Received: 16 May 2024 | Revised: 7 February 2025 | Accepted: 13 February 2025

DOI: 10.1002/geo2.70000

ARTICLE

Clusters in context: Towards a typology of industrial decarbonisation initiatives

Imogen Rattle[1] | **Peter G. Taylor**[1,2]

[1]Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds, UK

[2]Low Carbon Energy Research Group, School of Chemical and Process Engineering, University of Leeds, Leeds, UK

Correspondence
Imogen Rattle, Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK.
Email: i.k.rattle@leeds.ac.uk

Funding information
UK Research and Innovation, Grant/Award Number: EP/V027050/1 and EP/S029575/1

Abstract

Policy-makers and researchers are increasingly focused on the decarbonisation of clusters of energy-intensive industries. However, relatively little is known about the trajectory of different cluster decarbonisation initiatives. This paper aims to bring clarity to an emerging field. It highlights the evolving landscape of industrial decarbonisation initiatives, and the growing importance of clear definitions for effective communication and knowledge exchange among stakeholders. Drawing on insights from cluster theory, it proposes a typology of industrial cluster decarbonisation initiatives to understand and categorise different types of project. These four categories— 'forerunner clusters', 'dispersed clusters', 'classic clusters' and 'dispersed sites'—allow a more focused understanding of the policy implications and challenges associated with each type. To demonstrate the application of the typology, the paper presents profiles of three cluster initiatives that illustrate some of the dynamics involved. Through this work, we seek to provide guidance for future research and policy development in the transition towards a low-carbon industrial future.

KEYWORDS

cluster, global, hub, industrial decarbonisation, policy, typology

1 | INTRODUCTION

The industrial sector plays a key role in producing the foundational materials that support the global economy, including many of those necessary for decarbonisation. However, it is also carbon intensive, accounting for a quarter of global CO_2 emissions in 2022 (IEA, 2023a). The World Economic Forum estimates that at least half of industrial emissions occur within industrial clusters (World Economic Forum, 2022), which it defines as a 'co-located group of industry' (World Economic Forum, 2023b, p. 11). As pressure to mitigate climate change intensifies, a growing number of industrialised nations are investing in projects aimed at reducing carbon emissions from their industrial clusters (Rattle & Taylor, 2023). A cluster-based approach to industrial decarbonisation hinges on the premise that implementing decarbonisation technologies into groups of co-located industry will reduce the amount of upfront investment in transmission and distribution

The information, practices and views in this article are those of the author(s) and do not necessarily reflect the opinion of the Royal Geographical Society (with IBG).

infrastructure and mitigate development risks by ensuring a guaranteed customer base (Sovacool et al., 2022). The goal is to establish centres of development that capitalise on economies of scale and foster innovation, ultimately driving the entire sector towards decarbonisation.

As these initiatives gain momentum, there is increasing interest in policy and academic circles in place-based approaches to industrial decarbonisation, particularly in how the technical, policy and system integration lessons learned from industrial cluster decarbonisation might be used as a catalyst for decarbonising the entire industrial sector (Sovacool et al., 2022). The landscape is rapidly evolving, characterised by the use of an expanding array of terms that mirror the diverse approaches and strategies under exploration. As a result, there has been an increase in the number of international collaborations aimed at sharing knowledge and best practices in industrial decarbonisation, such as the Net Zero Industries Mission, launched as part of Mission Innovation 2.0 at COP26, the World Economic Forum's Transitioning Industrial Clusters initiative, launched in 2021, and the Climate Club, launched at COP28. However, with this proliferation of initiatives has come an overlap in the use of terms, with the same terminology sometimes being applied to different types of industrial decarbonisation initiatives.

As progress accelerates, clarity on definitions becomes increasingly important. Establishing a shared understanding of the type of initiative under discussion will be vital to foster effective communication and knowledge exchange between stakeholders (Taylor & Rattle, 2023). Until recently, research on industrial decarbonisation primarily focused on techno-economic modelling of specific technology interventions, such as Carbon Capture Utilisation and Storage (CCUS) and low-carbon hydrogen, or on case studies of single notable projects (Rattle & Taylor, 2023). While these studies offer valuable insights into the feasibility, effectiveness and potential impacts of specific decarbonisation strategies, comparing and synthesising their findings can be challenging. We believe that there is a need for a broader analytical approach, one that allows us to understand projects to decarbonise industrial clusters in the context of other types of place-based industrial decarbonisation initiatives and in relation to one another.

This paper aimed to address that gap. Our approach is twofold. First, we provide a classification of place-based approaches to industrial decarbonisation. Given the absence of mature examples, we focus here on hypothetical ideal forms, distinguishing these approaches based on their key features as outlined in policy documents. Second, we focus specifically on net zero industrial cluster initiatives, as one subset of place-based approaches, to examine how they may evolve in practice. Our analysis therefore draws a distinction between a *net zero industrial cluster*, as one example of an ideal form, and *net zero industrial cluster initiatives* as emerging, inchoate efforts, with the former referring to a conceptual category and the latter to actual, albeit early-stage, implementations.

To inform our work, we draw upon cluster theory. While the idea of using net zero industrial clusters to drive sector-wide decarbonisation is a recent policy development (Rattle & Taylor, 2023), theories of industrial agglomeration date back to the nineteenth century (Marshall, 1890). However, despite an extensive literature examining the factors that shape the evolution and trajectory of industrial clusters, these insights remain largely unexplored in the context of industrial decarbonisation. We believe this omission should be addressed. While the factors that generate locational advantage for net zero industrial cluster initiatives may not be identical to the factors that have benefited traditional industrial clusters, the importance of place remains paramount. This insight allows us to explore how local resources, infrastructure, regional policies, and proximity to markets or supply chains may influence the development of net zero industrial cluster initiatives and their ability to adapt to decarbonisation challenges. Industrial clusters that have thrived due to historic locational advantages may no longer retain a competitive edge in a net zero context. Focusing on these dynamics deepens our understanding of regional variations in capacity and highlights the potential repercussions of place-based strategies for driving the low-carbon industrial transition.

Therefore, our paper makes three contributions: first, by outlining the main characteristics of different approaches to place-based industrial decarbonisation so that readers can better understand the main features of each type; second, by applying insights from economic geography and business strategy to net zero industrial cluster initiatives to foster a more holistic understanding of the factors that may shape their development; and finally, by introducing a typology to categorise different types of net zero industrial cluster initiative and identify key traits that contribute to successful decarbonisation. This, in turn, explains why industrial clusters may follow different decarbonisation trajectories and highlights the challenges faced by those lacking the necessary resources for a successful transition. Our aim is to provide a framework for understanding how net zero industrial cluster initiatives may evolve and to critically examine the underlying assumptions of using industrial clusters to drive the low-carbon industrial transition.

The remainder of the paper is structured as follows. In Section 2, we provide the context for this study and the research approach upon which our findings are based. In the introduction to Section 3, we provide the background to industrial decarbonisation and discuss the growing prominence of place-based approaches in policy, highlighting net zero industrial clusters as one example of such an approach. Section 3.1 provides a review of recent empirical literature on net zero industrial cluster initiatives to establish what is known about their development. Section 3.2 provides an overview of place-based decarbonisation initiatives, outlining the key features that differentiate the various types. In Section 4, we provide an overview of theoretical perspectives on industrial agglomeration and highlight what they have to say about the factors that shape industrial cluster development. Having established the empirical and theoretical foundations of our argument, in Section 5, we draw from this literature to provide a simple typology to categorise net zero industrial cluster initiatives, explain how their decarbonisation trajectories may differ and present profiles of three initiatives—the North West and Black Country Clusters in the UK and the Port of Rotterdam in the Netherlands—to illustrate the practical application of our work. Finally, in Section 6, we conclude by discussing the implications of our findings, addressing the limitations of our work and providing suggestions for further research.

2 | BACKGROUND TO THE PAPER AND RESEARCH APPROACH

This paper arose from a study on international approaches to industrial cluster decarbonisation that identified a need for a clearer framework to grasp the dynamics of different initiatives (Taylor & Rattle, 2023). Employing a qualitative realist design, our analysis iterated between theory and data to explore the relationship between industrial cluster characteristics and decarbonisation trajectories (Maxwell, 2012). A rapid evidence assessment (Rattle & Taylor, 2023) identified several prominent place-based industrial decarbonisation initiatives from which we selected four. We undertook a desk review of academic literature, partner websites, policy documents and industry reports related to these projects to establish their key characteristics and identify interview candidates. At this stage, we discounted one initiative since it became apparent that the project was a hydrogen hub rather than a net zero industrial cluster. This decision helped define the object of our analyses and laid the groundwork for the discussion provided in Section 3.2.

Online interviews with cluster representatives and stakeholders took place between August 2021 and December 2022. They lasted between 36 and 60 minutes. In total, seven people were interviewed: three each for the North West and Black Country clusters, and one for the Port of Rotterdam. In interviews, we explored cluster backgrounds, project histories, outcomes and broader policy landscapes. Some further key informants preferred informal discussions due to commercial sensitivities. While these discussions have not been included in our dataset, we have used them to triangulate our findings. Thematic coding of secondary data and interviews was undertaken using NVivo12 to identify connecting patterns across the dataset (Seidman, 2013). This process was conducted alongside a review of academic cluster theory, the key elements of which are summarised in Section 4. Together, these components laid the groundwork for the typology presented in Section 5.

3 | INDUSTRIAL CLUSTERS IN CONTEXT

While numerous programmes have attempted to mitigate the environmental impact of industrial parks through water, waste and energy efficiency measures, policies aiming specifically at industrial decarbonisation are relatively recent. The shift was catalysed by the Paris Agreement on Climate Change (UNFCCC, 2015), which came into force in 2016. The Paris Agreement committed to restricting global average temperature increases to below 2°C above pre-industrial levels and to make efforts to limit it to 1.5°C. In doing so, it reshaped discussions on the decarbonisation of energy-intensive industry. Prior to the Paris Agreement, expectations were that industry would halve absolute emissions by 2050; the Paris targets required a much faster and more profound sectoral transformation (Bataille et al., 2021; Rissman et al., 2020). As a result of this relatively recent shift, comprehensive policies focused on industrial decarbonisation are still in their early stages, and the policy implications of achieving zero emissions in energy-intensive industries remain largely underexplored (Bashmakov et al., 2022).

It is broadly agreed, however, that energy-intensive industries face unique challenges when it comes to emissions reduction (Bataille et al., 2018; Fischedick et al., 2014). The sector is diverse in terms of both the processes it uses and the goods it produces. As a result, industrial decarbonisation will require a blend of bespoke technologies, including electrification, hydrogen and biomass fuel adoption, and CCUS, alongside process innovation and enhancements in resource and energy efficiency (Gailani et al., 2024). However, many necessary technologies are still at the demonstration stage and not yet ready for large-scale deployment. In addition, lower emission production processes typically come with higher initial costs, presenting financial barriers to adoption. Many industrial products are traded in international markets with low profit margins, making it more difficult for companies to cover the higher production costs of shifting to new technologies. Furthermore, industrial plants are often long-lived and capital-intensive, locking in high emission processes (Bataille et al., 2018; Fischedick et al., 2014). Because of these challenges, government intervention will be crucial to level the playing field and provide the necessary incentives for industry to accelerate the low-carbon transition (IEA, 2022). Targeted public financial support will be required to stimulate private investment in large-scale demonstration projects and the requisite infrastructure for low emission technologies, including facilities for CO_2 transport and storage, hydrogen production and high-voltage electricity transmission (Bataille, 2020). Since infrastructure development is expensive and there is already a skills shortage in necessary sectors, such as construction and operations (Lewis et al., 2023), deployment will necessarily be sequential. As a result, place-based industrial decarbonisation initiatives have come to the fore, as governments seek to prioritise investment in their most carbon intensive regions (Rattle & Taylor, 2023; World Economic Forum, 2024).

3.1 | Industrial clusters as a policy tool for driving the industrial transition

Northwest Europe is particularly suited to a place-based approach to industrial decarbonisation due to historical patterns of development that have led to highly clustered industries. The Dutch National Climate Agreement (Government of the Netherlands, 2019) identified the country's five main industrial regions as 'acceleration chambers' for the early implementation of low-carbon technologies, including green hydrogen and CCUS. The Port of Rotterdam, Europe's busiest port, initiated the Porthos (Port of Rotterdam CO_2 Transport Hub and Offshore Storage) project in 2017. The project aimed to capture CO_2 emissions from the port's highest emitting industries and store them in empty gas fields beneath the North Sea. Porthos began construction in spring 2024, making it the world's most advanced industrial cluster decarbonisation project.

The United Kingdom has similarity positioned itself as an early leader in industrial decarbonisation, becoming the first major economy to publish an Industrial Decarbonisation Strategy in 2021 (HM Government, 2021). This focused on decarbonising industrial clusters through the development of networks of low-carbon technologies and fuels, particularly CCUS and hydrogen (Hudson & Lockwood, 2023). The goal was to establish at least four low-carbon industrial clusters by 2030 and one net zero industrial cluster by 2040. Net zero industrial cluster initiatives have been supported through two key programmes. The Industrial Decarbonisation Challenge (2021–24) provided funding for the creation of regional net zero cluster roadmaps and feasibility studies for shared infrastructure. In parallel, clusters identified as most advanced in CCUS development were selected through a competitive process known as 'cluster sequencing' to proceed to negotiations for capital and revenue support through the relevant Business Models. In November 2021, two initiatives—HyNet and the East Coast Cluster—attained Track-1 status through the cluster sequencing process, enabling them to seek additional investment (DESNZ & BEIS, 2021). Subsequently, in March 2023, eight projects from Teesside and HyNet were selected as Track-1, phase two projects, eligible to enter negotiations for further support (DESNZ & BEIS, 2023).

Because of this first mover status, studies on industrial cluster decarbonisation have tended to focus on examples from the Netherlands and the UK. Initial work concentrated on the Port of Rotterdam (e.g. see Bosman et al., 2018; Gianoli & Bravo, 2020; Samadi et al., 2016, 2018; Schneider et al., 2020), as a frequently cited example of best practice. It is apparent from these studies that the advanced status of the Porthos project is largely due to the longstanding and proactive leadership of the Port Authority, which launched its first climate initiative in 2007 (Brownsort, 2019). Porthos has also been shaped by lessons from the Rotterdam Capture and Storage Demonstration (ROAD) project, an unsuccessful proposal for coal-fired power generation with CCUS that was cancelled in 2017. The cancellation underscored the importance of clarity in financing and a well-defined organisational structure for future similar work (Akerboom et al., 2021).

The UK differs from the Netherlands in taking a competitive funding approach towards clusters. This approach has had both positive and negative outcomes for participants. It is apparent that the requirement for stakeholders to develop cluster plans in collaboration has encouraged cross-sector partnerships and led to new networks of participants across multiple scales (Geels et al., 2023; Gough & Mander, 2022; Lai & Devine-Wright, 2024; Sovacool et al., 2023). However, the pace of required change and expanded organisational scope present their own set of challenges. Net zero cluster plans are organisationally intricate, both internally, due to the absence of a singular coordinating body, and externally, as supporting policies and institutions are still evolving (Sovacool et al., 2022). The involvement of multiple organisations amplifies the technical complexity of the work, introducing the risk of fragmentation and disputes over project priorities (Geels et al., 2023). While collaboration among the clusters is apparent, the competitive nature of funding inevitably fosters rivalries (Gough & Mander, 2022) and leads to disappointment and setbacks when some projects do not win (Zero

Carbon Humber, 2023). Similar to the Dutch experience of the ROAD project, a lack of clarity over the future financing of cluster projects has raised questions about the long-term viability of these initiatives (Geels et al., 2023).

These findings indicate that net zero industrial cluster initiatives offer potential for industrial decarbonisation, but their paths to achieving net zero emissions are likely to encounter obstacles. While projects in the Netherlands and the UK are at the forefront, internationally there has been a growing increase in interest in place-based approaches to industrial decarbonisation. The following section sets out the primary characteristics of the main project types.

3.2 | Cluster, oasis or hub: what's in a name?

As a starting point for analysis, industrial clusters are defined in the UK Industrial Decarbonisation Strategy as follows:

> ... places where related industries have co-located. Benefits include deploying and utilising shared decarbonisation infrastructure, enabling industry to reduce the unit cost for each tonne of carbon abated as well as opportunities for resource and energy efficiency and learning and innovation sharing.
>
> (HM Government, 2021, p. 119)

While this definition raises questions about the specifics—such as how to define 'industry', the degree of proximity required for co-location and which relationships might be most critical (e.g. dependencies on shared resources, integrated supply chains, similar production processes or overlapping markets)—the overall emphasis remains clear. The main goal of net zero industrial cluster initiatives is to achieve cost-effective reduction in industry emissions through shared infrastructure, and joint resource and energy efficiency initiatives supported by knowledge exchange. Similarly, the Dutch Climate Agreement (Government of the Netherlands, 2019) identifies industrial clusters as catalysts for the low-carbon transition, emphasising their pivotal role in driving innovation, collaboration and technological advancements, in particular in scaling up CCUS, green hydrogen and circular economy initiatives.

Separate from industrial cluster decarbonisation, but closely aligned with it, and using similar terminologies, are a new generation of hydrogen-specific production projects. Several countries, including Scotland (Scottish Government, 2022), India (Ministry of New and Renewable Energy, 2023) and the United States (Department of Energy, 2023), are launching regional hydrogen hub programmes. The most comprehensive definition of a hydrogen hub is provided in the Scottish Hydrogen Action Plan:

> A Regional Hydrogen Energy Hub is a geographic location (region, city, island, industrial cluster) that is host to the entire hydrogen value chain, from production, storage and distribution to end-use. Regional Hydrogen Hubs will include multiple end-users with applications ideally covering more than one sector
>
> (Scottish Government, 2022, p. 19)

Hydrogen hubs, therefore, are intended to function as anchor points of large-scale demand, bringing together existing and potential hydrogen users across different sectors from within the local areas. This co-location serves to enhance the cost-effectiveness of developing essential infrastructure, including pipelines, storage facilities and refuelling stations (World Energy Council, EPRI, & PwC, 2021). While the premise of aggregated demand and shared infrastructure is the same as for net zero industrial clusters, the proposed end-use application of hydrogen is wider. In the United States, the seven Regional Clean Hydrogen Hubs (H2Hubs) selected for award negotiation as part of a $7bn funding programme have a variety of potential end users, including industry, but also long-distance transportation, agriculture, energy storage and power generation (Office of Clean Energy Demonstrations, 2023). The overall aim of the programme is to kickstart the domestic hydrogen economy.

An alternative approach to hydrogen is underway in the United Arab Emirates, which unveiled its National Hydrogen Strategy (Ministry of Energy and Infrastructure, 2023) ahead of hosting COP28. The strategy sets the goal of becoming one of the world's largest hydrogen producers by 2031. In pursuit of this goal, it outlines plans to establish two hydrogen oases by 2031 and five by 2050. These oases are intended to develop a hydrogen supply chain, enhance infrastructure and reduce costs by clustering production and end-use applications. In addition, each oasis has been designated a key port to be retrofitted for exporting hydrogen and its derivatives (World Economic Forum, 2023a). While the initiative is in its early stages and information remains limited, the distinctiveness of hydrogen oases appears to be that they will be strategically sited to maximise the potential for hydrogen production, with a focus on the export market. Similar large-scale hydrogen projects focused on exports are also planned in Oman, with three coastal areas designated for renewable hydrogen production and export (IEA, 2023b). As the hydrogen economy gathers pace, we are likely to see further developments aimed at the export market, each with its own set of terminologies.

A number of recent policy initiatives on CCUS have introduced a parallel but distinct terminology of clusters and hubs specific to carbon capture. Within the European Union, the Net Zero Industry Act 2023 designated CCUS as a Strategic Net Zero Technology, setting an injection target of 50 Mtpa CO_2 storage capacity by 2030 (European Commission, 2023). Since not all EU regions have suitable geological conditions for storage, a shared transport and storage infrastructure based on a cluster and hub model will be required to deliver this goal (Global CCS Institute, 2023). In Malaysia, the New Industrial Master Plan 2030 (Ministry of Investment Trade and Industry, 2023) sets an objective for the governance mechanisms for industry deployment through a cluster-based approach and to roll out a first CCUS cluster in East Coast Malaysia, targeting hard-to-abate sectors, including industry. In Canada, the state government of Alberta is running a series of competitions to explore the establishment of carbon sequestration hubs (Government of Alberta, 2023). The initial focus is on addressing emissions from industrial areas, and a second competition will cover other areas of the province.

Based on these examples, we can define a 'CCUS cluster' as a location where multiple CO_2 emission sources, such as industrial facilities or power plants, are in close geographical proximity, creating opportunities for future shared capture, transportation and storage infrastructures. Rather than individual facilities implementing their own carbon capture solutions, these sources collaborate to reduce costs and project risks by employing a centralised CCUS infrastructure (Costa et al., 2019). A 'CCUS hub,' by contrast, is a facility serving as a central point for capturing, storing or utilising CO_2 emissions from various sources within a specific region or cluster. The hub typically includes infrastructure for capturing CO_2, transportation networks for moving the captured CO_2 and facilities for storage or utilisation. The Northern Lights project in Norway, which will provide the transportation, receipt and storage of CO_2 in a reservoir in the northern North Sea, is perhaps the best known example of a CCUS hub (Wang, 2024).

Our key point then is that while hydrogen hubs and oases and CCUS clusters and hubs may be associated with industry, they need not exclusively focus on the decarbonisation of industrial activities. We argue that understanding these distinctions is important. By clearly defining our objects of analysis, we can establish a shared understanding of what is being studied, which then informs our choice of methodologies, research questions and case studies. This clarity will be essential for designing effective policies, allocating resources efficiently and identifying the most appropriate pathways to achieve broader decarbonisation goals.

Table 1 summarises the main differences between the different types. For the remainder of this paper, we focus on net zero industrial cluster initiatives as a specific type of place-based decarbonisation initiative. We now turn to consider the insights that the literature on industrial agglomeration and business strategy can offer regarding this type of project.

4 | A BRIEF HISTORY OF INDUSTRIAL CLUSTER THEORY

The process of industrial transition will come about through a complex interplay of technological, market and socio-political factors that will operate between places and across different scales (Köhler et al., 2019). Historically, certain regions in Europe, such as Silesia in Poland, North Rhine-Westphalia in Germany, and Teesside and the Humber in England, have been characterised by high concentrations of energy-intensive industry for which the use of fossil fuels has provided both a significant source of economic prosperity while also leading to high levels of per capita greenhouse emissions (Roelfes et al., 2018; Webb et al., 2022). Within these regions, industrial clusters have formed as localised concentrations of sectors such as coal mining, steel or chemical production. While these industrial clusters are central to economic activity, they also contribute significantly to regional emissions. However, many high-carbon regions lack the resources and capacities to drive the low-carbon transitions within their industrial clusters (Roelfes et al., 2018). Bridging this capacity gap will be critical to mitigate climate change.

One strategy could be to identify and nurture existing pockets of good practice with the hope of triggering wider transformative change (Chertow, 2007). However, even the Port of Rotterdam, Porthos project—the most mature net zero industrial cluster initiative—has only recently entered the construction stage. From a policy-making perspective, this lack of mature projects presents a significant evidence gap since it is difficult to know which initiatives will succeed in delivering deep decarbonisation and therefore where to prioritise infrastructure deployment. Without targeted policies and investments, progress is likely to be slow, uneven and inefficient, creating further obstacles to achieving already challenging emissions reduction targets.

TABLE 1 Summary of place-based approaches to industrial decarbonisation.

Type	Main objective	Key features	Co-location of supply and demand	Existing industrial area	Primarily aimed at industrial customer
Net Zero Industrial Cluster	Cost-effective industrial emissions reduction Acceleration chambers for the low-carbon industrial transition	Multiple decarbonisation interventions. Shared infrastructure, joint efficiency initiatives, knowledge exchange	Yes	Yes	Yes
Hydrogen Hub	Hydrogen production	Initial focus on domestic market Networks of hydrogen producers and consumers	Yes	Yes	Project specific
Hydrogen Oasis	Hydrogen production	Focus on export market Sited near useful geologies, such as depleted oil wells and salt caverns	Yes	TBC	TBC
CCUS cluster	Shared carbon capture infrastructure, aiming to reduce costs and project risks by optimising resources and achieving economies of scale	Multiple sources of CO_2 emissions, such as industrial facilities or power plants	Yes	Project specific	Not limited to industrial activities; may also include emissions from non-industrial sources like power generation
CCUS hub	Shared carbon transportation infrastructure, aiming to reduce costs and project risks by optimising resources and achieving economies of scale	A central point for transporting or utilising CO_2 emissions from various sources within a specific region or industrial cluster	No	Project specific	

In the absence of mature net zero industrial cluster initiatives, it is useful to consult the broader academic literature on industrial clustering in order to identify the factors that underpin successful industrial clusters more generally. This body of research spans more than a century and is characterised by multiple theoretical perspectives from different disciplines, including economics, geography, sociology, urban studies and business strategy. It is beyond the scope of this paper to summarise the entire field (for reviews, see, among others, Bekele & Jackson, 2006; Feser, 1998; Lazzeretti et al., 2014; Newlands, 2003). Instead, we concentrate here on two key features of industrial clusters that are frequently discussed in relation to successful initiatives: locational advantage and firm interdependencies, to outline how understandings of industrial cluster dynamics have progressed and provide the theoretical groundwork for our subsequent typology.

The first formal classification of the reasons for industrial agglomeration was undertaken by Alfred Marshall (1890) in the *Principles of Economics*. Here, Marshall set out the tenets of agglomeration theory and highlighted the crucial role of physical conditions, such as climate, soil conditions and access to raw materials, in influencing firms' location decisions. He argued that, over time, a persistent geographical concentration of firms led to the emergence of external economies of scale. These included the development of a skilled labour market, specialised suppliers and services, and technological spillovers between firms. This triad of localisation advantages, in turn, attracted additional capital and labour to the area, fostering its growth and competitiveness and ultimately giving rise to specialised industrial districts. While Marshall's emphasis on tangible factors has been suggested to have more relevance to historical industrial clusters, at least in developed economies (Krugman, 2011), his work remains foundational in explaining how geographical proximity leads to locational advantage.

While early agglomeration theory focused on the spatial clustering of industrial firms, subsequent research shifted its focus towards examining the linkages between them, including production, service and marketing connections. This shift marked a transition towards understanding interdependencies among industries, a concept fundamental to growth pole theory. Originating from the work of François Perroux (1950), this concept gained significant policy traction during the 1960s and 1970s. Perroux argued for the identification and nurturing of propulsive industries: those industries that dominate other sectors because of their size, market power and role as lead innovators. Propulsive industries represent poles of growth that, through their linkages with other firms, can attract, focus and direct other economic resources. Growth pole policy, therefore, funnelled investment at select locations and sectors with the intent of stimulating economic activity.

In the aftermath of the economic upheavals of the 1970s, academic attention shifted from formal value chain linkages to exploring informal collaborative and informational networks. The Flexible Specialization School, in particular the work of Piore and Sabel (1984) and Brusco (1982) explored how clusters of small and medium enterprises (SMEs), such as those found in Emilia-Romagna, Italy, and Baden-Württemberg, Germany, came to compete successfully in global markets. Strong social networks, face-to-face encounters and tacit specialised local knowledge, underpinned by a shared culture, were identified as key elements contributing to these areas' successes.

Growth pole policy subsequently fell out of favour as a policy tool, since designated regions were often found to function as isolated enclaves of economic activity rather than contributing to broader regional development (Richardson, 1976). Work on flexible specialisation also drew scrutiny for focusing primarily on a small number of exemplar initiatives, raising questions about how broadly applicable its findings might be (Malmberg & Maskell, 2002). For our purposes, however, the core insight from these two fields is the importance of formal and informal linkages between firms in enabling knowledge exchange and innovation within industrial clusters. Geographical proximity may support the development of other forms of social, organisational and cognitive proximity, but in itself, it is not sufficient to enable shared learning (Boschma, 2005).

This focus on linkages gained further prominence in Michael Porter's *The Competitive Advantage of Nations* (Porter, 1990). Here, Porter argues that clusters of firms, characterised by vertical or horizontal relationships, play a vital role in driving regional economic growth and enhancing national competitiveness. His Diamond Model identifies four factors that interact to contribute to firm and, ultimately, national advantage. Factor conditions include basic and advanced resources such as natural resources and infrastructure. Demand conditions are shaped by market size, sophistication and competition, driving innovation. Related industries provide inputs and foster innovation, optimising supply chains and skills development. Finally, firm strategy, structure and rivalry influence competitiveness through innovation and differentiation. The components of the diamond collectively reinforce each other and lead to the formation of clusters that capitalise on knowledge spillovers and the investments in human and physical resources that geographical proximity brings. Consequently, as clusters mature, economic resources increasingly gravitate towards them, leaving unclustered industries at a disadvantage, since they are unable to compete.

While Porter's work faced criticism for a lack of conceptual clarity (Martin & Sunley, 2003) over the following two decades, his insights sparked intense policy and academic interest. Baron-Gutty et al. (2009); Feser (1998) and Torre (2006) have all sought to simplify Porter's approach to competitive advantage by focusing on two core dimensions of his model: location and interaction, to characterise different cluster types. While net zero industrial cluster initiatives are not directly analogous to industrial clusters as they are understood in Porter's theory—primarily due to their wider networks and focus on emissions reduction (Lai & Devine-Wright, 2024), a modified version of this framework can still be applied to industrial decarbonisation in order to characterise the potential trajectories of different net zero industrial cluster initiatives.

5 | A TYPOLOGY OF NET ZERO INDUSTRIAL CLUSTER INITIATIVES

Table 2 sets out how net zero industrial cluster initiatives can be classified using the two dimensions of clustering set out above. We use the concept of *locational advantage* to encompass three components: the foundational physical and factor conditions identified by Marshall (1890) and Porter (1990) as important elements of industrial cluster success; the degree of geographical proximity between firms, which will play a significant role in the cost-effective implementation of decarbonisation infrastructure; and the specific elements that have been identified as beneficial to net zero industrial cluster initiatives. These include proximity to carbon sinks and storage (such as geological storage for carbon capture and salt caverns for hydrogen storage), access to renewable energy sources, existing pipeline infrastructure, port facilities and a strategic location that facilitates access to industrial partners and the potential for expanding infrastructure to nearby clusters (Rattle & Taylor, 2023). In this context, we use *dispersed* to refer to a relative lack of geographical concentration in any of the three components of locational advantage.

We use the *degree of inter-firm linkages* to refer to both the formal networks of supply and value chains, as emphasised by Perroux, and the informal collaborative and informational networks identified in the work of the Flexible

TABLE 2 Types of net zero industrial cluster initiatives.

		Degree of inter-firm linkages	
		High	**Low**
Locational advantage	High	Type 1 *Forerunner clusters*	Type 3 *Classic clusters*
	Low	Type 2 *Dispersed clusters*	Type 4 *Dispersed sites*

Source: Adapted from Baron-Gutty et al. (2009, p. 447); Torre (2006, p. 21).

Specialization School and subsequent scholarship. Key factors contributing to the strength of these linkages for net zero industrial cluster initiatives include robust knowledge networks for information exchange, established formal and informal institutions, and pre-existing physical and information technology infrastructures (Rattle & Taylor, 2023).

Type 1, forerunner clusters, correspond to the 'Porter type' cluster, characterised by significant levels of both locational advantage and inter-firm linkage. Firms are in the same area, have strong links and maintain privileged relationships in terms of technology exchanges and knowledge transfers. They demonstrate a high level of geographic proximity, sometimes underpinned by shared infrastructure and strong linkages among member firms, both in terms of interactions and a common vision. These networks have often developed over many years.

Type 2, dispersed clusters, describes a scenario of strong inter-firm relations but a lower level of locational advantage. Historically, this type was believed to be characteristic of the more geographically dispersed advanced manufacturing sector (Feser, 1998), or clusters analysed at the national or regional level (Torre, 2006). For industrial decarbonisation, we suggest that it may refer to places with a long industrial history where firms have developed social, organisational and cognitive proximity over time.

Type 3, classic clusters, represents a situation with a strong locational advantage but limited organisational connections among firms. Historically, this pattern has been common in energy-intensive industrial regions often historically linked to a local resource (Porter, 1990). We have named this category 'classic clusters' since they are similar to the type of clusters that arose during the industrial revolution. While they may not align with Porter's cluster concept (Baron-Gutty et al., 2009), addressing the carbon emissions of these clusters will be vital to mitigate climate change.

Type 4, dispersed sites, represent a type of industrial organisation that has historically been of little interest to policy-makers, since they are not clustered in either dimension (Torre, 2006). However, for the purposes of industrial decarbonisation, these sites cannot be ignored, since their cumulative emissions may be significant. Tailored actions to reduce carbon emissions may be practical for strategically important sites, addressing the remaining sites poses a challenge that policy-makers have yet to address.

The value of classifying net zero cluster initiatives in this way is threefold. First, it identifies the key traits of clusters most likely to achieve early success in decarbonisation, to help guide the design of effective policies and the efficient allocation of resources. Second, it begins to explain why different clusters will follow different decarbonisation trajectories, with each evolving in distinct ways based on the strength of their networks and locational advantage, providing a basis for future comparative work. Third, by presenting the four types in relation to one another, the typology highlights that net zero industrial clusters, as depicted in industrial decarbonisation policy, are most closely aligned with Type 1. This comparison highlights the challenges faced by industrial areas that do not yet exhibit all of the 'forerunner' characteristics, drawing attention to the disparities and difficulties encountered by these regions. It also raises broader questions about how best to decarbonise these places. In the next sections, we present three cluster profiles, aiming to illustrate the characteristics and potential decarbonisation trajectories of different cluster types. The main points are supported by references to the relevant documents or interviews. Since all clusters are unique (Müller et al., 2012), we make no claim that our cases are 'typical'. Instead, we have selected them based on the insights they can provide into the potential trajectories of different projects (Stake, 1995).

5.1 | The Port of Rotterdam

The Port of Rotterdam is home to over 45 petrochemical companies and five oil refineries, including Shell Pernis, Europe's largest oil refinery. This highly concentrated industrial cluster accounts for 16–20% of total Dutch CO_2 emissions.

Strategically located at the mouth of the Rhine, the port has served as a gateway into Europe for centuries. Its fuel cluster originated in the late-nineteenth and early-twentieth centuries, responding to the emerging automobile industry, with further refineries established in the 1950s to meet post-war oil demands (de Haas & van Dril, 2022). Over recent decades, the Port of Rotterdam Authority has played a pivotal role in coordinating cluster development, investing in both physical and knowledge infrastructures (Brownsort, 2019). In 2003, it collaborated with Vopak Chemicals Logistics to establish MultiCore, an underground pipeline system facilitating chemical and gas distribution among firms. This initiative addressed infrastructure needs that individual firms were unlikely to fund independently (Sørensen et al., 2021). In addition, the Port Authority has a long history of supporting initiatives to foster collaboration among firms, sponsoring programmes such as Erasmus Smart Port Rotterdam and the sustainability- and innovation-oriented RDM Centre of Expertise (Hollen et al., 2015).

The Port of Rotterdam Cluster Energy Strategy outlines six projects designed to enhance sustainability and the energy transition within the Port, of which industrial CCUS is one (Port of Rotterdam, 2021). The Porthos project is a joint venture led by three state-owned entities: EBN, an upstream hydrocarbons company; Gasunie NV, the gas network owner; and the Port of Rotterdam Authority. The aim was to establish open-access joint CO_2 transportation and storage infrastructure for industries within the port. Given the high concentration of energy-intensive firms and the potential for CO_2 storage in the depleted P18-4 gas reservoir located 20 km offshore, the port was an obvious candidate for industrial CCUS (Arts et al., 2012). However, CCUS remains a contentious issue in the Netherlands, and its role in the industrial transition sparked significant debate during the development of the Climate Agreement (Interview #7). The Port Authority is an important stakeholder in the national debate on decarbonisation targets and strategies and engaged extensively across the political spectrum to build support for the Porthos project (Schneider et al., 2020; Sørensen et al., 2021). Porthos reached Final Investment Decision in autumn 2023 and began construction in spring 2024. However, the project encountered considerable challenges *en route* to this milestone, including a court case filed by the environmental campaign group Mobilisation for the Environment concerning the environmental impacts of nitrogen emissions during the construction phase (Porthos., 2022). The Dutch Council of State dismissed the case in August 2023, but legal proceedings have significantly delayed the project timeline, with costs projected to nearly triple (Dutch News, 2024).

The Port of Rotterdam provides an example of a type 1 *forerunner* cluster according to our typology. The port demonstrates high geographical concentration, access to shared infrastructure and offshore CCUS opportunities alongside well-established inter-firm linkages, actively supported by the Port Authority over many years. Initiatives like MultiCore demonstrate the Port Authority's capacity to implement shared infrastructure solutions that enhance efficiency for its tenants. However, as the recent court case demonstrates, even leading initiatives can face external challenges that may disrupt their decarbonisation pathways. Therefore, it is essential to also consider the broader external challenges and influences that may affect their success.

5.2 | The Black Country Industrial Cluster

The Black Country, located in the West Midlands of England, is the historic heartland of UK manufacturing. From the eighteenth century onwards, abundant coal deposits powered the region's mining and iron-smelting industries, while also supporting numerous smaller businesses, giving it a claim to being the world's first modern industrial cluster (Black Country LEP, 2020). However, in the second half of the twentieth century, following the decline of coal mining and the closure of several large steelworks, the region experienced significant deindustrialisation. Today, the area remains home to numerous specialised metal processing operations catering to the automotive, defence and aerospace industries and interconnected through supply chains (Interview #3). However, it lacks a major plant or refinery to serve as an anchor for the cluster, and a focal point for infrastructure investment. Instead, it is home to 3,500 manufacturing firms, mostly SMEs, across four local authorities. Rather than clustering around the now-vanished coal and steel works, the remaining firms are dispersed across the region, often integrated into residential areas and located near historic canal and rail links. They also face the challenge of limited space for low-carbon infrastructure (Repowering the Black Country, 2023). Despite the now-dispersed nature of the industrial geography, however, the Black Country maintains a distinct regional identity and sense of cohesion (Interview #1). Institutions such as the Regional Development Agency and, more recently, the Local Enterprise Partnerships, assisted in maintaining these linkages and provided a strong industry voice at local and Combined Authority levels (Interview #3) (Henderson, 2015).

The Repowering the Black Country programme was one of six industrial cluster decarbonisation projects funded by the UK government in 2021. Although the area was not initially identified as a cluster in policy documents, representatives from the programme obtained agreement from policy-makers to bid for funding on the grounds that the area contained a significant amount of industry (Interview #1). Since the geographic dispersion of industrial sites meant that CCUS and hydrogen were unlikely to be cost-effective decarbonisation options, the project focused on four elements: reconfiguring supply chains for circular economies; process optimisation within individual firms; alignment with national decarbonisation scenarios; and creating models for local Zero Carbon hubs, with a particular emphasis on heat (Black Country LEP, 2020). Over three years, the initiative developed plans and a replicable methodology for the decarbonisation of six Zero Carbon Hubs and secured £25 million for business energy efficiency programmes. The programme's legacy continues through the Black Country Industrial Cluster (BCIC), a non-profit collaboration coordinated by key partners of Repowering the Black Country. Part of its work is the Centre for Manufacturing Transition, which advocates for dispersed manufacturing in UK industrial and energy policy and facilitates the nationwide dissemination of solutions developed within the BCIC (Repowering the Black Country, n.d.).

The BCIC is an example of a type 2 *dispersed* cluster according to our typology. Despite the dispersion of industrial activities, inter-firm linkages and institutional infrastructure persist, serving as pillars for adaptation and development. The strong industrial identity of the Black Country served as a rallying point for local stakeholders, motivating them to pursue funding opportunities for decarbonisation. While the area may not appear as a cluster based on locational factors, social, organisational and cognitive proximity played a crucial role in establishing its identity as such.

5.3 | North West Cluster

HyNet is an industrial decarbonisation project focused on hydrogen production and CCUS within the North West cluster that extends from northeast Wales to northwest England. This cluster covers a diverse geography running from Wrexham and Flintshire through Cheshire, Liverpool City Region, Greater Manchester and into Lancashire. This area contains a significant concentration of heavy industry and power generation facilities, particularly around the Stanlow Refinery in Ellesmere Port, one of the largest oil refineries in the UK. Additionally, it is home to several gas turbines, biomass and energy-from-waste facilities, alongside over 30 large manufacturing facilities in sectors such as glass, cement and chemicals (Clery & Gough, 2022). The region's historical association with Imperial Chemical Industries has left it with a legacy of shared infrastructures and inter-firm networks, but more recent networking initiatives also contributed to the area coming to define itself as a net zero industrial cluster initiative.

Work on the development of the HyNet concept began in 2016. Recognising the key role that hydrogen and shared CCUS infrastructure projects would play in industrial decarbonisation efforts, consultancy firm Progressive Energy undertook an evaluation of potential CO_2 sequestration opportunities across the UK. Working alongside gas distribution company, Cadent, their assessment identified the north-west of England as a promising candidate for a cluster decarbonisation project. This selection was influenced by three primary locational factors: the near-depleted gas fields in Liverpool Bay, which were suitable for CO_2 storage; the Cheshire salt caverns, which offered the possibility of hydrogen storage; and the high level of industrial emissions, particularly around Ellesmere Port (Interview #6). Subsequently, Net Zero North West (NZNW), an industry-led organisation, was established in 2019 with support from city regions, LEPs and local academia to advance the broader cluster programme (Clery & Gough, 2022). The initiative arose from the recognition of the need for a stronger industry voice on industrial decarbonisation in the region (Interview #4). The region's long-term Cluster Plan was driven by its industrial partners through the NZNW, with support from the region's LEPs and the two Metro Mayors of Liverpool and Manchester. In 2021, HyNet attained Track-1 cluster status through the cluster sequencing process.

The North West Cluster provides an example of a type 3 *classic* cluster according to our typology, which through its network building efforts has strengthened inter-firm linkages and evolved towards type 1. Locational advantages were the initial reasons behind the development of the HyNet concept. Subsequently, relationship building within both the cluster and the broader region followed, fostering collaboration and alignment towards shared decarbonisation goals.

6 | DISCUSSION AND CONCLUSION

Typologies of clusters have often focused on type 1 initiatives in response to Porter's work on business strategy, which emphasised clusters as drivers of competitive advantage (Baron-Gutty et al., 2009; Feser, 1998). In the context of industrial decarbonisation, when the goal is to reduce an entire sector's emissions, conventional narratives of winners and losers become less useful. As our examples illustrate, there is the potential for a variety of cluster types to embark on successful decarbonisation initiatives, not only type 1. In this section, we consider the policy implications for each cluster type and provide suggestions for future research. We conclude with a discussion of the limitations of our work and some reflections on the value of revisiting theories of industrial agglomeration in the context of the low-carbon transition.

From a policy-maker's perspective, identifying type 1 'forerunner' clusters is often straightforward (Bergman & Feser, 1999). In the case of Porthos, the Port of Rotterdam was an important stakeholder in the national debate. This suggests that when decarbonising forerunner clusters, the main policy challenge may lie in ensuring that the necessary interventions, such as business models, funding streams, carbon prices and regulatory standards, are sufficiently well developed and resourced to facilitate progress. However, external factors can also have a significant impact on project development, irrespective of the type of cluster involved. Industrial clusters are embedded within local, regional and national contexts, and these contexts will shape their decarbonisation trajectories (Lai & Devine-Wright, 2024). Research has begun to explore how endogenous and exogenous dynamics shape the decarbonisation pathways of UK net zero clusters (Geels et al., 2023; Sovacool et al., 2024). However, more international comparative studies are needed to deepen our understanding of effective policy responses worldwide.

The Black Country Cluster shares similarities with many post-industrial areas that were once manufacturing powerhouses but have since experienced deindustrialisation, leading to fragmentation and specialisation. Type 2 'dispersed' clusters' may not have the highly emitting anchor sites and other locational advantages that make a clear business case for government investment in infrastructure. Consequently, they have not been the main focus of industrial decarbonisation initiatives to date (Rattle et al., 2023). However, their strong pre-existing networks present an opportunity for locally led implementation of tailored decarbonisation strategies. Government funding for interventions such as resource and energy efficiency programmes, industrial symbiosis and electrification is likely crucial for advancing decarbonisation efforts in these areas. The Black Country appears to have once been a type 1 cluster that, due to historic deindustrialisation, has evolved toward type 2. This suggests that identifying historical industrial clusters could be one means to pinpoint likely areas of development and target appropriate investments.

Identifying locationally advantaged type 3 'classic' clusters is theoretically simpler because of the scale of their operations and the significant emissions they produce. However, lessons from the failure of growth pole policy suggest that directing government investment to specific locations often fails to generate lasting success without the active involvement of companies and business associations (Richardson, 1976). In the North West Cluster, broader regional network building fostered a strong coalition for change enabling the cluster to evolve toward type 1. For regions with comparable industrial concentrations and decarbonisation potential, it is increasingly recognised that strengthening collaboration across clusters and regions will be a core component of delivering the industrial transition (World Economic Forum, 2025). However, in areas with less apparent decarbonisation potential, a different approach may be needed, such as supporting a network of smaller-scale initiatives aimed at fostering collaboration among local businesses. The question of capacity building for industrial decarbonisation is currently underexplored in academic and policy literature, but it is increasingly evident that strong relationships built on trust, collaboration and shared goals are likely to be crucial for success (Rattle & Taylor, 2023; Sovacool et al., 2024). Further research and policy attention towards understanding and enhancing these relationships will be essential to addressing the challenges of decarbonising industry.

Lastly, there are truly dispersed areas characterised by industries geographically separated and with limited inter-firm linkages. Cluster theory offers limited insights into the dynamics of the truly dispersed industrial sites that are categorised as type 4 in our typology. There is, we suggest, a pressing need for further research into this form of industrial arrangement. Rather than treating industry as a separate entity to decarbonise, a cross-sectoral approach may be better suited to these areas. Decarbonising industry could form part of a wider place-based approach, including the decarbonisation of buildings, transport and energy supply. Funding for both tailored decarbonisation strategies and attention to capacity building is likely to be key for these areas.

This paper proposes a typology of net zero cluster initiatives. However, it contains several limitations with regard to the generalisability of both our empirical data and our conceptual framework. Empirically, cluster research is frequently criticised for focusing on a small number of exemplar initiatives, raising questions about the broader applicability of its findings (Malmberg & Maskell, 2002). There is a risk that net zero cluster research is following a similar route, dominated by a handful of case studies from the Netherlands and the UK. While these cases serve as valuable starting points for analysis, the number of projects is currently small and regionally specific. In addition, the availability of cluster information is limited and not always updated in a timely manner, while stakeholders' understanding of cluster initiatives can vary significantly depending on the nature of their involvement. These factors present challenges in building a complete picture of cluster initiatives and should be taken into account when considering the accuracy and comprehensiveness of our typology. A more extensive and diverse sample of net zero cluster projects from different regions would enhance the generalisability of our findings and allow for a more nuanced examination of the different forms clusters may take. Additionally, longitudinal studies tracking the development and implementation of net zero cluster initiatives over time could provide valuable insights into the effectiveness of different approaches and strategies.

Conceptually, the notion of an industrial cluster originated as an analytical tool primarily suited to mature economies with well-established industrial areas (Baron-Gutty et al., 2009; Krugman, 2011). It remains to be demonstrated whether our typology is applicable to other country contexts and less mature industrial areas. We have focused here particularly on the decarbonisation of established areas of industry, but new industrial parks specifically designed and built to allow for waste heat sharing, industrial symbiosis and the sharing of hydrogen and CO_2 infrastructures have the potential to play an important role in decarbonising the sector (Bataille, 2020). At present, the extent to which new industrial parks could replace or supplement existing industrial areas is unclear. Future research will need to encompass evolving forms of industrial organisation if it is to provide comprehensive insights into the trajectories of the industrial transition.

More broadly, collapsing the complexity of how clusters operate into two dimensions inevitably oversimplifies the dynamics at play; no framework can capture every aspect of a phenomenon (Maxwell, 2012). Net zero industrial cluster initiatives are evolving entities influenced by numerous factors, including policy frameworks, technological advancements, market dynamics and socio-economic conditions. The industrial sectors within a cluster and the decarbonisation technologies and strategies that a cluster employs will both shape and be shaped by locational factors and inter-firm linkages. Further research may well adopt a more nuanced analytical framework that considers a broader range of factors influencing their development and outcomes.

Nonetheless, we believe that there is merit in revisiting cluster theory in the context of the industrial transition, both to provide a framework for understanding how different net zero industrial cluster initiatives may evolve, and also to identify and interrogate some of the underpinning logics of using clusters to kickstart the industrial transition. Traditional cluster theory is grounded in the concept of geographic proximity, shared networks and sectoral synergies, which drive efficiencies and innovation. However, the demands of net zero industrial clusters may require expanded frameworks that account for their distinct logistical, technical and economic challenges. Revisiting cluster theory in this light can provide a framework to examine how net zero cluster initiatives evolve, helping to identify the unique factors that support or hinder their development. By doing so, we can also interrogate the underlying assumptions in using clusters as a tool for accelerating the industrial transition. Both the outcomes of growth pole policy and Porter's work suggest that funnelling funding towards clusters may not have net positive regional benefits. Instead, clusters may develop at the expense of their surrounding areas. The implications for industrial decarbonisation require further investigation. We consider this paper a first step in that direction and hope it prompts further work in the area.

Industry is responsible for a quarter of global emissions, and decarbonisation of the sector is still in its infancy. A significant proportion of industrial activity is found in clusters, but by no means all. The field of study is large, encompassing a wide range of industries, processes and geographic locations. Undoubtedly, our understanding of the issues will evolve as the transition evolves. In this paper, we have aimed to provide clarity in the field by categorising different place-based approaches to industrial decarbonisation. We have then drawn on cluster theory to provide a framework through which to examine the dynamics shaping how different types of net zero industrial cluster initiatives have engaged in the industrial transition to date. By establishing clear definitions and frameworks, we hope to provide a foundation for further research and policy development in the ongoing effort to transition towards a low-carbon industrial future.

AUTHOR CONTRIBUTIONS

Imogen Rattle: conceptualization, methodology, investigation, writing – original draft, writing – review & editing. **Peter Taylor:** conceptualization, resources, writing – review & editing, supervision, funding acquisition.

ACKNOWLEDGEMENTS

We would like to thank our interviewees for their participation in this study and our reviewers for their helpful comments. We also thank participants at the Industrial Cluster Decarbonisation: Sharing International Experience workshop that took place in London in June 2023. Their identification of the need to classify clusters into archetypes to assist in knowledge exchange laid the groundwork for this paper. Any errors or omissions remain our own. This research was undertaken as part of the Industrial Decarbonisation Research and Innovation Centre funded by UK Research and Innovation (grant number: EP/V027050/1) and the UK Energy Research Centre, funded by the UK Research and Innovation Energy Programme (Grant number EP/S029575/1).

CONFLICT OF INTEREST STATEMENT

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 STATEMENT

The cluster, policy and academic documents that support the findings of this study were derived from sources in the public domain, and links are provided in the references. The interview data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

ORCID

Imogen Rattle https://orcid.org/0000-0002-9997-7422
Peter G. Taylor https://orcid.org/0000-0001-7456-3744

REFERENCES

Akerboom, S., Waldmann, S., Mukherjee, A., Agaton, C., Sanders, M. & Kramer, G.J. (2021) Different this time? The prospects of CCS in The Netherlands in the 2020s. *Frontiers in Energy Research*, 9, 644796. Available from: https://doi.org/10.3389/fenrg.2021.644796

Arts, R.J., Vandeweijer, V.P., Hofstee, C., Pluymaekers, M.P.D., Loeve, D., Kopp, A. et al. (2012) The feasibility of CO2 storage in the depleted P18-4 gas field offshore The Netherlands (the ROAD project). *International Journal of Greenhouse Gas Control*, 11(SUPPL), 10–20. Available from: https://doi.org/10.1016/j.ijggc.2012.09.010

Baron-Gutty, A., Figuière, C. & Simon, J.-C. (2009) From 'tradi-cluster'to 'neocluster': First step for a typology of industrial clusters in emerging economies: A case study of Thailand. In: Ganne, B. & Lecler, Y. (Eds.) *Asian industrial clusters, global competitiveness new policy initiatives*. Singapore: World Scientific Publishing Company, pp. 437–466. Available from: https://doi.org/10.1142/9789814280136_0015

Bashmakov, I.A., Nilsson, L.J., Acquaye, A., Bataille, C., Cullen, J.M., Fischedick, M. et al. (2022) Industry. In: Shukla, J.S.P.R., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D., Pathak, M. et al. (Eds.) *Climate change 2022: Mitigation of climate change. Contribution of working group III to the sixth assessment report of the intergovernmental panel on climate change, Chapter 11*. Cambridge: Cambridge University Press.

Bataille, C., Åhman, M., Neuhoff, K., Nilsson, L.J., Fischedick, M., Lechtenböhmer, S. et al. (2018) A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris agreement. *Journal of Cleaner Production*, 187, 960–973. Available from: https://doi.org/10.1016/j.jclepro.2018.03.107

Bataille, C., Nilsson, L.J. & Jotzo, F. (2021) Industry in a net-zero emissions world: New mitigation pathways, new supply chains, modelling needs and policy implications. *Energy and Climate Change*, 2, 100059. Available from: https://doi.org/10.1016/j.egycc.2021.100059

Bataille, C.G.F. (2020) Physical and policy pathways to net-zero emissions industry. *Wiley Interdisciplinary Reviews: Climate Change*, 11(2), e633. Available from: https://doi.org/10.1002/wcc.633

Bekele, G.W. & Jackson, R. (2006) Theoretical perspectives on industry clusters. Available from: https://researchrepository.wvu.edu/rri_pubs/92

Bergman, E.M. & Feser, E.J. (1999) In: Loveridge, S. & Jackson, R. (Eds.) *Industrial and regional clusters: Concepts and comparative applications. Reprint*. Morgantown, WV: West Virginia University. Available from: https://researchrepository.wvu.edu/rri-web-book/5/

Black Country LEP. (2020) Repowering the Black Country.

Boschma, R. (2005) Proximity and innovation: A critical assessment. *Regional Studies*, 39(1), 61–74.

Bosman, R., Loorbach, D., Rotmans, J. & van Raak, R. (2018) Carbon lock-out: Leading the fossil port of Rotterdam into transition. *Sustainability (Switzerland)*, 10(7), 2558. Available from: https://doi.org/10.3390/su10072558

Brownsort, P. (2019) *Methodologies for cluster development and best practices for data collection in the promising regions*. Available from: https://www.strategyccus.eu/sites/default/files/STRATEGY_CCUS_T2-1_ICCS_Methodology_V1.2.pdf

Brusco, S. (1982) The Emilian model: Productive decentralisation and social integration. *Cambridge Journal of Economics*, 6(2), 167–184.

Chertow, M.R. (2007) Uncovering. *Industrial Symbiosis*, 11(1), 11–30. Available from: https://doi.org/10.1162/jiec.2007.1110

Clery, D. & Gough, C. (2022) Cluster Mapping Report: Hynet Northwest (NW industrial cluster). UK Industrial Decarbonisation Research and Innovation Centre. Available from: https://idric.org/

Costa, I., Rochedo, P., Costa, D., Ferreira, P., Araújo, M., Schaeffer, R. et al. (2019) Placing hubs in CO_2 pipelines: An application to industrial CO_2 emissions in the Iberian Peninsula. *Applied Energy*, 236, 22–31. Available from: https://doi.org/10.1016/j.apenergy.2018.11.050

de Haas, J. & van Dril, T. (2022) Decarbonisation options for the industry cluster Botlek/Pernis Rotterdam. Available from: https://www.pbl.nl/sites/default/files/downloads/pbl-2022-decarbonisation-of-the-industry-cluster-botlek-pernis-rotterdam-4946.pdf

Department of Energy. (2023) US National Clean Hydrogen Strategy and Roadmap. Available from: https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf

DESNZ, & BEIS. (2021, November 1) October 2021 update: Track-1 clusters confirmed. Available from: https://www.gov.uk/government/publications/cluster-sequencing-for-carbon-capture-usage-and-storage-ccus-deployment-phase-1-expressions-of-interest/october-2021-update-track-1-clusters-confirmed

DESNZ & BEIS. (2023, 30 March) Cluster sequencing Phase-2: Track-1 project negotiation list, March 2023. Available from: https://www.gov.uk/government/publications/cluster-sequencing-phase-2-eligible-projects-power-ccus-hydrogen-and-icc/cluster-sequencing-phase-2-track-1-project-negotiation-list-march-2023

Dutch News. (2024, 8 March) Dutch carbon capture project Porthos soars in price. Available from: https://www.dutchnews.nl/2024/03/dutch-carbon-capture-project-porthos-soars-in-price/

European Commission. (2023) The Net-Zero Industry Act: Accelerating the transition to climate neutrality. Available from: https://single-market-economy.ec.europa.eu/industry/sustainability/net-zero-industry-act_en

Feser, E. (1998) Old and new theories of industry clusters. In: Steiner, M. (Ed.) *Clusters and regional specialisation*. London: Pion, pp. 18–40.

Fischedick, M., Roy, J., Acquaye, A., Allwood, J., Ceron, J.-P., Geng, Y. et al. (2014) Industry In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Technical Report.

Gailani, A., Cooper, S., Allen, S., Pimm, A., Taylor, P. & Gross, R. (2024) Assessing the potential of decarbonization options for industrial sectors. *Joule*, 8(3), 576–603. Available from: https://doi.org/10.1016/j.joule.2024.01.007

Geels, F.W., Sovacool, B.K. & Iskandarova, M. (2023) The socio-technical dynamics of net-zero industrial megaprojects: Outside-in and inside-out analyses of the Humber industrial cluster. *Energy Research & Social Science*, 98, 103003.

Gianoli, A. & Bravo, F. (2020) Carbon tax, carbon leakage and the theory of induced innovation in the decarbonisation of industrial processes: The case of the port of Rotterdam. *Sustainability (Switzerland)*, 12(18), 7667. Available from: https://doi.org/10.3390/su12187667

Global CCS Institute. (2023) CSS in Europe regional overview.

Gough, C. & Mander, S. (2022) CCS industrial clusters: Building a social license to operate. *International Journal of Greenhouse Gas Control*, 119, 103713. Available from: https://doi.org/10.1016/j.ijggc.2022.103713

Government of Alberta. (2023) Carbon Capture, Utilization and Storage Developing Storage Hubs to Meet Growing Demand [Press release]. Available from: https://www.alberta.ca/system/files/custom_downloaded_images/energy-fact-sheet-storage-hub-development.pdf

Government of the Netherlands. (2019) National Climate Agreement. Available from: https://www.government.nl/documents/reports/2019/06/28/climate-agreement

Henderson, S.R. (2015) From sub-regional networks to sub-regional localism: Experiences of collaboration in England's historical Black Country. *Regional Studies*, 49(9), 1497–1513. Available from: https://doi.org/10.1080/00343404.2013.845655

HM Government. (2021) Industrial Decarbonisation Strategy. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/970149/6.7279_BEIS_CP399_Industrial_Decarbonisation_Strategy_FINAL_PRINT_FULL_NO_BLEED.pdf

Hollen, R.M.A., Van Den Bosch, F.A.J. & Volberda, H.W. (2015) Strategic levers of port authorities for industrial ecosystem development. *Maritime Economics and Logistics*, 17(1), 79–96. Available from: https://doi.org/10.1057/mel.2014.28

Hudson, M. & Lockwood, M. (2023) Dead and unburied: The resurrection of carbon capture and storage in the UK 2015-2018. Available from: https://hdl.handle.net/10779/uos.25011683.v1

IEA. (2022) Achieving Net Zero Heavy Industry Sectors in G7 Members. Available from: https://www.iea.org/reports/achieving-net-zero-heavy-industry-sectors-in-g7-members

IEA. (2023a, 11 July) Industry. Available from: https://www.iea.org/energy-system/industry

IEA. (2023b) *Renewable Hydrogen from Oman*. Available from: Paris: https://www.iea.org/reports/renewable-hydrogen-from-oman

Köhler, J., Geels, F.W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A. et al. (2019) An agenda for sustainability transitions research: State of the art and future directions. *Environmental Innovation and Societal Transitions*, 31, 1–32. Available from: https://doi.org/10.1016/j.eist.2019.01.004

Krugman, P. (2011) The new economic geography, now middle-aged. *Regional Studies*, 45(1), 1–7. Available from: https://doi.org/10.1080/00343404.2011.537127

Lai, H.-L. & Devine-Wright, P. (2024) Imagining and emplacing net zero industrial clusters: A critical analysis of stakeholder discourses. *Geo: Geography and Environment*, 11(1), e00139. Available from: https://doi.org/10.1002/geo2.139

Lazzeretti, L., Sedita, S.R. & Caloffi, A. (2014) Founders and disseminators of cluster research. *Journal of Economic Geography*, 14(1), 21–43.

Lewis, E., Edwards, R. & Howe, J. (2023) Delivering the industrial decarbonisation challenge: Geographical considerations for decarbonisation. *Geography*, 108(2), 86–94. Available from: https://doi.org/10.1080/00167487.2023.2217631

Malmberg, A. & Maskell, P. (2002) The elusive concept of localization economies: Towards a knowledge-based theory of spatial clustering. *Environment and Planning A: Economy and Space*, 34(3), 429–449.

Marshall, A. (1890) Principles of economics. In Vol. I–VII.

Martin, R. & Sunley, P. (2003) Deconstructing clusters: Chaotic concept or policy panacea? *Journal of Economic Geography*, 3(1), 5–35.

Maxwell, J.A. (2012) *A realist approach for qualitative research*. Thousand Oaks, CA: Sage.

Ministry of Energy and Infrastructure. (2023) *National Hydrogen Strategy United Arab Emirates*. Available from: The United Arab Emirates' Government Portal: https://u.ae/-/media/Documents-2nd-half-2023/UAE-National-Hydrogen-Strategy-2023.pdf

Ministry of Investment Trade and Industry. (2023) *New Industrial Master Plan 2030*. Available from: Government of Malaysia: https://www.nimp2030.gov.my/nimp2030/modules_resources/bookshelf/NIMP_20303/NIMP_20303.pdf

Ministry of New and Renewable Energy. (2023, 4 Jan) Cabinet approves National Green Hydrogen Mission. Available from: https://pib.gov.in/PressReleasePage.aspx?PRID=1888547#:~:text=The%20Mission%20will%20result%20in,lakh%20crore%20in%20total%20investments

Müller, L., Lämmer-Gamp, T., Meier zu Köcker, G. & Christiansen, T. (2012) Clusters are individuals: New findings from the European cluster management and cluster program benchmarking.

Newlands, D. (2003) Competition and cooperation in industrial clusters: The implications for public policy. *European Planning Studies*, 11(5), 521–532.

Office of Clean Energy Demonstrations. (2023, October 13) Regional Clean Hydrogen Hubs Selections for Award Negotiations. Available from: https://www.energy.gov/oced/regional-clean-hydrogen-hubs-selections-award-negotiations

Perroux, F. (1950) Economic space: Theory and applications. *The Quarterly Journal of Economics*, 64(1), 89–104. Available from: https://doi.org/10.2307/1881960

Piore, M.J. & Sabel, C.F. (1984) *The second industrial divide: Possibilities for prosperity*. New York City, NY: Basic Books.

Port of Rotterdam. (2021, 11 October) Six infrastructure projects central in first CES Rotterdam-Moerdijk. Available from: https://www.portofrotterdam.com/en/news-and-press-releases/six-infrastructure-projects-central-in-first-ces-rotterdam-moerdijk

Porter, M.E. (1990) *The competitive advantage of nations: Creating and sustaining superior performance*. New York, NY: Macmillan Press.

Porthos. (2022, 22 Nov) Interim ruling by Council of State delays Porthos project. Available from: https://www.porthosco2.nl/en/interim-ruling-by-council-of-state-delays-porthos-project/

Rattle, I., Gailani, A. & Taylor, P.G. (2023) Decarbonisation strategies in industry: Going beyond clusters. *Sustainability Science*, 19, 1–19. Available from: https://doi.org/10.1007/s11625-023-01313-4

Rattle, I. & Taylor, P.G. (2023) Factors driving the decarbonisation of industrial clusters: A rapid evidence assessment of international experience. *Energy Research & Social Science*, 105, 103265. Available from: https://doi.org/10.1016/j.erss.2023.103265

Repowering the Black Country. (2023) *Exploitation Plan February 2023 Final Version (6.1)*.

Repowering the Black Country. (n.d.) The Centre for Manufacturing Transition. Available from: https://irp.cdn-website.com/c230d936/files/uploaded/RBC%20Leaflet%20-%20Final.pdf

Richardson, H.W. (1976) Growth pole spillovers: The dynamics of backwash and spread. *Regional Studies*, 10(1), 1–9.

Rissman, J., Bataille, C., Masanet, E., Aden, N., Morrow, W.R., Zhou, N. et al. (2020) Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070. *Applied Energy*, 266, 114848. Available from: https://doi.org/10.1016/j.apenergy.2020.114848

Roelfes, M., Wehnert, T., Mölter, H., Bagnoli, V., Doernbrack, A.-S. & Lehr, D. (2018) *Specification of regional challenges/typology of high-carbon industry regions*.

Samadi, S., Lechtenböhmer, S., Schneider, C., Arnold, K., Fischedick, M., Schüwer, D. et al. (2016) Decarbonization pathways for the industrial cluster of the Port of Rotterdam: Final report. Available from: https://nbn-resolving.org/urn:nbn:de:bsz:wup4-opus-66565

Samadi, S., Schneider, C. & Lechtenböhmer, S. (2018) Deep decarbonisation pathways for the industrial cluster of the Port of Rotterdam. Paper presented at the Eceee Industrial Summer Study Proceedings.

Schneider, C., Lechtenböhmer, S. & Samadi, S. (2020) Risks and opportunities associated with decarbonising Rotterdam's industrial cluster. *Environmental Innovation and Societal Transitions*, 35, 414–428. Available from: https://doi.org/10.1016/j.eist.2019.05.004

Scottish Government. (2022) Hydrogen Action Plan. Available from: https://www.gov.scot/binaries/content/documents/govscot/publications/strategy-plan/2022/12/hydrogen-action-plan/documents/hydrogen-action-plan/hydrogen-action-plan/govscot%3Adocument/hydrogen-action-plan.pdf

Seidman, I. (2013) *Interviewing as qualitative research: A guide for researchers in education and the social sciences*, 4th edition. New York, NY: Teachers College Press.

Sørensen, A.S., Storrs, K.D.P. & Drustrup, R. (2021) Exploring the feasibility of carbon capture, utilisation and storage in Denmark. Aalborg University. Available from: https://projekter.aau.dk/projekter/files/418753247/2021_CCUS_Master_thesis.pdf

Sovacool, B.K., Bazilian, M.D., Kim, J. & Griffiths, S. (2023) Six bold steps towards net-zero industry. *Energy Research & Social Science*, 99, 103067. Available from: https://doi.org/10.1016/j.erss.2023.103067

Sovacool, B.K., Geels, F.W. & Iskandarova, M. (2022) Industrial clusters for deep decarbonization. *Science*, 378(6620), 601–604. Available from: https://doi.org/10.1126/science.add0402

Sovacool, B.K., Herman, K.S., Iskandarova, M. & Hall, J.K. (2024) "Oh yes! Net-zero": Sociotechnical capabilities and regional innovation systems for British industrial decarbonization. *Environmental Innovation and Societal Transitions*, 51, 100852. Available from: https://doi.org/10.1016/j.eist.2024.100852

Stake, R.E. (1995) *The art of case study research*. Thousand Oaks, CA: Sage.

Taylor, P.G. & Rattle, I. (2023) Workshop on industrial cluster decarbonisation: sharing international experience note of key findings. Available from: https://idric.org/wp-content/uploads/Industrial-Cluster-Decarbonisation_Sharing-International-Experience_note-of-key-findings.pdf

Torre, A. (2006) Clusters et systèmes locaux d'innovation. Un retour critique sur les hypothèses naturalistes de la transmission des connaissances à l'aide des catégories de l'économie de la proximité. *Régions et développement*, 24(24), 15–44.

UNFCCC. (2015) Paris Agreement (in English). Available from: https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf

Wang, R. (2024) Status and perspectives on CCUS clusters and hubs. *Unconventional Resources*, 4, 100065. Available from: https://doi.org/10.1016/j.uncres.2023.100065

Webb, J., Johns, M., Roscoe, E., Giovannini, A., Qureshi, A. & Baldini, R. (2022) State of the North 2021/22 Powering Northern Excellence. Available from: https://www.ippr.org/research/publications/state-of-the-north-2021-22-powering-northern-excellence

World Economic Forum. (2022, August 2022) Transitioning Industrial Clusters towards Net Zero Initiative Introduction. Available from: https://netl.doe.gov/sites/default/files/netl-file/22CM_GS_Stark.pdf

World Economic Forum. (2023a) *Enabling Measures Roadmap for Low-Carbon Hydrogen Middle East and North Africa*. Available from: https://www3.weforum.org/docs/WEF_Enabling_Measures_Roadmap_for_Low_carbon_Hydrogen_in_the_Middle_East_and_North_Africa_2023.pdf

World Economic Forum. (2023b) *Transitioning Industrial Clusters towards Net Zero*. Available from: https://www3.weforum.org/docs/WEF_Tranisitioning_Industrial_Clusters_2023.pdf

World Economic Forum. (2024) Transitioning Industrial Clusters Annual Report. Available from: https://initiatives.weforum.org/transitioning-industrial-clusters/home

World Economic Forum. (2025) *Unleashing the Full Potential of Industrial Clusters: Infrastructure Solutions for Clean Energies*. Available from: https://www.weforum.org/publications/unleashing-the-full-potential-of-industrial-clusters-infrastructure-solutions-for-clean-energies/

World Energy Council, EPRI & PwC. (2021) *Working Paper National Hydrogen Strategies*. Available from: https://www.worldenergy.org/assets/downloads/Working_Paper_-_National_Hydrogen_Strategies_-_September_2021.pdf

Zero Carbon Humber. (2023, 31 March) Zero Carbon Humber respond to yesterday's Cluster Sequencing Phase 2 announcement. Available from: https://www.zerocarbonhumber.co.uk/news/zero-carbon-humber-respond-to-yesterdays-cluster-sequencing-phase-2-announcement/

How to cite this article: Rattle, I. & Taylor, P.G. (2025) Clusters in context: Towards a typology of industrial decarbonisation initiatives. *Geo: Geography and Environment*, 12, e70000. Available from: https://doi.org/10.1002/geo2.70000