Ships and Offshore Structures

ISSN: 1744-5302 (Print) 1754-212X (Online) Journal homepage: www.tandfonline.com/journals/tsos20

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To cite this article: Sören Ehlers (17 Dec 2025): From the titanic era to the AI era: smart technology to drive green transformation in shipping, Ships and Offshore Structures, DOI: 10.1080/17445302.2025.2603414

To link to this article: https://doi.org/10.1080/17445302.2025.2603414

SHIPS AND OFFSHORE STRUCTURES
https://doi.org/10.1080/17445302.2025.2603414

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From the titanic era to the AI era: smart technology to drive green transformation in shipping

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ABSTRACT
Maritime transportation, although highly efficient, remains carbon-intensive and must undergo substantial transformation to achieve decarbonisation and ultimately emission-free operation by the 2050 regulatory target. Given the typical 25-year design life of ships, this transition requires both continuous retrofitting of the existing fleet and the integration of new technologies in newbuilds at varying levels of readiness. Currently, the feasibility of carbon- and emission-free solutions depends largely on the availability of alternative fuels, whose limited supply and demand result in high costs and price volatility. In parallel, optimisation of onboard energy systems remains crucial. Technologies, such as heat pumps, direct-current grids, wind-assisted propulsion and advanced route optimisation, provide practical pathways to improved efficiency and reduced emissions. This paper reviews these technologies and discusses the key challenges to achieving emission-free shipping.

ARTICLE HISTORY
Received 24 November 2025
Accepted 8 December 2025

KEYWORDS
Decarbonization of shipping; smart maritime technologies; alternative fuels; energy efficiency and retrofit solutions; green transformation in maritime transport

1. Introduction

The evolution of seafaring vessels has been driven by the need to balance transportation capacity with energy efficiency – a necessity that has become increasingly urgent with rising fuel costs and tightening emissions regulations. As a result, a variety of strategies have been adopted, including the construction of larger vessels, the design of more efficient hull forms, and the integration of advanced propulsion systems. These measures have helped reduce ships' energy consumption while preserving their transport capacity. Nonetheless, certain improvements are constrained by physical limits, such as width restrictions imposed by lock gates or harbor infrastructure. Reducing vessel speed can lower fuel consumption, but this option must be applied carefully due to the suboptimal performance of directly connected internal combustion engines (ICEs) at reduced speeds. Today, the focus has shifted toward the adoption of alternative fuels as a pathway to transitioning toward a fossil-free energy system.

Despite its efficiency, maritime transportation is a highly carbon-intensive mode of transport, and significant efforts must be made to decarbonize shipping. Indeed, the current regulatory framework aims to achieve emission-free operations by 2050, with a 25-year design life for vessels, necessitating solutions that can be implemented both on existing operational fleets and in new builds, which have varying levels of technological readiness. With regard to alternative fuels, the current low demand and availability are subject to elevated prices and price fluctuations until a state of equilibrium is reached. Consequently, reliable forecasting of fuel prices and, by extension, the overall return on investment, remains uncertain.

The transition to a shipping sector that is entirely free of emissions represents a substantial challenge. At present, maritime transport is responsible for approximately 820 million tons of CO2 emissions on an annual basis, which is equivalent to 2.1% of global emissions. Despite the fact that ships are the lowest carbon-intensive mode of transportation, the majority of vessels rely on conventional fossil fuels, with over 94% of ships being fueled by these non-renewable sources. However, there is an increasing tendency towards alternative fuels, with more than half of new ship orders being constructed to operate on cleaner fuels such as liquefied natural gas, methanol or ammonia.

A substantial proportion of the global shipping fleet is in need of significant upgrades to meet future environmental regulations, with 31% of vessels being

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over 15 years old. Indeed, it is estimated that as much as 5% of existing ocean-going vessels will be required to undergo comprehensive modernization or scrapping by 2027 in order to meet the stipulated EEXI requirements. In order to address this challenge, a range of retrofit measures are being explored, including engine power limitation, energy-saving technologies such as waste heat recovery and sailing, and the adoption of alternative fuels like liquefied natural gas (LNG), ammonia, and methanol. A small but growing number of vessels have already been upgraded to be ready for these cleaner options. Furthermore, a variety of measures to reduce the carbon footprint can be implemented to optimize the existing energy system on board, including the integration of systems for alternative fuels such as batteries and hydrogen, the installation of alternative energy converters, the utilization of heat pumps, the transition to DC grids, and the exploration of technologies like sailing. Furthermore, route optimization has been demonstrated to be a highly effective strategy for minimizing emissions, achieved by reducing fuel consumption during journeys.

The Carbon Intensity Indicator (CII) is a key indicator that should be assessed. CII is a compliance measure that involves the assessment of ship performance and its comparison to various boundaries. It should be noted that these boundaries are becoming increasingly stringent with each passing year. In the event that the upper limit is exceeded, it is possible that operations may no longer be feasible. In the event of adherence to the potential criteria that may be in place in 2030, the result would be a vessel that is economically unviable within the current market. It is evident that a phased approach to compliance is required, with continuous retrofit solutions implemented as soon as new technologies become available.

The adoption of alternative fuels in shipping poses a significant challenge due to their lower energy density compared to traditional fossil fuels such as HFO or diesel. The utilization of alternative fuels, including liquefied natural gas (LNG), hydrogen, and methanol, holds promise in reducing greenhouse gas emissions. However, these fuels necessitate innovative solutions to circumvent their inherent technical limitations. In order to achieve success, it is imperative that alternative fuels are coupled with novel technologies and ship designs that can enhance energy efficiency and mitigate the repercussions of lower energy density on vessel operations.

2. Smart technologies and the challenges ahead

The utilization of hybrid energy systems has been identified as a potential solution for enhancing overall energy efficiency. Vessels exhibiting two distinct energy demand levels are designated to consider hybrid energy systems. A cruise ship serves as a pertinent example of this phenomenon. It is estimated that approximately 40% of her time is spent at port, where the hoteling load is dominant, and potentially around one quarter of the load required for transit. It can therefore be concluded that an energy system combining a lower base-load provision unit with a higher peak-load provision unit is ideal, as each can be sized to operate at its respective optimal operating point. Examples of lower load level energy systems include fuel cells, proton exchange membrane (PEM) or solid oxide fuel cells (SOFC), in combination with a buffer system, such as a battery.

In the case of the higher load level, the necessity of an internal combustion engine (ICE) is a probable outcome, with the requirement for such a device contingent upon the overall dimensions of the vessel. Nevertheless, alternative fuels, including methanol and CO2-free ammonia, can be utilized. Additionally, the integration of both systems through direct current (DC) grids has the potential to enhance the efficacy of fuel conservation. It has been demonstrated that the integration of a fuel cell system with batteries, in conjunction with an ICE, has the potential to generate cost savings in the low double-digit range. Furthermore, the utilization of direct current (DC) grids in lieu of alternating current (AC) has been shown to contribute an additional low single-digit percentage reduction in costs.

The utilization of alternative fuels constitutes a pivotal approach for the future. However, HFO and diesel exhibit superior space efficiency, both in terms of the energy system alone and in relation to the fuel tanks and associated systems. The utilization of liquefied hydrogen necessitates an augmentation in tank volume by a factor of at least two, whilst concomitantly requiring an escalation in bunkering frequency by an additional factor of two. Nevertheless, such an arrangement has the potential to substantial CO2 reductions of up to 85%, even in circumstances where diesel is utilized for a proportion of the onboard energy systems and as a backup. Moreover, alternative systems generally possess a lower mass than conventional internal combustion engines (ICEs) utilizing diesel, often by a factor of two. Consequently, they emerge as a highly viable option for weight-critical designs.

Another intelligent technological solution is the utilization of surplus waste heat. In the contemporary era, a plethora of onboard systems generate heat, which remains unutilized. One solution that has been proposed is the utilization of heat recovery technologies. The utilization of heat storage mechanisms, the employment of low-temperature heat pumps, thermoelectric generators, organic Rankine cycles, or combined steam turbine-power generators, has been identified as a potential strategy for achieving energy savings ranging from 3 to 10% when employed in conjunction with conventional onboard energy systems. The technology readiness level of a low temperature heat pump is very mature, thus allowing for a short return on investment (Brötje et al. 2024). When combined with alternative energy converters such as PEMFC or SOFC, the waste heat energy supply is increased even further.

It is reasonable to assume that energy will continue to incur costs in the future. In order to address this issue, there are two possible solutions for increasing the energy efficiency of ships: The utilization of a very small block coefficients or sails is recommended. Consequently, a variety of sail systems have been developed in recent decades, with several forthcoming vessels set to utilize them. In this regard, it is imperative to undertake a thorough evaluation of the route and vessel characteristics to ascertain the genuine advantages offered by any sail system. The Odyssa framework has been developed for the specific purpose of evaluating the operational performance of WASP ships (Firtz et al. 2025).

It is evident that operational aspects, particularly route optimization, can contribute to enhanced energy efficiency and conservation of resources, as well as emission savings. The timely arrival of goods at the port is an aspect that, from a technical standpoint, may no longer present significant challenges. However, it is imperative that all parties involved maintain effective communication to ensure the smooth execution of operations. In such cases, the transit of a vessel from port A to B is often subject to a hurry-up period, during which the vessel's speed may exceed the planned velocity. This is followed by a waiting period outside the designated harbor before the vessel is permitted to enter. Notwithstanding the fact that the waiting period is considerably shorter than the hurry-up or transit period, it compels a conventional ICE to function beyond its optimal operational parameters. This can lead to a maximum of 25% of the total journey emissions. Consequently, it is evident that the avoidance of the waiting period should be a straightforward consideration in any decision-making process aimed at conserving resources.

3. Concluding reflections

While the prospect of shipping that is entirely free of emissions is, in principle, achievable, it is evident that considerable progress is yet to be made in order to realize this objective. Currently, bridging technologies are available, but they are not a long-term solution, and their impact is limited to single-digit percentage improvements. In order to effect meaningful change, it is essential that the fleet undergoes continuous renewal and adaptation to new systems, thus ensuring that ships can incorporate cleaner technologies without compromising efficiency or effectiveness. A fundamental re-evaluation is imperative to enhance the utilization and allocation of green fuels, not solely within the shipping sector but also among various industries and on a global scale. This is essential to establish a more sustainable maritime sector.

It is evident that a single discipline is incapable of resolving the challenges at hand; thus, the ICSOS conference assumes a pivotal role by convening experts from diverse disciplines. This is intended as a literal statement, given that the subjects are all congregated within a single conference room. This distinctive characteristic of the ICSOS conference distinguishes it from the prevailing maritime conferences, which is characterized by the separation of subjects into separate conferences or parallel tracks. ICSOS, however, employs a distinct approach by overarching sessions and topics, thereby enabling participants to observe and comprehend diverse disciplinary perspectives on a shared or analogous theme. Consequently, the conference makes a substantial contribution to the understanding of the similarities, challenges and opportunities that exist across a range of subjects. Ultimately, these contributions are collated and published as high-quality academic journal papers as part of the Ships and Offshore Structures journal. This ensures that they are permanently archived for the benefit of the community.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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