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SPECIAL FEATURE: ORIGINAL ARTICLE

Accelerating Actions for Leveraging a Climate-Neutral, Sustainable Society

Decarbonisation strategies in industry: going beyond clusters

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Abstract

An effective and just industrial transition is necessary both to mitigate climate change and protect jobs, and as a precursor to enable other sectors to decarbonise. Activity is at an early stage and examples of successful sector-wide interventions to decarbonise industry do not yet exist. Governments of industrialised countries are beginning to develop policy and provide funding to support deployment of carbon capture and low-carbon hydrogen infrastructures into high-emitting industrial clusters, but options for sites outside of clusters, denoted here as 'dispersed sites', are also required. This paper takes a mixed methods approach to provide the first analysis of the issues facing dispersed industrial sites on their route to decarbonisation and to suggest solutions to the challenges they face. Using the UK as a case study, it first characterises dispersed sites in terms of location, emissions released, sectors involved, and size of companies affected. It then shows how these features mean that simply expanding the geographical scope of the present UK decarbonisation strategy, which focuses on the provision of carbon capture and low-carbon hydrogen, would face a number of challenges and so will need to be broadened to include a wider range of abatement options and other considerations to meet the needs of dispersed sites. While the solutions for each place will be different, these are likely to include some combination of the expansion of shared infrastructure, the development of local zero-carbon hubs, research into a wider range of novel abatement technologies and facilitating local participation in energy planning. The paper concludes with a discussion of remaining knowledge gaps before outlining how its findings might apply to industrial decarbonisation strategies in other countries.

Keywords Net zero · Transition · Industry · Cluster · Dispersed sites · Decarbonisation

Introduction

Energy-intensive industry accounted for 38% of total global final energy use in 2021 and directly emitted a quarter of global CO_2 emissions (IEA 2022). The sector has been historically characterised as 'hard to abate' facing numerous technical and commercial barriers to decarbonisation. These include long investment cycles, high energy use, low profit margins and trade exposure (Bataille 2020). Nonetheless, industrial materials provide the building blocks upon which the net-zero transition will be based (IEA 2020) and the sector employs 23% of workers globally (World Bank 2021). An effective and just industrial transition is, therefore, necessary both to mitigate climate change and protect jobs, and as a precursor to enable other sectors to decarbonise.

Typically, energy-intensive sectors, such as metals and minerals; chemicals; paper and pulp; glass; and oil refineries, co-locate close to geographically anchored resources such as transport and hydrocarbon infrastructures (John St. and Pouder 2006). This geographical concentration allows for the development of a skilled local workforce and specialised supply chains, and provides the potential for knowledge networks to develop amongst clustered firms (Porter 2011). As the transition from fossil fuels accelerates, steered by national decarbonisation pledges, and given impetus by Russia's invasion of Ukraine, activity on industrial decarbonisation has begun to move from debates about technical

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feasibility towards the deployment of low-carbon infrastructure into energy-intensive clusters. To this end, several major economies including the United Kingdom, Canada and the Netherlands are providing funding to support the deployment of hydrogen and carbon capture usage and storage (CCUS) demonstration projects into high-emitting industrial clusters and engaging in policy and business model experimentation to reduce carbon emissions (IEA 2021). Underpinning this activity is the hope that the economies of scale, opportunities for joint efficiencies and potential for shared learning provided by clusters will kick-start the industrial transition, anchoring early demand and fostering an initial market for low-carbon technologies (The Government of Canada 2020; Government of the Netherlands 2019; HM Government 2021a).

The UK was the first major economy to publish an industrial decarbonisation strategy in 2021 (HM Government 2021a). The headline ambition is to establish four low-carbon industrial clusters by 2030 and at least one fully net-zero cluster by 2040. Achieving this will require deploying CCUS into these clusters, capturing 6 $MtCO_2$ of industrial emissions per year by 2030 (HM Government 2021b). In support of this ambition, the Government has launched an Industrial Decarbonisation Challenge (IDC), which is providing £210 million to support the UK's six largest industrial clusters in their mission to decarbonise at scale. Phase 1 of the cluster sequencing process is complete with two coastal clusters in the north-east and north-west of England announced as 'Track-1' clusters, to be prioritised for CCUS and hydrogen deployment in the mid-2020s. As of late 2022, a shortlist of the CO_2 emitter projects to connect to these clusters has been released as Phase 2 of this process (BEIS 2022a).

However, as we will show in this paper, industrial clusters provide only half of the picture when it comes to industrial decarbonisation. This is literally true in the UK where almost half of industrial emissions come from dispersed sites, broadly defined in policy documents as "industrial sites located outside of industrial clusters" (HM Government 2021a, p. 158). Such sites are less likely to be geographically concentrated and many of them are less emissions intensive than those in the clusters, making the economics of building future hydrogen and carbon capture networks more challenging. Nonetheless, they too will require rapid decarbonisation to meet the UK's Net-Zero Strategy goals of reducing industrial emissions by 43–53% by 2030, and 63–76% by 2035, compared to 2019 levels, and the long-term ambition of a 87–96% reduction in 2050 compared to 2019 (HM Government 2021b). To date, however, the strategy for emissions reductions in dispersed sites has been largely limited to a focus on resource efficiency and energy efficiency (REEE) with an undertaking to "explore opportunities for faster decarbonisation of dispersed sites in the 2020s" (HM Government 2021b, p. 120).

As global activity on industrial decarbonisation gathers pace, now is an appropriate moment to ask what approaches might work to decarbonise dispersed sites. Decarbonising industry is not solely a technical challenge. The industrial transition is a sociotechnical process made up of multiple co-evolving elements, which incorporates markets, value chains, infrastructures, policies and social practices (Köhler et al. 2019). To date, however, the literature has tended to focus either on high level, cross-economy decarbonisation scenarios or roadmaps for a single sector or technology (Schneider et al. 2020) that in most cases concentrate on techno-economic factors but neglect the social and justice dimensions of transition (Johnson et al. 2021).

To complement and expand upon these studies, we apply a mixed methods approach incorporating quantitative data analysis and qualitative stakeholder analysis to explore both technical and social factors. Using the UK as an exploratory case study (Yin 2014), we address the following research objectives. First, to characterise dispersed industry in terms of the sectors and organisations involved and explore the implications for policy action. Second, to evaluate whether there is sufficient data available to enable decision-makers to set a strategy for emissions reductions in dispersed sites. Third, to examine the options available to dispersed sites to decarbonise across the different sectors. Our fourth objective is to synthesise these findings into a discussion of the implications for the UK's industrial decarbonisation ambitions. Finally, we identify what these lessons might mean for industrial decarbonisation strategies globally. Our findings suggest that parallel industrial decarbonisation strategies will be needed for clusters and dispersed sites if we are to avoid market distortions, carbon leakage and the risk of an uneven transition that leaves some places unable to decarbonise.

The remainder of the paper is structured as follows. First, we introduce the literature as it relates to industrial decarbonisation and note the present lack of studies that cover dispersed sites. Then, in the second section, we introduce our materials and methods. In "Results", we address objectives one to three, establishing the barriers and opportunities for the decarbonisation of dispersed industrial sites. In "Discussion", we address our fourth and fifth research objectives to discuss the potential risks that the UK approach presents to its ambitions to decarbonise industry and the lessons for industrial decarbonisation strategies internationally. Finally, in "Conclusions", we conclude with limitations and suggestions for further research.

Decarbonising industry from 'hard to abate' to thinking beyond clusters

The energy transition is a geographical process, requiring the reconfiguration of current patterns of economic and social activity (Bridge et al. 2013). To date, however, there has been little focus on how these dynamics might affect industry. This is likely because the imperative to achieve deep decarbonisation of industry is a relatively recent development, driven by the 2015 Paris Agreement objective to reach net-zero emissions by mid-century (Bataille et al. 2021). Prior to the Paris Agreement, industry was subject to less stringent requirements in recognition of the technical challenges to abatement that the sector faced. Since the Paris Agreement, inaction by industry is no longer an option. One consequence of this historical disparity is that understanding of industrial decarbonisation has lagged other sectors (Bataille et al. 2018). While the field is beginning to mature, at present, the focus remains on how to decarbonise specific industrial sectors, and the required technical interventions to do so, rather than the challenges and consequences of implementing these interventions into industrial areas.

Hence, since 2015, there has been a substantial body of work detailing overarching decarbonisation pathways for energy-intensive industry (Gerres et al. 2019; Nurdiawati and Urban 2021; Bataille 2020) and for specific energy-intensive sectors such as steel (Richardson-Barlow et al. 2022; Skoczkowski et al. 2020; Venkataraman et al. 2022); cement (Abdelshafy et al. 2022; Hills et al. 2016); chemicals (Griffin et al. 2018b); paper and pulp (Griffin et al. 2018a; Rahnama Mobarakeh et al. 2021); glass (Del Rio et al. 2022b; Griffin et al. 2021); lime (Simoni et al. 2022); food and drink (Atuonwu and Tassou 2021; Sovacool et al. 2021); ceramics (Ibn-Mohammed et al. 2019; Del Rio et al. 2022a); and refining (Nurdiawati and Urban 2022). In addition, there is a growing body of work on the potential for single decarbonisation interventions to abate emissions across a range of industrial sectors, and the associated opportunities and challenges of this approach. These studies consider the 'big ticket' interventions of CCUS (see for example: Alcalde et al. 2019; Massol et al. 2018; Meckel et al. 2021; Pilorgé et al. 2020; Waxman et al. 2021) and hydrogen (see for example: Affery et al. 2021; Edwards et al. 2021; Griffiths et al. 2021; Kakoulaki et al. 2021; Kazi et al. 2021), but also, the impact of REEE approaches. This work incorporates both modelling studies, which describe methodologies for quantifying the environmental benefits of various sustainability interventions, such as resource integration, circular economy and industrial symbiosis initiatives (see for example: Ahmed et al. 2021; Noori et al. 2021; Steubing et al. 2020) and also, the indicator frameworks by which the benefits of these interventions could be measured (Hu et al. 2005; Turgel et al. 2020).

There is, however, comparatively little research on deep-decarbonisation scenarios for specific industrial regions (Samadi et al. 2018) and those studies which have sought to do so (see for example: Martin 2020; Roelfes et al. 2018; Samadi et al. 2018; Schneider and Lechtenböhmer 2018; Schneider et al. 2020; Steubing et al. 2020) generally focus upon the industrial belt of North-West Europe which, while significant in its environmental impact, is not necessarily representative of how industry is distributed globally. It is apparent from existing studies that regional initiatives that take into account the conditions, infrastructures and linkages specific to particular areas will play a key role in enabling transformative industrial change (Martin 2020; Roelfes et al. 2018), but the circumstances that will enable or prevent this change remain under-researched. As industrial decarbonisation moves from planning into implementation, an emerging body of work has begun to critically engage with the real-world implications of this societal change (see for example: Devine-Wright 2022; Gough and Mander 2022; Upham et al. 2022). To date, however, the focus of these studies has been on the decarbonisation of industrial clusters. In this paper, we begin to think beyond clusters to address the challenges and opportunities of decarbonising dispersed sites.

To do so, it is helpful to first consider how we might categorise the different types of industrial, but not densely clustered, regions where dispersed industry is located. While typologies of industrial districts (Markusen 1999) and clusters (Boja 2011) are well established, and typologies of regions to inform the development of renewable energy strategies have been proposed (Lutz et al. 2017), a typology of industrial regions in terms of their decarbonisation potential, has yet to be defined. As Roelfes et al. (2018) note in their analysis of the top twenty greenhouse gas-emitting regions in Europe, there are significant differences between these regions, in terms of their economic structure, proximity to urban settlements, proportion of jobs in fossil fuel extraction, education levels, wealth and administrative arrangements. They conclude, "high-carbon industry regions are not all the same with regard to their socio-economic settings, leading to different capacities to drive low-carbon transitions" (Roelfes et al. 2018, p. 22).

In the absence of an established typology, the three-part categorisation developed by Tödtling and Trippl (2005) in their study of regional innovation policy provides a starting point for analysis. The authors characterise three regional types: old industrial regions, fragmented metropolitan regions and peripheral regions in terms of their main innovation capacities and challenges. Old industrial regions are dominated by large firms and mature industries, and are often characterised by technological and political lock-in. Metropolitan regions are highly diverse, but a lack of coordination and weaker networks can lead to fragmentation. Peripheral regions are characterised by institutional thinness and a lack of support organisations meaning innovation remains at a low level. While innovative capacity is only part of the picture when it comes to regional industrial decarbonisation (Roelfes et al. 2018), understanding industrial clusters as examples of old industrial regions, and dispersed sites as more often located in metropolitan and peripheral regions provides a heuristic framework to develop our understanding of the challenges and opportunities of decarbonising dispersed industry.

Materials and methods

A mixed methods approach was used to characterise dispersed industrial sites across the United Kingdom in terms of their sector, emissions, location and potential abatement options, together with information regarding the drivers and barriers for decarbonisation.

The qualitative data draw upon 30 stakeholder interviews conducted between July 2021 and November 2022. Interviews were conducted with experts from across the industrial decarbonisation domain, including representatives from energy-intensive sector organisations and firms, industrial clusters, trade unions, local and regional authorities, and think tanks. We undertook a purposive sampling approach (Robinson 2014) to select our informants based on their knowledge and experience of present UK initiatives to decarbonise industry, with a particular focus on those who had already begun to engage with the issues facing dispersed sites. Interviewees were identified through attending industrial decarbonisation webinars and workshops and through internet searches. We expanded upon this initial group through snowball sampling (Parker et al. 2019) where we asked interviewees to recommend other people in their networks who were working on relevant issues, continuing until data saturation was reached (Gaskell and Bauer 2000). Our findings were triangulated by attendance at public meetings and industry conferences, and discussions with policy actors (Carter et al. 2014). A summary of our participants is provided in Table 1.

Interviews took place online and lasted between 35 and 60 min. They took a semi-structured format in which interviewees were asked about the background to industrial decarbonisation in their sector, area or research field; the details of any decarbonisation initiatives they were working on and their experience of the process to date; and their opinions of how effective the present policy was in enabling industrial decarbonisation and how the field might develop. Interviews were audio recorded, transcribed and then thematically analysed using Nvivo 12 to identify the issues facing dispersed sites and the risks and opportunities presented by current policy. This process took a 'zigzagging' approach (Emmel 2013) to move between theory and data as findings were first identified and then refined.

The quantitative data for dispersed industrial sites were initially based on the industrial sector classification, site location information and emissions estimates contained in the Net-Zero Industry Pathways (N-ZIP) model (Element Energy 2020), which draws on the UK's National Atmospheric Emissions Inventory (NAEI 2022). The N-ZIP model has been used by the UK government to explore possible decarbonisation pathways for UK industry (HM Government 2021a), with a detailed analysis of the sensitivity of the model to changes in key assumptions undertaken by the UK Energy Research Centre (Gailani et al. 2021). The location of these dispersed industrial sites was then mapped using MATLAB.

The range of potential abatement options suitable for each industrial sector was identified using the N-ZIP data on energy use and emissions for each process as a starting point. A literature review was then conducted to identify alternative mitigation options that could be used to decarbonise the particular process. The options are categorised as shown in Fig. 1. The key options considered included feedstock substitution, fuel/energy switching (except hydrogen) and novel process changes. Hydrogen and CCUS options were then considered for those sectors for which the review found limited alternative decarbonisation options. This was to account for the fact that the deployment of hydrogen and CCUS infrastructure to enable the decarbonisation of dispersed sites is likely to face significant technical and economic barriers. The technical maturity of the abatement options was assessed using Technology Readiness Levels (TRLs). In some cases, where the information source for the technology did not explicitly provide the TRL, the UK government guidance on TRLs was used to categorise the technologies based on the description provided (UK Government 2014).

Results

Characteristics of dispersed industry in the UK

In this section, we characterise UK dispersed industrial sites in terms of their location, level of emissions released, the diversity of the sectors involved and the size of companies affected. We argue that these characteristics mean that in many parts of the UK, dispersed sites may require a broader mitigation strategy to the present government approach to the industrial clusters, which is focussed on large-scale hydrogen and CCUS infrastructure interventions.

Table 1 Interviewees by domain, pseudonym and area of operation

Domain	Pseudonym	Area of operation	Number of interviewees
Representative energy-intensive industry	UK steel	National	10
	Director of cement		
	Representative, paper sector		
	Representative, ceramics sector		
	Representative, glass sector		
	Representative of the chemicals sector		
	Food sector representative		
	Representative, minerals sector		
	Representative of metal processing industry		
	Representative, community trade union		
Think tanks and research organisations	Analyst, International Energy Agency	International	9
	Analyst, energy organisation		
	Cities network representative		
	Representative of environment think tank	National	
	Member of think tank		
	Representative, local authority network		
	Senior policy officer, non-governmental organisation		
	Member of energy system catapult's markets policy and regulation team		
	General manager, research and development organisation	North west England	
Local and regional authorities	Growth manager, Bradford	North east England	6
	Representative, energy hub		
	Local authority officer within West Yorkshire Combined Authority		
	Innovation lead, Liverpool City Region	North west England	
	Representative energy capital	West Midlands	
	Black country consortium		
Regional decarbonisation initiatives	Senior manager, Bradford	North east England	5
	Site manager, Bradford		
	Representative from a North West business organisation	North west England	
	Expert Advisor, Cheshire and Warrington Local Energy Partnership		
	Repowering the Black Country	West Midlands	

Dispersed sites are defined as those located more than 25 km (radial distance) from a major UK industrial cluster point. The total emissions from dispersed UK industrial sites are approximately 37.5 $MtCO_2e$ and can be disaggregated by sector and site type (point[1] and non-point source[2]) as depicted in Table 2. The data suggest two issues that may hamper the decarbonisation efforts of the UK's dispersed industry.

First, nearly half of the emissions come from industries that are energy intensive (cement, refining, paper, glass, lime, waste processing and non-ferrous metals). This makes their decarbonisation challenging due to the use of high-temperature heat processes for which there are currently limited abatement options. Those options that are available typically rely on using hydrogen or carbon capture, both of which are likely to require significant investment in new or upgraded infrastructure to be feasible. Furthermore, in the present, early stages of industrial decarbonisation, the economics of carbon capture and hydrogen projects are premised upon the presence of one or more 'anchor projects' and

[1] Point source sites are sources of emissions, at known locations, and their emissions data are available from regulatory regimes and national or local authorities.

[2] Non-point source sites are usually small emitters that do not fall under the UK emissions trading scheme and for which only the general location is inferred. They are represented in the map as a single site (point) in each UK region.

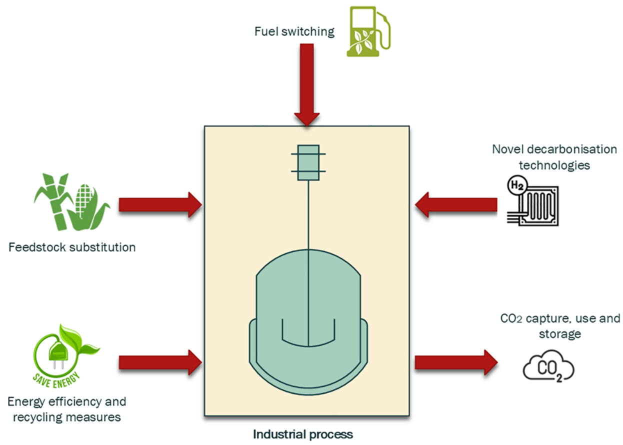


Fig. 1 Categories of abatement options for industrial processes

'anchor loads' (Australian Hydrogen Council 2021; Global CCS Institute 2016)—highly emitting industrial installations that will provide a sufficient volume of CO_2 and/or demand for hydrogen to kick-start development. It is for this reason that clusters have become the crucible for industrial decarbonisation. Dispersed industrial sites, by contrast, are often not geographically concentrated, meaning the economics of building these new infrastructures are likely to be attractive for only the highest emitting sectors and sites, such as cement. For the remainder, as the Industrial Decarbonisation Strategy (HM Government 2021a) acknowledges, geographical dispersal will make access to hydrogen and CO_2 networks harder and less cost-effective. In the longer term, if technology costs for carbon capture drop and wider system changes, such as repurposing the gas grid for hydrogen, go ahead, then access to these technologies may improve. In the short term, however, many dispersed sites will have access to fewer decarbonisation options than their clustered counterparts, leading to the potential for market distortions and regional inequalities, particularly if product standards begin to mandate the use of low-carbon products.

Second, the other half of the emissions come from non-energy-intensive industries characterised by many small emitters, with a wide diversity of production processes, for which electrification would in principle be an easier abatement route than either hydrogen or carbon capture. However, this will require the necessary electrical technologies to be both available and commercially viable and may also require the electricity network to be upgraded to support the extra demand.

The broad range of dispersed sectors makes it challenging for industry representatives to give a clear message when engaging with policymakers. These issues have come to the fore in metropolitan industrial areas like Bradford, a city in West Yorkshire and one of the earliest industrial towns in the UK. The area retains a strong industrial base, and the sector contributes significantly to the local economy, providing 12% of local employment compared to 8% nationally (City of Bradford MDC 2020). It is also an area of significant deprivation ranking as the fifth most income-deprived local authority in England (City of Bradford MDC 2019). The city has identified the need to engage proactively with the green industrial agenda in order to support economic regeneration and avoid businesses relocating elsewhere (The Bradford Economic Partnership 2021). In common with many industrialised areas in the UK, there is no single industrial cluster: industry is dispersed throughout the city. There are few highly energy-intensive sites, and no one sector predominates: rather there is a mosaic of industrial sites including vehicle manufacturing, aerospace, chemicals, textiles and food and drink. As a site manager in the city noted, this diversity presents challenges when engaging with

Table 2 Total emissions of dispersed UK industrial sectors, adopted from the Net-Zero Industry Pathway model (Element Energy 2020)

Industry sector	Number of point source sites	Point source emissions ($MtCO_2e$)	Non-point source emissions ($MtCO_2e$)	Total emissions ($MtCO_2e$)
Food and drink	144	2.96	2.83	5.79
Cement	7	4.00	0.19	4.19
Other chemicals	67	1.85	2.46	4.31
Waste processing	58	3.78	0.14	3.92
Refining	2	2.24	–	2.24
Vehicle manufacturing	23	0.43	1.59	2.02
Other minerals	128	1.56	0.22	1.78
Paper	32	0.90	0.59	1.49
Glass	13	0.54	0.5	1.04
Non-ferrous metals	10	0.27	0.60	0.87
Lime	2	0.55	0.07	0.63
Other industry	46	0.56	8.68	9.24
Total	532	19.82	17.72	37.51

government officials more used to thinking in terms of coastal megaclusters dominated by one or two highly emitting anchor sites.

> We have gone to BEIS [Department of Business Energy and Industrial Strategy] and said, "Look, guys. Here's our proposal for how do we try to match what you're doing in terms of offering support with diverse industrial bases like Bradford and tapping into the wider manufacturing base here, and here's our proposal on how to do it. So will you support us here?" Because there isn't an obvious funding stream for us to do that.

Interviewees from the Black Country, another metropolitan area with a long history of industrial activity, shared similar reflections about the emerging inequalities caused by a government focus on coastal clusters. The Black Country is located in the West Midlands, an inland area of the UK that is home to over 3000 energy-intense manufacturing businesses. As a result of its industrial heritage, metal processing remains the biggest sector of the local economy in terms of employment (Black Country LEP 2020) but, as for Bradford, activity is dispersed across the region rather than clustered in any one place. Initiatives are underway to protect and build upon local industrial strengths but as a representative of the regional Energy Capital Partnership commented, the geographical location of the region places it at a disadvantage that would not be easy to overcome: "national energy policy has very little benefit to the urban centres like the West Midlands. [...] Your opportunities are all coastal."

Another issue with the potential to hamper the decarbonisation efforts of the UK's dispersed industry is the split between point source sites that represent nearly 53% of the total emissions, and non-point source sites that represent the other 47%. Non-point source sites can be particularly challenging to decarbonise since they are mostly owned by small and medium enterprises (Make UK 2022) defined in the UK as any organisation that has fewer than 250 employees and a turnover of less than €50 million, or a balance sheet total less than €43 million (Foreign Commonwealth and Development Office 2022). This is a particular issue for the food and drink sector where representatives estimated that over 95% of businesses were small and medium enterprises SMEs, individually small operations which in aggregate contribute to making the sector one of the most highly emitting (Table 2); but, it was also noted as an issue for the ceramics, metal processing and chemicals industries.

Here, interviewees noted the challenges that SMEs face, first in terms of not having the capital to invest in low-carbon technologies but also more broadly in facing a knowledge gap both about the decarbonisation options available to them (see also "Understanding decarbonisation pathways for dispersed sites") and how they might obtain supporting funding. This complexity was challenging for larger organisations with dedicated staff, they argued, leaving SMEs with little chance of being able to engage. As a food and drink sector representative noted, "even the very big companies, they'll have an energy manager but even they won't have the full suite of technologies in their minds. Let alone smaller companies, of which food and drink is full."

A lack of resources, lack of expertise and the high capital costs are well-documented barriers to SMEs implementing sustainability measures (Álvarez Jaramillo et al. 2019); however, in the case of industrial decarbonisation, the issues have been exacerbated by a lack of obvious intermediaries to bridge these gaps. While the designated track-1 and track-2 clusters have cluster organisations to represent their interests to government, no similar organisations exist for dispersed sites in either metropolitan or peripheral areas. During interviews, participants suggested three ways to address this issue, but none of the options provides a complete solution. Sector organisations could play a role in collating information and highlighting it to their members, but their coverage was not total, and SMEs were less likely than larger organisations to be members. Nationally funded regional initiatives such as England's Net-Zero Hubs provided an alternative channel. There are five hubs in total—North West, North East and Yorkshire, Midlands, South West, and Greater South East—that between them cover all of England. Funded through the Local Net-Zero Programme, they were set up by BEIS to promote best practice and support local authorities to develop net-zero projects that can attract commercial investment (HM Government 2021b). However, the number of SMEs involved presented a significant logistical burden, particularly given the hubs' limited funding.

> That creates a bit of a challenge for us [...] if there's 50,000 small businesses that we want to try and decarbonise, compared to going out to the 18 large industry sites, it creates just an issue of marketing and getting the information and comms out there.
> Energy Hub Representative

Finally, in metropolitan areas, Combined Authorities, regional bodies made up of two or more local government areas with a mandate to address economic regeneration, provided a third option to engage with SME manufacturing firms. In theory, Combined Authorities, with their enhanced convening power and regional vision, offer a ready-made forum to engage with regionally significant issues such as decarbonising dispersed industrial sites. But while in some areas, like the West Midlands, the Combined Authority had set up an Energy Capital Partnership with industry within its remit, in other areas the Combined Authority's focus on industry was less pronounced. As the Energy Hub Representative continued: "On the Combined Authority side,

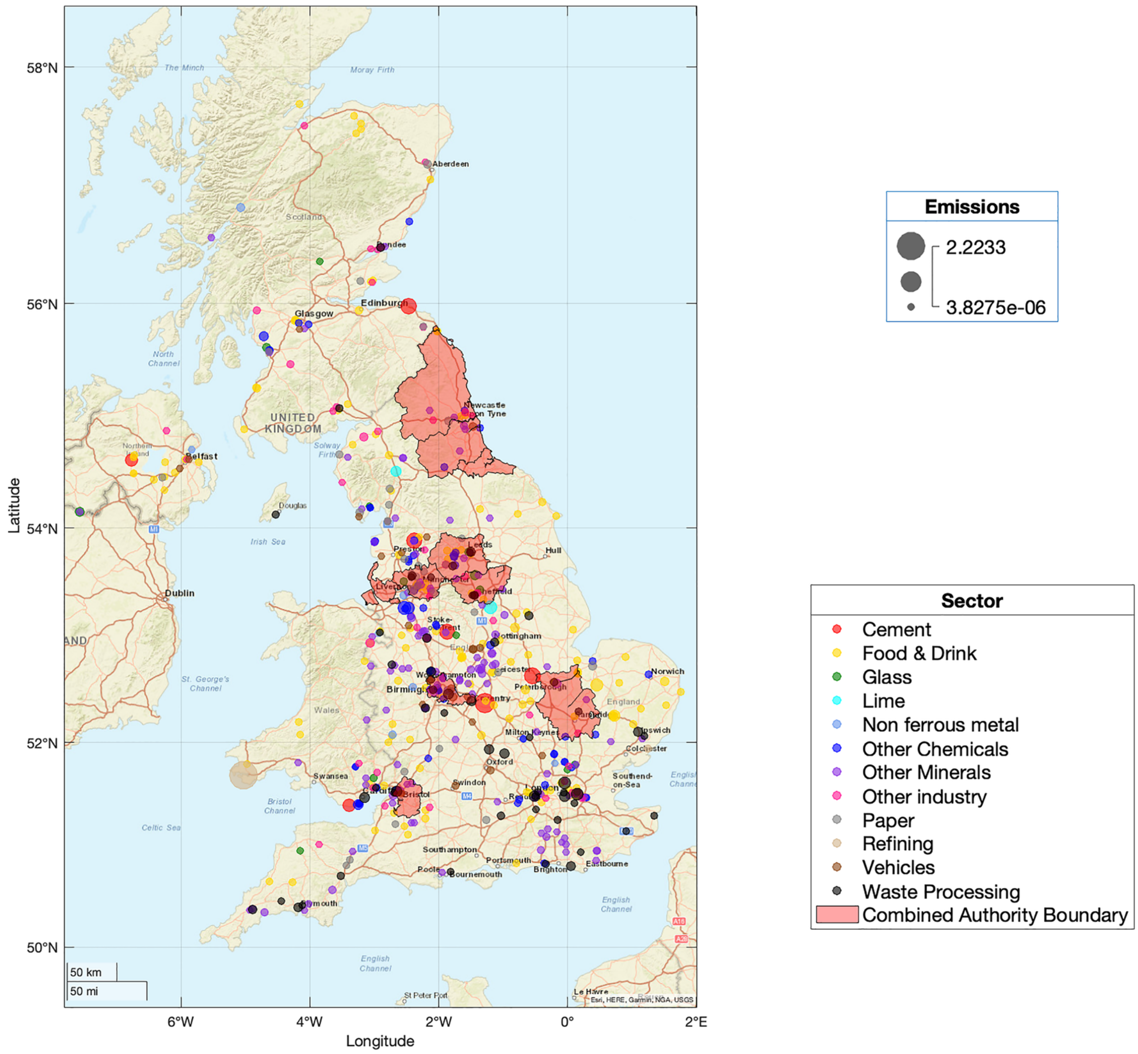


Fig. 2 Location of the UK dispersed sites by sector and emissions in $MtCO_2e$ mapped against Combined Authority areas, based on the data from (Element Energy 2020)

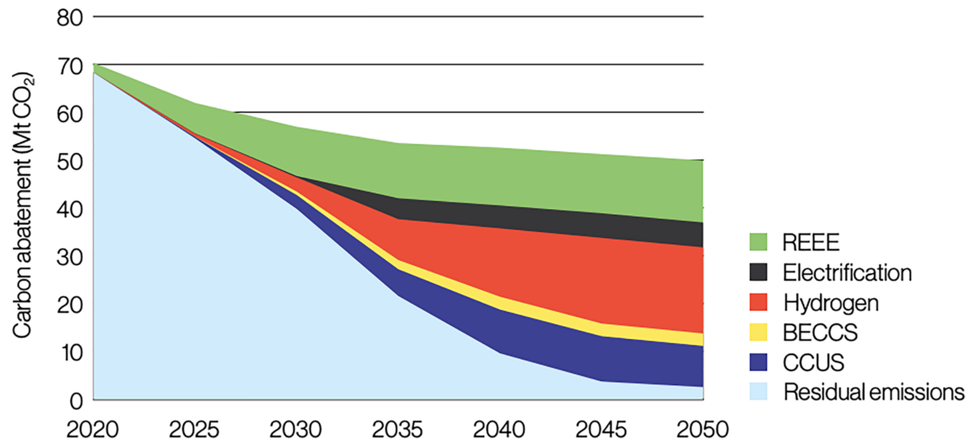
traditionally, and I'd say very much still, we are a transport organisation […] And there just aren't the links, as you mentioned, or the resources to focus on industry." Similar points about a lack of in-house expertise and connections with industry on the part of Combined Authorities were made by some sector representatives, who felt the consequent reliance on outsourcing was not always helpful in assisting them to decarbonise:

> We've had dealings with quite a few of the Combined Authorities, and the frustration we have is that they come out with these plans, and they usually pay a consultant. […] I'm not really sure the value of all these Combined Authorities, going away, paying a consultant, without consulting with industries.
> Representative Glass sector

Furthermore, Combined Authorities cover only ten metropolitan areas in England, which in total produce approximately 20% of dispersed site emissions (Fig. 2). Therefore, even if they were to lead on this issue, it would leave many places without an obvious coordinating body (Fig. 2).

When it comes to decarbonisation, therefore, industries in dispersed sites find themselves disadvantaged in four ways when compared to their cluster counterparts. First, by a lack of suitable funding streams; second, by limited access to decarbonisation infrastructures and technologies; third, by a lack of internal expertise, due in part to the high proportion of SMEs affected, and finally, due to a lack of intermediary organisations to bridge the gap between regional policy and local implementation. This risks growing market distortions as some sectors and places are able to decarbonise and some are not. Since all industry is required to decarbonise, irrespective of site and industry type, to achieve deep decarbonisation of the UK industry by 2050, in the following sections

Fig. 3 UK government's decarbonisation pathway for UK industry, national networks scenario (HM Government 2021a). Note: contains public sector information licensed under the Open Government Licence v3.0



we map out the potential pathways that would enable this to occur.

Understanding decarbonisation pathways for dispersed sites

The UK government's modelling of a net-zero pathway for UK industry, as depicted in Fig. 3, shows that industrial sites—including dispersed sites—are expected to rely mainly on hydrogen and CCUS to decarbonise energy use, along with REEE to reduce the demand for such energy inputs. This result is predicated on the existence of extensive infrastructure networks for CO_2 and hydrogen transport and storage across the country to make these abatement options widely available to dispersed industry. However, as discussed in "Characteristics of dispersed industry in the UK", such extensive coverage of hydrogen and CCUS infrastructure faces a number of challenges, and significant national coverage seems unlikely in the medium term. Therefore, different mitigation options—at least in the short to medium term—such as electrification or the use of biomass may have a greater role in decarbonising dispersed sites than currently envisaged by the Government's scenario (Gailani et al. 2021; Frontier economics 2021).

One reason for the UK government scenario relying substantially on the use of hydrogen and CCUS technologies to reach net zero may be an incomplete representation of alternative decarbonisation options in the N-ZIP model used to create the pathway. Whereas hydrogen and CCUS are, in principle, applicable widely across many industrial sectors, the alternative abatement options are often sector or process specific and some are not yet commercially available, at least in part as a result of not having been given the same attention or support by government. While the N-ZIP model accounts for the infrastructure costs needed for dispersed sites, it does not treat them separately to clusters in terms of the decarbonisation options that are available.

For instance, dispersed cement sites may rely on novel mitigation options for dispersed sites (beyond CCUS) such as reducing the clinker to cement ratio using different cementitious raw materials (Gartner and Sui 2018), which reduces the process emissions that largely come from clinker production. Similarly, processes that can use decarbonised electricity, such as high-temperature industrial heat pumps, electric steam crackers and microwave-assisted drying, may have important roles in the future for decarbonising food and drink, chemicals and paper sites, respectively, and these technologies are currently missing from the N-ZIP model (Rademaker and Marsidi 2019; Rattanadecho and Makul 2016; Doughty 2022).

Lack of data on industrial decarbonisation options was a prominent theme that emerged from the interviews. Interviewees believed this gap had been caused by two factors, neither of which was specific to the UK. First, a focus within national governments on modelling the options for the heaviest emitting sectors and places. This was driven by the urgency of action on industrial decarbonisation, and the need to prioritise government funding streams given the high costs of the required infrastructure. This focus, however, had the potential to generate unintended consequences. As a member of an intergovernmental energy organisation reflected, "it's amazing to me how much of the fiscal conversation ends up being led by what is modelled, because that really shouldn't be the case. We should be trying to model everything equally." In practice, however, modelling tended to focus on the heaviest emitting sectors of steel, cement and chemicals, all of which require hydrogen and CCUS, to the detriment of many of the other sectors that make up industry within dispersed sites.

The second factor which exacerbated this issue was a lack of available data on industry at the regional and local levels which, were it available, could inform conversations with government. Historically, the management of industrial strategy has not fallen within the purview of local authorities, meaning there is little institutional capacity to engage with the issue and a lack of knowledge about the location and processes of less highly emitting installations. A member of a global cities network described industrial decarbonisation as something of a "blind spot" within their work, while a UK representative of an environmental think tank member described the situation as follows, "More locally, well, I was talking to the CCC [climate change committee]. I think there's just a lack of very detailed knowledge on where industry is, particularly when you're looking broadly, including the long tail."

While our research identified several local authorities in England that had recognised this issue and were proactively undertaking initiatives to map their local industrial sectors, it was apparent that the identified initiatives were in metropolitan areas that had the necessary vision and institutional capacity to engage. Not all local authorities were equally able to engage with these challenges and interviewees were not optimistic that this situation would rectify itself, particularly given worsening economic conditions. A second think tank member noted, "We're very far away in this country, I think now, from having local authorities which do more ambitious things, as opposed to local authorities which basically are trying to deliver their statutory services without going under."

Enablers for dispersed industry

Having characterised the nature of dispersed industrial sites in the UK and the issues they are facing, in this section, we set out some possible ways to accelerate their decarbonisation. Four areas are highlighted: the potential for shared infrastructure; the implementation of low-carbon hubs; the development and deployment of alternative abatement options; and improved governance arrangements. In practice, these are not separate interventions, rather industrial areas are likely to draw from several of them in order to decarbonise their sectors.

Shared infrastructure

To investigate the possibility of dispersed industrial sites benefiting from shared decarbonisation infrastructure such as CO_2 and hydrogen transport and storage, information on their location and sector was mapped using a Geographical Information System (Fig. 4). The sites are widely distributed across the country making it difficult to create regionalised infrastructure projects, particularly since sites with similar infrastructure needs are not necessarily close to each other (see, for instance, cement and lime sites). Some dispersed sites are 'truly dispersed' that is, located far away from major cluster points (dotted circles in Fig. 4) and have very few, if any, other sites nearby. However, creating 'mini' clusters in middle, south, north-west of England, east of Northern Ireland and South Wales may provide opportunities for shared infrastructure that would provide access to suitable abatement options, while reducing the costs of decarbonisation.

Low-carbon hubs

Given the diversity of dispersed industrial sites, both in terms of sector and organisation type ("Characteristics of dispersed industry in the UK"), and the range of mitigation options appropriate to each sector, the optimal decarbonisation approach for each place will vary. This means a place-based approach to industrial decarbonisation is needed, focussed on infrastructures and interventions bespoke to the local industrial base. The task is not straightforward, due in part to the lack of data on dispersed sites ("Understanding decarbonisation pathways for dispersed sites"); however, two government-funded initiatives provide a possible template for other areas to follow, although work is at an early stage of development.

The first of these is the clean growth hub (CGH) concept which forms one strand of the South Wales Industrial Cluster's decarbonisation strategy (SWIC 2022). The aim of the CGH is to integrate future business operations with an existing industrial anchor site, to allow for the sharing of waste heat, material symbiosis and the development of low-carbon energy centres, both to enable fuel switching and to provide a single emissions point for future deployment of CCUS (Energy Forum 2021). In addition, there is the potential to integrate heat sharing with domestic heat networks. Present exploratory work is focussing upon the Port of Barry where an existing chemicals' cluster is in place. However, the concept is at an early stage and will require funding, stakeholder engagement and a yet-to-be identified strategic actor to take the project forward (Associated British Ports 2022).

Arguably, the zero-carbon hubs (ZCHs) approach being piloted in the Black Country (UKRI 2021) provides a more radical approach. Here, the aim is to reconfigure the existing local industrial base through supporting local businesses to proactively relocate into a new type of industrial park—the ZCH. Each ZCH will be designed around decarbonising the anchor industrial processes that are specific to the region's core industries: in the Black Country, metal processing. Present work is focussed upon developing four demonstration hubs, each to contain a mix of local businesses selected to maximise opportunities for industrial symbiosis, with plans to be operational by 2030. Each hub will also have its own energy centre, designed to deliver low-carbon heat and electricity, with options for generating hydrogen fuel in the future (Black Country LEP 2020). The work will be aligned with the infrastructure plans of district energy network operators and local transport planners to ensure their future investments align with the changing transport and

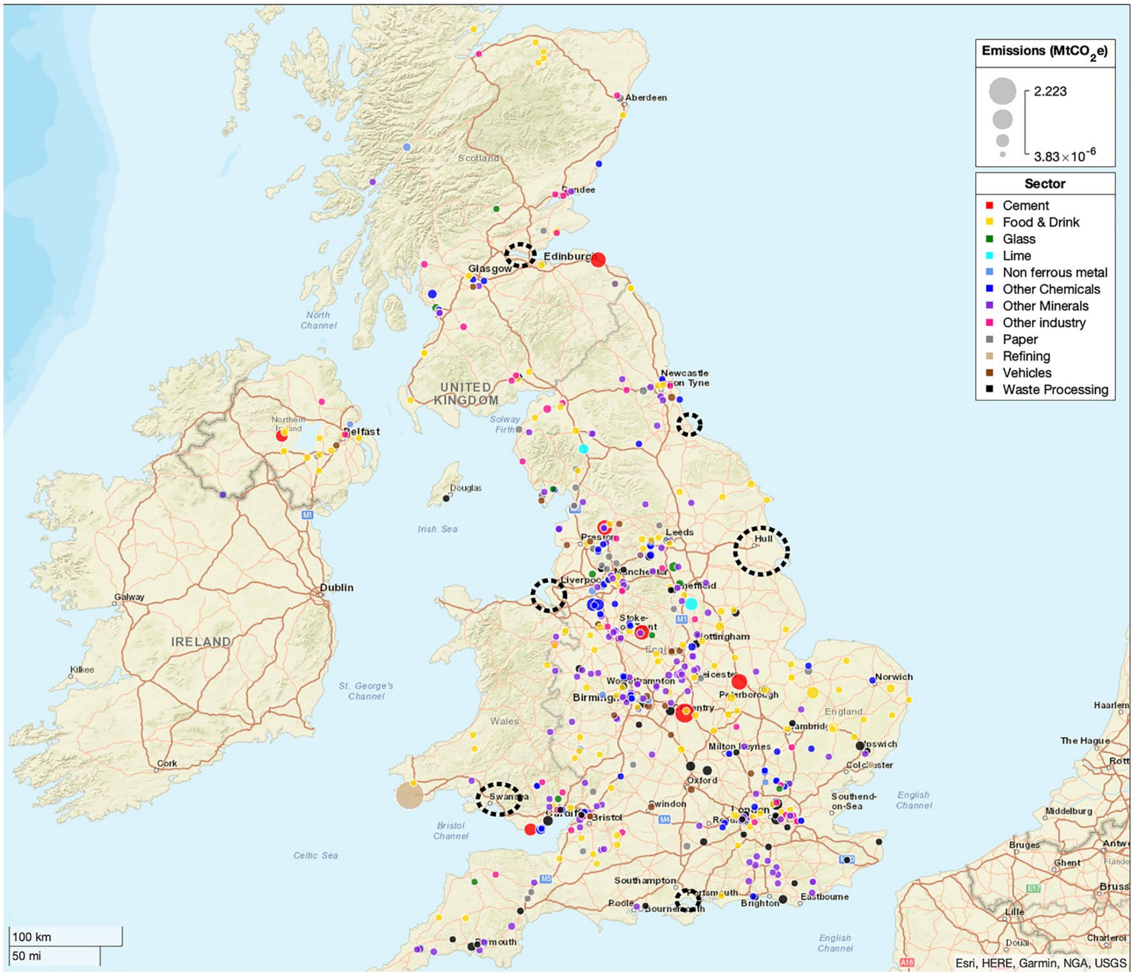


Fig. 4 Location of the UK dispersed sites by sector and emissions scale in $MtCO_2e$, (*Oval shape*) is a UK cluster point, based on the data from Element Energy (2020)

Table 3 Key novel mitigation options for the main UK dispersed industry

UK sector	Mitigation option	TRL	Source
Cement and lime	Electric kilns—cement Cold lime production—lime	5 2	Simoni et al. (2022), Coolbrook (2022)
Food and drink, paper, non-ferrous metals[a] and other industry	Electrification of steam boilers and/or using biomass for combined heat and power (CHP) technology	9	Tagliaferri et al. (2018), Marsidi (2018)
Glass	Energy switching the glass furnace to electricity Fuel switching the glass furnace to biofuel	6–7 8	Papadogeorgos and Schure (2019)
Refining	Furnaces electrification	3	Oliveira and Schure (2020)
Waste processing[b]	CCUS technologies	5–8	AECOM (2022)
Other minerals	Innovative technologies for firing and drying of ceramics such as electric kilns	3–4	Cerame Unie (2021)
Other chemicals[c]	Novel electrical steam crackers	4–5	Geels (2022)

[a]Non-ferrous metals sector within the UK do not include primary aluminium manufacturing

[b]This sector includes mainly energy from waste plants

[c]Other chemicals sector does not include Ammonia productions and bulk chemicals

energy demand which ZCH will entail. If piloting is successful and funding forthcoming, 10–50 ZCHs focussed on different industrial activities could be distributed across the Black Country, to decarbonise the local industrial base.

Developing a wider set of abatement options

In the absence of shared infrastructure options, Table 3 provides an overview of some of the key mitigation options that could be relevant to dispersed sites, but which are often overlooked as they are currently not commercially or widely available. The Technology Readiness Level (TRL) ranges in Table 3 reflect the range of the technologies suitable to decarbonise the sector. For instance, for waste processing, there are several CCUS technologies to decarbonise the sector such as those based on amine scrubbers and molten carbonate fuel cells, with different TRLs (AECOM 2022).

Dispersed sites belonging to the food and drink, paper, non-ferrous metals, other chemicals and other industry sectors may benefit most from decarbonising the electricity and heat currently provided by natural-gas-fired combined heat and power (CHP) and steam boiler technologies. CHP technologies can use biomass or hydrogen fuels, while electric boilers and heat pumps can be used to satisfy the heat demand instead of steam boilers, resulting in significant emission savings (Tagliaferri et al. 2018; Element Energy 2020).

Some novel electrification options are available to decarbonise high-temperature processes such as electric kilns (RotoDynamic Heater technology) for cement-making (Coolbrook 2022), electrical steam crackers for chemicals (Doughty 2022), electric glass furnace for glass making (Del Rio et al. 2022b) and microwave-assisted drying and electric kilns for ceramics (Besier and Marsidi 2020). Those technologies need further research, development and demonstration (RD&D) to bring them to market maturity. However, in contrast to hydrogen and CCUS, the UK has not yet introduced any RD&D funding programmes solely dedicated to developing decarbonisation options based on the use of electricity. Industries can apply for grant funding for feasibility and engineering studies for electrification options (UK Government 2022), but the UK has some of the highest electricity prices for industrial users amongst IEA reported countries (BEIS 2022b) meaning that many of the electrified technologies are not currently competitive routes to decarbonisation. However, there is significant pressure on the UK government from industry to reform electricity pricing, and a change of policy approach combined with a funding mechanism to support the additional operational and capital costs of electrification should incentivise deployment (Climate Change Committee 2022). Nevertheless, electrifying high-temperature industrial processes are still likely to require massive electricity network upgrading that will entail high costs and long planning times (Marquand 2022), introducing the potential for further regional inequalities if different places electrify their industry at different rates.

Alternative governance arrangements

Whatever route it takes, industrial decarbonisation will not occur without institutions and intermediary organisations to provide a regional vision and direction (Truffer and Coenen 2012; Martin 2020). The importance of regional networks in providing the supporting institutional infrastructures needed to promote innovation, facilitate cooperation between firms and public authorities, and manage environmental issues is well established in the broader industrial cluster literature (see for example: Refsgaard et al. 2021; Wang and Cao 2017; Zeng and Bathelt 2011). Conversely, a lack of integration between national and regional policy incentives; a lack of institutional platforms that span historically separate domains, such as municipal and industrial heat; and a lack of skilled individuals have all been identified as barriers to cluster initiatives achieving transformative change (Martin 2020). So far, however, these lessons have not been applied to dispersed sites.

To date, action on dispersed industrial sites in the UK has been driven by metropolitan areas with strong industrial identities but, to decarbonise the sector as a whole, concrete action is needed also in peripheral areas where our research uncovered little evidence of activity to date. This is particularly true when it comes to meeting the increased need for electricity, which will arise not only due to decarbonised industrial processes using electricity, but also from hydrogen production using electrolysis, and to power carbon capture plants. While low-temperature electrification technologies, such as heat pumps, are presented as one early option for fuel switching in dispersed sites (HM Government 2021a), in practice, the timescales for this will depend on the power capacity available on the electricity network. Local electricity network operators will need to accommodate not only the requirements for the industrial sector to electrify in any particular place, but also increased electricity demand from other sectors, such as domestic heating and transport, with overall demand forecast to double by 2050 (BEIS & Ofgem 2022). Without coordination between local, regional and ultimately national frameworks, dispersed industry in different areas will electrify at different rates, leading to the potential for further market distortion.

The UK, and in particular England, has long been unusually centralised in its approach to government (Heseltine 2012) and a formal regionalised approach to industrial strategy does not presently exist (Business Energy and Industrial Strategy Committee 2021). One solution could be an expanded role for local area energy plans (LAEP): "a data driven and whole energy system, evidence-based approach that is led by local government [and] developed collaboratively with defined stakeholders" (Energy Systems Catapult 2021, p. 8). LAEP provide a systematic means for local areas to identify the most effective way to meet their local net-zero target. However, at present, their implementation is piecemeal and, as critics note, local authorities will be unable to move to the delivery phase without allocated budgets (Citizens Advice 2021). Proponents of LAEP are calling for further action from national government to support local authorities in undertaking LAEP, to integrate energy planning with land use planning frameworks and, crucially, to clarify who is responsible at the sub-national level for coordinating energy planning across regions (Energy Systems Catapult 2022). The Levelling Up agenda, which was intended to address the UK's entrenched regional inequalities through support for devolved powers, appeared to offer an opportunity to develop this new governance framework. However, while policy documents focussed on industry, such as *The Ten Point Plan for a Green Industrial Revolution* (HM Government 2020) and the *Industrial Decarbonisation Strategy* (HM Government 2021a), were enthusiastic about the potential for industrial decarbonisation to reinvigorate the UK's industrial heartlands and level up the UK, the *Levelling Up the United Kingdom White Paper* (HM Government 2022) itself offered little new in the way of policy or funding to deliver this ambition. There is provision within the White Paper for a devolution framework that will provide local authorities "opportunity to adopt innovative local proposals to deliver action on climate change and the UK's Net Zero targets" (HM Government 2022, p. 140). These could, in theory, be used to assist with regional LAEP coordination (Energy Systems Catapult 2022); however, it appears unlikely that many local authorities will take on this task without first being assigned formal responsibility and funding to do so.

Discussion

In the preceding sections, we have described some of the important characteristics of dispersed industry in the UK and the decarbonisation challenges that it faces. These challenges include: the geographical spread of industrial sites, the diversity of sectors involved, the small size and lack of capacity of many of the companies, incomplete information on appropriate abatement options and how these may vary with location, the low TRL of some electrification options combined with the high cost of electricity, uncertainty around the availability and planning of supporting infrastructure and a lack of institutional capacity and leadership at the local level. Some of these challenges are specific to the UK due to its highly centralised approach to decision-making, whereas other issues will be shared by countries around the world. Here, we discuss the implications of our findings in both cases.

Implications for the UK

The UK has historically had a centralised approach to decision-making in many areas including energy and emissions reduction. This philosophy has informed its approach to industrial decarbonisation but we argue the top-down approach used for decarbonising the major industrial clusters that focuses mainly on the deployment of hydrogen and CCUS is unlikely to be appropriate for the wider decarbonisation of UK industry. Rather a more complex and nuanced policy environment will be needed that recognises the diversity of sectors and company sizes, incentivises a wide range of abatement options, provides greater certainty on the roll-out of supporting infrastructure, strengthens local capacity to act and leverages the synergies between the decarbonisation of industry and other sectors at a local level.

The UK is one of the front-runners globally in addressing the challenge of achieving deep decarbonisation of industry. While there are examples of successful initiatives to address the environmental impact of industry in particular places (Perrucci et al. 2022; Tudor et al. 2007) and innovation is beginning to deliver fossil-free industrial products (Vetter 2021), international examples of well-established and successful approaches to decarbonise the entire industrial sector are not readily available. Further work is, therefore, needed by government and industry to develop a strategic approach that is appropriate to the UK's situation. However, there are still some key gaps in our current knowledge that require further investigation to inform the UK's strategy, some of which national government is best placed to lead on, others of which require a more localised approach.

Ensuring a diversity of abatement options are available to industry, together with publicly available data about them. The IDC is providing significant funding to develop and deploy hydrogen and CCUS technologies through activities that are focussed on the clusters. This will no doubt provide important learning about these decarbonisation approaches that will be relevant to dispersed industry. However, so far much less attention has been given to alternative decarbonisation options such as greater electrification and the direct use of biomass. Further work is, therefore, urgently needed to understand the potential for a menu of options to decarbonise high-temperature heat processes and numerous process-specific technologies across a range of sectors. This information could then be used to identify those technologies that require further RD&D to bring them to market and the best mechanisms to do this. This is an example of where national government could play a role through the provision of information on the range of abatement options that may be applicable to a particular sector. A recent review of the availability of industrial data concluded that it is not currently fit for purpose and that "there is an urgent need for a public data strategy which gathers linked data on emissions, technologies, and related environmental, social and economic impacts" (Norman et al. 2020).

Exploring the potential to group dispersed industry to support decarbonisation. A key challenge for dispersed industry is the availability of the supporting infrastructure to support decarbonisation, whether this be for electricity, hydrogen and/or CCUS. In the case of electricity, the challenge is having the necessary capacity in the network to support increased demand, which may involve both upgrading existing connections and possibly building new power lines. For hydrogen, the most likely options would be to repurpose the existing gas distribution infrastructure coupled with a new hydrogen transmission network. Unless hydrogen gains a significant share of demand in other sectors, it seems unlikely that a future hydrogen network will have anywhere near the geographical reach of natural gas. In the case of CO_2, the building of pipelines and/or the development of a truck or ship transport network would be needed, and this is likely to be focussed on regions where significant CO_2 capture makes them economically viable.

Two potentially complementary approaches have, therefore, been suggested. The first is to identify areas of significant industrial activity that have the potential to become "mini-clusters" and so be the focus for enhanced or new infrastructure development. Depending on the geographical spread of emissions within these mini-clusters, then the second approach would be to co-locate certain industries in low-carbon hubs thus allowing them to share the benefits of improved infrastructure availability and build upon synergies between different industrial processes. Further work is needed to identify which areas might form these mini-clusters and hubs and what infrastructure would be needed. This would need to be combined with an economic and social analysis of the desirability and acceptability of such an approach.

Building local capacity for facilitation and energy planning. The Government's approach to decarbonising the large industrial clusters relies on groupings of industrial companies, public bodies, technology providers, research organisations, sector bodies and energy utilities coming together to form "projects" that can bid for government funding. This bottom-up, competitive approach may be appropriate when there are relatively few large organisations involved in a small number of projects. However, the challenge of decarbonising dispersed sites is likely to require a different organisational approach, with strong local leadership an important element. Historically, the UK system of governance has not supported this approach meaning that local action to identify dispersed sites and develop strategies for them is at present piecemeal and poorly resourced. There is currently a wide range of awareness and capacity at the local level about the need for decarbonisation in general and the specific challenges facing industry in particular. Some areas, such as the Black Country, have proactively engaged with the issue. Other areas lack obvious leadership and, therefore unless there are efforts to strengthen local capacity, are likely to fall behind in decarbonisation efforts. A patchwork approach at which different areas proceed with decarbonisation at different speeds is likely to introduce regional distortions with both winners and losers. Further work is needed to explore whether a more consistent local approach is possible and what kinds of organisations (existing and new) should be involved. A possible way forward in England may be to give industrial decarbonisation more visibility by including them in LAEP, if this approach has widespread use across the country.

International implications

Countries and regions will develop a pathway to industrial decarbonisation that is shaped by their existing infrastructures and sectors, policy priorities and resources. There is no one-size-fits-all approach. However, while the details of our analysis are UK specific, many of the challenges and potential solutions will be relevant in other countries. Some places, such as the Netherlands, have a highly centralised industrial structure ideally suited to cluster decarbonisation, and a dozen major energy-intensive businesses which collectively account for over 60% of CO_2 emissions (Government of The Netherlands 2019). For countries where industrial emissions are distributed in this way, the development of local ZCH is arguably less pressing than in the UK where emissions are almost equally split between clusters and dispersed sites. Nonetheless, exploring alternative abatement options will remain an important area of research.

Other countries operate systems of government that provide greater opportunities for a regionally specific approach to the issue than are available to many areas in the UK. The German federal state of North Rhine-Westphalia (NRW) produces 15% of the EU's primary steel and 15% of high-value base chemicals (Schneider and Lechtenböhmer 2018). In 2022, the NRW government launched NRW.Energy4Climate, a state company with responsibility to provide an integrated regional approach to decarbonising the energy, manufacturing building and transport sectors (NRW.Energy4Climate n.d). In places where institutions such as these exist, building additional local capacity for facilitation and energy planning may not be necessary but integrating different sectors into low-carbon hubs may still be required.

In industrialised nations, such as Japan and Australia, where hydrogen has been positioned as a cross-sector, society-wide vector for decarbonisation (COAG Energy Council 2019; Ministry of Economy Trade and Industry of Japan 2017), the location of hydrogen infrastructure may determine the sequence of industrial decarbonisation, rather than the location of industrial clusters determining where hydrogen is first deployed. Hence, we see Australia seeking to prioritise the development of hydrogen hubs that will aggregate users of hydrogen from industrial, transport and energy sectors into one place (COAG Energy Council 2019). Co-location provides the potential for the economies of scale, opportunities for joint efficiencies and shared learning. However, without an approach which also considers capacity and abatement options for areas outside of hubs, this approach also has the potential to introduce regional distortions.

Conclusions

This paper uses the example of the UK to highlight the importance of developing decarbonisation strategies for industry that go beyond the clusters of energy-intensive industries that currently receive most attention by both researchers and policymakers. We have characterised the nature of these dispersed industrial sites in terms of their number, geographical distribution, level of emissions, diversity of sectors and size of companies. We argue that a range of factors related both to the companies themselves and the environment in which they operate mean that the technologies and policies needed to support their decarbonisation needs to be significantly different to those used to decarbonise the large industrial clusters.

We found that the potential enablers to decarbonise dispersed sites are exploring the benefits of shared infrastructure across sites, the implementation of low-carbon hubs, the development of alternative novel abatement options (electrification options in particular) and improved governance arrangements, employing a more decentralised approach than has historically been the case in the UK.

Since our case is drawn from one country, the generalisability of our findings is necessarily limited. Nonetheless, the UK is one of the first major economies to begin implementing a national cluster decarbonisation programme and, because its industrial emissions are split almost evenly between clusters and dispersed sites, our findings provide an early indication of the challenges that may face the many other countries that possess a variety of more and less concentrated industrial areas. As work progresses, research into the specifics of how industrial decarbonisation is developing in particular countries and regions, and comparative studies between them, are likely to form a fruitful area of further study. Developing a more in-depth categorisation of industrial areas according to their sectoral make up, institutional capacity and appetite to engage with the industrial decarbonisation agenda will provide an important component of this analysis.

Industrial materials provide the building blocks upon which the net-zero transition will be based. Though the sector is hard to abate, there have been significant advances in our understanding of the task since the Paris Agreement was adopted. Industrial clusters are an obvious starting point in this work but, as we have shown, they are not the end point of the process. As work on industrial decarbonisation moves from planning into the implementation stage, it is time to begin thinking beyond clusters. In this paper, we provide a first step towards a more comprehensive analysis.

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Declarations

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