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Communication

Research and innovation identified to decarbonise the maritime sector

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Abstract

The maritime sector requires technically, environmentally, socially, and economically informed pathways to decarbonise and eliminate all emissions harmful to the environment and health. This is extremely challenging and complex, and a wide range of technologies and solutions are currently being explored. However, it is important to assess the state-of-the-art and identify further research and innovation required to accelerate decarbonisation. The UK National Clean Maritime Research Hub have identified key priority areas to drive this process, with particular focus on marine fuels, power and propulsion, vessel efficiency, port operations and infrastructure, digitalisation, finance, regulation, and policy.

Keywords: maritime; decarbonisation; sustainability pathway; UK National Clean Maritime Research Hub; research priority

1. Introduction

In 2018, the International Energy Agency reported that international shipping emitted 708 million tonnes of CO_2 equivalent and consumed 9.2 exajoules of energy from fossil fuels. To meet the goals of the Paris Agreement and account for expected growth in shipping volumes up to 2050, greenhouse gas (GHG) emissions from ships must be reduced by 75–85% per ton-mile. Ships also produce the largest quantities of emissions for nitrogen oxides (NO_x), sulphur oxides (SO_x), and particulate matter (PM) in the transportation sector and are a significant source of carbon monoxide (CO) and hydrocarbons (HC) emissions. The International Maritime Organisation (IMO) has introduced mandatory measures to increase energy efficiency (Energy Efficiency Existing Ship Index, EEXI) and report CO_2 emissions (Carbon Intensity Indicator, CII), and in 2023 agreed the ambition for international shipping to achieve net-zero GHG emissions by or close to 2050. The IMO has suggested a range of solutions for future vessels, including improving power and propulsion systems, using biofuels, hydrogen and synthetic fuels, enhancing energy management and voyage optimisation, improving vessel design, and bettering fleet management and incentives [1].

The UK National Clean Maritime Research Hub have engaged with the maritime community to further identify research and innovation needed to transition towards a net-zero GHG future and improve air quality.

2. Identified research and innovation needs

2.1 Marine fuel scale up and safe use

Ammonia, hydrogen, e-fuels *etc.* are future clean fuels for marine vessels. Whilst their use has already been explored, they have not been deployed at significant scale. Currently, the sector lacks a comprehensive understanding of potential feedstocks, energy demand, costs, embedded emissions, and other pertinent details associated with production at scale. There is a need to facilitate and identify the optimum deployment of large-scale fuel production facilities and gain better insight in the environmental impact of fuel switching from a whole-system perspective based on material flow analysis and life cycle assessment.

There are unanswered questions around the most appropriate opportunities to deploy compressed and liquified hydrogen, methanol, and ammonia for maritime sector. These are particularly focussed on safe storage, handling and operational issues associated with these new fuel alternatives. Further research is necessary in relation to dealing with the risks associated with toxicity, fire, and explosion. For example, this includes the requirements for onboard ventilation to prevent flammable/toxic mixture propagation, the impact of atmospheric conditions on dispersion and hazard distances.

Power and propulsion for long-distance shipping requires very large amount of energy in the form of fuel to be stored onboard. The excellent volumetric and gravimetric energy density of existing marine fossil fuels has made this possible but is a challenge for the new low-carbon alternatives. The relatively poor volumetric energy density of hydrogen currently restricts its use in a marine context, with compressed hydrogen storage more suitable to some inland and short-sea shipping applications. Improved volumetric energy density can be achieved by using liquified hydrogen or a hydrogen carrier fuel, such as ammonia. However, a greater understanding of liquified hydrogen and ammonia bunkering is necessary and will support efficient system development and inherent safety protocol development. Computational fluid dynamics models of compressed hydrogen bunkering have already been developed and are being produced for liquified hydrogen. Further theoretical, numerical, and experimental research is necessary in the development of efficient systems and inherently safer operations and practices. There is a need for experimental data and a better understanding of the underlying physics, material selection, protocols for conformable tank systems (multiple tanks), and pressure recovery phenomena in horizontal and vertical tanks for liquified hydrogen.

Considering space limitations, reducing hazard distances onboard is extraordinarily difficult. Thus, new prevention and mitigation strategies are necessary for the safe use of hydrogen and ammonia. Further experiments and simulations of the release and dispersion are required to gain insights into underlying physical phenomena, which is crucial in the development of predictive safety models. Some areas of increased research identified in the maritime context are as follows:

- Modelling of multi-phase releases during bunkering and dispersion in the atmosphere.
- Modelling of wind variability and its effect on atmospheric ammonia dispersion.
- Hazard distances for unscheduled releases of liquified hydrogen and ammonia (concentration decay, flame length and stability).
- Fundamentals of cryogenic hydrogen combustion.
- Hazards of impinging non-reacting and reacting jets.
- Oxygen enrichment and condensed phase explosions for large-scale liquified hydrogen releases.
- Rain-out for liquified hydrogen releases.
- Multi-peak nature of boiling liquified expanding vapour explosion (BLEVE) for liquified hydrogen tanks.
- Consequences of liquified hydrogen releases in enclosures and confined spaces.
- Heat and mass transfer during liquified hydrogen tank release through a vent stack.
- Coupled CFD/Finite Element Method (FEM) modelling for storage tank rupture onboard vessels.

Addressing these research gaps is important, and an International Code of Safety for Ships using Gases or Other Low-flashpoint Fuels (IGF Code) for hydrogen, especially for liquified hydrogen, is crucial for its deployment.

Liquid organic hydrogen carrier (LOHC) fuels are compounds capable of storing and releasing hydrogen through reversible chemical reactions. They offer a promising solution for hydrogen storage and transport due to their high hydrogen content and relative safety compared to compressed or liquefied hydrogen. Advancements in LOHC fuel synthesis methods, such as utilising renewable energy for hydrogenation reactions, novel catalysts, new reaction engineering techniques improving efficiency, as well as the integration of LOHC fuel systems into existing energy infrastructure, are promising. However, the development of efficient regeneration processes, the scalability of LOHC fuel production for long-distance voyages, the use with existing ship designs (retrofit) and onboard safety protocols, and the optimisation of transport infrastructure are areas that need further attention. Additional development is necessary to reduce the energy required for both hydrogen loading and unloading, the need for catalysts to facilitate hydrogenation and dehydrogenation reactions, and the cost of LOHC fuel systems compared to other methods to store hydrogen.

2.2 Power and propulsion systems

Disruptive power and propulsion systems have the potential to operate with high efficiency and net-zero GHG emissions across the maritime sector. Greater electrification and new power generation and distribution methods can improve system performance and efficiency. Advancement in internal combustion engine technology, carbon capture and storage (CCS), new power cycles, and fuel cell systems can enable the switch to new low-carbon fuels, such as methanol, hydrogen, and ammonia. Innovation will provide the opportunity to deliver novel vessel propulsion and auxiliary power systems, and support ports to operate efficiently and as hubs to provide energy services. The use of new electrical drives and advanced energy storage can optimise supply and demand, whilst novel control strategies can be developed to optimise their integration with DC microgrid systems and other powertrain components.

Internal combustion engine development requires further combustion characteristic experimentation and evaluation of the potential new marine fuels, for example using a high-pressure constant volume vessel and diffusion flame combustor. Hybrid engine systems have the potential to exploit, for example, dual-fuel methanol with hydrogen enrichment, mono-fuelled methanol passive and active jet ignition, as well as novel cryogenic heat recovery and indirect ammonia latent heat recovery. Challenges remain with respect to the continuous operation of spark-ignited hydrogen engines under ultra-lean conditions. Also, the deployment of split-cycle engines and linear-engine generators for power and propulsion applications needs to advance.

Research on high-power ammonia and hydrogen fuel cell systems is currently geared towards understanding the current-voltage behaviour, enhancing durability, optimising structure, maximising efficiency, and minimising emissions of proton-conducting solid oxide fuel cells (PC-SOFC) at the level of large single cells. Scaling solutions for large-scale applications and their integration into marine power delivery systems are being investigated. Options for the integration of CCS, including post-combustion CO_2 scrubbing, pre-combustion molten carbonate fuel cells (MCFC), and molten salt reactor (MSR) technologies coupled with internal combustion engines, need further research through thermodynamic modelling, techno-feasibility analysis, and economic evaluation.

Different AC and DC architectures for shipboard power distribution have been proposed over many years. Existing AC distribution systems are not ideal because of the difficulty in voltage and frequency regulation and the need to convert the power twice for electric motors and energy storage devices. Additional drawbacks include increased fuel consumption to keep the speed of the generator within the allowed range, and the presence of low-frequency transformers that increase cost and weight of the electrical systems. DC distribution systems are currently considered very promising for many vessels, albeit concern still exists with voltage regulation and protection.

Novel modular DC power architectures can improve the power quality of the electrical systems and zonal electrical distribution systems are preferred for their modularity as power flows are controlled and exchanged between zones. Disturbances cannot propagate between electrical zones as they are decoupled by power electronic converters. Energy storage systems can be connected within an individual zone to support loads locally. Thus, different types of energy storage including batteries, supercapacitors and superconducting magnetic energy systems are being investigated.

A focus on electronic DC circuit breakers is required, and new architectures of DC/DC converters enabling fault interruption only acting on the switching, like dual-active bridge topologies, should be explored to ensure continuity of operations and fault resilience. To improve voltage stabilisation, the converters can be controlled with different dynamic response to regulate the power transfer within the zone and between zones to achieve the desired power split between the primary power source(s) and the energy storage. Further work is needed to examine if protection systems can adequately protect the system with sufficient logic selectivity when it comes to DC networks. A challenge exists to raise the voltage above 1 kV DC for large vessels because of the lack of suitable DC circuit breakers. Also, smart DC control systems have not been standardised yet, and this limits industrial adoption.

Addressing these issues will increase the electrification of vessels and the utilisation of integrated renewable and battery technologies. Additionally, the design of electrical power systems can be optimised, leading to increased efficiency and zero-emission range. Potential challenges include the limited lifetime of batteries which requires the development of new chemistries and technologies to reduce the degradation of active materials, and the need to increase the voltage levels above 1 kV DC or 6.5 kV AC for large vessels which would require the development of new power converters and motor drives adapted for marine use.

Hybrid marine propulsion systems have become increasingly complex due to the emergence of various decarbonisation technologies, e.g., low-carbon fuel engines, hydrogen fuel cells, batteries, wind propulsion, and carbon capture storage. Many of these technologies have yet to be optimised, assessed, nor extensively tested in the marine environment. Developing advanced optimisation strategies for hybrid drive design and operation, supported by real-life data, can alleviate major concerns, and facilitate the implementation of retrofit and new build projects integrating emerging decarbonisation technologies. The development of effective decision-making tools that are informed by techno-economic-environmental assessments of relevant decarbonisation technologies can assist in the design and operation of hybrid systems onboard ships. Multi-objective optimisation techniques can be developed to minimise conflicting objectives, such as cost, emissions, and performance.

Integrating real-life operational profiles, geographic and weather data, and other relevant factors, data-driven models will allow high-resolution spatial and temporal analyses using advanced optimisation algorithms, which are necessary for developing optimal energy management strategies in real time. This will allow the best new or retrofit designs to be identified. Current decision-making tools rely on data and algorithms without considering human factors, and the best solutions might become out of date as decarbonisation technologies advance.

Approximately 80% of GHG emissions from shipping comes from large bulk carriers, tankers, and container ships [2]. These vessels transport more than 75% of the world’s trade volume and have typical operating lives of 25 to 30 years as part of a large legacy fleet. To provide a sense of scale, the rated output of the main internal combustion engine in these larger ships is typically more than 20MW and over 100MW in the largest vessels. Their main engines are predominately low-speed two-stroke designs with approximately a 70% market share [3]. These engines have the highest power density and fuel efficiency and are mostly directly coupled to the propellor(s) and running on heavy fuel oil.

All current two-stroke marine engines, including those capable of dual-fuel operation with methanol and ammonia, rely on diesel fuel pilot ignition which results in high GHG and other harmful emissions. Examples of research and innovation related to large slow-speed two-stroke diesel engine retrofit technologies are as follows:

- Novel retrofittable clean combustion systems that do not rely upon pilot fossil fuels as the source of ignition.
- Disruptive retrofit emissions after-treatment systems compatible with operating on low carbon fuels.
- New compatible waste heat recovery technologies enabling a step change in overall system efficiency.

Market analysis indicates that the medium-speed, four-stroke diesel engine, typically less than 10MW, could provide a good commercial opportunity [4]. The potential challenges and limitations include the compromise between the high efficiency of current propulsion engines and the inherently cleaner four-stroke internal combustion engine technologies.

Nuclear propulsion systems have the potential to transform the marine operational landscape. There has been increased interest in civil nuclear propulsion technologies recently but there is a need for research to address challenges associated with technological complexity, high initial investment costs, public perception and acceptance, regulatory hurdles, and concerns over nuclear proliferation. Furthermore, ensuring nuclear-powered vessels’ safe operation and maintenance poses unique challenges requiring specialised expertise and infrastructure. There is a need for better understanding of the total cost of ownership and comprehensive techno-economic analysis. Crucial questions persist regarding the integration of nuclear propulsion systems with existing commercial vessel designs, optimal reactor configurations for different vessel types, and the long-term implications of nuclear waste management. Concerns over safety and environmental impact may hinder industry acceptance and regulatory approval, thereby limiting the realisation of potential benefits in terms of emissions reduction and operational efficiency.

2.3 Port and vessel support infrastructure

Manoeuvring and docked vessels, cargo-handling equipment, and other infrastructure, heavy and light duty vehicles, and rail locomotives all contribute towards GHG emissions and air pollution in ports. Therefore, decarbonisation and improved air quality require a combination of measures, for example enhancing operational efficiency for ship docking and goods handling, upgrading hydrogen or electrically powered equipment, redesigning port infrastructure, as well as adopting cold ironing (shore power) and integrating renewable energy solutions. Further research and innovation are necessary to understand the combination of measures which will work most effectively for a specific port and the viable pathways to adopt them.

A better understanding of the contribution ports can make to the transformation of the maritime sector and the consequential effects on stakeholders and on the associated supply chains is important. Decarbonisation would be accelerated through co-development and information sharing between stakeholders. Ports should increasingly be considered as an energy hub, providing energy services for their operation, and the vehicles and vessels within this ecosystem.

The development of digital twins for ports would enable them to streamline operations, make strategical plans, improve energy efficiency, and reduce emissions. Optimised energy supply and demand could be achieved through exploitation of renewable energy and energy storage, and the application of machine learning and artificial intelligence (AI) could enhance port logistics and smart energy management. Further technical, economic, and political research is needed with respect to the operation of potential clean shipping corridors, exploring for example, data gathering, storing and analytics, to develop business cases and inform policy development and incentive schemes.

Ports will experience substantial changes and require new infrastructure and the switch to new fuels during the net-zero GHG emission transition. As ports are often situated close to densely populated areas, communities are concerned about the development of new port infrastructure, including road and buildings construction. Some ports have installed air quality monitoring devices around their geographical boundary but the long-term socio-economic-environmental impacts of port operations and effective strategies to decarbonise and minimise air pollution need to be explored. Near-port communities are often deprived and suffer disproportionately from port operations. This raises social aspects which present a challenge and need for research to identify place-based responses.

Ports play a key role in the wider energy system, where a large percentage of handled goods are energy related. The need for decarbonisation and the established logistics between ports and existing energy users have placed ports in a good position to pursue new energy solutions, for example to exploit renewable energy, energy storage, integrated energy systems, smart grids *etc*. Ports are typically blessed with space for renewable energy infrastructure and access to water required to produce hydrogen and ammonia for example. Additional infrastructure and supply chain development will be required to exploit this opportunity.

All ports have their own specific renewable energy potential and markets for sustainable fuels. This could be direct use of renewable energy on site, as well as fuel supply for residential, industry and transportation. Research and innovation to provide novel energy solutions that can be effectively integrated into port infrastructure, meet energy demand, and provide resilience, while minimising environmental impact is needed. The retrofit of existing port infrastructure with new energy solutions would need to minimum disruption to port operations, as well as understand the capacity of ports and the markets that they have the potential to service is crucial.

2.4 Vessel design and efficiency

Design of low-carbon ship, integration of novel marine propulsion, and development of decision-support tools considering energy systems, energy consumption, life-cycle emissions and cost analysis are current areas of research and innovation for both retrofit and new build vessels. Utilising multi-agent reinforcement learning, the design of ship hulls and propellers could be optimised, and digital twins could be developed to evaluate speed-power performance of any vessel types. Accurate emulation of full-scale ship behaviour and robust integrated designs can be achieved by structuring experimentation with simulations of advanced propulsion systems.

Integrating new power and propulsion systems, including wind-assisted technology, and the bunkering and storage of new marine fuels will necessitate vessel redesign. Powertrains and fuel tanks with different capacities, volumes, and weights need to be accommodated whilst ensuring safety. Maximising their technical performance and minimising environmental impact is crucial, and the options for vessel decarbonisation at a system level, in terms of energy consumption, cost, and emissions, are complex. Therefore, the development of decision-making support tools to explore these options is important.

Improvement in the energy efficiency of vessels is essential to reduce fuel consumption, to substantially reduce operating costs and associated GHG emissions. This can be achieved by improving existing or developing new energy-saving technology (EST), for example drag-reducing systems, such as air lubrication, new hull coatings, improved propulsion systems, and waste heat recovery systems. The performance of novel EST needs to be assessed, optimised, and compared under varying operational conditions and vessel configurations to maximise fuel savings and emissions reduction, and minimise the potential environmental impacts, considering manufacturing materials, fuel consumption, and end-of-life disposal. The economic feasibility and lifecycle impact associated with retrofitting EST to vessels need to be presented to ship owners/operators, considering upfront investment, fuel savings, maintenance, downtime, and other relevant factors during retrofit. Due to the diverse range of vessel types, sizes, and operational profiles, integrating novel EST into both conventional and novel ship designs whilst ensuring compliance with international regulations and standards presents a major challenge.

The shipping industry is undergoing a rapid transformation, as digitalisation and related technologies enable the increasing adoption of remote and autonomous vessel systems. The advent of these technologies has the potential to realise improved operational efficiency and better safety outcomes when using new marine fuels such as hydrogen and ammonia. These systems use AI and other advanced technologies to perform tasks that would normally require a crew, such as navigation, control, communications, and maintenance. Thus, vessels will likely be equipped with intelligent and adaptable technologies, requiring a wide range of sensor data to provide situational awareness either for the remote crew or the onboard autonomous systems. Furthermore, within the wider skills context, research is necessary to identify the changing nature and skills required in the future. Current research is developing systems for effective autonomous and remote operations, but further work is required to determine the form of future navigational and control algorithms for this application. It is necessary to identify the key points of risk faced in deploying intelligent and self-learning systems and explore the ethical considerations regarding their equivalency to safe operation by a human counterpart. Research and innovation will be necessary to maintain adequate situational awareness for safe and effective operation of remote-control centres and to assure the capability of autonomous systems. The findings will be important to provide an initial framework to assist in assurance testing of autonomous vessels. Without empowering maritime staff with training, they will lack the skills to effectively troubleshoot advanced computational systems, make sense of large volumes of information and data, and deal with emergency response. For vessels to operate in shared mixed environments where autonomous, remote-controlled, and manned vessels interact, challenges faced in technology, regulation, assurance, security, and skill development are compounded.

2.5 Digitisation, maritime operations, and finance

Improved maritime sector operations will involve structured and unstructured data associated with cargos, vessels, equipment, fuels, energy, relationships, and communications. As these data are heterogenous, state-of-the-art research applies data analytics and machine learning to generate actionable knowledge, aiming to improve business practice for enhanced economic and emission performance. In a business context, AI-enabled optimisation techniques are being developed to carry out real-time forecasting using multiple variables for vessel and shoreside operations and provide just-in-time arrival operation, which can significantly reduce fuel use and emissions. Further economic, financial, and managerial implications of using this technology need to be explored.

Challenges induced by decarbonisation include variations in the operating income and the operational, maintenance, and capital costs associated with vessels, which will affect shipping investment. As such, sustainable finance research and investigation into how the cost of capital will affect investment decisions are becoming increasingly important for shipping. This will assist stakeholders, for example, owners, shipping companies, investment banks and capital providers, policy makers, regulators, and consumers of shipping services. This work will provide an understanding of maritime decarbonisation from microeconomic, financial, and managerial perspectives.

Current dominant marine communication technologies (e.g., shore-based cellular stations, high-frequency radio, and expensive satellites) face challenges such as short coverage, low bandwidth, insecurity, and unavailable cross-domain transmission. Real-time vessel data communication involves the immediate exchange of information between vessels and shore-based systems to enhance maritime operations and safety. While recent research has focused on event detection from Automatic Identification System (AIS) data, existing approaches often rely on ad-hoc methods that handle only predefined types of vessel behaviour. If machine learning is deployed to enable real-time predictive vessel behaviour, this can be incorporated into various intelligent systems, including vessel collision prevention, vessel route planning, operation efficiency estimation, and anomaly detection systems.

Areas where enhanced capability is required include improvement in offshore communication network capacity, standardisation of data formats, protocols for secure transmission, and interoperability among different vessel systems and shore-based platforms. Addressing these issues will improve efficiency, safety, and reduced accident risks in maritime operations. While advancements are under way, offshore maritime communications still suffer from slow communication speeds and limited capacity, despite the growing demand for information exchange and big data analytics. In line with the rise of digitalisation and autonomous ship operation, there is a surge in data generated from sensors, requiring real-time transmission for remote voyage monitoring and control, exacerbating the strain on existing maritime communication infrastructure. Research and innovation are needed to enhance the volume, velocity, and variety of information exchange between vessels and onshore communication networks. This would facilitate better event and anomaly detection, forecast vessel behaviour, and inform operation planning at ports and inland logistic centres.

There is high uncertainty among shipping investors regarding not only the technological dimension of maritime decarbonisation but also about the implications of the current and forthcoming regulations on the industry. Following the revised 2023 IMO GHG Strategy and the entrance of shipping into the European Union’s Emissions Trading System (EU ETS) on 1 January 2024, it is now important to examine the impact of regulations on investments. Investigating this will inform the economic and financial models developed, as well as the maritime operations. Understanding how stakeholders will perceive the actual effects that current and forthcoming regulations will have on the functioning of the maritime industry is important. Regulatory and policy implications on maritime operations with respect to the business models of different stakeholders, primarily ship owners/operators, financiers, and charterers requires research. Whilst marine regulations are under development at international, regional, and national levels, these regulatory frameworks may not align with each other. Such complexity and uncertainty present challenges and the need for further research in this area.

Approximately two-thirds of the population in the UK live within 10 miles of the coast (and 95% within 30 miles) [5] and the vast majority of import and export of goods pass through seaports. The interaction with road freight is critical and more than half of UK road freight CO_2 emissions are attributable to heavy goods vehicles (HGVs). While the development of electric and hydrogen power trains for HGVs will reduce carbon emissions, particulates from tyres, brakes, and road dust are set to increase. Rail presents another alternative for freight movement; however extensive electrification infrastructure and electric power train deployment will be necessary to reduce GHG emissions.

Increased freight movement by coastal shipping has the potential to greatly reduce GHG emissions per tonne transported and could save extensive infrastructure, road and rail vehicle drive train conversion costs. Thus, moving freight by coastal routes offers advantages from both commercial and environmental perspectives. Knowing that infrastructure and supply chain development will be required to exploit this opportunity, further research is necessary to understand the potential to increase coastal freight movement.

3. Future outlook

As the maritime sector is a hard-to-abate sector, significant effort is required to reduce GHG emissions and air pollution, and thus facilitating the transition to net-zero and sustainable maritime transportation. There are a number of identified areas in which further research and innovation are urgently needed, including:

- Marine fuels, including ammonia, hydrogen, liquid organic hydrogen carriers and e-fuels.
- Power and propulsion, including electrical systems, highly modular microgrids, clean (two- and four-stroke) internal combustion engines, zero-emission power cycles, ammonia and hydrogen fuel cell systems, nuclear propulsion systems, and integrated vessel carbon capture and storage.
- Vessel design and efficiency enhancement, including digital twins for vessels to support speed-power performance evaluation, integration of new marine propulsion technology, novel energy-saving devices, autonomous vessels, and decision-support tools, considering energy systems, energy consumption, life-cycle emissions, and costs.
- Port and vessel support infrastructure, including efficiency improvement for ship docking and goods handling, equipment upgrade, infrastructure redesign, cold ironing, renewable energy, air pollution impact, and novel solutions such as energy storage, integrated energy systems, and smart grids.
- Digitalisation, finance, regulatory frameworks, and policy initiatives, taking advantage of AI-enabled optimisation models, real-time vessel data communication, considering risk and uncertainty, as well as developing modal shift, *i.e.*, utilising coastal shipping to move freight to create marine freight highways.

This list is not exhaustive but provides an insight into main areas of research that the UK National Clean Maritime Research Hub has initially identified with the support of a wide range of maritime stakeholders.

Additional relevant topics, associated with dynamic vessel emissions estimation, improved voyage optimisation, boil-off and sloshing effects of liquified hydrogen, and circular economy solutions for all marine equipment have been suggested and will be explored further in the near future.

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Competing Interests

No competing interests exist.

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