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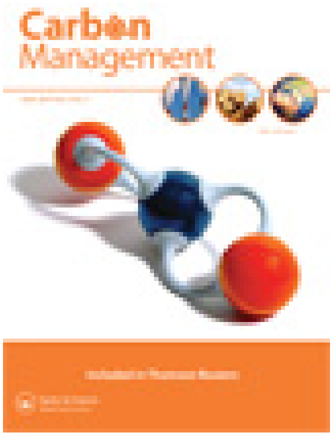

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Technologies for the high seas: meeting the climate challenge

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Research Article

Technologies for the high seas: meeting the climate challenge

Carbon Management (2014)

Paul Gilbert*, Alice Bows-Larkin, Sarah Mander & Conor Walsh

Background: Progress toward decarbonizing shipping has been slow compared with other sectors. To explore the scope for an urgent step-change cut in CO_2, this paper presents results from a participatory technology roadmapping exercise. **Results:** Combining existing incremental and novel technologies with slow-steaming can deliver reductions in CO_2 of over 50% even in the short term for existing ships. However, roadmaps for three vessel types illustrate barriers to change including the sector's complexity, infrastructure lock-in and a need for tailored market and vessel-specific roadmaps to support decision-making. **Conclusions:** Through technology and engineering, the outlook for the shipping sector to significantly cut its CO_2 emissions, even in the short term, is promising. Nevertheless, the scale of change requires support to demonstrate how the long-term low-carbon vision offers enough benefit to overcome necessary short-term investment.

Introduction

Signatories to The Copenhagen Accord have committed to “hold the increase in global temperature below 2 degrees Celsius, and take action to meet this objective consistent with science and on the basis of equity” [1]. This commitment requires global GHG emissions to peak as soon as possible, and, given the significance of cumulative emissions, any delay limits the probability of avoiding a 2°C rise [2,3]. Moreover, accepting that the global commitment to 2°C is a reasonable one, then implications for all energy-consuming sectors are stark, and generally underestimated. Debate around and progress toward decarbonization in the shipping sector is no exception, and the challenge is an arduous one, as plainly demonstrated by Anderson and Bows [4].

Despite the urgency for rapid decarbonization, the only CO_2-related policy adopted by the International Maritime Organization (IMO) to date is a revised MARPOL ANNEX VI that now includes the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) [5,6]. While this goes some way toward curbing the growth in emissions, many industry and academic stakeholders alike recognize that if industry growth rates are to be maintained, additional policy instruments complementing the EEDI and SEEMP are needed [4,7]. Indeed the industry's own projections illustrate an expected 300% growth in emissions from 1990 levels by 2050 [4,5] if additional measures are not put in place [8]. Clearly, more than just a simple recognition of the problem is needed to overcome barriers to making progress toward significant decarbonization. Even if decarbonization was considered by shipping industry stakeholders to offer short-term (and longer-term) economic benefits, the industry's complex nature and interaction with other modes of transport makes devising policies that successfully constrain absolute emissions extremely challenging [7].

While there are optimistic intentions being voiced by some parts of the industry to deliver on its goal of making a “fair and proportionate” contribution to “hold the increase in global temperature below 2 degrees Celsius,” meeting this challenge will likely require a radical overhaul of the shipping system [4]. This leaves the shipping sector with a mammoth task ahead: to urgently consider policy instruments and

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Key terms

Slow-steaming: When ships operate at slower speeds, thereby reducing their energy consumption significantly.

Retrofit: Fitting the existing fleet of shipping vessels with new technologies with the aim of reducing energy consumption and cutting CO_2 emissions.

Roadmapping: A tool used to explore how technologies might develop over time, including an assessment of barriers faced and opportunities to take advantage of.

Flettner rotors: A wind-propulsion technology for ships that harnesses the Magnus effect using rotating cylinders.

Cumulative emissions: The CO_2 that accumulates in the atmosphere over time.

Step-change: Emission reductions that are non-incremental, providing emission cuts greater than 3% in one year.

Radical change: Fundamental change to current technologies and/or to business as usual.

measures that can deliver absolute and significant cuts to emission in the short and medium as well as the longer term. It is easy to dismiss such aspiration as "impractical," "implausible" or even "inconceivable." Nevertheless, this paper draws attention to a suite of feasible options for delivering cuts to emissions over and above what is currently considered in the mainstream. The research explicitly goes beyond incremental change and, with the assistance of stakeholder engagement and a roadmapping exercise, explores opportunities for and barriers against "radical" technological mitigation that could complement other operational or demand-side measures.

Rethinking technological mitigation

If the sector is to meet the decarbonization challenge, then there are a range of radical and/or step-change mitigation measures that warrant examination in terms of CO_2 benefits, opportunities and trade-offs. Whereas other studies focus on cost-effectiveness [9–11], this paper takes a bottom-up engineering approach, with technical capability its starting point. However, clearly, technology is interconnected with operations and practices, and therefore the "step-change" in absolute emission reduction may only emerge through addressing all three. Nevertheless, the technology entry point is justified given that, unlike the situation in international aviation [12,13], opportunities for decarbonizing shipping are numerous. Furthermore, despite these opportunities, detailed analysis of how to decarbonize the shipping sector through the use of novel or "niche" technologies is under-researched.

This paper takes output from a technology roadmapping workshop [14], which explored options for new-build low-to-zero-CO_2-emission ships, and the retrofit of existing ships to significantly reduce their relative CO_2 emissions. With a framing of cumulative CO_2 emissions, this paper assesses technology measures against demonstration capability and flexibility to highlight the significance of short-term implementation, particularly retrofit. Following the guidance of stakeholders, a range of market and vessel types is explored. Furthermore, shipping is considered within the wider energy system in terms of competing demand for fuels, grid capacity, local pollutant control, lock-in and longevity. The objectives of the paper are to:

- Describe the technology roadmapping approach;
- Outline the vessel types selected with the rationale for their selection;
- Present 2050 visions of decarbonized vessels in relative terms;
- Discuss the timescales, barriers and opportunities faced in making a low-carbon transition;
- Outline the policy implications and consequences of change in the context of the wider energy system.

The roadmapping approach

Overview of the technology roadmapping approach

Technology roadmaps are intended to inform R&D planning and identify research, business, government or other strategic goals, supporting the future development of a particular technology [15]. Developed through a structured and transparent process and ideally involving stakeholders representing a mix of disciplines and perspectives, their purpose is to identify the technology milestones necessary to achieve a stated outcome. Implicit in the roadmapping process is the identification of barriers to technology development and devising strategies to address them within set timeframes. In contrast to other sectors, where technology roadmaps are commonly developed, there has been limited application within the marine sector with the exception of exercises focused on a zero emission roll on roll off (RoRo) vessel [16] and medium-voltage direct power for navy vessels [17].

The roadmapping process was broadly informed by and adapted from that described by Placet and Clarke [15], and designed to integrate the expertise of a diverse group of stakeholders representing a broad cross section of actors from across the shipping industry. Breakout groups focused on three ship types, and were structured around the following steps:

- Goal definition: outline visions of zero-carbon new-build and retrofitted decarbonized (> 90% CO_2 cut) ships;
- Plot the pathway: define technology goals, working backwards from goals to outline the stages of development and timing;
- Navigate gaps and barriers: consider barriers to technology development and penetration and how these may be overcome.

Table 1. Characteristics of the chosen vessel types.

Vessel type	Service/market	Average vessel size (dwt)†	Tonnage share of global fleet†	Share of CO_2 emissions‡,§	Typical power demand (MW)‡,#,††	Typical design speed (knots)‡
Small vessels (< ~3000 dwt)	Liquefied natural gas carriers; ferries and passenger ships; offshore supply vessels	1726	6.5%	10%¶	> 2	Various
Small vessels (~3000–10,000 dwt)	General cargo	5182	6.9%	11%	2.1	12
Container	Deep sea and feeder	39,505	12.9%	22%	17.2	22
Bulk carriers and tankers	Liquid and dry bulk	63,420 (bulk), 45,251 (tanker)	40.6% (bulk), 33.1% (tanker)	39%	6.3 (bulk), 9.2 (tanker)	14 (bulk), 15 (tanker)

†Data from [54].
‡Data from [28].
§Approximated based on 2007 fuel sales (international and domestic shipping).
¶Reflects RoRo, RoPAX, ferries, etc. operating on coastal routes.
#Refers to main engine demand at average engine loading.
††Data from [55].

The groups developed technology roadmaps, and results of discussions were fed back to other participants during plenary sessions. A final plenary discussion focused on the wider system implications of decarbonizing shipping, and externalities that may impact on the sector.

Vessel selection for the analysis

For the technology roadmapping process, three vessel categories were selected:

- Small vessels (general cargo and other)
- Container vessels
- Bulk carriers and tankers

These three vessel types represent and capture a diverse range of the global shipping fleet. They differ in size, power demand, superstructure and hull characteristics, and speed, and serve different markets with trade routes covering both short- and deep-sea shipping. Table 1 outlines the main vessel characteristics. To consider potential decarbonization technologies by 2050, stakeholders were asked about:

- Designs of new-build and retrofitted decarbonized vessels;
- The potential of the technology to penetrate the sector;
- The flexibility of the technology to be combined with another;
- The maturity of the technology and how this could progress over time.

The vision for decarbonized vessels

An important outcome of the roadmapping process was stakeholder–academic engagement over some of the key technologies or changes considered most likely to both be feasible and offer a step-change in CO_2 emissions.

Renewable energy for propulsion and for supplementary/auxiliary power

Sails

A range of sail designs is being developed, either fixed or rigid. They can be lined with solar panels (e.g., Solarsailor and Eco Marine Power), or have traditional designs manufactured using advanced composite materials and can be free-standing, free-rotating Dyna-rig systems (e.g. Maltese Falcon, B9 Shipping and the Modern Merchant Sailing Vessel). A range of sail-assisted cargo ships have been or are being developed [18], but many such projects have come into financial difficulty, or are concepts as yet untested at commercial scale. Near-term technical barriers include material selection for the masts – steel being cheaper, composites being lighter – and the arrangement of the masts – tripod or single mast.

Kites

Kites are attached to the bow of the vessel via a cord capable of resisting a force of up to 1 MN and are computer controlled from the deck. They can be operated at high altitudes to capitalize on stronger winds, and are not limited by deck space. In terms of technical capability, the Society of Naval Architects and Marine Engineers (SNAME) consider kites to be most applicable to vessels with a minimum length of 30 m and a speed restriction of 16 knots [11]. Skysails are the only company that offer towing kites to the commercial fleet, and less than 10 were in operation in 2013.

Flettner rotors

Flettner rotors harness the Magnus effect for propulsion. The technology is proven and the first use on a commercial vessel was in 1926. Enercon developed their E-Ship 1 (roll on lift off [RoLo] 12,800 dwt), using a four Flettner arrangement, which made its first voyage in 2010 [19]. Likewise, Greenwave have tested a full-scale working prototype [19]. From evaluating experience to date, SNAME provide an upper limit for vessel size of 60,000 dwt [11].

Energy storage and fuel cells

Batteries with electric drive

Batteries can store electricity supplied from land via cold ironing for propulsive and auxiliary engine power. Relative savings depend on the carbon intensity of the battery-charging source. The electric motor is most applicable on ferries and cruise vessels as they have frequent load changes. Although considered a mature technology in the automotive industry [20], costs, reliability, storage capacity and overcoming losses in electric propulsion are the main barriers for developing a demonstration scale applicable to shipping. Lithium-ion batteries are the most promising technology [21], and Ferguson shipyard in Port Glasgow launched a diesel-electric and lithium-ion battery hybrid RoRo vessel in 2013. Other potential forms of energy storage include flywheels, super-capacitors and superconductors.

Fuel cells

Solid oxide fuel cells (SOFC) are the most applicable for marine use, with 1-MW fuel cell power plants being developed on land. Proton exchange membrane devices (PEM) are more suitable for auxiliary engines. The main technical barriers are cost, restricted vessel size, efficiency at high loads and low power-to-weight ratio. Fuel cells could use hydrogen or methanol. Hydrogen can be produced conventionally from methane steam reforming, fossil fuel or biomass gasification, or water electrolysis. Although burning hydrogen does not release CO_2 directly, indirect emissions need to be accounted for, including fuel manufacturing.

Less carbon-intensive fuels (over the full life cycle)

Liquefied natural gas

The main driver for this fuel switch is legislation to control the release of SO_x and NO_x emissions [22][1]. The main short-term challenges are changes to infrastructure in ports and storage on ships, and the price when compared to heavy fuel oil (HFO). In addition, the energy density of liquefied natural gas (LNG) is lower than that of HFO, which could result in the need for more frequent refuelling. Existing life-cycle assessment studies suggest that LNG offers GHG savings from a “wells to propeller” perspective, but highlight the importance of methane slip [23,24].

Biogas

Methane, produced along with CO_2 from anaerobic digestion of biodegradable waste, in its liquefied form, has the potential to be blended alongside fossil-based LNG. As part of its circular economy system, B9 Shipping is exploring manufacturing biogas from food waste for use on vessels. Nonetheless, scale-up and competition with land-based energy from waste facilities could limit the potential for shipping. Furthermore, the use of biowaste for any fuel is subject to external drivers such as a government's wider policies on waste management.

Biofuels and micro-algae

Liquid biofuel can be used in a diesel engine, requiring only small modifications of the main engine [11]. There are three generations of biofuels, with third-generation microalgae being one of the most promising for shipping, as it could be cultivated and refined in close proximity to ports and coastal areas. In addition, less refining is required compared with fuel for road and aviation, benefitting diesel engines that can burn lower grade residual fuel. However, limitations with cost compared to heavy fuel oil and the scale of algae fuel required for meeting shipping demand mean that this technology measure is unavailable in the short term.

Nuclear

Incorporating nuclear propulsion into ships involves the same principles as in a steam vessel, but in this case the heat source is a small nuclear reactor. Launched in 1955, the USS *Nautilus* submarine was the first nuclear-powered vessel [26]. However, despite a small number of commercial vessels being built since, the technology has not progressed beyond usage in the military or for ice-breaking. The advantage of nuclear power is that it enables the vessel to run for long periods of time without the need to refuel, it has a high level of autonomy and there is a reduced level of local pollutants compared to HFO [27]. There are minimal CO_2 emissions associated with operating the reactor; however, there are emissions associated with the extraction and re-processing of spent fuel [26].

Emission capture and removal technologies

CO_2 scrubbing

Ecospec has developed a patented process (CSNOX), used on exhaust gases to capture and discharge CO_2 into sea water, whereby ultra low frequency wave electrolysis treats seawater, which in turn becomes highly reactive, removing CO_2, SO_x and NO_x [19,101]. This seawater can then be discharged into the sea.

Carbon capture and storage (CCS) technology

Two options exist for CCS technology. First, sequester CO_2 from the exhaust gases via chemical or physical membranes and store it on the vessel, before transferring it to land-based storage facilities. The CO_2 would be transported offshore by pipeline to depleted oil and gas reservoirs or deep saline aquifers [35]. Second, sequester CO_2 on land when producing biofuels or H_2. The technology is currently being developed for land-based CO_2-emitting sectors – in particular, coal-fired power stations.

Other "incremental" technologies

There are numerous incremental technologies that alone or in combination can provide step-change emission reductions. The IMO outlines them as changes to vessel design, hull and superstructure, and power and propulsion systems [28]. Prominent technologies discussed by stakeholders were counter-rotating propellers and further propeller optimization to capture more energy from the wake; micro bubbles to minimize frication and power demand; waste heat recovery to maximize waste exhaust heat; and bulbous bows to improve water flow around the hull. Further information on incremental technologies and other operational measures can be found elsewhere [18,28,29]. Operational measures are not the focus of this paper; however, in order to benefit from the technologies in the visions, stakeholders identified that slow-steaming would have to be commonplace, and part of the design specification for new builds.

Vessel visions

For each of the vessel categories, the vision for the decarbonized new-build vessels is presented in Table 2, and the decarbonized retrofitted vessels in Table 3. These incorporate the technologies outlined above and are based on the stakeholder-devised roadmaps. The relative CO_2 savings for each technology grouping are presented. Where multiple data sources are considered, the range is provided in brackets and the median value used. The total CO_2 saving for each vessel category is a non-added accumulation of the individual savings for each technology.

Table 2. Visions of the decarbonized new build vessels in 2050.

Small vessel (new build)		
Generic technology measure	**Specific technology measure**	**Relative CO_2 saving (%)**
Operational measures	Slow steaming (8–12 knots) *(short-term)*	45%[†]
Incremental measures	Propeller optimization, micro bubbles, counter-rotating propeller *(all short-term)*	12%[‡] Prop optimization 4.5% (3–6%); bubbles 3.5% (0–15%) (reflects smaller ferry); contra prop 4.5% (0–12%)
Renewable energy	Deep sea: depending on service – sail and kite *(short-term)*, Flettner rotor	15.5%[§] Kites chosen due to vessel size (0–35%)
Energy storage	Short sea and small vessels (< 3000 dwt): batteries with cold ironing or fuel cells	12.5%[¶] (8–16%)
Fuel switch	Short sea: LNG *(short-term)*; biogas Deep sea: LNG *(short-term)*; biogas or nuclear	10–75%[#] (100% LNG → 100% biogas) 10–95% (LNG → nuclear). Value depends on fuel mix.
Emissions capture	Potential for CO_2 sequestration	0–65%[††]
Total		**Short sea – 67–97%** (Assuming all technical and operational measures are adopted. Range reflects fuel switch; lower bound assumes LNG with no CCS and upper bound assumes biogas with high efficiency CCS) **Deep sea – 64–98%** (Assuming all technical and operational measures are adopted with no energy storage. Range reflects fuel switch; lower bound assumes LNG with no CCS and upper bound assumes nuclear).

(*Continued*)

Table 2. (*Continued*)

Container (20,000 TEU and 3000 TEU vessels; new build)		
Generic technology measure	**Specific technology measure**	**Relative CO_2 saving (%)**
Operational measures	Slow steaming (10 knots) *(short-term)*, reduced ballast voyages *(short-term)*	80%[‡‡]
Incremental measures	Counter-rotating propellers, ship design optimization *(all short-term)*	24%[§§] Contra prop (as above); Container ship design optimization 20% (14-26%)
Renewable energy	Kites (20,000 TEU) *(short-term)*	15.5%[§] Kites chosen due to deck space constraints (0–35%)
Energy storage	Fuel cells (20,000 and 3000 TEU)	12.5%[¶]
Fuel switch	Hybrid: Biofuel (and fuel cells) (20,000 TEU)	30–80%[¶¶] Reflecting different ranges of fuel cell savings and different savings due to fuel switching.
Emissions capture	Potential for CO_2 sequestration	
Total		**92–98%** (Assuming all technical and operational measures are adopted. Range reflects fuel switch; lower bound assumes fuel cell for propulsion in conjunction with a fuel switch to rapeseed derived fuel and upper bound assumes high fuel cell efficiency and the use of biogas.
Bulk carriers and tankers (new build)		
Generic technology measure	**Specific technology measure**	**Relative CO_2 saving (%)**
Operational measures	Designed for slow steaming (5–6 knots) *(short-term)*, with a wider range for maneuverability *(short-term)*	70%[##]
Incremental measures	Improved hull design, zero ballast, minimized accommodation to improve efficiency *(all short-term)*	17%[†††] Design [bulkers 14% (12–17%)]; ballast 3.5% (0–7%)
Renewable energy	Kites *(short-term)* and/or Flettner rotors	15.5%[§]Kites as above 15%[‡‡‡] Flettner rotor (0–30%)
Energy storage		
Fuel switch	LNG (short-term); micro-algae	10–70%[§§§] (reflects 100% LNG to 100% biodiesel)
Emissions capture	CO_2 removal prior to 2030 via scrubbing and potential for CO_2 sequestration	0–70%[¶¶¶] 0–65%[††]
Total		**81–98%** (Assuming all technical and operational measures are adopted. Range reflects fuel switch; lower bound assumes LNG with no CCS and upper bound assumes algal-derived biodiesel and high efficiency CCS)

LNG = Liquified natural gas.

†General cargo 7000 dwt; 30% speed reduction. Authors' own calculation based on the International Maritime Organization's second greenhouse gas study [28].

‡Median abatement potentials used for all technologies [19,56,57].

§Median abatement potentials used for all technologies [18,19,56].

¶Based on a hybrid energy system with energy storage including fuel cells, on a small ferry [58].

#[59].

††[60].

‡‡Ship speed reduced by 60%, cargo utilization increased from 70 to 90% to reflect reduction in ballast voyages. Authors' own calculation.

§§Design optimization data taken from Winkler [61]; median abatement potentials used for all technologies [19,56,57].

¶¶Fuel cell data from Tronstad and Endresen [62]; biofuel data from Chryssakis and Vartdal [58].

##Ship speed reduced by 60%. Saving assumed inclusive of voyage optimization. Authors' own calculation based on the International Maritime Organization's second greenhouse gas study [28].

†††Design optimization data from Winkler [61]; ballast data from Crist [56].

‡‡‡Median abatement potentials used for all technologies [19,56].

§§§LNG data from Bengtsson et al. [59] and Chryssakis and Vartdal [58]. Algal lifecycle data taken from Campbell et al. [63].

¶¶¶Ecospec where the American bureau of shipping suggests a removal rate of 30–55% for CO_2 emissions.

Table 3. Visions of the decarbonized retrofitted vessels in 2050.

Small vessel (retrofit)		
Generic technology measure	**Specific technology measure**	**Relative CO_2 saving (%)**
Operational measures	Slow steaming (8–12 knots) *(short-term)*, hull blasting *(short-term)*	38%[†,‡] Blasting 4% (0–10%)
Incremental measures	Waste heat recovery *(short-term)*	6%[§] (0–10%)
Renewable energy	Kite *(short-term)* or Flettner rotor (depending on service)	15.5%[¶]
Energy storage		
Fuel switch	Re-engine (see fuel switch in Table 2)	10–75%[#]
Emissions capture		
Total		**55–88%** (With exception of heat recovery, all technical and operational measures are assumed to be adopted. Range reflects fuel switch; lower bound assumes LNG with no heat recovery and upper bound assumes liquid biogas with heat recovery)
Container (20,000 TEU and 3000 TEU vessels; retrofit)		
Generic technology measure	**Specific technology measure**	**Relative CO_2 saving (%)**
Operational measures	Slow steaming (10 knots) *(short-term)*, voyage optimization *(short-term)*	62%[††]
Incremental measures	Counter-rotating propeller, propeller optimization, bulbous bow *(all short-term)*	15%[‡‡] Prop optimization 2% (1–5%) (chosen as it specifies retrofit); bulbous bow 9% (0–20%)
Renewable energy	Kites *(short-term)*	15.5%[§§] (0–30%)
Energy storage		
Fuel switch	LNG *(short-term)* or biofuels	10–75%[¶¶]
Emissions capture		
Total		**75–93%** (Assuming all technical and operational measures are adopted. Range reflects fuel switch; lower bound assumes LNG and upper bound assumes liquid biogas)
Bulk carriers and tankers (retrofit)		
Generic technology measure	**Specific technology measure**	**Relative CO_2 saving (%)**
Operational measures	Slow steaming (5–6 knots) *(short-term)*, tank redesign for multi-use, cold ironing	74%[##] Slow steaming 51%[##]; Tank design 45%[##]; cold ironing[†††] 2% (15–40% at port)
Incremental measures	Waste heat recovery from engine *(short-term)*	6%[‡‡‡] (0–12%)
Renewable energy	Kite or solar *(short-term) or* Flettner rotors for auxiliary	17% (Flettner and solar) kites 15.5%[¶]; Flettner rotor 15%[§§§]; solar 2%[¶¶¶] (0–4%)
Energy storage		
Fuel switch	LNG *(short-term)*	10%[###]
Emissions capture		
Total		**78–81%** (assuming all operational measures are adopted. reflects the fuel and use of renewables; lower bound assumes use of Flettner rotors without use of solar energy, heat recovery or LNG and upper bound assumes use of solar technology, kites, heat recovery and LNG)

LNG = Liquified natural gas.

[†] General Cargo 7,000 dwt. 30% Speed Reduction. Own calculation based on the IMO's second greenhouse gas study [21]. Includes emission multiplier to reflect impact of low engine loading on specific fuel consumption [64].

[‡] [18,19,56].

[§] Median abatement potentials used for all technologies [19,28,56,57,61,65].

[¶] Median abatement potentials used for all technologies [48].

[#] Range represents LNG to liquefied biogas (LBG) from Chryssakis and Vartdal [58] and Bengtsson et al. [59].

[††] Fuel cell data from Tronstad and Endresen, biofuel data from Chryssakis and Vartdal [50]. Includes multiplier to reflect impact of low engine loading on specific fuel consumption [64].

[‡‡] Counter-rotating propellers; median abatement potentials used for all technologies [48,49]. Prop optimization from Mortensen [57]. Bulbous bow from Crist [56], Hobson et al. [18] and Lockley and Jabaro Martin [20].

[§§] Median abatement potentials used for all technologies [48].

[¶¶] Median abatement potentials used for all technologies [48].

[##] Ship data taken from the International Maritime Organization's second greenhouse gas study [28]. Authors' own calculation based on speed reduction and removal of empty running for average-sized bulk carrier. Includes multiplier to reflect impact of low engine loading on specific fuel consumption [64].

[†††] In reference to Mediterranean ports [66]. Contribution of port emissions [67].

[‡‡‡] Median abatement potentials used for all technologies [18,19,28,56,57,61,65,68].

[§§§] Median abatement potentials used for all technologies [48].

[¶¶¶] [56].

[###] [58].

Technological pathways, barriers and opportunities

Maximizing the technologies available offers opportunities for a step-change decarbonization in the shipping sector if barriers are overcome. The insights from stakeholders and the wider literature highlight five emergent themes, namely:

- A need for market- and vessel-specific roadmaps;
- Scale, uncertainty and demonstration;
- Lock-in, co-benefits and timeframes;
- Economics, markets and governance;
- Acceptability and labor.

These themes are discussed below with insight from the stakeholders where appropriate.

A need for market- and vessel-specific policies

There is no silver bullet to deliver decarbonization. A decarbonized fleet will need a portfolio of solutions including renewable propulsion, alternative fuels and/or CO_2 removal technologies, in addition to a plethora of energy efficiency measures, changes to operations and altered patterns of trade. With varied markets, services and vessel types, each with its own particular characteristics suitable for some but not all technological interventions, the sector will benefit from bottom-up and market-specific roadmaps including tailored policy instruments to support progress toward high levels of decarbonization in the near term (< 20 years). For example, although there is merit in pursuing batteries on short-sea services, they are inappropriate for vessels requiring large power demands. Likewise, large tankers have greater potential to harness the wind through kites and Flettner rotors, compared to smaller vessels operating closer to shore and across busy shipping lanes where there are more practical barriers to implementation.

Scale, uncertainty and demonstration

Upscaling niche technologies, such as wind propulsion, is an important step toward meaningful decarbonization. According to stakeholders, barriers to doing so include economy of scale for alternative fuel production and related infrastructure, uncertainty associated with the functionality and feasibility of renewable forms of propulsion at full-scale and wider system and sustainability implications (see section entitled ‘Repercussions on the wider energy system and sustainability’).

Economies of scale

For many of the 2050 vessel visions, a fuel switch provides the largest individual technology-related saving, as shown in Tables 2 and 3. However, such a change requires a reliable infrastructure capable of producing, distributing and storing new fuels. For widespread adoption of biofuels, economies of scale need to be enhanced during production, yet bio-refineries are not currently commercially viable. Workshop participants deemed that microalgae production systems and scaled-up hydrogen storage facilities are three more decades away from being fully developed. Existing marine engines are currently unable to burn these alternative fuels and, if retrofitted, would require dry-docking and modification [30]. However, it is anticipated that new builds could incorporate appropriate engines in the near term [31]. With the tightening of sulfur regulations, the potential switch to low-sulfur diesel and, to a lesser extent, LNG, is already creating uncertainty for the industry with regard to jobs and longevity of routes [32,33]. A more radical shift to unconventional fuels could potentially worsen confidence. On the other hand, the timeframe for upscaling wind propulsion for shipping could be considerably shorter, given broader infrastructural support is much less of an issue.

Uncertainty and demonstration

There is a wealth of experimental and computational research exploring renewable propulsion such as kites, Flettner rotors and sails for use on vessels [34,35]. The continuation of blue-skies research is vital, but while computational models demonstrate step-change savings [36], there is uncertainty surrounding how renewable forms of propulsion fare in real-life weather conditions. Furthermore, there are practical challenges to installing and deploying these technologies at an operational level. One way to overcome uncertainty surrounding the level of real savings to be made is to assess real-time data on ship performance, and by fuel efficiency checks (similar to those proposed by the EU [37]). In the case where a technology measure is not yet at demonstration capacity, the shipping sector could take heed of the military and land-based energy sectors. “For but not with” (or “capture ready” in the case of CCS technology at power stations) is a design concept in the military where a new technology is not installed, or only partially installed, on, for example, a ship to reduce costs and/or to future-proof design. Under this concept, the shipping sector could prepare for wind-assisted propulsion in new designs, for example, in terms of deck space and necessary power supply.

Lock-in, co-benefits and timeframes

Lock-in of high carbon fossil fuels, uncertainty over renewable propulsion and low-carbon fuels, and timeframes for deployment are three barriers to addressing climate change. Of immediate concern in shipping is how to address the tightening of fuel sulfur content limits. However, a rather short-sighted approach is being taken to tackle this problem [32] by proposing a switch to low-sulfur diesel or LNG, or to use scrubbers. Adoption of these alternative fuels requires new infrastructure and modification to marine engines; such alternatives do little to address CO_2 and serve to increase it or limit the potential measures to control CO_2 emissions in the longer term. Pursuing co-benefits by addressing CO_2 and SO_x emissions in parallel could reduce the impacts of infrastructure lock-in, as well as potential lock-out of future low-carbon fuels. Nonetheless, the continual pursuit of complying with sulfur regulation without meaningfully facing up to the wider systemic issues of climate change means the sector is likely to need to invest in further changes to fleet and fuel infrastructure in the coming decades. The argument of lock-in is not just made in the shipping industry, but is an important element of the general decarbonization debate [38–40].

The cumulative nature of CO_2 emissions means that failing to implement mitigation measures in the short term makes the challenge harder if not impossible in the long term [41]. While LNG offers short-term abatement in terms of CO_2 reduction, ultimately it can only ever be an interim part of a more radical transition toward a low-carbon shipping system. The pathway to achieve decarbonization is as important as the end-point reached. If technologies are introduced too late (i.e., post 2040) then although the fleet may decarbonize, cumulative CO_2 emissions will be too high. Timeframes are very important, which is why market-specific roadmaps and implementation strategies are needed to help avoid lock-in, and ensure the low-carbon technologies can develop in the short to medium term. Technologies identified by workshop participants that offer co-benefits in the short term (< 10 years) are: wind-assisted propulsion (kites, sails and Flettners), small-scale (1-MW) fuel cells and a partial penetration of biofuels. By 2030, with appropriate infrastructure in place: biofuels, H_2, nuclear, 10-MW fuel cells and battery electric are feasible. There is no room for LNG in the longer term unless it is coupled with CCS, and it is only viable as a transition fuel if the supporting infrastructure can be used for lower carbon fuels such as biogas or hydrogen.

■ Economics, markets and governance

Economic models are considered important for providing advice on strategic planning to industry stakeholders and policymakers. Yet conventional economics is unsuitable for determining monetary cost when considering long (40-year$^+$) timeframes, a step-change disruption, or the true cost of "damage" to society from climate impacts [42]. With the current geopolitical crisis in Russia and the uptake of unconventional gas in the US, the unpredictability of the oil price is once again illustrating the challenges faced by those hoping to make short- and longer-term predictions around trade activity. Given an absence of reliable long-term "costs" or a broader global governance driver, it is unsurprising that workshop stakeholders raised concerns over the short-term, upfront costs of investing in new technologies when considering significant decarbonization – an issue further exacerbated by the late-2014 fall in oil price. Day-to-day decisions tend to be disconnected from a potentially more resilient long-term strategy, with the complexity of actors blurring the trail between short-term business decisions that can hamper longer-term improvements. Furthermore, there is arguably more at play than simply cost [43]. According to workshop participants, risk, institutional relationships, a disconnect between national and international interests, availability of finances and the influence of industry bodies and other organizations all play a role. Unpicking some of these issues helps to more closely define what some of the barriers to change are and identify enabling mechanisms that could facilitate decarbonization.

Traditionally, the shipping sector lags behind technological development occurring in other sectors, with a smaller resource dedicated to research. It tends to experience slow uptake [44] of new fuels/technologies – which could be significant if considering bio-derived fuels, as there are constraints on availability when put into context with the land and food nexus. At the same time, it can benefit from faster technology development in other sectors and adopt the "lessons learned" and best practice.

The stakeholders stressed that high initial capital cost associated with new technology will be compared with return on investment and concern over safety. External support is therefore desirable for trying a technology that has no obvious short-term competitive advantage. Through funding bodies in the UK, such as the Energy Technologies Institute and Innovate UK, there is funding for first movers when demonstrating novel ship designs. However, it will be necessary to demonstrate not only an idealized and financially viable performance, but operational energy efficiency or CO_2 savings also. Furthermore, according to stakeholders, the information needs to flow from bodies trusted by the industry (such as Oil Companies International Marine Forum [OCIMF], Baltic and International Maritime Council [BIMCO] and International Chamber of Shipping), including independent advice on payback periods. Trusted bodies that currently provide classification approval on the basis of safety could extend their remit to include environmental performance. Data generated and freely disseminated by these bodies have the potential to support performance analysis, further reducing risk. Raising the profile of demonstrable energy-saving technologies could even lead to pressure to tighten the IMO's EEDI, which currently incentivizes only incremental change.

Some of the more radical technology changes likely require governmental subsidy and political support. In the case of nuclear ships, while some routes and ports are already unrestricted for trade, many are not. Furthermore, national rather than international support raises the issue of "no more favorable treatment", with its clash in the climate debate with "common but differentiated responsibility" [7]. Perhaps multi-national organizations with supply-chain influence could play a role here. Interrelationships between "customers" such as supermarkets, and "clients" including ship brokers, charterers, builders and so on, traditionally influence costs, but can also influence carbon intensity. Arguably the most significant low-carbon development in recent (2009–2010) years has been slow-steaming, in response to higher fuel prices, increased fleet capacity and slowing demand. If organizations broadened their concept of the environmental issues relevant for shipping, from local pollution to low carbon transportation of goods, this might be the quickest and easiest way to demonstrably cut emissions. Moreover, the slower the ships, the more potential for radical technologies to provide a greater share of propulsive power [36].

While there is clearly a strong desire for shipping decarbonization to be addressed globally, any implementation of global regulations, standards or incentives has to be enacted at a regional and/or national level. There is thus potential for local influence. For instance, short-sea shipping is subject to coastal regulations for safety and environmental performance, differing from place to place. If the EU were to implement an efficiency standard across its ports, workshop participants discussed how this could provide a level playing field for short-sea shipping, but cover a substantial portion of world trade.

▪ Acceptability and labor

While commercial nuclear-powered ships exist, their use is limited to niche applications by the navy and for ice breakers [45]. Although nuclear power generation is established on land, there has not been a new nuclear station built in the UK since 1995, with concerns over costs, safety and the disposal of waste being key barriers [46]. As climate change mitigation and maintaining security of supply drive resurgence in political support for new nuclear plants, issues related to licensing of reactor designs, disposal of waste and public acceptability still need to be resolved. Workshop participants highlighted that similar issues come into play for nuclear power to be deployed more widely for marine applications. Along the same lines, if hydrogen is to be widely used, ships have to be designed so that it can be stored and used safely onboard, and similar concerns over safety will need to be overcome.

The design, build, maintenance and operation of vessels that incorporate new technologies require new skills for those working within the shipping industry [31]. Stakeholders stressed how, from an engineering and naval architecture perspective, ships will need to be designed and/or modified to accommodate renewable technologies such as sails, or to locate nuclear reactors appropriately. Specialist shipyards for the installation and re-fuelling of reactors may be required. Designing for the re-use of materials requires a different mindset and skill set than those required when designing a product to be discarded when a ship is taken out of service. Similarly, the use of new materials such as composites or fiberglass will require different tooling and skill sets within shipyards and of those working in them. In a similar way to seafarers requiring new skills, and thus training, to meet the requirements of the SEEMP [47], using new technologies effectively also requires new skills. Given the potential diversity of fuels or propulsion methods, those working in the marine sector may need to have expertise across a broad range of technologies, or, alternatively, more specialism may be required.

▪ Repercussions on the wider energy system and sustainability

The introduction of Emission Control Areas (ECAs) has increased the awareness of alternative fuels, albeit with a limited impact on decarbonization. Other studies have highlighted how a decarbonization of the land-based energy system could impact the shipping sector [48]. Nonetheless, exploring how the sector is responding to the challenges that alternative fuels present suggests that the sector is considering its own future in isolation. The majority of discussion has been rather short-sighted and mainly sectoral based. However, when the shipping sector is put into context with the wider energy system, more pressing challenges start to present themselves.

Competing end users

There are high hopes for alternative fuels across many sectors. However, biofuels deserve particular attention as a limited resource that plays an important role in the energy, water and food nexus – not to mention wider sustainability impacts [49] and uncertain carbon savings [50,51]. With this in mind, where and how should alternative, low-carbon fuel sources be prioritized? And in the case of the shipping sector, where should investment in alternative fuels be channelled? Shipping often plays second fiddle in technology deployment when compared with the aviation and automotive sectors. If it wants a market lead, it will not be able to wait for technology to filter down. Furthermore, the successful use of alternative fuels in land-based applications does not necessarily mean they will transfer smoothly for use on a ship. Exploring how vessels could transport goods in a low-carbon manner raises fundamental questions with regard to the sector's development. If the sector wants to secure significant CO_2 cuts it would be wise to consider forms of propulsion that do not compete with other sectors, such as Flettner rotors, kites and sails. There are clearly socio-technical and economic issues to overcome in supporting their development and more widespread deployment, with port infrastructure, trade routes and timings all requiring exploratory analysis [36]. Nevertheless, incentivizing these technologies through economic policy instruments offers the chance for a resurgence in ship technology manufacturing and development, while at the same time supporting the industry in being compliant with ECAs and carbon objectives.

Grid implications

The prospect of putting more demand onto the grid is another systems-level repercussion. The UK's low-carbon energy transition likely requires new demands from electricity for heat and land-based transportation [52]. If batteries, renewable electrolysis (for hydrogen) and cold ironing become prominent within shipping, this constitutes additional demand on the grid. The load increase would require smarter use of existing electricity networks through demand-side management or, alternatively, further grid expansion. The additional load presented by shipping must be considered alongside the existing challenges to decarbonizing a grid serving a greater number of end users.

The role of materials and design

Cutting full life-cycle emissions is closely connected to growing debates around resource and material efficiency [53]. However, a life-cycle view benefits from coordination between designers, owners, operators, ports, staff, and so on. Two options outlined by workshop participants to reduce life-cycle emissions are replacing steel for the hull and superstructure with lightweight composite materials with lower carbon intensity per unit of material produced, and incorporating into ship building the concept of the circular economy and modular design with vessels produced from reused hulls and superstructure. Steel that cannot be reused is recycled – preventing scrappage to ensure that a proportion of ship material enters into a cradle-to-cradle system, with ship carbon intensity reduced as a consequence.

Urgency and opportunity

The stakeholder roadmapping exercise developed visions for newly built and retrofitted vessels in 2050. Nevertheless, a considerable amount of discussion involved deriving pathways to change, focusing on timeframes as a key aspect for step-change mitigation. Delivering very low-carbon vessels by 2050 is important, but the scope for achieving significant and absolute CO_2 reductions in the short to medium term (before 2030) is required, as long as avoiding 2°C remains the political goal. This paper demonstrates that there is a range of technologies that do offer scope for such change – particularly if retrofitted to the existing fleet. The most promising options – such as wind propulsion retrofitted to existing ships, where larger-scale infrastructural change is not necessary – will deliver even greater savings if slow-steaming is an essential prerequisite. The benefit of pursuing this approach is that for some vessels, relative emissions savings of $> 55\%$ could be achieved within 5 years. This potential for front-loading the emissions savings, while eventually achieving even greater reductions fleet-wide, is in line with the science of climate change, where addressing cumulative emissions rather than long-term emission reduction targets is central to delivering the 2°C target. Furthermore, failing to implement measures immediately will only serve to make the challenge harder, if not impossible, at a later date. By presenting the feasibility of short-term change, it is up to stakeholders and decision-makers to explore policy measures that could support the industry in realizing the great potential for eliminating fossil fuel from this sector.

Conclusions

Climate change mitigation is required by all sectors, and shipping is no exception. While the mitigation debate has come somewhat late in the day to the shipping sector, with a great challenge ahead, the outlook is perhaps surprisingly bright. Despite slow and limited progress to improve the carbon intensity of shipping to date, there are real opportunities to deliver a step-change in shipping CO_2 in the short to medium term. Using three vessel types to explore technology roadmaps in the face of climate change, opportunities, barriers and wider policy implications have been explored with stakeholder participation. Combining a range of existing incremental and more radical technological changes with a shipping system optimized for slow-steaming offers feasible cuts to global CO_2 of over 55% in the short term and $> 90\%$ improvements in relative emissions intensity in the longer term. Absolute savings will depend on growth rates in terms of demand for shipping, technology uptake, vessel turnover and wider operational efficiency measures. Exploiting change in both new build and retrofit will be essential if the climate change challenge is to be met. Building on the analysis of available technologies coupled with knowledge of the diverse nature of the shipping industry points to a need for tailored market- and vessel-specific solutions.

The complex nature of the shipping sector is its biggest barrier to change, but many other barriers emerged when debating the possibility of a radical change to deliver on low-carbon objectives. Uncertainty over how to upscale the production infrastructure necessary for alternative fuels must be overcome given the substantial scope for CO_2 savings in this area. Incentivizing the use of renewable propulsion requires new confidence in their operational performance that can only be provided by full-scale demonstration projects and, given the urgency of the challenge, there is no option but to retrofit the existing ships in addition to trialling and testing new low-carbon ships for future trade.

Making progress toward a low-carbon shipping system is also being delayed by the focus on new sulfur regulations. The approaches to meeting sulfur targets are concentrating on options that will lock the system into future high-CO_2 fuels, and potentially lock out change that could deliver on both objectives, such as renewables. Classification of novel technologies is identified as another barrier hindering a much-needed more radical shift. Perhaps more fundamentally, and core to the decarbonization problem in general, is a tendency to look for short-term financial gain from decisions that have very long-term repercussions impossible to “cost” in any conventional sense. To meet the 2°C goal, all sectors will need to look beyond simple payback periods, given the very high probability that the high-carbon future on the horizon is simply not worth risking weak decisions in the short term. Whole-system change is necessary, and will not emerge from conventional decision-making tools.

Finally, it is clear that the shipping sector is intertwined with other parts of the economy, with decision making around low-carbon pathways in other transport modes and industries likely to influence and constrain decarbonization in shipping. Competition for the same low-carbon fuels or additional power from the grid will be rife, with technological development often happening more rapidly in other less complex, less conservative sectors, and public perceptions are also important as they could slow decarbonization efforts. Nevertheless, shipping does have some options that others cannot harness – wind propulsion ticks many boxes for shipping, but is the sector willing to take that risk? At the end of the day, there remains a naïve assumption that incremental and longer-term technology changes will be sufficient to avoid climate change. This is completely at odds with the science. Cumulative emissions must be at the heart of any low-carbon decision making; urgency and substantial short-term change are necessary – a fact that needs to be faced up to and that reframes the options on the horizon.

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Future perspective

There is a limit to the range of exciting and new technological developments in the decarbonization agenda within many sectors. The timescale of change necessitates that technology improvements alone cannot deliver the immediate cuts to CO_2 emissions demanded by a 2°C global temperature target. This highlights a need to refocus, and conduct a deeper and more thorough exploration of opportunities for rapidly cutting energy demand through its appropriate and effective use. Here, sociology and political science may have a more important role to play in this regard than engineering and physical science. The shipping sector, by contrast, has had an absence of political drive to reduce its CO_2 emissions until relatively recently, which has led to a neglect of the huge potential for technological as well as operation and demand-side change available. While some of the technologies offering opportunities for cutting energy demand or decarbonizing the energy supply might not be new, their application to shipping is novel and interesting, and is emerging as an area of research for academics and industry specialists worldwide. Moreover, if fuel prices return to a rising trajectory, there will be greater incentives for shipping stakeholders to invest in renewable and other low-carbon technologies that fit with efficient modes of operation and can be retrofitted to existing ships. Even without a rise in costs, opportunities for exploiting alternative propulsion options that, in some cases, deliver low-carbon energy sources that do not compete with the needs of other sectors become more attractive.

Within the shipping sector, there is not a one-size-fits-all technology. Smaller vessels operating between island nations, for instance, will have different needs to large container vessels making long voyages on the high seas. Yet the variety of decarbonization options, coupled with operational change, opens up space for small- and large-scale blue-skies and applied research to demonstrate how a low-carbon shipping system could support international trade. Clearly, there are many barriers to overcome, as outlined in this article, but at least the timescale and technologies offer feasible hope to be harnessed. If the shipping sector is to meet the challenge posed by 2°C, this can only be delivered with significant investment in the engineering necessary to demonstrate how low-carbon shipping has the potential to become a reality, and soon. High growth rates in trade are expected to continue, so finding ways of cutting absolute emissions in the short term gives academics an important and interesting focus.

Executive summary

Background:

- The commitment to avoiding 2°C of warming requires all fossil-fuel consuming sectors to decarbonize as a matter of urgency, and the shipping sector is no exception.
- The MARPOL ANNEX VI now includes energy efficiency measures, but if the absolute growth in activity is to be maintained, complementary and much more stringent policy instruments will be necessary.
- This research explicitly looks beyond incremental change and, with the assistance of stakeholder engagement, explores opportunities for and barriers against “radical” (urgent and deep) CO_2 mitigation.

Results:

- Three technology-focused roadmaps are developed, for both new-build and retrofitted vessels, through a process of stakeholder engagement.
- All three identify both short-term and longer-term potential for significantly decarbonizing ships – over 50% and over 90%, respectively.
- The most promising technologies for delivering short-term cuts include wind propulsion, small-scale fuel cells and some penetration of biofuels, all significantly benefiting from slow-steaming as a prerequisite.
- Important emergent barriers to overcome include the current focus on cutting sulfur emissions, leading to lock-in to high carbon infrastructure, as well as issues of economies of scale and demonstration.
- The variety of ship types and markets in the sector points to a vital need for tailored market- and vessel-specific solutions for supporting the delivery of new concepts and technologies.
- Interconnections with the wider energy system are important, with shipping facing an opportunity to harness one particular power source without competition from other sectors – wind power at sea.

Conclusions:

- The shipping sector has many short-term and longer-term options for decarbonization. Support for articulating how change can materialize can assist its low-carbon transition.
- Cumulative emissions must be at the heart of any low-carbon decision making – urgency and short-term change is necessary. Retrofitted wind propulsion combined with slow-steaming offers scope for such change.

Note

[1] The IMO Marpol Annex VI stipulates that from January 1, 2015, the maximum allowable sulfur content of marine fuel combusted in an ECA will be 0.1%. Outside of the Emission Control Areas (ECAs), Marpol Annex VI limits global marine fuel sulfur content to 0.5% by 2020.

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