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Review

Factors driving the decarbonisation of industrial clusters: A rapid evidence assessment of international experience

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ABSTRACT

Reducing industrial emissions to achieve net-zero targets by the middle of the century will require profound and sustained changes to how energy intensive industries operate. Preliminary activity is now underway, with governments of several developed economies starting to implement policy and providing funding to support the deployment of low carbon infrastructure into high emitting industrial clusters. While clusters appear to offer the economies of scale and institutional capacity needed to kick-start the industrial transition, to date there has been little systematic assessment of the factors that may influence the success of these initiatives. Drawing from academic and grey literature, this paper presents a rapid evidence assessment of the approaches being used to drive the development of low carbon industrial clusters internationally. Many projects are still at the scoping stage, but it is apparent that current initiatives focus on the deployment of carbon capture technologies, alongside hydrogen as a future secondary revenue stream. This model of decarbonisation funnels investment into large coastal clusters with access to low carbon electricity and tends to obscure questions about the integration of these technologies with other decarbonisation interventions, such as material efficiency and electrification. The technology focus also omits the importance that a favourable location and shared history and culture appears to have played in helping progress the most advanced initiatives; factors that cannot be easily replicated elsewhere. If clusters are to kick-start the low-carbon industrial transition, then greater attention is needed to the social and political dimensions of this process and to a broader range of decarbonisation interventions and cluster types than represented by current projects.

1. Introduction

1.1. The imperative to decarbonise industry

Energy intensive industry is one of the most critical, but also one of the most challenging, sectors to decarbonise. Since 2000, industrial carbon dioxide emissions have been growing faster than for any other sector [1] and by 2021 industry was responsible for directly emitting a quarter of global emissions [2]. Historically, the sector has been shielded from pressure to decarbonise due to the political imperative for governments to preserve national competitiveness, retain jobs and prevent carbon leakage [1]. Change was further impeded by the perception that industry was hard-to-abate, due to its heterogeneity, high capital costs, trade exposure, long-lived facilities and the cost sensitivity of its products [3]. The release of process emissions by some sectors provided an additional hurdle, since these are the result of chemical reactions and so cannot be avoided through the use of carbon-neutral fuels [4]. More recently, however, the Paris Agreement objective - which requires reaching net zero emissions globally by the middle of the century - has begun to shift this narrative [5]. Governments in developed economies across Europe, East Asia and the Pacific, and the Americas are providing funding for demonstration projects in industrial decarbonisation and engaging in policy and business model experimentation to support these activities.

Industrial decarbonisation will require a suite of policy and technical interventions. On the policy side, these include incentives to drive demand for low carbon products, price carbon and support manufacturers' competitiveness; support for improvements in material and resource efficiency; support for the research and development of novel technologies and approaches to decarbonisation; and support to ensure the necessary infrastructures are in place [6]. On the technical side, these include resource and energy efficiency (REEE) approaches, including

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industrial symbiosis and circular economy initiatives; feedstock substitution; fuel switching to lower carbon options such as biomass or low carbon electricity; novel decarbonisation technologies such as low carbon hydrogen[1] and carbon capture and storage (CCS) to remove and store residual emissions [3].

While the pathway that each country and region takes will be shaped by its political and economic context [7,8], interventions such as REEE measures and circular economy initiatives are, in principle, aspatial, that is, available to industrial sites wherever they are located. The requirement for new infrastructure, however, means that technologies such as CCS and low carbon hydrogen will likely be deployed sequentially, initially into the areas where they offer the most abatement potential. The investment required for these infrastructures is substantial and beyond the capacity of industry to fund, meaning governments must lead on the issue. Activity is now beginning to accelerate, as countries compete to gain a competitive advantage in technology development. The United Kingdom, the United States, Canada and the Netherlands have all implemented policies to support the deployment of hydrogen and CCS demonstration projects into high-emitting industrial areas, and are engaging in business model development in support of this work [9–12]. It is these areas of high industrial activity – termed clusters in UK and EU policy documents [9,13], but more often hubs in the Americas [10,12,14] and Australia [15] – that form the subject matter of this review.

1.2. Clusters as gateways to change?

The role of industrial clustering in facilitating innovation and learning between firms is well established within the field of economic geography. One of the most influential proponents is the economist Michael Porter who defines clusters as "a geographically proximate group of interconnected companies and associated institutions in a particular field, linked by commonalities and complementarities" [16 p. 16]. While criticised as a "chaotic concept" [17] so broad in application that it offers little conceptual clarity, these dual traits of geographical concentration and inter-firm linkages underpin much subsequent work on clusters, both as an analytical construct and a policy tool to improve regional economic performance. Following publication of Porter's *The Competitive Advantage of Nations* in 1990 [18], policies and strategies to support the development of clusters as engines of regional growth have become widespread across high, low and middle income countries [19,20].

Similarly, using spatially targeted interventions to reduce the environmental impact of industry is well established within the industrial ecology literature. The eco-industrial park concept has been current since the early 1960s [21]. Many countries, including the United States, the Republic of Korea, China, India, the Netherlands, Finland and Japan, have implemented policies to support their development and promote sustainable industrial production, including interventions such as pollution prevention, REEE, industrial symbiosis, and water, waste and energy management [22], albeit with varied degrees of success in achieving their environmental objectives [22,23]. In part, the issue is one of diversity. Clusters are individuals [24] and differences in industrial sectors, energy structures and geographical characteristics lead to different opportunities for low carbon development, meaning there is no one-size-fits all approach [25].

Using industrial clusters to accelerate deep decarbonisation, however, presents a challenge on a much larger scale. Decarbonising energy intensive sectors with high combustion and process emissions will entail the co-location and integration of multiple infrastructures. Different solutions will be appropriate to different clusters [7] but will likely include facilities for carbon dioxide transport utilization and/or storage; technologies for low carbon hydrogen production and storage; high voltage electricity transmission for industrial electrification and hydrogen electrolysis and, ideally, access to low carbon energy sources to power these processes [26]. Technology, however, is only one part of the picture. Industrial production is a socio-technical system, made up of multiple moving parts: technologies and infrastructures, but also markets, policies, industry structures and value chains [27]. Change will be required in multiple, interlinked, areas for the system to transition to a more sustainable model.

In theory, the arguments for kick-starting this process through industrial clusters are compelling on economic, environmental and social grounds. The International Energy Agency's (IEA) *Future of Hydrogen* report identifies clusters as "gateways" [28 p.177] for the deployment of clean hydrogen since they allow the co-location of supply and demand, de-risking investment and providing a guaranteed customer base through which to scale up production. Geographical proximity additionally provides the potential to improve the efficiency of many industrial processes through shared district waste heat schemes, and combined heat and power [26]. The benefits of clustering in developing the regional linkages, networks and institutions which support innovation are already well known and form the subject matter of extensive policy literature [18–20]. As a result, there is increasing interest in the role that clusters can play in industrial decarbonisation in both policy and academic circles. Two major global initiatives, the World Economic Forum's *Transitioning Industrial Clusters Towards Net Zero Initiative* [29], and the Clean Energy Ministerial's *Global Ports Hydrogen Coalition* [30], launched in 2021, and an emerging body of academic literature has begun to consider the potential for industrial clusters to drive deep decarbonisation [31–33].

In practice, there is considerable uncertainty about how this process will develop. In principle, using industrial clusters to drive deep decarbonisation appears to combine the aims of both growth-orientated clusters, aimed at regional economic development, and eco-industrial parks, aimed at reducing environmental impact, but the process will be subject to pressures that neither of these pre-existing forms face. In particular, the reliance of industrial decarbonisation clusters on infrastructure funding from government introduces new challenges for both parties. Reviews of CCS projects in Europe [34] and the United States [35] makes it clear that reliance on government funding has historically proved a double-edged sword for these initiatives, leaving projects vulnerable to political veto. From a government perspective, there is a tension between allowing individual clusters the freedom to follow their own decarbonisation pathway while also ensuring the total carbon mitigation delivered is sufficient to meet national net zero targets. Findings from previous research suggest it is difficult for governments to control clusters' strategic direction without stifling innovation and initiative [36]. Industrial decarbonisation clusters therefore have an uncertain path ahead of them, and their path is not yet understood.

To date, there has been little assessment of how industrial cluster decarbonisation initiatives are progressing; the key elements that might underpin their success; or the strategies and interventions being deployed to achieve this. It is apparent that contextual factors will be important. As Bataille [26] notes, the investment case for the deployment of decarbonisation infrastructure will vary between industrial clusters and regional competitive advantages are likely to play a key role. The appropriate mix of policy instruments to enable key decarbonisation technologies, such as CCS, will likewise vary markedly between countries, dependent on local market conditions and institutional factors [8]. The specifics, however, remain under researched. Given the urgent need to reduce greenhouse gas emissions from industry, this review seeks to address this gap by undertaking a rapid evidence (REA) assessment of the literature on industrial cluster decarbonisation. The main question it seeks to address is: *What approaches are being used internationally to drive the development of low carbon industrial clusters?*

[1] For the purposes of this review, low carbon hydrogen is taken to mean blue and green hydrogen. Blue hydrogen is produced by the steam reformation of methane with CCS and emits CO_2, although to a lesser extent than methane. Green hydrogen is produced by the electrolysis of water. When powered by renewable energy it is the lowest carbon option but the technology is not currently widely deployed.

This guiding question is addressed through five sub-questions:

1. What policies and business models are being adopted to drive decarbonisation of industrial clusters?
2. Is there any evidence to indicate the advantages of specific configurations of sectors or technologies for decarbonising industrial clusters?
3. How are leading cluster decarbonisation initiatives governed?
4. What locational factors have advanced the development of cluster decarbonisation projects?
5. What are the lessons for policy?

Our analysis reveals the literature to date has been dominated by techno-economic assessments of the feasibility of deploying decarbonisation interventions into clusters, with limited focus on the institutional and social aspects of this process. Many leading industrial cluster decarbonisation projects appear to be carbon capture initiatives that aim to incorporate blue hydrogen as an additional revenue stream, as governments manoeuvre to gain first mover advantage in the hydrogen economy. While this approach is likely to accelerate the decarbonisation of those coastal industrial clusters that are well positioned for offshore CCS, the extent to which this model can be successfully applied to other industrial clusters and regions to kick-start their transition remains unclear.

The remainder of the paper is structured as follows. In Section 2, we introduce the REA methodology and discuss the approach used in this study. In Section 3, we provide details of the generated corpus, then present our results, structured according to our five sub-questions. In Section 4, we conclude by discussing the limitations of our work and providing suggestions for future research.

2. Methods and materials

The process for REAs was developed by the UK Government Social Research Service [37] and further refined by the UK Energy Research Centre (UKERC) [38]. REAs have been designed to maintain rigour in searching while delivering results rapidly within constraints imposed by cost and time [39,40]. While REAs should be as systematic and thorough as possible, their reduced scope entails a number of acknowledged limitations when compared to a full systematic review. These include a relatively limited examination of quality, the omission of difficult-to-obtain material and foreign language studies and a lower number of databases searched [40]. These characteristics mean REAs are best used at policy development stages when information about the effects of interventions is required; when it is known questions remain unanswered; and to map a topic area in order to direct future research, potentially providing a basis for a subsequent full systematic review [37]. REAs therefore provide a starting point upon which future research can build. The approach used in this study followed a process established for previous REAs [38,41,42]. The main steps are set out below.

2.1. Determine the research objective and method

A preliminary literature review conducted in final quarter of 2021 confirmed the challenges facing energy intensive industry on the route to decarbonisation and revealed growing interest in using industrial clusters both to kick-start this transition and to stimulate economic recovery in the aftermath of the Covid-19 pandemic [7,11,26,43–45]. Because of the range of factors that could shape industrial cluster decarbonisation, we began with a broad overarching research objective: to establish the approaches being used internationally to drive the development of low carbon industrial clusters.

2.2. Establish an expert steering group

Having determined our main research objective and method, we established an expert steering group of six end-users to advise us on our research questions and search terms. The steering group was made up of industrial cluster representatives, industry experts from UK and international agencies, and academic experts on the political and technical dimensions of industrial cluster decarbonisation.

2.3. Agree search terms, databases, timeframes and inclusion criteria

Our search terms and research questions were identified through the preliminary literature review and subsequently reviewed and refined by our steering group. We selected three groups of search terms, the first relating to energy intensive industry and decarbonisation approaches, the second to clusters and hubs, and the third to policy and business models. Wildcards were included to account for differences between British and American spellings, and the use of plurals. A full list of search terms, including wildcards and Boolean operators, is provided in Appendix A.

Our primary source of data was Scopus, an academic journals resource, selected because of its broad journal coverage [46]. Searches in Scopus were undertaken in English only and results restricted to publications available free of charge or that were available to the authors under academic licencing agreements.

We supplemented the coverage through use of Google Search. Care is needed when using Google Search and similar search engines in evidence reviews for two main reasons. First, the information returned is tailored to the individual and replicability is not guaranteed [47,48]. The effects of personalisation can be reduced by signing out of personal accounts, using incognito browsing and undertaking a verbatim search [49] but these are not perfect solutions [50]. Nonetheless, internet search engines are an importance source of literature, particularly in the case of low and middle income countries where they may be the only be the only way to access policy and working papers [51,52].

A second issue with Google Search is the very large number of results returned. For this study these were estimated by Google to be between 1030 and c.1,300,1000 results per search string. The issue of when to stop searching in time-limited reviews, such as REAs, is a key one, but there is limited guidance on when this should be [53]. In order to manage the volume of data returned by Google Search, we applied the concept of saturation, that is searching ends when no further new perspectives are added by new publications [54], in combination with a cut-off point. The first 20 results from each Google Search were taken forward to the first screening stage described below. Where saturation had not been reached by 20 results, the first 100 results were screened.

The timeframe for searches are dictated by review topic [54]. In this instance, we did not specify a start date for our searches so as not to exclude lessons from longer-standing place-based initiatives, such as eco-industrial parks, that might also apply to industrial decarbonisation clusters. The end data of our review was 2021, to account for the rapidly developing nature of the field.

Studies identified in the search underwent two screening stages. Firstly, in order to eliminate studies irrelevant to the search question, a single reviewer screened results based on their title and abstract or, in the case of grey literature, executive summary. Publications that passed this stage had their bibliographic details recorded and their full text reviewed. To allow the research to focus on material that most closely matched the research requirements, in the second screening stage documents were allocated a relevance rating established by examination of the full document text.

2.4. Identifying studies to include in the review

In total, 644 searches were undertaken between November 2021 and April 2022. A PRISMA flow diagram outlining the process is provided in Appendix B. This process gave a final corpus of 58 documents identified through Scopus and 66 identified through Google, making 124 in total. A list of the documents included in our corpus is provided in appendix C.

2.5. Synthesis

A single reviewer undertook a close reading of the selected documents in order to identify the lessons for industrial cluster decarbonisation contained within each. In accordance with the qualitative nature of the aims of our study, the analysis took the form of a narrative synthesis of the corpus [54]. Each document was reviewed against the first four sub-questions for evidence on the effects of interventions, and on the factors shaping the implementation of interventions [55]. Findings were grouped thematically according to the sub-questions and then analysed to establish the present evidence on the topic, to explore relationships between the findings from different initiatives and, where evidence was available, to develop theory on how these factors were shaping industrial cluster decarbonisation initiatives and why. Once we had established the sectors, technologies, policies, business models, governance arrangements and locational factors that underpinned current initiatives, we undertook a synthesis of our findings to address the final research question. Our overall aim was to establish the present status of cluster decarbonisation initiatives and assess the state of the field, including gaps in our knowledge and inconsistencies in the findings.

2.6. Review of output

Finally on completion of the REA, the report was reviewed by the steering group to ensure the research questions had been addressed and identify if further work was required. The final output of that work forms the basis of this review.

3. Results

3.1. Overview of corpus

Just over half (53 %) of the documents in the corpus were grey literature that had not been published in peer-reviewed journals. A significant proportion of technology specific information came from publications by bodies with commercial interests in advancing their case. Cluster-specific information was often contained in cluster prospectuses written for an audience of policy makers. While no disparities were detected between the arguments in these publications and the academic literature, the high proportion of grey literature should be borne in mind when assessing the findings of this review. The majority of the documents were published in the last ten years, confirming that the field is in an early stage of development. Publications have increased rapidly since 2016, suggesting that the Paris Agreement has indeed led to an increased focus on energy-intensive industry in both academic and policy spheres.

Table 1
corpus documents by primary research focus.

Primary research focus	Percentage of publications
Carbon capture technologies	36 %
Cluster decarbonisation	19 %
Circular economy and industrial symbiosis	14 %
Hydrogen	10 %
Clusters and innovation	6 %
Other	15 %
Total	**100 %**

Table 1 provides a summary of the corpus by research focus. There was a strong focus within the on techno-economic assessments of single decarbonisation interventions and a concurrent lack of cross-cutting assessments and more general comparative analyses. Chief amongst the technologies assessed were CCS or carbon capture and utilization (CCU)[2]; hydrogen, and circular economy and industrial symbiosis approaches. One consequence of this single interventions focus is a knowledge gap around meso-level perspectives. Within the grey literature, high-level roadmaps and action plans predominated. Within the academic literature, much of the evidence base consisted of detailed modelling studies. With a few notable exceptions, there was little consideration of how industrial cluster decarbonisation strategies might be integrated and implemented in practice.

Table 2 provides a summary of the corpus by its primary geographical focus. There was a strong focus on Europe, and in particular industrial clusters in the Antwerp-Rotterdam-Rhine-Ruhr Area (ARRRA) of North-West Europe. Recent UK initiatives to decarbonise industrial clusters in the north of England also formed the subject of a number of publications. Global reviews, particularly of the prospects for hydrogen and carbon capture, but also of cluster initiatives more generally, were more prominent amongst the grey literature.

3.2. Policies and business models to support industrial cluster decarbonisation

Appropriate government policies and business models will be essential to support the deployment of the new infrastructures, technologies and energy sources required for the industrial transition, since at present there is limited market 'pull' for low carbon industrial products. However, the nascent status of many industrial cluster decarbonisation initiatives meant our review uncovered limited evidence on the specific policies and business models needed to drive industrial decarbonisation within clusters. Instead, publications focussed either upon the general need for policy support and appropriate business models or,

Table 2
corpus documents by primary geographical focus.

Primary geographical focus	Number of publications
Europe	21
United Kingdom	19
Global	15
Netherlands	12
China	10
United States	9
Australia	6
Germany	5
Spain	3
Belgium	2
Iran	2
Italy	2
Nordic countries	2
Taiwan	2
Brazil	1
Canada	1
Kazakhstan	1
Malaysia	1
Republic of Korea	1
Slovenia	1
Sweden	1
N/A	7
Total	**124**

[2] Carbon capture and storage (CCS) and carbon capture and utilization (CCU) are separate but linked technologies with different abatement potentials. Where the literature is specific to one, then the appropriate abbreviation has been used in the text, otherwise the term 'carbon capture technologies' has been used.

reflecting the strong focus within the corpus on single decarbonisation interventions, the appropriate policies and business models to drive the uptake of carbon capture and hydrogen technologies. The studies reviewed revealed two significant gaps in our knowledge. First, the extent to which policy and business models for existing carbon capture and storage projects, many of which rely on enhanced oil recovery and vertical integration of operations, might transfer to cluster decarbonisation projects. Second, given that industrial cluster decarbonisation will require the deployment of a suite of interventions, how policies and business models for different technologies might be designed to support rather than compete with each other.

3.2.1. National and regional policy to support industrial cluster decarbonisation

There was clear consensus within the literature that action on industrial cluster decarbonisation would only occur within clear and consistent long-term climate frameworks. The Dutch Port of Rotterdam industrial decarbonisation initiative, Porthos, is the EU's most advanced industrial CCS project and has received Project for Common Interest status. As such, it formed the subject of a number of assessments. Schneider et al. [56] identify sufficiently high carbon prices, support for market introduction, green investment support, roadmaps and infrastructure planning as key elements in enabling the project to deliver. Samadi et al. [57 p.407] note the importance of "adequately ambitious, stable and predictable," climate change mitigation policy at national and EU level and the Rotterdam-Moerdijk Industry Cluster Work Group itself [58 p.20] identify a "long-term stable investment climate and multi-annual stable legislation and regulations" as their first framework condition for success. In a review of UK CCS clusters, Stork and Schenkel [59] express a similar view on the need for national policy clarity to support decarbonisation and boost business confidence.

Regional initiatives that take into the account the conditions, infrastructure and linkages specific to clusters are also identified as playing a key role in enabling transformative industrial change [56,58,60,61]. Clusters are unique and may require bespoke support to decarbonise. This process will require regional cooperation [62] and close engagement with regional policy makers [63,64]. Despite this acknowledged requirement, however, publications incorporating a regional perspective were relatively few. This scarcity is noted several times throughout the corpus, in studies presenting deep decarbonisation scenarios for industrial regions [57,65]; as a general feature of transitions literature [60]; and in a recent policy review of CSS projects within ten European countries [66]. In the case of industrial cluster decarbonisation, the reason appears to be that initiatives are not yet mature enough for regional policy interventions to play a significant role. Rather most initiatives are being driven by national governments.

Unsurprisingly, given that infrastructure development is a defining feature of industrial decarbonisation clusters and the costs involved are significant, the need for public funding to allow clusters to attract and anchor further private investment was an underpinning theme in many cluster generated publications [62,67–69]. At the present early stage of development, however, the specifics of the sources and mechanisms for funding appear to be less important than the funding being sufficient, consistent and long term. Cancellations, such as the withdrawal of funding for the White Rose CCS project in the UK Humber cluster in 2015, and the cancelation of the Port of Rotterdam ROAD project for coal-fired power generation with CCS, in 2017, are likely to damage business confidence and provide a significant impediment to future initiatives [70,71].

3.2.2. Policy and business models for carbon capture within clusters

Large scale infrastructure projects are expensive and require substantial upfront capital investment. Carbon capture technologies are no exception [72]. The high costs, financial and technical risks and weak market incentives for private investment in low carbon infrastructures mean that many current carbon capture projects are either state owned, state supported through capital grants and ongoing revenue support, and/or generate an additional revenue stream.

Frequently, the additional revenue stream for existing projects comes from using captured CO_2 for enhanced oil recovery (EOR), a process whereby pressurized CO_2 is used to extract additional oil from existing wells. Historically, the most commercially successful CCS projects have been those incorporating EOR [71]. As a result, most operational facilities are located either in counties such as China, UAE and Saudi Arabia, where political frameworks favour full public ownership, or in hydrocarbon producing countries such as the USA, Canada and Norway that have existing frameworks of financial support for carbon sequestration through tax credits and carbon taxes [73]. As a result, the policies and business models used in existing CCS projects may not transfer directly to the decarbonisation of industrial clusters in other locations.

In addition, ramping up deployment of carbon capture to reach net zero commitments is forecast to require a more than hundred-fold increase in storage capacity, suggesting new forms of policy support will be required [74]. Of particular relevance to clusters is policy to mitigate the interdependency risk, whereby operators of transport and storage (T&S) facilities are dependent on the source of emissions staying in business for their operations to remain commercially viable. Historically, most projects have incorporated a single point source emitter and vertical integration of operations, whereby a single party operates the whole value chain. This model is used in a number of existing CCS facilities often, although not always, when provision is by government or through a state operated enterprise.

There was consensus within the literature that capturing CO_2 from clusters and using shared infrastructure for the subsequent T&S stages could, in principle, offer multiple benefits over the single point source emitter approach, including driving down unit costs, increasing economies of scale, offering flexibility, and making decarbonisation infrastructure accessible to a wider range of industrial emitters, including smaller projects [64,71,75]. A review of CCS projects by Haines [71] and of CCS business models by Element Energy [76] suggests that government backing of decoupled shared T&S facilities provides the most viable option for addressing this challenge. There was little detail within the corpus, however, about how government backed shared infrastructure might operate in practice, reflecting the present lack of attention being paid to the integration challenges that clusters will face.

3.2.3. Policy and business models for hydrogen within clusters

Many of the academic articles identified in the review took a single disciplinary approach to hydrogen, often modelling the techno-economic effects of single interventions [77–79]. As Edwards et al. [80] note, it is rare for technical, social or policy elements to be integrated in a multi-disciplinary manner. The grey literature tended to focus on single sectors or high-level roadmaps [15,28,43,81–84] rather than the challenges of implementing and integrating hydrogen into specific industrial clusters. There was, however, consensus across both grey and academic literature that industrial clusters provide governments an opportunity to kick-start the hydrogen economy [43,58,68,69,80,81,84–86]. In a review of hydrogen's potential for the G20, the IEA [43] sets out a suite of five near-term policy priorities to ramp-up the deployment of low carbon (blue or green) hydrogen through industrial clusters. These are to set targets and policy signals; to support demand creation; to mitigate investment risk; to support R&D and demonstration projects and to harmonise standards and remove barriers. The corpus was reviewed with these recommendations in mind, however while there was consensus within the literature that these were important priorities, the publications reviewed did not provide any examples about the success, or otherwise, of policy interventions to address them.

The most important element in creating a favourable investment environment for low carbon hydrogen was agreed to be scale. It is for this reason that industrial clusters, particularly coastal industrial clusters, were identified as the potential birthplace for the hydrogen economy [43]. Industrial clusters are unique in that all the elements of the hydrogen value chain are present in one place, providing a complete system of hydrogen production, supply, and industrial utilization, alongside carbon capture [87]. Linked to the cluster concept is the hub concept applied in Australia [81,84] where production and demand are co-located but where the focus is on green hydrogen production and therefore carbon capture is not required.

3.3. Configurations of sectors and technologies for decarbonising industrial clusters

Integration is at the heart of industrial cluster decarbonisation. For shared infrastructure to function, it will be necessary to integrate multiple industrial sectors and technologies, running under different operating constraints. Identifying synergies between different sectors and technologies would allow governments to pinpoint promising clusters of industry, accelerating the industrial transition. Similarly, identifying the trade-offs between sectors and technologies that arise during cluster decarbonisation could offer important insights into barriers to the transition process and prevent duplication of effort. However, while the number of potential configurations of sectors and technologies is large, the literature focussed upon carbon capture, hydrogen, and the integration of hydrogen production with carbon capture and storage for the production of blue hydrogen. The present focus of research on industrial clusters therefore appears to be as much about the potential for clusters to kick-start the hydrogen economy as it is about the industrial transition. The following sections summarise our key findings.

3.3.1. The optimal configuration of sectors for carbon capture

The potential for carbon capture technologies to play a role in decarbonising multiple energy intensive sectors and a range of emission sources is a key reason for its inclusion in many national decarbonisation roadmaps [35,88]. Integrating multiple sectors into a shared T&S network, however, will not be a straightforward task. [89]. In many cases the CO_2 released by industry is not pure but mixed with other components. The composition of the resulting flue gas directly influences the capture costs: a high purity CO_2 stream reduces the cost per tonne of CO_2 avoided [89]. Cement [73,90], lime production [91], ethanol manufacturing [89] and ammonia production [92] were identified as promising sectors for this reason. The number of points of emissions is also significant. The more flue-gas stacks a site has, the greater the number of carbon capture points needed, increasing the overall costs of operations. The refining sector was identified as more complex in this respect [89,90], due to the large number of small emissions sources. The sectors located within any given cluster therefore will shape how economically viable carbon capture will be as a decarbonisation option.

In practice, however, while sectoral configuration is important it does not appear to be the deciding factor in present carbon capture initiatives. The Global CCS Institute [73] provides a snapshot of CCS networks in operation and development. Of those in development, projects that propose to incorporate hydrogen, petrochemical and/or chemical production are relatively common, while projects which propose to use CCS for biomass and aluminium production are not. There are however no obvious groupings of sectors which dominate the results, suggesting that the source of CO_2 is less important at project development stage than the presence of multiple anchor emitters providing sufficient volumes of CO_2 to kick-start development. Amongst the operational projects, the unifying factor is the use of EOR to provide a revenue stream.

3.3.2. The optimal configuration of sectors for hydrogen

In contrast to studies on carbon capture, where the literature focussed upon the technology's suitability for particular industry sectors, much of the literature on hydrogen focussed upon its versatility and potential to act as a substitute for conventional fossil fuels, both across industrial sectors and within the broader economy [43,68,69,80,81,85]. The literature focussed upon the need to build capacity along the value chain of hydrogen production, storage, use, import and trading [68,86]. Here, industrial clusters were positioned as enablers: providing a consistent source of large scale demand which would provide support for the development of technologies, regulatory and business models for hydrogen production [85,93]. The specific features of such clusters however were not considered, most likely because many hydrogen cluster projects are still at the initiation stages [85].

3.3.3. Synergies between decarbonisation technologies

A third, smaller, strand of work considered synergies between different decarbonisation technologies. Here, the main focus was on carbon capture technologies as an enabler of the hydrogen economy [74,86]. The imperative to become a first mover in the hydrogen economy appears to be a major factor driving industrial cluster decarbonisation initiatives. For example, a report commissioned by the Port of Rotterdam argues: "Low-carbon hydrogen, such as green and blue hydrogen, offers a unique and rare opportunity for the Port of Rotterdam to remain a globally important energy and chemistry hub in the future," [68 p.2]. Similarly, a report commissioned by the North Sea Canal Area argues for the creation of regional hydrogen infrastructures to "help reduce emissions and at the same time build a sustainable, new revenue model for the region and for the Netherlands," [69 p.33]. In relation to the UK, a report by Progressive Energy [87 p.21] on the HyNet project argues, "given that hydrogen is necessary, there is an urgent need to develop both the nascent market and the associated infrastructure. Both of these take time to deliver; early production into low-risk markets enables deployment."

In this context, many advocates for carbon capture technologies portrayed blue hydrogen as a lower cost bridge fuel for low carbon green hydrogen, and carbon capture as a necessary enabler of change [86]. It is outside of the scope of this review to assess the merits of this argument but it is apparent that hydrogen production is a common feature of many early carbon capture networks [73]. To this extent, the assessment of the Global CCS Institute that "jockeying for a chance to win market share in clean hydrogen supply is a significant factor in the growth of early-stage CCS project studies," (*ibid* p. 19) appears justified. When taken in tandem with blue hydrogen's potential to provide a secondary revenue stream to bolster the commercially viability of carbon capture projects the two technologies appear inextricably linked. Industrial clusters as both producers and users of hydrogen, and early candidates for the deployment of carbon capture technologies are likely to be the birthplace of any future hydrogen economy.

3.3.4. Trade-offs between decarbonisation technologies

Finally, a fourth strand of work considered the challenges of integrating different decarbonisation technologies and the potential trade-offs between them [94–97]. There was an implicit assumption within much of the corpus that decarbonisation interventions will either be cumulative in their effects, with sequential deployment as technologies reach maturity [94] or, at worst, run in parallel without interference [62]. Little attention was given to the potential for conflict, trade-offs or carbon lock-in whereby some interventions might lead to 'blind alleys' offering emissions reductions in the mid-term, but unable to provide a route to zero or near-zero emission pathways necessary to meet net-zero targets.

One notable exception is a case study by Janipour et al. [97] into Dutch chemical industry clusters. Here, three potential conflicts were identified, between electrification and CCS; between electrification and hydrogen; and between energy and material efficiency and deep emission reduction technologies. Those who believed electrification and CCS were incompatible argued that once electrification was complete, chemicals clusters would have no need for CCS rendering the technology obsolete – a stranded asset. Complicating this picture, in the mid-term interviewees agreed that CCS offered the lowest cost option and least disruptive route decarbonisation. However, if blue hydrogen became the dominant fuel before electrification was complete, there was a risk that electrification would stall. Incremental improvements to energy efficiency meanwhile, were subject to long payback times which were not compatible with the required pace of transition to deeper emission reduction technologies. Upgrading current plant to improve energy efficiency therefore could also result in stranded assets. As a result, the study offers a number of useful contributions to this review, in identifying potential trade-offs, in bringing into question the assumption that investment in energy efficiency measures present a no-regrets option and in demonstrating the value of a case study approach. Research into the issue of trade-offs and barriers will become increasingly important as industrial cluster decarbonisation initiatives evolve.

3.4. Cluster governance

Since decarbonisation infrastructures are expensive and there is currently limited market pull for their deployment, a significant proportion of funding for existing projects comes from governments. As the deployment of decarbonisation infrastructures will be sequential, at least in the initial stages, policymakers are required to decide which clusters will be prioritised for decarbonisation. While the prioritization process varies between countries, it is apparent that advanced cluster decarbonisation initiatives have often taken a proactive approach to identifying themselves to policymakers as suitable candidates. The governance structures of these clusters is therefore an important area of research since it appears to have a bearing on where and when the industrial transition will begin. Our review reveals a number of lines of inquiry, but there is a clear need for further comparative case study research to investigate the governance of cluster decarbonisation projects in context.

The organisational forms that clusters can take vary according to the institutional and political differences between nations and regions; the technology field the cluster is operating in; its strategic focus (research or industrial development); the number of members and the local social context [20,24]. They may also evolve over time as the cluster matures [36]. The review identified two ways in which a cluster's organisational form could affect its governance arrangements: the configuration of its network and the source of strategic direction.

In terms of network configuration, the industrial cluster decarbonisation initiatives identified in this review most often took a hub and spoke model consisting of larger anchor firms mixed with smaller starts ups and SMEs [98]. This feature is likely to reflect two key features of industrial decarbonisation at its present early stage. First, the type of sectors involved. In energy intensive industry, where economies of scale, high energy inputs, and high capital intensity create high barriers to market entry, a small number of firms often take dominant position [93]. Second, the predominance of carbon capture and hydrogen projects within the literature reviewed. While the role is not necessarily held by the same firms, there is considerable overlap between the concept of anchor firms within a cluster and the requirement for large-scale anchor projects to kick-start the deployment of carbon capture and hydrogen infrastructures [64,81,99].

A second distinction can be drawn between bottom-up clusters, generally initiated by private firms and evolving organically, and top-down clusters, which come about as result of government initiatives to promote regional competitiveness [19,36]. In bottom-up clusters, member firms drive development and assign tasks to the cluster organisation. In top-down clusters, direction is set by the government, with cluster organisations playing a mediating role between achieving these aims while supporting firms' competitiveness. In practice, most cluster programmes adopt a combination of approaches [19,20] and the initiatives identified in this review likewise took a hybrid form, with most having a greater or lesser extent of prior existence, but being given strategic direction by government in order to be eligible for funding to implement hydrogen and carbon capture technologies.

In terms of industrial decarbonisation, however, the defining feature of present well-established initiatives appears to be the longstanding involvement of a strong lead organisation; and the specifics of governance arrangements seem less important than the presence of a shared identity. The literature was unanimous on the importance of a strong central organisation to advocate for the cluster, coordinate activity and generate a shared vision [59,62,71,100–104]. The Port of Rotterdam Authority and the Teesside Collective (now Net Zero Teesside, a partner in the UK East Coast Cluster) are both identified as exemplars in this respect [62,71,73,75,100,102,105] . At first sight, the membership and structure of these organisations differs significantly. The Port of Rotterdam Authority is an unlisted public limited company first incorporated in 2004, before which it was a municipal department of the city authority [106]. The municipality of Rotterdam and the Dutch government are joint shareholders. By contrast, the Teesside Collective was launched in 2015 as a group of five large energy intensive companies specifically focussed upon decarbonisation and coordinated by Tees Valley Combined Authority [62,70,104]. Despite these differences both the Teesside cluster and the Port of Rotterdam have identified carbon capture technologies as critical to their mid-term survival and appear committed to its implementation; both clusters have seen government funding for previous CCS initiatives cancelled and have continued to pursue new opportunities.

One commonality underpinning the two clusters is the presence of shared history and culture. This element appears to play an important role for clusters implementing carbon capture technologies since these take significant time to develop and are subject to frequent hold ups. As Haines [71 p.9] notes in a global review of 12 CCS proposals, "a major obstacle in early years is maintaining a core organisation which is able to carry a CCS cluster project forwards." Similarly, when identifying Teesside as a cluster decarbonisation model for Houston to follow, Friedmann et al. [62 p.9] observe that Net Zero Teesside is "one of the longest-lived consortia developing an industrial hub in Europe or anywhere." Brownsort [100] similarly identifies the close-knit relationships amongst companies in Teesside as a key strength of the cluster initiative, attributing this collaborative culture to many of the main facilities previously being owned by Imperial Chemical Industries (ICI).

The length of time that it takes to build up such a culture should not be underestimated. ICI's involvement in Teesside spanned seven decades, beginning in 1926 and ending with gradual disinvestment during the 1980s [107]. The Port of Rotterdam was established as a chemicals cluster following the Second World War, although the port itself has been in existence for centuries [68]. Its commitment to decarbonisation is also longstanding, with the Port Authority launching its first climate initiative in 2006 [100]. These findings accord with the literature on clusters as drivers of innovation, which is unanimous in stressing the importance of historical context in explaining why clusters emerge, how they develop and whether they prosper [60,61,85,98,101,107–113]. The presence of a skilled workforce [110,113,114]; strong knowledge networks that facilitate the exchange of knowledge, information and ideas [60,110,111,113,114]; established formal and informal institutions [61,110,112,113] and pre-existing physical and information technology infrastructures [61,72,109,111,113] are all important features in ensuring continued cluster success. However, while broadly acknowledged within the economic geography literature, these insights do not yet appear to have been transferred to the domain of industrial cluster decarbonisation.

3.5. Locational factors

Location is a foundational element that will shape the range and economic feasibility of the decarbonisation options available to clusters [25,94]. It will be a key element of determining which clusters will be prioritised for decarbonisation infrastructure, and which will not. The review identified six locational features that enhanced the suitability of leading industrial cluster initiatives for decarbonisation interventions.

These were often strongly linked to their suitability for carbon capture and storage and hydrogen opportunities.

3.5.1. Proximity to sinks and storage

Numerous academic studies sought to map industrial emission sources against sink sites. Generally, these publications were orientated towards future developments, asking whether the process under consideration could provide a techno-economically viable means by which a cluster could decarbonise. Most mapping studies focussed upon opportunities for CCS [62,89,92,115–121]. By contrast, publications which mapped heat sinks and sources [122], or locations with potential for industrial symbiosis [123] were relatively few.

Proximity to suitable geological storage is clearly advantageous for clusters seeking to develop CCS since it minimises transport costs and improves technical feasibility. It is particularly beneficial for project economics if the subsurface geology is already well characterised, as is noted to be the case for many of the existing or potential coastal clusters in the UK [100], the US Gulf Coast [62,88,124] and the Port of Rotterdam [75]. Repurposing depleted gas reservoirs removes the need for decommissioning, reducing demands on the public purse.

Proximity to salt caverns for large scale gaseous hydrogen storage is also a benefit for those clusters seeking to develop this option. Salt caverns provide the best option for seasonal subsurface storage due to their low construction costs and leakage rate, high discharge rates and the minimal risks of contamination when compared to repurposing depleted oil and gas reservoirs [80]. The USA and the UK have experience in using salt caverns for hydrogen storage, but their geological availability is region specific [43]. Within the grey literature, proximity to salt caverns was mentioned as an advantageous factor in several cluster prospectuses [67,68,87], but the feature was not widely discussed in the academic literature.

3.5.2. Proximity to renewable energy sources

Access to large volumes of renewable energy supports direct electrification and powers the processes to produce green hydrogen [94]. Proximity to renewable energy resources such as offshore windfarms and large scale photovoltaic installations are noted as important features in assisting the decarbonisation of the Humber industrial cluster and China's Suzhou Industrial Park (*ibid.)* The proximity of the Port of Rotterdam to the North Sea provides opportunities for the cluster to access offshore windfarms, however, the densely populated and highly industrialised nature of North-West Europe means the region's energy demands are unlikely to be met by local renewable production and will remain dependent on imports [68].

3.5.3. Access to pipeline and infrastructure

Reusing existing natural gas infrastructure for T&S of CO_2 and hydrogen has the potential to reduce projects' capital costs, and increase their financial viability, although safety measures for transporting CO_2 at supercritical pressures through populated areas will need to be developed and existing pipelines renovated accordingly [71,94]. Access to existing pipeline infrastructure is noted as an asset in the case of clusters in Grangemouth and St Fergus, and Humberside, UK [100]; Houston, USA [124]; and for the Ports of Amsterdam [69] and Rotterdam [68] in the Netherlands. Rotterdam and Amsterdam are particularly well situated in this respect since they form key elements of the proposed national hydrogen backbone which, if it proceeds to operation, will link Dutch industrial clusters with future German and Belgian hydrogen networks [83]. Conversely, existing infrastructure may not be sufficient and require upgrading before cluster decarbonisation can occur; grid capacity constraints are noted as a limitation for electrification in the Humber region [70].

3.5.4. Port facilities

Ports possess numerous advantages as sites for industrial cluster decarbonisation. They provide a natural focus point for energy intensive industry, which often locate in their vicinity [75]. They act as logistical hubs for flows of industrial materials and wastes, providing opportunities for circular economy initiatives [102]. They are well positioned to take advantage of a future international trade in low carbon fuels, such as hydrogen and ammonia [68]. The IEA [43] notes that industrial ports are particularly suitable for hydrogen development since many of the chemical and refining installations presently using hydrogen are located in coastal industrial regions. A switch to low carbon forms of hydrogen in these areas, therefore, entails significantly lower costs than for other locations since storage and distribution systems are already in place and processes optimised for hydrogen.

3.5.5. Strategic location

Few publications expressly consider the strategic implications of a cluster's location, but when it comes to industrial decarbonisation this feature may yet come to prove one of the most important determinants of eventual success. The Port of Rotterdam is noted to be particularly well located in this respect. Firstly, in providing a politically neutral and stable base of operations [68]. Secondly, in its proximity to a complex and well established network of industrial partners; both suppliers and customers [93]. Thirdly, in its key position as the interchange between mainland Europe and the North Sea Basin [100]. This location gives it the potential to enable the deployment of CCS/CCU in other nearby industrial clusters in future, linking the industrial clusters of Antwerp, Ruhr, North Rhine-Westphalia and Le Havre [75].

3.5.6. Community support

Few papers identified in this REA explicitly addressed the importance of social acceptance to the success of cluster decarbonisation initiatives, beyond an acknowledgment that the social implications of decarbonisation technologies needed to be understood [80] and that broad stakeholder engagement would form an important part of ensuring future success [34,35,57,62,64,68,72,125]. This observation held true for the majority of industrial cluster decarbonisation studies in the corpus, not only those focussed on hydrogen and carbon capture. For example, Noori et al. [126] note a need for further research on the social factors which enable industrial symbiosis within industrial clusters while Stegmann et al. [127] note that social aspects are neglected in the analysis of circular bioeconomy cluster strategies. One exception is a paper by Sharma et al. [119] which sets out in detail the stakeholder engagement plan for developing a green-field industrial scale CCS project in Western Australia, however no further information was present in the corpus about the success or failure of this initiative.

Where the social implications of cluster decarbonisation initiatives for surrounding communities were addressed, these were generally presented uncritically in terms of projected benefits, such as job creation and preservation and the development of workplace skills [84,124,125,128]. Technology specific publications were more likely to mention the need for further development of safety measures for the T&S of CO_2 and hydrogen [71,80]. However, at present there appears to be little acknowledgement in the literature that industrial cluster decarbonisation involves the implementation of multiple novel technologies in a particular location, each carrying with it the potential for local disruption and its own safety issues. The cumulative effect of these interventions has the potential to be greater than the sum of the parts and is, we suggest, deserving of specific consideration.

3.6. Policy implications

This section provides a synthesis of the key themes alongside lessons for cluster decarbonisation policy. It is apparent that technology choice is shaping which clusters are emerging as frontrunners in industrial decarbonisation, at least within countries with mixed market economies. In countries with centrally planned economies, where state ownership of infrastructure and industrial facilities is more common, different dynamics may apply but the review uncovered limited information on this issue.

Within countries with mixed market economies, many industrial cluster decarbonisation projects appear to be carbon capture initiatives that aim to incorporate blue hydrogen as an additional revenue stream, in a bid to gain first mover advantage in the hydrogen economy [73,86]. This approach benefits clusters in countries that have existing hydrocarbon industries, that are proximate to offshore geological storage; and that have present or potential future access to large amounts of low carbon energy, through wind power, solar power, or other means. The need to gain government funding to finance carbon capture at scale advantages clusters with mature knowledge networks and a shared history of joint working. The approaches being used internationally to drive the development of low carbon industrial clusters, therefore, are presently focussed on a very specific type of cluster. While this strategy has the potential to deliver rapid decarbonisation in some high-emitting regions and countries, particularly North-West Europe where high-emitting industry is often already clustered [101], the lessons learned may have limited applicability to the remainder of the world's industrial regions. For example in China, the world's largest industrial emitter, many industrial regions are sited inland [129].

Based on this analysis, we suggest three policy recommendations to assist in driving industrial cluster decarbonisation globally. Firstly, there is an urgent need to develop policy and business models to decarbonise the industrial clusters that do not fit the pattern outlined above. A substantial body of evidence confirms that each industrial cluster is unique, emerging organically from local conditions over a period of decades [20,24,130]. As such there will be no single pathway towards industrial cluster decarbonisation, rather clusters will follow a range of paths drawing from a suite of abatement options that includes hydrogen and carbon capture technologies but also electrification and REEE [25,94]. Policy to support industrial electrification and REEE interventions did not receive a great deal of attention in the corpus, but these interventions have the potential to deliver decarbonisation in places where carbon capture is not economically viable. Industrial electrification and REEE may not be novel technologies to the extent that green hydrogen is, but they will still require government funding and policy support to implement at scale.

Secondly, the focus on carbon capture and hydrogen technologies obscures questions about the integration of these technologies with other decarbonisation interventions. They will not run along separate tracks, rather there will be trade-offs between them and the possibility for perverse incentives. Policymakers need to understand these interactions and ensure that policy takes a holistic approach. At present, there is limited consideration of this issue within the corpus. This is a significant omission since clusters do not remain static [20]. The infrastructures deployed over the next decades may not evolve as fast as the places to which they are deployed. The management of industrial decarbonisation will be an ongoing process and effective cluster policy must be flexible enough to respond to changing economic and technology environments [24,131]. Policymakers and cluster organisations must ensure that decarbonisation technologies and clusters evolve in concert if one is not to become a barrier to the other. This will require more attention to regional and local context than is presently found in the literature.

Thirdly, the present technology focus tends to ignore the historical factors which form important elements of cluster success. Present frontrunner clusters may already possess these attributes, but not all industrial clusters and regions have equal capacity to engage in the low carbon transition [61]. There are distributive justice implications for the regions without these attributes that may consequently lag in attempts to decarbonise. There is an extensive body of sustainability literature that engages with the concept of a just transition and an emerging body of work that focusses particularly on industry [132] however there was little consideration of these issues within the corpus. Future policy for cluster decarbonisation should consider how to support these areas, in addition to providing funding for infrastructure.

4. Conclusion

This review provides a summary of the available evidence on industrial cluster decarbonisation. Through a narrative analysis of 124 documents, it aims to identify the policies and business models being used to drive the decarbonisation of industrial clusters internationally and the aspects of sectoral and technological configuration, locational factors and governance arrangements that have played an important role in the most mature current initiatives. It suggests that present industrial cluster decarbonisation initiatives have specific features that may be difficult to replicate elsewhere. If clusters are to kick-start the industrial transition, then greater attention is needed to the social and political dimensions of this process and to a broader range of decarbonisation interventions and cluster types than are represented in current projects.

There are number of limitations to the REA approach. These include searches being conducted in English only, leading to a possible over-representation of European and North American initiatives within the corpus. The high proportion of grey literature reflects the nascent status of the field and the present lack of peer-reviewed literature on the topic but should be taken into account when assessing the findings of this review. Use of Google Search to identify grey literature carries with it the possibility of personalisation. We mitigated this risk as far as possible, but we cannot exclude it entirely. The use of a cut-off point for Google searching was dictated by the timeframes of the REA but means the results cannot be read as definitive. Finally, our results draw entirely upon secondary resources. As cluster decarbonisation initiatives mature, primary data collection and case study analysis focussing on the contextual factors that shape the success or failure of these projects will provide greater insight into the factors at play.

With these limitations acknowledged, the review suggests a number of avenues for future research. Chief amongst these is a greater focus on the social and political dimensions of industrial cluster decarbonisation. The present academic literature is heavily focussed on techno-economic modelling of decarbonisation interventions, despite an extensive body of literature within economic geography, innovation policy and sustainability studies on the importance of non-technical factors in galvanising or preventing change.

Greater attention is also needed to approaches to industrial cluster decarbonisation policy outside of North West Europe and North America and in particular to clusters in developing and centrally planned economies, to the integration and sequencing of decarbonisation interventions, and to the potential for industrial electrification and REEE. In future, systematic reviews of the evidence in these areas could provide greater clarity on the success of these approaches.

Industrial decarbonisation is a rapidly developing field. Since this review was undertaken, the EU Net Zero Industry Act 2023 has set an EU-wide goal to achieve an annual carbon capture capacity of 50 million tonnes by 2030. In the USA, the policy focus is on hydrogen. As of summer 2023, the Regional Clean Hydrogen Hubs competition is underway, with regional consortia bidding for a share of $7 billion to establish six to ten hydrogen hubs across America. The details of the initiatives presented in this review are likely to become out of date as events proceed, but the policy focus on carbon capture, hydrogen and competitive funding approaches for industrial decarbonisation projects at present remain constant. This review has documented what is presently known about industrial cluster decarbonisation and set out the areas where further research is required. In doing so it has provided a benchmark against which future developments can be assessed.

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CRediT authorship contribution statement

Imogen Rattle: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. **Peter G. Taylor:** Conceptualization, Resources, Writing – review & editing, Supervision.

Declaration of competing interest

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

Data availability

Appendix C provides a complete list of the publications included in the corpus

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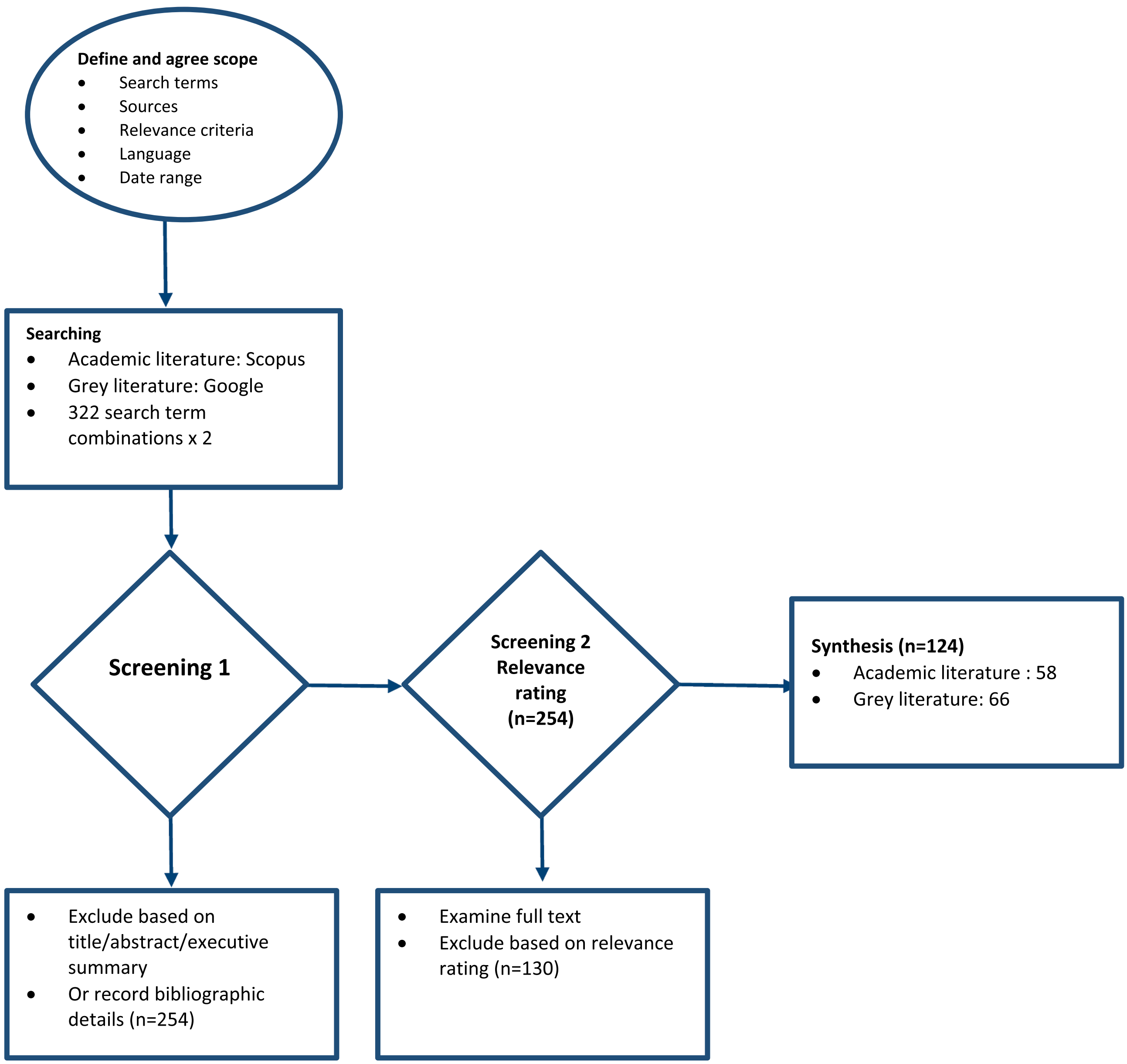
Appendix A. Search terms

Technology, sector and decarbonisation keywords	AND	Co-location keywords	AND	Policy keywords
Industr* decarboni*ation OR				Innovat* OR
"Energy intensive" OR				R&D OR
Steel OR				"Research and development" OR
Cement OR				Financ* OR
Refining OR Refinery OR				Grant* OR
"Chemicals industry" OR				Incentive* OR
Glass OR				Loan* OR
Paper AND Pulp OR				Subsid* OR
Ceramics OR				Tax* OR
Food AND drink				Polic* OR
Kiln* OR		Cluster OR Clusters OR Hub* OR Consortium		Regulation* OR
Foundr* OR				Standard* OR
Furnace* OR				Instrument* OR
"Green hydrogen" AND industr* OR				Business AND model*
"Clean hydrogen" AND industr* OR				
"Blue hydrogen" AND industr* OR				
Electrification AND industr* OR				
"Carbon capture" AND industr* OR				
CCUS AND industr* OR				
DACCS AND industr* OR				
"Greenhouse gas removal" AND industr* OR				
GGR AND industr* OR				
"Negative emissions" AND industr*				

Appendix B. PRISMA flow diagram



Appendix C. Documents included in corpus

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