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Critical review and recommendations for strengthening health and safety and major accident prevention regulations for carbon capture and storage in UK ports☆

Wassim Dbouk [a,*], Damon Teagle [a], Lindsay-Marie Armstrong [b,†], Johanna Hjalmarsson [c,†], Stephen Turnock [d], Alexandros Ntovas [c,†]

[a] Southampton Marine and Maritime Institute, University of Southampton, United Kingdom
[b] Sustainability and Resilience Institute, University of Southampton, United Kingdom
[c] Institute of Maritime Law, University of Southampton, United Kingdom
[d] Civil, Maritime and Environmental Engineering, University of Southampton, United Kingdom

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ABSTRACT

Carbon Capture and Storage (CCS) is an essential component of the UK Government's net-zero strategy. Policies emphasize the need for flexible and accessible CO_2 transport and storage networks, with shipping emerging as a key non-pipeline transport modality to connect industrial clusters to offshore storage. In this article, we assess whether current health and safety and major accident prevention regulations adequately govern the risks posed by expanding CO_2 handling and storage in UK ports to support CCS deployment.

Our analysis identifies three regulatory gaps. First, while the Port Marine Safety Code addresses regulatory complexity in UK ports through establishing uniform national standards for marine safety, it cannot regulate the emerging risks of anticipated large-scale CO_2 shipping activities without clear performance standards in specific legislation. Second, duly appointed harbor masters must be well-informed to effectively exercise the powers granted under the Dangerous Goods in Harbour Areas Regulations (DGHAR) to reduce serious accident risks associated with increased CO_2 shipping. Third, the Control of Major Accident Hazards Regulations (COMAH) currently exclude temporary CO_2 storage and do not include CO_2 within their scope, limiting their effectiveness for major accident prevention in port storage scenarios.

To address these gaps, we recommend issuing tailored guidance under DGHAR to clarify risk management responsibilities for CO_2 shipping and amending COMAH to include CO_2 storage and recognize CO_2 as a dangerous substance. These reforms are essential to protect port communities, ensure robust risk management, and support the safe, sustainable expansion of CO_2 shipping as a critical enabler of CCS.

1. Introduction

Carbon Capture and Storage (CCS) is a critical mitigation option in global efforts to address climate change and achieve net-zero emissions by mid-century. As governments and industries scale up CCS deployment to meet the Paris Agreement's (PA) 1.5° goal, its importance grows for decarbonizing hard-to-abate sectors and supporting the transition to cleaner energy systems. When integrated with continued efforts to

Abbreviations: CLP, European Regulation (EC) No 1272/2008 on classification, labelling and packaging of substances and mixtures as amended for Great Britain; EA, HMG's Environment Agency; IMDG, International Maritime Dangerous Goods; IMO, International Maritime Organization; IPCC, , Intergovernmental Panel on Climate Change; MAP, Major Accident Prevention; MSMS, Marine Safety Management System; NPT, Non-Pipeline Transport; PMSC, Port Marine Safety Code; SHA, Statutory Harbour Authority.

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* Corresponding author at: Southampton Marine and Maritime Institute, University of Southampton, Boldrewood Innovation Campus, Southampton, SO16 7QF, United Kingdom.

E-mail addresses: W.dbouk@soton.ac.uk (W. Dbouk), Damon.Teagle@southampton.ac.uk (D. Teagle), L.Armstrong@soton.ac.uk (L.-M. Armstrong), J.Hjalmarsson@soton.ac.uk (J. Hjalmarsson), S.R.Turnock@soton.ac.uk (S. Turnock), Alexandros.Ntovas@southampton.ac.uk (A. Ntovas).

† University of Southampton, Highfield Campus, Southampton, SO17 1BJ, United Kingdom.

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reduce CO_2 and other greenhouse gas (GHG) emissions, CCS contributes to the global shift toward sustainable energy solutions. The latest IPCC Report (AR6) (Calvin et al., 2023) and recent energy outlook reports (IRENA, 2024; IEA, 2024) emphasize the urgent need to expand CCS to meet climate targets. Despite challenges such as geographically limited geological storage and potential socio-cultural barriers, these reports indicate that robust policy instruments, public support, and technological innovations can mitigate these obstacles and make CCS a viable approach to decarbonization (Calvin et al., 2023).

1.1. The role of shipping in the UK Government's vision for CCS

The First Global Stocktake decision adopted at the 28th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP28) highlighted the urgent need for deep, rapid, and sustained emissions reductions to achieve the PA's temperature goal (IEA, 2025a). It called on Parties to accelerate mitigation efforts by transitioning from fossil fuels in energy systems (para. 28(d) and promoting low-emission technologies, including CCS (para. 28(e)). However, it allowed Parties to determine their contributions in "a nationally determined manner", according to their different national circumstances.[1]

In the UK, the Climate Change Committee's (CCC) has emphasized the key role of CCS in every scenario considered for national emission reduction (IEA, 2025b). Given that industry is responsible for about 16 % of the UK's GHG emissions (Rt Hon Chris Skidmore MP, 2024, para. 394), CCS has become a cornerstone of His Majesty's Government's (HMG) industrial decarbonization strategy. Successive governments have supported CCS through policy initiatives, including 'The Ten Point Plan for a Green Industrial Revolution' (Department for Business, Energy & Industrial Strategy, 2024), the Energy Security Strategy (British energy security strategy, 2025), and the Energy Security Plan (Powering Up Britain: Energy Security Plan, 2024). The current Government has reaffirmed this commitment, aligning CCS projects with the nation's net-zero objectives and providing substantial funding (Hansard, 2024; CCSA, 2024a; Change, 2024). Most recently, the UK's Modern Industrial Strategy identified CCUS as a national priority within the clean energy sector, introducing £9.4 billion in new capital funding to accelerate deployment through 2029 (Department for Business and Trade, 2025, p. 45). This sustained policy focus underpins the central role of CCS in meeting the UK's net-zero ambitions and fulfilling its international climate commitments.

A key challenge for the UK's CCS expansion is transporting CO_2 from industrial clusters that lack direct access to pipelines infrastructure to permanent geostorage. For these clusters, shipping is a cost-effective non-pipeline transport (NPT) solution, particularly for industrial hubs located far from offshore storage sites (Element Energy, 2024a). For instance, the Solent industrial cluster could rely on shipping to transport CO_2 to geostorage sites in the North or Irish Seas, over 400 km away, due to challenges of unlocking storage potential in the English Channel (BBC News, 2024). Onshore shipping infrastructure for handling, temporary storage, and transfer will be required at clusters with direct storage access (e.g., the North-west and East-Coast clusters) as they would need to receive CO_2 from regions without storage capacity. Developing such NPT solutions is crucial for scaling up CCS in a sustainable way in the UK and across Europe.

HMG's Department for Energy Security & Net Zero (DESNZ) recognized this reality in the "Carbon capture, usage and storage: a vision to establish a competitive market" policy paper (December 2023) (Department for Energy Security and Net Zero, 2024a). The paper emphasized the importance of offering a range of CO_2 transport methods, including NPT, to enable "flexible and open access" Transport and Storage (T&S) networks (Department for Energy Security and Net Zero, 2024a, p. 41). However, it also acknowledged the difficulty in determining the specific application of each transport method in the 2030s (Department for Energy Security and Net Zero, 2024a, p. 41). According to the Carbon Capture and Storage Association's (CCSA) CCUS Delivery Plan 2035, shipping could enable domestic projects to capture up to 15 million metric tonnes of CO_2/year by 2035 and facilitate the import of an additional 20 million metric tonnes of CO_2/year from neighboring countries (CCSA, 2024a).[2]

1.2. Research gap

Academic literature on CO_2 transport has focused primarily on techno-economic analysis to assess and optimize how different methods can best serve various CCS projects and scenarios. Some studies have examined safety regulations and energy requirements across transport methods (Sleiti and Al-Ammari, 2022), whereas others have established that shipping is a cost-effective non-pipeline transport solution (Vakili et al., 2025). These studies highlight the critical role of temporary port storage for supporting CO_2 shipping, but focused on related costs, technical requirements for loading and unloading (Vakili et al., 2025; Zakkour and Haines, 2007), and the feasibility of temporary storage in onshore tanks compared to offshore floating platforms (Sleiti and Al-Ammari, 2022).

Although there is substantial literature on legal and regulatory barriers to CCS deployment, the particular challenges of CO_2 shipping as a NPT method have received less attention. Most studies address the regulation of offshore geological storage (Zakkour and Haines, 2007), typically examining its governance under dumping-at-sea frameworks and the implications for cross-border CCS (Henriksen and Ombudstvedt, 2017; Marston; Arlota and Gerrard, 2024; Sutton et al., 2025; Weber, 2021). Some analyses consider how these frameworks may hinder scaling up CO_2 shipping for CCS (Weber, 2021), but discussions on regulatory framework readiness for CCS project deployment rarely address the specifics of CO_2 transport or the need for temporary port storage (Romasheva and Ilinova, 2019).

Where the literature does scrutinize the legal and regulatory aspects of CO_2 shipping, it predominantly centers on liability issues from CO_2 T&S activities (Gola and Noussia, 2022; Argüello and Bokareva, 2024; O'Brien, 2025; Weber and Tsimplis, 2017). Topics include the legal classification of CO_2 (such as whether it qualifies as a dangerous cargo or hazardous substance) (Weber and Tsimplis, 2017; Roggenkamp, 2018), the applicability and scope of liability regimes in shipping scenarios (O'Brien, 2025; Weber and Tsimplis, 2017; Roggenkamp, 2018), and the extent or limitation of liability for different actors (Weber and Tsimplis, 2017). Some studies investigate whether health, safety, and environmental regulations impose additional technical requirements for CO_2 T&S, notably in the USA (Arlota and Gerrard, 2024). Others offer broader analysis by comparing the legal and regulatory frameworks for CO_2 shipping and pipeline transport, including safety standards, climate leak protections, liability, as well as the structure of contracts and risk-sharing among stakeholders (Roggenkamp, 2018). Nonetheless, most discussions of CO_2 storage focus on offshore geological sites, not the need for temporary port storage within the shipping chain.

Leading international assessments echo these gaps. The International Energy Agency stresses the need for CO_2 infrastructure growth and a shift from single-operator projects to shared CCUS hubs, highlighting the role of coordinated storage development at ports (Fajardy et al., 2025). However, the focus remains on market and deployment challenges, not

[1] Parties failed to operationalise paragraph 28 of the decision during COP29 due to disagreements over its interpretation and on the structure of the Mitigation Work Programme, arising from differing priorities and national circumstances.

[2] This estimation is based on the "Enabling Industry Pipeline" deployment scenario, whereby industry is not constrained by HMG technology specific targets and is enabled to deploy projects identified by cluster leads to meet HMG's capture ambitions.

on port-specific safety management or regulation (IEA, 2025c). Similarly, the IPCC's Sixth Assessment Report underscores the role of CCS for mitigation but does not systematically examine regulatory or safety challenges specific to temporary CO_2 storage and handling at ports (Calvin et al., 2023).

Moreover, jurisdictions differ in how their regulatory and policy approaches address CO_2 transport and storage, particularly regarding port handling and temporary storage. In the United States, federal policy prioritizes large-scale geological storage and pipeline safety, with little attention to port-based temporary storage. The 2024 U.S.-Japan CO_2 Shipping Feasibility Study confirms that permitting port-based CO_2 shipping and storage remains a first-of-a-kind challenge, lacking established regulatory processes or clear inter-agency coordination (Derek et al., 2025). Recent federal rulemaking on pipeline safety also omits port-specific storage and emergency response protocols (IEA, 2025d). In contrast, the European Union's Connecting Europe Facility supports cross-border CO_2 transport infrastructure, including projects integrating ports as shipping hubs (IEA, 2025e; IEA, 2025f; Regulation (EU), 2013). Yet, within the EU framework, detailed safety regulations and risk assessment standards for port CO_2 handling are still to be developed.

These trends reveal a significant gap in both scholarship and policy focus on the handling and storage of CO_2 in ports, overlooking CCS scenarios where shipping serves as a NPT modality. As will be discussed in the following sub-section, this lack of policy attention to port-based CO_2 management is highly relevant to the UK. While liability frameworks can deter negligence by imposing compensation requirements (Dbouk, 2025, pp. 281–286), they principally address the consequences of incidents that have occurred rather than proactively managing risks. In contrast, preventive risk management, established and enforced through safety regulations, is essential for promoting compliance and minimizing the risk of harm. Despite the importance of such preventive measures, regulatory challenges related to temporary CO_2 storage in ports remain largely unexplored in the literature. There is a lack of research on risk assessment models tailored to the unique hazards of temporary CO_2 storage in ports, such as the risk of asphyxiation or rapid phase change following a release. Existing literature also does not discuss the absence of standard emergency response protocols for CO_2 leakage incidents in ports, a crucial aspect of effective health, safety, and environmental risk management. These gaps highlight the need for further research and regulatory attention to ensure port safety management systems account for the specific characteristics and risks associated with handling and storing CO_2 during CCS shipping operations.

1.3. Rationale and structure

Despite HMG's strategic ambitions for large-scale CCS, recent policy and regulatory efforts have primarily emphasized techno-economic viability, focusing on cost reduction and commercial frameworks rather than operational safety (Department for Energy Security and Net Zero, 2024b). This has resulted in a regulatory landscape aimed at market confidence and efficient capital deployment, exemplified by the economic licensing and oversight introduced through the Energy Act 2023, with the Office of Gas and Electricity Markets (Ofgem) as the economic regulator for CO_2 T&S infrastructure (Department for Energy Security and Net Zero, 2025a). Recent government and parliamentary reports reaffirm this focus on cost and investor certainty as the main approach to scaling up CCS (Committee of Public Accounts, 2024, 2025; Department for Energy Security and Net Zero, 2025b). In parallel, UK regulatory development around the storage component of CCS has concentrated on permanent geological storage offshore, rather than temporary storage in ports. This includes the establishment of licensing and permitting regimes administered by the North Sea Transition Authority, supported by requirements for environmental and strategic impact assessments to ensure safe development of offshore sites (Dbouk et al., 2024, Section 3.2.4).

However, this focus has not extended to comparable regulatory scrutiny of health and safety (H&S) and major accident prevention (MAP) for CCS operations in UK ports. As shipping becomes an essential part of CCS infrastructure, CO_2 port-based operations will increasingly include shipping, loading/unloading, temporary storage, de-re-pressurization, and transfers to/from other transport modes such as road, rail, barge, or pipeline networks. Compared with the relatively modest and contained CO_2 operations in current industrial and commercial uses, NPT shipping for CCS will involve much larger volumes and greater operational complexity (Gola and Noussia, 2022; Brown et al., 2017).

These new operational realities pose important safety challenges. CO_2, though non-flammable, can be toxic if inhaled in high concentrations and, being heavier than air, may accumulate in confined or low-lying spaces, presenting risks of hazardous exposure, including asphyxiation. It is generally stored cyrogenically (−20 to −50 °C) at moderate to high pressures (10 to 25 bar) (Vakili et al., 2025) with consequent safety challenges. Large-scale handling and storage operations in CCS-enabled ports increase the potential consequences of accidental release (Ministère de l'écologie, 2024, p. 6502).[3] To ensure safety, duty holders must implement robust precautionary measures to address the hazards associated with CO_2 releases from pressurised storage in ports, especially given the ongoing uncertainties in predicting associated risks (Health and Safety Executive, 2024a).

Recognising this gap, here, we critically examine whether current H&S and MAP regulations for UK ports are sufficient to address the emerging risks from increased CO_2 shipping and storage in support of CCS, and propose targeted recommendations for regulatory improvement informed by our findings. This is crucial not only for the safety of port workers, nearby populations and to protect essential facilities, but also to maintain public confidence in the safety of CCS infrastructure, a key factor that may influence public acceptance of CCS deployment (Carlisle et al., 2023; Braun, 2017). Our analysis addresses the shipping and temporary storage elements of the operational interfaces highlighted in Fig. 1 below, namely port-to-port CO_2 shipping and direct shipping for offshore injection, reflecting the evolving role of ports as key hubs in CCS chains. We use the port of Southampton as representative example of a loading port from which CO_2 may be shipped to other UK ports for transfer to permanent offshore geological storage, or directly to offshore storage sites. This scenario draws on the Marchwood energy recovery facility in the Solent Local Industrial Decarbonisation Plan (LIDP) Transitioning Pathways report, which identifies shipping as a critical enabler of decarbonisation by allowing emitters to bring CO_2 by various modes to the port, where it is liquefied and stored temporarily before shipping (The Solent local Industrial Decarbonisation Plan, 2025). In this scenario, we assume CO_2 is temporarily stored as liquified CO_2 (LCO_2) to maximize storage efficiency through its high density. By contrast, maintaining CO_2 in supercritical or gaseous form typically requires greater energy inputs, more complex technology, and considerably larger storage capacities (Sleiti and Al-Ammari, 2022).

In Section 2, we describe how the complex legal and regulatory framework governing UK ports creates significant compliance challenges for both port operators and regulators, notably with regards to the regulation of risks posed by dangerous substances. Drawing on our analysis of recent port freight data and the CCSA's CCUS Delivery Plan projections for CO_2 shipping volumes in support of CCS in the UK, we then argue that the anticipated expansion of CO_2 shipping will introduce novel operational and safety risks that are not clearly addressed in existing regulations and for which port stakeholders may not yet be fully prepared. We then examine the theoretical framework based on which such risks would be addressed in the UK, highlighting the performance-

[3] For example, an accidental release of 15 tonnes of CO_2 from a fire extinguishing installation in Mönchengladbach in 2008 led to the intoxication of 107 people, 16 of whom having to be hospitalised with 1 more seriously afflicted and requiring intensive care (Ministère de l'écologie, 2024).

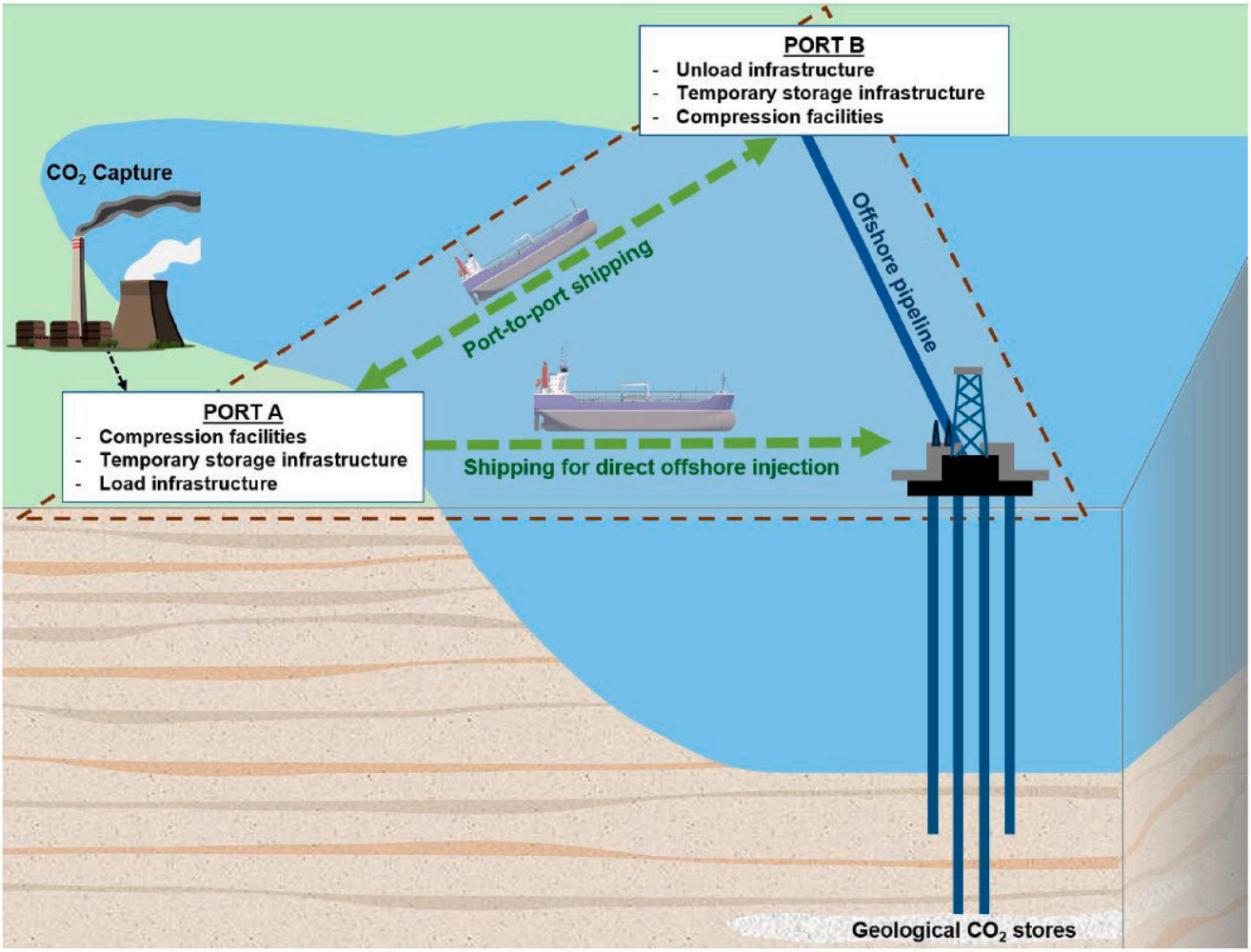

Fig. 1. Connections (in dotted green) between UK ports and offshore storage in the CO_2 shipping chain (Element Energy, 2024b, para 1.2+).

based regulatory approach that underpins the H&S culture in UK ports.[4] In particular, we analyse the Port Marine Safety Code (PMSC), specifically developed by HMG's Maritime and Coastguard Agency (MCA) to address regulatory complexity by establishing a consistent approach to marine safety and standardising practices across UK ports. We argue that, while the PMSC helps foster a proactive safety environment and grants flexibility to port operators in meeting applicable standards, its effectiveness diminishes when specific Regulations lack clear performance goals appropriate for managing new risks, including those emerging from evolving patterns in the handling and storage of substances.

Building on these findings, in Section 3 we turn to two specific regulations governing dangerous goods in UK ports: the Dangerous Goods in Harbour Area Regulations 2016 (DGHAR) and the Control of Major Accident Hazards Regulations 2015 (COMAH). We show that while DGHAR empower harbour masters to effectively manage risks posed by CO_2 carriers moving through ports, bespoke official guidance is needed to raise awareness about emerging risks associated with increased CO_2 shipping. We also identify two regulatory gaps in COMAH regarding temporary CO_2 storage for CCS: first, temporary storage is currently excluded from the Regulations' scope; and second, CO_2 is not included among the substances that trigger major accident prevention duties. These gaps create uncertainty and leave duty holders without clear performance goals for managing major accident risks, thereby diminishing the effectiveness of the PMSC in this context. To address this, we propose amending COMAH to explicitly include temporary CO_2 storage and designate CO_2 as a dangerous substance.

If implemented, our recommendations will build a coherent safety framework that supports the safe and sustainable growth of CO_2 shipping in UK ports. This framework will ensure that duty holders are well informed about the risks they must manage and have clearly defined performance goals for managing risks. Should HMG advance CCS expansion through increased CO_2 shipping, these reforms will better align regulatory oversight with national CCS policy direction.

2. The challenge of governance complexity and the limits of port safety regulation for CO_2 shipping in the UK

This section addresses the governance and regulatory frameworks shaping H&S and MAP in UK ports in the context of anticipated CO_2 shipping growth for CCS. In sub-Section 2.1, we outline the structure of UK port governance and analyse Southampton's port traffic data to illustrate how governance challenges will intensify with increased CO_2 shipping. In sub-Section 2.2, we examine the regulatory approach underpinning H&S and MAP, focusing on the role of the performance-based PMSC in managing risks arising from CCS shipping and storage.

[4] Performance-based regulation is a regulatory approach that focuses on setting outcome targets for regulated entities and allows them discretion in how to achieve those outcomes, rather than prescribing specific measures.

2.1. CO_2 shipping for CCS will heighten compliance challenges in UK ports

According to estimates from July 2024, there are 983 ports and harbors in the UK, split across three categories: trust ports, private ports, and municipal ports.[5] Trust ports are managed by local independent boards; private ports are private entities which often own large trust ports that were privatized in the 1990s; and municipal ports are publicly owned by the local authority. This is one feature of the complex governance structure for ports in the UK, which is characterized by the following elements (Stewart et al., 2024):

- Although HMG's Department for Transport (DfT) oversees the UK-wide maritime transport policy, ports policy is devolved. However, the main items of legislation pre-date Scottish and Welsh devolution settlements.
- There is no uniform definition of a port in the UK. Ports are managed by Statutory Harbour Authorities (SHA), the legal entities responsible for harbour areas determined by factors such as port type and size.
- Different governmental authorities oversee specific aspects of the port environment. The MCA performs the UK's "Port State" functions by implementing international conventions such as MARPOL (International Maritime Organization, 2024a) and SOLAS (International Maritime Organization, 2024b).[6] HMG's Marine and Maritime Organisation (MMO), HMG's Environment Agency (EA), and their devolved equivalents in Wales, Scotland, and Northern Ireland are responsible for marine environmental protection. HMG's Health and Safety Executive (HSE) has the overarching responsibility over H&S aspects (Health and Safety Executive, 2024b). It collaborates closely with the MCA to ensure comparable levels of H&S for seafarers on merchant ships and fishing vessels as applies to workers ashore (Department for Transport, 2024b,Maritime and Coastguard Agency, 2024a). However, overall compliance with the PMSC (discussed below) remains under the MCA's remit.
- SHAs are responsible for managing and operating harbors. Their powers, duties, and areas of jurisdiction are defined by local Acts of Parliament or Harbour Orders under the Harbours Act 1964 in Great Britain or the Harbours Act (Northern Ireland) 1970. While these frameworks share core features, specific provisions vary between ports. Additional actors also have defined responsibilities within the port environment, particularly in relation to the transfer of dangerous liquids and gases between ship and shore, including berth operators and ship masters.
- Ports in the UK principally operate on a commercial basis without Government support. They are often in competition with each other, both domestically and internationally, and with other modes of transport. The main sources of revenue for UK ports include harbour dues, other charges for the use of the harbour, and income from property (Department for Transport, 2024a).
- A plethora of laws and regulation govern various aspects of marine safety within a UK port environment, at varying levels. For example, while Regulations such as DGHAR and COMAH address risks posed by the passage and storage of dangerous goods in ports, byelaws provide detail on the respective powers and duties of different actors within specific ports. The Merchant Shipping Act 1995 also contains provisions conferring authority to SHAs to adopt H&S measures, but these are mostly with regards to providing aids to navigation and removing wrecks and abandoned vessels.

A 2023 MCA report identified forty-seven pieces of legislation relating "to port management and/or the handling of hazardous goods within a port environment" (Maritime and Coastguard Agency, 2023). The report highlighted around twelve "key" guidelines documents published by HMG or devolved administrations, alongside Guidance Notes from the MCA, the HSE and other authorities (Maritime and Coastguard Agency, 2023). Significantly, most port stakeholders consulted in the report indicated that this entanglement of laws and regulations makes it difficult to determine roles and responsibilities within harbour management (Maritime and Coastguard Agency, 2023). We argue that this complexity is likely to become more pronounced as ports are required to accommodate the expected increase in CO_2 shipping for CCS, which will alter freight patterns and introduce new operational challenges for port stakeholders. To illustrate how these shifts may play out in practice, we focus on the port of Southampton, analysing shipping freight data to better understand the scale and nature of the anticipated changes.

In 2023, 425.86 million tonnes of cargo passed through UK major ports, including 169.26 million tonnes of liquid bulk cargo. The port of Southampton accounted for 30.62 million tonnes of total freight (around 7.2 % of the UK total), including 18.25 million tonnes of liquid bulk cargo (approximately 10.8 % of all liquid bulk cargo) (Maritime statistics: interactive dashboard, 2024a). Nationally, liquid bulk volumes declined from 180.03 to 169.26 million tonnes from 2022 to 2023 (drop of 5.98 %),[7] with a corresponding drop from 19.89 to 18.25 million tonnes for Southampton (drop of 8.25 %) (Maritime statistics: interactive dashboard, 2024a).

More recent data show that liquid bulk through UK major ports decreased a further 11 % in Q1 2024 compared to Q1 2023, dropping to 40.5 million tonnes, though Southampton's liquid bulk tonnage remained broadly stable (Maritime statistics: interactive dashboard, 2024b). Importantly, out of the 169.26 million tonnes of liquid bulk moved through UK ports in 2023, 17.95 million tonnes (10.60 %) were liquid gases, with only 0.31 million tonnes of these (1.73 %) passing through Southampton (Maritime statistics: interactive dashboard, 2024a).

Commodity-specific data on liquid bulk cargo, including LCO_2, is not publicly available. While this prevents accurate assessments of current or future LCO_2 freight volumes through UK ports, the figures above can be analysed against the CCSA CCUS Delivery Plan 2035. The latter estimates that shipping could facilitate the capture of up to 35 million tonnes of CO_2 annually by 2035, with 15 million tonnes attributed to domestic projects and 20 million tonnes to neighbouring countries, as outlined in sub-Section 1.3 above. When this projected volume is compared to the 17.95 million tonnes of liquid gases passing through all UK ports in 2023, it becomes evident that the anticipated scale of CO_2 shipping for CCS will substantially shift freight activities at UK ports. Moreover, with CO_2 shipping being an attractive NPT option particularly for the Solent and South Wales industrial clusters, it is reasonable to expect that the largest increase in LCO_2 freight in support of CCS plans will impact these clusters' ports should the CCUS Delivery Plan materialise.

Techno-economic analyses provides important insights into how changes in freight patterns, driven by the adoption of CCS shipping, could affect port operations in the UK. Although policy documents and CCS sector plans do not explicitly specify required in-port storage capacities, it is possible to estimate the minimum temporary storage needed by combining publicly available emissions data with shipping

[5] Privately maintained list of these ports can be accessed at Ports.org.uk.

[6] The MCA is responsible for implementing UK and international law and safety policies to ensure safety at sea and prevent pollution and loss of life. It develops legislation and guidance for HMG on maritime matters and provides certification for seafarers. It collaborates with the HSE to develop compatible legislation and guidance notes on H&S and ensure consistency in their enforcement.

[7] This drop is consistent with a declining trend in the tonnage of liquid bulk cargo passing through UK ports since 2000 (290.55 million tons), with the exception of 2020 and 2021 due to the COVID-19 pandemic.

capacity per voyage (Vakili et al., 2025; Element Energy, 2024b, p. 22). For example, a techno-economic analysis focused on the Solent cluster indicates that 5.9 million tonnes of CO_2 could be transferred annually from the port of Southampton by ship (Vakili et al., 2025). It also shows that, to optimise operations, ports would need temporary in-port storage to accommodate between one and two times the capacity of the CO_2 carriers, depending on their size (ships with 7500 to 32,000 m^3 CO_2 cargoes modelled in (Vakili et al., 2025)). This estimated storage volume is several orders of magnitude greater than the quantities involved in documented CO_2 storage accidents resulting in casualties, which have involved approximately 15 tonnes of CO_2.[8] This vast difference underscores the significant major accident potential posed by CO_2 shipping and temporary storage within ports. It emphasizes the necessity for H&S and MAP regulations that are specifically tailored to the unique risks of CO_2 handling in these environments, which existing regulatory frameworks do not fully address.

2.2. Limitations of the port marine safety code for managing health and safety, and major accident risks from CO_2 shipping in UK ports

The management of H&S and major accident risks related to handling CO_2 in UK ports is underpinned by two principal pieces of legislation: the Health and Safety at Work Act etc. Act 1974 and the Management of Health and Safety at Work Regulations 1999. Together, they establish a framework underpinned by a performance-based regulatory approach that requires duty holders to minimize identified risks "so far as is reasonably practicable" (Health and Safety Executive, 2024c). Instead of mandating specific actions, this framework sets general goals for safety and risk management, giving duty holders the flexibility to determine how best to achieve them. This approach fosters proactive risk management and continuous improvement in H&S standards (Health and Safety Executive, 2024c). Risk reduction measures must be implemented until risks are reduced to a level that is as low as reasonably practicable (ALARP), requiring a balance between the risk and the time, cost, and difficulty of further reduction (Guidelines for HSE inspectors - HSE, 2025; Maritime and Coastguard Agency, 2024a).

To help address regulatory complexity, the MCA developed the PMSC, most recently updated in April 2025, supported by the Guide to Good Practice on Port Marine Operations (GGPPMO). Endorsed by HMG, devolved administrations, and maritime sector representatives, these instruments provide guiding principles for interpreting and applying the legal framework governing port safety. While compliance with the PMSC is not mandatory, the Code establishes a national standard against which the policies, procedures, and performance of SHAs and other relevant organisations[9] may be evaluated. This helps reduce inconsistencies arising from variations in how SHAs' powers, duties, and jurisdictions are defined in local Acts or Harbour Orders, and addresses confusion linked to the complex governance structure outlined in sub-Section 2.1.

The PMSC is underpinned by a performance-based regulatory approach. Duty holders are given flexibility to determine how best to achieve the goals for safety and risk management established by the regulator, and are required to appoint individuals accountable for compliance. A central requirement of the PMSC is for duty holders to develop, adopt, and implement a Marine Safety Management System (MSMS) to discharge their duties and ensure the safety of the harbour and its users.

Marine safety requirements that MSMS must satisfy under the Code are determined through a Risk Assessment process (Maritime and Coastguard Agency, 2024a, para. 3.3) which requires harbour authority boards and managers to fully understand the safety standards set out in legislation to avoid failing in their duties or exceeding their powers (Maritime and Coastguard Agency, 2024a, paras. 3.3, 4.1). The Risk Assessment involves identifying hazards, analysing risk levels, considering those exposed, and evaluating whether existing controls and the powers, policies, systems, and procedures in place adequately address the overall risk profile to enable effective discharge of statutory responsibilities (Maritime and Coastguard Agency, 2024a, paras. 3.3; 5.2). Building on this, Formal Safety Assessments are undertaken when risk assessments result in risk controls that may require cost-benefit evaluation (Department for Transport, p. 24, para 5.8). This process generally follows the International Maritime Organization's (IMO) five-stage Formal Safety Assessment methodology, which includes hazard identification, risk assessment, development of risk control options, cost-benefit analysis, and recommendations for decision-making. Formal Safety Assessments thus provide a structured and documented evaluation of all hazards and risks against objective criteria or standards of tolerability, offering a rigorous basis for decision-making and demonstrating compliance with statutory safety obligations (Maritime and Coastguard Agency, 2024a, para 5.5).

The GGPPMO clarifies that the duties of SHAs consist of three types: statutory duties imposed either in local or general legislation, common law obligations, and fiduciary responsibilities including duty of care, loyalty and confidentiality (Maritime and Coastguard Agency, 2024a, para. 4.1). It also provides guidance on what these duties entail for SHAs under the PMSC. Notably, a SHA's commitment to facilitating the safe navigation and operation of vessels must include discharging its existing statutory duties and powers (Maritime and Coastguard Agency, 2024a, paras. 1.3; 6.3), and each SHA's safety plan must include a clear statement of legal duties and powers (Maritime and Coastguard Agency, 2024a, para 4.3). Moreover, it is the responsibility of each SHA to ensure its powers are sufficient to meet current obligations, which forms part of the ongoing review process for legal compliance (Maritime and Coastguard Agency, 2024a, para 3.3).

Relevant to our study, SHAs have emergency preparedness and response duties under the PMSC, including their duty to comply with DGHAR and COMAH (Maritime and Coastguard Agency, 2024a, paras. 4.9.2; 4.9.4). However, a challenge arises where existing legislations do not require duty holders to address emerging or novel risks. If Regulations do not impose clear and appropriate performance goals, these risks may be omitted from risk assessments and MSMSs, creating regulatory gaps. To prevent this, the GGPPMO notes that all legislations should be reviewed regularly to ensure they remain fit-for-purpose in changing operational contexts (Maritime and Coastguard Agency, 2024a, para. 3.3). This necessity extends beyond the regulation of CO_2 activities to encompass alternative fuels and maritime decarbonisation, where the rapidly evolving green transition will disrupt traditional fuel handling and waste disposal practices. This issue is particularly relevant where regulations may exclude certain substances from their scope due to underestimating novel risks from changes in handling and storage practices. Moreover, even when clear requirements and adequate powers exist, duty holders may fail to recognize emerging hazards that deviate from established norms, limiting the effective exercise of those powers.

Such challenges risk undermining the effectiveness of the Code's performance-based approach in novel scenarios. Although the PMSC relies on duty holders to actively meet regulator-set safety goals, without regulatory clarity and proactive oversight, unclear performance standards could result in significant safety risks for workers and nearby communities, ultimately undermining public confidence in the expansion of CCS infrastructure. This underlines the critical need for regular legal review, robust hazard identification, and explicit regulatory guidance to ensure port safety management systems remain responsive and effective amid evolving operational risks, particularly as UK ports prepare for increased CO_2 shipping in support of CCS and related

[8] See footnote 3 and accompanying text.

[9] Such as a marine terminal, jetty or berth operator, who may not have any statutory powers or duties but will need to consider the appropriate interpretation and applicability of duties incumbent upon SHAs under the Code and under common law (i.e., duty of care to all harbor users).

challenges related to wider maritime decarbonisation.

The following section explores these issues in greater detail by assessing the suitability of DGHAR and COMAH in addressing the risks associated with the anticipated growth in CO_2 shipping in support of CCS.

3. The specific regulatory framework governing the handling and storage of dangerous goods in UK ports

In this section, we examine the regulatory framework governing dangerous substances in UK ports, focusing on DGHAR and COMAH. In sub-Section 3.1, we analyse how DGHAR empower harbour masters to manage risks posed by CO_2 carriers transiting ports and consider the need for additional official guidance to address emerging risks from increased CO_2 shipping. In sub-Section 3.2, we assess the application of COMAH to CO_2 activities, identify regulatory gaps related to temporary storage and substance classification, and discuss the implications for MAP.

We do not address other merchant shipping regulations governing ship-to-ship transfers, or international guidelines for ship-to-shore transfers, which fall outside the scope of this article.[10]

3.1. The Dangerous goods in harbour area regulations 2016

DGHAR aim to ensure the safety of shipping operations involving dangerous goods *as they transit through* ports, harbors and harbor areas by providing for specific measures to reduce the risk of serious accidents (Health and Safety Executive, 2024, para 15). The HSE's Approved Code of Practice L155 (ACP L155) provides practical advice on how to comply with these Regulations.[11] In this sub-section, we argue that while harbor masters of SHAs are granted broad powers under DGHAR to manage and mitigate risks of serious accidents, emerging hazards associated with the anticipated increase in CO_2 carrier traffic through UK ports require targeted communication and awareness-raising by the MCA. Such communication is essential to ensure duty holders fully recognise these novel risks and effectively manage them by leveraging the powers granted under DGHAR. This approach aligns with the performance-based regulation framework under the PMSC, where duty holders are responsible for identifying, assessing, and managing risks, while the MCA plays a supporting role by providing oversight, guidance, and ensuring duty holders remain adequately informed of evolving risks.

LCO_2 is included in Class 2.2 "non-flammable, non-toxic gases" in the IMO's International Maritime Dangerous Goods (IMDG) Code, and therefore falls within the scope of the Regulations' definition of "dangerous goods" (International Maritime Organization, 2024c).[12] "Operator" is defined under DGHAR, in relation to any mode of transport or a berth other than by road, as "the person who has operational control of it for the time being". In a shipping context, this will typically depend on the type of charterparty contracted into to set the terms for the use of the vessel. Under a voyage charterparty, the "operator" is likely to be the registered shipowner, whereas under a time charterparty, it is likely to be the charterer of the vessel. Within a CCS context, some suggest that the CO_2 shipping chain, including port infrastructure, is expected to be owned and operated by one entity through a joint venture (Element Energy, 2024b, para 6.3.4)[13] but this is only one mode of operation. Regulation 5 lays out the scope of application of DGHAR, specifying that the Regulations apply to "every harbour area"[14] in Great Britain. Commenting on this regulation, ACP L155 noted that "the boundary of Great Britain extends to those areas of the shoreline exposed at low tide" (Health and Safety Executive, 2024, para. 47). However, the Code acknowledged that some SHAs extend into territorial waters. In such instances, DGHAR only apply to premises and activities defined in article 6 (only in relation to monobuoys)[15] and article 11 of the Health and Safety at Work etc. Act (Application outside Great Britain) Order 2013. This includes pipelines that connect monobuoys to storage facilities within a harbor, and the loading, unloading, fueling and provisioning of a vessel (Health and Safety Executive, 2024, para. 47).

A key requirement for ship operators under Regulation 6 is to give advanced notice to the harbor master of the harbor area, the berth operator (where the goods are to be brought to a berth), and where relevant, to the harbor master of any abutting or overlapping harbor area, of any vessel bringing any dangerous goods into the harbor area. Such notice must be given no less than 24 h and no more than 6 months before the dangerous goods are brought into the harbor area. It must be in writing and must contain enough information to enable a "proper evaluation" of the H&S risk created by the goods (Regulation 6, para. 4). Notice is not required in respect of vessels carrying non-explosive dangerous goods passing through the harbor area without unloading in that area, or of dangerous substances in a pipeline (Regulation 6, para. 5).

A duly appointed harbor master generally has wide powers of direction to regulate when and how ships enter, depart from, and move within harbor waters, and for related purposes. This includes giving directions to prohibit any vessel from entering or requiring its removal if the harbor master is satisfied that the vessel's condition or the nature or condition of its cargo pose a "grave and imminent danger" to the safety of people or property. Additionally, if the potential sinking or foundering of the vessel in the harbor might "prevent or seriously prejudice" the use of the harbor by other vessels, such actions could be mandated. Section 52 of the Harbours, Docks and Piers Clauses Act 1847 and Regulation 7 of DGHAR recognize these powers which can also be expanded for individual ports. For example, section 5 of The Port of Southampton Harbour Revision Order 2020 (Marine Management Organisation, 2024) provided for additional power for the harbor master to make directions for related purposes, including regulating the loading or discharging of cargo, fuel, water or ships' stores or the embarking or landing of persons.

Other key provisions under DGHAR include the recognition under Regulation 25 of the right for SHAs to make byelaws in respect of their harbor area prohibiting the entry or regulating the entry, carriage, handling or storage of dangerous goods; and the requirement under Rection 10 for SHAs to have an "effective emergency plan" in place before dangerous goods are brought into the harbour, designed to

[10] Notably the Merchant Shipping (Ship-to-Ship Transfer) Regulations 2020 and the MCA's MSN 1829 (M) (Maritime and Coastguard Agency, 2024b), for ship-to-ship transfers; and The International Safety Guide for Oil and Tanker Terminals, 6th Edition (OCIMF, 2024), for ship-to-shore transfer.

[11] DGHAR are also complemented by the Merchant Shipping (Dangerous Goods and Marine Pollutants) Regulations 1997 which apply to ships carrying dangerous goods in bulk while they are in UK waters and to UK ships carrying such goods wherever they may be (regulation 5) and impose specific requirements for the handling, stowage, and carriage of such goods on ships.

[12] ACP L155 added that "[l]iquefied gases covered under the International Gas Carriers (IGC) Code will be in scope of the regulations as they will meet the criteria in the IMDG Code for Class 2 (Gases)" (*Dangerous Goods in Harbour Areas Regulations 2016*, 40) Health and Safety Executive, 2024.

[13] Given that all shipping infrastructure is likely to be dedicated to a single CCS project for several years or decades, joint ventures are likely to be common practice and are already being considered by shipping and infrastructure companies.

[14] Regulation 2(1) defines "harbour area" as "any harbour, natural or artificial, and any port, haven, estuary, tidal or other river or inland waterway navigated by seagoing vessels" and includes "any monobuoy connected to one or more storage facilities in a harbour area and its monobuoy area".

[15] Regulation 2(1) defines "monobuoys" as "a mooring buoy at which dangerous goods may be loaded onto or unloaded from a vessel and which is connected to one or more storage facilities in a harbour area and includes any pipeline connecting to it".

manage any emergencies related to those goods handled or present in the harbour.[16] The Port of Southampton provides a clear example of how SHAs exercise these regulatory powers by issuing detailed guidance to port users, thereby supporting compliance with DGHAR and enhancing overall safety management within the harbor area. As the SHA for the Port of Southampton, ABP Southampton has the responsibility for enforcing Parts II ("entry of dangerous goods into harbour areas") and III ("marking of vessels") of DGHAR in the harbor area against persons other than itself . For this purpose, it has produced guidance to assist masters, shipowners, agents, and transport operators in preparing the information required by the harbor master, for example by requiring them to complete a checklist of information in accordance with Schedule II of the Regulations before entering the Southampton Pilotage Area (Lockwood, 2022).

The regulatory framework and enforcement powers described above demonstrate that harbor masters duly appointed by SHAs possess ample authority under DGHAR to effectively manage and mitigate the risks of serious accidents involving LCO_2 occurring in port areas. However, we argue that the anticipated growth of CO_2 shipping in support of CCS will introduce new risks associated with the increased movement of CO_2 carriers through UK ports (see data analysis under sub-Section 2.1) and recommend that the MCA engages with the CCS sector and shipping stakeholders to produce a Marine Guidance Note (MGN). This MGN would raise awareness of the implications of shifting LCO_2 freight trends for ship operators, port authorities, terminal operators, and others.[17] It could mirror HSE guidance on the major hazard potential of CCS (Health and Safety Executive, 2024a) or on conveying CO_2 via pipelines which aim to support operators and enforcing authorities with understanding related risks and complying with applicable regulations (Health and Safety Executive, 2025).[18] This need for ongoing regulatory adaptation is not exclusive to CO_2 shipping: the evolving use of alternative fuels in maritime transport is poised to introduce novel risks that require anticipatory guidance and regulatory clarity to support effective safety management across UK ports. Given the fragmented structure of port governance in the UK, and the reliance of the PMSC on the establishment of clear performance goals within relevant regulations, the absence of such guidance may result in an underestimation of risks or uneven enforcement of safety standards, notably in the development of emergency response plans for CO_2 shipping.

3.2. The Control of major accident hazards regulations 2015

In contrast to DGHAR, COMAH are concerned with the regulation of the risk of "major accidents"[19] occurring in establishments in the UK due to the *storage* of dangerous substances therein. This sub-section examines the scope and requirements of COMAH and assesses their applicability to the temporary storage of CO_2.

Section 2(1) of COMAH defines "storage" broadly as "the presence of a quantity of dangerous substances for the purposes of warehousing, depositing in safe custody or keeping in stock" and "establishment" as "the whole location under the control of an operator where a dangerous substance is present in one or more installations, […], *in a quantity equal to or in excess of the quantity listed in the entry for that substance in Schedule 1*" (emphasis added). When applicable, the Regulations impose a duty on operators[20] of establishments to take all measures necessary to (1) prevent major accidents, (2) to limit their consequences for human health and the environment, and (3) to demonstrate to the HSE that they have taken all measures necessary pursuant to the Regulations. As explained in Section 2, in the context of storage of dangerous substances in ports, the "operator" is the duty holder appointed by the SHA, responsible for demonstrating regulatory compliance to the MCA and for developing and implementing an effective MSMS that manages identified risks.

Based on Section 2(1)'s definition, the question of whether the requirements incumbent upon duty holders are triggered in relation to storage activities in ports depends upon the *type* and *quantity* of substance(s) listed in Schedule 1 stored therein. Schedule 1 lists the substances to which the regulations apply by (1) specifying categories of dangerous substances (Schedule 1, Part 1), and (2) naming specific substances (Schedule 1, Part 2).[21] The categories of substances and mixtures are determined in accordance with the retained European Regulation (EC) No 1272/2008 on classification, labelling and packaging of substances and mixtures as amended for Great Britain (CLP) (Department for Transport, 2024c; Health and Safety Executive, 2024d), based on their health hazard, physical hazard, and environmental hazard properties. For example, the regulations apply with regards to flammable gases in excess of 10 tons, oxidizing gases in excess of 50 tons, or Hydrogen, as a named substance, in excess of 5 tons.

However, Schedule 1 does not currently include CO_2 - either within a listed category of dangerous substances[22] or as a named dangerous substance. Section 3(2)(cb) of COMAH excludes its application to the transport of "dangerous substances" and to directly related *temporary* storage, including the loading/unloading and the transport "to and from another means of transport at docks". These two factors constitute barriers for the regulation of the temporary storage of CO_2 under COMAH. In a UK port context, this entails that the PMSC requirement for duty holders to ensure compliance with regulations on managing dangerous substances does not extend to controlling major accident risks associated with CO_2 temporary storage activities. This creates a regulatory gap concerning ports, a critical component of the shipping infrastructure necessary to provide the "flexible and open access" T&S networks required to accommodate CO_2 flows from diverse sources across the UK in support of CCS.

The HSE has recognized that gaps of knowledge continue to affect the current understanding of CCS major hazard potential, including with regards to the behavior of CO_2 if released in its dense and supercritical phases (Health and Safety Executive, 2024a). In light of this uncertainty, the HSE also indicated its readiness to extend relevant existing legislation such as COMAH to encompass CCS activities based on emerging evidence about their associated risks. In the meantime, the authority is

[16] This plan should be developed in consultation with the emergency services and any other relevant bodies and requires the coordination of other plans which might be required under other pieces of legislation, such as the Civil Contingencies Act 2004 and the Management of Health and Safety at Work Regulations 1999.

[17] See for example MGN 37(M) which offers guidance on the Merchant Shipping (Dangerous Goods and Marine Pollutants) Regulations 1997 (Maritime and Coastguard Agency, 2024c).

[18] The MCA and the HSE set a common objective of achieving comparable levels of H&S on merchant ships and fishing vessels as applies to workers ashore [Department for Transport, 2024b, pp. 37-39]

[19] Defined as "an occurrence such as a major emission, fire, or explosion resulting from uncontrolled developments in the course of the operation of any establishment to which these Regulations apply, and leading to serious danger to human health or the environment (whether immediate or delayed) inside or outside the establishment, and involving one or more dangerous substances", regulation 2(1) of COMAH.

[20] Defined as "the person who is in control of the operation of an establishment […], regulation 2(1) of COMAH.

[21] Some named substances could fall within the categories set out in Schedule 1 Part 1, but they are subject to lower quantity thresholds when they are specifically named in Schedule 1 Part 2.

[22] The categories included in Schedule 1, Part 1 are: (1) for health hazards - acute toxicity; (2) for physical hazards – explosives, flammable gases, flammable aerosols, oxidising gases, flammable liquids, self-reacting substances and mixtures and organic peroxides, pyrophoric liquids and solids, oxidising liquids and solids; (3) for environmental hazards – hazardous to the aquatic environment; and (4) for other hazards - substances or mixtures with hazard statement EUH014, substances and mixtures which in contact with water emit flammable gases, and substances or mixtures with hazard statement EUH029.

relying on collaboration with the CCS sector to create a positive feedback loop which enables an evidence-based proactive regulation of CCS activities. It achieves this by placing the responsibility on the sector to continue to address existing gaps of knowledge in order to achieve comparable safety standards to other energy, chemical and pipeline industries (Health and Safety Executive, 2024a). However, the HSE's emphasis solely on the omission of CO_2 from the list of "dangerous substances" (without any reference to the Section 3(2)(cb) exclusion) suggests that it is not envisaging the regulation of T&S networks in its consideration of the regulation of CCS activities under existing major accident hazard legislation (Health and Safety Executive, 2024a).

Any prospective expansion of the scope of COMAH to cover CO_2 storage activities in UK ports as part of CCS must involve (1) deleting the exclusion under regulation 3(2)(cb), and (2) recognising CO_2 as a "dangerous substance" under COMAH. Whilst the first condition is straightforward, simply requiring a legislative amendment to remove the relevant exclusion, the second raises more complex regulatory issues that warrant further examination.

One approach is to add CO_2 as a named substance in Part 2 of Schedule 1, based on its ability to displace oxygen and cause asphyxiation when released from pressurised storage in significant quantities. This option provides the highest degree of regulatory clarity and avoids the need for contentious debates about how CO_2 should be classified under the CLP.

Another possibility is for the HSE to collaborate with the CCS sector to review and potentially revise the classification of CO_2 so that it meets the criteria for one of the hazard categories listed in Part 1 of Schedule 1. This process would require careful consideration of the risks associated with handling and storing large volumes of CO_2 in CCS contexts. Internationally recognized guidelines from organisations such as the Organization for Economic Cooperation and Development and the European Chemicals Agency set out procedures for classification under the CLP (European Chemicals Agency, 2024). However, CO_2 has typically been classified based on physical hazards relevant to conventional transport and storage, which may not reflect the potentially greater risks posed by large-scale CCS activities. Currently, it is classified under paragraph 2.5 of Annex I to the CLP as a "compressed gas", "liquefied gas", "refrigerated liquified gas", or "dissolved gas", and is given hazard statements H280 (contains gas under pressure, may explode if heated) or H281 (contains refrigerated gas; may cause cryogenic burns or injury) (Gas, 2020; Liquide, 2022; CryoService Ltd, 2010). However, "gases under pressure" is not a COMAH trigger category in Part 1 or Schedule 1, and, in accordance with HSE guidance, it is the classification of substances rather than their labelling or packaging which is relevant for COMAH purposes (Health and Safety Executive, 2015, para. 369).

To ensure CO_2 is covered by COMAH, HSE could develop guidance to support CCS stakeholders handling and temporarily storing CO_2 fulfilling their responsibility for correctly classifying CO_2 in line with the CLP (recital (16), CLP; article 4, CLP).[23] Such guidance should aim to address the risk of underestimating the potential hazards associated with large-scale CO_2 storage in ports by ensuring that classification reflects the substance's properties in conditions that arise during CCS activities, not just in "normal" atmospheric or laboratory settings. For instance, under current CLP criteria for acute inhalation toxicity, gaseous CO_2 is often tested at harmless levels rather than as part of a mixture with other pollutants presenting acute toxicity. Similarly, traditional aquatic toxicity testing uses aqueous solutions of the test substance, which may not accurately represent the potential impacts of releasing large quantities of liquefied CO_2 into aquatic environments in CCS scenarios. A more robust assessment would consider factors such as pressure, temperature, concentration, purity, storage quantities, phase changes, interactions with other substances, and context-specific risks. Through such an approach, CO_2 could be classified as acutely toxic or hazardous to the marine environment, both of which are hazard categories listed in Part 1 of Schedule 1, thus bringing it within COMAH's scope.

Alternatively, Paragraph 5 of Part 3 of Schedule 1 to COMAH provides a mechanism to include substances not named in Part 2 and not classified under Part 1 if they present a major accident potential equivalent to regulated substances. Section 2 of COMAH defines a "major accident" as "an occurrence such as a major emission, fire, or explosion resulting from uncontrolled developments in the course of the operation of any establishment to which these Regulations apply, and leading to serious danger to human health or the environment (whether immediate or delayed) inside or outside the establishment". Accordingly, the relevant consideration under Paragraph 5 is whether the substance can cause such "serious danger", regardless of its classification or listing under other Parts of Schedule 1.

There is strong evidence to suggest that CO_2 in CCS contexts meets this threshold. HSE guidance highlights the risk of fatal asphyxiation associated with CO_2 (Health and Safety Executive, 2024f). CO_2 is classified as a "substance hazardous to health" under the Control of Substances Hazardous to Health Regulations 2002 (Health and Safety Executive, 2024h; Health and Safety Executive, 2024i), and is subject to workplace exposure limits under EH40/2005 (Health and Safety Executive, 2024i). Documented incidents involving CO_2 leaks have resulted in fatalities, demonstrating its potential for major harm through its cryogenic effects and its capacity to displace oxygen in confined or low-lying spaces.[24] The Environment Agency also lists a range of environmental hazards associated with CO_2 storage in a CCS context, including potential impacts on air, water, land, climate, and ecology (O'Leary, 2002, pp. 6–8).

Although gaps in knowledge remain, the significant risks to health and the environment make a compelling case for recognizing CO_2 as having equivalent major accident potential to substances regulated under COMAH, particularly those listed under acute toxicity and environmental hazard categories in Part 1. Insofar as these risks relate to environmental harm, this approach is also supported by the duty under section 19 of the Environment Act 2021 to apply the precautionary principle in the face of scientific uncertainty (DEFRA, 2025a). On this basis, CO_2 should be provisionally assigned to an analogous regulated category, bringing establishments where it is stored within the scope of COMAH.

In summation, COMAH apply to establishments where substances which are deemed "dangerous" are present at or above the thresholds set out in Schedule 1, provided that no applicable exclusions prevent its application. Recognising CO_2 as a "dangerous substance" can be achieved by one of three mechanisms: explicitly listing it as a named substance in Part 2 of Schedule 1; classifying it within a hazard category in Part 1 of Schedule 1; or assigning it based on equivalent major accident potential under Paragraph 5 of Part 3. While the second and third routes may potentially include CO_2, explicit naming it in Part 2 offers the highest level of legal certainty and is the most effective way to ensure predictable application of COMAH. To illustrate, Table 1 compares how these routes apply to CO_2, methane (CH_4), and ammonia (NH_3) in the context of large-scale storage.

As presented in sub-Section 2.2 and in line with the performance-based approach for the regulation of H&S and MAP risks in UK ports, a key expectation from duty holders is to adopt and implement MSMSs based on a formal assessment of risks which confirms the SHA's compliance with relevant duties under existing legislation. By expanding the scope of application of COMAH to apply to temporary storage activities when CO_2 is present in excess of specified thresholds, the HSE

[23] The HSE plays a supervisory role in overseeing compliance with the CLP and may conduct audits, inspections, or enforcement actions to ensure that substances are classified correctly and in accordance with regulatory requirements (Health and Safety Executive, 2024e).

[24] See footnote 3 and accompanying text.

Table 1
Comparison of COMAH applicability criteria for carbon dioxide, methane, and ammonia with reference to classification under the CLP.

Substance	Included as a named substance in Part 2 of Schedule 1	Properties fit within the categories listed in Part 1 of Schedule 1	Applicability of Part 3, Paragraph 5
CH_4	No	Yes – e.g. highly flammable gas (87, para. 5.2)	Not needed
NH_3	Yes	Yes – e.g. acute toxicity; flammable; hazardous to the aquatic environment	Not needed
CO_2	No	No – substance classified as "compressed gas" under the CLP (not listed in Part 1, Schedule 1)	Yes – equivalence with acute toxicity based on (Health and Safety Executive, 2024g; Health and Safety Executive, 2024h; Health and Safety Executive, 2024i; O'Leary, 2002); and hazardous to the aquatic environment (DEFRA, 2025a; DEFRA, 2025b)

would establish a clear "performance goal" for duty holders to aim to achieve in the regulation of the activity rather than allow them to base their behavior on their subjective assessment of hazards and risks.

4. Conclusions and policy recommendations

In this article, we examined the legal and regulatory framework governing H&S and MAP in UK ports, assessing its suitability for managing the risks associated with increasing CO_2 shipping in support of CCS. As recognised in UK Government plans, shipping is a key enabler of CCS expansion, particularly for industrial clusters without direct pipeline access to storage sites. Given the importance of CCS in achieving the UK's net-zero commitments and its role in meeting the Paris Agreement's mitigation goal, it is essential that regulations governing CO_2 shipping infrastructure keep pace with its growing role in enabling the UK's CCS expansion. Ensuring that regulations governing CO_2 shipping infrastructure provide robust protection for port workers, nearby communities, and the environment is critical to the safe and sustainable deployment of this transport modality.

In Section 2, we examined the legal and regulatory landscape governing UK ports, highlighting how numerous laws and fragmented governance create significant compliance challenges for port operators and regulators, including regarding the handling and storage of CO_2. Our analysis of port freight data and CCS sector projections showed that the expected expansion of CO_2 shipping will introduce new large scale operational and safety risks that existing regulatory frameworks may not fully address. We focused on the role of the performance-based PMSC in harmonizing marine safety standards across UK ports and promoting a proactive safety culture. However, we identified limitations of the PMSC when specific regulations do not establish clear performance goals essential for managing these emerging risks. We emphasized the importance of duty holders adopting and implementing MSMSs based on objective risk assessments, and the need for clear performance goals in specific legislation and regulatory guidance to ensure these systems adequately address novel hazards.

In Section 3, we analysed DGHAR and of COMAH, two key regulations for the management of dangerous vessels and dangerous substances in ports. We examined the applicability and relevance of the powers and duties thereunder to effectively govern CO_2 activities in UK ports. We found that the former recognizes suitable powers to SHAs and duly appointed harbor masters to manage risks associated with increased traffic of CO_2 carriers passing through UK ports. However, relying on our analysis of expected CO_2 freight trends in sub-Section 2.1, we argued that novel challenges will emerge from the passage of larger quantities of CO_2 through ports in support of CCS. To address these challenges, we recommend that the MCA develops specific guidance to raise awareness about emerging risks for relevant stakeholders, including port authorities and terminal operators. The development of such guidance is commonplace and can be informed by the MCA's engagement with relevant governmental bodies (MMO; EA; HSE), CCS stakeholders including SHAs, and the wider research community.

With regards to COMAH, our analysis identified two barriers to the application of major accident prevention and control requirements for dangerous substances to CO_2 storage activities in ports and proposed recommendations clear recommendations for each. The first barrier is the exclusion under regulation 3(2)(cb), which currently exempts the transport of dangerous substances and directly related temporary storage from the scope of the regulations. Removing this exclusion through legislative amendment would extend COMAH's reach to cover CO_2 storage in ports, thereby addressing this limitation. The second barrier concerns the omission of CO_2 from the list of substances that, when present in excess of specified thresholds, trigger the application of COMAH. We advanced that there are three routes for overcoming this barrier. The first is to name CO_2 explicitly in Part 2 of Schedule 1, recognising the specific risks it poses in the context of CCS, especially those arising from its potential to cause asphyxiation and major harm. This route provides the greatest legal certainty and clarity but requires a direct amendment of COMAH through a statutory instrument, following public consultation and Parliamentary approval. The second is to ensure an accurate and context-specific classification of CO_2 under the CLP that reflects the actual risks associated with large-scale CCS operations and ensures it fits within one of the hazard categories listed in Part 1 of Schedule 1. While the responsibility for classification rests with CCS stakeholders, this process could be facilitated by the HSE developing clear guidance on how CO_2 should be classified in CCS contexts, in collaboration with industry and the research community. The third method is to treat CO_2 as possessing equivalent major accident potential as regulated substances under Paragraph 5 of Part 3 of Schedule 1. Consistent with its commitment to update COMAH based on emerging evidence, the HSE could advance this approach through a formal review drawing on new scientific and incident data to determine whether CO_2 should be regulated under this provision. In all cases, recognition of CO_2 as a dangerous substance for the purposes of COMAH requires an approach that fully encompasses the risks posed by its handling and storage at the scale anticipated for CCS shipping. Such measures will help ensure that establishments storing CO_2 in quantities above threshold levels are brought within the scope of COMAH, and that the regulatory framework is sufficiently robust to meet the challenges of a growing CCS sector in UK ports. Practically, addressing these barriers would clearly extend the "performance goals" enshrined in COMAH – namely the requirement for operators to prevent major accidents and to limit their consequences for human health and the environment – to temporary CO_2 storage activities in UK ports, which duty holders would need to demonstrate compliance with in their MSMSs.

The recommendations outlined above are crucial for the MCA and the HSE as they work to uphold adequate safety standards for both seafarers and shore-based workers. To improve clarity, we summarised them and presented them in Table 2. Modernizing regulatory frameworks will enable the UK to support the safe and sustainable expansion of CCS, reinforcing its leadership in global decarbonization efforts. Robust safety measures for CO_2 shipping will not only protect port communities but also foster public trust in CCS as a viable climate solution. As CO_2 transport networks become increasingly international, regulatory clarity will strengthen the UK's position as a leader in cross-border CO_2 T&S services. Ultimately, however, the implementation and impact of these recommendations will depend on whether the HMG

Table 2
Summary of key findings and recommendations, including implementation pathways and operability assessment.

Regulatory instrument	Identified regulatory gap(s)	Recommendation(s) to fill the gap (s)	Recommendation(s) implementation pathway(s)	Recommendation operability assessment
PMSC	Limited efficiency in the absence of clear performance goals in specific legislation and/or regulatory guidance	Ensuring that clear performance goals are set out in relevant legislation and that appropriate guidance is issued where needed	Depends on the specific legislation in question	N/A
DGHAR	Lack of awareness of novel risks to be introduced by the passage of larger quantities of CO_2 through ports in support of CCS	Issuing specific guidance to clarify risk management responsibilities for anticipated substantial increase in CO_2 shipping operations	The guidance can replicate similar HSE documents on the major hazard potential of CCS and its development can be informed by the MCA's engagement with relevant governmental bodies, CCS stakeholders, and the wider research community	The issuance of such guidance is common practice when new operational circumstances arise, and the MCA has a proven track record of producing them. Developing this guidance should be relatively straightforward but will depend on the realization of HMG's plans to rely on CO_2 shipping for CCS
COMAH	(1) The transport of dangerous substances and directly related temporary storage is currently excluded from the Regulations (2) CO_2 is not currently considered as a dangerous substance under the Regulations	Amending the Regulations to remove the exclusion of temporary storage and recognize CO_2 as a dangerous substance	The exclusion can be removed through legislative amendment. CO_2 can be recognized as a dangerous substance by (1) adding it as a named substance in Part 2 of Schedule 1 through a direct legislative amendment, (2) formally reviewing its classification under the CLP in a manner that it fits within one of the hazard categories listed in Part 1 of Schedule 1, or (3) treating it as possessing equivalent major accident potential as regulated substances under Paragraph 5 of Part 3 of Schedule 1	Statutory instruments are the usual legislative mechanism for amending COMAH and have been relied on before (for example, to implement the Seveso III Directive (Directive 2012/18/EU) in 2015). This route can be used to remove the exclusion of temporary storage and add CO_2 as a named substance in Part 2 of Schedule 1, providing the greatest levels of legal certainty and clarity, but it will hinge on policy developments. The responsibility for reviewing the classification of CO_2 under the CLP rests with CCS stakeholders but could be facilitated by the HSE through developing clear guidance on how CO_2 should be classified in CCS contexts. This is a longer process and depends on greater coordination between different stakeholders. Treating CO_2 as having equivalent major accident potential depends on the HSE's review of CCS hazards, drawing on new scientific and incident data and collaboration with relevant stakeholders. This route offers the advantage of not requiring reclassification of CO_2 (which can have implications for other regulations) or direct amendment of COMAH, but it depends on buy-in from regulated entities.

moves forward with its current plans to rely on shipping as a NPT solution for CCS. By acknowledging this dependency, we provide a pragmatic perspective on how regulatory change must be aligned with broader policy decisions that shape the future of CO_2 shipping in the UK.

Building the evidence base in this emerging field is essential to meet the growing demand for comparative research, as more countries gain regulatory experience with CO_2 shipping and port storage. This paper also offers insights to support the adaptive review of regulatory frameworks for alternative fuels in maritime transport, helping ensure they remain fit-for-purpose amid evolving technologies and sectoral changes. While our analysis focuses on CO_2 shipping and storage regulation in the UK, the methodology and key findings offer valuable perspectives for international regulatory developments in maritime CO_2 shipping, port storage, and alternative fuels.

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CRediT authorship contribution statement

Wassim Dbouk: Writing – original draft, Investigation, Formal analysis, Conceptualization. **Damon Teagle:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Lindsay-Marie Armstrong:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Johanna Hjalmarsson:** Writing – review & editing. **Stephen Turnock:** Writing – review & editing, Project administration, Funding acquisition. **Alexandros Ntovas:** Supervision.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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