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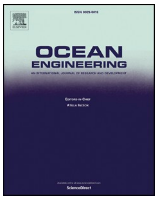

Review of ship energy efficiency

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ABSTRACT

Energy efficiency has become increasingly relevant in the current economic and environmental situations. This paper aims to create a map of the state of the art of the energy efficiency on the marine sector, both in the scale of the individual ships and the entire industry. The first point of interest will be an examination of the regulatory framework of the shipping sector in regards of energy efficiency.

Next there are the procedures implemented on ships with the aim of diminishing their consumption and emissions. These measures range from modifications of the design to the operational practices. Following that will be the potential advances that the industry could implement on a bigger scale to enhance the efficiency of the whole sector.

Finally, an overview of the main obstacles for the implementation of these measures will be examined. While the current standards are a temporary solution and several of the most prominent improvements require further investigation, the continuous effort increases the potential of this sector for optimization.

These factors emphasize the utility of this review as an introduction to help other studies have a solid understanding of the state of the art of energy efficiency in the naval industry.

1. Introduction

Global warming was first predicted in 1896 by Swedish chemist Svante Arrhenius, and has been a hotly debated topic among scientist, politicians, and environmental experts alike. It might be a slow and gradual process, but the long-term consequences could be catastrophic, including elevated sea levels, crop failure and famine, changes to plant and animal populations, and serious health effects. (Khasnis and Nettleman, 2005)

Today, environmental protection is one of the main concerns of our society, and one of the best-known causes of environmental risk is greenhouse gas (GHG) emissions, especially CO_2. The most common source of this gas is as a by-product of combustion reactions, and most transportation systems today use internal combustion engines, including the maritime sector. International shipping accounts for about 78% of global trade in metric tonnes, while emissions from this sector contribute about 2,4% of global GHG emissions in international trade. While it might seem small, if nothing is done these emissions will continue to grow with the sector, rising from 50% up to 250% of CO_2 emissions from 2012 to 2050 (HÜFFMEIER & JOHANSON, 2021). (Wang, 2018)

A solution to some of these problems is not only to try to use alternative energy sources, but also to increase energy efficiency within ship systems, not just in the sense of reducing emissions, but also increasing the performance of the ship. An improved performance means both a smaller ecological footprint in the sector and a non-negligible economic saving by making better use of each unit of fuel. The possible fuel savings that could be achieved range from 25% up to 75% via more efficient operations of existing ships and designing of new ships efficiently (Beşikçi, 2016). And so, over the last few decades, several projects and organizations have been created by various governments worldwide to minimize the consumption and pollution in the sector. The most prominent of these is the International Maritime Organization (IMO), responsible for the introduction of the Energy Efficiency Design Index in 2011 (Ančić et al., 2018)

Despite being named as an "energy efficiency index", the EEDI is primarily a CO_2 emission measurement, which is usually related to the energy efficiency, but it only evaluates a part of the ship's power system and in only one operating point, meaning that its usefulness as an energy efficiency measure is questionable (Ančić et al., 2018). This is a problem shared by other regulations, which almost exclusively keep track of the energy efficiency from the perspective of the CO_2 emissions, making a study of the energy efficiency by itself a complex and difficult affair.

Abbreviations: AFS, Anti-Fouling Systems; BWM, Ballast Water Management.

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Abbreviations

GHG	Greenhouse emissions
IMO	International Maritime Organization
MARPOL	International Convention for the Prevention of Pollution from Ships
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Index
DCS	Data collection System
EEXI	Energy Efficiency Existing Ship Index
MEPC	Marine Environment Protection Committee
SOLAS	Safety of Life at Sea
STCW	Standards of Training, Certification and Watchkeeping for Seafarers
SEEMP	Ship Energy Management Plan
CII	Carbon Intensity Indicator
MRV	EU Monitoring, Reporting and Verification
SRR	European Ship Recycling Regulation
CSI	Clean Ship Index
HKC	Hong Kong Convention
PP	Poseidon Principles
SCC	Sea Cargo Charter
LNG	Liquified Natural Gas
COGES	Combined Gas turbine Electric and Steam
ORC	Organic Rankine Cycle
HPS	Hybrid power systems
IPS	Integrated power systems
LCA	Life Cycle Assessment
I.4	Industry 4.0

There are some long standing efforts to increase the efficiency of the ships independently of their CO_2 emissions, due to the increasing price of the fuel which can account for 50–60% of the overall costs in ship operations. Reducing it by just 1% can mean hundreds of thousands of dollars saved every year in large vessels. (Ang, 2017) These measures range from reducing power required for propulsion (Hochkirch and Bertram, 2010), both in design (Lützen and Kristensen, 2012) and during operations (Moustafa et al., 2015), to more efficient employment of fuel energy by alternative engine systems (Dedes et al., 2012a), to the partial substitution of fuel power by renewable energies (Mckinlay et al., 2021)

Some studies have also been done regarding the energy efficiency itself from several different perspectives (Baldi, 2013) along with the potential problems and factors that might hold back the industry from realizing the potential of most of the cost-effective energy efficiency measures. (Johnson and Andersson, 2016) (Rehmatulla and Smith, 2015)

However, the lack of a normative directly dedicated to the examination and enforcement of energy efficiency greatly undermines the effectiveness and impact of many of these efforts. There are some proposed solutions that deal with part of the problem, like the development of wider metrics that encompass areas that the current normative leaves out (Blanco-Davis and Zhou, 2016) or the implementation of a more modern and interconnected lifecycle framework on the ships.(Ang, 2017) But they require a considerable investment to be implemented in such a way that they transform the sector's landscape.

1.1. Objectives

Because of the complexity of this discussion, this paper will aim to develop a map of the current state of the Energy Efficiency in ships from a practical point of view. This overall objective can be divided in three fronts:

- Present a broad look of the legislature and normative that have an impact on energy efficiency.
- Carry out a comprehensive study of the efforts made in the last decade to increase to increase the energy efficiency of the ships.
- Display some options that have been proposed to expand the energy efficiency of the entire maritime transport sector, along with discussing potential obstacles these energy efficiency measures might have for their implementation.

The main contribution of this review is to serve as an introduction to help other studies have a solid understanding of the current state of the maritime sector and its stance on energy efficiency, as the continuous effort made in this field helps bring the industry closer to a greener tomorrow.

2. Regulatory framework

Something that must be stressed is that there is no normative directly addressing energy efficiency on ships as their main point of regulation. The existing rules about ship efficiency are not autonomous, but are dependent of those concerned about ambient pollution, specifically about greenhouse emissions to the atmosphere. For example, the main measurement of energy efficiency, the EEDI, is not appropriate for some types of ships or those which use certain power systems, and its method of measuring efficiency is directly connected with CO_2 emissions (Ančić et al., 2018)

It is thus vital to comprehend the origin and the main concern of the current normative to understand the investigation and research done in the field of energy efficiency in ships. Therefore, a series of regulations will be shown, along with their reach and a description of the main enforcements. Even those regulations not directly concerned with the energy efficiency can impose limitations in the development of more energy efficient ship systems.(Table 1)

Below is the evolution of the previously shown regulations from their creation to the present day, with an added description of each date and highlighting those who are more relevant to the sphere of energy efficiency in ships. The IMO in particular is so important in the global context of this subject that it will be described in its own section.

2.1. International maritime organization (IMO)

The next table will show the general timeline of the creation of the most important IMO measures and normative to the field of energy efficiency, while also highlighting the most relevant: (IMO; Anon) Table 2.

Other important dates of conventions being adopted are the following:

- 2001: Implementation of the convention about anti fouling systems (AFS 2001)
- 2004: Adoption of the convention about ballast water management to prevent the invasion of alien species is adopted (BMW 2004)

With all these conventions and more, The International Maritime Organization (IMO) is the most prominent of the entities in charge of managing the efficiency of the maritime transport sector(IMO,). IMO's role is to create a level playing field so that shipowners have a variety of ways to solve their financial problems in such a manner that they do not require budget cuts that jeopardize the safety of the personnel, the structure, or the environment, as well as generally promoting innovation and efficiency. Most other systems dealing with energy efficiency or

Table 1
Main regulations of ship.

Name	Reach	Description
International Maritime Organization	International	United Nations specialized agency with responsibility for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships.
EU Monitoring, reporting and verification	European	European strategy for progressively integrating maritime emissions into the Green House Gases policy by the organized monitorization of fuel consumption of ships.
European Ship Recycling Regulation	European	Normative seeking to reduce the negative impacts linked to the recycling of ships, along with imposing a number of safety and environmental requirements.
Clean Shipping Index	European	Practical tool for evaluating and classifying the environmental performance of ships, with discounts on port and faraway dues for those that best comply.
Hong Kong Convention or the Safe and Environmentally Sound Recycling of Ships	International	Normative intended to address all the issues around ship recycling, including regulations for the design and operation or an inventory of hazardous materials.
Poseidon Principles	International	World's first sector-specific, self-governing climate alignment agreement amongst financial institutions, establishing a global framework for assessing and disclosing the climate alignment of ship finance portfolios.
Sea Cargo Charter	International	Framework for disclosing the climate alignment of ship chartering activities around the globe, setting a benchmark and actionable guidance for that end.

especially environmental impact of ships usually rely on IMO criteria to establish their own measures. The structure of the International Maritime Organization is as it follows: (See Fig. 1)

The sub committees also influence and assist the Maritime Safety Committee, besides being open to all Member States. The most relevant facet of the IMO in the sphere of energy efficiency is its technical committees, most critically; the Marine Environment Protection Committee or MEPC, which regulates the affairs concerning the protection of the marine environment and the questions of energy efficiency through CO2 emissions.

The IMO has also created several conventions that are very significant and important for navigation, with the key examples being:

- International Convention for the Safety of Life at Sea (SOLAS)
- International Convention for the Prevention of Pollution from Ships (MARPOL)
- International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW)

The most important convention in the objective of energy efficiency is by far the MARPOL.

2.1.1. The MARPOL convention

The MARPOL, or International Convention for the Prevention of Pollution from Ships, is the main international convention covering prevention of pollution of the marine environment by ships from either operational or accidental causes. While originally created in 1973, an updated version was adopted in 1978 and the combined instrument entered into force first in 1983, but the entirety of the regulations proposed wouldn't be completely enforced until 2005. The structural organization of the MARPOL convention consists of a series of regulations aimed at minimizing pollution from ships, divided in six technical annexes with specific instructions to prevent concrete methods of pollution: Fig. 2.

Table 2
Timeline of the IMO regulations.

Date	Description of the relevant changes in that date
1948	- The IMO is created in Geneve with the name of Inter-Governmental Maritime Consultative Organization or IMCO
1958	- The organization enters into force
1967	- The Torrey Canyon disaster demonstrates the scale of the pollution problem, especially about transport of oil.
1973	- The biggest measure for avoiding pollution, the International Convention for the Prevention of Pollution from ships MARPOL, is implemented. (Modified in 1978)
1997	- The MARPOL protocol was approved with regulations about pollution, including cargo spilling, waste waters and air pollution.
May 2005	- The MARPOL convention enters into full force
April 2009	- **First mention of the concepts of EEDI (Energy Efficiency Design Index) and EEOI (Energy Efficiency Operational Index) to reduce Greenhouse gases, in the MEPC 59**
August 17, 2009	- Begins the circulation of Guidelines for voluntary use of the EEOI.
July 2011	- **The EEDI becomes necessary to any new ships. (By "new", this means any ship whose contract is made after January 2013, that enters the building phase after July 2013 or those which are delivered after July 2015)**
October 2016	- Adoption of the IMO DCS (Data Collection System, MEPC 70), allowing the monitorization of fuel usage and other proxies for transport work.
March 2018	- The DCS system comes into full force
January 2019	- **Start of the first reporting period of the DCS system**
November 2020	- The EEXI is approved at MEPC 75 as an extension of the EEDI to help evaluate ships built before 2013. It is expected to come into force at the next MEPC.

The most important part of the MARPOL for the subject of energy efficiency is Annex VI: Prevention of Air Pollution from Ships, the last one to enter into force and which from 2011 also covers mandatory technical and operational energy efficiency measures aimed at reducing greenhouse gas emissions from ships.(IMO,)

Among these measures are the most important ones related to the area of energy efficiency nowadays as defined by the IMO itself. These are the following:

- **Energy Efficiency Design Index (EEDI)**: This is the most important technical measure for new vessels, and its main function is to promote the usage of more energy-efficient equipment and machinery in new ships. This measurement aims to be gradually adjusted every five years to stimulate continuous innovation and technical development of the design phase, starting with the baseline reference value in 2013 (Phase 0) and ending with a value around 30% lower depending on the type of ship in 2025 and beyond (Phase 3). While it's mostly dedicated to cargo ships, but there's an amendment in 2014 to account for the evaluation of Ro-Ro and passenger ships, with their corresponding reference values.
- **Energy Efficiency Operational Index (EEOI):** This technical measure allows shipowners and operators to measure the fuel efficiency of a ship in service and to gauge the effect of any changes in the operation like improved voyage planning or more frequent propeller cleaning.
- **Ship Energy Efficiency Management Plan (SEEMP)**: It is an operational measure that provides an approach for shipping companies to manage the efficiency performance of ships and fleet over time using, for example, the EEOI as a monitoring tool. The

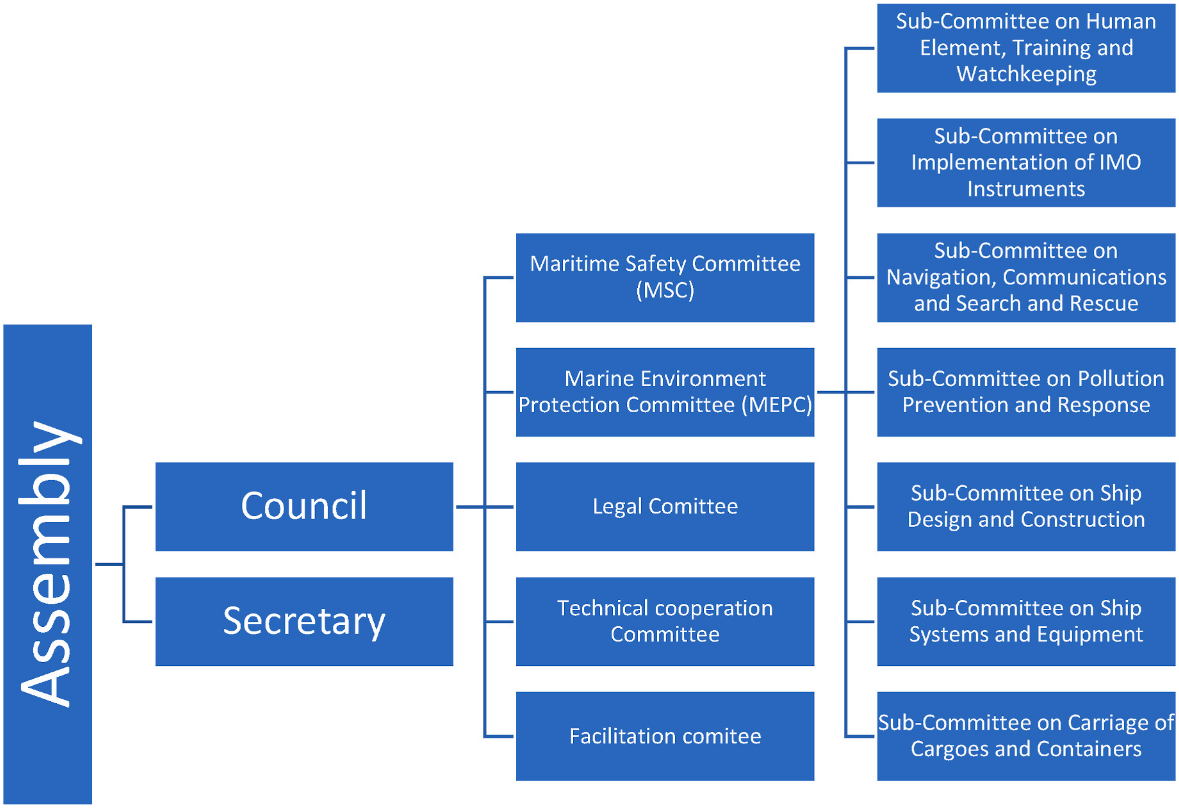

Fig. 1. Structural management of the International Maritime Organization.

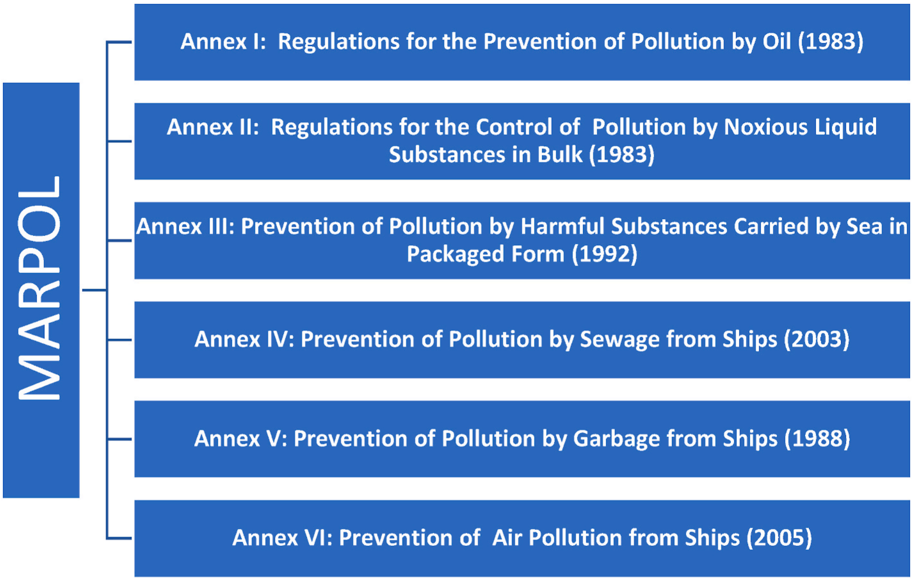

Fig. 2. Structure of the MARPOL convention.

development of the SEEMP incorporates best practices for fuel efficient ship operation and guidelines for voluntary use of EEOI on ships.

In conjunction, these measures help promote new technologies and practices when seeking to optimize the performance of a ship (IMO,) However, in June 2021 the MEPC adopted some new amendments to the Annex VI of Marpol to improve further the energy efficiency of ships and are expected to enter into force on 1 January 2023. The measures in question are:

- **Energy Efficiency Existing Ship Index (EEXI):** Appears in the amendment MEPC 333(76). The main function of this measurement is to evaluate the performance of ships in a similar way to the EEDI, covering the same ship types and sized but applicable to all existing vessels regardless of their build date. Owners of ship managers need to calculate the EEXI of ships in their fleet and make sure that their EEXI values are lower than the required EEXI.

- **Carbon Intensity Indicator (CII)**: Introduced in four amendments explaining the indexes and how to work with them, from the MEPC 336(76) to the MEPC 339(76). This measurement determines the annual reduction factor needed to ensure the continuous improvement of the ship's operational carbon intensity within a specific rating, on a diminishing scale from A to E. This is an ongoing task that requires to be calculated every year starting from 2023 and must be reduced annually. Any ship classified as E or with three consecutive years as D must submit a corrective action plan to achieve rating C or better.

The adoption of the new measures would build on IMO's previously adopted mandatory energy efficiency measures, to lead shipping on the right path towards decarbonisation (International Maritime Organization, 2021).

2.1.2. Ship classification according to the IMO

Before dwelling into other regulatory systems besides the IMO, it must be noted that there are several kinds of vessels depending on their function and said function can impose some constraints in the types of efficiency measures the ship can implement before its performance is diminished.

Because of this, some types of ships have more specific regulations provided to them, like in the case of the EEDI where each type of ship uses different parameters when calculating the value of reference. This is also the main reason several studies center their efforts on specific kinds of vessels for a more focused approach, even if in most cases their measures can also be implemented on other ship types.

And so, according to the IMO, there can be distinguished several important cargo ship types: (Imo, 2011)

- **Tanker**: A ship constructed or adapted primarily to carry either an oil or other chemicals in bulk in its cargo spaces.
- **Bulk carrier**: A ship which is intended primarily to carry dry cargo in bulk, like ore.
- **Gas carrier**: A cargo ship constructed or adapted for the carriage in bulk of any liquified gas.
- **Container ships**: A ship designed exclusively for the carriage of containers in hold and on deck.
- **General container ships**: It refers to a hip with a multi-deck or a single deck hull designed primarily for the carriage of general cargo. (This excludes specialized dry cargo chips like livestock carrier, barge carrier, heavy load carrier, yatch carrier and nuclear fuel carrier)
- **Refrigerated cargo carrier**: A ship designed exclusively for the carriage of refrigerated cargoes in holds.
- **Combination carrier**: A ship designed to load 100% deadweight with both liquid and dry cargo in bulk.

There are other types of ships that the IMO touches upon but are not dedicated to the transport of cargo, with the **Ro-ro** and **Passenger** ships being the most important among those. The main measure of those ships is not the deadweight but either the cargo space or the number of passengers respectively, so the normative for them is registered accordingly.

Of all these kinds of ships, those who compromise most of the total ships emissions according to the International Council of Clean Transportation Report of 2013 are the Container ships (23%) the Bulk Carriers (19%) and the Oil Tankers (13%) (Amoraritei, 2019) (Constantin and Amoraritei, 2018) Because of this a lot of the studies regarding energy efficiency measures come from them, but there are still some noteworthy works done on the behalf of other types of ships, most notably cruisers.

Before moving on to the rest of the regulations, it's sensible to point out some of the most recent trends in compliance with energy efficiency requirements among different types of ships.

As of 2017, an analysis realized using official IMO data and conducted by the organization Transport and environment showed the following results regarding EEDI and energy efficiency of several types of cargo ships: Table 3

It's possible to see that many of the ships that have been evaluated are already complying with the EEDI requirements of beyond 2025, which is the last phase established in the normative and the strictest. Of special note are the containerships, of which more than 70% comply with the regulations and can reach up to 58% more efficiency than the baseline, compared with the post-2025 requirements of 30%. This stands in stark contrast with the bulk carriers, of which the best ships barely manage to reach 27% of energy efficiency and only 1% get even close to the level of the post-2025 EEDI requirements.

While this is a very positive situation for the containerships type of ships, especially since they emit around a quartet of the global ship CO2 emissions, this also means that the regulation is not fulfilling its objective of promoting better designs or technological innovation. The study even suggests that the performance of the best ships in the fleet would be a good place to start when revising existing or setting new EEDI requirements. (Transport & Environment, 2017):

2.1.3. Specific european regulations

The next set of regulations that will be examined are those that are implemented specifically at a European level, or those who are originated in a European country. The main organizations examined will be the EU Monitoring, Reporting and Verification (MRV), the European Ship Recycling Regulation (SRR) and the Clean Shipping Index (CSI). The dates that are especially relevant will be highlighted(Table 4).

2.2. Other international regulations

The following table will show the general timeline of the creation of other international regulations outside the IMO that possess some relevancy to the subject of energy efficiency in ships. The main organizations examined will be the Hong Kong Convention (HKC), the Poseidon Principles (PP), and the Sea Cargo Charter (SCC). Those which have the most impact will be highlighted (Table 5).

2.3. Generalized framework of energy efficiency

In this section only the specific regulations that have a direct impact on the energy efficiency of the ships are shown, consisting of those that were already highlighted in the previous sections in chronological order (Table 6).

Whether because of the desire to apply to the regulations or because of initiative, currently there is a continuous effort in the research of this field, both in a general sense or applied to specific types of ships.

The next sections will be dedicated to examining several advancements and proposals for power optimization on the ships. The process of optimization consists of the selection of the best solution out of many feasible ones based on a set of criteria, which in this case includes the maximum possible energy efficiency. (Papanikolaou, 2010) This will help to portray a clearer picture of the current situation and of the of the

Table 3
Energy efficiency trends on differen types of cargo ships.

Type of cargo ship	Efficiency improvements of new ships relative to the baseline EEDI value of 2013.	Share of ships built in 2013–2017 already complying with the post-2025 EEDI target.
Containerships	58% more efficient	71% of built containerships
General cargo ships	57% more efficient	69% of built general cargo ships
Gas carriers	42% more efficient	13% of built gas carriers
Oil Tankers	35% more efficient	26% of built oil tankers
Bulk Carriers	27% more efficient	1% of built Bulk Carriers

Table 4
Timeline of the European regulations.

Organization	Date	Description
MRV	June 2013	- The European Commission proposes a strategy for progressively integrating maritime emissions into the Green House Gases policy.
MRV	April 2015	- The strategy is adopted by the European parliament.
MRV	July 2015	- The strategy comes into force.
MRV	**January 2018**	- **Shipping companies must monitor fuel consumption, carbon emissions and other relevant information for each ship under their responsibility. First reporting period until December.**
SRR	November 2013	- The SRR is proposed by the European parliament to help a quick ratification of the Hong Kong Convention.
SRR	**December 2013**	- **The SRR enters into force.**
CSI	14 November 2017	- The Swedish maritime administration approves the regulations on fairway dues.
CSI	**January 2018**	- **The system is implemented, rewarding environmentally high vessels with lower faraway dues.**

Table 5
Timeline of other international regulations.

Organization	Date	Description
HKC	May 2009	- The convention for the Safe and environmentally sound recycling of ships is adopted.
PP	November 2017	- Initial convening of financial institutions on climate risk in ship finance.
PP	April 2018	- IMO Agreement sets level of ambition.
PP	June 2018	- Workshops on climate risk and collective ambition held in Singapore, London, and NYC.
PP	August–September 2018	- Drafting group begins work on initial principles, which become known as the Poseidon Principles.
PP	October 2018	- Industrial feedback sought on initial draft of Poseidon Principles at Global Maritime Forum Summit in Hong Kong.
PP	November 2018–February 2019	- Drafting group completes Poseidon Principles, incentivizing banks and other financial institutions to support the objective of the IMO reduction of emissions.
PP	**18 June 2019**	- **Launch of the Poseidon Principles in New York City.**
SCC	June 2018	- Workshop on climate risk and collective objective for the Poseidon Principles in London.
SCC	September 2018–April 2019	- Workshops in Singapore and Geneva to gather feedback from a broad group of stakeholders on the development of the Sea Cargo Charter.
SCC	October 2019	- Drafting group kick-off meeting at the Global Maritime Forum Annual Summit in Singapore.
SCC	November 2019–March 2020	- Drafting group begins work on initial principles, which becomes known as the Sea Cargo Charter.
SCC	March 2020	- Series of webinars to seek feedback on initial draft of the Sea Cargo Charter from a wider group of stakeholders.
SCC	March 2020–July 2020	- Drafting group completes the Sea Cargo Charter, providing a similar framework to the Poseidon Principles, but applied specifically to charterers.
SCC	**7 October 2020**	- **Launch of the Sea Cargo Charter during the Global Maritime Forum Virtual High-Level Meeting.**

Table 6
Generalized framework timeline.

Scope	Date	Description
IMO	**April 2009**	- First mention of the concepts of EEDI and EEOI to reduce Greenhouse gases, in the MEPC 59.
IMO	**July 2011**	- The EEDI becomes necessary to any new ships. (By “new”, this means any ship whose contract is made after January 2013, that enters the building phase after July 2013 or those which are delivered after July 2015).
European	**December 2013**	- The Ship Recycling and Regulation (SRR) comes into force.
European	**January 2018**	- The Clean Shipping Index is implemented, rewarding environmentally high vessels with lower faraway dues.
European	**January 2018**	- Shipping companies applying to the MRV must monitor fuel consumption, carbon emissions and other relevant information for each ship under their responsibility. First reporting period until December.
IMO	**January 2019**	- Start of the first reporting period for all the ships included in the Data Collection System.
International	**18 June 2019**	- Launch of the Poseidon Principles in New York City.
International	**7 October 2020**	- Launch of the Sea Cargo Charter during the Global Maritime Forum Virtual High-Level Meeting.

research being done in this field.

To put this into perspective, the initial IMO GHG strategy aims to reduce carbon intensity of international shipping by 2030 by 40% compared to 2008. The draft amendments on 2020 to the MARPOL convention would require ships to combine a technical and an operational approach, and so, most of the measures can be divided between those that need to be enforced while designing a ship, and those that can be applied to the ship in the operational phase.

3. Energy efficiency at the design stage

Ship design is a complex endeavour that requires successful coordination of many disciplines, as the ship itself consists of an intricate system integrating a variety of subsystems and their components. (Papanikolaou, 2010) But from the last decade alone there has been a conscious effort not only to reduce emissions, but also the cost per voyage of the vessels, of which the price of fuel is a significant contributor (Ang, 2017).

The biggest advantage of modifications on the design of the ship is that once implemented they don’t require constant monitoring and adjustments to have an optimal performance, only requiring the regular ship maintenance. This leaves the ship with an optimized efficiency and ecological footprint since its foundation and for the duration of its useful life. The methods proposed to improve their efficiency range from alternative fuels and engines to hull modification and exhaust gas waste heat recovery. (Tokuşlu, 2020)

To evaluate the impact of these measures, there exist numerous methods depending on the type of the ship, but most use the EEDI implementations as a baseline. This is not a requirement, however, and it makes it more difficult the task of evaluating the effectiveness of some of these measures. Therefore, there will be separate sections for those studies that use the EEDI and another one for those that don’t, with each section being divided depending on the type of modification done.

3.1. *Studies that employ the EEDI as an evaluation tool*

The EEDI is a very useful as a point of comparison between different measures despite its shortcomings, because having a standardized set of values makes it easier to evaluate the impact of a system. The following table shows several studies about measures regarding energy efficiency, alongside the type of ships evaluated and their impact on them in terms of EEDI reduction (Table 7).

The next sections will expand the information on the studies depicted on the table, divided by the type of modifications performed on them.

3.1.1. *Modification of hull parameters*

The optimization of the hull form is a longstanding method of improving the performance of the ships for various objectives, ranging from increasing the hydrodynamic performance to enhanced survivability and transport efficiency. (Papanikolaou, 2010) Therefore it should not come off as a surprise that there have been attempts to reduce the EEDI by enhancing the shape of the ship.

The overall the effects of the form of the ship hull is considerable, as one study proven by using historical data of tankers of the last 30–40 years. Analysing the adimensional design parameters of the ships and their corresponding EEDI values, the conclusion reached was that the EEDI of the analysed ships has been increasing for the last decades due to several factors like a higher block coefficient and lower length displacement ratio. Returning those values to their historical minimum can reduce the EEDI significantly (10–15%) without sacrificing cargo capacity. (Kristensen and Lützen, 2012)

The direct influence of the design parameters on the consumption of the ship has also been observed, mostly concerning the length, beam, and draught of the vessels. An increase of 1% in any of them for a given deadweight reduces the block coefficient of the ship and results in a decrease in power demand. Said decrease ranges from around 4,6% in the case of length, 2% in the case of beam, and 2,8% in the case of draught. The positive impact of increasing the beam is reduced because of the increased beam-draught ratio (B/T) which increases the residual resistance on the ship. All these variations also influence the EEDI, although in a smaller proportion than the fuel demand, between 2.5% and 0.7% per meter subtracted depending on the parameter. Conversely, an increase of 1% in the design speed of the ship generally results in a rise of power demanded, roughly 2,9%. While all these analyses were performed on Panamax tankers, the study also concerned itself with the efficiency of bulk carriers. (Lützen and Kristensen, 2012)

3.1.2. *Propulsion system optimization*

As the CO_2 emissions are influenced by the installed power of the main and auxiliary engines as well as the quality and quantity of fuel burned in them, one of the main ways to reduce greenhouse emissions is by the optimization of the main engines and therefore the propulsion system of the ship. (Amoraritei, 2019)

New technologies have been very helpful in this regard, and some studies have simulated the energy efficiency of some innovative propulsion systems for cruise ships. Cruise ships were chosen because the range of accommodations required for passengers make it more imperative to optimize the energy of the ship. Of all the systems analysed, the dual pressure steam systems and specially the Organic Rankine Cycles offered the greatest potential benefits for the cruise ship industry, reaching a better EEDI, operational efficiency and lower fuel consumption than the rest, even if only by a low margin. (El Geneidy, 2018)

Another example of attempts at engine optimization are the electric propulsion systems, whose economic and environmental impact is being investigated to achieve more efficient ship operations in commercial, cruise and naval vessels. One of these research projects studied two electric propulsion options on a Passenger ship, a diesel electric and a combined gas turbine electric and steam (COGES). The latter was found out to have lower EEDI (Encompassing less than 90% of the reference EEDI in contrast to the almost 95% of the Diesel electric) and can be proposed as an upgraded and cost-effective option for ships that use gas turbines as their main propulsion. (Ammar and Seddiek, 2021)

It's also worth mentioning that some types of vessels have more specialized requirements within their systems, which in turn demands peculiar responses. Of these types of ships, a common example are the gas carriers, due to the very precise requirements of their cargo. For example, the LNG is transported at −160 °C and at near atmospheric pressure, which inevitably causes the LNG to boil off due to imperfect insulation and sloshing in the tanks, and it is the need to handle this boil off gas that has created very distinct demands in the propulsion of these ships, in which steam power predominates. Besides a steam turbine, some other options have also been considered, like a slow speed diesel with re-liquefaction plant, and a dual fuel diesel electric propulsion. Of those three the last one seems to be the most efficient and the only one that complies with Phase 3 of the EEDI, but only regarding CO2, if methane is included, it has the highest emission rate. (Attah and Bucknall, 2015) In other areas, however, the LNG carriers are remarkably like the rest of the cargo ships. Unlike the engines, the propulsion systems for LNG carriers do not have specific propulsive requirements, and several factors like speed, trade distance and maintenance cost can be used to select the system most adequate for each case. (Huan, 2019)

3.1.3. *Hybrid propulsion systems*

Hybrid energy system or Hybrid Power System (HPS) is a broad term used to describe a structure consisting of a combination of a prime

Table 7
Design measures that assesed their impact using the EEDI.

Type of modification employed	Description of the method	Type of ship examined	Impact	Source
Modification of hull parameters	Restoring historical adimensional design parameters like block coefficient.	Tankers and bulk carriers of all sizes.	The EEDI values are reduced between 10 and 15% in the fleets examined.	(Kristensen and Lützen, 2012)
	Reduction of main ship dimensions like length and beam	Panamax tankers with influence of bulk carriers.	The EEDI values diminish between 2.5% and 0.7% per meter subtracted.	(Lützen and Kristensen, 2012)
Propulsion system optimization	Innovative propulsion methods like the Organic Rankine Cycle	LNG carriers.	The EEDI diminishes up to 0.3 below the reference case in the best systems.	(El Geneidy, 2018)
	Electric propulsion systems.	Passenger vessels.	Both structures examined comply with phase 3, but the COGES system has greater margin of error.	(Ammar and Seddiek, 2021)
	Specific LNG carrier propulsion	LNG carriers exclusively.	Of the systems examined, only the diesel electric complies with phase 3, but with a heavy methane slip.	(Attah and Bucknall, 2015)
Hybrid propulsion systems	Hybrid systems on general cargo carriers	Small and fast general cargo carriers.	Two of the investigated cases comply even with the strictest phase of the EEDI.	(Øverleir and AuthorAnonymous, 2015)
	Fleets of hybrid systems	Ro-Ro and Passenger ships.	Both types of systems examined have EEDI values below the reference of the ship.	(Ančić et al., 2018)
Alternative fuel sources	Varied array of alternative technologies like shaft generators.	Very large crude carrier.	The combined effects of innovative technologies produces a drop in the EEDI of up to 0.34, around 16%.	(Faitar and Novac, 2016)
	Propulsion for Liquid hydrogen tankers.	Liquid hydrogen tankers exclusively.	The optimal system analysed was a steam turbine with a hydrogen boiler and complies even with phase 3 of the EEDI.	(Ahn, 2017)

mover and an electrical energy storage system, usually some form of battery. This device stores the energy produced by the prime mover during lighter loads and releases it under heavy loads. This reduces the fuel requirement of the prime mover and allows it to operate constantly at maximum efficiency. Although this measure has yet to be implemented on a large scale for several types of ships, there are others that have been more widely considered, for example ferries, tugboats, fisher vessels and other small craft (Nal et al., 2022)

This should not be a detriment to the implementation of hybrid systems in other vessels. One example of the considerable potential of these systems is in the general cargo carriers. Despite the market being increasingly dominated by specialized vessels, the general cargo ship segment is a shipping sector that is crucial for the global trade to function. These vessels are often specialized for niche markets, but also optimized for carrying many types of cargo, which leads to a poor EEDI performance. This has been the motivation of analysing the possibility of using a hybrid energy system, and it was found that said system has many advantages like enabling cold ironing, eliminating frequent load variations and easier power redundancy. The overall efficiency is also higher, with two of the studied cases complying with even the strictest phase of the reference EEDI. (Øverleir and AuthorAnonymous, 2015)

The existence of these kinds of innovative systems has created a need to evaluate their efficiency as well, and a new methodology has been introduced to evaluate efficiency on ships with Hybrid Power Systems that can be applied to ro-ro and passenger ships. This methodology also evaluates Integrated Power Systems (IPS), characterized by a centralized electric power generation for both main and auxiliary systems and the application of electric propulsion. After analysing the technical properties of ships delivered in the last 15 years, the results indicate that most ships with IPS or HPS have their EEDI values below of their value of reference, which indicates a high efficiency. This analysis employed a total of 384 ships, meaning that the methodology can be employed to evaluate entire fleets (Ančić et al., 2018)

3.1.4. Alternative energy sources

The introduction of alternative energies on board is a very promising and enticing way of increasing energy efficiency on the ships but they require a careful examination before they can be implemented on large scales.

This careful examination was the reason to use a Very Large Crude Carrier as a testing site for several of those technologies, while examining the changes caused in its EEDI value and the reduction of emissions. The results show that wind turbines, photovoltaic panels and shaft generators are an effective way of reducing carbon emissions. The study also points out that this effect can be enhanced by other measures like employing LNG as a ship propulsion fuel, which also has the advantage of eliminating nearly all SO_X emissions. (Faitar and Novac, 2016)

Another promising energy source is hydrogen, whose employment has been increasing in the last decade. This has caused the creation of specialized ships to transport it like liquid hydrogen tankers, which have specific requirements because of the cargo they hold. A study was made to evaluate several propulsion system options for this type of ships, based on the cost-benefit ratio and the EEDI of each of the alternatives. The results show that the optimal propulsion for this type of ships is one that uses a steam turbine with a boiler that uses hydrogen Boil-off-gas, managing to comply even with Phase 3 of the EEDI. (Ahn, 2017)

3.2. Studies of the last 10 years that use other parameters

The need for a regulation is best highlighted in the studies that don't employ the EEDI to standardize the benefits acquired from their measures. The result is that the way those studies calculate the impact of their methods varies greatly, from fuel consumption to CO_2 emissions in tons to economic benefits, as shown in the table below (Table 8).

All these measures will be explained in more detail below, divided by the type of modification as with those that employed the EEDI.

3.2.1. Modification of hull parameters

The process of optimization of the ship by reducing its hull resistance it's based on an attempt to decrease the wetted surface for the vessels, and its focus resides mainly on design alterations to minimize drag resistance and in the usage of different bulb and stern types to reduce the impact of the waves. (Tsoukatos, 2014) However, it should be noted that hull resistance is not only determined by the shape of the ship, but also

Table 8

Design measures that assesed their impact without using the EEDI.

Type of modification employed	Description of the method	Type of ship examined	Impact	Source
Modification of hull parameters	Periodic cleaning of the hull.	Eight Aframax crude carriers.	Fuel consumption reduced between 9% with underwater cleaning and 17% with dry-docking.	(Adland, 2018)
Propulsion system optimization	Optimization of engine and propeller under rough weather.	LNG Carriers.	The best matching fuel, engine and propeller profile has provided an economic gain of over 5.1%.	(Marques et al., 2019)
Optimization of auxiliary systems	System structure and energy flow of the ship.	Chemical tanker, noted to be applicable to all kinds of ships.	Some improvements like the Waste Heat Recovery system can provide around 72% of the auxiliary power requirement in sea going mode, even in suboptimal circumstances.	(Baldi, 2013)
	Cold ironing	Bulk carrier ships and cruise ships.	Operating costs and energy consumption of bulk carriers diminish by up to 75%. Near complete CO2 emission reduction in cruise ships. Both cases during port operations.	(Iris and Lam, 2019)
Hybrid propulsion systems	Hybrid battery diesel propulsion for bulk carrier fleets.	Bulk carriers of all sizes.	The installation these systems could save fuel up to 1.27 million dollars per vessel and per year, on top of an improvement in overall ship efficiency between 2 and 10%.	(Dedes et al., 2012)
	Fuel-cell based hybrid electrical propulsion system.	Aframax crude oil tanker.	The system achieves between a 9% and 16% CO2 emission reduction in indirect and direct coupling systems respectively.	(Giap, 2020)
	Multi-Scheme strategy fuel cell propulsion system.	Inland passenger ship FCS Alsterwasser.	Implementing the proposed strategy can produce a maximum energy saving of 8%.	(Bassam, 2017)
Alternative fuel sources	Harnessing wind power using Flettner rotors.	Tankers and bulk-carriers, unfeasible for Ro-Pax and containerships	With the four rotors employed, CO2 emissions are reduced by 9272 ton/year and fuel consumption by 22.28%	(Seddiek and Ammar, 2021)
	Employment of solar photovoltaic system.	Ro-Ro ship.	The system can up to 7.76% of the energy demand of the ship and saves 7.38% of the annual fuel consumption.	KARATUĞ & DURMUŞOĞLU (2020)
	Usage of hydrogen fuel cells.	LNG tanker.	The equipment covers 43% of auxiliary power demand and reduces CO2 emissions by 2343ton/year.	(Mckinlay et al., 2021)

by area and roughness of its underwater surface (Bertram and Taşdemir, 2017).

This marks the importance not only of special coatings and minimizing appendages to decrease frictional resistance, but also the contribution of hull fouling (Marine growth) to increased emissions, and therefore the importance of hull cleaning in fleets. A study was developed within a small fleet of Aframax tankers, and the results indicate that periodic cleaning can reduce fuel consumption significantly, with the reduction being more appreciated when the vessel is loaded than in ballast conditions. Another important factor noted was that dry docking leads to greater reductions than underwater hull cleaning. The fuel savings went from 9% with underwater cleaning, already 3 tonnes of fuel per day at around 1000$/day, to 17% with dry-docking. (Adland, 2018)

3.2.2. *Propulsion system optimization*

While the study of the main engine is a very important endeavour, optimizing of the propellers is also a focal point of propulsion efficiency, with existing methods like the reduction of rotational losses and an optimal pitch. The effectiveness of this methods vary, for example while fixed pitch propellers are generally more efficient, the employment of a controllable pitch propeller can be better if the ship has a wide range of operational points. (Hochkirch and Bertram, 2010) Therefore, the characteristics of the propeller should be considered on the evaluation of the propulsion system.

One example of this is the study of the design, synthesis, and operation of a marine energy system for LNG carriers. Various propellers, 16 engines and 4 operational profiles were assessed trough an algorithm whose objective was to maximise the net value and economic benefit under rough weather. The approach has shown gains of up to 5,1% with the best matching set and highlighted the need to explore a broad range of propellers and engines, while also considering the weather conditions in an integrated way (Marques et al., 2019)

3.2.3. *Optimization of the auxiliary systems*

Minimizing the power required for the equipment on board, whether by the usage of more efficient devices or by reducing losses in the power grid, is a fundamental way to increase the energy efficiency of the ship. However, there are other effective practices like operating the auxiliary engines at variable speeds depending on the electric loads present or the employment of new system architecture (HÜFFMEIER & JOHANSON, 2021).

To create a more efficient system architecture, it is necessary to understand the energy flow of the ship. This means it's important to discern where energy in its different forms is generated, converted, and used on board of the vessel. The case study selected by the document was a chemical tanker, in which besides the propulsion and auxiliary power systems, there are also converters, thermal and electric consumers, and cooling systems. All of these play a vital role in the power grid of the ship, and a careful analysis helps identifying the main inefficiencies and take the necessary steps to correct them, with one of the most notable being the Waste Heat Recovery system, labelled as a promising solution for improving ship energy efficiency and which can provide around 72% of the power requirement in sea going mode. (Baldi, 2013)

Other possible approaches to the optimization of power systems in a ship can include power quality standards, different frequency ranges and impact of power converter topologies on each of those frequency ranges. (Kumar and Zare, 2019) One of the aspects that can influence this method is the employment of Cold Ironing.

During docking, most ships turn off their main engines, and the energy for activities such as power system maintenance, lighting or refrigeration are supplied by the auxiliary engines. Cold ironing is the term used for the practice of connecting the ship to a shore-side power when in harbour so that the ship's power generators can be shot down during the hotelling activities.(Iris and Lam, 2019) The name "Cold Ironing" derives from the fact that this phenomenon causes the machinery space and hull iron to turn cold. This system is frequently used by General Cargo ships and ships with hybrid systems and is expected that it will be implemented in more ports in the years to come. (Øverleir and AuthorAnonymous, 2015) It's also very promising for cruise ships because of the high amount of power required by the passengers that stay on board during hotelling, despite the challenges like proper voltage, connection and grid characteristics required. (Iris and Lam, 2019)

3.2.4. *Hybrid energy systems*

The success of the hybrid battery-diesel-electric system in automotive industry has created interest in its usage as a propulsion system in ships, and some studies have been made to test its viability in bulk-carriers. Results indicate that such an installation will fit in modern bulk carriers without significantly affecting the main dimensions of the ship, and that proper allocation of the weight may even be used to improve the trim of the ship, despite conversion losses potentially being significant (Dedes et al., 2012). While the results of the tests indicate that savings depend on the storage system, the availability of energy and the displacement of the vessels, those savings can be very significant. On dry bulk ships a hybrid system could save up to 1.27 million United States Dollars per vessel and per year, and the improvement in the overall efficiency of the ship could be between 2% and 10% (Dedes et al., 2012a).

Besides the implementation of the prime mover and the energy storage system on the rest of the ship structure, how both parts of the system are arranged with regards to each other can also result in a considerable difference. A crude oil tanker was used as an experimental site to a fuel-cell-based hybrid electrical propulsion system, helping investigate whether an indirect coupling between engines and fuel cells or a direct coupling including heat and material interaction were more efficient. Direct coupling, despite requiring a more complex configuration, seems to be the most efficient, as this supplies the remaining fuel from the fuel cell to the engine and the exhaust of said engine is provided to the fuel cell system. The benefits go from a 9% CO_2 emission reduction in indirect coupling to a 16% reduction with direct configuration. (Giap, 2020)

Some innovations have also been made within the organization of those systems since they possess a higher complexity than a regular energy system architecture. Optimizing the hybrid hydrogen fuel-cell propulsion system of a ship has been the main objective of the creation of a multi-scheme energy management strategy aiming to minimize their fuel consumption on the inland passenger ship FCS Alserwasser, notable for being the world's first fuel cell passenger ship. After the implementation, the performance in terms of total consumed energy, fuel, cost, and stresses seen in the components in a daily ship operation routine of 8 h was evaluated. The results indicate that the proposed multi-scheme strategy can achieve energy and fuel consumption savings of 8% and 16.7% respectively without further cost. (Bassam, 2017)

3.2.5. *Alternative energy sources*

One of the analysed ways of providing the ship with alternative energy sources is by harnessing wind power. This can manifest by the existence of wind turbines on board to generate electricity using wind energy, or by assisting propulsion with the usage of rigid sails and other wind-powered devices to reduce the power required by the engines to move the boat, such as with the "Rotor Sails", also known as Flettner rotors.

These devices are a form of wind-based propulsion that consists of a spinning cylinder with an endplate affixed to the top, mounted vertically to the deck of the ship. (Pearson, 2014) Their main principle of operation is the Magnus effect, a phenomenon exhibited by a spinning body in a fluid flow incident upon it. The cylinder employs a motor to rotate around its axis, and when the wind current attacks the rotating cylinder, it dampens the air on one direction and accelerates it in the opposite one. This causes a high and a low-pressure zone respectively on each side of the cylinder, generating a lift force in the perpendicular direction of the wind flow, alongside a smaller drag force on the parallel direction. The produced thrust can be calculated as the summation of the lift and drag forces in the ship direction (Seddiek and Ammar, 2021)

These systems require a few accommodations in their candidate ships, namely sufficient clear deck space with no immediately adjacent structures like cranes, along with suitably strong mounting points. This makes some types of vessels like Ro-Pax and containerships unsuited for this type of device, while being ideal for others like tankers and dry bulk carriers. (Pearson, 2014)

In the analysis examined, despite having their output determined by both the ship and the wind's direction and speed, the Flettener rotors also contributed to considerable energy savings, more than 20% of the annual ship fuel consumption in the bulk-carrier analysed, which was operating between Daminetta (Egypt) and Dunkirk (France). In that same case study, the selected four rotors would be able to support the ship's economy in only 6 working years, on top of achieving a considerable levelized cost of energy. (Seddiek and Ammar, 2021)

Despite these developments, however, what's perhaps the most well known alternate energy source is probably solar power, from which there also have been several studies. One of these studies exemplifies this contribution by the adaptation of the power system of a Ro-Ro ship. For the layout of solar arrays of the chosen vessel, there was an increase of nearly 8% of the total efficiency and 7,4% reduced fuel requirements. The investment of the panels has also been analysed and found to be profitable (KARATUĞ & DURMUŞOĞLU, 2020). An additional usage of solar panels is in the covering of refrigerated areas, both in ports and in ships not only because the obtained electricity can be used for electrical equipment, but because the shadowing of such areas reduces need for cooling systems. (Iris and Lam, 2019)

One last particularly noteworthy and effective solution besides solar and wind power is the usage of hydrogen fuel cells, which are already present in some hybrid systems. Hydrogen is becoming increasingly common as an energy storage mechanism and can be created using green energy sources for minimal carbon emission. On a large ship, a modest addition of a 3 MW fuel cell with 770 m^3 of compressed hydrogen can deliver 10.6 GWh of energy per year and reduce annual CO2 emissions by over 2300 tons (Mckinlay et al., 2021)

4. Energy efficiency in the operational stage

While the specific results of each measure require further research, the development and usage of the methods discussed until now seems promising within the sector.

But while all the methods previously described can contribute to a very significant energy saving and achieve considerable reductions in greenhouse gas emissions and fuel costs, their main drawback is that they can only be applied on the early conceptual stages of ship construction and design. Already existing ships can require an extensive overhaul to employ them, a process that can impose a significant cost.

However, during the operational phase, older ships can reduce their emissions with relatively easy means like fuel change and voyage optimization, even though there is a limit on how much impact those measures can have while being safe or financially realistic. These operational measures can be applied to any type of ship without any extensive overhaul or a change in their design, and the studies regarding that front predate even the creation of the EEDI. (Kajanen, 2011) (Table 9).

Each of the methods described will be expanded below:

4.1. Slow steaming

Ship operational performance depends on a huge number of aspects, including varying drafts, speeds, encounter angles, sea states, fouling effect and engine degradation conditions of the ship. Despite this, some reliable models already exist to evaluate various courses according to several objectives like maximizing safety and minimizing fuel consumption and voyage time. (Lu, 2015)

One of the most common ways to minimize power consumption is with the technique of slow steaming. This is already a popular practice in container ships, which can save between 16 and 19% of fuel with only a 5% reduction in speed. While this study also encompasses other methods of energy efficiency, a notable observation made is that the same reduction in speed can provide fuel savings of around 13% in ships like bulk-carriers and tankers and is applicable to other types as well. (Hochkirch and Bertram, 2010)

Additional fuel savings could be achieved by reducing electrical demand of auxiliary equipment, 70% of which can be caused by pumping. One study determined that there was great potential to improve energy efficiency when variable pumps were used, achieving 60% of electrical power demand reduction from the main engine cooling system. This study resulted in a reduction of 296.2 tons of fuel consumption for containership of 4200 TEU employed as a base model, which also meant 207,300-dollar savings and 924 tons of CO_2 discharge avoidance for the same ship. (Dere and Deniz, 2019)

While incredibly valuable on its own right, the practice of slow steaming has the drawbacks of making the ship less stable and increasing the time the ship spends at sea. This increases the importance of selecting the optimum route for the ship operators, which by itself is already a very valuable practice for increasing the energy efficiency and reduce Greenhouse gas emissions.

4.2. Route optimization

One key factor in operational energy efficiency is the influence of environmental factors such as wind speed and direction, water speed and depth. The evidence seems to point to the wave height and wind speed as the main detrimental factors to the energy efficiency, which distort the numerical model of the EEOI compared to the experimental data. Time-variety and uncertainty associated with these factors can make determining optimal sailing speeds difficult by static methods, even with empirical data of the sea states. (Tran, 2019)

However, some possible dynamic approaches have already been proposed, determining the optimal sailing speeds under specific real-

Table 9
Operational measures.

Type of modification employed	Description of the method	Type of ship examined	Impact	Source
Slow steaming	Reduction of travel speed.	Bulk carriers, tankers, and containerships	For a speed reduction of 5%, bulk-carriers and tankers have fuel savings of 13% and containerships of 16–19%	(Hochkirch and Bertram, 2010)
	Auxiliary system compliance to slow steaming.	Containership	The coordination of the auxiliary systems reduces the CO_2 emissions by 948 t/year and fuel consumption by 296.2 tons per year.	(Dere and Deniz, 2019)
Route optimization	Optimal speed under varying sea conditions.	Inland Cruise ship but is specifically noted to work on different ships.	Both fuel consumption and emissions can be reduced by about 28% in ideal cases, saving around 2961 kg/trip.	(Wang, 2018)
Trim optimization	Optimal trim configuration.	Bulk carriers	The highest reduction in resistance was almost 14%, depending on the draft and the speed.	(Moustafa et al., 2015)

time updated environmental factors, which allows to save fuel oil while ensuring the engine performance.(Lu et al., 2013) This is also a valid option for all kinds of ships, since its basis is speed optimization, and it could be applied to entire fleets. The study has shown that both fuel consumption and GHG emissions can be reduced by around 28% in ideal cases, saving up to 2961 kg of fuel per voyage. For now, the proposed method can improve ship energy efficiency more effectively than the static optimization method by about 2% (Wang, 2018)

4.3. *Trim optimization*

While there are several ways to reduce the ship resistance against the vessel's motion, one of the simplest ways to do it is with the selection of the appropriate vessel trim with respect of the average draft conditions. This method functions in conjunction with slow streaming and route selection since it depends on the results of both, but its impact is considerable and has been categorized as the Optimal Trim Configuration (Perera et al., 2015)

The most efficient trim varies depending on several factors like the loading conditions and the speed of the ship, along with other aspects like speed and wind direction, the draft, and the power of the main engine. Despite these drawbacks, in the studied cases the highest reductions could reach almost 14%, which means that existing ships can get a huge gain for a minimal cost (Moustafa et al., 2015). This is especially true if optimum trim can be achieved by shifting weights while avoiding taking ballast water, since increased displacement can cause higher resistance and thus higher fuel consumption (Sherbaz and Duan, 2014)

5. Energy efficiency on the maritime sector

All the methods examined until this point are significant and can go a long way to make ships more efficient, but they might not be enough to fulfil the GHG strategic aims of the IMO. If the main objective is to create a significant impact on the entire sector, some modifications might be needed that encompass the whole naval industry, and whose amendments have a greater scope that one vessel at the time or even an entire fleet.

Some steps have already been taken with this approach in mind, and one of the first proposed changes has been the modification of the current norms for energy efficiency.

5.1. *Modifications of the current standards*

While the current normative provides a temporary solution to the problem of energy efficiency, there exist several potential improvements that require further investigation. As was previously stated in section 1, despite its great utility, the measurement of the Energy efficiency Design Index has some deficiencies that keep it from being as useful as it could be for measuring energy efficiency rather than the rate of CO_2 emissions, and it's also more specialized for cargo vessels. This has been what drove many studies about polishing the regulations to be more compatible with other types of ships.

Some of the earliest studies even predate even the enforcement of the EEDI, and one of them evaluated possible consequences of its usage and change of phase in the ships. While it concluded that improving the EEDI in a vessel also improves its energy efficiency, it also pointed out some of the flaws in the system, like the fact that it allows higher EEDI for smaller vessels, that further phases require a reduction in speed, and that it doesn't allow for sister vessels. (Hasan, 2011)

The process of verification has also come under scrutiny, since it's performed at the vessel's design speed and design loads, and under calm-water conditions. This is even though calm seas are an exception in shipping, and that ships usually operate at lower speeds that their design ones, resulting in reduction of GHG emissions lower than their reduction in EEDI scores. (Lindstad and Bø, 2018)

Furthermore, there are some vessels for which the EEDI is simply not appropriate, of which the Ro-Ro and passenger ships are the most prominent, and there have been some attempts at making changes in the way they are evaluated, even by the IMO itself, which proposed a correction in 2014. On the other hand, a study proposed alternative ship correction factors for those ships in the EEDI equation. For both ships under study, a linear approach led to a higher (even marginally) correlation coefficient when calculating the required EEDI reference compared to the one adopted by the IMO (Ančić et al., 2015)

Additionally, there has also been a new approach to the very definition of EEDI for ro-ro and passenger ships, rather than only the correction factor. The document introduces the concept of "Reference surface" as a function of the ship's capacity and speed instead of the Reference line. It also expands the EEDI calculation to different loads to provide a better comparison between ships. (Alisafaki and Papanikolaou, 2017)

Another area that the current normative is poorly suited to evaluate are the shallow water areas since the values of the ships that operate in that environment are difficult to control. (Xiao, 2015) Despite accounting for a small portion of the total global CO_2 emissions from shipping, inland transport is very important for individual countries, both economically and environmentally, but whose lack of energy and emissions benchmarks present a big impediment to their performance. (Simić, 2014) Because of all of this, there have been studies focusing on the possibility of reducing CO_2 emissions by implementing a revised EEDI formulation adapted to Inland Waterway transport, since the EEDI is designed around sea-going ships. (Hasan, 2020) Some studies have proposed concepts like the EEDI*, which use the service speed of the ship and the engine power to evaluate their efficiency. (Simić, 2014), or the $EEDI_{INLAND}$, which has proven to be an effective tool for the analysis of the efficiency of the inland oil tankers examined and for the evaluation of energetic improvements in them. (Hasan, 2020)

More on that note, there have also been attempts to rectify other problems whenever it was possible, and some of the more recent studies even attempted to find a different, more exhaustive definition of the EEDI in general with the aim to encourage innovative technologies. The proposed EEDI calculation was modified to include multiple operation points, in addition to propose ranking ships based on various energy performance categories rather than a pass/fail criterion (Ančić et al., 2018a) This last point is remarkably similar to the recently adopted Carbon Intensity Indicator and it's method of classifying ships depending on their emission ratios.

As a final observation of the normative, it has been determined that in its current form, the implementation of the EEDI alone cannot reduce the CO_2 emissions from ships below the required environmental levels regardless of the policy. But it can be expected that an adjusted policy in conjunction with the corresponding measures will reduce the total CO_2 emission from ships below levels required to maintain sustainable seaborne transport and to stabilize the CO_2 concentration in the atmosphere. (Ančić and Šestan, 2015)

5.2. *Life cycle assessment as a supporting measurement*

While the changes in the EEDI could prove highly beneficial for all the ships in the sector, there is also some precedent for supplying basic indicators like the EEDI or the EEOI with more application-specific metrics. This allows the vessel owner and/or operator to focus on areas of performance that are of particular interest for them. (Ballou, 2013) This usage of supplementary metrics to support current regulatory measures is a very notable approach, as there are limits to the use of one single metric to serve as a measure of overall efficiency for other situations like evaluating an entire fleet with different ship types.

This is where the Life Cycle Assessment or LCA can be most helpful, as a standardised performance method for the entire life of a vessel, aiding in the application of the EEDI and the EEOI.

The LCA is a methodology that helps identify environmental opportunities within the different phases of the life cycle of a product or system, which in turn provides prospects for the design and re-design of those products and systems. One advantage of the LCA is that it encompasses additional substances in its carbon accounting besides CO_2, unlike the EEDI or the EEOI.

But its most important application in the sector is that, when applied to ships, the LCA offers data about energy utilisation trough different stages within the vessel's lifetime, like construction, maintenance, and scrapping. (Blanco-Davis and Zhou, 2016) This has already been demonstrated within a proposed risk-based conceptual ship design method for bulk carriers, which considers the life cycle assessment in addition to the energy efficiency of the ship and its propulsion. An optimal design solution was obtained, based on the EEDI, shipbuilding, operation, and resale costs at the end of the service life, which were used as input variables in a risk-based analysis. Several possible solutions for increased efficiency were also considered, ranging from hull lines optimization to speed reduction. (Garbatov and Georgiev, 2021)

These studies conclude that the potential of the LCA as a complementary tool should not be neglected, to both newbuilds and existing vessels, due to its reliability and accessibility of information.

5.3. Big data and information technologies in the maritime industry

Besides the modification of the normative, enhancing the internal organization of the industry is a monumental endeavour, and requires effort from the part of several levels of organization to be effective. Ship construction is not like many other industries, because unlike consumer products where the components are mostly homogenous and manufactured in large quantity, ships are considered engineering structures that are highly customised and constructed in low quantities.

Industry 4.0 is a proposed method to revolutionise ship design, manufacturing, and operations in a smart product through-life process that brings energy efficiency to the forefront. Despite being more dedicated to the mass production of consumer products, several of its most prominent technologies like intelligent robots and automated simulations have notorious potential applications in the ship industry. (Ang, 2017)

The usage of even only one of those technologies can go a long way in improving the efficiency of the whole stage and its capacity to function in an integral manner, and the Big Data Analytics are a notable example of this.

Big data is characterized by its large scale, fast evolution, and high diversity, making it hard to analyse using traditional methods. (Yan, 2018) This is a huge problem faced by the ship's operational measures because effective navigation strategies are based on accurate ship performance and navigation information. (Perera and Mo, 2016)

Big data analytics can extract a significant amount of hidden information and knowledge by analysing sizable datasets in various types, and thus assisting in the decision making, which is crucial to determine the optimal speeds under different and variable environmental conditions, among other activities regarding optimal ship enterprise.

The data concerning ship energy efficiency optimization can be divided into two categories. On the one hand, there is the operational data, including sailing speed, position, and fuel consumption. On the other hand, there is environmental data like wind speed and water depth. The process of analysis would commence by collecting the required data with onboard sensors.

Upon completing the collection of data, the next step is data processing, which includes replacing low quality data points for linearly interpolated values. The procedure also includes route division and the determination of the optimal engine speed for each type of navigational environment. This process can be applied to all kinds of ships and environments, including inland waterways, and can effectively reduce ship energy consumption and CO_2 emissions. (Yan, 2018)

Other possible data flow chart can be divided in two main sections. One of them would be an onboard application that consists of sensor faults detection, data classification and data compression steps. The other one a shore-based application that consists of data expansion, integrity verification and data regression steps, allowing them to evaluate ship energy efficiency under various navigational and operational conditions. (Perera et al., 2015)

The best way to handle the data flow would depend on the type of ship and its conditions, but the intelligent decision supporting capabilities of the big data analysis could eventually become a part of the navigational strategy at a global level.

5.3.1. Integrated total approach to ship construction

The huge number of complex interactions that exist within the systems of a ship, even applying only to one of the stages of the lifecycle of a vessel, makes it very important not only to manage large amounts of data, but also to broaden the scope of the efficiency research as much as possible.

Taking for example the operating efficiency, focusing on improving it only in a few specific areas without considering the impact on other operating requirements can lead to underwhelming total results. In that example, applying low-friction hull paint may improve fuel efficiency at sea, but its lower durability or resistance to marine growth may require more frequent and higher cost maintenance.

Therefore, the management of ship efficiency should be an integrated total endeavour that extends across not only the ship, but preferably the entire fleet. There are several steps to help with this even without the usage of new technology, most notably setting realistic goals, using historical data to establish energetic baselines, and having a robust training program with support for all levels of management. (Ballou, 2013)

It should be noted that this effort applies not only to operational concerns, but also on the design of the ships. By 2011, there already was a case study in tankers trying to integrate not only the processes, but the design methods themselves with the use of specialized software. That optimization approach to ship design was developed considering several aspects of the early development like main dimensions and hull form, and with a database of variants it became easy to search for the preferred combination of measures. (Papanikolaou, 2011)

For said combination of measures to achieve maximum efficiency in design, all parts of the vessel must be coordinated effectively, which means it's crucial to find the best possible arrangement between ship systems from the very initial design stages. This requires large amounts of data but is the best way to achieve a good balance between ship speed, cargo area, low fuel consumption and low emissions. Some studies dedicated on this front have been made, one of them using two containerships, and the results seem to indicate that not all the engines examined who meet the speed criteria comply with the EEDI, even with the most optimal propeller for the delivered power, with the current hull form. (Constantin and Amoraritei, 2018)

A similar aim of finding the most optimal design choice led to the search of a ship design methodology using algorithms. The results of the experiment indicate a meaningful improvement on the EEDI, the port efficiency, and carrying capacity, along with the reduction of ballast water and design speed. (Koutroukis, 2013)

5.4. Integrated total approach to ship industry

Individual I.4 technologies like the Big data analytics can be applied on their own at each lifecycle stage to reduce power consumption and improve energy efficiency, but just like what happened in the above example with the broaden scope of the efficiency of a ship, the maximum benefit can only be achieved by coupling various I.4 technologies across the entire ship lifecycle.(Ang, 2017)

There have already been some studies that focus on a potential framework that helps to integrate various I.4. technologies and addresses key concerns on each step of the lifetime of a vessel. The main challenges on each step are the following:

- **Ship Design**: Ship performance data is not made accessible to the shipyard after the vessel is constructed and delivered to the ship owner or operator, making it difficult for a shipyard or ship design firm to monitor performance to improve its future designs.
- **Ship Manufacturing**: The poor linkage to the ship design process means that digital data, like drawings, cannot be fed directly into workshop machines and require certain pre-processing to be performed manually before they can be executed.
- **Ship Operations**: Among others, cyber security, and the difficulty of integrating different ship systems and equipment into a single operating platform.

A possible way to solve these issues is with a two-way closed loop of information between smart design, smart manufacturing, and smart operations, with all these systems giving feedback to each other to improve the efficiency of the whole process, as noted in the article "*Energy-Efficient Through-Life Smart Design, Manufacturing and Operation of Ships in an Industry 4.0 Environment*" (Ang, 2017). The proposed framework operates as follows:

- The **Smart Design** receives ship operational data and can use it to improve energy efficiency of future ships and forecast costumer needs and environmental regulations, considering them on future projects. The connection to the manufacturing process allows to take any production clashes into account to improve the designs.
- The **Smart Manufacturing** can receive the design output as a virtual prototype, allowing for the machines to share information about stock levels, problems or faults, and changes in orders or demand levels to increase efficiency on the supply chain. The information received from the operational process allows any defects found after the delivery of the vessel to be monitored and fed back to the shipyard to improve the manufacturing process.
- The **Smart Operation** receives the results of the rest of the framework, using the information provided to the design and manufacturing phases to acquire better repairs, and upgrades, ending with a final product with a more efficient design that can be manufactured in an intelligent and integrated way.

While the obstacles that face the maritime sector in the search of more energy efficiency are substantial and a lot more research is needed on the subject, Industry 4.0 and its interconnectivity are noted to be among the most important innovations for the future of the entire maritime transportation sector.

6. Barriers to energy efficiency

Despite the existence of all these seemingly cost-efficient technical and operational measures, shipping companies appear reluctant to adopt them, in a phenomenon called "energy efficiency gap" that is present in several industries. (Johnson, 2013) The definition of "barrier" to energy efficiency is any postulated mechanism that inhibits investment in technologies that are efficient both energetically and economically. They generally differ based on both industry and region. (Rehmatulla and Smith, 2015) This energy efficiency gap they generate is well known in several industries, and there are already some policy instruments designed with the intention of minimizing it on the maritime industry, most notably the Ship Energy Efficiency Management Plan (SEEMP) from the IMO, with varying degrees of success. (Johnson, 2013)

In most cases, the disparity between the usage of the measure and their potential appears to be a case of conflicting interests. For example, in chartering market, the main beneficiary of the operational savings associated with low-carbon technologies (The charterer, the party that hires the vessel) is often not the one that has invested in such technologies (The owner, the party that owns the vessel). (Dirzka and Acciaro, 2021). Therefore, even if the total cost can be diminished by adopting a specific measure, in a lot of cases the one responsible for funding said measure might not benefit from it. This is also one of the reasons that operational measures like slow steaming are the most frequently implemented (Rehmatulla and Smith, 2015).

Beyond the fragmentation of responsibilities regarding the usage of energy, there are other obstacles to the development of the energy efficiency in shipping. Some of the key areas for the existence of the energy gap are the following:

First, the current organizational structures, which inhibit learning and innovation. (Johnson and Andersson, 2016) Energy management is not an immediate fit but may require new organizational forms and new infrastructure to accommodate performance monitoring. Though what is the most optimal technical and organizational solution may vary. (Johnson, 2013) In the previous example of the chartering market, the shipowner might be able to recoup the investment in energy efficiency through higher charter rates for the savings in energy made by the charterer. (Rehmatulla and Smith, 2015)

On that front, collaborative and transdisciplinary research projects can help both companies and researchers if a mutual interest is found. Communication and competence are necessary, in-house or from a third party, as is the commitment of management to providing resources to propel efforts forward. (Johnson, 2013)

On the other hand, there is the uncertainty and asymmetries in the information regarding the measures and their day-to-day performance. (Johnson and Andersson, 2016) Lack of trusted performance data in contractual relationships may inhibit increased efficiency in the longer term due to adverse selection and moral hazard problems. (Johnson, 2013)

All of these require further research to understand the role of energy use and efficiency internally in a shipping organization. Two ways in which to accomplish this has been suggested:

- Understanding further how knowledge and competence on energy issues can be enhanced internally in shipping organizations.
- Investigating further the role and use of monitoring of energy.

Both measures require more research to be done in the field, not only in the energy efficiency of individual ships, but on an industrial level, to bridge the energy efficiency gap in shipping. (Johnson and Andersson, 2016)

7. Conclusions

The field of energy efficiency in ships is currently in development and without generalized solutions, with different obligations for each type of ships and most of the normative being focused on the reduction of emissions. While that approach is reasonable given the current environmental concerns, that has also led to some complications. For example, EEDI has created a situation in which the ships put more emphasis in minimizing their index levels rather than reducing fuel and energy consumption.

This isn't necessarily a bad thing for an efficiency point of view, since in most cases increasing the efficiency of a ship is a complicated process that needs to be carefully planned to be cost effective, which requires time. However, the reduction of the EEDI is only a temporary solution until more permanent measures are taken, and the system of the EEDI itself presents some blind spots like the lack of regard for inland ships and the flawed evaluation of Ro-Ro and passenger ships that reduce its effectiveness even at its intended purpose of reducing emissions.

This article has shown several prominent ways in which a higher energy efficiency can be achieved, both by improvements on the entire industry as well as form a direct modification in the handling of the ships, either by a design or an operational perspective. In both cases there has been a significant effort to both update and improve existing measures, and to find and implement new innovative ones. All these measures require further research, but they bring the maritime industry closer to an ecologically friendly sector.

Future highlights for energy efficiency measures could include the increased usage of digitalization systems to optimize the route taken by the ships, a higher connectivity and feedback between the different steps of the ship life cycle to make the entire process more efficient, as well as an increased coordination between different methods for increasing energy efficiency to create an optimal combination for the ship.

It should be note that, while there are several complications on the industry that impede the full improvement and application of even the most cost-effective of these measures, there is also a continuous effort in the development of adequate solutions to those problems, ranging from the increased reliability of the practical measures of the ships, to changes in the way the industry itself is organized and coordinated.

All of this endeavour contributes to minimizing the energy efficiency gap, reducing the rift between the present-day, and a not only more competitive but also ecologically green future.

CRedit author statement

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