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Review Article

Harnessing cutting-edge technologies for sustainable future shipping: An overview of innovations, drivers, barriers, and opportunities

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Abstract

Sustainable shipping technologies are advancing considerably, but results are fragmented. This study, thus, reviews the literature and organizes the results into cohesive clusters based on their defining characteristics, drivers, barriers, and opportunities. The first cluster, automation technologies**,** includes autonomous navigation, remote machinery operation, automated maintenance, and cargo handling systems. These technologies streamline operations, reduce human error, and improve safety, thereby driving efficiency and sustainability in maritime transport. The second cluster, digital technologies**,** covers tools such as the Internet of Things (IoT), big data analytics, blockchain, digital twinning, and augmented and virtual reality. These innovations enable real-time monitoring, predictive maintenance, and the optimization of vessel performance, leading to cost savings, reduced emissions, and improved decision-making capabilities. The third cluster, Carbon emission reduction technologies**,** focuses on decarbonization strategies including alternative fuels, battery-electric and hybrid propulsion, renewable energy capture, and technologies for reducing emissions via hull and propeller efficiencies, waste heat recovery, and exhaust treatment. These solutions play a vital role in meeting the industry's decarbonization targets. Finally, the fourth cluster, advanced emerging technologies, includes advanced sensors, robotics, advanced materials, human-computer interaction, human augmentation, and artificial intelligence (AI) algorithms. These cutting-edge innovations support automation and enhance ship operations, and pave the way for future advancements in sustainable shipping. This study has broad implications for industry stakeholders, including shipowners, operators, technology vendors, and policymakers. For instance, shipowners can leverage automation and digital technologies to optimize fleet management, reduce operational costs, and improve energy efficiency, enhancing sustainability. Policymakers and shore regulators can learn about future technologies and their barriers and opportunities and, thus, prepare for future actions. Overall, this study provides valuable insights for both practitioners and academics, offering a comprehensive overview of the latest developments and best practices in sustainable shipping.

1. Introduction

The maritime industry is experiencing a transformative phase driven by the rapid development of advanced technologies (Ölçer et al., 2023). These innovations, encompassing automation, digitalization, decarbonization strategies, and intelligent systems, have the potential to reshape maritime transport. Technologies such as autonomous navigation, artificial intelligence (AI), the

Internet of Things (IoT), big data analytics, and alternative fuels have already begun making their mark in shipping operations.

Notably, the climate change crisis, mostly triggered by Greenhouse Gas (GHG) emissions, is intensifying, initiating enormous wildfires, hurricanes, droughts, and floods, and causing the sea level to rise, impacting around 39 million people only 2018 (UN, 2020). To contain climate change (GHG emissions reduction), all industries need to comply with the target set by the Paris Agreement to limit global temperature rise to well below 1.5 - 2.0 °C. Shipping GHG emissions are no exception, because they are part of the cause of climate change and, thus, the whole of the maritime transport industry needs to decarbonize (Bouman et al., 2017).

It is worth noting that maritime transport is still dependent on fossil fuels which produce anthropogenic emissions, including those that harm the environment, such as GHG emissions and air pollutants (sulfur emissions (SOx), Nitrogen Oxide (NOx) and particular matters (PM) (Alamoush et al., 2021, 2022). Even if ships are seen as efficient modes of transportation, in terms of emissions per unit of cargo carried, if ship emissions are compared with countries, their GHG emissions is equal to the sixth largest emitter among nations (GM, 2021). The International Maritime Organization's (IMO) fourth GHG study revealed that international, domestic, and fishing (total shipping) GHG emissions have increased from 977 million tons in 2012 to 1,076 million tons in 2018 (a 9.6 % increase) (IMO, 2020). In 2012, ships emitted 962 million tons of CO_2 emissions, while in 2018, this amount grew to 1,056 million tons (a 9.3 % increase). Overall, the share of shipping emissions in global anthropogenic emissions has increased from 2.76 % in 2012 to 2.89 % in 2018.

Against this background, it is worth noting that shipping decarbonization regulations are being fast-tracked; particularly, the IMO, as a regulator for the shipping industry, introduced the Initial GHG strategy in 2018, and revised and adopted it in 2023. The IMO, based on the adopted GHG 2023 strategy, promised to reduce the total annual GHG emissions from international shipping by at least 20 %, striving for 30 %, by 2030, and 70 %, striving for 80 %, by 2040, respectively, compared to 2008; that is to say, that the industry aims to reach net zero emissions by, or around, 2050 (Alamoush et al., 2023; Alamoush & Ballini, et al., 2024). Due to the nature of shipping, engaging port handling and service, trucks, and railways transport, which are energy intensive, the shipping activities share of global carbon emissions increase (Alamoush, 2024a, 2024b). While the industry lags behind in its sustainable performance, a question can be raised about the value of future technologies for achieving the industry's environmental targets, such as the decarbonization.

There have been various studies that introduced and examined shipping technologies from different aspects. These include the study of alternative fuel economic, technology, and policy challenges (Wang & Wright, 2021), ammonia (Gerlitz et al., 2022), biogas (Dahlgren et al., 2022), autonmous technology trends (Koikas et al., 2019), trends for ships and shipping (Bertram, 2020), wind capture (Rehmatulla et al., 2017), solar ships (Nyanya et al., 2021), energy efficiency (Viktorelius & Lundh, 2019), additive manufacturing (DNV, 2017), digitalization (UNCTAD, 2019), digital twinning and augmentation (Lloyd's Register, 2015), port technologies for shipping decarbonization (Alamoush et al., 2022), Maritime Autonomous Surface Ships (MASS) navigation (Campbell et al., 2012; Liu et al., 2016; Perera, 2018), hardware and software (Perera et al., 2012), system architecture (Rødseth & Tjora, 2018), ship design (Tang et al., 2020), and communications (Höyhtyä, 2019; Rødseth & Kvamstad, 2012).

Yet, despite accumulating research, insights remain fragmented due to an emphasis on individual technologies or clusters. A consolidated study on the technologies used in maritime operations, encompassing all aspects, has yet to be undertaken. Most studies have not adequately investigated the factors influencing the adoption of such technologies. Identifying challenges and enablers is essential for informed, dependable decision-making regarding fleet and operational future plans by stakeholders. This study fills these gaps by examining and evaluating the primary technologies contributing to maritime sustainability. Given such, this study aims to conduct a semi systematic literature review to explore recent and future technological developments while critically evaluating the factors that facilitate or hinder their implementation. In this sense, this study is informed by an extensive literature review and presents a comprehensive perspective on the future-shaping and sustainable technologies in shipping.

The novelty of this work lies in its all-encompassing nature, which integrates multiple technologies, examining their challenges and prospects, to provide a comprehensive view of the maritime sector's technological landscape. Collating crucial findings related to automation, digitalization, advanced technologies, and sustainability in shipping is very important for scholars and practitioners. Ship owners, charterers, managers, seafarers, seafarers' unions, ports managers, technologists, academics, manufactures, classification societies and insurance firms, and regulators (e.g., maritime administrations) can gain inspiration and comprehensive understanding of future sustainable maritime transport technologies. They can acquire a more profound knowledge of the drivers of the adoption of such technologies and of ways to minimize the effect of barriers to this adoption. In addition, this study consolidates scattered knowledge about emerging maritime technologies, providing academics and scholars with a comprehensive reference for understanding their industry-transforming capabilities.

The study is organized as follows: Section one introduces the topic relevancy and the goal of this study, Section two comprises materials and methods, Section three shows the results, containing the four clusters of technologies, i.e., automation technologies, digital technologies, carbon emission reduction technologies, and advanced emerging technologies. Within this section, the study delves into specific technology innovations, their drivers, barriers, and potential contributions to maritime sustainability. The last Section four is the conclusion, which summarizes the work and offers some implications and recommendations to overcome barriers and capitalize on technologies drivers.

Table 1 Inclusion and exclusion criteria.

No.	Filtering	Inclusion criteria	Exclusion criteria
1	Language	Studies published in English	Non-English articles
2	Data and study type	Empirical studies, systematic reviews, chapters, proceedings, and technical reports	Any study or report that lack clear and comprehensive methodology and data
3	Title reading	Main themes relating to shipping and technologies (the core topic)	Duplicates and any odd titles that are not specifically related to the core topic, e.g., nontechnical studies, and those that address other generic shipping technologies
5	Abstract and conclusion reading	Studies with methodological rigor, including solid technical reports consistent with the purpose of the study	Studies which are not methodologically rigorous, or are very generic
			Weak and repetitive conference proceedings that are covered by peer-reviewed articles
6	Full paper reading	Only abridged studies that belongs to the established themes that achieve the study objectives	Studies that address the same topic

2. Materials and methods

This study implements a semi systematic literature review (SSLR), according to the guidelines in Denyer and Tranfield (2009); Jesson et al. (2011); and Petticrew and Roberts (2008). SSLR utilizes systematic search strategies, similar to the systematic, but allows flexibility in selecting relevant studies. Additionally, SSLR investigates broad themes, rather than answering a specific question. While SSLR maps key themes, trends, and gaps in a broad research area rather, the results are presented qualitatively.

The search was conducted in October 2024. Sensitive search terms for titles and keywords were selected to assemble a broad collection of studies and to permit detailed analysis. Two search iterations were conducted to identify studies (i.e., academic peer-reviewed articles, conference proceedings, book chapters, and technical and industrial reports). The first combination included search terms related to shipping sustainable technologies: (shipping OR maritime OR marine). The second combination included search terms related to the core of the review: (technologies OR alternative fuels OR decarbonization OR green OR low carbon OR renewable energy OR smart OR energy efficient). Scopus[a] (http://www.scopus.com) was the main database used for the search, in addition to Google Scholar (used to search for technical reports). This ensured the broad consideration of a variety of literature.

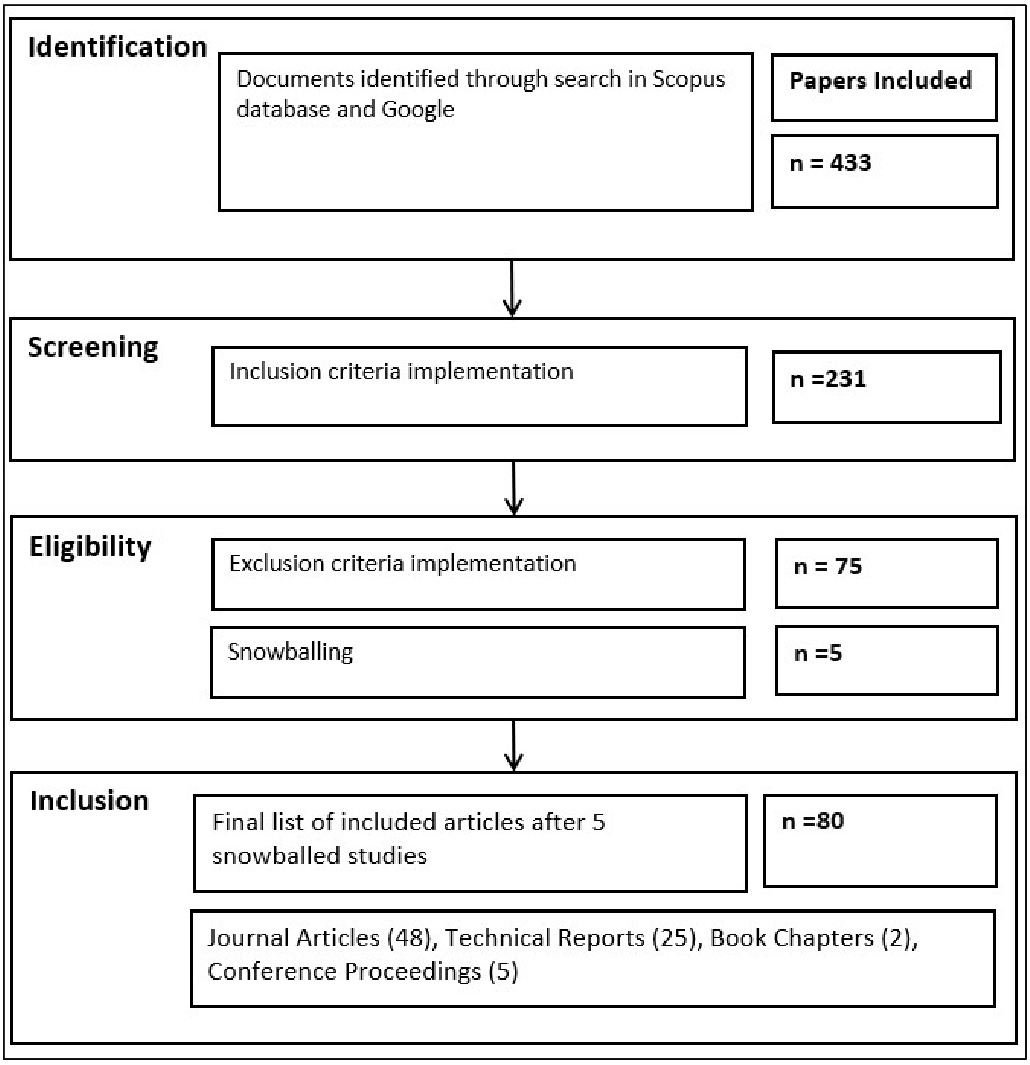

Figure 1 PRISMA framework for the SSLR.

[a] One of the largest databases of scientific journals, books, and conference proceedings

The search resulted in 433 studies; however, exclusion and inclusion criteria were established, see **Table 1**. The criteria were applied through the Prisma checklist in accordance with guidelines in Liberati et al. (2009), as shown in **Figure 1**. Considering that this SSLR aimed to establish themes of technologies, and not to go through all relevant studies, i.e., not to analyze all the papers, repetitive studies were not included. There were 80 studies in the final list, including: 48 peer-reviewed articles, 2 books and chapters, 25 technical and industrial reports and 5 conference proceedings. After collection of the included studies, a qualitative analysis was conducted in order to establish various themes and build the architecture, in two stages: first, each author independently reviewed the studies and established themes; then, the authors synthesized the findings and resolved conflicting themes to minimize potential biases.

3. Results: Technology clusters

3.1 Cluster 1: Automation technologies

Autonomous technologies have advanced considerably in recent years (Ölçer & Alamoush, 2025). This is manifested by the scale of project prototypes that have focused on Maritime Autonomous Surface Ships (MASS). MASS, according to the IMO, is defined as “a ship which, to a varying degree, can operate independently of human interaction” (IMO, 2018).

It is worth noting that the use of automation technologies indeed advances sustainability pillars in the maritime transport. As can be seen in **Table 2** below, the technologies contribute to the social aspects, as it improves safety in addition to yielding sustainable and efficient operations and providing economic benefits and improvements in environmental gains.

Table 2 Drivers and benefits of automation technologies.

Category	Key points
Social	Solution for seafarer shortage Pursuit of gender parity Improvement in quality of seafaring jobs Safe, reliable, and secure operations
Environmental	Less water pollution Energy efficiency Less air emissions Greener ships and electrified engines
Economic	Capital cost saving Operational cost saving (crew cost) Smart and efficient operations Supply chain optimization and resilience

Source (Alamoush et al., 2024)

Although there are potential advantages to automation technologies, evident barriers could impede their adoption in the maritime industry, along with other implications. **Table 3** summarizes these barriers, which include concerns about the safety of the ship and other security risks, in addition to economic implications.

Automation technologies can be used in MASS, and also in conventional shipping, which includes autonomous navigation, situational awareness, collision avoidance, automated engineering systems, remote cargo management, and remote and automated maintenance and repair.

Table 3 Barriers to automation technologies.

Category	Key points
Safety risks	Concerns over the safety of autonomous systems and their reliability in avoiding accidents
Economic implications (cost issues)	High initial investment and ongoing operational costs related to implementing automation technologies
Security risks	Vulnerabilities to cyberattacks or other security breaches in autonomous systems
Legal and regulatory barriers	Lack of clear regulations and international legal frameworks governing the use of automation technologies
Technical and commercial issues	Challenges in integrating new technology with existing systems and ensuring commercial viability
Environmental issues	Potential negative environmental impacts, such as energy use or pollution from new technologies
Public perception issues	Skepticism or fear from the public regarding the safety and benefits of automation in shipping
Business acceptance issues	Hesitancy from the shipping industry to adopt new technologies due to disruption of current practices
Skills and competency limitations to run MASS	Lack of skilled workforce trained in operating and maintaining autonomous systems

Source (Alamoush et al., 2024)

3.1.1 Autonomous navigation

Autonomous navigation (AN) concerns the ability of a ship to navigate on its own and, thus, avoid collisions and maintain a safe course to reach its destination. AN is realized by training or programming the ship, in addition to the use of data related to the ship's behavior in various nautical environments. Onboard computers and software, in addition to sensor technologies, enable situational awareness and collision avoidance systems, thereby enabling decision making. In general, autonomous navigation banks on artificial intelligence (AI) (intelligent analytics), which depends on machine learning algorithms, in addition to deep learning approaches. AI, considering advances in machine learning, is becoming a great technique for shipping autonomy (Noel et al., 2019).

The virtual captain (AI software) enables decision making and action taking processes, and is in charge of defining the overall trip (from origin to destination), considering long term data, ship real-time data, and shared information from cooperative vessels (Perera, 2018). Situational awareness (SA) technologies support the virtual captain. SA technologies are sensory instruments to identify, monitor, and forecast threats and objects, including their specific characteristics and parameters, enabling the ship to detect obstacles and help in avoiding collisions (Zhou et al., 2019) (Aslam et al., 2020).SA technologies, as per details in Alamoush & Ölçer (2025), include the following:

- Day and night vision cameras
- Advanced sensor modules that conduct lookout duties
- Light Detection and Ranging (LIDAR) and Laser Detection and Ranging (LADAR)
- Sound detection sensors
- Weather sensors
- Underwater (subsea) sensors (e.g., side scan sonar, Unmanned Underwater Vehicles (UUVs))
- Virtual reality (VR) and augmented reality (AR) equipment[b]
- Drones

[b] AR overlays digital elements onto the real world, while VR immerses users in a fully digital environment.

- Sensor fusion technology[c]
- Internal databases

Additionally, collision avoidance (CA) technologies support AN and are considered decision support systems for the crew onboard (Zolich et al., 2018). CA enables ships to avoid impediments and detect all kind of obstacles, i.e., dynamic (e.g., fishing vessels, cargo vessels, pleasure yachts, small speed boats), and static (e.g., terrain features, banks/shallows, offshore structures, rocks) (Heffner & Rødseth, 2019; Schiaretti et al., 2017). The CA system decides what actions the ship should take, contingent on AI algorithms (machine learning and deep learning) that provide the right decisions in light of the information and data collected from the SA subsystem. The CA decisions take into account environmental effects, such as wind and ocean currents, waterway traffic density, and ship dynamics and maneuverability (Höyhtyä et al., 2017). With respect to intelligent motion control, i.e., trajectory tracking, path following, maneuvering, steering, and heading controls (Campbell et al., 2012), AI techniques and methods include deep learning frameworks, with algorithms as the core technologies. Many techniques that enable automatic steering are available, which mimic a helmsman and accounts for ships dynamics (via deep learning frameworks) (Perera, 2018), linearity and non-linearity effects (rolling, pitching, yawing, etc.), and environmental impact (waves, currents, wind) (Liu et al., 2016; Campbell et al., 2012). One of the key technologies that supports ship motion is the dynamic positioning system (DP), which is a computer-controlled system that automatically maintains a vessel's position and heading (Lloyd's Register, 2017). DP software depends on AI algorithms- deep learning. DP considers the kinematic and dynamic constraints and, hence, automatically enables the ship to keep its position or course by using its propellers, rudders, and thrusters (Rødseth & Bolbot, 2020). DP is linked to SA sensors, and restricts areas of maneuver (waypoint boundaries).

3.1.2 Remote and automated operation of machinery (engines and generators)

Technologies have recently enabled unmanned machinery space, i.e., remote control and automation of propulsion engines and steering (steering gears, rudder and thruster), in addition to electrical generators that feed the electrical systems, control systems, navigation systems, and electronic equipment. The main pillars of machinery automation are: (1) condition monitoring devices that enable the addressing of technical issues before the occurrence of failures; (2) inbuilt technical resilience systems that may limit the consequences of technical failures; (3) backup systems; and (4) fail-safe functions incorporated into safety critical systems as last resort (MUNIN, 2016). This automation requires actuators, i.e., devices that can make something move or operate. The condition/vehicle health monitoring system depends on monitoring technologies that utilise sensors that monitor and collect real conditions of engineering components (e.g., the status of all systems, including maintenance records and fuel change-over) (CCS, 2018). The collected information is used as inputs for maintenance actions (e.g., inspection, overhaul, or discard). Additionally, diagnostic and prognostic algorithms use statistical information to determine the Remaining Useful Life (RUL) of components, thus enabling knowledge and planning for timely and proactive maintenance (Manno, 2015).

3.1.3 Automated maintenance and repair

In the automation of maintenance and repair, most functions carried out by shipboard staff are expected to be delegated to the Artificial Chief Engineer (software based on AI algorithms), including the support of the Remote Control Centers (RCCs). Future maintenance and repair would consider

[c] Sensor fusion technology is crucial to reducing the amount of data collected from several sensors and, thus, only reports required and useful data to the communication internal decision making system or remote operators. It combines, extracts, and classifies features in the obtained data, using, for example, deep neural networks (AI algorithm) (Poikonen, 2018). Hence, sensor fusion balances sensor strengths and weakness, increases reliability, and widens sensing capability (Mukhtar et al., 2015).

not only the ship, but also the entire fleet (AAWA, 2016). To enable automated and remote maintenance and repair, various capabilities are required, including the design of easily maintainable systems. Modular design is a key that allow the changing of faulty subsystems with functioning ones that are kept for contingencies, with the faulty units being easily replaced onshore (Manno, 2015; Ghaderi, 2020). Similarly, self- regulating equipment is important**,** e.g., for switching to a second filter if the first does not function anymore (Kooij et al., 2018; Manno, 2015). New smart materials are also required which could reduce the need for maintenance (e.g., self-recovering materials) (Manno, 2015). For example, metallic, ceramic, polymeric, and composite materials can be used to achieve improved strength, toughness, and durable capabilities and other useful functionalities. Nano-materials can be used to provide desirable functionality such as sensing, self-cleaning, self-healing, enhanced electrical conductance, and shape modification (Lloyd's Register, 2015). The same is true regarding the use of robotics and drones and Augmented Reality equipment (see sections 3.4.2). On this basis, many benefits are foreseen by having automated and remote maintenance and repair systems, including (DNV, 2014):

- Provision of diagnostics, prognostics, and risk tools
- Increased safety and reliability and industry transparency
- Reduced number and frequency of inspections and repairs
- Improved spare parts exchange and logistics
- Reduced costs related to maintenance and downtime, thus preserving asset value
- Improved design

However, problems can occur within remote and automated maintenance and repair; for example, if something breaks down and physical maintenance is required on one hand, and on the other hand if there was a loss in communication (fail). This indicates that replacing seafarers early on may pose risks as, until now, humans are still significantly more able to adapt to failures. Therefore, such issues should be solved in a way such that systems and spaces can be remotely inspected and repaired, including the abatement of any likely calamity (Kooij et al., 2018).

3.1.4 Cargo handling and stowage

The transportation of cargo traditionally involves the crew's physical interaction, such as observation, oversight, and direct intervention in case of issues. However, additional tools, like sensors, cameras, alarms, drones, robotics, AI-based software, and digital technologies (such as IoT and RFID systems), can enhance monitoring and security, ensuring automated control of the cargo (Kooij et al., 2018). These technologies can detect cargo shifts, leaks, moisture, and temperature changes, providing the RCC (Remote Control Center) with situational awareness for prompt action. RFID systems and other sensor types will also facilitate the real-time tracking and monitoring of containerized goods (Manno, 2015). Drones, which are already used by DV for tank inspections on ships, could replace manual inspections (Kooij et al., 2018). IoT devices can significantly enhance cargo condition tracking (e.g., temperature and humidity), while sensor technology maintains optimal environmental settings. Wireless monitoring solutions, including ZigBee protocol systems, are also being explored (Aslam et al., 2020). Additionally, stability calculations related to loading and unloading will require intelligent automated systems. These systems could enable autonomous ships to share stability calculations and stowage plans with port automation systems (cargo handling equipment) through communication technologies like IoT (Perera, 2018).

3.2 Cluster 2: Digital technologies

The recent era of the fourth industrial revolution is labelled as intelligent information technology (Schwab, 2016). Intelligent information technology (IIT) involves technologies that employ high-level information processing activities for cognition, learning, reasoning, and decision-making (Im et al., 2018). Such technologies enable the interworking, integration, and sharing of all kinds of data between ships' internal systems and external resources by means of digital Information and Communication Technologies (ICT). Industrial digitalization transforms traditional paper-based information handling approaches into data driven applications (Perera, 2018).

Recent studies have illustrated the need for intelligent information systems that can improve ships' data collection, computing, analytics, and connectivity, e.g., ships mobile applications, clouds, Bigdata, analytics and edge computing, and the Internet of Things (IoT) for smart and autonomous ships (Garcia-Dominguez, 2015; Im et al., 2018; Aslam et al., 2020; Perera, 2018). IIT and ICT work as enablers for digitalization and automation on ships, which together are called maritime informatics, i.e., understanding, predicting, advising, and improving maritime activities in digital means (Lind et al., 2021). The maritime informatics objective is to promote standardized digital data sharing to achieve high levels of coordination and resource utilization, with the ultimate goal of using shared and accumulated data in new types of shipping analytics (Lind et al., 2021). It is worth noting that utilization of such technologies enables many functions in, and improved connectivity of, ships with automation technology, and relieves the work pressure on seafarers and RCC operators.

Digital technologies yield a variety of benefits and opportunities. For example, they provide avenues for route optimization, improvements in safety of navigation, engine and fuel optimization and efficiency (e.g., the fuel optimization system (FOS) to reduce the fuel consumption-sustainability), improvements in vessel performance monitoring, and increased collaboration and data sharing among ships' agents, owners, operators, and managers, shippers and consignees, in addition to collaboration with other ships, ports, and supply chains, such as inland waterway ships and multimodal transport (trucks and rail ways). Additional benefits are the transparency and scalability of ship data, which can be approached by, for example, flag and coastal states, authorities, classification societies, regulators such as the IMO, and manufacturing and repair companies. It is argued that the use of intelligent information technologies may pose data and competence issues, i.e., ships' data can be exposed, and competence fades away. However, the data is still owned by the ships; how this data is shared, and who can access it, are easily managed. In addition, these technologies augment, rather than replace, competence by assisting in the assimilation of information specifically in task intensive environments (Earthy & Lützhöft, 2018). The following **Table 4** summarizes the drivers and barriers for this technology.

The intelligent information technologies that are applicable for existing conventional shipping and MASS are: IoT, big data platforms, big data analytics, cloud services (storage, IT services, edge computing, and data analytics), E-navigation and block chains, digital twinning, 3D and 4D printing, and Augmented Reality (AR) and Virtual Reality (VR), along with other digital technologies.

3.2.1 Internet of Things (IoT)

Ships can connect to the internet through external links (satellite and terrestrial links, such as 5g and LTE, etc.). Ship sensors, monitors, and other devices can be connected altogether through the internet when the internet is enabled internally by an internal network via Wi-Fi, Li-Fi, and cables. In addition, connection of ships devices can be directly established by 5G and LTE technologies (Garcia-Dominguez, 2015; Im et al., 2018), similar to applications in driverless cars.

The Internet of Things (IoT) has emerged as the concept of connecting things to the internet. However, it does not mean only physical and conceptual connection; rather, it means that new functions and values are created, making use of new data when things (devices) are connected (Im et al., 2018). IoT is defined as a "worldwide network of interconnected objects uniquely addressable, based on standard communication protocols, and allows people and things to be connected Anytime, Anyplace, Anything and Anyone, ideally using Any path/network and Any service" (Aslam et al., 2020).

The IoT aggregates any networking-capable devices under the assumption of common networking protocols, such as the Internet Protocol (IP) (Zolich et al., 2018). As maritime transport embraces automation and digitalization with a tremendous increase (thousands) of connectable devices and sensors, onboard vessels' connection between devices and to the Internet can be established via digital equipment using IP stack protocol (Garcia-Dominguez, 2015). The custom Inter-Module Communication (IMC) protocol has been proposed for interconnecting different systems. Ideally, the IMC protocol activities include the IPv6 and the IPv6 over Networks of Resource-constrained Nodes ((6lo)WG), which provide comprehensive interconnectivity (interoperability) within heterogeneous maritime networks (satellite, Wi-Fi, 5G, and 6G, among others) (Zolich et al., 2018).Recent research efforts have been made to facilitate using the maritime IoT by means of very high frequency (VHF) links available on the majority of ships (Palma, 2018). Authors have demonstrated interoperability through utilization of Internet Protocol version 6 (IPv6); however, this has provided limited data rate networks (Tens of kbps).

Table 4 Barriers and drivers of digital technologies, including the ICT and IIT.

Drivers	**Barriers**
Big data can be utilized for optimization and efficiency, condition monitoring, maintenance, and early warning (recognition of problems)	Cybersecurity issues, e.g., external interferences by viruses, piracy, and terrorist attacks
Technologies increase connectivity of ships	Data protection issues and privacy, as companies may not reveal their data that contains commercial secrets and intellectual property
Understanding businesses and customers	Data integrity and data quality issues, i.e., current data in shipping is inconsistent, patchy, and sometimes unreliable
Faster data handling	Restriction in communication tools, e.g., low bandwidth
Accelerate development in communication, especially in bandwidth	High implementation costs
Increase crew and employees' productivity	Lack of the necessary data analysis and other skills required to exploit technologies
Reduction in life cycle costs	
Enable smart ships which facilitate access to data by: • Classification societies, which can have access to data for safety and classification purposes, or for other additional services as driven by client demand • Ship owners, who can have access to the full material state of the ship • Operators, who can have full control of operational and performance data • Cargo owners, who can have full access to the material state of their cargoes and schedules • Regulatory authorities, such as flag states, who can be able to obtain full statutory compliance information • Port states, who can have access to safety, cargo, and personnel information	

Source: (Lloyd's Register, 2015; Lloyd's Register, 2017; Ölçer et al., 2023)

On the other hand, the paradigm of Internet of Ships (IoS) has emerged as a novel application of the IoT, following the advancement of e-navigation. IoS refers to the network of interconnected maritime objects, either physical or infrastructure, that belongs to the ship, port, waterways, and the whole maritime transport (Aslam et al., 2020)[d]. Onboard ships, IoS interconnects sensing and monitoring devices (cargo, machinery, navigation, etc.) through heterogenous communication technologies, thus enabling collection, sharing, and exchange of data for processing internally and externally (ship-to-ship/to-shore), which ultimately opens the space for intelligent applications that enhance safety, route planning and optimization, collaborative decision making, environmental monitoring, and energy-efficient operations (Aslam et al., 2020). Automation would be enhanced by, for example, real time and automatic faults detection and resolving, preemptive maintenance, cargo tracking and management according to specific requirements, loading and offloading of cargo, and berthing.

Furthermore, IoS enables ship-to-ship robust and secure communication, enabling collision avoidance, routes sensing, and other arrangements. New IoT hardware enables the capabilities for sensing, tracking, and data analytics by utilization of powerful means of edge computing and communication with cloud platforms (Silverajan et al., 2018). For example, ship owners can carry out data analytics using historical and current data to boost ship's efficiency and reduce fuel consumption (Aslam et al., 2020). Several hardware platforms exist to run IoS applications (e.g., computation and analytics), particularly within power-constrained devices, such as Smart- Things, Arduino, UDOO, T-Mote Sky, Phidgets, Intel Galileo, and Raspberry Pi. Additionally, real-time operating systems (software) have emerged that support the functionality of IoS, such as Contiki, TinyOS, LiteOS, RiotOS, and Android (Aslam et al., 2020).

3.2.2 Big data platforms

Ships' operations on a day-to-day basis produce huge amounts of data, structured and unstructured, with fast velocity and different attributes. The data can be collected and stored in various onboard and offboard resources as large and complex sets. What matters is what can be gained out of such a big volume of data, taking into consideration that traditional software may not be able to provide desired insights (Garcia-Dominguez, 2015; Aslam et al., 2020). Big data management platforms are the right platforms to store and process generated data (from sensors, devices and other objects) on, and thus support in-depth analysis (e.g., statistical analysis, analytics, data mining), expand data capacity, and provide infrastructure to automate decision making, among others (Im et al., 2018). Big data platforms fulfils various requirements, e.g., uniform database naming, management, and information coding, and thus handles a huge variety of data, supporting different mainstream data formats (e.g., XML, JSON, CSV, and binary) (Aslam et al., 2020). Datafication will create new business models, as all historical and real-time data can be used by third party projects or on a daily basis. Big data companies would be best placed for maritime transport, as the stakeholders become more connected and share information (Rajapakse & Emad, 2019). Recently, new big data platforms have been created that can support storing and processing tremendous amounts of collected data (e.g., Hadoop, Spark, Kafka, and MongoDB) (Aslam et al., 2020). In addition, regional or dedicated data monitoring centers have appeared in the shipping industry, e.g., China Ocean Shipping Group, and Europe's information collaboration service concept[e] (Deling et al., 2020). Such applications advance the development of MASS.

In autonomous ships, big data is generated and processed in two ways. First is the internal ship data base, which is the in-memory platform that collects, processes, and stores all ship data (either collected internally or received from external links). Within the ship, various software (AI) can be used to provide quick analysis and decision making; that is, onboard data analytics to support real-time ship operations, for example, local edge-processing servers (Höyhtyä & Martio, 2020).

[d] Presented a comprehensive overview of Internet of Ships (IoS) and its state-of-the-art emerging applications in the maritime industry.

[e] For supporting inland navigation, traffic management, transportation management and multi-modal transport providing users with static information, e.g., electronic maps, laws and regulations, and dynamic information (e.g., vessel registration and vessel position, cargo information, and estimated time of arrival) (Deling et al., 2020).

Compression and expansion of ships' big data through deep learning techniques were proposed to improve ship energy efficiency based on effective decision support systems (Perera & Mo, 2016). Second is the external big data platform, where data from the ship (including many ships from the same, or different, fleets) is collected, stored, and processed. The external platform can be onshore or on the clouds (see next section- clouds). Thus, different services application and analysis algorithms can be implemented using big data, either onboard or onshore, to improve decision making, or even approach specific data quickly online/offline (Im et al., 2018; Garcia-Dominguez, 2015).

3.2.3 Big data analytics

Big data analytics is the process of analyzing big data to reveal hidden patterns, unknown correlations, ambiguities, and market trends, among other beneficial information (Lloyd's Register, 2015). While some data analytics can be conducted onboard ships, customized applications and computing and analytics can be retrieved from cloud services (Aslam et al., 2020). Data stored internally can be analyzed using various AI algorithms and other software that provide quick analysis and decision making- *onboard data analytics*- and support real-time ship operation, for example, local edge-processing servers (Höyhtyä & Martio, 2020). Big data stored externally (offboard/onshore) can be interpreted by different service applications and analytics algorithms (deep learning), that is, to improve decision making, or even approach specific data quickly online/offline (Garcia-Dominguez, 2015; Im et al., 2018). An example is the case of energy efficiency improvement. Additionally, cognitive systems can be utilized as a data interpreter for humans, thereby combining machine learning and natural language processing to deliver an intuitive interface between a person and a machine (Lloyd's Register, 2015). Overall, analytics of big data, either onboard or offboard, improve crews' abilities to perform efficiently and enable sustainable operations while maintaining safety of navigations. For example, crews may get real time warnings and alerts on issues onboard ships, and receive ways to fix errors (Garcia-Dominguez, 2015).

By utilization of computation and analytics[f] resources, data can be analyzed, calculated, and processed, thus providing decisions that support, for example, but not limited to, safety enhancement, route planning, real-time cargo monitoring, fault detection/prevention, energy efficiency, and automatic berthing (Aslam et al., 2020). **Figure 2** below shows how big data analytics can be utilized in the maritime industry in terms of enabling and supporting communication and navigation systems, metrological and oceanographic data, condition monitoring, and cargo management and design, among others.

3.2.4 Cloud services (storage, IT services, edge computing)

Very common as an on demand, clouds provide different and interconnected services. Without the need for servers, attractive cloud services (i.e., storing and processing data online) can be provided to users anytime, anywhere, using wireless mobile terminals and internet (Im et al., 2018), mostly as a pay-as-you-go service, with high security.

Cloud service deployment models are divided into public, private, and hybrid services. Public services are managed by a third service provider for an unspecified majority; private services are limited services that configure services to an enterprise, while hybrid services are a combination of public and private with a service restriction, thereby setting up private policy for data sharing and, thus, share only necessary information with stakeholders (Im et al., 2018). On the other hand, the services provided are also divided into three models, i.e., Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS). IaaS provides limited services, such as servers, storage, virtualization, and networking, PaaS extends IaaS's services by providing middleware and runtime, while SaaS encompasses IaaS and PaaS services and further provides various applications

[f] Data analytics implement analysis methodology, machine intelligence techniques based on smart data handling algorithms, to observe hidden data patterns, clusters, correlations, and other useful information of the data (Perera & Mo, 2016).

and data; thus, all computing services through hardware and software, including updates and maintenance, are included therein. Overall, the selection of service models depends on how much a business wants to own and maintain IT equipment, hardware, and software. In addition, cloud services enable storage (uploads) of big data, acquirement of information technologies (IT), and sharing and circulating data and information among various stakeholders (Im et al., 2018). Clouds can be big data platforms and, considering the growth of big data, clouds are preferable due to their high processing power and storage capacity. Through cloud services, heavier analytics can be conducted where computational resources usually exist, and data can be accessed by ships when they are well connected[g], or offline at shore stations (Aslam et al., 2020).

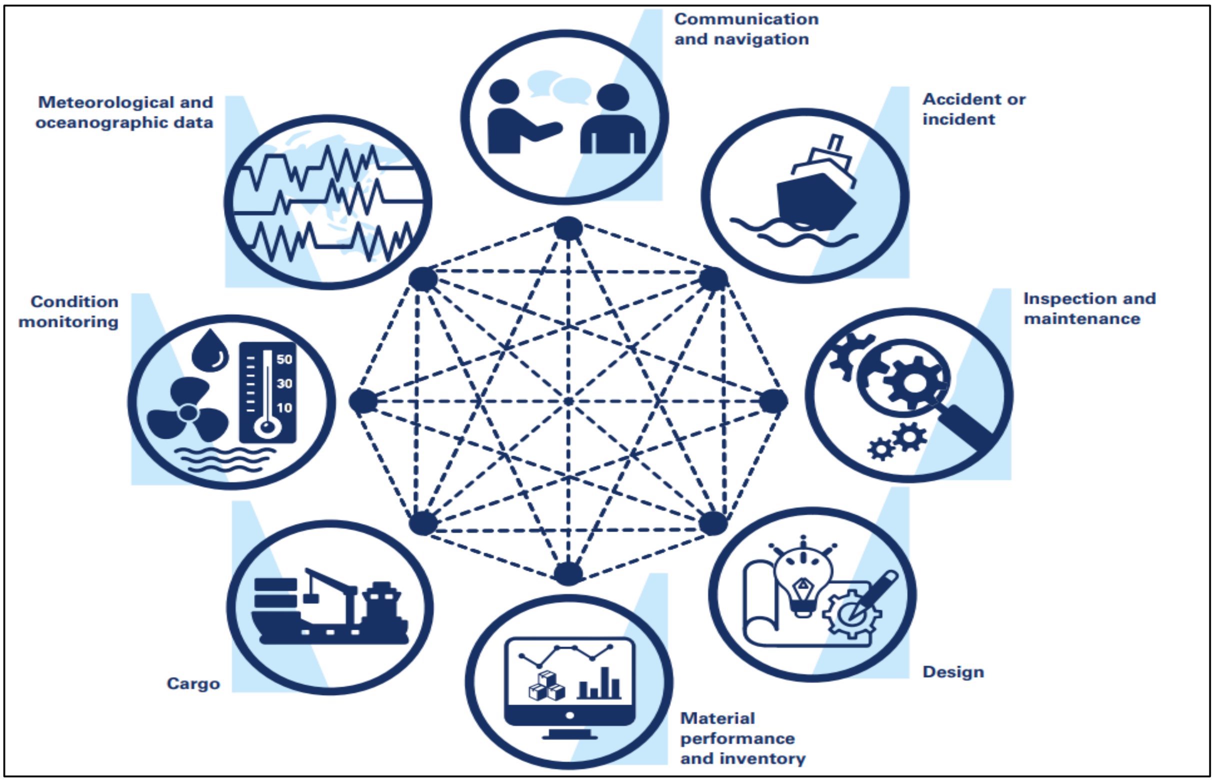

Figure 2 Multiple connections of big data analytics.
Source: (Ölçer et al., 2023)

Ships that uses cloud services can share data with RCCs, other ships, and other stakeholders onshore (owners, operators, VTS, ports, authorities, etc.) (Garcia-Dominguez, 2015). Shared data can include everything collected onboard (e.g., position, course, speed, AIS data, type of ship, draught, near vessel information, near objects detected, etc.), in addition to information on environment (e.g., weather factors such as winds, atmospheric pressure, rain, snow, tides and waves, etc.) (Garcia-Dominguez, 2015). Cloud platforms that support maritime industry big data storage are numerous (e.g., Nimbits, ThingWorx, OpenIoT, Xively), which additionally provide extended computational facilities for processing data and the hosting of IoS applications and services (Aslam et al., 2020). To this end, cloud services are vital for automation and remote operation of MASS, bearing in mind the large amount of data generated from various devices and sensors and received from outside resources, which can be collected and stored onboard and onshore, in addition to clouds.

[g] Satellite and terrestrial communications (LTE and 5G) support clouds and edge computing services

3.2.5 Blockchain

Blockchain technology is one of the foremost technological advances in the fourth industrial revolution. As a game changer, the technology enables real-time tracking and management of logistics activities and assets within the whole supply chain, thereby enabling the safe sharing of data among relevant parties without the use of traditional documents, but rather through data sovereignty (WBG/IAPH/WPSP, 2020). Blockchain is defined as a "distributed database solution that holds a continuously growing list of data records which must be confirmed by all participating nodes, and in order to be recorded in the chain, transactions have to be confirmed by the nodes participating in it" (Yli-Huumo et al., 2016). Overall, blockchains are considered one of the most auspicious technologies that would facilitate digital transformation, carrying the potential to realize industries' concerns in relation to trust, data integrity, traceability and transparency, the inclusion of smart contracts, intensive paperwork, tedious processes, and timeliness, thereby intertwining them with information technologies to authenticate and validate information (Pu & Lam, 2021; Accenture, 2018).

In the maritime domain, via blockchain, shipping companies can differentiate their services and reduce costs and save time. Thus, the maritime companies began to enter the blockchain domain, e.g., Maersk, NYK, ZIM, APL, and the Port of Rotterdam, including some alliances, such as the Global Shipping Business Network (GSBN) (Pu & Lam, 2021). Maersk has digitalized maritime transactions merging with IBM block-chain technology, so as to minimize the need for middlemen such as freight forwarders or agents (Rajapakse & Emad, 2019). In addition, blockchains in shipping can be integrated with other digital technologies, such as the Internet of Things (IoT), smart grid, and 3D Printing (Pu & Lam, 2021; Huh et al., 2017). Such integration enables efficient real-time monitoring, tracking, and tracing. The technology is not only restricted to shipping, but also extends to various maritime stakeholders other than ship owners, operators, and managers, e.g., banks, ports, government, classification societies, shipyards, technical services and manufacturers, shippers, consignees, and freight forwarders (Pu & Lam, 2021). According to recent research, there are various features of blockchain that can be relevant for the maritime industry (Pu & Lam, 2021); see **Table 5**.

Table 5 Relevant blockchain technology features for the maritime sector.

Features of blockchain	Relevance to the maritime industry (examples)
Distributed system	Building of cross-national platforms for information sharing related to maritime surveillance and maritime trade
Immutability	Tracking and tracing of information; issuing digital certificates
Peer-to-peer transmission	Transferring bills of lading; direct cross-border payment
No single point of failure	Enhancing maritime cybersecurity
Time-series data	Tracking and tracing information; recording the history of bills of lading
Visibility	Providing real-time shipping information to involved parties; enhancing information sharing in the industry
Anonymity	Providing guaranteed anonymous channels for whistleblowing
Smart contracts	Adjusting marine insurance premiums automatically and settling payments automatically

Source: (Pu & Lam, 2021)

Blockchain is still developing in the maritime industry, and thus can be grouped into: 1) electronic bills of lading (e.g., bolero, cargoX, Tradelens), 2) ship operations (e.g., reducing paper work, enhancing information sharing, tracking and tracing information, distributed ledger platforms), 3) ship finance (e.g., cross-border payment, ship financing, escrow accounts), and 4) marine insurance (e.g., underwriting, claims fraud reduction) (Pu & Lam, 2021). These categories automate processes in shipping and therefore are considered a catalyst for MASS and automation advances. Information sharing is claimed to reduce shipping costs, i.e., a reduction by up to US$300 per container, and through sharing container capacity, container business is expected to save nearly USD 6 billion, and reduce about 4.5 million tons of CO_2 emissions per annum (Seatrade Maritime News, 2018). Blockchain indeed benefits the advance in digitalizing seafarers' certification, class certification, ship and class registries, contracts and documents, and bills of lading on the one hand, and on the other hand, automating insurance processes, underwriting, and tracking and tracing, which all reduce fraud, while at the same time integrating IOT and 3D printing services (Pu & Lam, 2021).

Figure 3 Digital twin of a ship.

3.2.6 Digital twinning

In the digital era, fast-growing computing and gaming industrial power opened the space to develop scale models in virtual environments. Digital twins are seen as one of these technologies, which could be defined as "analogue scale models (virtual replica of physical item) that replicate actual physical assets, with the added functionality of integrating processes, people, systems, and devices (e.g., actual control system software and emulated control system hardware)" (WBG/IAPH/WPSP, 2020; DNV, 2018b). Digital twins have three important characteristics, i.e., a virtual model that corresponds to the physical model, real-time connection that connects all sources (sensors, working conditions, location, positions, etc.), and data visualization. In brief, the digital twin is a precise visual copy made by feeding real-time data streams into the model, while integrating these streams make the model come to life.

Figure 3 shows an example of a digital twin of a real vessel, which requires the inclusion of mathematical models of the physical ship, ship-specific dynamics, power system, propulsion system, positioning system, ballast system, and sensor systems, in addition to the control systems such as dynamic positioning, automation systems, and autonomous and remote navigation systems.

For autonomous ships, the created model can be used to test, among others, navigation algorithms, sensors, and COLREGs regulation maneuvers in autonomous and remote control ships. The algorithms can then be evaluated against a large set of scenarios. In addition, the functionality implemented in software independent of the physical parts, such as sensors, can be easily verified (DNV, 2018b). Verification and optimization can be utilized for not only the AI machine learning techniques, but also for full-scale testing. The digital twin can be used for real-time monitoring of ships, and also for reporting purposes, thus making it instrumental in examining future events (e.g., facilitation of data analytics) (WBG/IAPH/WPSP, 2020; Lloyd's Register, 2017; Lloyd's Register, 2015).

Digital twinning in shipping enhances sustainability by optimizing vessel operations, reducing fuel consumption, and lowering greenhouse gas (GHG) emissions. It allows for predictive maintenance, reducing downtime and unnecessary repairs, which minimizes waste and resource use. Furthermore, digital twins can improve route optimization, leading to more efficient shipping operations and a smaller environmental footprint. However, barriers include the high cost of implementation, integration with existing systems, and the need for advanced data management capabilities. Additionally, cybersecurity risks and the lack of standardized regulations in the maritime sector can hinder adoption.

3.2.7 3D and 4D printing

3D printing, called additive manufacturing, is an evolving prototype for manufacturing layer-by-layer materials (DNV, 2017), taking into account that the manufacturing process does not change the geometry of the design, while at the same time adding more freedom to designs; see **Figure 4**. 3D printing makes possible the manufacturing of various materials with complex geometry, e.g., non-linear holes and honeycombs, that traditionally incur high production costs (Lloyd's Register, 2015). 3D and 4D aims to deliver high-quality, low-cost products and systems by using emerging trends such as open source designs (Lloyd's Register, 2015). 3D printing was utilized to produce large cars and different plane components in the aviation sector, while maritime manufacturing utilized it to produce adaptable hull forms to address issues resulting from changing ships' loading conditions and speed profiles (Lloyd's Register, 2015).

In-situ 3D and 4D printing will be introduced to produce critical items onboard ship items (Lloyd's Register, 2015). The technology allows organizations, or even a ship itself, to gain access to an archive of digital designs for immediate in-situ printing, rather than upholding physical inventories of spare parts and/or waiting for orders to be transported (DNV, 2018a). It is also helpful particularly in case it is difficult to get components for older or obsolete machinery. Classification societies, such as DNV and the Port of Singapore terminal operators (PSA), have attempted to leverage 3D technology for manufacturing marine parts and even vessel building (Pu & Lam, 2021).

3D printing will be beneficial for onboard maintenance and repair. While every part in the engine room will be electronically tagged to generate valuable information for maintenance and repair purposes, 4D printing technology, in combination with exoskeleton robots and augmented reality, will boost maintenance (onboard and remote) where service teams would have the tools and parts ready in advance (Lloyd's Register, 2015). The potential application of 3D printing in ships, particularly with smaller crews, would enhance the whole crew capability- human augmentation.

3D and 4D printing technologies in shipping contribute to sustainability by enabling on-demand production of ship components, reducing the need for large inventories and long-distance transportation. These technologies can also produce lighter, more efficient parts that contribute to fuel savings and reduced emissions. The ability to quickly manufacture spare parts locally further reduces downtime and waste in the supply chain. Barriers include the cost of advanced equipment, material limitations for 3D printing in harsh maritime environments, and the need for specialized technical skills. Additionally, integrating 4D printing, which involves materials that change over time or in response to conditions, remains a complex challenge in the maritime sector due to its novelty and developmental stage.

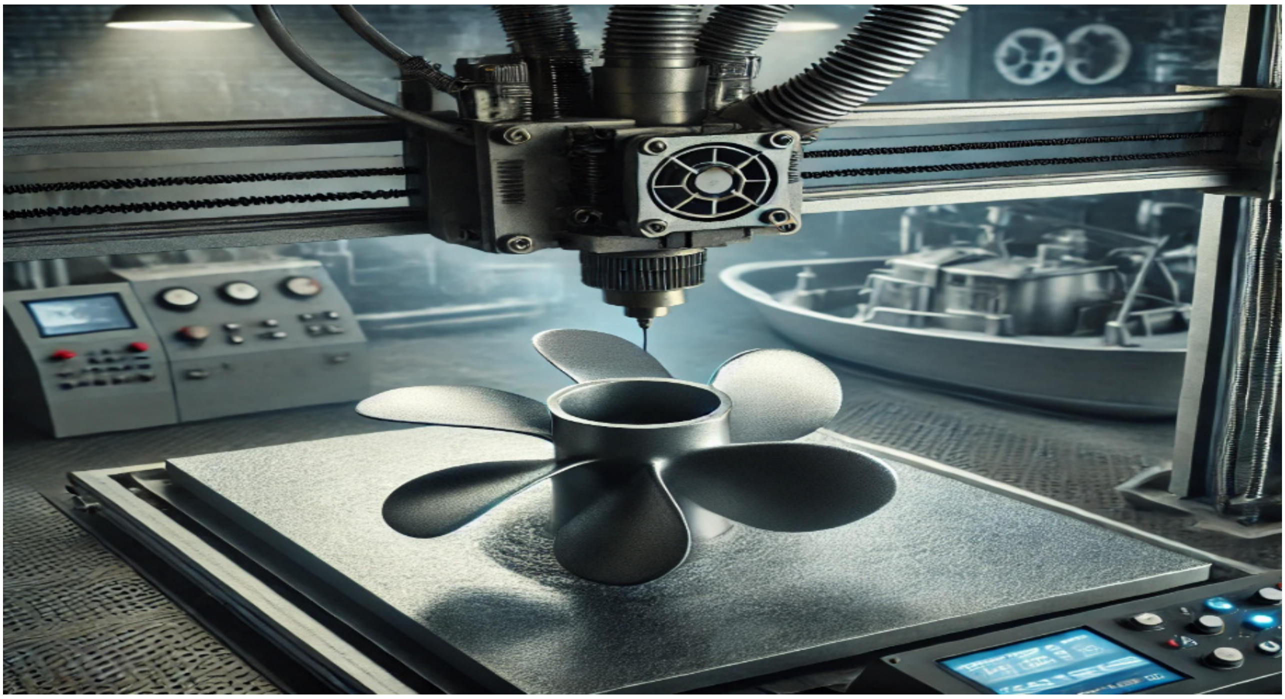

Figure 4 Additive manufacturing.

3.2.8 Augmented reality (AR) and virtual reality (AR)

Virtual reality (VR) creates a 3-D computer-generated environment that a user can explore and interact with. These virtual environments can be projected on screen, or through a particular device, e.g., a head-mounted-display. VR suggests a broad immersion of a human in the virtual world coupled with simulation. VR technologies are not widely used in maritime simulators, which once used allow trainees to acquire virtual experience across vessel operations and maintenance, normal operations, repairing, surveying, including risk management, emergencies, and evacuation procedures. Additionally, VR is relevant to the testing and validation of complex products (DNV, 2014; DNV, 2016; Balcombe et al., 2019).

On the other hand, augmented reality (AR) connects the real world with the virtual one with the aid of a device, where data from a virtual system (e.g., digital twin) are inserted precisely where it is necessary. AR is beneficial to both manufacturing processes and maintenance tasks, as it supports the visualization of hidden areas. VR and AR are equipped with haptic technologies (3D graphics) which provide tangible sensations for the operator through the application of mechanical load (forces, rotation, motion, etc.), thereby enabling the connection of an action to a consequence visually and through touching. Future technologies may include haptic and even smell technologies.

AR and VR equipment, e.g., headsets, tablets, and interactive flat screen displays, cave and curved wall displays, and hemispheres and domes (see **Figure 5** below), can be used on the bridge by watch officers, enabling 3D immersive display (Glenn Wright, 2019; Heffner & Rødseth, 2019). For example, the captain and watch officers can use a giant screen display (VR/AR) which overlays the surrounding environment of the ship with an augmented reality view supported by AI tools that spot and label all the moving and static objects around the ship (Glenn Wright, 2019). In the case of fully autonomous MASS, these technologies are used by SCC operators.

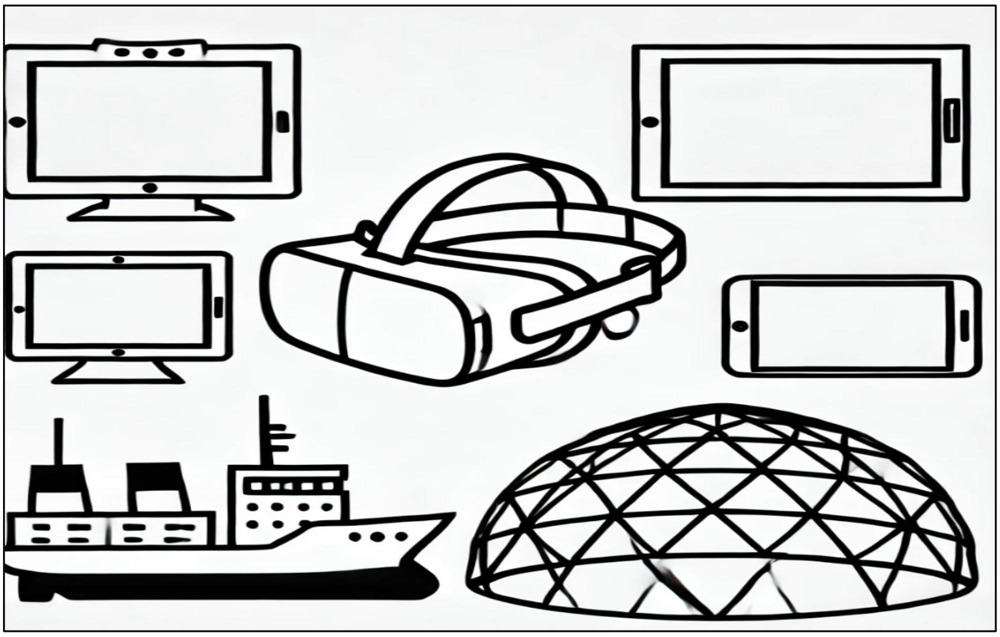

Figure 5 AR and VR equipment.
Source: Authors

Augmented Reality (AR) and Virtual Reality (VR) technologies offer sustainability benefits by improving training, maintenance, and operational efficiency in the shipping industry. AR and VR can simulate real-world scenarios for crew training without the need for physical resources or travel, reducing carbon footprints. They also aid in remote inspections and repairs, minimizing the need for expert travel, which in turn reduces fuel use and emissions. By enhancing situational awareness through real-time data overlays, AR can optimize navigation and fuel efficiency, further contributing to environmental sustainability. However, barriers include the high initial investment in AR and VR equipment, the need for robust data infrastructure, and the challenge of integrating these technologies into traditional ship systems. Additionally, some maritime professionals may resist adopting AR and VR due to unfamiliarity or perceived complexity, which can slow down widespread implementation.

3.3 Cluster 3: Carbon emission reduction technologies (decarbonization technology)

Minimizing fuel consumption and reducing carbon emissions through various technologies and energy efficiency have become a big challenge for maritime transport, in light with strict IMO regulations, i.e., the Energy Efficiency Existing Ship Index (EEXI) and the carbon intensity indicator (CII) (Alamoush et al., 2022). The IMO target is to reduce shipping GHG emissions by at least 70 %, striving for 80 % by 2040, and to have net zero emission by or around 2050. Another target is to reduce CO_2 emissions per transport work by at least 40 % by 2030. Currently, technical and operational measures are utilized to improve ships energy efficiency (e.g., trim and route optimization, propeller and hull technologies, etc.). Radical and step change technologies are required to transit shipping into zero or near zero carbon emitters. Following **Table 6** are the drivers and barriers to the introduction of such technologies, retrieved from Alamoush et al. (2023).

3.3.1 Alternative fuels

Biofuels

Biofuels are biodegradable and have the potential to significantly reduce CO_2 (GHG) emissions. In many cases, they can be used as a 'drop-in' fuel, blended with conventional fuels, requiring minimal engine modifications. First-generation biofuels, such as straight vegetable oil (SVO), hydrotreated vegetable oil (HVO), fatty acid methyl ester (FAME), and bio-ethanol, are available in substantial quantities (Foretich et al., 2021). However, their widespread use is limited due to sustainability concerns, especially during production, which can involve trade-offs such as land use. A major challenge for large-scale adoption of these biofuels is securing sufficient production volume (WÄRTSILÄ, 2022). Additionally, their emission reduction potential is debated, particularly due to air pollution from the cultivation process. Using waste oils could mitigate some of these issues, but their availability for large-scale production remains a challenge (Kim et al., 2020).

Importantly, advanced biofuels offer lower GHG emissions than conventional biofuels and rely on feedstocks with fewer sustainability concerns. The most relevant advanced biofuels for international shipping include Fischer-Tropsch diesel (FT-Diesel), pyrolysis oil, ligno-cellulosic ethanol (LC Ethanol), bio-methanol, dimethyl-ether (produced from bio-methanol or biomass-derived syngas), and liquefied biogas (LBG). Another potential fuel, metals (e.g., Saab Kockums), has also been considered, though its relevance is likely minor (Bertram, 2020; Serra & Fancello, 2020; Balcombe et al., 2019; Xing et al., 2020). The primary barriers to adopting biofuels in shipping are their cost and availability.

Table 6 Barriers and drivers Carbon emission reduction technologies.

Drivers	**Barriers**
Environmental benefits (decarbonization and health benefits)	Organizational and structural barriers (e.g., political and legislative structures)
Technical improvements	Behavioral barriers (e.g., perception of benefits)
Economic/ financial gains (energy efficiency)	Market failures (e.g., split incentives)
Policy and regulatory pressures	Non-market failures (e.g., technical uncertainties, hidden costs, access to capital, lack of adequate infrastructure)
Allowing the emission trading system (ETS) as economic measures, which drives shipping to use alternative fuels to avoid financial penalties	Security of energy supply

Methanol and ethanol

Since methanol is in the early stages of market introduction, it can be used in marine engines and as a blend in dual-fuel engines, offering a moderate reduction in CO_2 emissions compared to HFO or MGO, depending on its production method. For example, the methanol-powered ship Stena Germanica achieved a 25 % reduction in CO_2 emissions. Methanol can be produced from various sources, including natural gas, catalytic hydrogenation of waste CO_2, and biomass. One of its advantages is that methanol is easier to store and distribute than LNG, as it remains liquid at room temperature. While methanol is available in large quantities, its global availability for shipping is limited due to insufficient infrastructure and bunkering facilities. Additionally, concerns about its life cycle emissions and high costs persist. Other alternative fuels include ethanol, traditional fuels like fatty acid methyl esters (FAME), and even unconventional options such as glycerol (Balcombe et al., 2019; Xing et al., 2020).

Hydrogen

Hydrogen is primarily used as a fuel in fuel cells, which can efficiently generate low-carbon electricity by harnessing the chemical energy of hydrogen or other fuels. Fuel cells offer higher efficiency in electricity generation compared to traditional engines, achieving up to 60 % efficiency, while conventional engines typically reach only 40 % (Balcombe et al., 2019; Xing et al., 2020). However, storing compressed hydrogen requires heavy-duty structures to contain the fuel at high pressures, and cryogenic storage faces the challenge of continuous hydrogen boil-off, limiting its storage duration or requiring ongoing energy input for liquefaction. Hydrogen itself is also a greenhouse gas, with a GWP100 of approximately 5.8. There are several issues linked to hydrogen, such as concerns about emissions during its production, transportation, storage, and use (e.g., pipe purging, and both planned and unplanned releases), along with the high costs of infrastructure, retrofitting, and safety measures. For instance, there is significant variability in the environmental impact of different hydrogen production methods, including renewable electrolysis, natural gas reforming, and biomass gasification, which range from 113 to 997 gCO_2eq./kWh. Hydrogen is commonly stored as a compressed gas (up to 700 bar), in liquid form (cryogenic), or in a solid state (metal hydrides). It is important to note that commercial vessels carrying hydrogen must comply with the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code), though the current version of the code does not yet permit the transport of liquid hydrogen.

Ammonia

Ammonia (NH3) is produced using power, air, and water in a process where nitrogen is extracted from air using electricity and then combined with hydrogen. Ammonia can be utilized directly in marine propulsion engines, either through combustion or in a fuel cell. It can be stored as an anhydrous compressed liquid at a moderate pressure of 1 MPa (10 bar) or stored under atmospheric pressure if cooled to 240 K (–33 °C). Ammonia engines are still in the developmental phase but pose several technological challenges that require further research. Ammonia is difficult to ignite and burns slowly due to its low reactivity, meaning most engines will need a reliable ignition source. Early-generation engines will likely require a pilot injection of conventional fuels (MDO, HFO) or biofuels (HVO, FAME) to ignite ammonia. Future engine generations might use hydrogen produced from ammonia as the ignition source. Nonetheless, ammonia is highly toxic, raising safety concerns for seafarers in the event of an accident.

Synthetic fuels

Synthetic fuels and e-fuels, also known as electrofuels or power-to-liquid fuels, are produced by synthesizing carbon dioxide (CO_2) and hydrogen (H_2) using renewable energy (Solakivi et al., 2022). They mimic conventional fossil fuels and can be used as direct drop-in replacements in existing marine engines (Lindstad et al., 2021). The production process typically involves gasification of biomass or fossil feedstock to generate synthesis gas, which is then refined through processes like Fischer-Tropsch synthesis or steam methane reforming, depending on the desired fuel type (Zincir, 2022). The carbon neutrality of these fuels largely depends on the source of carbon feedstock and the energy used in production. Coupling their production with carbon capture and storage can further enhance their sustainability. While synthetic and e-fuels are gaining recognition as a potential long-term solution for decarbonizing the shipping industry, their viability depends on the cost of renewable electricity, advancements in electrolyzer technology, and the economic feasibility of CO_2 capture (WÄRTSILÄ, 2022).

Critical consideration

While alternative fuels are presumed to reduce or neutralize shipping carbon emissions, the Life Cycle Analysis (LCA) is a very important footstep that should always be considered; that is, to make sure that reductions do not leak into other areas or are offset by other operations. The LCA method is a tool that can present a holistic view of a product's life cycle. The LCA work comprises four main phases: 1) goal and scope definition, 2) inventory analysis, 3) impact assessment, and 4) interpretation. The ISO 14040 (principles and framework for Life Cycle Assessment (LCA)) provides more information and details about the basics of LCA. A new LCA method for the shipping industry (Live-LCA) was built by Park et al. (2022), which can prevail over the drawback of conventional LCA, thus supporting the evaluation of the environmental performance of a shipping fleet. LCA of hydrogen focusing on developing requirements for sustainable maritime vessels was investigated in Sullivan (2022). Overall, achieving shipping decarbonization requires all stakeholders' cooperation, collaboration, and coordination, including shipping companies, ports, energy providers, maritime authorities, ministries, private sectors, and academia, among other governmental and non-governmental entities.

The following **Table 7** summarizes the drivers and barriers of the previously mentioned fuels.

Table 7 Summary of alternative fuels drivers and barriers.

Fuels	Drivers	Barriers
Biofuels	Biodegradable; reduces CO_2 emissions; can be used as 'drop-in' fuel with minimal engine modifications; advanced biofuels offer lower GHG emissions; potential use of waste oils mitigates sustainability concerns	Sustainability concerns (land use, air pollution from cultivation); debated emission reduction potential; limited large-scale production capacity; high costs
Methanol & Ethanol	Moderate CO_2 reduction; can be used in dual-fuel engines; easier to store and distribute than LNG; available in large quantities from various sources (natural gas, biomass, CO_2 hydrogenation)	Limited global bunkering infrastructure; high costs; life cycle emissions depend on production method; concerns about sustainability and scalability
Hydrogen	High efficiency when used in fuel cells (up to 60 vs. 40 % in conventional engines); can be produced from renewable sources (electrolysis, biomass); does not emit CO_2 when used as a fuel	Storage challenges (high pressure, cryogenic boil-off, energy-intensive liquefaction); high costs of infrastructure, retrofitting, and safety measures; variable environmental impact based on production method
Ammonia	Can be produced using renewable energy; suitable for direct combustion or fuel cells; can be stored at moderate pressures; potential for future hydrogen-ammonia engine integration	Difficult to ignite, burns slowly; requires pilot fuel for ignition; toxicity and safety concerns for seafarers; still in early developmental phase, requiring further research
Synthetic Fuels & E-Fuels	Lower lifecycle GHG emissions if produced using renewable energy; compatible with existing marine engines as drop-in fuels; can be produced domestically, reducing fossil fuel dependency; blends with conventional fuels using existing infrastructure	High production costs, especially if renewable energy is scarce; hydrogen-based fuels are not fully drop-in compatible; currently not commercially viable; lower energy efficiency in conversion processes; feedstock availability challenges

3.3.2 Battery electric and hybrid propulsion

Electric propulsion (EP) systems use an electric motor, powered by energy stored in systems such as batteries. Battery technology is advancing rapidly due to demands from other industries. Recent innovations include lithium-sulfur, lithium-air, and aluminum-ion batteries, along with developments in graphene-based batteries (Ampah et al., 2021). Despite these improvements, batteries still have a much lower energy density by volume and mass compared to fuels, even those with low energy content like ammonia. An emerging technology that could complement batteries is the supercapacitor, also called the ultracapacitor. Unlike batteries, which rely on chemical reactions, supercapacitors store electrical charge directly (Kim et al., 2020). They offer faster and more frequent charging, but have lower storage capacity compared to batteries. In the future, supercapacitors, especially graphene-based ones, will likely be widely used where rapid charging and discharging of large amounts of electricity are required. The environmental impact of EP systems depends on the source of electricity used (Kim et al., 2020). Expanding the necessary infrastructure, both at ports and onboard vessels (such as charging facilities), could enhance the shipping industry's decarbonization efforts. Hybrid electric systems, which combine internal combustion engines with battery storage (e.g., diesel-electric systems), are particularly well-suited for electric drives. Electric motors themselves are advantageous because they require minimal lubrication and maintenance. However, advanced battery technology will be needed to support long-range voyages on oceangoing vessels, especially beyond 2050 (Sæther & Moe, 2021).

3.3.3 Shipboard capture of renewable energy

Wind and solar energy offer promising ways to cut GHG emissions in the maritime industry. A plan has been introduced to launch a wind-powered car carrier by 2025[h], which aims to reduce emissions by 90 %, using wind as the main propulsion and an auxiliary engine as backup (Nyanya et al., 2021). Ships powered primarily by wind tend to operate at lower speeds than those with conventional power systems. Wind energy can be applied to both new vessels and retrofitted ships, serving as either a main or supplementary power source, known as wind-assisted ship propulsion (WAPS). Wind energy technologies include Flettner rotors, kites, spinnakers, soft and wing sails, and wind turbines (Xing et al., 2020). Fuel savings from these systems vary depending on the type of technology and the route, with reductions ranging from 2 - 24 % for a single Flettner rotor, 1 - 32 % for a towing kite, and up to 25 % for eConowind sails (Xing et al., 2020; Lan et al., 2015). However, the adoption of wind technologies is hindered by unfamiliarity, safety concerns, and limited data on costs.

Solar energy is another renewable option, although its contribution is generally smaller than wind, depending on the ship's route. Solar panels onboard can reduce CO_2 emissions by 0.2 - 12 %, and combined wind and solar systems can deliver fuel savings of 10 - 40 %. However, the salty ocean environment can cause wear on solar panels, limiting their use. Additionally, ocean energy is being explored, with some companies like Witt Limited and MI New Network developing technology to capture energy from wave motion (Lloyd's Register, 2017).

3.3.4 Hull technologies to reduce emissions

Efficient hull designs can optimize both the hull shape and superstructure, reducing fuel consumption by up to 15 % in large ships and cutting CO_2 emissions by up to 50 % (Serra & Fancello, 2020). These benefits, however, depend on specific design requirements and operating at slower speeds. Air lubrication technology (Bertram, 2020), which is still under development, shows promise, but is more effective at higher speeds, meaning its fuel-saving potential decreases with the industry's shift towards slower sailing.

Sustainable hull paints and coatings play a critical role in improving operational efficiency by reducing drag (Balcombe et al., 2019; Bertram, 2020). Over time, ships accumulate microorganisms like bacteria, algae, and barnacles on their hulls, which can significantly increase drag and fuel consumption by as much as 40 - 50 % in severe cases. On average, a ship's hull roughness increases by 40 μm annually, raising fuel consumption by 1 - 1.2 % each year. To combat this, anti-fouling paints are widely used to prevent the buildup of marine organisms and corrosion, though harmful tributyltin (TBT) compounds have been banned due to environmental concerns. More eco-friendly alternatives include biocide-based paints (self-polishing or ablative coatings) and biocide-free

[h] https://www.theoceanbird.com/the-oceanbird-concept

solutions like silicone elastomers or mechanical cleaning systems. Technologies like hull-cleaning robots and air-trapping ferns are also emerging, alongside ultrasonic anti-fouling systems, which show promise in keeping hulls clean without chemicals (Park & Lee, 2018).

3.3.5 Propellers efficiencies to reduce emissions

Future ships still have to optimize hydrodynamically; that is, to reduce fuel consumption and, thus, GHG emissions. Propulsion improving devices (PIDs), also known as energy saving devices (ESDs), may be integrated in ships; for example, Bertram (2020):

- Pre-swirl fins (normally combined with nozzles), such as in the Mewis duct for full hulls or twisted fins for slender hulls, which can provide 2 - 3 % efficiency
- Contra-rotating propellers or vane wheels which have better design and solve traditional issues with lubricants
- Costa bulbs (e.g., the Ultimate Rudder of Nakashima Propellers) possibly combined with twisted rudders.

3.3.6 Waste heat recovery

It's important to note that about 10 - 25 % of the heat generated by the powertrain is lost as ambient heat, going unused. Waste Heat Recovery Systems (WHRS) onboard ships capture this heat from exhaust and coolant systems and convert it into useful energy, either mechanical or electrical, achieving fuel savings of 4 - 16 % (Balcombe et al., 2019). Various technologies offer different efficiencies, including the Steam Rankine Cycle, Organic Rankine Cycle (ORC), and Kalina Cycle (Balcombe et al., 2019; DNV, 2014). The ORC, a simple and compact system, uses an organic fluid to convert energy efficiently at lower temperature differentials without high costs. The Kalina Cycle, on the other hand, extracts more heat by using a mixture of ammonia and water, which boils over a range of temperatures, enhancing efficiency through distillation. While WHRS adds capital expenses, the resulting fuel savings often lead to a payback period of less than three years. However, retrofitting this system on every vessel can be challenging.

3.3.7 Exhaust treatment technologies

Exhaust gas treatment technologies are among the methods to reduce ship emissions when using residual fuels, such as Selective Catalytic Reduction (SCR), ammonia slip catalysts, and Exhaust Gas Recirculation (EGR), although these technologies are still in development (Lloyd's Register, 2015; Lloyd's Register, 2017; Balcombe et al., 2019). The advancement of methane oxidation catalysts could enhance their effectiveness. Additionally, carbon capture and storage (CCS) technologies aim to capture CO_2 emissions from exhaust gases. CCS directly addresses emissions at their source, with a few operational plants currently existing onshore. One development for ships is the Calix RECAST system, designed to scrub exhaust gases, capturing up to 85 - 90 % of CO_2. The heat produced during the reaction can be recovered and used to generate power or can be integrated into an existing waste heat recovery system, reducing fuel consumption. Another technology, the dry lime scrubber, converts CO_2 into inert limestone, which can be discharged into the sea, contributing to additional CO_2 removal by forming calcium bicarbonate.

CCS technology can potentially cut CO_2 emissions by at least 50 % and may generate revenue if carbon markets become more viable. There are three primary types of CCS technology (DNV, 2014): chemical absorption, which uses a solvent to absorb CO_2; membrane separation, which passes exhaust gases through membranes that filter out components; and pressure swing absorption, which separates CO_2 by utilizing the tendency of gases to adhere to solid surfaces under high pressure. However, progress in this field is slow due to high capital investment, operating costs, and limited incentives, along with the absence of a strong CO_2 market. While research into applying CCS in shipping continues, the technology is seen as energy-intensive, potentially shifting emissions from one sector to another.

3.4 Cluster 4: Advanced technologies

3.4.1 Advanced sensors

Upcoming ships will rely heavily on smart technology, with sensors integrated into all aspects, including the hull, engines, auxiliary systems, cargo, and smaller devices (Ölçer et al., 2023). These sensors will generate large amounts of data, either processed onboard or externally, to enhance decision-making (Lloyd's Register, 2017). Sensors will monitor everything from the ship's physical surroundings, like ocean conditions, to the ship's internal operations, even capturing crew health and performance data (Lloyd's Register, 2017). Continuous digital monitoring will be possible through an interconnected sensor system. Numerous modern ship systems rely on these sensors, such as IoT applications for real-time control and monitoring. These sensors also serve as enablers for cognitive systems, using AI, machine learning, and natural language processing to improve interaction between humans and technology, leading to improved ship management and situational awareness (Bertram, 2020).

Sensor technology is advancing with trends toward miniaturization, low-energy use, integration of sensors with actuators, and efficient data transmission (Lloyd's Register, 2017). Emerging fields include biosensors that use biological components for real-time environmental monitoring of ship pollutants. Future sensors will need to be rugged, wireless, and capable of remote sensing, featuring self-calibration, fault tolerance, and high-speed data transmission, while being environmentally friendly for easy disposal after use. The drivers and barriers of advanced sensors can be seen in **Table 8** below (derived from Lloyd's Register (2017); Ölçer et al. (2023); Bertram (2020)):

Table 8 Barriers and drivers of the advanced sensors.

Drivers	**Barriers**
Operational efficiency, for example, the condition monitoring (CM) and condition-based monitoring (CBM) will be improved, in addition to the safety of ship through real time monitoring analysis.	Data transfer, which supports the use of sensors and data collection, is still difficult due to limitation in the bandwidth and required power supply.
Financial gains due to improvement of the equipment life cycle period (life span). This decreases the capital expenditure.	Data quality (uncertain information) and cybersecurity (safety and security can be compromised by viruses, piracy and terrorist attacks).
Technologies' connectivity, for example, development of big data, robotics, and the IoT	

3.4.2 Robotics and drones

A robot can handle intricate tasks autonomously. Robots can perform a range of tasks, including assembly and disassembly, collaboration with humans or machines, and inspection and exploration activities. Robots could possess cognition, versatility (including flying, swimming, climbing), imitation (human and animal actions), multiple senses (speaking, touching, listening), and adaptability (to work in various environments, wirelessly and battery-powered) (Lloyd's Register, 2015). Robots' decision-making independence varies, encompassing remote control, supervision, collaboration and full autonomy. The global prevalence of robots would be significantly advanced by advancements in technologies including sensors, cognition, miniaturization, communication, robot-to-robot communication, and motion control. Robots have been showcased in the field of shipping. Robots, such as drones, sniffers, dispensers, rappelers, builders, and firefighters, can perform various functions both onboard and offboard a ship. The following **Table 9** presents the drivers and barriers to robotics and drones.

Table 9 Barriers and drivers of robotics and drones.

Drivers	Barriers
Industry acceptance due to the ability to integrate with other digital technologies, IoT, and big data.	Uncertainties in technological advances, objection by non-governmental organizations (NGOs) and seafarers, maturity of regulations, and skills of seafarers to be able to operate robots.
Increased safety of the crew.	Risks regarding cost increases in capital expenses (CAPEX) due to purchase of expensive robots and operating expenses (OPEX) due to training and maintenance.
Ability to conduct 24/7 intervention	
Being necessary as a future requirement considering the shortage of crews.	
Cost effectiveness.	
Legal and regulatory requirements (sustainability and safety and security of crews).	

3.4.3 Advanced materials

Advanced materials (metallic, ceramic, polymeric, and composite) are used to achieve specific physical attributes, such as enhanced strength, toughness, and durability (Lloyd's Register, 2015). Advanced functional properties, including environmental sensing, self-cleaning, self-healing, enhanced electrical conductance, and shape modification, can be achieved through nano-scale designs. These materials include GRP, aluminum, graphene, 3D woven composites, aluminum oxynitride (AlON), and metal foam (Lloyd's Register, 2015).

According to different studies(i.e., Lloyd's Register, 2015; Lloyd's Register, 2017; Ölçer et al., 2023) features of advanced materials can be divided into:

- Materials fine-tuned at the micro- or nano-scale, which possess extraordinary combinations of strength, toughness, malleability, and self-healing properties. Anti-corrosion coating, enhanced by graphene, provides superior corrosion resistance. Graphene, essential for energy storage innovations like capacitors, enables ultra-rapid charging (within 16 seconds) and exceptional longevity (up to 10000 charges) without capacitance degradation.
- Polymer matrix composites and carbon fiber-reinforced plastics, which are composite materials capable of replacing steel. These materials provide lightweight, stronger, corrosion-resistant, and durable options. Besides machinery, other materials can help reduce noise and vibration.
- Bio-inspired and bio-based materials with protective chemical or physical properties against surface challenges like abrasion, fouling or icing**.** Bio-composites and adhesives can be derived from natural and sustainable resources.
- Light, versatile and sustainable materials that include advanced high-strength steel, aluminum, glass fiber, and carbon fiber composites, which can be self-repairing, healing or cleaning.

Advanced materials, such as composite structures for superstructures and hatch covers, thermal insulators for cargo holds, self-repairing composite materials for propellers and rudders, ceramic or metal composites for engines, and self-healing coatings for anti-corrosion and anti-fouling purposes for the hull (graphene films), can all be utilized in various ways in ships (Lloyd's Register, 2015; Ölçer et al., 2023; Lloyd's Register, 2017). The following **Table 10** presents the drivers and barriers to advanced materials.

Table 10 Barriers and drivers of advanced materials.

Drivers	Barriers
Protection of people, assets, and the environment due to having properties that protects against fire, improved stability, ergonomics, sustainable sourcing (safety).	Economic issues, such as CAPEX, insurance costs, availability of materials, and price volatility.
Lightweight, i.e., reduction of energy consumption, reducing the need for HVAC, less need for ballast, increased speed, and improved noise and vibration properties.	Material property issues, such as durability at sea and degradation, repairability, predictivity for failure, and fouling.
Improved operational and maintenance efficiency.	Safety issues in terms of exposure to fire, required regulation, and health.
Improved corrosion-resistance.	Manufacturing issues, such as customization to marine environment and machinery, formidability, and connection between different materials.
Extended lifetime.	End of life issues, i.e., recycling.
Allowance of operations in more extreme conditions.	Skills requirements.
Decreased operation costs, by improving fuel economy and increasing cargo handling capacity.	

3.4.4 Human-Computer Interaction (HCI)

In the loop human-computer systems presently employ common interfaces like keyboards, mice, and displays, which are designed by Human-Computer Interaction HCI technologies for effective human-computer interaction (Lloyd’s Register, 2015). The human brain's unique features necessitate that HCI bridge the complex gap between it and computer processing systems. The HCI field encompasses concepts from computer science, cognitive science, psychology, design, and visualization (Lloyd’s Register, 2015). Multi touch displays are exemplified by smart phones and tablets in HCI technology advancements. HCI technologies will allow computers to intelligently understand human needs, commands, and preferences. These technologies now include gesture control, speech recognition, and eye tracking capabilities. Future technology, inclusive of AI, may generate brain-computer interfaces and intelligent personal assistants. With the growth in automation in shipping, there is a need for advanced technology like augmented and virtual reality to keep computers and humans interconnected (e.g., contact lens displays and 3D organic light emitting diode (OLED) displays that aid speech, handwriting, touch, and gesture capabilities) (Ölçer et al., 2023). The drivers and barriers, according to Ölçer et al. (2023); Lloyd’s Register (2015), to HCI are presented in **Table 11** below.

Table 11 Barriers and drivers of human-computer interaction.

Drivers	Barriers
Minimizing user error.	HCI technology is dependent on unpredictable consumer tastes, culture, and fashion.
Enhancing user experience.	Maturity of technology, i.e., there is a slowdown in required research.
Improving situational awareness.	
Improving productivity and performance of the crew and efficiency.	
Enhancing users’ ability to make reliable decisions and minimize errors	

3.4.5 Human augmentation

Human enhancement incorporates diverse technologies from fields like medicine (Lloyd's Register, 2017). This technology, including pharmaceuticals, implants, prosthetics, and exoskeletons, strives to augment human performance and cognitive abilities beyond standard levels and restore lost functions in injury or illness (Lloyd's Register, 2015). Ships can utilize lightweight modular exoskeletons to boost crews' strength for lifting heavy loads, preventing fatigue and injuries; see **Figure 6**. Crews can be aided in managing stress and fatigue through the use of cognitive augmentation devices featuring closed-loop brain-computer interfaces. The technology can also improve user focus through brain stimulation with transcranial direct current stimulation (tDCS).

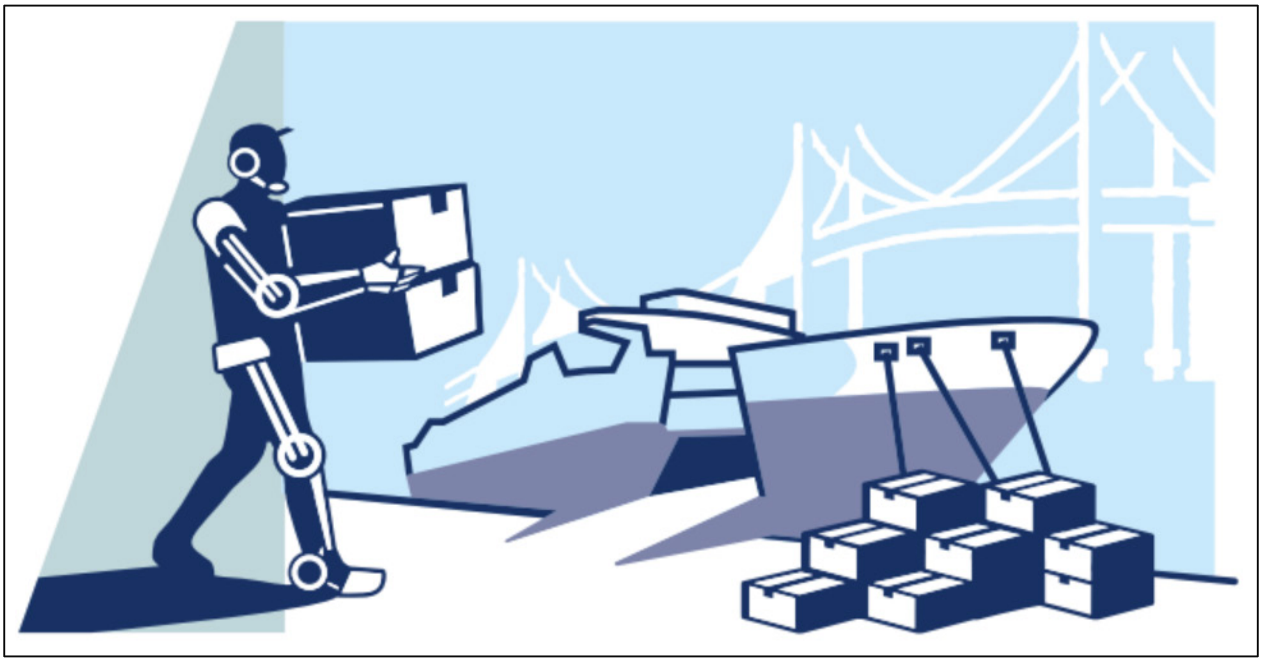

Figure 6 Seafarers' augmentation.
Source: (Ölçer et al., 2023)

The **Table 12** below summarizes the drivers and barriers for human augmentation.

Table 12 Barriers and drivers of Human augmentation.

Drivers	**Barriers**
The need for efficient operation by fewer crews.	Requirements for legal framework.
Increased reliance in automation and augmentation of human cognitive and physical capabilities.	Ethical and social issues (acceptability, privacy, and health consequences).
Increased health and safety of vulnerable crews.	Financial barriers, as the cost-benefit of human augmentation may not outweigh other alternatives (e.g., robot use).
Increased resilience and physical endurance of crews.	
Functioning at higher rates and rapid decision making (performance).	
Monitoring of state of crews.	

3.4.6 Artificial Intelligence algorithms (AI)

Artificial intelligence (AI) refers to specialized computer software that forms the foundation of a ship's smart and autonomous operations. AI encompasses a wide range of technologies, including machine learning, deep learning (such as deep neural networks), cognitive computing, and natural language processing (Lloyd's Register, 2015). Essentially, AI enables machines to simulate human-like intelligence, allowing them to process information, solve problems, and make decisions independently (Ölçer et al., 2023). Machine learning, a key aspect of AI, involves algorithms that analyze and categorize data to generate decision-making logic. However, handling unstructured data can be complex for machine learning, which is where deep learning comes into play. Deep learning, a subset of machine learning, uses layered artificial neural networks that function similarly to the human brain, mimicking human decision-making processes (Lloyd's Register, 2017). This makes deep learning particularly useful for creating autonomous ships, as it can replicate the actions of a human helmsman.

AI is fundamentally the simulation of human cognitive processes by machines, primarily computers. Key factors driving AI advancements include processing power, connectivity, and technologies like voice and image recognition. It is important to note that AI depends heavily on other technologies, such as sensors (for monitoring conditions and situational awareness), communication systems, and cybersecurity measures (Lloyd's Register, 2015; Bertram, 2020).

In essence, AI enhances machines' ability to perform tasks that mirror human behavior with minimal or no human input. In the maritime industry, AI has significant potential for both crewed and autonomous vessels. AI-driven software, such as virtual assistants, can aid human crews by providing real-time, contextual information to support decision-making (Lloyd's Register, 2015). For unmanned ships, AI processes data through machine learning and deep learning to autonomously make quick, accurate decisions (Ölçer et al., 2023). Advanced AI systems are capable of rapid analysis and decision-making that surpass human capabilities. AI plays a crucial role in enabling various Maritime Autonomous Surface Ship (MASS) technologies, supporting navigation, remote operations, maintenance, cargo management, and communication. The following **Table 13** are the drivers of and the barriers to AI utilization (derived from different sources, i.e., Ölçer et al., 2023; Lloyd's Register, 2015; Lloyd's Register, 2017; Bertram, 2020).

Table 13 Barriers and drivers of Artificial Intelligence.

Drivers	Barriers
AI speeds up tasks and improves productivity while minimizing human errors.	
Automating processes through AI leads to lower operational costs and more efficient resource management.	The rise of AI may lead to job losses as machines take over roles traditionally held by humans.
AI can take on dangerous tasks, reducing the need for human involvement in high-risk situations, thereby improving safety.	AI raises significant questions about privacy, trust, and autonomous decision-making, leading to skepticism
AI enables quick data analysis and decision-making, which is crucial for dynamic tasks like navigation and maintenance.	The rapid development of AI poses challenges for creating appropriate laws and regulations.
AI simplifies complicated procedures such as cargo management, making operations smoother and more efficient.	As AI systems grow in complexity, they become more vulnerable to cyberattacks, posing risks to security.
	Integrating AI systems into existing infrastructures can be expensive, which may hinder adoption for some companies.

4. Conclusions

In conclusion, this study has reviewed the current literature on key technological advancements in the maritime industry, categorizing them into four distinct clusters: automation technologies, digital technologies, carbon emission reduction technologies, and advanced emerging technologies. Each of these clusters presents significant potential for improving sustainability within maritime operations, and face certain barriers and drivers.

Automation technology, including autonomous navigation, automated machinery operations, and cargo handling systems, is driven by the need for increased efficiency, reduced human error, and improved safety. However, barriers such as high upfront costs, regulatory challenges, and the need for skilled labor hinder widespread adoption. Digital technologies, such as IoT, big data, blockchain, and AR/VR, offer real-time monitoring, predictive maintenance, and enhanced decision-making. Drivers include the demand for cost reduction and operational optimization, but barriers exist in the form of cybersecurity risks, data privacy concerns, and the need for robust infrastructure.

Carbon emission reduction technologies focus on alternative fuels, energy-efficient propulsion systems, and waste heat recovery, contributing to decarbonization goals. The primary drivers are regulatory pressures to reduce emissions and the growing global demand for green shipping. However, barriers include technological limitations, the high cost of implementation, and the lack of standardized regulations. Advanced emerging technologies, including AI, robotics, advanced sensors, and human augmentation, are powered by the pursuit of innovation, automation, and enhanced operational capabilities. The key barriers here include technological complexity, ethical concerns, and the absence of standardized frameworks for integration. Opportunities for sustainable maritime transport arise from the adoption of these technologies. The maritime sector can capitalize on innovations that improve energy efficiency, reduce emissions, and drive operational efficiency.
Despite the clear benefits, the adoption of these technologies faces barriers such as regulatory challenges, cybersecurity risks, and high upfront costs. To overcome the existing barriers, industry players must prioritize collaboration and knowledge-sharing. Partnerships with technology providers can facilitate smoother technology transfer, while regulatory standardization can ensure consistency in implementation. Opportunities exist in the form of government incentives, collaboration with technology providers, and knowledge-sharing initiatives, which can help stakeholders overcome these challenges and drive sustainable innovation. Addressing cybersecurity concerns and building resilient, secure systems will be essential in maintaining trust and minimizing risks as the industry embraces digitalization. Policymakers need to support education and training, develop training to improve skills and competencies of seafarers, and prepare for the socioeconomic shifts. These actions, combined with government support and incentives, can drive innovation and reduce the cost of adoption.

This study provides valuable insights for ship owners, charterers, managers, and seafarers, seafarers' unions, ports managers, technologists, academics, manufactures, classification societies and insurance firms, and regulators (e.g., maritime administrations). By reviewing and clustering the technologies into a single framework, this study offers a comprehensive understanding of the opportunities these innovations present for maritime transport. Stakeholders can also gain a deeper understanding of the barriers to adoption and the steps needed to mitigate them in the future. For practitioners, this study serves as a practical resource to enhance operational efficiency and sustainability. For academics, it contributes to the scholarly discussion by consolidating fragmented knowledge about emerging technologies, offering a "one-stop shop" for understanding how these technologies can transform the maritime industry.

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