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Original research article

Transitioning or tinkering at a net-zero economy? Introducing an assessment framework for industrial cluster decarbonisation in the United Kingdom

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ABSTRACT

Decarbonising industrial clusters globally is crucial in combating climate change and is integral to the United Kingdom's ambition of achieving a net-zero economy by 2050. The absence of holistic frameworks that provide a nuanced understanding of the broad spectrum of mitigation options for decarbonising industrial clusters, coupled with a deficiency in real-world empirical evaluations, present a substantial barrier in realising set targets for reducing CO_2 emissions. The increasing fragmentations in industrial decarbonisation frameworks further exacerbates the challenge of identifying the necessary and sufficient actions for achieving optimal industrial decarbonisation and net-zero transitioning. This paper proposes an assessment framework for industrial cluster decarbonisation and aims to address the existing gaps, particularly in the assessment of social, economic, and environmental impact of any deployed technology. Focusing on a wide range of technologies, sectoral strategies, and regional dynamics, the proposed framework is driven by specific key performance indicators and a comprehensive human and data-driven analytical approach that reflects descriptive, diagnostic, and prescriptive insights on the Teesside industrial cluster in the United Kingdom. Following the validation of the proposed assessment framework, empirical findings from 30 in-depth semi-structured interviews, two workshops, focus group meetings and the literature on industrial decarbonisation reveal that the framework recognises the complex interplay of technology and decision-making in the transition to net-zero of industrial clusters. The article concludes that the proposed assessment framework can assist stakeholders, policymakers, and researchers in assessing the impacts of energy transition, which is critical to policy design and decision-making while also contributing to achieving sustainable decarbonisation goals.

1. Introduction

In view of the Climate Change Challenge, the 2015 Paris Agreement states the need to transition towards 'carbon neutrality' greenhouse gas (GHG) emissions. European Union (EU) countries are required to intensify their policies and strategies towards the aim of the Paris Agreement, i.e., to support the global response to the climate change challenge by maintaining global temperature rises down to 1.5 °C [1,2]. In the last two decades, the EU has made significant commitments to stabilising the global climate challenge. In December 2019, the EU member states decided to achieve 'climate neutrality' by 2050 to align their commitments with the Paris Agreement on climate change. The commitments are part of a wider initiative on the 'European Green Deal' with wide-ranging policy initiatives to transition to a sustainable economy. Likewise, a 'European Climate Law' was proposed in March 2020 to achieve a legally binding climate neutrality target across the EU [3–5]. The UK and some EU nations, such as France, Germany, Italy, Spain, and the Netherlands, have established a 2050 target date and propagation support across the EU (EU-27). Some Nordic EU member countries have implemented stricter targets: Norway, Finland, Iceland, and Sweden have decided to achieve 'climate neutrality' by 2030, 2035, 2040 and 2045, respectively [6].

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In the UK, a net-zero (carbon neutrality) legally binding target by 2050 was introduced in June 2019, thus, positioning the UK as the first major economy that passed a net-zero emissions law. Also, the UK government reviewed its Climate Change Act (CCA) to include the revised net-zero GHG emissions target and queried the Climate Change Committee (CCC) on the reliability of achieving the net-zero target by 2050. The CCC argued that the net-zero targets by 2050 are feasible with advanced technologies, improvements in people's lives, and expected economic cost, incorporating a well-designed policy that would reduce emissions further across the UK's economy [7]. Grand Challenges have been set through the industrial strategy to attract inward investment, innovation, new business, new technologies, and employment opportunities. The Industrial Clusters Mission (ICM) would establish the world's first net-zero carbon industrial cluster by 2040 and four low-carbon clusters by 2030, aimed at enhancing green industrial revolution by developing global low-carbon technologies, services, and systems to support climate change [8]. However, achieving the net-zero target requires extensive innovative and systematic change across all industrial sectors.

Furthermore, the industrial decarbonisation strategy (IDS), which illustrates an indicative roadmap on how the UK can maintain a thriving industrial sector that aligns with the net-zero target without pushing emissions and business abroad, was designed. The strategy includes the UK industry sectors such as metals and minerals, chemicals, food and drink, paper and pulp, ceramics, glass, and oil refineries and less energy-intensive manufacturing such as vehicles, wood products, pharmaceuticals, and electronics. The UK industry sector's businesses are responsible for one-sixth of UK emissions; thus, the transformation of the manufacturing processes is fundamental to achieving the UK emissions targets over the next decades. Likewise, the Ten Point Plan is implemented in the UK for a Green Industrial Revolution (GIR). Based on the Ten Point Plan, the industrial decarbonisation strategy establishes the government's vision for a low-carbon UK industrial sector in 2050, which provides the long-term certainty the industry needs to invest in decarbonisation [9]. The Ten Point Plan sets out the UK government's approach that supports development, green jobs, and acceleration of the net-zero target.

Nevertheless, transitioning to carbon neutral economy is a core challenge for the state and stakeholders involved, including policymakers. On the pathway to achieving the decarbonisation targets, the state and policymakers are faced with a series of hard choices relating to the level of funding for reasonable decarbonisation actions and other supports required for research, development, and deployment of strategies and technologies. Considering the resource constraints, feasibility, and applicability of many proposed technologies, the measure of successful decarbonisation hinges upon adopting a systematic approach to effectively assess the potential benefits and impacts of any deployed technology. It has been suggested in the literature [10,11] that developing an assessment framework can significantly support the evaluation of the impacts of the strategies aimed at reducing carbon emissions and therefore provides stakeholders and policymakers with a further option when planning to achieve net-zero targets. This will, in turn, help to mitigate technology investment risk while considering social factors such as job and unemployment. However, the systematic approach to assessing the impacts is a challenging process that requires a plethora of human and data-driven analytical approaches to evaluate and quantify their benefits both technically, economically, socially, and environmentally.

This paper presents an effective assessment framework explaining the processes to guide the development of decarbonisation options assessment on industrial and wider economic activities. The proposed framework involves stakeholder engagement throughout the assessment process and is driven by strategy-specific Key Performance Indicators (KPIs) that can be used to evaluate CO_2 emissions, energy use, investment cost, the socioeconomic and environmental impacts of net-zero transition, and a comprehensive human and data-driven analytical approach that reflects descriptive, diagnostic, and prescriptive insights on the industrial cluster. KPIs are essential in industrial cluster decarbonisation frameworks because they provide baseline metrics to benchmark progress and optimise solutions tailored to local industrial cluster contexts. Availability of appropriately selected KPIs can help stakeholders track and manage the transition to cleaner energy sources, ensuring that actionable net-zero transition goals are defined and achieved. This enables well-informed decisions aligned with wider environmental, economic, and social goals. However, choosing the right KPIs is not a trivial task, as different technology options may have different impacts and trade-offs on various aspects of net-zero emissions transition. Therefore, a broad and flexible assessment framework is needed to evaluate the full benefits and potential impacts of decarbonisation technologies. Such a framework can help to identify the most suitable technology options for achieving net-zero emissions, as well as the potential barriers and enablers for their deployment.

Although there is no magic solution to evaluate the full benefits and potential impacts of decarbonisation technologies, our proposed assessment framework is flexible enough to adapt to changes in technology and policy. It recognises the complex interplay of technology and how the transition to low-carbon energy shapes decision-making, or conversely, how policy influences the development and transition to net-zero of industrial clusters while also contributing to sustainable decarbonisation goals. The rest of the paper is organised as follows: Section 2 presents a background and overview of the UK industrial cluster, and a comprehensive review of both global and regional industrial decarbonisation frameworks. In Section 3, the overview of research methodological framework and the proposed industrial decarbonisation assessment framework are presented. Validation of the assessment framework, discussion, research limitation and recommendations for future research are presented in Section 4. Section 5 concludes the paper.

2. Background

Over the years, numerous industrial decarbonisation frameworks have emerged for evaluating the transition to a net-zero landscape. To explore the complex landscape, we present a comprehensive assessment of both global and regional paradigms. Our scrutiny delves into the transition pathways, the specific decarbonisation framework, their key characteristics, strengths, and inherent limitations. This broad overview will lay the foundation for developing an industrial cluster decarbonisation framework which can be adapted to various geographic settings.

2.1. Related work

The authors in [10] utilised an integrative framework for stakeholder engagement which provided a retrospective guidance for designing a Just transition. Although the authors explored multiple themes linked to net-zero transition based on diverse perspectives, the practical implementation of their considered Just transition pathways could be problematic due to the qualitatively framed context of the study. In [11], their industrial decarbonisation model was framed using broad concepts and policies aimed to drive private sector involvement in clean innovation technologies. Although the research adopted a simplified approach encompassing an economy-wide transformative interdisciplinary approach, it lacked specific sectorial implementation strategies potentially leading to challenges in real-world application. A generalised industrial decarbonisation framework was introduced by [12], covering three core processes and multiple pathways: (i) a dematerialisation or recycling pathway; (ii) retention of core existing processes or implementation of fundamental alterations pathways; and (iii) a decision on whether to pursue carbon capture and storage (CCS) or GHG free heating sources. While the study addressed the policy, economic, and technological aspects of various decarbonisation pathways, it overlooked the development of a comprehensive and adaptable climate model capable of dynamically adjusting to multiple decarbonisation scenarios. A robust climate model is essential for providing a more nuanced understanding of the complex interactions between policy, economics, and technology and is crucial for assessing the potential impacts and effectiveness of different decarbonisation strategies and decision-making processes. The authors in [13] introduced a decarbonisation framework for the global industry between 2020 and 2070, aiming to achieve rapid decarbonisation with limited consideration for future outcomes. Despite encompassing a comprehensive evaluation of decarbonisation interventions across the demand and supply sides, integrating technological, social, economic, and policy dimensions, using analytical tools to model the intricate interplay among these crucial facets dynamically was neglected. Consequently, the absence of such modelling hindered the holistic understanding of the resulting impacts of the decarbonisation strategies considered.

The study in [14] developed an integrated assessment framework (IMAGE) to simulate interactions between society, the biosphere, and the climate system. The framework allowed the exploration of long-term dynamics and impacts of global changes resulting from socioeconomic and environmental factors. The framework comprises system-dynamic sub-models representing historical and potential future responses with predefined set of rules and rule constraints. However, combining all decarbonisation strategies dynamically posed challenges for the researchers and resulted to inconsistencies. Furthermore, their modelling framework encountered difficulties in accurately depicting net-zero carbon and alternative pathways towards achieving full decarbonisation within the industrial sector. These challenges emphasise the need for further refinement and enhancements to industrial decarbonisation frameworks to adequately capture and represent the complexities inherent in the dynamic interactions of decarbonisation strategies and the achievement of complete decarbonisation in the industry sector.

In [15], the authors introduced an optimisation framework, enabling the optimisation of complex problems with multiple objectives. The framework was exemplified using the case of the carbon capture and utilisation (CCU) system for an industrial park. To identify the system's optimal performance concerning environmental (CO_2 emission reduction) and economic aspects, the researchers devised an optimisation framework using artificial neural network (ANN)-based surrogates, allowing simultaneous cost-efficient optimisation. Their study also examined the dual effect of carbon pricing on the CCU system. Predicting the impact of carbon taxes on the techno-economic performance of CCU has always proved to be a complex task; thus, they proposed an optimisation approach that can serve as a valuable tool for determining the optimal solution under various carbon price scenarios. A critical drawback of their industrial decarbonisation framework is the fundamental disregard for deploying renewable energy sources. This limitation poses a grave concern as it offers a solution independent of the growth and development of the renewable sector, thereby hindering the urgent need for sustainable and environmentally friendly energy alternatives. This emphasises the necessity for comprehensive and inclusive approaches that prioritise integrating and expanding renewable energy sources in decarbonisation strategies. Furthermore, the authors' optimisation framework overlooks important social implications of transitioning to a net-zero economy, particularly the potential for job creation. The framework does not adequately consider the wider societal impacts of achieving net-zero emissions targets by overlooking this aspect. A more comprehensive and inclusive approach is needed to ensure a just transition considering decarbonisation's environmental and socioeconomic aspects.

Moving to regional decarbonisation assessment frameworks, the study in Asia [16] employed a multi-region Asia-Pacific Integrated Model (AIM)/End-use recursive-dynamic energy system framework based on the Cplex solver in the General Algebraic Modelling System (GAMS) to analyse industrial decarbonisation in the context of global net-zero CO_2 emissions. The AIM/End-use model utilised a detailed technology selection framework from 2010 to 2050 and employed linear programming algorithms to identify the technology options that minimise system costs while meeting external service demands and achieving a specific level of GHG emission reduction. However, it is important to acknowledge the limitations of the applied modelling framework. The authors focused on technological pathways for emissions reduction, without incorporating broader societal transitions that could also impact emissions. This highlights the necessity of exploring alternative methodologies and considering a broader range of factors beyond technological constraints.

Furthermore, the authors in [17] focused on analysing alternative CO_2 peaking-net zero scenarios for India's energy sector, considering breakthrough technologies that could rapidly advance in price and deployment under an optimistic scenario. They utilised the Global Change Analysis Model (GCAM) to assess sectoral pathways towards a net-zero future in India. To analyse net-zero scenarios within GCAM, exogenous emission constraint trajectories were provided to limit emissions at specific levels, and the model estimated the carbon price required to achieve these constraints using an emission constraint approach. The model iteratively determined the most cost-effective methods to meet the emission constraints, inducing energy system transformations towards cleaner energy sources across sectors. However, the framework employed in the study has certain limitations. Firstly, it solely focuses on CO_2 emissions from India's energy sector, neglecting other GHG emissions that contribute to the total emissions profile. Moreover, the modelling approach primarily emphasises the implications of economic choices, which is an important factor but not the sole determinant of a successful transition to net-zero. The study did not incorporate other critical elements, such as social and political factors, that also play pivotal roles in shaping the pathway to a sustainable future. Also, it is important to note that the framework utilised in the study has a restricted range of technology options, focusing solely on CCS and Hydrogen. This limited selection of technology options may overlook other innovative and promising solutions that could contribute to the net-zero transition. Considering a broader array of technology alternatives would provide a more comprehensive and diverse analysis of the pathways towards achieving a sustainable and decarbonised future.

In Europe, the researchers in [18] proposed a comprehensive six-pillar framework for industrial decarbonisation policy, which can be tailored to different national and regional contexts. The framework considers factors such as access to cleaner feedstocks and energy sources and local versus global perspectives, which influence the six pillars in diverse ways. The pillars include policy directionality, knowledge creation, market creation, governance and change capacity building, international policy coherence, and socioeconomic implications. The authors emphasise the importance of policy strategies encompassing all mitigation options, ranging from material demand management to electrification and CCS. However, a significant limitation of their framework is the lack of a holistic and integrated assessment of the identified six pillars. While each pillar is individually recognised, the framework fails to analyse the interactions and interdependencies among them comprehensively. A more integrated approach considering how the pillars influence and reinforce one another would offer a more robust foundation for developing effective industrial decarbonisation policies. Furthermore, the study did not address a quantitative assessment of the impacts of implementing an industrial policy framework on the transition to net-zero emissions. The absence of a quantitative evaluation limits the ability to conduct a robust assessment of the issues using data analytics. Without quantitative analysis, estimating the potential effectiveness, costs, and trade-offs associated with different policy interventions within the framework becomes challenging. This underlies the need to develop an integrated assessment framework that explores interactions and synergies of its elements. Additionally, conducting quantitative evaluations of the impacts of industrial policy frameworks on net-zero transitioning would provide valuable insights for policymakers and stakeholders, enabling informed decision-making and effective resource allocation towards achieving sustainable and decarbonised industrial clusters.

The authors in [19] introduced a source-to-sink assessment methodology for hydrocarbon-limited countries, employing a ‘hubs and clusters’ strategy. They applied this methodology in a case study focused on Spain. The framework identifies emission hubs in various industrial sectors as sources of CO_2 emissions for potential CCS deployment. The framework selects each emission hub's priority storage structure and alternative backup structures through a systematic screening and ranking process using the multi-criteria decision-making (MCDM) method. One significant advantage of the hubs and clusters framework is its potential to reduce the development cost of CCS deployment by enabling multiple CO_2 emitters to share infrastructure such as pipelines and storage complexes. However, the primary limitation of the framework stems from its reliance on the screening and ranking process facilitated by the MCDM method. While this approach aids in decision-making based on multiple criteria, its capacity to capture the dynamics of decarbonisation, perform scenario modelling, and predict and optimise future scenarios is considerably limited. Consequently, the insights obtained from the framework may be constrained due to its inability to comprehensively account for complex and evolving factors related to industrial cluster decarbonisation. To address this limitation, it would be beneficial to explore complementary or alternative methods that offer more comprehensive scenario modelling capabilities.

Table 1 provides an overview of the existing literature on decarbonisation frameworks pertaining to different regions of the world. The overview highlights the technology pathways, their characteristics, strengths, and inherent weaknesses. Thus, paving a way to exploring the trends and key themes emerging from the surveyed literature, shedding light on the popularity of certain decarbonisation technologies, the relevance of KPIs, and the need for more comprehensive frameworks.

A notable trend in the surveyed literature on industrial decarbonisation frameworks, showcasing various authors' strategies, pathways, and models to achieve a net-zero transition pathway presented in Table 1 is the prominence of carbon capture, electrification, and the utilisation of hydrogen as essential components of industrial decarbonisation. These technologies are widely acknowledged for their potential to reduce industrial emissions. However, the specific implementation strategies for these technologies can vary significantly across different frameworks. For example, the UK's framework in [20] employs a net-zero principles that encompasses carbon capture, considering the economic and societal factors associated with its deployment. Meanwhile, Japan's model [16] emphasises technical mitigation options like hydrogen and electrification, highlighting the diverse approach taken by different regions and countries. Although the technology readiness level of Hydrogen remains low in most cases, with many frameworks targeting demonstration and pilot projects [29], the technology option appears poised for growth. Recent research suggests that hydrogen is viewed as a technology with a relatively high readiness level for industrial cluster decarbonisation [30]. Several studies, including those from Spain [19] and the UK [20] highlight the potential of hydrogen as a key enabler in reducing emissions. However, it is essential to acknowledge that the practical applicability and scalability of hydrogen-based solutions in real-life contexts still necessitate further examination and evaluation. While carbon capture remains a critical technology in several industrial decarbonisation frameworks, there is no consensus on its inclusion or phasing out. In the UK, the research community focused on CCS hold contrasting perspectives regarding the technology's economic potential and adoption rates [31].The UK's [20] approach considers carbon capture in the context of net-zero principles, focusing on its political and economic aspects. However, some frameworks, like Spain's [19], rely on a multi-criteria decision-making method for carbon capture, indicating that its effectiveness may vary based on specific contexts and technologies. This diversity in approaches underlines the need for careful consideration of the role of carbon capture in industrial decarbonisation.

Key Performance Indicators (KPIs) play a critical role in evaluating the effectiveness of industrial decarbonisation models. These KPIs are often context-specific and reflect the unique objectives of each framework. A review of the studies in Table 1 highlight the importance of considering various dimensions, including environmental, economic, technical, policy, social, energy security, thermodynamics, and geographical factors when assessing the impact of decarbonisation efforts. However, a common limitation is the lack of a holistic integrated assessment framework that quantifies the collective effects and trade-offs between supply and demand-side actions [13].

Some limitations can be found from the corpus of literature as summarised in Table 1. Overall, while most of the studies offer valuable insights into specific aspects of decarbonisation, such as technology, economic, and policy dimensions, they often fall short of providing a holistic and detailed understanding of the broad spectrum of mitigation options available for industrial cluster decarbonisation. Another drawback is the narrow focus on specific technology options and the absence of empirical evaluation in real-world contexts. For example, the global framework in [11] provides a broad overview of policies but lacks specificity on sectoral strategies and regional dynamics, hindering its usefulness in practice. This limitation is reflected in other frameworks (e.g., [22,24]) that prioritise theoretical perspectives over empirical evidence, making it problematic to adapt these models for use in industrial settings. To address these gaps, innovative approaches are imperative. An in-depth framework for industrial decarbonisation should encompass a wide range of technologies, sectoral strategies, and regional dynamics. Such a framework should be built on dynamic modelling and analytical tools that can adapt to the evolving industrial landscape. It should also consider societal changes, and cost-effectiveness alongside technological options to achieve sustainable and responsible transition to net-zero. The integration of systems modelling and policy analysis, that adapts to the evolving industrial landscape is imperative. This enhanced framework would foster more robust and practical assessments of decarbonisation strategies and contribute to the expedited transition of industrial clusters towards a net-zero economy. The following section provides an overview of the UK industrial cluster, including the operation of Teesside industrial cluster, used as a case study in the current research.

2.2. *UK industrial clusters*

UK industries consist of about 350 separate combinations of subsectors and technologies devices [32]. The UK manufacturing processes range from highly Energy Intensive (EI), such as steel production and chemicals processing, to Non-Energy Intensive (NEI), such as electronics fabrication. Typically, the EI subsectors utilise large quantities of high-temperature process energy, while the NEI subsectors tend to be dominated by the energy associated with space heating. The UK GHG emissions from industrial sectors are illustrated in Fig. 1. Steel, chemicals, cement, aluminium, glass, ceramics, and lime are the subsectors releasing significant process emissions [6].

The UK industrial cluster consists of many industrial sites within proximity to one another. Table 2 shows the UK industrial clusters with their respective emissions levels, including Humberside, South Wales, Merseyside, Teesside, Grangemouth, Southampton, and Black Country [33].

The businesses in each industrial cluster often share resources and infrastructure, and are seen as important hubs of economic activity as they secure 1.5 million jobs, export goods and services worth £320 billion, and have £150 billion Gross Value Added (GVA) to the UK economy [34]. However, they also emit carbon significantly and contribute to climate change, accounting for 25 % of the UK GHG emissions, with more than two-thirds of emissions coming from EI industries [35]. The industrial clusters have set a goal to establish the world's first net-zero carbon industrial cluster by 2040 and at least one low-carbon cluster by 2030 [36,37]. Various sectors are co-located and

Table 1
A summary of industrial decarbonisation framework literature.

Author	Country	Transition pathway (s)/options	Industrial decarbonisation framework	Framework evaluation process	Key framework characteristics	Strengths	Limitations
[10]	UK	Just transition pathways	An integrative framework for stakeholder engagement in just transitions based on 14 relevant themes	Provides retrospective guidance for designing a just transition	Evaluative themes exploring the justice issues of industrial cluster decarbonisation namely: politics, space, and institutions; new processes and procedures; and correlates of acceptance and resistance.	Key strengths include extensive literature review, prioritisation of diverse stakeholder voices, and utility for both prospective guidance and retrospective evaluation	Limited implementation strategies for each pathway can lead to difficulties in translating the framework into practical real-world settings
[11]	Global	Clean energy technologies; zero-emission vehicles; CCS; and energy efficiency	Concepts and policies framing to enable innovation and growth towards net-zero emissions	Broad overview and synthesis of theoretical and empirical evidence on policies	Economy-wide policies and institutional changes to promote and manage private sector investment in clean innovation technologies	Economy-wide transformative approach using innovation theory and political economy based on interdisciplinary perspectives	Lack of specificity on sectoral strategies and regional dynamics, and the absence of empirical evaluation in real-world settings has implications for its capacity to address the unique challenges and opportunities within different industries and geographic areas, alongside its practical applicability.
[12]	Global	Recycling; alterations pathway; and CCUS/GHG free heating sources such as solar thermal, biomass, synthetic methane, etc.	Generalised energy-intensive industry decarbonisation options	Decision Tree analysis of decarbonisation choices and options	Initial integrated approach for a well-managed transition, aiming to minimise stranded assets, unemployment, and social distress	The framework is multi-dimensional, exploring policy, economic, and technological aspects of various decarbonisation pathways	Overlooked the development of a comprehensive and adaptable climate model capable of dynamically adjusting to multiple decarbonisation scenarios
[13]	Global	Energy efficiency; CCS; Electrification; Hydrogen; carbon substitution; and circular economy Interventions	Generalised supply and demand-side decarbonisation framework	Qualitative evaluation of various supply-side and demand-side mitigation options	Evaluation of supply and demand-side technical and policy interventions	The decarbonisation framework encompassed the major options across both supply-side and demand-side intervention measures, providing an expansive overview of the available technologies and policy measures.	The framework falls short of presenting a comprehensive integrated assessment model that quantifies the collective effects and trade-offs between supply and demand-side measures
[14]	Global	Bioenergy; CCS; electrification	Recursive-dynamic IMAGE integrated assessment model	Model's robustness evaluated by assessing its responses to four distinct decarbonisation narratives in six global regions	Assesses models' decision-making capacity and adaptability in selecting among technology options, energy efficiency, and fuel substitution alternatives	Investigated net-zero pathways for major industrial sectors and value chain; captures multiple technology options; and captures differing regional dynamics across multiple regions.	Limited integration across sectors. Beyond carbon pricing, there is a clear need for coupling between industry decarbonisation initiatives and the broader framework of energy system transformation
[15]	EU	CCU and electrification	Multi-objective Optimisation framework of an integrated CCU system	Hypothesised industrial park case study digitalised with neural network surrogates and optimised for GHG emissions reduction and economic performance via 3-level approach		The framework balances environmental and economic objectives, and explores a level of interactions between the sub-systems involved in their framework	It considers only environmental and economic aspects and overlooks societal considerations, which could lead to an incomplete and potentially unsustainable approach. The presented multi-objective optimisation framework was only implemented using a hypothetical case, thus practical application and scalability in real-

(continued on next page)

Table 1 (*continued*)

Author	Country	Transition pathway (s)/options	Industrial decarbonisation framework	Framework evaluation process	Key framework characteristics	Strengths	Limitations
							world settings remains to be tested.
[16]	Japan	Bioenergy with CCS; energy efficiency improvements; utilisation of low carbon energy carriers; nuclear power; Hydrogen; electrification	Multi-region AIM/ End-use Recursive Dynamic Model	2050-based modelling of the modified AIM/End-use model under different scenarios for technology availability and CO_2 emission constraints	Features detailed bottom-up systems optimisation pathways for Japan across all energy demand and supply sectors	An expansive framework encompassing costs and policy implications of different ambition levels	Focused only on technical mitigation options and ignores societal implications of the modelled scenarios
[17]	India	Alternative peaking and reduction of CO_2 emissions via Renewables; solar; nuclear; CCS; hydrogen; electrification; biofuels; and energy efficiency.	Global Change Analysis Model (GCAM)	Evaluated through scenario analysis using GCAM to assess alternative peaking years, net zero target years, and technology availability	Mainly involves transitioning from high fossil fuel sources to electricity, CCS, and hydrogen in industry to achieve deep decarbonisation	Sets emission constraints, estimates the required carbon price, and iteratively determines cost-effective methods for achieving these constraints within India decarbonisation context	Overlooks wider transformative systemic changes beyond technological solutions such as societal changes, that could impact emissions
[18]	EU	Materials efficiency, recycling, demand reduction, and circular economy approaches using energy efficiency, etc.	Comprehensive policy approach built on six pillars	Evaluated by synthesising perspectives from diverse literature and formulating a structured policy framework.	Broad, multifaceted policy approach encompassing technology, governance, markets, and social dimensions	The framework adopted a comprehensive multifaceted approach	Framework neglected the aspects of empirical analysis and demonstration / operationalisation using real-life settings
[19]	Spain	CCS; bioenergy with CCS; hydrogen; renewables; energy efficiency; and electrification	Source-to-sink assessment framework based on a ‘hubs and clusters’ approach	Using MCDM method to rank potential storage structures for CO_2 emission hubs in Spain	Characterised by hub-and-cluster -based matching of industrial CO_2 emitters and storage structures for cost-effective, large-scale CCS development.	The framework is comprehensive in nature, encompassing the consideration of different decarbonisation technologies, and the potential for significant CO_2 emissions reduction.	Reliance on the MCDM method for decision-making, which is not very effective in capturing the dynamic and complex aspects of industrial cluster decarbonisation. Its potential to provide an in-depth understanding of the issues related to net-zero transitioning is constrained.
[20]	UK	CCUS	Net-zero principles framework stages	Based on socioeconomic questions covering the framework stages	CCUS with political-economy context; characterised by the application of net-zero principles considering economic and societal factors.	The Framework considers the political economy of net zero ambitions, including the Just Transition and broader fiscal issues.	Application to the case of CCUS was primarily qualitative, limiting the ability to quantify and analyse the dynamic aspects of CCUS deployment
[21]	UK	CCS and Hydrogen	System business modelling based on the Resource Technology Network (RTN) framework	Industrial clusters use case analysis	Hydrogen production with CCS (H_2-CCS) in large scale; CO_2 storage capacity (Mt per year); gas distribution network conversion rate to H_2, CCS, CO_2 emission.	The framework enables integrated techno-economic modelling to assess different decarbonisation pathways, including the use of H_2 and CCS at scale.	The focus was on CCS and hydrogen, thus overlooks the potential contributions of other innovative and emerging technologies
[22]	UK	Pre-covid energy futures versus post-covid energy futures	Energy futures framework utilising a participatory qualitative future by engaging stakeholders	Use case analysis based on future scenarios	Evaluative themes exploring the following qualitative drivers such as cost and affordability, equity or fairness, activism, resistance to change, and preservation.	The Futures framework is participatory and explore a wide range of plausible decarbonisation futures amidst uncertainty.	Mainly a qualitative approach and unsuitable for predicting future scenarios based on advanced dynamic modelling
[23]	UK	Clockwork, Patchwork, Leading the Way, System and consumer Transformation, Zero Carbon Britain, and Balanced Pathway	Analysis of seven UK net-zero pathways based on energy demand, behavioural shifts, policy measures, end-use systems, and supply of electricity and hydrogen	Comparative evaluation of multiple pathways	Common features of the seven decarbonisation pathways: Heating demand and supply, transport demand and supply, industrial demand, land use and biomass, emissions removals, hydrogen and low carbon fuels,	The framework can identify key trends and trade-offs across different pathways providing insights into key technologies, infrastructure, and system integration challenges	The framework does not fully analyse and capture the dynamic nature of net-zero scenarios, thus limiting the study's ability to provide a comprehensive and tailored approach for modelling and assessing

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Table 1 (*continued*)

Author	Country	Transition pathway (s)/options	Industrial decarbonisation framework	Framework evaluation process	Key framework characteristics	Strengths	Limitations
					electricity demand, electricity mix, storage and flexibility, lifestyle, and behaviour.		complex dynamics of transitioning to a net-zero future
[24]	UK	Industrial cluster decarbonisation of the Northwest region of England through the transition to a hydrogen economy	Extension of Accelerating and Rescaling Transitions to Sustainability (ARTS) framework based on stakeholder interviews	Use case evaluation	Acceleration of hydrogen transitioning based on five acceleration mechanisms namely replicating, upscaling, instrumentalising, partnering, and embedding	Provides an empirical analysis of challenges and strategies for accelerating the transition to hydrogen based on local sustainability transition initiatives	Mainly a qualitative approach. The described ARTS framework would benefit from more empirical evidence on the effects of the mechanisms on net zero transitioning within the context of an industrial cluster
[25]	UK	CCS industrial cluster decarbonisation pathways	The social Licence to Operate (SLO) framework comprises seven pillars based on cluster mapping, documentary analysis, and in-depth interviews.	Industrial clusters use case analysis	CCS based on Social Licence to Operate (SLO), examining social indicators pertinent to industrial cluster decarbonisation	Provides an in-depth analysis of social licence dynamics and stakeholder narratives to inform acceleration of CCS deployment	The framework is qualitatively framed but has limited quantitative assessment of the effectiveness of CCS in achieving decarbonisation targets for industrial clusters
[26]	UK	2050 net-zero Industrial cluster decarbonisation	RTN-based Mixed integer linear programming (MILP) framework. Optimises costs, emissions savings, and other impacts	Validated using a hypothetical cluster to a toolkit developed from the framework	Various hydrogen and CCUS-based KPIs linked to multi-domains, such as environmental, technical, economic, policy, social, energy security, thermodynamics, and geographical	The framework promotes the adoption of a cluster perspective rather than a site-based approach to industrial decarbonisation, thus facilitating improved efficiencies through co-dependency problem analysis	The framework was implemented using a hypothetical small cluster with arbitrary high-level cost assumptions. A real-word industrial site/cluster would more effectively provide practical understanding of carbon capture strategies, addressing the nuances and complexities of real industry scenarios.
[27]	UK	Cluster decarbonisation framework	'Outside-in' and 'inside-out' framework lens focusing on technology, stakeholders, and institutions	Industrial cluster use case analysis	CO_2 emissions reduction, hydrogen production capacity, total capital investment	By analysing net-zero transition of a real-world case study from a socio-technical lens, the framework shapes the inclusion of complex dynamics associated with net zero transition of industrial clusters	The framework drew qualitative insights from the megaproject literature but did not include a concrete assessment methodology for the net-zero transition in the Humber cluster, which could limit its ability to provide a robust and practical approach for evaluating the transition process in the specific context of the Humber cluster. Wider impacts of the megaproject such as job creation and losses were also not integrated in the framework.
[28]	UK	Environmental sustainability, energy decentralisation via a hydrogen economy	The social construction of technology framework with social groups, interpretive flexibility, technological frames, and closure/ stabilisation aspect	Industrial cluster use case analysis	Various hydrogen and CCUS indicators examined on multi-domain concepts namely: technical, economic, political, and socioenvironmental dimensions	The strength of the decarbonisation framework lies in its adoption of a socio-technical perspective, examining the interests and interpretive frames of different stakeholder groups, offering a deeper insight into the societal factors that influence decarbonisation mega projects	The study's exploration of net-zero frames encompassing political, economic, technical, and socio-environmental dimensions lacked a quantitative assessment of emission reductions, thus undermining its ability to provide concrete and measurable insights into the effectiveness of different approaches in achieving substantial emission reductions

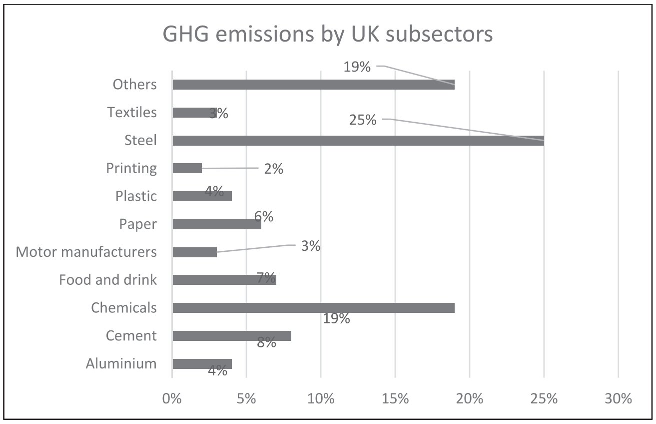

Fig. 1. UK industrial greenhouse gas emissions [6].

Table 2
UK industrial cluster breakdown by sector [33].

UK industrial clusters	GHG emission ($MtCO_2$)
Humberside	12.5
South Wales	7.3
Merseyside	6.3
Teesside	6.1
Grangemouth	5.0
Southampton	3.5
Black Country	1.4

functionally connected in the UK industrial cluster involving suppliers, manufacturers, service providers and other business organisations who consume gas, electricity, heat, steam and/or feedstock in their production or operation. Meanwhile, a range of technologies could be adopted for decarbonisation. For instance, switching to alternative fuel such as hydrogen and bioenergy; integrating renewable energy; electrifying heat; recovering heat; storing energy; improving energy efficiency; capturing, utilising, and storing the captured carbon emissions, etc. These technologies could be applied in different combinations, considering investment costs, finance and return on investment, performance, savings in operation cost, reduction in carbon emissions, and regulatory requirements to define net-zero pathways that would meet the needs of the stakeholders. As such, decarbonising industry sectors is complex but currently most industrial stakeholders have no or very limited experience and knowledge in defining their decarbonisation strategy. Altogether, this presents huge interdisciplinary challenges.

Teesside serves as a representative case study among the various industrial clusters in the UK, allowing for a comprehensive understanding of the challenges and opportunities specific to UK's regional decarbonisation efforts. Teesside is a region in the Northeast of England with five distinct boroughs: Darlington, Hartlepool, Middlesbrough, Redcar and Cleveland, and Stockton-on-Tees. Tees Valley Combined Authorities (TVCA) have jointly represented these five boroughs since April 2016. Teesside has the UK's first Net-zero power plant and the world's largest biomass power plant [34]. The Teesside region is a high energy intensity area due to the huge concentration of energy-intensive industrial activities, with five power plants producing 1449.3 MW, with nuclear energy contributing 81.7 % of the energy production capacity [38]. The Teesside region comprises the UK's largest chemical cluster, one of the largest associated GHG emissions, and the second-largest carbon emission region in the UK [39,40]. The region has different types of chemical industries: hydrocarbon separations, petrochemical manufacturing, pharmaceuticals, etc., as shown in Fig. 2 below. The chemical industry is concentrated across three main areas in Teesside: Billingham, Wilton, and Seal Sands/North Tees, about 12 miles east to west on either side of the River Tees [34]. The major source of emissions in the Teesside industrial comes from the chemical, waste collection, treatment & disposal sectors, iron and steel sectors, and refining sectors.

Particularly, Wilton international park in the Teesside cluster designed for energy intensive industry such as chemical and process plant is seen as a representative case study to test new ideas and projects including the demonstration of the proposed decarbonisation assessment framework. The site has seen a significant investment in low

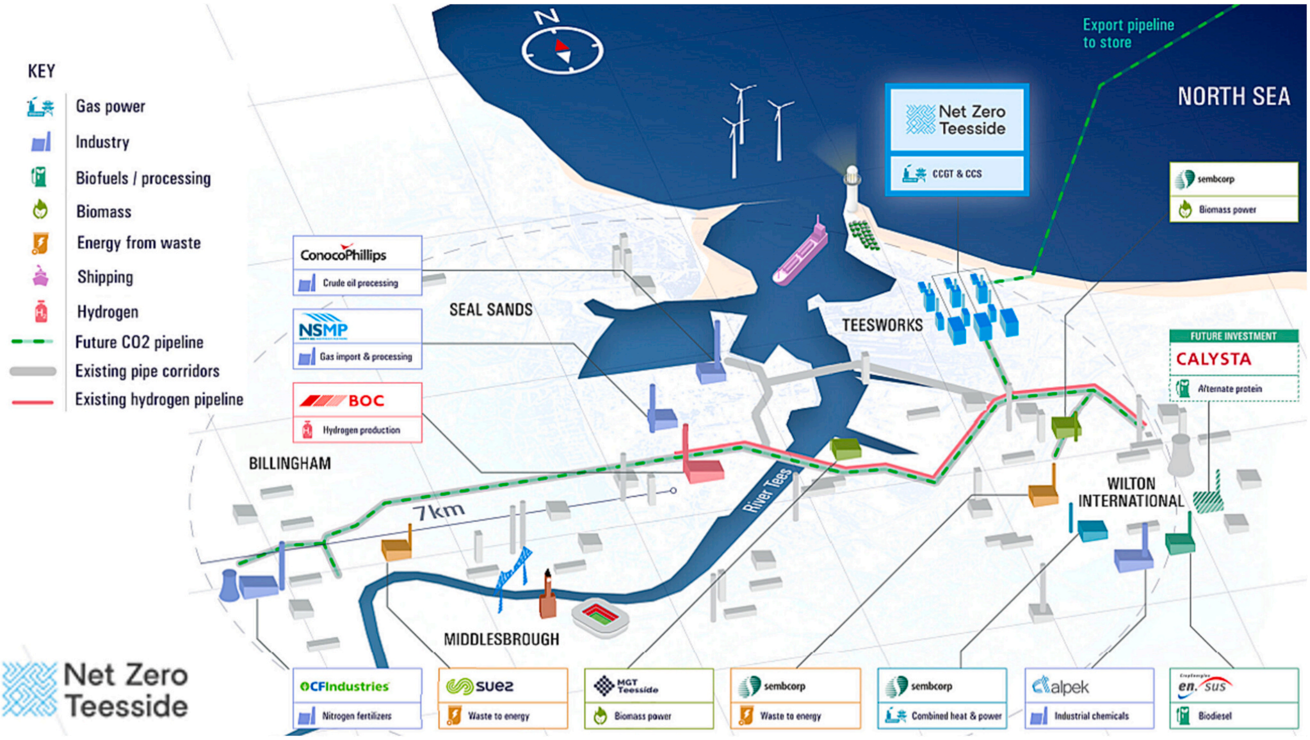

Fig. 2. Distribution of industries in the Teesside cluster [34].

carbon processes such as biofuels, green energy, and plastic recycling. A typical example is a planned development of Tees Green Hydrogen consisting of 1.5 MW Wind farm and 50 MW Solar farms by EDF Renewables, to power the hydrogen electrolyser for green hydrogen production. In addition, there are already several projects ongoing in the Teesside Cluster where hydrogen will be produced at scale. This will include a mix of green hydrogen, blue hydrogen at large scale and bio-hydrogen at low scale, as well as several options that energy providers are evaluating. Whereas the HyGreen Teesside project is targeting 60 MWe of green hydrogen production by 2025, the H2Teesside project is aiming at blue hydrogen production facilities, targeting 1.2GW hydrogen production by 2030 [41,42]. In the short term, options such as a combination of the transport of hydrogen by road and existing private networks as well as the constructions of new pipelines for industrial use may be explored. For commercial and residential use, it is envisaged that existing gas pipelines will be used, where hydrogen will be transported up to 20 % hydrogen blend, which can be increased in the future. Industry will need to define hydrogen deployment strategies to establish how to introduce hydrogen at the premises. Depending on the equipment and processes, companies may vary from introducing hydrogen gradually at low levels of blends, which may only affect the adjustment of processes and very minor modifications, to the investment in new equipment to manage heating processes using hydrogen at high concentrations. Modifications of equipment (e.g., burners, controls etc., that can be used in boilers, ovens, etc.) will depend on the blend percentages. However, gas infrastructures in industry and health status of apparatus will be required before the adoption of hydrogen, so it is expected that standards and policies will come in due course.

The authors in [43] recently quantified the baseline energy demands of the Wilton industrial park in the Teesside industrial cluster based on data collected from the utility and operations departments. Fig. 3 below shows actual (baseline) annual primary energy consumption (in GWh/year) of the cluster site.

The energy demands shown in Fig. 3 includes the consumption of natural gas, biomass fuel, waste fuel, electricity imports and exports. Given the planned hydrogen production capacities elaborated earlier and examining these within the context of the baseline energy needs of the Teesside industrial cluster, hydrogen can contribute significantly to meeting the energy demands of the cluster. Hydrogen can be used as an energy source in a variety of applications, including as a replacement for natural gas. The total potential hydrogen production from these projects is substantial and can be utilised to reduce the reliance on conventional energy sources like natural gas, biomass, and waste, thus helping to decarbonise the cluster's energy supply. Consequently, hydrogen can meet the heavy demand for process heating in the cluster required by industry and buildings as energy can be stored in the form of hydrogen when electricity prices are low, and consumed to supply process heating when electricity prices go up. This will offer flexibility and electricity price arbitrage. Energy supply by hydrogen can absorb shocks and balance demand and supply in energy supply chains. As such, will improve buffer capacity of energy systems for improved resilience. Primarily, hydrogen may be used around transport of heavy truck vehicles, industrial heating processes where electrification is not effective and heating for domestic.

In the broader context, decarbonisation strategy based on CCUS is also a pivotal objective of the Teesside Industrial cluster. The relevance of CCUS remains pronounced, especially in some industrial sectors where emission reduction via direct carbon capture and storage is of utmost priority [44]. Additionally, nuclear and biomass energy sources play a significant role in the energy production capacity of the region. Nonetheless, following consultations with stakeholders, we observed a growing emphasis on embracing hydrogen-based solutions and technological advancements in electrification particularly the increasing use of solar PV and wind turbine, coupled with energy storage systems in the decarbonisation efforts of the Teesside industrial cluster. Therefore, the proposed framework is aligned to specific KPIs designed to explore the potential of electrification and the adoption of hydrogen within Teesside's economy-wide decarbonisation strategies. Renewable sources such as wind and solar play various roles in the emerging energy landscape within industrial cluster as they are typically used for electrolytic production of green hydrogen, electrification of transport in the case of Electric vehicles, enhancing energy storage capacity, etc. [45]. More so, hydrogen sourcing is derived from steam methane reforming to meet the requirements of the industrial cluster. Consequently, there is a need for retrofits to be put in place for the use of hydrogen. Such retrofits include the modification of existing gas turbine engines to run on hydrogen fuel, assessment of the capabilities of gas turbines to burn hydrogen, etc. In lieu of readily available retrofits for hydrogen use, efficiency improvement optimisation process using advanced control systems can be used to enhance the efficiency of the existing process without requiring extensive modification. Although recognising the constraints in electrification and technology readiness of the use of hydrogen such as ability of existing infrastructure to adopt hydrogen pipes, financial cost, risk, reusability, government policies, etc., the rapid implementation

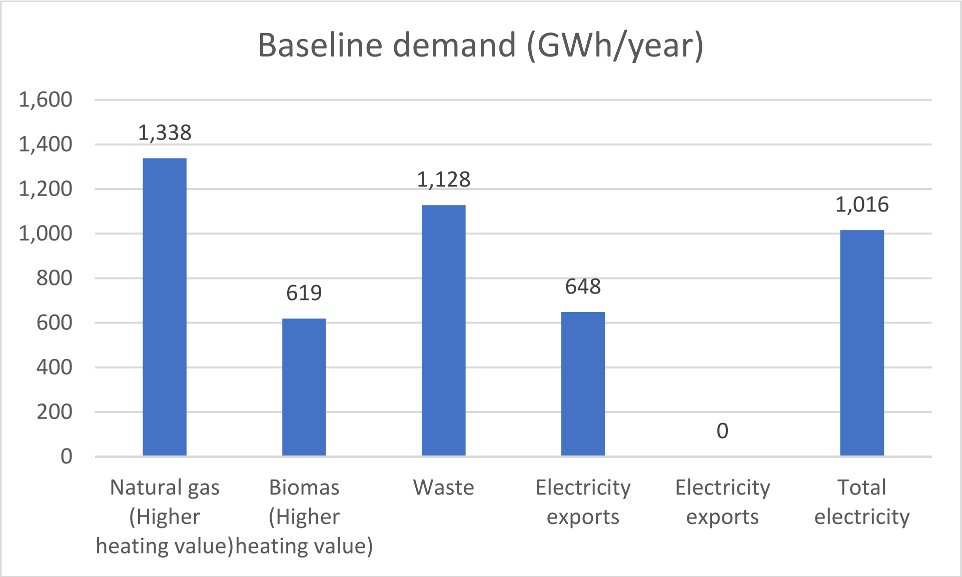

Fig. 3. Baseline energy demand for Wilton Park.

represents a greater technological change in energy efficiency, electrification, and use of hydrogen particularly in low and medium temperature processes. As such, this study is designed to engage multiple types of energy as well as technology experts focused on industry.

3. Methodology

3.1. Overview

The study adopts a mixed methods approach as its methodological framework. As shown in Fig. 4, developing the industrial decarbonisation assessment framework entailed employing qualitative and quantitative research methods.

The methodology follows a six-step approach starting with a literature review to understand the existing knowledge on industrial decarbonisation frameworks, methodologies, and best practices. This phase facilitates the definition of the framework's scope and system boundary in step two. The third phase of the research methodology is focused on exploratory research, which involves identifying relevant stakeholders. Qualitative research methods such as semi-structured interviews, focus groups, and surveys were employed to engage with targeted industrial stakeholder groups, enabling a comprehensive exploration of their perspectives, concerns, and expectations. The importance of formulating technical or business questions to the target stakeholders in the industrial cluster is apt for the successful support of the framework described in this paper. Related studies (e.g., [46]) identified the main stakeholders of the decarbonisation process described in their research and developed targeted questions for each stakeholder. This exploratory phase is vital in identifying KPIs that align with the stakeholders' needs. The KPI development includes identifying goals, selecting the most relevant indicators, and receiving feedback from stakeholders on the usefulness of the KPIs [47]. The KPIs are tracked during diagnostic analytics to monitor progress, project objectives, and targets. The proposed assessment framework considers economic, social, environmental, policy, and technological KPIs [13,48]. These KPIs can be used to assess the impact of a decision modelling tool for industrial decarbonisation transition that balances environmental and financial perspectives [49]. The identified KPIs are ranked based on relevance, availability, measurability, reliability, scalability, familiarity, and phase application attributes [47]. For data collection in step four, qualitative and quantitative methods are employed. Quantitative data is collected from various sources, including UK local authority and regional greenhouse gas emissions, national statistics, the National Atmospheric Emissions Inventory, and the literature. Qualitative data is collected from the Teesside industrial cluster industry specialists through expert-guided interviews and workshops. This includes data from workshops, semi-structured interviews, focus groups, etc. The fifth phase of the study's methodological approach focused on developing and evaluating the proposed assessment framework. Adopting a participatory approach due to the iterative nature of the process, stakeholders were involved in the framework's development to ensure alignment with the defined scope and system boundary. The final methodological step involved documenting and communicating the framework development process. Overall, this methodological approach facilitates a comprehensive examination of the industrial decarbonisation framework, incorporating diverse research methods and stakeholder engagement to ensure a robust and informed evaluation.

3.2. Proposed framework

The industrial decarbonisation assessment framework, as depicted in Fig. 5 is introduced in this paper. Its conceptualisation draws upon the profound impact of the underlying decarbonisation literature and extensive stakeholder inputs, ensuring a comprehensive and robust approach to industrial decarbonisation. The framework encompasses five crucial components, each vital in the assessment process. The framework's components consist of identifying potential stakeholders, stakeholders' communication, engagement, and KPIs, decarbonisation technology definition, data collection, and system evaluation. These five components of the industrial decarbonisation assessment framework are interconnected and interdependent. The framework recognises the importance of stakeholder engagement, data-driven decision-making, and the integration of appropriate decarbonisation technologies to achieve meaningful and sustainable industrial decarbonisation. Considering these interrelationships, the framework offers a comprehensive approach that supports effective planning, implementation, and evaluation of decarbonisation strategies within industrial sectors. The outcomes specific to each component are presented in Sections 3.2.1 to 3.2.5.

3.2.1. Identification of stakeholders

The assessment framework's first step consisted of identifying

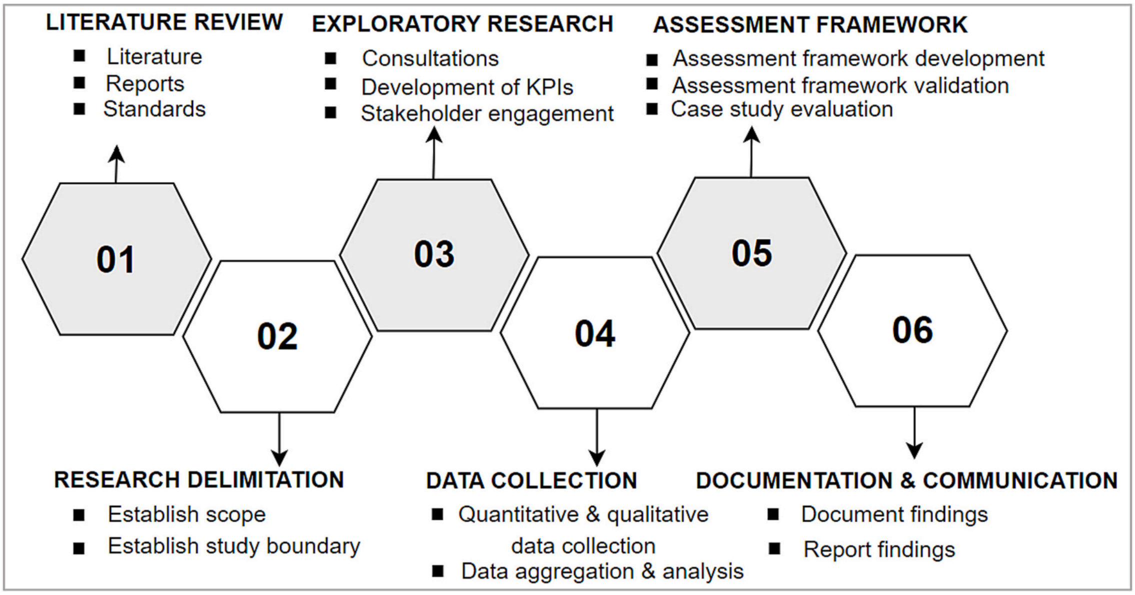

Fig. 4. Research methodology adopted for the framework development.

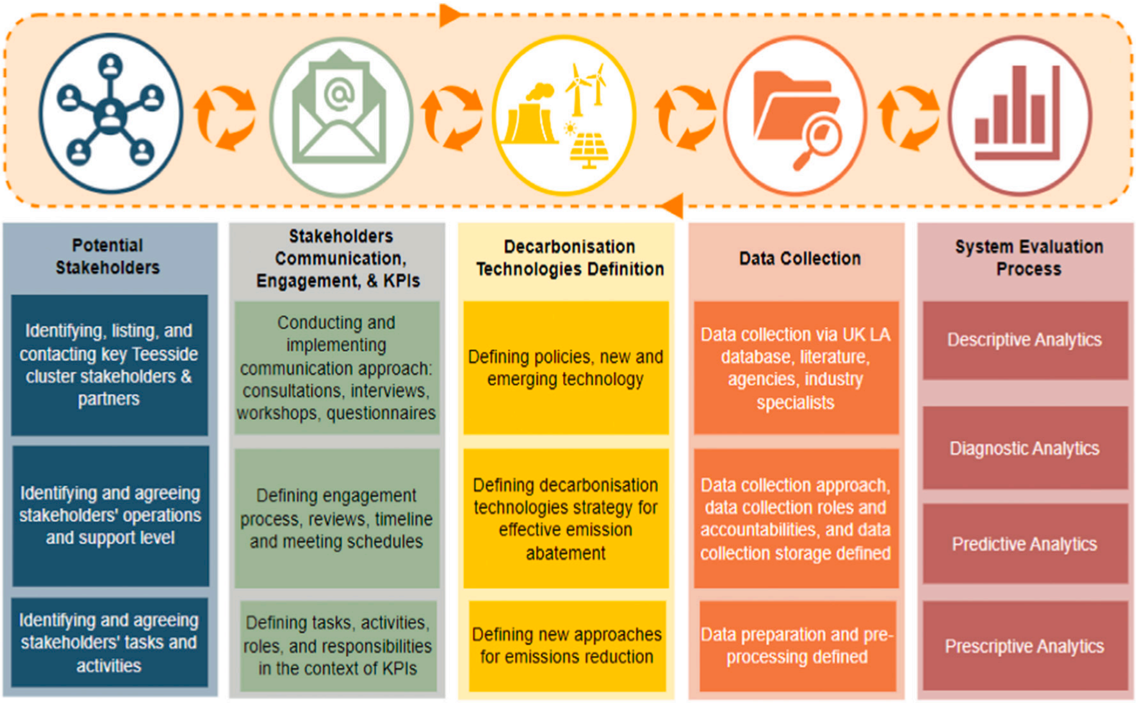

Fig. 5. Proposed framework.

potential stakeholders. Potential stakeholders and partners in the Teesside industrial cluster were identified for consultations, semi-structured interviews, and engagement to understand how the UK industrial decarbonisation strategy and other policies affect the Teesside industrial cluster. Thirty stakeholders were identified for this study. The stakeholders are grouped considering sectors, sub-sectors, sites, scope, technologies, and cluster relationships, and they include any information specific to their company. Fig. 6 presents the stakeholders identified for the study.

In addition, stakeholders' operations, expertise, and level of support were defined. Regular stakeholders' consultation was conducted to clarify technical or business concerns in the framework development.

3.2.2. *Stakeholder communication, engagement and KPIs*

Stakeholders identified in the previous stage were engaged through regular communication to identify, analyse, plan, and implement activities and actions to ensure all the project requirements were met. Every stakeholder communication and engagement are driven by the project aim and objectives, including a clear purpose of the engagement, as this is crucial to understanding their requirements. The engagement process involved clear information and communication, reviews, timelines, and meeting schedules, such as essential data and information required for the framework assessment. Likewise, approaches such as forms, semi-structured interviews, questionnaires, emails, and workshops were developed and implemented. Several interviews and

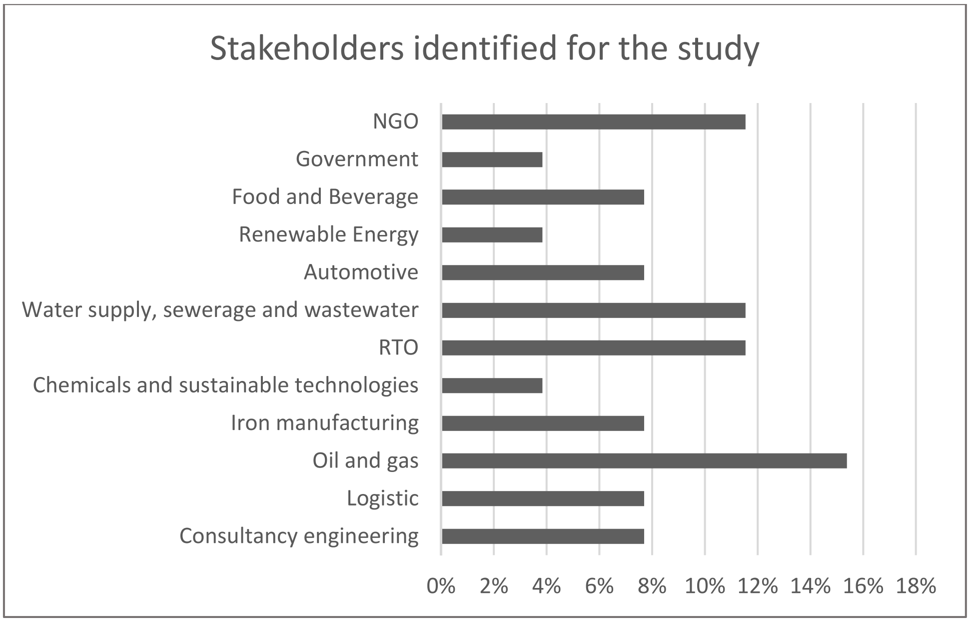

Fig. 6. Stakeholders identified for the study.

questionnaires tailored to each stakeholder operation were conducted and administered to capture data and information from the key stakeholders and their representatives across the Teesside industrial cluster. The iterative process involved analysing data alongside information found in the literature to make sense of the emerging findings. Similarly, workshops were organised to facilitate individual interaction, foster collaboration, gather comments, feedback, and input from participants. This was done to actively engage stakeholders and academic partners in the analysis, reporting, and validation of the questionnaire results.

Furthermore, stakeholders were involved in developing KPIs to help track progress and goals in managing energy and resources to reduce the carbon footprint in low-carbon industrial activities [49]. This involves a high level of stakeholder engagement and collaboration to ensure the relevancy, applicability and validation of reasonable actions and results [47]. Although recognising in the context of Teesside industrial cluster, the concentration of large chemical production facility, nuclear power plant and biomass plant, etc., coupled with the emerging CCUS strategy, there is increasing need for electrification and adoption of hydrogen-based solution which is the focus of the selected KPIs. The KPIs have been categorised into five domains of industrial cluster decarbonisation based on the decarbonisation literature: technology, environment, economic, social, and policy. Identifying relevant KPIs was a key output from the second phase of the proposed assessment framework. 40 KPIs were identified for the Teesside industrial cluster, as shown in Table 3.

Table 3

Some key performance indicators for framework assessment.

KPI	Domain	Units
Production capacity of solar PV	Technology	MW
Production capacity of wind turbine	Technology	MW
Production capacity of hydrogen	Technology	MW
Changes in power generation	Technology	MW
Total electricity consumption	Technology	MW
Performance degradation of solar PV	Technology	% / y
Performance degradation of wind turbine	Technology	% / y
Performance degradation of hydrogen	Technology	% / y
Conversion rate of hydrogen	Technology	% / y
Emission coefficient (Grid)	Environment	% / y
Raw materials	Environment	Tonnes
Fuel use	Environment	Tonne of oil equivalent
Energy	Environment	GW/year
Climate Change	Environment	Tonnes CO_2 equivalent
Total CO_2 emission	Environment	tCO_2 / y
Total CO_2 emission reduction	Environment	tCO_2 / y
GHG emission	Environment	tCO_2_eq / y
Total GHG emission reduction	Environment	tCO_2_eq / y
Investment cost of solar PV	Economic	£ / kWh
Investment cost of wind turbine	Economic	£ / kWh
Investment cost of hydrogen	Economic	£ / kWh
O&M cost of solar PV	Economic	£ / kWh
O&M cost of wind turbine	Economic	£ / kWh
O&M cost of hydrogen	Economic	£ / kWh
Average electricity price	Economic	£ / kWh
Total hydrogen implementation cost	Economic	£ / kWh
Total cost of increased wind turbine installation	Economic	£ / kWh
Total cost of increased Solar PV installation	Economic	£ / kWh
Jobs created from investment in solar PV	Social	Job / kWh
Jobs created from investment in wind turbine	Social	Job / kWh
Jobs created from investment in hydrogen	Social	Job / kWh
Income and employee's health	Social	Qualitative
Population growth	Social	% / y
Rate of urban expansion and development	Social	% / y
Migration rate	Social	% / y
Public engagement and acceptance	Social	Qualitative
Research & development incentives	Policy	£ / year
Industrial emissions and energy efficiency standards	Policy	Qualitative
Emissions data and other disclosure requirements	Policy	Qualitative
Low carbon materials certification	Policy	Qualitative

The essential KPIs for industrial decarbonisation include yearly energy generation and consumption, CO_2 emissions per MWh of generated energy, and cost of investment in renewable energy [47]. The KPIs presented in Table 3 can thus be used to assess industrial cluster decarbonisation.

3.2.3. Decarbonisation technologies definition

The decarbonisation technologies definition component focused on the development of effective emission abatement strategies through the establishment of policies and the integration of new technologies. Following a top-down approach, the framework aimed to identify and prioritise relevant technologies contributing significantly to decarbonisation efforts. To ensure a comprehensive assessment framework, a wide range of decarbonisation technologies suitable for the specific needs of the Teesside industrial cluster were meticulously identified. These technologies encompassed renewables such as solar and wind, hydrogen, CCUS, natural gas, oil, nuclear, and coal. The selection of these technologies considered their feasibility and scalability within the Teesside cluster, emphasising the practicality of implementation. The framework centred on the concept of electrification using renewable energy sources, as it demonstrated the most promising potential for reducing emissions effectively. Among the renewable options, solar photovoltaic (PV), wind power, and generic hydrogen were specifically chosen as the preferred alternatives for decarbonisation within the Teesside industrial cluster. These options were deemed well-suited to the local conditions considering the availability of resources and technological advancements. By prioritising these specific renewable options, the framework ensures a focused and targeted approach to decarbonisation, aligning with the overall objectives and constraints of the Teesside industrial cluster. These technologies, coupled with the appropriate strategies and policies, are anticipated to drive significant emission reductions, and pave the way for a sustainable and low-carbon future in the region.

3.2.4. Data collection

In this phase of the assessment framework, data collection, preparation, classification, analysis, and storage procedures necessary for the evaluation process were established. To gain insights into the Teesside industrial cluster, data was gathered from various sources, including literature and stakeholders such as government agencies, local authorities, life cycle assessment databases, and industry. Initially, the collected data had a qualitative nature as it focused on the net-zero transition requirements of the selected stakeholders. The measured data was based on time series data from various metering systems deployed by industrial partners in the Teesside industrial cluster and other government database sources. These data can be used to calculate the technical, economic, and environmental KPIs for the Teesside industrial cluster, as discussed earlier in the paper. Roles and responsibilities for data collection and storage were assigned to ensure a well-defined data preparation and pre-processing process, ensuring the accuracy and reliability of the collected data. Importantly, the data collection mechanism maintained a flexible approach to accommodate emerging data as the evaluation progressed. Artificial Intelligence (AI) based on Machine learning approach was considered for data preparation, training, and testing. Machine learning techniques such as Artificial Neural Network (ANN), Support Vector Machine (SVM), etc., can identify patterns and trends and can be used to predict future energy scenarios and its associated costs of renewable integration and industrial emissions [50]. To use ANN, historical data on renewable energy costs and other factors such as weather, energy demand, etc., are used as input parameters in the ANN model, to train and identify patterns to predict future energy costs. Statistical error measures such as Mean Absolute Percentage Error (MAPE), Mean Square Error (MSE), etc., are used to evaluate the prediction performance of the ANN model. The performance evaluation is essential for making decisions about investment in distributed and renewable energy projects.

3.2.5. System evaluation

This framework component was implemented through a holistic human and data-driven analytical approach. The evaluation process was systematically planned to analyse data and information to provide evidence-based justifications for framework assessments, facilitate recommendations, and improve effectiveness and reliability for future practices. The system evaluation comprises the following approach, as presented in Fig. 7.

i. Descriptive Analytics: The process involves data mining, KPIs definition and tracking, and data visualisations to learn from past behaviours, occurrences, and trends, as well as monitor progress, project objectives and targets.
ii. Diagnostic Analytics: This stage involves further data analysis to establish trends and relationships between variables and provide insight into the reasons for the occurrence using probability theory, data analytics such as regression and time series, and root cause analysis. The descriptive and diagnostic approach measures and tracks KPIs against the project plan, target, and deviations.
iii. Predictive Analytics: The predictive analytics approach applies statistical analysis, machine learning, and neural networks techniques to investigate all the described and diagnosed industrial cluster data, analyse the likelihood of an event occurring, and answer the question, “What is likely to happen next?” to inform what could happen in the future.
iv. Prescriptive Analytics: Prescriptive analytics incorporate the predicted data to perform dynamic modelling, optimisation, and decision-making, considering constraints to provide automated, time-dependent, and optimal decisions. Prescriptive analytics answers the question, “What should be done?” and “Why should it be done?”.

4. Validation of proposed framework and discussion

4.1. Assessment framework validation

A thorough validation process was conducted to ensure the framework's robustness and reliability. This validation assessed the framework's clarity, comprehensiveness, and applicability in addressing the unique challenges and opportunities within the Teesside Industrial Cluster. The framework validation was informed by stakeholder requirements and priorities captured in Table 4 below, consequently providing the measures upon which the framework was validated. The validation process comprised two main stages. First, 9 industry specialists with a minimum of 15 years of expertise in decarbonisation and industrial processes, selected from industries, research institutions, and governmental bodies, participated in semi-structured interviews to review the framework and provide feedback. The panel evaluated the framework's theoretical foundation, methodology, and suitability for assessing decarbonisation strategies specific to the key requirements of the Teesside industrial cluster. The validators emphasised the benefits of the proposed framework, including its iterative and non-linear approach, potential to significantly reduce time and costs associated with assessing net-zero transition pathways (from approximately six months to a few hours), and its adaptability to changes in the technology landscape within the Teesside industrial cluster. The valuable insights and recommendations received during this stage were pivotal in refining and enhancing the framework.

In the second validation stage, focus group discussions were organised following IDRIC regional workshop on industrial decarbonisation for Teesside cluster at the Wilton's Industrial Park. The focus groups were moderated following a practical guide in [51] and provided an opportunity for researchers, academics, and industrial representatives to learn about the proposed framework for decarbonisation activities going on in the region. The decarbonisation framework and its development were presented by the authors of the current paper. Handouts of the framework were thoroughly explained and distributed to the participants including industrial experts to critically analyse and share their opinion within the group, while also responding to relevant questions. Based on the initial discussions, the participants were encouraged to provide comments on the decarbonisation framework including the potential for generic adaptation to other industrial clusters. This generated some interesting conversations, exchange of opinions and new ideas about the framework among experts, proffering recommendations for areas of improvement. The obtained feedback and responses from the validation process was reviewed and used to refine the framework, which was demonstrated in subsequent workshop. The validation processes provided insights into the framework's practicality, usability, and its alignment in decarbonisation strategies, challenges, and objectives.

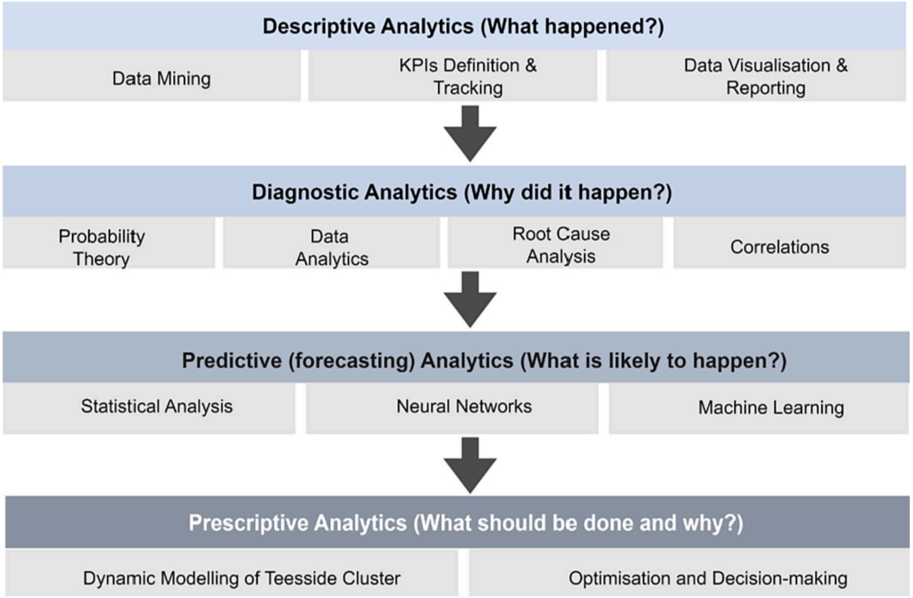

Fig. 7. Evaluation approach.

Table 4
Summary of findings from stakeholder engagement for industrial cluster decarbonisation.

Sector	A condensed summary of areas of interest discussed
Engineering consultancy	• Digital carbon capture reduction footprint models • Decarbonisation models • Life cycle analysis (LCA) and efficiency analysis for H_2 storage systems • Conversion of Metal-organic frameworks (MOFs) for H_2 storage • Viability of storing hydrogen in natural geological locations
Logistic	• Technologies costs • Prediction models for energy transition – hydrogen and green fuels • Decarbonisation of transport (road and maritime) • Hydrogen infrastructure • LCA of hydrogen infrastructure • Electrification of port operations
Oil and gas	• Socioeconomic models for transition • Models to understand demand versus production • Hydrogen storage in a geological location • Hydrogen storage models • Decarbonisation of chemical processes • Hydrogen transportation in pipelines • User acceptance
Iron manufacturing	• Decarbonisation using hydrogen.
Chemicals and sustainable technologies	• Electrification • Markets and opportunities
Research and Technology Organisations (RTO)	• Decarbonisation of steel-making processes • Industrial decarbonisation
Water supply, sewerage, and wastewater	• Hydrogen fuel for transportation • Life cycle analysis of sewerage • Techno-economic studies for the implementation of solutions • Impact of the proliferation of electrolysers on water supply and effluent disposal.
Automotive	• Adoption of industries to decarbonise logistic operations and processes.
Renewable Energy	• Electrification/green energy transition • Energy production, skills, and Job creation
Food and Beverage	• Decarbonisations of processes
Government	• Cluster decarbonisation • Policy interventions • Job creation, social and economic impacts • Future energy scenarios (prediction models)
Non-Governmental Organisations (NGOs)	• Cluster decarbonisation • Job creation • Industry and economic impacts • Future energy scenarios (prediction models) • Manufacturing decarbonisation

4.2. Discussion

An assessment framework for industrial cluster decarbonisation comprising five key steps was proposed in this paper. The unique features of the embedded components of the proposed framework outlined in this paper are thoroughly examined through a critical discussion, comparing, and contrasting it with existing frameworks. This comparative evaluation aims to comprehend the distinctive aspects and contributions of the proposed framework. The stakeholder identification, communication, and engagement process that follows in our proposed framework (i.e., the first two components) adopts a rigorous combination of positivism (via questionnaire and surveys) and interpretivism (via interviews and workshops), which is comparable to the approach described by Ho et al. [52]. The benefits of effectively communicating and engaging with identified stakeholders in the proposed industrial cluster decarbonisation framework include improved collaboration, a better understanding of the Teesside industrial cluster's carbon emission sources, and a more targeted intervention. Stakeholder engagement has been employed in previous studies. For instance, the approach developed by Copeland et al. [22] involved engaging relevant stakeholders who could effectively shape comprehensive and realistic future scenarios in their participatory qualitative Energy Futures framework. Other studies, such as [24,25], likewise described engagement with stakeholders as crucial to the transition to a net-zero carbon future. Our proposed framework differs from most available industrial cluster decarbonisation frameworks as it employs “quantifiable measures” or KPIs linked to decarbonisation goals in the stakeholder engagement process. It has been acknowledged that selecting KPIs for energy transition at the city level often lacks transparency and objectivity [53]. As a solution, expert judgements have been proposed to identify the key KPIs [54]. Therefore, our framework includes various approaches to engage and communicate with expert stakeholders to address this issue. Table 4 provides a simplified overview of the key findings from engaging with 30 companies grouped by the industrial sector in the Teesside cluster through semi-structured interviews and workshops.

The areas of interest of the stakeholders as shown in Table 4 were considered in the development of our assessment framework. The domains of interest evidently stretch across technological (e.g., hydrogen infrastructure, electrification, energy production, green energy transition, etc.), environmental (e.g., LCA of hydrogen infrastructure, LCA of sewerage, impact of the proliferation of electrolysers on water supply and effluent disposal, etc.), economic (industry and economic impacts, markets and opportunities, technologies costs, etc.), and social dimensions (policy interventions, job creation, skills, user acceptance, etc.). Furthermore, as shown in Table 4, there is a strong interest in the adoption of industrial decarbonisation assessment models suitable for predicting future energy scenarios, industry and economic impacts, job creation, energy demand versus production, and socioeconomic models for energy transition. Consequently, our framework was designed to align with the captured interests of stakeholders. This collaborative approach facilitated the identification of crucial requirements for industrial decarbonisation. Our framework comprises about 40 KPIs tailored to electrification strategy and utilisation of hydrogen, which can be used to assess the decarbonisation of the Teesside industrial cluster. These KPIs offer crucial information on metrics such as CO_2 emissions, energy consumption, investment costs, and the socioeconomic and environmental impact of transitioning to net-zero.

The third component of the proposed framework aimed to evaluate decarbonisation technologies by defining policies for new and emerging technologies, proposing a decarbonisation technology strategy for effective emission abatement, and developing new approaches for emissions reduction. The KPIs of the framework previously described in Section 3.2.2 of this paper comprised political, technological aspects, economic and environmental factors. The relationship between policies and technologies in the development of decarbonisation pathways has been elaborated in the literature [12,18,55]. Developing policy-informed abatement options like CCUS, hydrogen fuel switching, electrification, and bioenergy with CCS, are critical for lowering the carbon footprint of heavy and energy-intensive industries like chemicals, cement, iron and steel, and refining. Moreover, it promotes the detailed design of industry-scale technologies and shared infrastructure for cost-effective deep decarbonisation of industrial clusters [34]. As a result, our framework is flexible enough to adapt to changes in technology and policy. It recognises the complex interplay of technology and policy, as well as how the transition to low-carbon energy shapes political power and decision-making, or conversely, how politics influences the development and transition to net-zero of industrial clusters. In addition to developing a balance between policy and technology, the developed framework also defines and suggests a decarbonisation technology strategy that will enable effective emission abatement. The decarbonisation technology strategy must be well-defined, achievable, and aligned with the industrial cluster's abatement goals to achieve effective emission abatement. Thus, the framework methodology can consider a wide range of technology options to evaluate all approaches to Teesside industrial decarbonisation comprehensively. Hence, developing a methodology with no inherent bias towards any technology option is important.

The developed framework is similar in some respects to comparable frameworks that have defined and aligned their technology pathways (e.g., CCS, CCUS, Hydrogen, etc.) with the abatement goals of specific countries and regions. However, our framework considers the unique characteristics of the Teesside industrial cluster, including the types of industries present, the existing infrastructure, and the region's economic and social needs. For economic and social aspects, capital expenditure (CAPEX), operating expenses (OPEX), and job creation metrics due to renewable fuel switching are relevant [56]. Our framework is highly iterative, and the decarbonisation technology definition highlighted in this third phase was achieved through collaboration among key stakeholders (i.e., industry players, policymakers, researchers, and community representatives) in the Teesside industrial cluster, as described in the first and second phase of the framework. This resulted in identifying the most viable decarbonisation technologies for the Teesside region, considering factors related to the KPIs including scalability and technical feasibility.

The fourth phase of the proposed framework was designed to collect and prepare carbon emission data. Our proposed framework uses a mixed methods approach to collect quantitative and qualitative data. Meanwhile, an artificial intelligence (AI) based on Machine Learning approach was considered for data preparation, training, and testing. Our mixed-method data collection technique follows a common approach in the literature, using multiple data collection methods [24,27]. Overall, the framework is developed to obtain measured data (or technical data) required to test and validate decarbonisation technology tools. The fifth phase of the developed framework describes analytical techniques that are executed to perform a system evaluation of the overall framework system. The evaluation process is based on pre-processed data from the data collection phase, such as carbon emission energy consumption and generation as well as renewable investment cost data. The process quantitatively investigates quantified or measured information to generate numerical data. It assesses, predicts trends, and optimises solutions. The decarbonisation roadmap for the Teesside industrial cluster would require a detailed industrial system analysis considering uncertainties and interdependencies. Therefore, the suggested approach would be prescriptive analytics, as described in Section 3.2.5 of this paper. This would consist of systems modelling, constraint-based optimisation, scenario, and sensitivity analysis. Although the use of scenario-based frameworks is common in the literature, e.g., [17,22], the adoption of optimisation frameworks based on multiple constraints to find the optimal capacity combination of selected technological, environmental, economic, and social abatement options that can achieve a target CO_2 reduction with minimum cost or maximise the CO_2 emissions reduction within a specified investment cost target represents an innovative and systematic transformation when compared to existing approaches. An example of an evaluation technique based on an optimisation approach has been adopted in [26]. However, our framework encompasses a broader set of KPIs, policy and social indicators, which was omitted in their study. The significance of incorporating robust stakeholder-based decarbonisation requirements into an assessment framework is underscored by the findings discussed in this section.

4.3. Limitations and future work

In assessing the impacts of industrial cluster decarbonisation projects, the effective use of energy and carbon footprint depend on the decarbonisation strategy and are peculiar to the cluster's stakeholder requirements and other factors such as climate and regional geographical characteristics [57]. Hence, the KPIs of individual cluster projects and strategies can vary extensively from one industrial site and cluster to another and for regions across the world. The proposed assessment framework presents a step-by-step methodological process which can be adapted to the requirements of other industrial clusters strategy. While a single case study of Teesside Industrial cluster was analysed in this paper, additional industrial clusters across geographical regions will be required to be adapted to this framework and analysed if a generic industrial decarbonisation assessment norm is to be established around the methodological framework. Although the framework presented a data collection approach, estimation of the confidence level of technology pathways through predictive and prescriptive data analytics to provide a quantitative assessment of the risks and uncertainties associated with the selected combination of renewable energy technologies is an area of further work. It is envisaged that this will leverage on the framework's capacity to evaluate the synergies and risks involved in trade-offs during technology deployments. We also caution that further work is needed to implement the assessment framework and fully quantify the benefits obtained in planning, design, and delivery of various emerging industrial cluster decarbonisation strategies including CCUS projects and studies, and this is also an area of ongoing work.

5. Conclusion and future work

This paper has successfully developed and validated an assessment framework that places utmost importance on stakeholder requirements for industrial clusters to address the essential elements of energy transition and decarbonisation comprehensively. The proposed assessment framework is valuable, offering support and a holistic approach to evaluating KPIs regarding economic feasibility, policy constraints, and social and environmental impacts, as well as the potential co-benefits stemming from technology integration. By adopting an iterative and dynamic approach, the core application of the framework demonstrates its effectiveness in capturing the intricate interplay between the multipartite factors in the assessment process. The iterative nature of the framework ensures that it can adapt and respond to evolving circumstances and changing priorities, while its dynamic nature facilitates a thorough analysis of the industrial cluster's transition to renewable energy sources. Integrating stakeholder perspectives and decarbonisation requirements within the framework contributes to a comprehensive understanding of the challenges and opportunities associated with this transition. Furthermore, this study's framework serves as a practical tool for assessing the feasibility of energy transition and enhances the overall understanding and knowledge in this field. This paper's emphasis on an industrial cluster-based framework approach aligns with the growing recognition that collective efforts and collaborations among industries in a shared geographical region can lead to more efficient and sustainable decarbonisation strategies. Although there is no magic solution to evaluate the full benefits and potential impacts of decarbonisation technologies, this assessment framework can assist stakeholders, policymakers, and researchers to assess the effects of energy transition, which is critical to policy design and decision-making while contributing to sustainable decarbonisation goals.

Abbreviations

AI	Artificial Intelligence
AIM	Asia-Pacific Integrated Model
ANN	Artificial Neural Network
ARTS	Accelerating and Rescaling Transitions to Sustainability
CAPEX	Capital Expenditure
CCA	Climate Change Act
CCC	Climate Change Committee
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilisation and Storage
EI	Energy Intensive
ETS	Emission Trading System
EU	European Union
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIR	Green Industrial Revolution

GVA	Gross Value Added
IDRIC	Industrial Decarbonisation Research and Innovation Centre
IDS	Industrial Decarbonisation Strategy
IPCC	Intergovernmental Panel on Climate Change
KPI	Key Performance Indicator
NEI	Non-Energy Intensive
NZED	Net-zero Energy District
OPEX	Operating Expense
PDA	Predictive Analytics
PSA	Prescriptive Analytics
RTN	Resource Technology Network
SCE	Stakeholders Communication and Engagement
SOL	Social Licence to Operate
SVM	Support Vector Machine
TVCA	Tees Valley Combined Authority
TVR	Tees Valley Region

CRediT authorship contribution statement

Chris Ogwumike: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Anderson Akponeware:** Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Adepeju Oyewole:** Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – original draft. **Huda Dawood:** Conceptualization, Data curation, Funding acquisition, Investigation, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. **Ruben Pinedo-Cuenca:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Project administration, Resources, Validation, Writing – review & editing. **Janie Ling-Chin:** Data curation, Formal analysis, Investigation, Supervision, Validation, Visualization, Writing – review & editing. **Anthony Paul Roskilly:** Conceptualization, Funding acquisition, Project administration, Resources, Validation, Writing – review & editing. **Nashwan Dawood:** Conceptualization, Data curation, Funding acquisition, Project administration, Resources, Software, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

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