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Navigating reconfiguration and systems disruption: Decarbonization pathways for UK industrial clusters

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ABSTRACT

Industrial decarbonization is not a linear transition but a contested process of meta-system transformation, shaped by the interplay of system reconfiguration and system disruption. While reconfiguration involves modular adaptations, component substitutions, and architectural shifts, disruption unsettles industrial interdependencies, redrawing sectoral boundaries. Existing frameworks often treat these as separate pathways; we argue they are interwoven. By advancing meta-system transformation as a conceptual lens, we move beyond sectoral silos to capture how decarbonization reshapes industrial architectures. This perspective of transformation and disruption clarifies how transitions unfold, how they might accelerate, and how they can be steered toward structural change. Examining the UK's largest industrial clusters, we trace how decarbonization is unfolding across infrastructures, markets, and governance. While fuel switching, carbon capture, and electrification drive change at the plant level, the introduction of shared hydrogen and CO_2 networks creates wider systemic disruptions. These shifts do not simply displace incumbents but restructure industrial coordination, and may reinforce new dependencies.

1. Introduction

The decarbonization of industrial sectors represents one of the most pressing and complex challenges of the 21st century. Long regarded as "hard-to-decarbonize," heavy industries—such as steel, chemicals, cement, and oil refining—have historically received limited policy attention despite their outsized contribution to climate change. These sectors account for 24 % of direct global greenhouse gas emissions and 34 % of direct and indirect emissions, including those from electricity and heat generation [1]. Tackling industrial decarbonization is, therefore, critical for achieving global climate targets [2]. Recently, leading economies have advanced ambitious net-zero policies, aiming to accelerate the industrial transition [3,4]. Nevertheless, industrial decarbonization is not merely a matter of technological substitution, capital injection, or isolated sectoral adjustments [5]. Moreover, uncertainty about the economic feasibility of retrofitting heavy industry creates significant barriers to transformation [6,7].

Sustainability transitions and industrial transformation research have long debated the drivers and mechanisms of decarbonization. Existing industrial decarbonization studies largely are bound by sector [8,9], industry [10], or firm-focused dynamics [11]. This leaves little room for assessment of system-level structural shifts. System Reconfiguration and System Disruption offer useful but partial explanations of these shifts. System Reconfiguration captures modular adaptations and component substitutions, continuity and adaptation within an evolving system [12,13]. System Disruption, by contrast, entails structural ruptures that reshape market structures but also may destabilize industrial coordination [14]. Yet these perspectives fail to account for the increasing interconnection of industrial infrastructures where decarbonization strategies no longer evolve in isolation but involve cross-sector coordination, planning, and delivery.

Using the UK as a case study, this article investigates the industrial decarbonization transition as a meta-system. Two main questions guide the analysis: (1) How are industrial decarbonization pathways shaped by technical infrastructure, actors and networks, markets, and policies at both the system and meta-system levels? (2) How do interactions across these levels structure reconfiguration processes, component substitutions, and architectural shifts within industrial clusters? The study is grounded in a rich, original dataset comprising 111 expert interviews complemented by field visits and extensive document analysis. Methodologically, we combine stated preferences (expert interviews), revealed preferences (site visits), and secondary data (published reports

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and papers) to achieve robust triangulation.

Our mixed-method approach addresses a critical gap in energy and low-carbon transitions research where single-method analyses remain dominant [15]. In addition, while previous studies have focused on discrete industrial sectors—such as steel [8,9], chemicals [7,16], and oil refining [17,18]—we foreground our analysis on the cross-sectoral interdependencies that are emerging as multiple industrial regimes decarbonize in parallel. Indeed, industrial systems are embedded within evolving networks of technologies, infrastructures, markets, and regulatory frameworks that span sectoral boundaries [19–21]. Rather than treating decarbonization as a sector-specific challenge, we highlight the systemic transformations that unfold through cross-industry coordination, shared infrastructures, and governance shifts [22].

To capture these dynamics, we extend transition frameworks by embedding meta-system architectural change into industrial decarbonization, integrating System Reconfiguration and System Disruption perspectives [12–14]. While often treated as distinct, the interaction of System Reconfiguration and Disruption processes reshape industry beyond sectoral boundaries [21]. Building on system change typologies [23], we develop an integrative *meta-system* transformation. Our conceptual model can effectively capture ongoing decarbonization processes that involve shared infrastructure, cross-sector interdependencies, as well as key elements of both reconfiguration and disruption—ranging from firm-level modular substitution of technology to industry-wide restructuring of shared industrial infrastructure.

This conceptual framework can be explained through a brief exposition. Though industrial decarbonization is shaped by resource competition, regulatory tensions, and large-scale infrastructural shifts, it often comes down to technological integration [11]. Technologies such as fuel-switching and carbon capture and storage (CCS) require plant-level reconfiguration but do not disrupt core production processes—that is, they are modular adaptations which may stabilize existing industrial architecture (i.e., System Reconfiguration). Yet the transport and storage of both hydrogen and CO_2—needed for CCS as well as industrial hydrogen production and delivery—requires the build out of large-scale shared infrastructure (i.e., System Disruption). The multi-system interactions which need to manifest to bring these architectural changes to fruition, in turn, necessitate integrative meta-system transformation.

This article is structured as follows: Section 2 presents the conceptual background and introduces the theoretical framework. Section 3 details the research case and methods, then discusses the theoretical framing for the case. Section 4 presents empirical findings, followed by a critical discussion in Section 5. Section 6 concludes with implications for policy and practice.

2. Conceptual approach: Systems Reconfiguration and Systems Disruption

This section introduces and situates the conceptual frameworks that underpin this study—System Reconfiguration and Disruption—which have grown from the Multi-Level Perspective (MLP). Then, by explicitly theorizing industrial cluster decarbonization as unfolding through meta-system interactions, we explain how our approach helps to assess modular adaptations (reconfiguration) and radical shifts (disruption), offering a comprehensive framework to capture the complexity of low-carbon transitions.

2.1. Multi-Level Perspective

The MLP conceptualizes transitions as involving interactions between processes at three analytical levels: (1) radical innovations that provides the seeds for transitional change; (2) an incumbent system and regime, which are stabilized by multiple lock-in mechanisms and develop along predictable trajectories; (3) exogenous landscape developments that can put pressure on the sociotechnical system [24–27].

Radical innovations with respect to industrial decarbonization refer to transformative technologies and processes that achieve deep emissions reductions beyond incremental gains [28]. Such innovations are central to UK's industrial decarbonization efforts, which aligns with the MLP's first analytical level. The UK government has, indeed, formally recognized the importance of radical innovations, emphasizing flagship demonstration projects as a key mechanism [29]. Separately, in relation to the MLP's second analytical level, modular substitution of technologies to existing industrial systems—which are predicated on long-term sunk investments—can create strong lock-in mechanisms [30,31]. While such lock-ins have contributed to the perception of energy-intensive industries as "hard-to-decarbonize" [32], recent UK policies explicitly address these barriers through large-scale and long-term public funding for industrial innovation and related projects [33–35]. These commitments could potentially unlock path-dependency in heavy industry (Martin and Sunley, 2010).

Lastly, drawing on the MLP's third analytical level, there have been important landscape developments such as the 2016 Brexit referendum (which led policymakers to perceive foundational industries as strategically important for the UK economy), the COVID-pandemic (which further reinforced the view that the UK should maintain foundational industries because relying on international supply chains increased vulnerabilities) [36], the UK's commitment to net-zero GHGs as a country by 2050, and the 2021–2022 gas price shock (which significantly increased costs for existing industrial regime operations and highlighted their economic vulnerability).

2.2. System Reconfiguration

Industrial decarbonization involves not only straightforward substitution of low-carbon technologies but a whole-system's reconfiguration spanning production, distribution, and consumption systems [12]. We draw on System Reconfiguration to specifically understand how modular add-ons or replacements of system components ensue in industrial systems [11,37]. Unlike abrupt disruptions, System Reconfiguration underscores the gradual and sequential nature of transformation, wherein changes accumulate over time to reshape entire industrial ecosystems. This perspective highlights how industrial transitions unfold through cumulative, multi-scalar transformations, involving both modular substitution and structural shifts [38].

A central focus of System Reconfiguration is architectural change, which involves shifts in how system components interact and align [12,39]. This in turn implies that reconfiguration will affect "more or less profound changes in the basic architecture" ([40]: 3). As Andersen et al. [38] emphasize, system architecture is shaped by both institutional logics and technological structures, guiding how industries evolve through processes of reconfiguration rather than wholesale replacement. Consequently, system architecture is "underpinned both by a particular institutional logic and by a set of architectural technologies [which] indirectly help the system serving its societal function by enabling and guiding the interplay of multiple core technologies" ([38]: 2–3). These architectural changes range from localized modifications to cross-sectoral infrastructure realignments, occurring alongside modular substitutions and component-level adaptations, reflecting the multi-system dynamics that accelerate or constrain net-zero transitions [41].

Rather than being confined to incremental adjustments or architectural transformation alone, System Reconfiguration acknowledges that industrial systems consist of multiple interdependent elements—technologies, infrastructures, actor networks, and institutional logics—arranged in a particular way. This system structure opens up space for multiple pathways of change, including modular substitutions, component-level adjustments, shifts in system architecture, and reconfigurations in governance and coordination mechanisms. These change processes may unfold independently, sequentially, or in combination, depending on how different elements of the system interact and evolve over time. Table 1 schematically summarizes the varied and interrelated types of change processes that occur within System Reconfiguration.

From the standpoint of sustainability and low-carbon transitions, architectural reshaping refers to shifts in the linkages between system elements, such as the transition from centralized to decentralized electricity systems integrating storage, smart grids, and flexible demand management. As Kivimaa et al. (2021: 3) argue, "disruption in the context of sustainability transitions should be understood as a high-intensity effect in the structure of the sociotechnical system(s)." This raises a critical challenge for theories of system change. Cherp et al. [42] propose a meta-theoretical framework for energy transitions—conceptualizing them through techno-economic, socio-technical, and political lenses—yet their work does not explicitly account for industrial clusters or multi-system interactions, limiting its applicability to industrial decarbonization. Similarly, Sovacool et al. [43] examine the social construction of net-zero industrial megaprojects but do not fully theorize their role in meta-systemic architectural change. It follows that the architecture of industrial systems is not static but shaped by the interplay of technological conditions, policy regimes, and market structures (see Fig. 1).

Industrial operations do not simply reorganize in response to new technologies; they are shaped by institutional arrangements, regulatory incentives, and market restructuring [37]. While energy sub-systems—such as boilers, burners, and furnaces—may undergo modifications, the underlying architecture of industrial production remains largely intact, reinforcing systemic inertia in decarbonization. Despite policy commitments to industrial transformation, fundamental shifts often fail to materialize at the plant level, where production processes remain constrained by deep-seated path dependencies. For instance, two dominant decarbonization technologies—carbon capture and storage (CCUS) and hydrogen production, transport, and storage—illustrate this tension. Fuel-switching (natural gas to hydrogen) and CCS retrofits are modular substitutions because they replace specific components within an existing system while keeping the overall industrial process intact [44]. Therefore, upstream, both rely on modular substitution rather than incremental change. By contrast, the transport and storage of both CO_2 and hydrogen require large-scale System Reconfiguration, necessitating extensive infrastructure redevelopment and cross-sector integration [45]. This dynamic reveals a central paradox of industrial decarbonization: while energy sub-systems undergo modular technological shifts, the deeper structure of industrial production remains resistant to change. Addressing this inertia requires a framework capable of capturing meta-system transformation, one that accounts for the interdependence between industrial processes, energy infrastructures, and institutional configurations.

Table 1
Analytical framework to map systems reconfiguration.

	Core elements reinforced	Core elements substituted
Architecture unchanged (linkages between components)	*Modular Incrementalism: Small adjustments within existing systems, such as efficiency improvements or minor technology upgrades.*	*Modular Substitution: Replacement of specific components while maintaining the broader system structure (e.g., swapping fossil-based hydrogen with green hydrogen).*
	System-System Symbiosis: Coexistence of two systems that reinforce each other through shared infrastructure or resources (e.g., CCS retrofits enabling low-carbon production).	*System-System Switching: Transition from one dominant system to another without fundamentally altering the system architecture (e.g., natural gas-based ammonia shifting to renewable ammonia).*
	Niche-System Hybridization: Introduction of a new technology or process that integrates with existing systems without full substitution (e.g., blending green hydrogen into natural gas grids).	*Niche-System Replacement: New technology fully substitutes an incumbent system within an existing industrial framework (e.g., replacing coal-based steelmaking with hydrogen direct reduction).*
Architecture changed (new linkages, systemic Reshaping)	*Architectural Stretching – Existing system architecture expands to accommodate new components (e.g., addition of hydrogen pipelines to existing industrial networks).*	*Architectural Reshaping – System-wide transformation driven by the integration of new infrastructures across multiple industries (e.g., hydrogen and CCS infrastructures forming a new industrial meta-system).*
	Meta-System Integration – Multiple systems, traditionally separate, become interconnected through shared infrastructure, regulatory frameworks, or markets (e.g., industrial clusters aligning under a unified hydrogen economy).	*Meta-System Disruption – Large-scale restructuring of industrial systems that challenges established market structures and governance regimes (e.g., transition from fossil-fuel-based production clusters to renewables-based hubs).*

Source: Adapted from McMeekin et al. (2019: 1226)

2.3. Systems disruption

The Systems Disruption perspective extends the MLP by emphasizing the role of disruptive events and the interplay of multiple innovations in driving system-wide reconfiguration [11,14]. Unlike System Reconfiguration, which captures gradual yet cumulative structural realignment, System Disruption focuses on exogenous shocks and radical pressures that destabilize incumbent systems. As articulated by Johnstone et al. (2020: 5), "radical interference in one or more elements of a stabilized socio-technical system, causing pressure to alter the system more than incrementally towards improved sustainability."

Disruptive pressures—whether technological breakthroughs, regulatory interventions, or business model transformations—can trigger and accelerate system reconfiguration. Likewise, reconfigurations within industrial systems can create enabling conditions for disruptive shifts in markets and governance structures. This bi-directional interplay can illuminate policy discussions on how technological choices and institutional support shape shifts in ownership structures and industrial coordination. Kivimaa et al. [13] identify four key dimensions of System Disruption, which align with core elements of the MLP: (1) markets and business models, (2) regulations, policies, and formal institutions, (3) actors and networks, and (4) behavior, practices, and cultural models (Table 2).

A final consideration is the role of incumbent actors, who remain central to heavy industrial sectors. While the MLP frequently addresses incumbents, their position becomes even more significant when viewed through the lens of meta-system architecture and System Disruption. As Lindberg et al. (2019: 3) note, incumbents tend to "favor policies, and transition pathways, that are less disruptive." This does not, however, imply outright resistance to change (Berggren et al., 2015; Geels et al., 2016; [46]). Architectural change helps explain the paradox of incumbent adaptation during periods of disruption ([38]: 15). Rather than uniformly resisting change, incumbents actively pursue adaptive strategies: "they can and do reorient, and architectural change can also take place without major disruptions to incumbent actors" ([38]: 2).

Meta-system change with respect to incumbents, therefore, involves transformations that span multiple dimensions, reshaping not just technology and infrastructure but also markets, business models, regulations, policy frameworks, actor networks, ownership structures, and cultural practices [13]. Understanding how these dynamics unfold is essential for identifying pathways that engage incumbents while driving System Reconfiguration. Building on system change typologies [13,23], we introduce integrative meta-system transformation, representing a fifth pattern of multi-system interaction beyond Raven and Verbong's typology. This framework synthesizes System Reconfiguration and System Disruption, recognizing that industrial transitions unfold

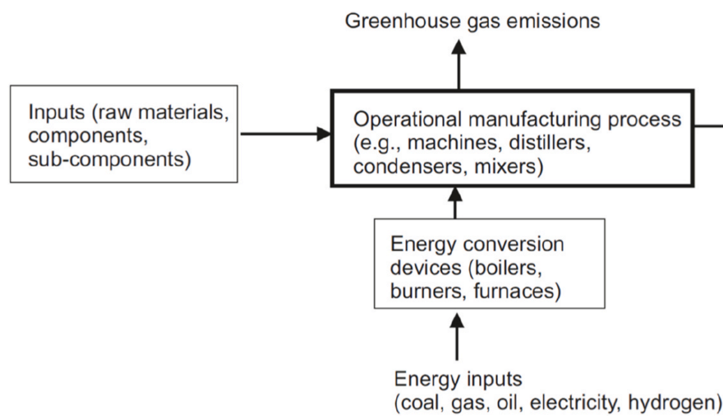

Fig. 1. Schematic representation of industrial manufacturing processes.
Fig. 1 source: Authors.

Table 2
Theorizing multiple dimensions of Systems Disruption.

Dimension of disruption	Explanation
Technology	Novel technology disrupts dominant technology and infrastructure by differentiated qualities Requires initial shielding from mainstream selection pressures
Ownership and actors	Emergence of new actors in production and supply Changing ownership of assets (in terms of kind of actors), with implications on justice and democracy Incumbent actors' reduced influence or fight back
Markets and business models	New value propositions and ways to capture value Reducing market share of incumbent companies New entrants and new business models from incumbents (connected to the actor dimension)
Regulation	Dis-alignments between disruptive innovation and existing regulation, calling for regulatory change Regulatory interventions to intentionally disrupt non-sustainable systems

Source: Johnstone et al. [14].

through both modular adaptations and deeper structural shifts within an evolving system.

Rather than treating reconfiguration and disruption as distinct pathways, we emphasize their interaction within a meta-system framework. We therefore extend existing transition perspectives by incorporating meta-system architectural change into the analysis of industrial decarbonization. This addition refines the conceptual understanding of how multi-system interactions drive industry-wide transformations, and captures the technological shifts and structural realignments that reconstitute shared industrial infrastructure. For example, on the one hand industrial decarbonization relies on non-disruptive technologies like fuel-switching and carbon capture that modify energy sub-systems without changing core production processes. On the other hand carbon capture, *utilization*, and *storage*—as well as hydrogen *transportation*, and *storage*—introduce systemic system disruption since they require entirely new industrial infrastructure shared amongst different industries and industrial actors. The following section details our case study and methodological approach, outlining how our data captures these theoretical and empirical challenges. After developing our case study, we elaborate further on this framework in Section 5 using concrete examples from our research findings.

3. Case study selection and research design

To examine System Disruption and System Reconfiguration in the industrial decarbonization meta-system, we conducted a qualitative study on the UK's cluster-based strategy, which integrates top-down policy instruments with bottom-up industrial initiatives. The 2021 Industrial Decarbonization Strategy set a target of reducing emissions by 3 $MtCO_2e$ annually by 2030, aiming for at least one net-zero cluster by 2040. A key pillar of this approach is shared pipeline infrastructure for CCUS and hydrogen deployment. CCUS is framed as a bridging technology, both reducing direct industrial emissions and enabling "blue hydrogen" production from natural gas until "green hydrogen"—using renewable energy and electrolysis—can become cost competitive. To support these transitions, the UK government introduced a £1 billion CCUS Infrastructure Fund and a 15-year revenue support mechanism for industrial carbon capture. The Labour government has since committed £22 billion to CCUS [47]. The Net Zero Hydrogen Fund subsidizes low-carbon hydrogen production, while a regulated investment model aligns hydrogen transport and storage with industry needs. By 2030, four CCUS clusters are expected to be operational, capturing 20–30 $MtCO_2e$ annually, with a 50 $MtCO_2e$ target by the mid-2030s (HMG, 2023b). Hydrogen targets have also doubled—from 5 GW (2021 UK Hydrogen Strategy) to 10 GW by 2030, with at least half to use green hydrogen (2022 British Energy Security Strategy). These policies may wellreinforce existing infrastructures but also open up pathways for System Reconfiguration and technological substitution.

The collection of empirical data proceeded as follows. First, we catalogued the top five industrial clusters in terms of their total volume of carbon dioxide-equivalent (CO_2-e) emissions (see Fig. 2). We then conducted original research across the Humber (10.03 CO_2-e/year), South Wales (8.98 CO_2-e/year), Merseyside and the Northwest (5.04 CO_2-e/year), Grangemouth and the Scottish Cluster, (5.01 CO_2-e/year),

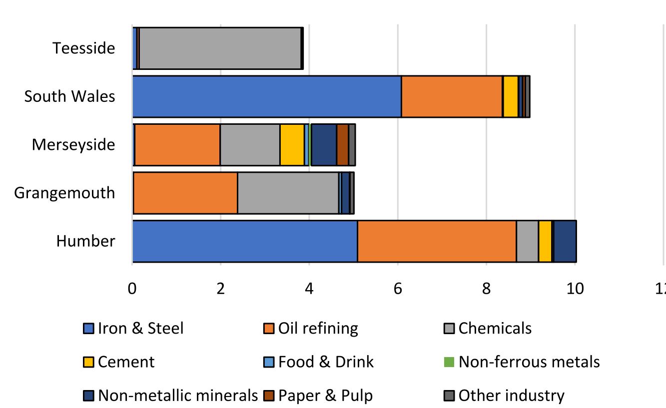

Fig. 2. CO_2 emissions (in Mt) from different industrial sectors (excluding power generation) in 2018 in six UK clusters.
Fig. 2 source: Constructed using data from Ref. [29]: 121.

and Teesside (3.82 CO_2-e/year). Notwithstanding the outsized GHG profiles of these five clusters, they are also in the process of developing several net-zero megaprojects with capital expenditures as high as £46 billion for the Humber alone [48,49].

These data collection procedures were supported primarily by interview data. Since industrial decarbonization is an emerging socio-technical paradigm [50]—wherein experts across technology, governance, markets, and regulation play salient roles in thought-leadership and coordination—interview data can help shine light on variegated assessment of respective technological interpretations, and the identification of niche or radical innovations [19,51,52]. This also reduces the need to await publicly available secondary data sources [5].

Interviews were conducted with 111 expert respondents from February 2022 to January 2023 (see Table A1 in the Appendix). We intentionally included a diverse range of perspectives from industry (who dominate our sample, given the topic), and also central government policymakers, local authorities, and members of academia. Within industry, we were able to secure interviews with some of the most prominent actors in each cluster. In brief, interview questions 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 by a professional transcription service. They were then inductively coded by the authors using Wordstat and NVivo to ease the identification of key themes and topics. This resulted in the identification of diverse and nuanced views of policy, governance, and technology, with respect to the industrial decarbonization meta-system architecture. To ensure the anonymity of Respondents, we coded them by number (*e.g.*, R01 to R111). To complement the interviews, members of the research team also conducted a total of 52 site visits (Fig. 3). The site visits enabled direct observation of cluster-specific infrastructure, plans for construction, and local civil society, each of which are consequential to the ongoing transition. Finally, we supplemented the study with qualitative analysis of externally-facing presentations and reports from the private sector, local and central government policy papers, internal planning documents, trade-journals and other industry-specific publications. This includes project diagrams, maps, and visual charts, some of which we present below. 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.

3.1. Theoretical scaffolding: the multi-levels of the industrial decarbonization meta-system

In principle, the UK's net-zero industrial cluster plans are buttressed by support for individual industrial decarbonization projects. In aggregate, these qualify as array projects, defined by a "dispersed collection of different systems that function together to achieve a common purpose […] considered a 'super system', thus expressing its nature as a conjunction or conglomeration of systems" ([53]: 611). The extent to which the UK's decarbonization strategies and policies can induce requisite innovations—which revolve around megaprojects and industrial clusters—remains an open question, however [3,49].

The panoply of projects currently advancing in the UK are embedded in large-scale infrastructure systems. For example, at least two massive (and "first-of-a-kind") carbon capture and transport systems are set to capture point-of-source emissions from an array of GHG-emitting facilities in industrial clusters. In addition, several hydrogen transport and storage systems are expected to carry low-carbon hydrogen from new production facilities to industrial plants, and also store hydrogen energy for future usage. Decarbonization plans therefore include projects that reconfigure existing plants and industrial regimes, specifically the installation of CO_2 capture technologies, fuel switching, and the integration of low-carbon hydrogen. These technologies are the current focus of the central government's industrial cluster approach.

Architecture change is not confined to internal reconfigurations within individual industries but can also emerge externally, shaped by new interconnections at the industrial cluster level [38] The

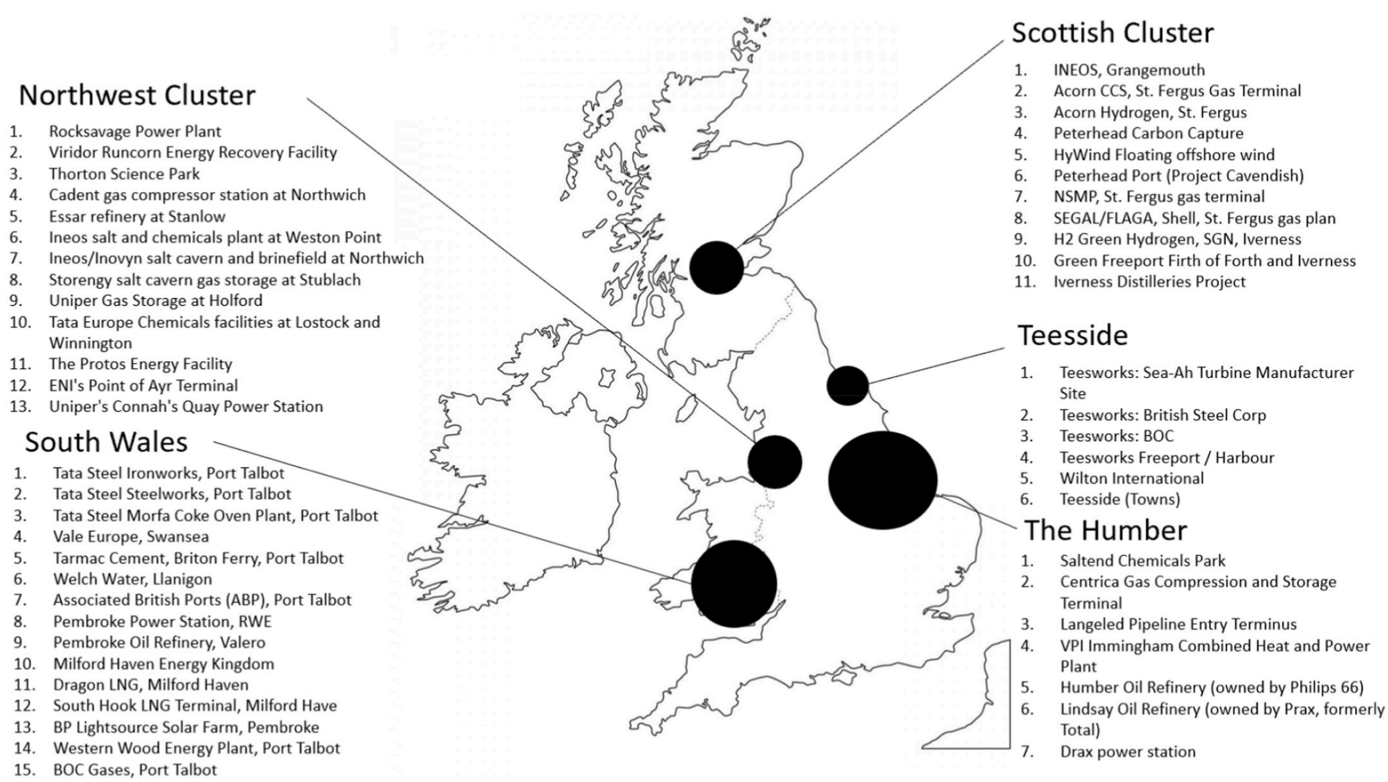

Fig. 3. Overview of top five industrial clusters (by carbon emissions) and locations of site visits (N = 52).
Fig. 3 source: Authors. Note: the size of the black circles corresponds to the volume of industrial affiliated carbon emissions, based on HM Government [29].

development of CCUS and hydrogen infrastructures, particularly in relation to CO_2 and hydrogen storage, exemplifies this process of modular substitution, introducing a new architecture of technical linkages that integrate previously separate industrial systems into a broader meta-system. This underscores the importance of analyzing multi-system interactions, as cross-sectoral dependencies add complexity to transition pathways [54]—where advances in one domain may inadvertently constrain diversification in another [39]. Crucially, these interdependencies can materialize even in the absence of structural change within individual plants. These dynamics align with the 'second-order systems' concept from Large Technical Systems studies [55,56], which describes infrastructures that transcend individual industrial sectors.

To both contend with the novelty of technologies and plans involved in the UK's industrial decarbonization efforts and policies—and recognizing that it sits within a meta-system—we conceptually structure our analysis along three lines of inquiry: (1) the construction of a meta-regime architecture that links multiple industrial regimes, especially through hydrogen and CCS infrastructures; (2) the incorporation of some niche-innovations into industrial regimes, either as front-end replacement in the energy sub-system (fuel switching from natural gas to hydrogen) or as back-end add-ons (carbon capture); (3) the production of green and blue hydrogen as niche-innovations that feed either into co-located industrial plants or into the hydrogen infrastructure system. In the following section, we build on these perspectives to present our findings.

4. Four dimensions of prospective disruption in net-zero industrial pathways

This section is organized along the following key themes, drawing mainly from Table 2 above: technology and infrastructure; actors and networks; markets and business models; regulation, policies, and formal institutions. Our extension, the integrative meta-system, is then fully fleshed out in the Discussion section.

4.1. Technology and infrastructure

The most obvious disruptive element is technological disruption in response to recent government funding interventions [57]. These include the Industrial Energy Transformation Fund (IEFT) (£315 million), the Industrial Decarbonization Programme (£170m), and the Industrial Strategy Challenge Fund (ISCF) (£210 million), which are expected to drive innovation and help build out critical infrastructure (CCC, 2019; Garvey and Taylor, 2020; Devine-Wright 2022; [58]). In addition, the £1 billion coupled with the recently announced £22 billion for CCUS are expected to make carbon capture a reality in at least two clusters. Last, the £240 million Net-zero Hydrogen Fund, and £171 million as part of the Industrial Decarbonization Challenge (IDC), are meant to accelerate technological innovation and implementation for hydrogen technologies (HM Government, 2021; [36]).

An entirely novel policy development revolves around government plans to decarbonize *vis-a-vis* blue hydrogen production (using methane and CCS), green hydrogen production (using renewable energy and electrolyzers), fuel switching from natural gas to hydrogen, as well as bioenergy with carbon capture and storage (BECCS). These technologies are supported through actionable and enforceable timetables to achieve net-zero [29]. The low hanging fruit, according to R43, is hydrogen for fuel switching, which is considered "doable now" even though technical challenges are already evident (R43). Implementation, however, demands significant changes to "technical modules", as outlined by R28:

> *We have a project in our TBM mill looking at switching hydrogen, green hydrogen for our CH4. It's not as simple as just switching hydrogen for CH4, it's a different mass and so therefore it's a different heat transport with the burners. The burners have to be changed. The dynamics of the reheat furnaces have to be changed, it's not just a switch one out switch one in.*

Though R28 understood this process as challenging, R43 drew attention to potentially softer, incremental changes to the system because: *Companies are very willing to switch hydrogen for natural gas, even though there is a cost of the upgrade, meaning that you have to change your valves, your controllers, your TSOVs, your flamers, your burners.*

Respondents voiced concerns, however, about the inherent complexities underlying the UK's industrial net zero cluster plans that are so reliant on technological innovation (R54; R52; R75). Expectations of technological component add-ons are further complicated by the unique characteristics of each industrial cluster, which are in part moderated by corresponding supply and demand of industrial decarbonization technologies. These complexities are evident in examples from the different industrial clusters, and their independent challenges owing to existing industrial operations.

For instance, the operations of the chemical industry are the focus of decarbonization in Teesside [59], whereas Grangemouth and much of the Scottish cluster will focus on chemicals, refining, and storage of CO_2 offshore (from the Scottish cluster and other clusters). Steel and iron production are the largest sources of emissions in South Wales; accordingly, to rapidly draw down emissions, these industrial operations must find a way to decarbonize through greener processes such as electric arc furnaces; alternatively, South Wales will export carbon as there are no carbon storage options locally. The Humber and Merseyside/Northwest span several sectors such as iron and steel, oil refining, cement, chemicals, food and drink, and metals; industrial decarbonization in these two clusters will be a great challenge. The Merseyside and the East Coast Cluster (which includes the Humber and Teesside) have the most advanced CCUS plans, and both were selected in October 2021 as winners of the government's track-1 CCUS competition. Teesside is already building carbon capture utilization and storage systems to be used by 2026, and the Humber expects widespread use of industrial hydrogen by 2028. Fig. 4 shows observational data from our site visits which illustrate some of the infrastructure currently slated for industrial decarbonization across the five clusters.

Respondents drew attention to the distinct elements of disruption and innovation within each vector of decarbonization technologies (R51; R52; R68). The disruptive nature of hydrogen storage and supply technologies for the conventional oil and gas supply system surfaced as a main concern. In contrast to CCS, which is already successfully used in other countries, largescale hydrogen storage and transport—outside of the United States [60]—are new-to-the-world technical challenges that demand significant innovation, as articulated by R52:

> *In terms of hydrogen storage, there's far more innovation going around at the moment. We are definitely out there on the edge, looking at different stuff. There's a lot of big mixing hydrogen in with ammonia, to create ammonia as being the base storage, which is easily transportable [...] This idea is quite advanced and quite radical.*

A respondent from the cement industry, R69, viewed fuel switching as a radical solution alongside hydrogen, requiring substantial reconfiguration of some business units:

> *Up to the time the hydrogen economy comes into place we will all be using transitional fuels. But hydrogen will be zero carbon. So its disruptive potential is huge. It is going to be very, very, very important for us and for a lot of our processes and business units. So it is quite transformational.*

A Respondent from the South Wales Industrial Cluster (R66) seconded this view, noting that a switch to hydrogen fuel is likely to trigger further knock-on effects and reconfigurations: "*hydrogen is definitely disruptive in that it performs in a way perhaps that other fuels don't. It allows you to use it across multiple different sectors. It can replace diesel, it can replace gas, it can replace electricity [...] it can be disruptive in that sense.*" R51 (an academic researcher) concurred but went further to outline the

Fig. 4. Depicting technology and infrastructure across the largest five carbon-emitting industrial clusters across England, Scotland, and Wales
Fig. 4 source: Authors. Panel A shows the carbon capture and storage site at VPI Immingham. Panel B the Essar Oil Refinery in the Northwest. Panel C the Port Talbot Steelworks in Wales. Panel D shows the BOC facility at Teesside. Panel E shows the Ineos facility at Grangemouth.

transformative effects on energy supply, particularly pressure on renewable energy supply to create green hydrogen. Since there are plans to blend fossil and hydrogen fuels, heavy industries such as cement or steel are confronted by a "*doubly disruptive*" transition.

Carbon capture, utilization, and storage (referred to as CCS and CCUS interchangeably throughout our interviews) is construed as vital to achieving industrial decarbonization, according to government's plans as well as some respondents, though this is the subject of ongoing debate [57,61,62]. The difference in opinion centered on *where* CCS would be integrated. In many cases carbon *capture* is meant to be affixed to existing industrial plants; in this setting, CCS would be an add-on, component technology, unlikely to be accompanied by much disruption to operations. On the other hand, carbon *transport and storage* constitute an immense change to the meta-system architecture since it requires building new pipelines—or repurposing vintage pipelines—and delivering carbon to storage sites, mainly located in the North Sea.

To this point, however, R13 suggested that the oil and gas (O&G) industry has experience in the back-end carbon transport and storage technologies:

> *I think there is enough expertise and experience out there. I think you also have oil and gas companies, the likes of BPs and Shells of this world, or Harbour Energies of this world […] who are very familiar with operating*

Fig. 4. (*continued*).

gas or gas liquid systems. They are very familiar with operating reservoirs and drilling or pumping gas, etc.

Harkening back to System Disruption outlined by prior research [63, 64], R68 (a gas network actor) outlined the potentially massive opportunities for O&G sectors and actors.

The UK has a great opportunity with CCUS, and particularly because we have the geology, and we have the industrial skills in order to make it work and make it deliver. It has taken us a long time to realize that offshore oil and gas skills are really useful […]. This is disruptive, and it also enhances the disruptive potential of hydrogen.

The technical infrastructure for CCUS and hydrogen were often spoken about together. For example, the East Coast Hydrogen Network (see Fig. 5) plans to connect hydrogen production and distribution in the three initial clusters (Teesside, Humber, Merseyside). An ambitious 7

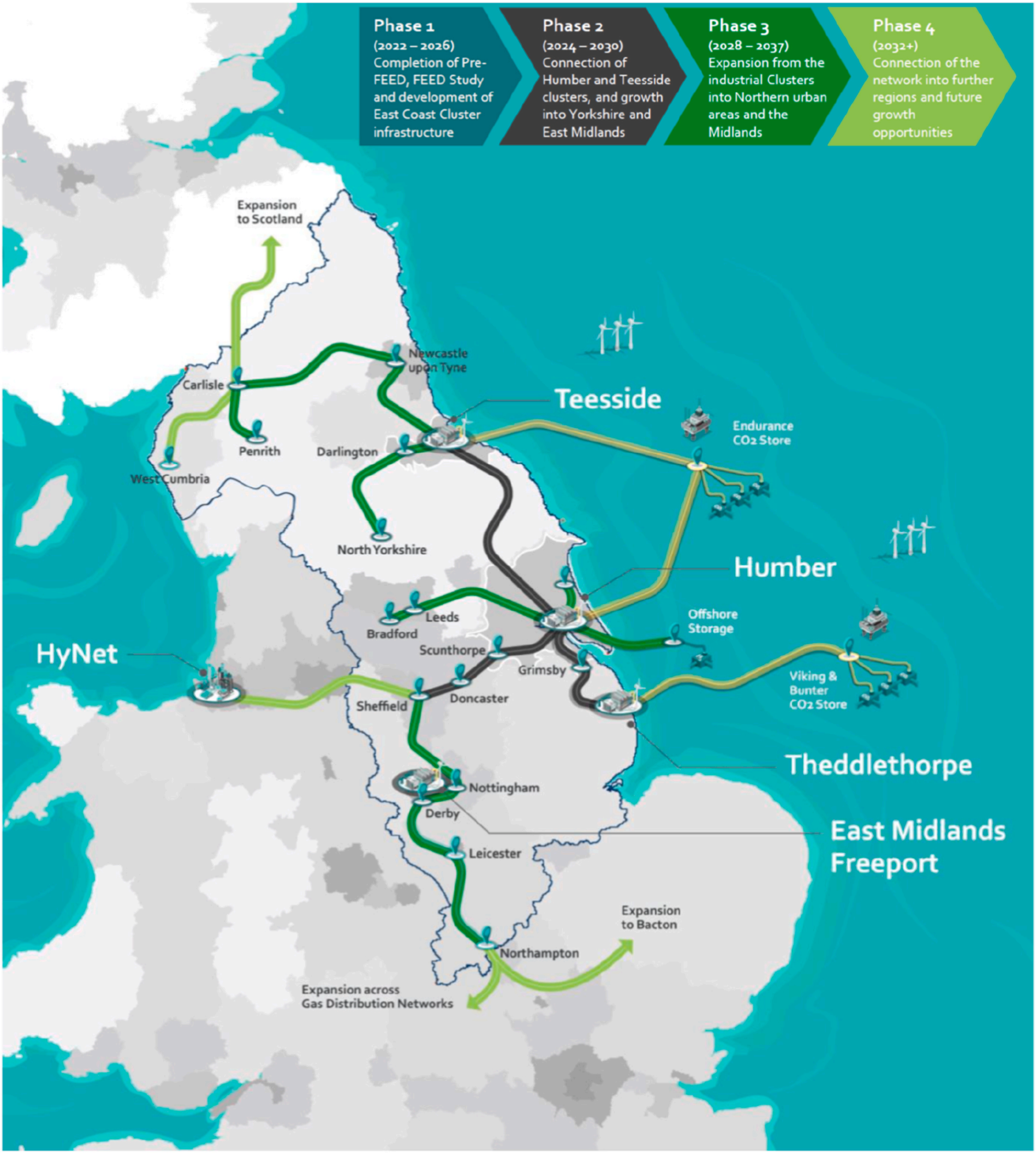

Fig. 5. Plans for an East Coast Hydrogen Network with full completion scheduled for 2032–2037.
Source: *East Coast Hydrogen Feasibility Report*, p. 5

GW hydrogen production target is set for 2030 (Northern Gas Networks, Cadent, and National Grid 2021). These plans align with the views of R57 (a gas system actor), who noted that hydrogen production needs a proper regional and spatial network to function as well:

> *hydrogen production must occur in a regional or nationwide network […] the individual production sites will vary in size and type but will be probably […]built around existing grid infrastructure […] [with] access to deep water ports, access to cables and all that sort of stuff, but it has to all come together as part of a single, regional network so you can bring hydrogen into an area, enable a conversion, and then utilize existing infrastructure once you've got hydrogen to where you need it.*

R88 (a CCS-system developer) reinforced the view that facility-specific disruptions, and related supply chain issues, were coming to the fore along "the whole CCUS value chain." This will cause System Disruption in the transformative side of "post-combustion" as there "will be significant modifications to plants, some of which are running 24/7, 365 days a year, to implement this post-combustion and other technologies." Disruptive industrial reconfigurations need not only arise from the deployment or coupling of hydrogen and CCUS, however. For instance, R47 mentioned the potential for net-zero pathways to interlink with nuclear power, distributed renewables such as wind and solar, or even tidal power and bioenergy. Multiple respondents, moreover, expected that CCUS could be integrated with bioenergy—into so-called BECCS networks (R02, R03, R06, R11, R25, R28, R32, R46, R55, R67, R93, R98); whereas others (R58, R83, R85, R93) mentioned strong couplings to biochar, a form of charcoal made with biomass. Hence, here we observed a range of different technological expectations based on how system integration unfolds—with potentially significant changes to the meta-system and system architecture.

Lastly, spatial and co-locational elements, as opposed to technological know-how, were seen as pivotal for systemic transformation, as outlined by R65 (an academic researcher):

> *The competitive advantage in the UK is nothing to do with the technology side, because I think the UK does not have competitive advantage through mastery of technology. It has got an advantage because it has got places in the North Sea where you can stick carbon dioxide, and places where you can stick it underneath the sea rather than underneath the land.*

4.2. Actors, networks and cooperation

Throughout the interviews we discovered that the UK's net-zero industrial cluster plans currently suit the agenda of incumbents, especially incumbent industrial actors. Incumbent firms own and operate almost all major assets that are targeted for industrial decarbonization. This finding is consistent with prior research dealing with incumbent interest in modular substation and add-on technologies such as *carbon capture* [40,65]. Incumbents often find ways to, moreover, leverage opportunities by working with more nimble companies through their supply chain (Berggren et al., 2015; Geels et al., 2016).

The first main implication is that, should new entrants become involved, they must work closely with incumbents. R58 (an industrial consultancy) explained that:

> *When we're looking really large capital infrastructure projects, such as underground CO_2 injection, then we need to lean on the people with the money, the capital, and the expertise to do it, such as the big oil and gas majors. [On the other hand], when we're looking at niche technologies, or people who'll be engaged in executing those kinds of projects, there's a huge number of service providers, component providers, and engineering firms […] And these tend to be, typically, smaller SME type operations serving the larger operators.*

As mentioned in Section 3, site visits to the industrial clusters provided us with deeper on-the-ground understanding. Notwithstanding incumbent interests, we directly observed ongoing instances of collaboration driven through co-location of large and small companies, technology providers, researchers and consultants. For instance, our visits to Northeast England confirmed that net-zero projects, including hydrogen and CCS, were already breaking ground in the Humber through new actor coordination. We also observed several "megaprojects" that are breaking ground: the large-scale BECCS retrofit at Drax, new onshore pipelines for hydrogen and CO_2 transport from high GHG operations including Drax and SSE power stations, a power station and two oil refineries at Immingham, a power station and chemicals park in Saltend, and Easington gas terminal. In addition, there are plans are develop offshore carbon storage in the Endurance saline aquifer [49]. Beyond modular substitution, such as fuel-switching and CCUS, there are plans for blue hydrogen production projects at Saltend chemicals park, green hydrogen production with electrolyzers at Immingham, and hydrogen storage projects in onshore salt caverns or offshore empty gas fields.

Though more nimble companies may pioneer radical innovations [66], large-scale deployment requires collaboration with incumbents who have complementary assets requisite for meta-system change—consistent with Tripsas [67], Rothaermel [68] and Rothaermel and Hill [69]. The scope for niche innovation in new entrants was addressed by R56 (North Sea Transition Authority): "*net-zero innovation only comes from the bottom up, smaller companies which are playing a huge role by innovating individual steps […] but they will have to work with the incumbents*." Furthermore, from the perspective of a hydrogen supplier, R75 (Carbon Trust) argued that "*there's loads of innovation that can be seen across the hydrogen space. Primarily, it is coming from the small companies. Even the incumbents recognize that.*"

4.3. Markets, business models, and industry-level disruption

A third dimension involves new value propositions which were giving rise to novel business models and financing arrangements (R50). R53 (British Geological Survey) spoke about the disruptive effects on business strategy stemming from the integration of CCS and hydrogen systems:

> *Disruptions to business strategy through new business models […] for completely transforming how a national economy uses oil and gas […]. It's a new value proposition where the only way to keep their companies thriving and growing is* via *net zero policy.*

With respect to emerging business models, R50 (Energy Transition Advisor Limited) also characterized net-zero policies as creating multiple new value propositions, even though these were not yet carefully fleshed out:

> *low-carbon energy development to energy storage, hydrogen storage, carbon storage and even starting a direct air capture business, the opportunities are immense, and they set up the UK to be one of the first in the world where this is happening […] You say the industry, what is that industry? It's one that doesn't really exist right now. If you're being a little bit brutal about it, it's a big waste disposal industry*.

On the other hand, one respondent envisioned that government's decisive actions and steadfast support could engender multiple new opportunities, especially for incumbent actors in the cement, steel, chemicals, and glass industries (R60). In this vein, R60 (a CCS technology company) underscored the potential ramifications for scaling novel decarbonization technologies, even in fairly isolated sectors such as cement. From a business perspective, they asserted that "*we don't install things if they're not going to make money out of it*."

R60 went on to state that:

> "*it's a proper business model behind this stuff, we're already planning to learn from the UK to roll out our hydrogen and carbon capture systems across [….] I think the most exciting thing is actually the idea that these big industries are going to capture their CO_2 anyway. Most of it's going to cost them money to dispose of. Why not use our technology to use some of it to help defray the cost of the rest which is so expensive*.

Other respondents were, however, less sanguine about the prospects of incumbent-actor innovation. R54 (a carbon recycling firm) stated that the implementation of large-scale capital-intensive low-carbon technologies was very challenging for previously sclerotic and slow-evolving industries such as steel and chemicals because

> *if you're making chemicals, you have to predict the markets, five years down the line, to build a dedicated plant to make acetone, let's say. So you can't react quickly to market conditions. But net zero is changing the fundamental market conditions, commodity price fluctuations, and so on. That is super disruptive to the chemical industry, because it's really speeding up the time that you can react. Not even mentioning the fact that*

you are avoiding fossil inputs into the chemical sector, which, in itself, is super disruptive.

Sector-specific disruptions were similarly unfolding. For example, R36 (a glass manufacturer) identified areas of disruption in markets for the glass industry as hydrogen and CCUS come online. R36 remarked, similarly, on the competitive dynamics resulting from plant-specific reconfigurations that are providing scope future business opportunities: "*net-zero represents an incredible and fantastic change to disrupt the manufacturing process and build or upgrade furnaces, to upgrade our technology, to consider high use of electrification and of hydrogen.*"

R59 (Engineering Construction Training Board) similarly noted that incipient clustering processes would unlock substantial new investment opportunities: "*ultimately the ambition is for all of these things to be transformative, to create a green UK, to launch a new green engineering construction industry […] it's putting the UK on the path for Industry 4.0.*" R30 (an energy consultancy representative), in turn, framed it as a competitive opportunity that demands greater awareness: "*the issue is if we don't decarbonize at some point our industries are not going to be competitive particularly in some of the large markets. We're not going to be able to keep those jobs and those skills around.* R13 (Humber local authority) referred to this as a "reversal of offshoring," arguing that:

Although Zero Carbon Humber started as a climate project, it suddenly became a broader issue. People began to see the element of competitiveness brought into the equation […] one can sell the ability for people to invest in this region, tackle net-zero aspirations. It's a reversal of what we've done for many years, reduced CO_2 emissions by offshoring manufacturing. Industrial clusters and freeports can even export greener products […] Britain could be the new leader for green steel, green chemicals, green consumer items.

Indeed, these arguments are supported by a recent analysis by McKinsey & Company [70]; it is estimated that up to £1 trillion could be captured by UK businesses by 2030, especially the manufacturing industries. As Fig. 6 summarizes, these business opportunities relate not only to direct emissions savings and reductions at industrial firms but also to sell greener goods and services, enabling customers and other suppliers to follow suit.

4.4. Regulation, policies, and formal institutions

Another area of potential disruption—distinct from infrastructural and technological disruption—revolves around regulations, policies,

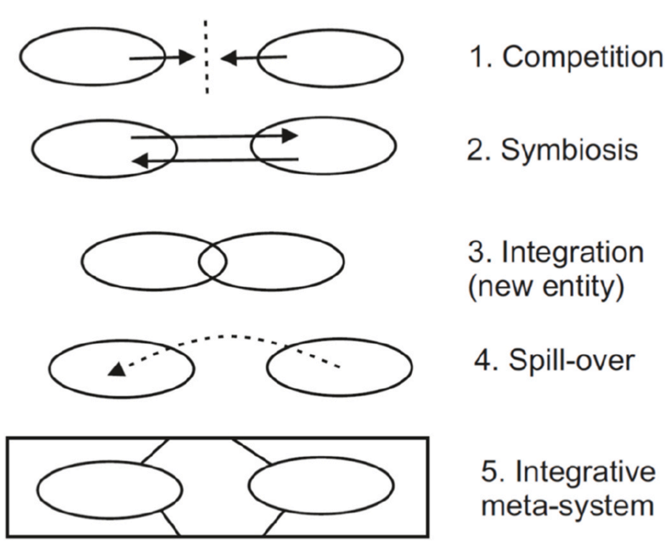

Fig. 6. Our addition of a fifth pattern of multi-system interaction. Source: Authors, building on to Raven and Verbong [23].

and institutions. Regulatory interventions are needed to explicitly target non-sustainable systems (R18; R38), and net-zero projects simply would not go forward in the absence of substantial government support: "*hydrogen and CCUS are big, site-specific technology, they do not spread naturally. It has got to be made to happen. I don't think it will happen without government* support" (R65). R74 (oil and gas engineering firm) concurred when they noted that "*the most amazing thing driving industrial decarbonization right now is the policy framework*."

A respondent from Hull city council followed on this point (R38):

The scale and pace of change for delivering net-zero in the UK are very important policy issues right now. Policymakers here recognize the danger of slowing down the scale and pace of the low-carbon transition that we need to get to, to be able to meet that 2050 target […] we have to show we can tackle the really hard stuff. So there is a window open right now, to decarbonize, and it stretches from now to the very early 2040s.

In addition, respondents identified the benefit of sustained political commitment behind net-zero; a line was drawn between politics, policies, regulations, and industrial actors. R1 (from BEIS) spoke about this alignment, noting that:

The UK has invested considerable political resources in setting up a regulatory environment, with the right funding. That is say the UK spent a longtime developing business models to demonstrate how you can fund net-zero in the absence of an international carbon price. You basically need industry to start this process because many industries only have certain opportunities for deploying kit when it's related to overhauls or maintenance.

R11 (electricity generator) concurred and reiterated the important temporal dimensions laden in net-zero commitments:

It's a race to see who wants to go first, the only question is who that will be […] usually you hear that the political nature of net zero projects is always a risk, but here in the UK we don't hear any real opposition. Even if there was a significant change, and the government goes from Tories to Labor, everyone is still on board.

This point is supported by Keir Starmer's recent doubling down of support for CCUS—to the tune of £22 billion, which has been warmly welcome by industry [71].

National level policies and plans are recently buttressed by a wave of more local policies at the level of cities, local enterprise partnerships, and regions which influence industrial decarbonization pathways and processes. In Western England, for example, the Cheshire and Warrington Local Enterprise Partnership have an Energy and Clean Growth Strategy aiming to deploy hydrogen power and heating systems at scale by 2040; similarly, Cheshire West and Cheshire Council have a cross-party task force to plan for net-zero implementation [72]. The cities of Liverpool and Manchester also have enforceable carbon neutral strategies. In Eastern England, the City of Hull has a net-zero target for 2050. In Wales, Zero 2050 South Wales is being implemented, and Scotland developed its Net Zero Nation initiative which is targeting a net-zero economy by 2040.

An important driving force behind UK decarbonization policy, also falling in line with the discussion above, revolves around the need to draw together incumbent and smaller firms. R54 (a carbon recycling firm) picked up this theme, drawing attention to the collaborative opportunities between incumbents and new entrants:

the small companies are bringing a lot of new disruptive technology to the party. But they need to work with the large companies. We need to work with those who have money, who have standing, who have the infrastructure and resources that we can use to make a project viable. [There is an emerging] marriage of expertise coming in between incumbents and new entrants, or new business models and partnerships, and a willingness from the old-school people to embrace it.

Lastly, our findings reveal a tension between modular vs. more transformative change to the system architecture (see Table 3). This lends greater credence to the observed contestation in the UK decarbonization transition [73], with requisite degrees of impact on national sociotechnical pathways (R04; R06; R23; R26).

5. Discussion: alternative dimensions of systems change

Whereas Section 4 presented our empirical results, here we unpack the results by discussing the critical disruptive elements such as radicality, incumbency, and systems change within our meta-system framework.

5.1. Radicality of disruption and incumbency

Industrial decarbonization in the UK's industrial clusters reflects a tension between System Disruption and System Reconfiguration within a meta-system. Relevant to System Reconfiguration are projects that reconfigure existing plants and industrial regimes—notably through CO_2 capture technologies, fuel switching, and the integration of low-carbon hydrogen. While some changes to energetic operations are occurring, the UK's decarbonization strategy largely relies on front-end fuel switching and back-end CCUS—measures that do not necessarily alter the meta-system architecture. Although emerging niche innovations—such as biochar, direct air capture, and BECCS—do indeed signal the potential for transformative and more radical change [74], our findings indicate that incumbent actors largely control the transition.

Leveraging public funding and existing infrastructure, incumbent actors favor incremental changes and modular upgrades, such as hydrogen retrofits and carbon capture technologies, which on the front-end can integrate into the existing industrial landscape rather than displace it. This dominance of incumbents aligns with the concept of creative accumulation, where new technologies enhance existing capabilities without displacing established systems [75]. For example, blue hydrogen and CCUS are attractive because they involve front-end modifications rather than overhauling operational processes or market structures [76].

Transport and storage infrastructure for these technologies, however, requires deeper systemic changes, presenting significant challenges, and indicative of System Disruption. Indeed, the integration of CCUS and hydrogen infrastructure, on the back-end, is much different from front-end modular substitution. Transport and storage for CO_2 and hydrogen are not merely technological add-ons but architectural transformations, linking previously separate industrial regimes into a new meta-system. This shift necessitates new governance mechanisms and cross-sectoral coordination, moving beyond conventional niche-system dynamics. Furthermore green hydrogen—even in sectors like buildings and heating—will require modifications to upstream inputs, adjustments in production processes, and infrastructure adaptations, alongside updates to end-use appliances. These shifts stem from hydrogen's distinct chemical and physical properties, necessitating a cluster-based strategy to minimize disruptions ([37]: 281).

This transition is better described as a negotiated transformation, where incumbents adapt their strategies, resources, and partnerships to align with net-zero objectives. While niche innovations may catalyze broader shifts [77], their scaling depends heavily on collaboration with these dominant actors. This balance of incremental reconfiguration and limited disruption highlights the complexity of industrial decarbonization pathways and the ongoing influence of incumbency in shaping system transitions.

Table 3
Analytical framework to map systems reconfiguration.

	Core elements reinforced	Core elements substituted		
Architecture unchanged (linkages between components)	*Modular incrementalism*	*Modular substitution* System-system switching	 Niche-system hybridization	 Niche-system replacement
Architecture changed	*Architectural stretching*	*Architectural reshaping*		

Source: Authors, with concepts adapted from McMeekin et al. [12] and Andersen et al. [38].

5.2. Meta-systems, reconfiguration, and architectural change

The non-disruptive aspects of decarbonizations pathways are appealing for incumbent industries and actors. Although most of the technologies are expensive and require plant-specific reconfiguration, they often do not disrupt core operational processes. At the industrial plant level, we have mainly identified moderate adjustments and reconfigurations in the energy sub-system. Though these changes will involve *novel* technologies, since they do not change the way industry produces its materials, they are thus far largely non-disruptive. For example, fuel-switching and CCS are retrofits and add-ons [61,78].

Our findings suggest a specific pattern of multi-system interaction in which new CCUS and hydrogen infrastructures *could* lead, however, to the creation of an entirely new meta-system, the architectural reshaping of which involves multiple industrial regimes in particular clusters. These separate industrial regimes are becoming integrated through their connection to wider infrastructures (for hydrogen and CCS), which thus create a new system architecture. The architectural reshaping within the context of industrial cluster decarbonization can be more fully understood as multi-system interactions owing to the co-location of industrial systems within industrial clusters. We therefore propose adding a fifth pattern to the widely cited typology introduced by Raven and Verbong [23] (Fig. 7).

Industrial decarbonization pathways are shaped by the interplay of technological integration, resource competition, and regulatory tensions. These dynamics often manifest through adaptations—such as add-ons, hybridization, or modular substitutions—which can trigger further waves of innovation [11]. Architectural transformations within socio-technical systems are rarely confined to isolated shifts; rather, they involve long-term, multi-dimensional change across infrastructures, markets, and regulatory frameworks [13].

In the UK, these complexities are particularly evident in the evolving hydrogen transport and storage infrastructure. Several projects aim to distribute low-carbon hydrogen from new production facilities to industrial plants, with additional storage capacity planned to secure future energy reserves. The integration of green hydrogen into sectors such as steel presents further challenges, requiring a 4.1 GW expansion of wind energy, 3.5 GW of solar capacity, and 0.83 GW of hydrogen storage [79]. These major system shifts necessitate the alignment of diverse actors, infrastructures, and regulatory frameworks, reinforcing the need for coordinated governance and systemic adaptation (see Fig. 7 and Table 4).

5.3. Limitations

Though our mixed-methods research was carefully designed there are, inherently, several fundamental limitations. We first caution that, while adhering to strict anonymity of respondents provided greater scope for expression of true opinions, it will be difficult to replicate this study. Replication of studies based on anonymous interview data is, however, recognized as one major drawback of this method [80]. In addition, given that decarbonization in industrial clusters has just begun, the data is inherently prospective, largely based on plans and predictions. This means that there is a risk for hype building which cannot be discounted, especially concerning hoped for performance expectations of novel technologies [62,81,82].

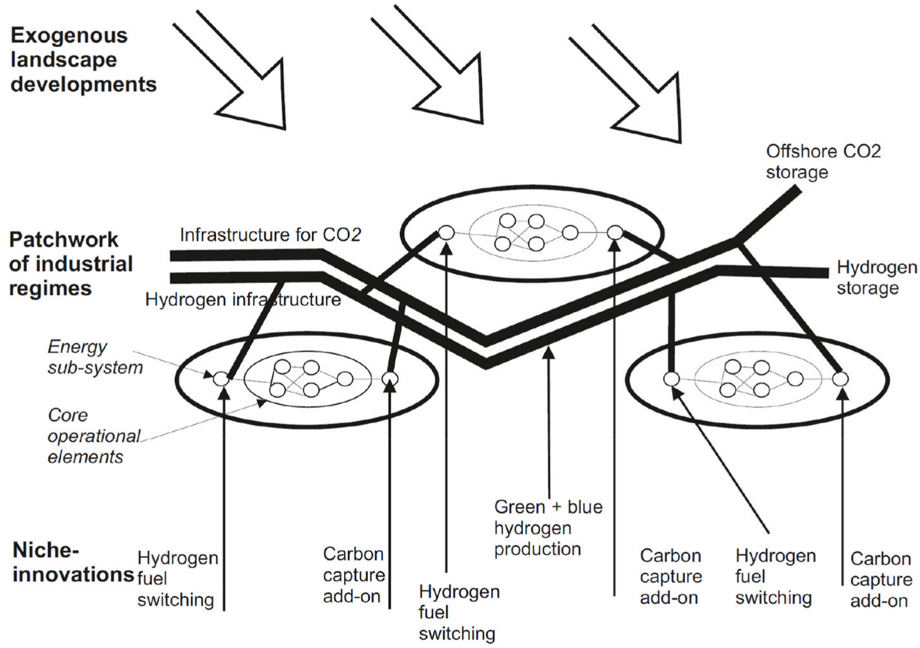

Fig. 7. Conceptualizing disruption and reconfiguration in UK net-zero industrial clusters.
Source: Authors

Table 4
Mapping systems reconfiguration within industrial decarbonization pathways in the United Kingdom.

Linkages (couplings) between system components	Core elements reinforced	Core elements substituted		
Architecture unchanged (linkages between components)	*Modular incrementalism* - adjustments in existing burners in industrial firms (so they can burn H2 instead of gas) - replacing old gas pipes with plastic ones for H2 - scaling up (need for bigger “futuristic” furnaces in some cases; more demand for steam power etc.) - use of existing pipeline corridors	*Modular substitution* System-system switching: - building new H2 production facility that would substitute partly for fossil fuel	Niche-system hybridization: - adding on of carbon capture technology on industrial plants - production of blue hydrogen (by adding CCS-system to natural gas supply) - initial blending of hydrogen (blue or green) with natural gas so it can be used in existing burners and furnaces	Niche-system replacement: - small amounts of green hydrogen (from wind and solar) substitute for natural gas - creation of new hydrogen storage reservoirs
Architecture changed	*Architectural stretching* - expansion of gas supply infrastructures (if the creation of blue hydrogen requires more gas per unit of energy) - extension (and strengthening) of electricity grids to enable green hydrogen - electrification in steel and chemicals - repurposing of old gas pipelines for H2	*Architectural reshaping* - creation of new CCS infrastructures (including storage) that create new linkages between firms from different industries in particular clusters - creation of new hydrogen infrastructures that create new linkages between firms from different industries in particular clusters		

6. Conclusion

This study advances the meta-system perspective, framing industrial decarbonization as a multi-system transition rather than an isolated sectoral shift. By integrating Systems Reconfiguration and Systems Disruption frameworks, we show how industrial clusters serve as key sites of negotiated transformation, where incumbent actors, emerging technologies, and policy frameworks intersect. Through 111 expert interviews, 52 site visits, and extensive document analysis, we capture the tension between systemic stability and technological disruption.

Achieving deep industrial decarbonization will require accelerated infrastructure deployment, policy realignment, and stronger multilevel governance to catalyze wide-ranging architectural shifts. UK industrial clusters illustrate how reconfiguration and disruption interact, with hydrogen, clean ammonia, and carbon capture layering onto existing infrastructures rather than displacing them—though architectural changes remain on the horizon for upstream and back-end infrastructure. Oil and gas assets are being repurposed for CO_2 and hydrogen storage, fostering synergies between legacy systems and low-carbon solutions.

This reflects an evolutionary transformation, where industrial regimes prioritize adaptation over rupture. As illustrated in the integrative meta-system framework, industrial decarbonization cannot be reduced to discrete system interactions. Instead, these cross-industry linkages coalesce into a broader meta-system, where interdependent infrastructures, regulatory environments, and technological platforms shape long-term system trajectories. Future research could extend this framework to explore how meta-systems evolve over time, identifying the conditions under which system-wide integration gives way to structural reorganization. By capturing these multi-system interactions, scholars can refine transition theories to account for sectoral interdependencies, emergent coordination mechanisms, and the dynamic role of incumbents in shaping industrial futures.

CRediT authorship contribution statement

Kyle S. Herman: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation. **Benjamin K. Sovacool:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Data curation, Conceptualization. **Frank W. Geels:** Writing – review & editing, Supervision, Formal analysis, Conceptualization. **Marfuga Iskandarova:** Investigation.

Declaration of competing interest

The authors declare the no financial interests/personal relationships which may be considered as potential competing interests influencing this work.

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Appendix

Table A1
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	Oxford University	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

(*continued on next page*)

Table A1 (*continued*)

Code	Institution	Type	Date
R50	Energy Transition Advisor Limited, Storegga	Industry	06.10.22
R51	Herriot-Watt Uni.	Academia	05.10.22
R52	Kellas Midstream	Industry	05.10.22
R53	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	BGS	Policy-Research	27.10.22
R65	ICL, Just Transition Scotland	Academia	26.10.22
R66	SWIC/Industry Wales, Baxter360	Industry	27.10.22
R67	hydrogen centre/Uni S. Wales	Academia	28.10.22
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. 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	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.

Interview Guide

Updated September 2022

Warmup question: Tell me/us more about yourself, your background, and how you became interested in net-zero projects.

Technology implementation, experimentation and knowledge:

- Where did the idea [for this particular megaproject] come from? Whose idea was it? Who are the lead actors and broader coalitions for each project?
- What are the specific implementation and deployment plans, including the role of learning and experimentation?
- What are the technical skills and capabilities needed for this megaproject?
- What will it cost (whether capital expenditures, operational expenditures, or total cost)?

Policy, governance and management:

- How does the megaprojects sit within the wider policy and regulatory landscape?
- Considering other megaprojects in the UK, what's your level of confidence in this one?
- How consistent are the support policies for megaprojects within the UK?
- How is such a project managed in practice, how are systems being integrated (or not)?

Benefits and risks:

- What are the possible benefits to the megaproject?
- What are the technical and commercial risks, including different types of risks (environmental, financial, political, social, etc.)? [
- Do you have any backup or contingency plans to address risks or uncertainties?
- What do you envision as the most significant challenges to implementation?

Business strategy, incumbency and disruption:

- What is the overall business strategy or vision behind the project, what does involvement mean for the future of the industry?
- To what degree is the project/technology disruptive or transformative?
- What is the role of smaller companies in the project, how balanced it is between large incumbents and small new entrants? What innovative technologies are they coming up with? Will you license or seek to buy out smaller firms?
- What is the competitive advantage for doing this project within the UK?

Equity, vulnerability and just transitions:

- Who stands to "win" the most from the project, and who stands to "lose?"
- What possible inequitable community impacts could emerge?
- What impact will the project have on vulnerable groups
- If social backlash occurs, do you have a plan for addressing it?

Last question (snowballing): Is there anyone else you recommend we contact for an interview? We are not only looking for recommendations, but actively seeking for missing contacts! So please could you share important contacts with us or introduce by email? Any other relevant stakeholders/companies etc. that you think we should talk to will help make our research stronger.

Data availability

The authors do not have permission to share data.

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