identification of these challenge also points towards "potential areas where the state can pursue decarbonization in energy-intensive industry and points the way to an active role of the green state in governing industrial decarbonization and greening industry" (Hildingsson et al., 2019: 909).

4.2. Net-zero industry, incumbency and deep decarbonization

As Section 2.2 indicated, a theme worth expanding upon is whether net-zero ambitions in the UK benefit incumbents or new entrants. Findings in favor of the former would broadly support the notion that net-zero in the UK is, paradoxically, being driven by fossil fuel incumbents, who already form part of an existing national policy regime for natural gas.

Natural gas provides both the fuel for carbon and the storage space (in depleted offshore oil and gas fields) for carbon dioxide. Consistent with this view, R65 expressly identified incumbents as a key driver of net-zero because of their knowledge and financial depth: "incumbents have the deep pockets you need and access to capital resources to make it happen. This is the kind of area, things like the breakthrough coalition, this is just not the kind of things they fund … This is not an area where, I think, you're going to find it very easy to attract venture capital, because it's not disruptive enough, quite frankly, which is why, I think, there will be a lot of incumbency in it." This response brings awareness to the "dual role" of incumbents in industrial decarbonization: even though much of the scholarship focuses on how incumbents might hinder transitions, there well may be a "the dual role of incumbents, as maintainers of the status quo and as possible change agents" (Hildingsson et al., 2019: 924)

R70 reinforced this point by suggesting that the oil and gas industry, rather than the electricity industry, would drive the net-zero agenda acting as the strongest agents of change. As they explained:

"From a transformative leadership potential, I think oil and gas companies are quite interesting in a number of respects. They've made enormous profits over the years, absolutely disgraceful in many respects. I spoke about risk and risk is really important. If we look at the conventional power industry, the electricity industry, it tends to be pretty risk averse. Introduction of new technologies over the years tends to have been very slow and so on. Offshore oil and gas and the big oil and gas companies literally in their DNA have a pioneering spirit, which means that they're hugely capable and competent. They've got a very, very high degree of understanding of technologies and engineering. Their approach to risk, probably because in the past they've had quite deep pockets, they have a very, very different approach to risk. They tend to undertake technical risk way before maybe many other sectors. When you're talking about CCUS, generally speaking the issue with that when we go down to risk is your entry point for an industrial CCUS system is £1bn, it's at that level. You can't do a little demonstrator at a few hundred thousand or a few million, it just doesn't capture what you need to do. I think oil and gas companies are probably the only companies that could potentially take that risk at scale."

R56 also spoke about how those leading the net-zero transition "will be those that have pioneered the transformation and hopefully those are supply chain companies from the UK, starting with oil and gas." R53 added that, though industrial decarbonization will be truly transformative and disruptive, it is important that such efforts are "transformative in a way that is achievable. It's an economic thing, it's a financial thing. And I think it's wanting that transformation to say, 'Yes, we're prepared to pay for that.'"

Not all of the actions and tactics taken by incumbents need to be progressive or transformative. R76 framed net-zero transitions within industry in more incremental terms, saying that:

> "With the bigger incumbents, I think there's a big risk that some of them will get left behind because they're not thinking, "How can we develop new business models to a) keep our business viable, but b) make sense in a net-zero world?" Instead, they're thinking about, "How can we find some new solutions that comply with net zero but hold up our existing business models?""

R42 also framed incumbent action by their supportive rather than disruptive potential, noting that:

> "Yes, one of the real benefits about deploying hydrogen and CCUS is a) we're able to reuse existing assets, b) we're able to keep the introduction of new hardware to a minimum, reusing the existing assets, and c) we're able to do it in line with existing maintenance programs, again reducing cost."

They noted that these three factors do enable expedited final investment decisions and deployment in practice, admitting that "hydrogen supply from Equinor is timetabled to be of approximately 2026."

Without incumbency support, decarbonization of clusters will likely fail, a finding echoed by Bernstein and Hoffman (2018), Turnheim and Sovacool (2020), Sovacool et al. (2020), Werner et al. (2022), Rattle et al. (2024), and Groves et al. (2024). The incumbency issue is perhaps paradoxically shaped by previous policies that established the clusters in the first place (Devine-Wright, 2022). Given the long-term policy commitments and accumulate capabilities, there is a lock-in effect that provides little alternative for decarbonization: without the resources, including organizational capabilities, infrastructure and technological expertise, it would be almost impossible for the clusters to decarbonize without essentially shutting down (Rattle and Taylor, 2023). This of course would be economically devastating and thus politically unrealistic.

Firms in industrial clusters are more likely to be protected from radical, competency destroying creative destruction than those not within a cluster (Gilbert, 2012), especially if collective visions have emerged. In addition to incumbency, another finding concerns differing industrial patterns of innovation. For decarbonization, new innovations related to for example hydrogen or carbon capture and storage require firms to acquire new and distinct capabilities that require new strategies, but may be able to do so without underling operational processes and mandates of the incumbents (Geels, 2022), which would otherwise be a difficult, expensive and risky process that has hampered sustainable innovation (Hall et al., 2019).

Reconfiguration and transformation issues rarely surfaced from our interviews, which may be due to 'protection' through association within the cluster, and the notion that collective visions regarding decarbonization have emerged. For example, Trippl et al.

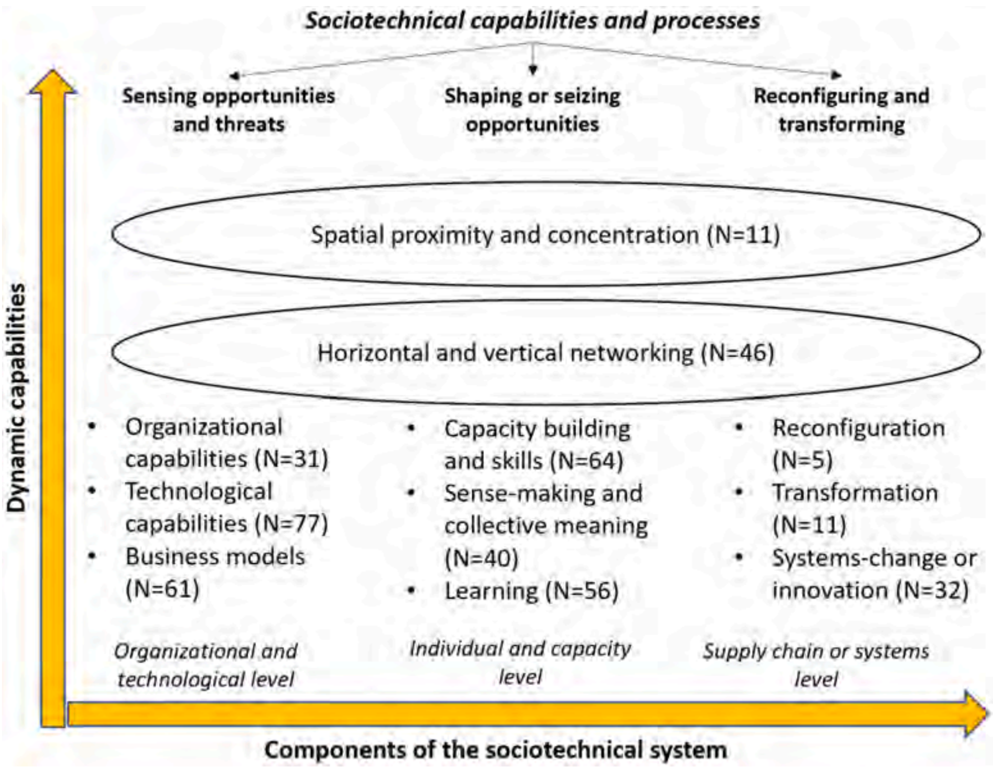

Fig. 6. Sociotechnical capabilities and processes being developed via British industrial decarbonization.
Source: Authors, modified from Gruchmann et al. (2021) to focus on industrial clusters. Data is derived from the expert interviews mentioned in Section 3 ($N = 111$). The N given for each category in the table refers to the number of times each theme arose during an interview, regardless of whether it came up once or repeatedly. Because all three elements (organizations, individuals and, systems) exist within the industrial clusters, we modified the agency and time categories in line with the sociotechnical system framing; and, because all three pathways (sensing opportunities, shaping opportunities, reconfiguring and transforming) are evident, our diagram specifies the three simultaneous interactions.

(2020) identify four pathways that industries can harness to reorient their sectors towards sustainability—path renewal, path diversification, path importation, and path creation. Given the prominence of incumbents, the UK situation more closely aligns with path renewal, introducing new green technologies such as hydrogen or CCUS within existing institutions and business models, and path diversification, where resources or skills are transferred from conventional "brown" or dirty industries to cleaner sectors, in this case that being the gas supply, gas transportation, and hydrogen supply sectors.

4.3. Sociotechnical capabilities and learning

CoRIS and net-zero pathways interact with, and shape, capabilities and learning dynamics at multiple scales (see Fig. 6). First, at the *organizational and technological level*, multiple respondents spoke about capabilities and business models. Indeed, R53 stated that "A multitude of technical skills and capabilities are needed for net-zero, effectively it's a whole chain of capabilities, you have to have [CO_2] capture capabilities, you have to have [CO_2] transportation capabilities, you have to have CO_2 storage capabilities. Capabilities are needed for geoscientists, engineers, it covers practical technicians, even legal capabilities. It's effectively a wide range of skills … it's an enormous range of activities that come together, to be able to have an operable carbon capture and storage project." At the technological level, R74 added that, although some capabilities such as engineering design and construction are highly technical, others apply to managerial elements such as project execution, logistics, human resources, safety, and even social messaging and political negotiation.

R62 brought awareness of dynamic capabilities and emerging markets, including the importance of experimental capabilities and the ability to learn, to share information, and to slowly scale up from prototype designs to fully erected decarbonization infrastructures at scale. There were, however, differential views regarding the incrementality of capabilities; whether or not they were incremental, radical, or transformative. Moreover, there were open questions pertaining to the possession of these capabilities among incumbents, or if new entrants would be needed to plug capabilities gaps. R50 was confident that, for the most part, incumbent firms do have the "technical skills and capabilities, what we need is the same sorts of skills that the oil and gas sector routinely uses: subsurface, wells, building pipelines, all of those things, we just need the same sorts of skills. There are only some slight differences … All in all, it's not that difficult and there are a lot of engineering companies that have managed to do projects that are involved in this space, let's say. The technical skills and capabilities are similar to an oil and gas project, and they're readily available." R61 was similarly confident that technical skills already existed to transition to a net-zero industrial clusters: "basically, it's engineering, isn't it? It's all the usual disciplines within engineering. Particularly chemical engineering, mechanical engineering, electrical engineering. There's a whole range really we have the skills." This view corresponded to R23, expressed the following: "I'm very much in the camp from the skills perspective and talking evolution not revolution. And for things like HyNet specifically, at its heart, it is engineering, it's pipelines, it's manufacturing and construction of components, and then making it work. The only difference is the gas that's flowing through it."

These more upbeat perspectives on technical skills, however, were contrasted by others such as R47 who said that "from a capabilities perspective, net-zero is inherently challenging, because the projects have not been integrated in this manner before or done a scale before, the UK is sort of flying in the dark and just hoping the skills will develop in time." R69 took this stance as well, stating that

Fig. 7. The "Oh Yes! Net Zero" Campaign in the Humber, UK, 2022.
Source: Authors, during a visit to Hull and the Humber in March 2022. Other advertisements encouraged students or the unemployed to "sign up now and support Hull as we lead the UK to a Net Zero Future" or made appeals that "You can help Hull change the world." The campaign is still live and running and readers can even join it by going to https://www.ohyesnetzero.co.uk/.

"hydrogen, CCS, net-zero, these are not existing asset bases, they are opening up entirely new fields. So we need people who have an awareness, have knowledge of CCUS storage, carbon capture technologies, knowledge of chemistry of the solvents, things like that, which currently nobody has." This means that, while some sectors such as Oil and Gas might well have some needed skills such as building pipelines and sending carbon into storage sites, at the front-end a substantially higher degree of high-tech and managerial skills are needed, but not yet forthcoming.

The central government has developed "business models" for CCUS, and is in the final stages of doing the same for hydrogen energy. Respondents spoke about how emergent business models for net-zero technologies were shaping sociotechnical capabilities. R24 detailed the CCUS business model, explaining that it is "designed to bring forward power CCS and also the transport and storage infrastructure to enable the CO2 to be transported and stored permanently … we've gone down the Contract for Difference type approach, where you essentially put in place private law contracts agreed between government and emitters and you agree a subsidy strike price and a reference price and so on. We've been working on those over the last couple of years." R24 added that the CCUS business model is rooted in a public goods-centric regulatory framework "similar to like you see in sewage network, water networks and so on. Where we've got to, is that for power CCS and industrial carbon capture, that business model is nearly complete."

For hydrogen, respondents (R24, R30, R67, R98) spoke about how business models under development are likely to create a reference price for natural gas prices, and then offer hydrogen as an energy carrier at a premium above that price. These responses aligned with what Lochhead (2020) identifies as distinct business models connected to net-zero industry: (1) A model for industrial carbon capture storage dependent on direct government support (for both CAPEX and OPEX); (2) A model for low-carbon hydrogen, by contrast, that can stimulate private sector investment for fuel blending as well as all low carbon production methods; (3) A Power carbon capture business model that provides mechanisms for payment for low carbon generating capacity; (4) A carbon transport and storage model drawing on experiences from other regulated network models.

At the *individual and capacity level*, respondents discussed more micro-level skills and capacity building efforts, as well as learning and experimentation. R108 spoke about the creation of the UK's net-zero skills' academies. These include HyNet academy in the Northwest of England and Net Zero Teesside's work with sixth form (the UK's equivalent of high school) and higher education colleges. Local capacities and support were demonstrably on display in The Humber, which ran a campaign called "Oh Yes! Net Zero" to drum up public support (see Fig. 7). It launched the "Oh Yes! Net Zero" campaign in March 2022 with a keynote speech from dignitaries such as the president for COP26, Alok Sharma (also the former State Secretary for Energy and Business).

Finally, at the *supply chain or systems level*, within our data we identify important elements fitting within RIS, such as reconfiguration, renewal, redirection, and transformation. Indeed, transformation of the O&G industry was raised by R60 who stated that "I don't believe that the oil and gas industry can operate as they have been in a net-zero domain, their offshore expertise needs entirely reconfigured if we talk about hydrogen and CCUS." The significant reconfiguration challenges for industrial hydrogen process as well as the business opportunities, nearly had R69 at a loss of words: "up to the time the hydrogen economy comes into place we will all be using transitional fuels. But hydrogen will be zero carbon. So it is huge. It is going to be very, very, very important for us and for a lot of our processes and business units. Yeah, so it is quite transformational. It will be transformational. Huge I tell you, huge." R98 was

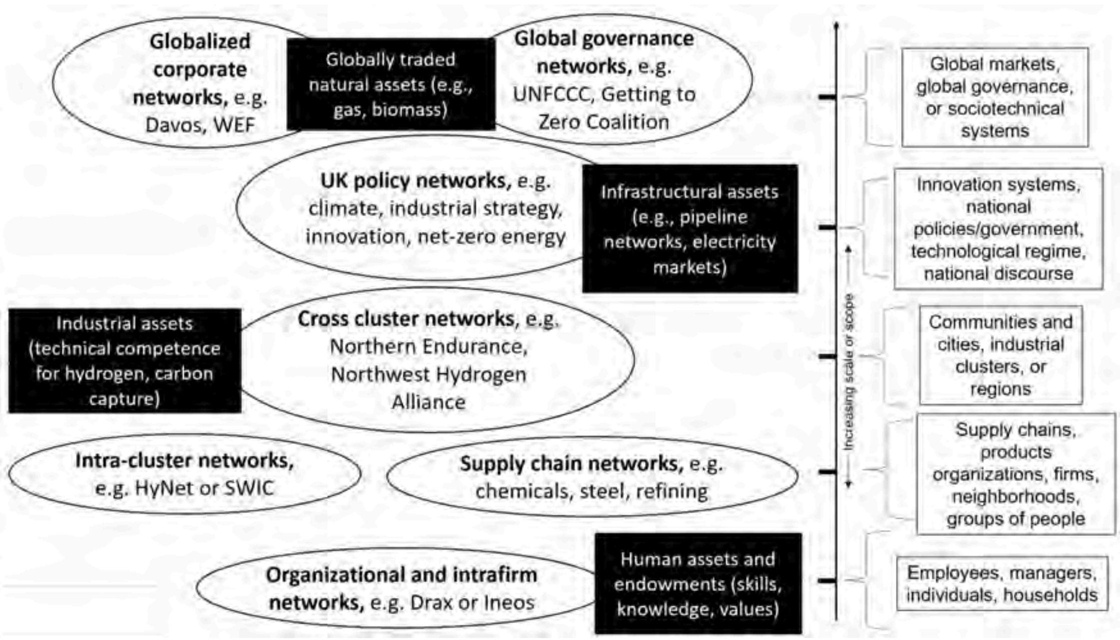

Fig. 8. Multi-scalar flows of technology, knowledge, networking and assets with UK net-zero pathways.
Source: Authors, including Bugge et al.'s (2022) typology of green industrial of assets. SWIC=South Wales Industrial Cluster. UNFCCC=United Nations Framework Convention on Climate Change. WEF=World Economic Forum.

similarly emotive in the words they used, noting that "industrial CCUS or hydrogen is not a plug and play technology, you have to build everything, it's not like renewables where you could just plug it into a grid which exists. It's a massive undertaking."

5. Discussion: scale, transformation, and dynamic processes in industrial decarbonization

Whereas Section 4 emphasized Results based on original evidence and data, we have taken liberty in Section 5 to transmute those Results into looser or more forward-looking statements and interpretations, which also contribute to some of the key theoretical debates mentioned in both Sections 2 and 4. This has been organized around the three core themes of scale (Section 5.1), transformation (5.2), and dynamic processes (5.3).

5.1. Industrial decarbonization unfolds as a multi-scalar process

As Fig. 8 indicates, industrial decarbonization features governance and networking processes that are inherently multi-scalar. We find that there are multi-scalar issues within the UK net-zero industry networks, which tie together organizational, supply chain, intra and inter-cluster networks, as well as policy networks, globalized corporate networks, and global governance networks. What these multi-scalar issues also demonstrate is the role of different green industrial assets (posited by Bugge et al., 2022) but reveals how these occur at different levels, with natural assets such as natural gas or biomass (needed for BECCS) strongly shaped by local factors, but infrastructural assets such as hydrogen and carbon pipeline networks shaped by national and regional factors. Industrial assets are shaped by cluster level factors and human assets more conditioned by local and community factors and endowments.

As Fig. 8 also illustrates, industrial decarbonization reflects a multi-scalar process that involves all three of Coenen et al.'s (2021) distinction between transitions *in, of,* and *by* regions. Our analysis confirms the salience of some processes *in* regions such as place-based factors and mechanisms including local industry culture, industrial knowledge, and connection to local supply chains and intra-cluster networks such as HyNet or SWIC. It however also confirms processes *of* regions such as differences between our industrial clusters in terms of employment patterns, industrial structure, and even fuel and energy choices, for example HyNet being shaped strongly by hydrogen and oil refining at the Essar complex, the Humber region by biomass and BECCS at Drax, but South Wales more on hydrogen for steelmaking. We also see differentiation in terms of access to regional infrastructure, with HyNet orientated towards carbon capture and storage in the Irish Sea via pipeline, the Humber towards storage in the North Sea via pipeline, and South Wales towards shipping-based carbon capture and transport. It lastly demonstrates the presence of processes *by* regions including different agents of change, such as the prominence of Progressive Energy and Cadent in HyNet, contrasted with Equinor and Drax in the Humber, or Tata Steel in South Wales or Acorn in Grangemouth. The salience of these three different levels of processes confirms Coenen et al.'s (2021) argument that the influence and direction of regional transitions are mutually constitutive across place-based factors, differences in regional structure, and different actor coalitions.

5.2. Industrial decarbonization exhibits both incremental and transformative patterns of change

Industrial decarbonization in the UK has, perhaps confusingly, elements of transformative change alongside elements of incremental change. To make this argument, we begin by highlighting how decarbonization strongly conforms to, and showcases the utility of, both the notion of a CoRIS as well as the framework for green industrial structuring articulated by Jakobsen et al. (2022). According to these authors, green restructuring can be either light, with isolated policy, a focus on existing markets and adaptation of existing instruments, or deep, with multi-level policy integration, new resources, and new markets and instruments. Similarly, according

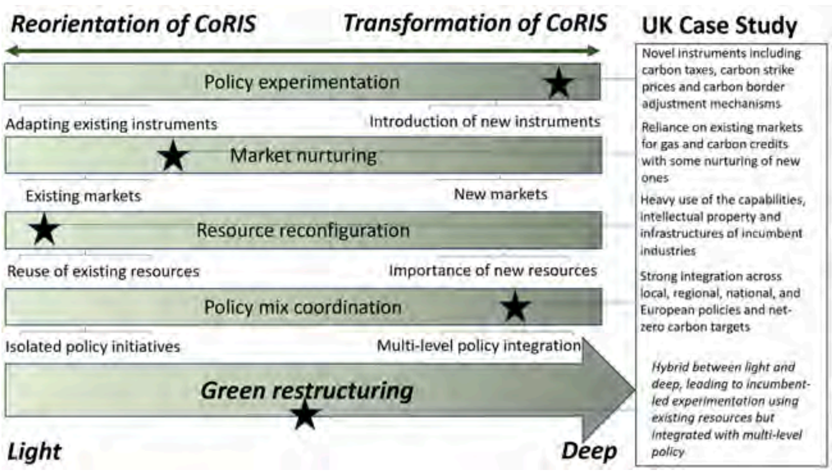

Fig. 9. Visualizing the distinct challenge-oriented regional innovation systems (CoRIS) for green restructuring in the UK.
Source: Authors, based on the framework introduced by Jakobsen et al. (2022) and Isaksen et al. (2022).

Isaksen et al. (2022), CoRIS can be more conservative, utilizing existing assets that serve merely to reorient a RIS towards incrementalism, or more radical, challenging existing assets in ways that lead to transformative RIS.

Fig. 9 depicts these dual trends of light/reorientation vs. deep/transformation as a continuum, and it plots the example of British industrial decarbonization according to each dimension. The UK is transformative in terms of its use of novel instruments such as carbon taxes, differentiated strike prices and carbon border adjustment mechanisms, and also transformative in its multi-level integration of policies at the local, national, and even European levels. The UK is more focused on the reorientation of existing markets (for gas and carbon credits) and especially for resources (heavy use of the capabilities, intellectual property, and existing infrastructures of incumbent industries).

The result is that, overall, the UK's green industrial restructuring can be understood as a hybrid between reorientation and transformation. Contestation also arises, with critics on opposing aisles arguing for swift transformation and stepwise incrementalism. This could also explain why the UK has so much support for industrial decarbonization, as it can bring together actor coalitions across incumbents and new entrants, as well as actors focusing on incrementalism as well as transformation.

5.3. Industrial decarbonization involves dynamic processes that coevolve across a spectrum of sociotechnical attributes

Industrial decarbonization in the UK is a sociotechnical process that involves a multitude of physical or material and non-physical and immaterial elements. Geels and Penna (2015) note that, within industrial networks, technical knowledge, mindsets, beliefs, missions, and norms can all shape behavioral and cognitive learning that feed into corporate political strategy as well as the economic positioning of firms. There is, however, much debate on how various micro/change processes lead to bigger strategic change. In UK clusters, innovations around hydrogen and CCUS shape and are shaped by micro-processes, which co-constitute and co-construct each other. In this vein, McKinley et al. (2014) distinguish between flexible and inflexible innovations. Innovation flexibility refers to the degree of malleability of the innovation after it has been introduced to the market; flexibility is dependent on (1) the range of possible post-introduction configurations a new product, service, or production process can take on and (2) the speed of transition between those configurations. Thus, a flexible innovation is one in which there is a wide range of possible post-introduction configurations that the innovation can assume and the speed of transition between those configurations is rapid. Both CCUS and hydrogen are excellent examples of flexible innovation because they can be configured at various scales and capacities (from individual boilers to power plants to entire industrial clusters), locations (offshore and onshore, subsea or terrestrial), and even sources of energy (natural gas, renewables, imports from Norway). When an organization is in a state of rigidity, new versions of existing product, service, or process architectures are suppressed, and the organization is unlikely to manifest innovations in any of these spheres. The opposite appears to be occurring within the UK clusters.

Dynamic capabilities in particular have been recognized as necessary to allow firms to build and reconfigure competences to address rapidly changing environments (Teece et al., 1997), which is the case for decarbonization. Dynamic capabilities can facilitate decarbonization transitions but requires more explicit policies and incentives that can provide the foundation for effective business models (Werner et al., 2022). Although innovation is central to all the elements discussed above, relatively few studies explore, in depth, how firm-level capabilities are accumulated for decarbonization, and fewer empirically. Although widely recognized as critical to firm performance and sustainable transitions, they are intangible, difficult to identify and quantify (Nightingale, 2004). This is perhaps particularly necessary for industrial clusters, given the important role of incumbents that we identified in our field studies. However, as pointed out by Bocken and Geradts (2020), corporations typically lack dynamic capabilities suitable for sustainable business model innovation, because the perceived financial benefits are poorly defined, i.e. there is no business model.

6. Conclusion

With the vast majority of the scientific, government and business communities reaching consensus over the impacts of climate change, industrial sectors throughout the world will soon need to undertake progressive action. The UK, through its industrial cluster sequencing initiatives, is committed to net-zero industry. These clusters, which account for more than half of the nation's industrial emissions, are embarking on decarbonization journeys across a range of industries such as chemicals, iron and steel, and refining.

Returning to our research question concerning the sociotechnical pathways, capabilities, and regional innovation systems emerging to support industrial decarbonization, we found that UK industry is further along the pathway towards net-zero infrastructure than many may expect. Indeed, even though the UK remains a regime deeply committed to energy market liberalization (Iskandarova et al., 2021), fossil fuel investments in natural gas (Krausmann et al., 2008; Johnstone et al., 2017) and state-support for capital-intensive and centralized nuclear power infrastructure (Johnstone and Stirling, 2020), the 2007 UK Climate Change Act marked the first attempt to reign in the private sector, and its industrial decarbonization plans and policies also present as first-of-a-kind for a major industrialized country. So far, the policy focus centered on technological systems and infrastructure appears well thought out. In addition, by focusing on multi-level changes to organizations and technology, individual skills and capabilities, and systems innovation, the government also hopes to drive forward industrial decarbonization. The UK government is offering business models and financial support for the various net-zero industrial projects, which, in the absence of highly stringent regulations on emissions, would not otherwise be undertaken by industry since added costs would significantly reduce their international competitiveness.

Further, UK policy is developing the technical standards for hydrogen and CCS (e.g., what constitutes low carbon hydrogen, and what is an acceptable and bankable capture rate for CCS). It is steering various forms of policy learning and stakeholder engagement (e.g. consultations, expert groups, bilateral talks), which led to adjustments in policies and business models and a virtuous cycle of responsive regulation. It is further harnessing an inherently spatial process that sees regional innovation systems configure and adapt to promote social proximity and multitudinous forms of physical and social networking, some of which is international.

We identify how industry is utilizing a CoRIS tailored around industrial decarbonization. It is responding to a well-defined problem (climate change) and targets (e.g. 2 °C), backed by significant policy intervention and the near-term deployment of multiple abatement options spanning hydrogen, carbon capture, renewables, and energy and material efficiency. While it remains a question whether the UK's industrial clusters can fully leverage important elements of regional innovation systems, they are beginning to harness momentum building on central and local government support. The UK approach seems to recognize that the stakeholder networks and regional governance dynamics of industrial decarbonization are a multi-actor, multi-technological, multi-scalar process unfolding via hubs and clusters.

Lastly, our study points the way towards future research gaps. One is a need to triangulate our empirical findings with other stakeholders and with critical assessments concerning whether measurable progress is actually being made. Representative national or local surveys specific to industrial decarbonization, rather than decarbonization generally, can also help validate our findings. This can include sector-specific surveys covering various modes of industry, or specific forms of transport such as carbon pipelines. Other forms of evidence including stated preference techniques such as community interviews, household diaries, or focus groups, or revealed preference techniques such as embedded ethnography, naturalistic observation, or spatial analysis would further complement our research design. Better understanding how the technical industrial decarbonization options being implemented, such as hydrogen and CCS, differ in their risk, uncertainty, investment needs, intersections across sectors, and timing would also be fruitful.

CRediT authorship contribution statement

Benjamin K. Sovacool: Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Formal analysis. **Kyle S. Herman:** Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Formal analysis. **Marfuga Iskandarova:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Jeremy K. Hall:** Writing – review & editing, Writing – original draft.

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.

Data availability

The data that has been used is confidential.

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