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From Today to 2050: Challenges and Opportunities for the Maritime Industry

State of the art and considerations by the RINA Italian Decarbonization Committee with the participation of Assarmatori and Confitarma.

Introduction by the Chair

“I believe that decarbonization is the greatest industrial revolution of the modern era, especially for hard-to-abate sectors like Shipping. For a long time, shipowners have felt a deep sense of frustration at being labeled as polluters when many of their ships are modern and technologically advanced.

Ships have specific characteristics determined by their routes, types, and sizes, which require diversified solutions. This paper is the summary of work carried out by all stakeholders (classification societies, designers, engine makers and related parts manufacturers, equipment suppliers, fuel traders, and, of course, shipowners themselves and the associations representing them) to identify the technical solutions available today and analyze those that could become available in the future.

Clear international standards are the most significant accelerator upon which the industry can rely in the context of this challenge: only in this way is it possible to invest in the right direction. The uncertainty of international regulatory developments and the rush for local legislation, on the contrary, create stagnation.

The shipping industry is also certain that emission reduction has nothing to do with the competitive advantage of individuals because the benefit to the entire world is much greater than what any single enterprise could gain from it.

I hope that this work can be a useful description of the state of the art for policymakers and all stakeholders, helping them understand the challenges that lie ahead for the sector. The future cannot be built on often utopian statements from individual shipowners or stakeholders.

I want to thank the RINA Decarbonization Committee and RINA as a whole for the great work done, showing that together we sail with even greater safety”.

Salvatore d’Amico

Chair of RINA Italian Decarbonization Committee

Executive summary

International shipping represents less than 3% of global anthropogenic CO_2 emissions. Nevertheless, the reduction of carbon dioxide emissions, as well as greenhouse gases in general, by the maritime sector is a common goal at the international, European, and national levels. To cover the consumption of the maritime sector with green synthetic fuels (e-fuels), it would be necessary to use more than half of all the renewable energy currently produced in the world.

Each ship differs in type, installed power, type of navigation, and therefore, the optimal solution for its decarbonization should be considered based on the combination of these characteristics. It is evident that a single solution cannot be decisive for all ships and for their entire lifecycle, considering that emissions limits will become increasingly stringent over time.

Both the International Maritime Organization (IMO) and the European Union (EU) are developing their own strategies and measures to mitigate greenhouse gas (GHG) emissions and reduce the effects of global warming. These measures, which must be implemented independently and are based on two different approaches, generate management burdens and, more critically, market distortions. For these reasons, it is of absolute importance to reach an international agreement that surpasses local or regional requirements.

It is reiterated that, regarding international regulations, it is fundamental to have a uniform approach agreed upon at the IMO level. In addition, to avoid each Administration making unaligned decisions, introducing disparities in treatment for ships flying different Flags, it would be appropriate to apply uniformly the recommendations approved by the IMO in the form of recommended resolutions, unified interpretations, circulars, or guidelines.

At the latest MEPC 80, both preliminary guidelines regarding the Life Cycle Assessment (LCA) approach for marine fuels and guidelines for the immediate use of sustainable biofuels on board (pending the final application of the LCA Guidelines) were approved. These are steps in the right direction, one for assessing the real environmental impact of fuels and the other for enabling the immediate use of biofuels as drop-in solutions for existing fleets.

In addition to having a clear and transparent regulatory framework, it is also necessary to develop options applicable to the existing fleet, such as the use of drop-in solutions. Biofuels, for example, can be blended with conventional fuels or used in pure form, allowing for substantial reductions in CO_2 equivalent emissions. For this path to be viable, two fundamental factors must not be forgotten: the availability of the fuel and the sustainability of its cost.

Carbon capture, which prevents its release into the atmosphere (Carbon Capture and Storage - CCS), is currently the only technology capable of making fossil fuels compatible with short-term emission reduction goals. It could be one of the transitional solutions for the maritime industry in the coming years for specific types of vessels. Although the technology is mature on land, investments are needed to support the initial research and development phase for onboard application, as well as the necessary logistics chain for the ultimate carbon sequestration.

The use of liquefied natural gas (LNG), which allows for a reduction of around 20% in CO_2 compared to traditional fuels, despite its fossil origin, confirms itself as a transitional fuel. New ships that choose this alternative fuel, depending on their type and operational profile, will be able to employ reforming technologies combined with carbon capture and onboard hydrogen production (for use in combination with LNG) before transitioning to complete conversion to fuels such as methanol, ammonia, and hydrogen. In this case as well, research and development for onboard application of new fuels should be supported both financially and by a clear regulatory framework, as well as adequate infrastructure to support the production and distribution of various fuels.

The use of nuclear energy onboard holds promises and is worthy of further exploration, although the technology, especially related to new generation reactors and particularly small modular reactors (SMRs), is still in the study and experimentation phase, with public acceptance being one of the most critical aspects.

Many ships spend part of the time required for their commercial operations in urban ports, such as those operating regular liner services. To reduce, if not eliminate, local pollutant emissions such as SO_x, PM (smog), and NO_x, it is effective to power the ship, while in port, with shore power ("cold ironing" or "onshore power supply - OPS"). Additional benefits of this solution include the reduction of CO_2 emissions if the land-based energy is entirely or partially generated from renewable sources, as well as the reduction of noise pollution resulting from the shutdown of onboard power generators. Many ships are already equipped to be powered from shore, and it is essential to invest in port logistics as well.

The decarbonization process of fleets necessarily follows two tracks:

- that of new ships (including major transformations involving the replacement of one or more main engines), which can fully benefit from the new technologies and alternative fuels gradually made available by the industry.

that of the existing fleet, which, unable to use fuels with significantly different characteristics from current fuels, will need to reduce the quantity of emissions from fossil fuels by adopting suitable operational procedures, accepting an impact on service, consumption reduction techniques, and, where possible, the use of increasing proportions of compatible fuels such as biofuels.

The overall result depends on the combination of these elements, and especially in terms of time, on the rate of new ship/new fleet replacements that can be achieved.

The decarbonization process of the maritime sector depends almost entirely on land-based production and distribution infrastructure, over which shipping companies can stimulate but which largely depends on factors/circumstances that are beyond the control of shipowners.

In addition to the inherent logic of production and the market, in which the maritime sector is often less influential/decisive than other sectors (consider heavy road transport or aviation), land-based production and distribution infrastructure are strongly influenced by existing regulatory/authorization systems. These must be, as repeatedly emphasized in this document, clear and consistent, especially at the international level.

Lastly, we should not underestimate the difficulties associated with the "social acceptance" of certain solutions, such as the construction of new coastal storage facilities for gas, methanol, or ammonia, not to mention the "social acceptance" of solutions based on new "nuclear technologies."

The issue of costs directly and indirectly connected to the decarbonization process of the maritime industry is one of the central challenges of a journey that is not in question and that the maritime sector has already started to undertake decisively. This issue of costs includes elements (one of them being that decarbonization cannot be achieved at zero cost) that must be clear to everyone, especially those who are called upon to make policy and financial support decisions. The costs resulting from the ongoing process will burden everyone, either in terms of higher transport service costs or in terms of public resources that governments will need to allocate to accelerate, if not solely to support, the energy transition. It is important to emphasize that direct costs, understood as the costs that have a more immediate impact on the budgets of shipping companies, such as CAPEX and OPEX required to advance the decarbonization process, are very high.

Investments in fleet renewal and the high costs of new fuels must lead legislators to consider the following:

- Invest in the maritime sector most of the incomes from the application of the ETS to the maritime sector and from the Fuel EU Maritime.
- Incentivize those who invest in new ships/technologies.
- Reduce the price differential between existing fuels and future alternative fuels, up to covering it.

Regarding the second point, it is essential that any financing instruments put in place be consistent with the technologies available, in line with the time required to complete the respective projects and aware of the global shipbuilding production structure. It must be avoided that economic resources are made available that cannot then be spent, not because of shipowners' bad intentions, but because they are linked to the achievement of unrealistic technological goals or because they need to be realized within timeframes that are incompatible with project complexity or shipbuilding production capacity.

This document, prepared in collaboration with members of the RINA Italian Decarbonization Committee and with the participation of Assarmatori and Confitarma, aims to describe the many solutions on the table, analysing their potential and critical aspects, in order to promote ambitious choices in the short term that will enable the shipping industry to easily achieve the goal of net-zero emissions by 2050."

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1 Emissions related to maritime transport

1.1 Shipping vs. Other Sectors

International maritime transport accounts for less than 3% of global anthropogenic CO_2 emissions.[1].

Year	Total CO_2 Emissions from Anthropogenic Activities	Total Shipping CO_2 emissions	Shipping Emissions as a % of Global Emissions
2012	34,793	962	2.76%
2013	34,959	957	2.74%
2014	35,225	964	2.74%
2015	35,239	991	2.81%
2016	35,380	1,026	2.90%
2017	35,810	1,064	2.97%
2018	36,573	1,056	2.89%

Figure 1-1 Absolute CO_2 Emissions (Million Tons) with data from the "Fourth IMO GHG Study 2020"

The fourth IMO study on greenhouse gases (2020 IMO GHG Study) highlighted the following aspects:

- Greenhouse gas (GHG) emissions, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), expressed in CO2e, from total maritime transport (international, domestic, and fishing) increased from 977 million tons in 2012 to 1,076 million tons in 2018 (+9.6%). In 2012, CO_2 emissions were calculated at 962 million tons, while in 2018, this value increased by 9.3% to 1,056 million tons of CO_2 emissions.
- The share of maritime transport emissions in global anthropogenic emissions increased from 2.76% in 2012 to 2.89% in 2018.
- Within a new allocation of international maritime transport based on the voyage, during the same period, CO_2 emissions also increased from 701 million tons in 2012 to 740 million tons in 2018 (a 5.6% increase). However, this growth rate was lower than that of total maritime transport emissions and represented an approximately constant share of global CO_2 emissions during this period (about 2%).

Despite the absolute increase in CO_2 emissions from 2012 to 2018, it should be noted that during this same period, the global fleet grew in terms of the number of vessels (+12.5%), cargo capacity in DWT (+25.3%), and gross tonnage (GT) (+25.5%)[2]. Therefore, if CO_2 emissions are considered relative to the number of vessels or cargo capacity in DWT or GT, they decreased, making maritime transport one of the most efficient sectors within the transportation industry.

In this context, it should be noted that international shipping transports more than 80%[3] of global cargo volume. As international shipping is a crucial link in the logistics chain, any action aimed at reducing emissions that could result in higher costs for the sector or reduced connectivity services should be carefully considered to

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[1] Data from "*Fourth IMO GHG Study 2020*". Data analysed in all Chapter 1 paragraphs are form that study except for part relevant to EU.

[2] Clarkson

[3] REVIEW OF MARITIME TRANSPORT 2022 UNCTAD

avoid issues related to inflation, distribution of essential goods such as food and medicines, especially in remote areas of the world, and possible repositioning of major ports in regions where regional regulations are more favourable than those of other regions that have more stringent and ambitious limits than those imposed internationally by the IMO.

Regarding CO_2 emissions in the European context, the transport sector contributes for the 29%, and maritime transport represents 4% of total emissions[4].

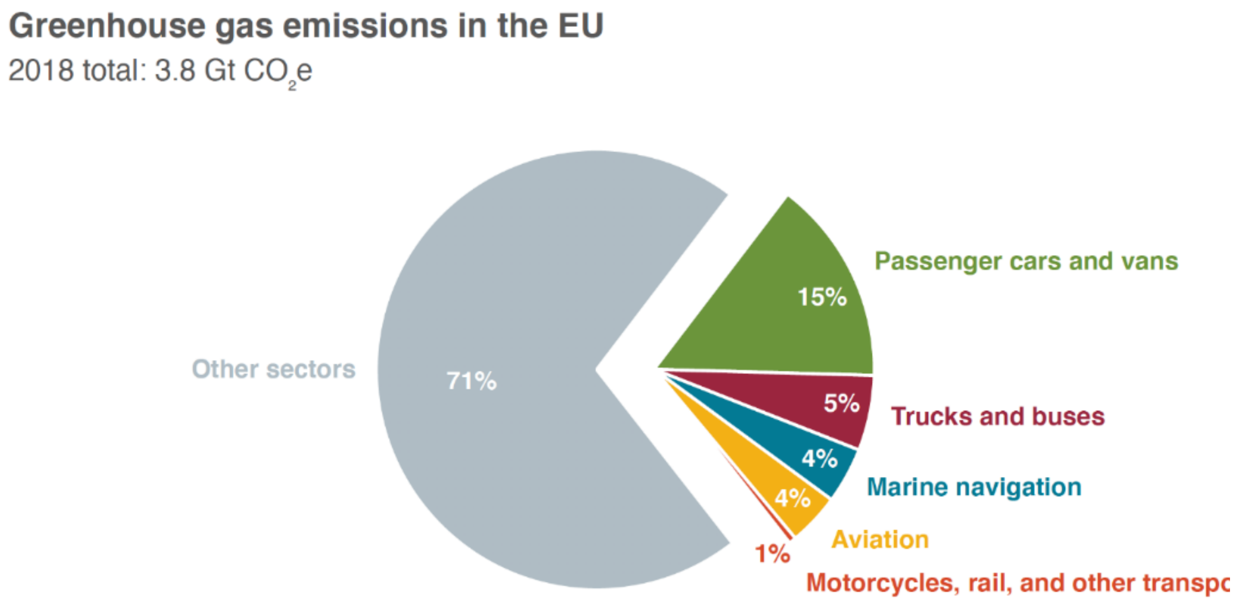

Figure 1-2: Percentage of CO_2 emissions in the European context attributed to the transport sector and shipping.

Regardless of the numbers mentioned above, the reduction of carbon dioxide and greenhouse gas emissions by the maritime sector is still a common goal at the international, European, and national levels.

Therefore, to prevent "carbon leakage" phenomena, it would be desirable for various regulations to be as aligned and consistent as possible.

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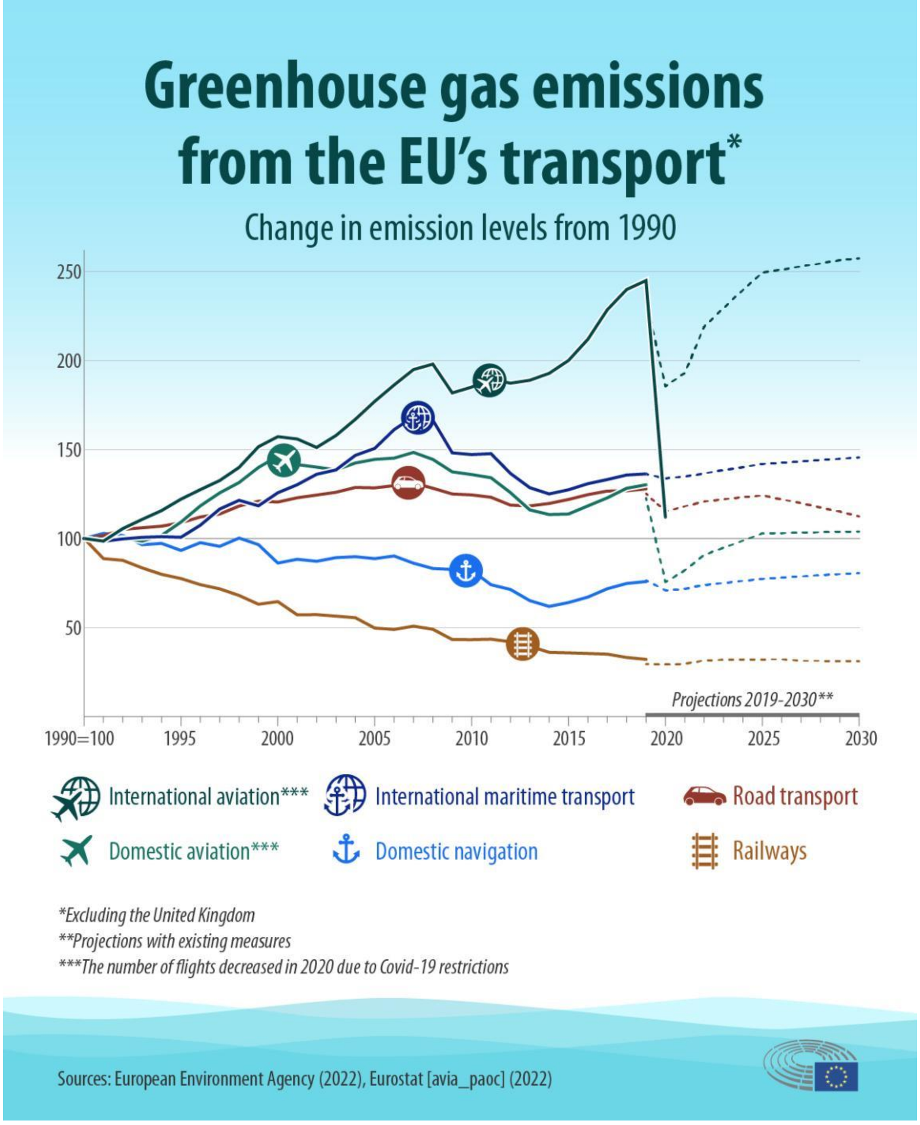
[4] Dati da studi International Council on Clean Transportation


Greenhouse gas emissions from the EU's transport*

Change in emission levels from 1990

*Excluding the United Kingdom
**Projections with existing measures
***The number of flights decreased in 2020 due to Covid-19 restrictions

Sources: European Environment Agency (2022), Eurostat [avia_paoc] (2022)

Figure 1-3: Emission Variation by Type of Transport [5]

It should be noted that even in the European context, 77% of European foreign trade and 35% of trade between EU Member States takes place by sea [6]. For this reason, maritime transport is a fundamental part of the international supply chain. When compared to other transportation sectors, and net of physiological declines due to the COVID-19 pandemic, both international and national shipping are among the sectors that have seen the most significant emission reductions in recent years, especially when compared to the aviation and automotive sectors, as previously highlighted.

1.2 Emissions by Different Ship Types

According to the latest IMO GHG study, even though the absolute emissions have increased in recent years (from 701 million tonnes in 2012 to 740 million tonnes in 2018), the carbon dioxide intensity per unit of transport

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[5] Variations in greenhouse gas emissions in EU transport from 1990 to 2019 (and projections from 2019 to 2030). European Environment Agency.

[6] European Maritime Transport Environmental Report 2021

(expressed in cargo capacity per nautical mile or cargo transported per nautical mile) has decreased for almost all types of ships[7].

The most significant reductions are related to bulk carriers, followed by tankers, container ships, and general cargo ships among the cargo ships considered in the study, as shown in the figure below.

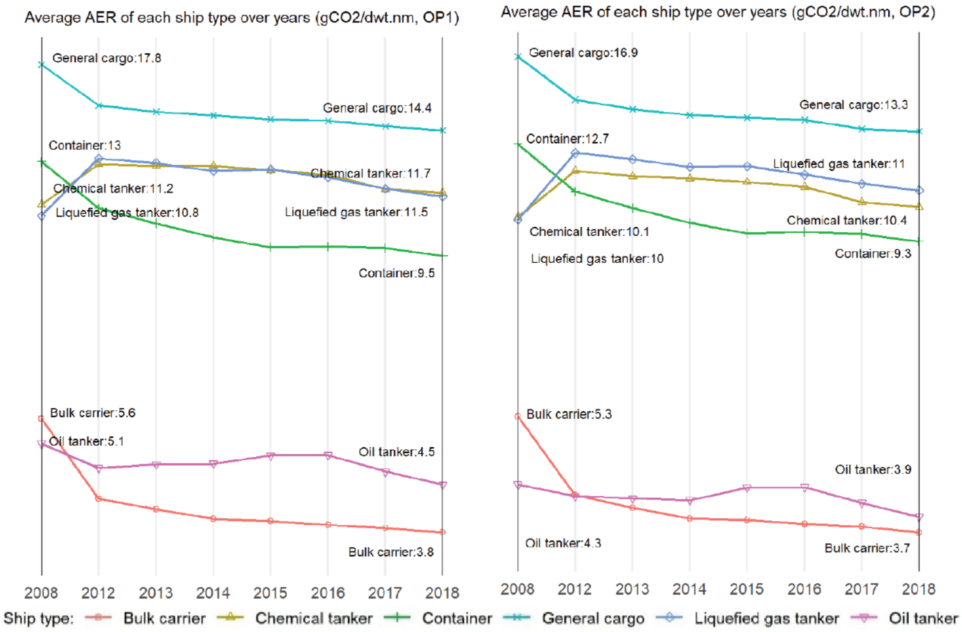

Figure 18 – *Carbon intensity levels of typical cargo ships over years (in AER; left panel: vessel-based; right panel: voyage-based)*

Figure 1-4: Carbon Intensity trends - Data from "Fourth IMO GHG Study 2020" "Fourth IMO GHG Study 2020"

The most significant reductions in terms of CO_2 per vessel from 2012 to 2018, sourced from the 4th IMO GHG Study, are related to the Ro-Ro (roll-on/roll-off) and Ro-Pax (roll-on/roll-off passenger) sectors, where CO_2 emissions per ship decreased by 34.2% for Ro-Ro and 34.6% for Ro-Pax. This is also considering newer ships with higher capacity, allowing for the transport of more cargo.

Type	No of vessels	No. of vessels	CO_2 Total	CO_2 Total	CO_2 per vessel	CO_2 per vessel	Change
Unit	#	#	*mil.t*	*mil.t*	*t*	*t*	*%*
Year	2012	2018	2012	2018	2012	2018	2012-2018
Ro-Ro	1.518	2.600	18,2	20,5	**11.989**	**7.885**	**-34,2%**
Ro-Pax	2.592	3.994	36,4	36,7	**14.043**	**9.189**	**-34,6%**

Figure 2 5: Emissions in the Ferry Sector 2012-2018 "Fourth IMO GHG Study 2020"

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[7] Table 2 - Estimates on carbon intensity of international shipping and percentage changes compared to 2008 values: "Fourth IMO GHG Study 2020".

It's also important to note that in the European context, as early as 2001, the European Commission introduced the concept of "Motorways of the Sea" to promote intermodal maritime transport as a more efficient and sustainable alternative to road transport. According to an analysis by the SRM research centre, in 2022, maritime intermodality reduced road traffic by approximately 2 million trucks, equivalent to about 53 million tonnes of goods, resulting in a reduction of 2.2 million tonnes of CO_2. The latest SRM study published in July 2023 estimates that this year, thanks to maritime intermodality, the Motorways of the Sea, mainly represented by the Ro-Ro and Ro-Pax sectors, will remove approximately 2.2 million trucks and heavy vehicles from the roads in Italy, transporting a total of 58 million tonnes of goods by sea, thus reducing CO_2 emissions by 2.4 million tonnes. Furthermore, for routes longer than 800 km, more than 2.6 million heavy vehicles will be eliminated from the roads, resulting in the transfer of 69 million tonnes of goods from the road network to maritime routes and a reduction in CO_2 emissions by 2.9 million tonnes.

It is also interesting to note the distribution of GHG emissions in various operational phases for each type of ship. Depending on the type of ship, there are differences in the share of emissions occurring during navigation compared to manoeuvring, anchoring, or mooring phases. Among the six most important ship types for emissions inventories, chemical tankers and oil tankers have, on average, the majority of their total emissions (more than 20%) associated with phases near or in the port or terminal. However, even though not shown in the graph, it is evident that cruise ships have also improved their performance in terms of CO_2 values since 2008, as shown in the data from the study. [8].

Container ships, cruise ships, and oil tankers have the smallest share of their total emissions associated with navigation due to the predominant time spent in slow navigation and/or port or nearby phases, while for gas carriers and vessels, the greater share of their emissions is associated with navigation.

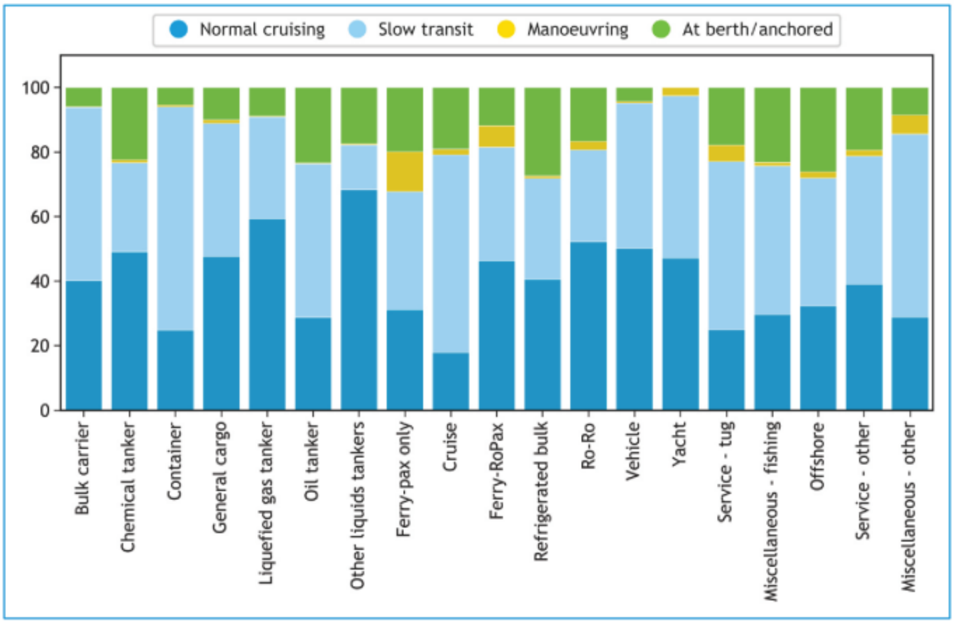

Figure 6 – *Proportion of international GHG emissions (in CO_2e) by operational phase in 2018, according to the voyage-based allocation of emissions. Operational phases are assigned based on the vessel's speed over ground, distance from coast/port and main engine load (see Table 16)*

Figure 1-5: Emissions Distribution by Ship Type and Operational Phase

Finally, it is also useful to analyse estimated fuel consumption based on different users, such as main propulsion engines, auxiliary engines for power generation, and boilers.

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[8] Tables 62 and 63 - Estimates on carbon intensity of international shipping and percentage changes compared to 2008 values: "Fourth IMO GHG Study 2020*"*.

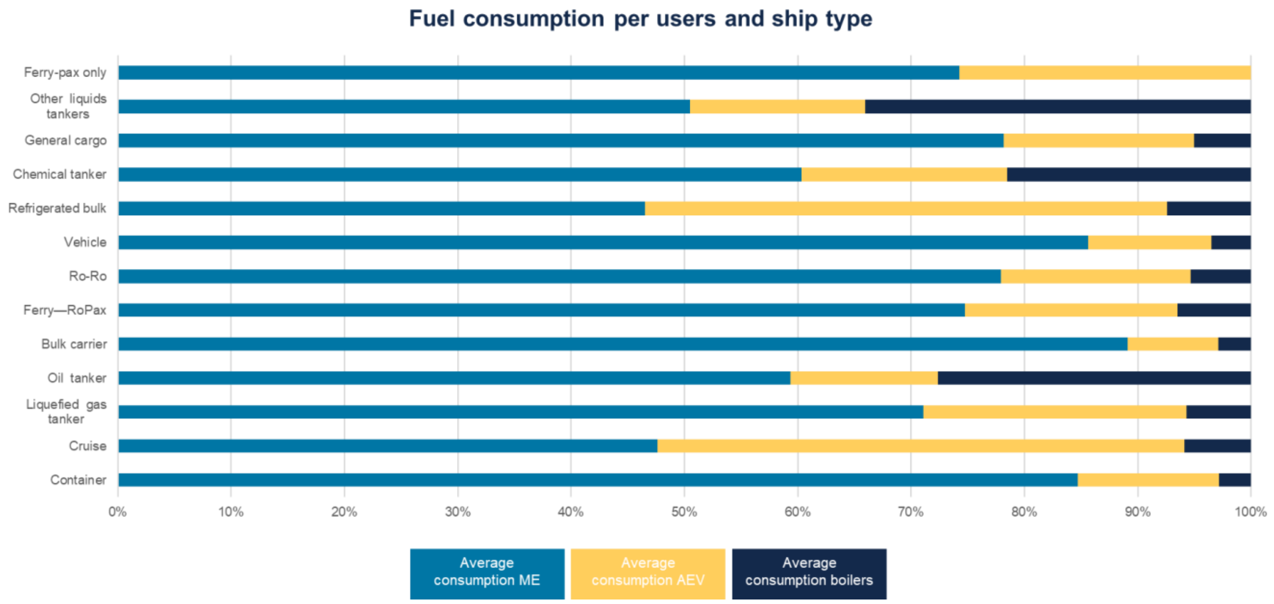

Figure 1-6:Consumption % by ship Type and User

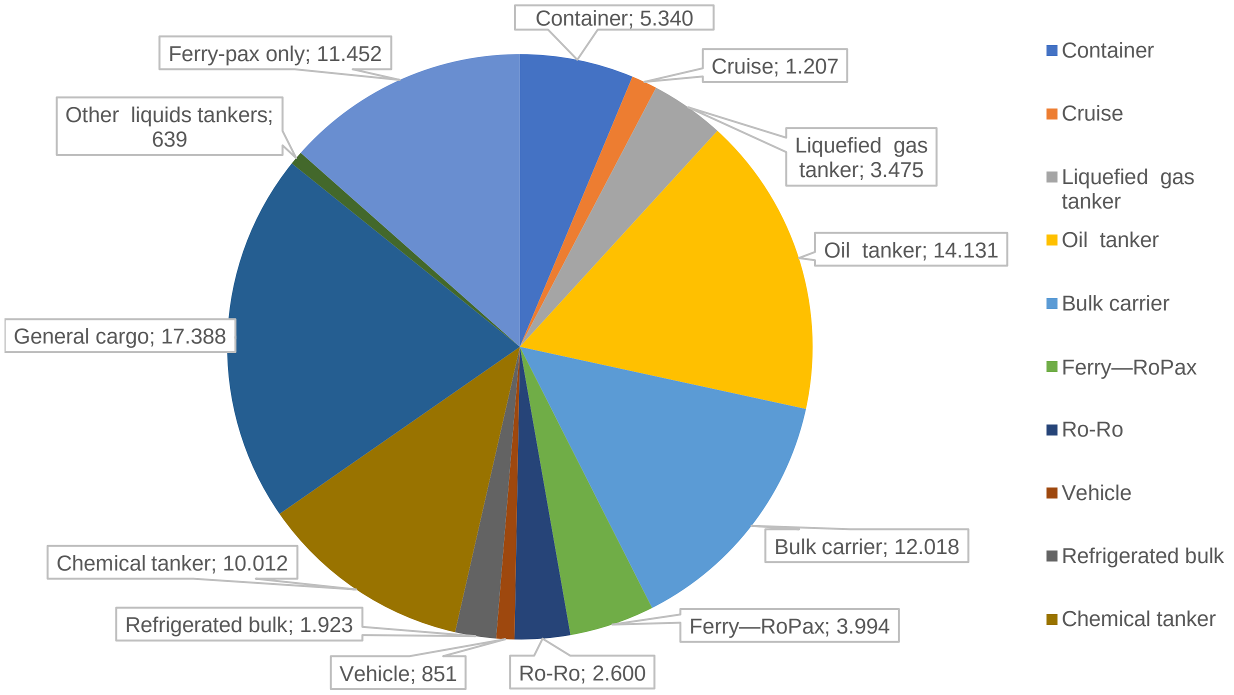

Figure 1-7: Number of Analysed Ships by Ship Type

The use of energy for propulsion remains the primary energy demand for all types of ships, although for some types of ships such as cruise ships and refrigerated bulk carriers, the total energy demand for propulsion is approximately equivalent to the total derived from auxiliaries and boilers.

1.3 Emissions by Installed Power

The fourth IMO greenhouse gas study also analyses emissions in relation to ship type and size, estimating the average installed power to provide a comprehensive picture of fleet emissions, both in terms of CO_2 and GHG (Greenhouse Gas) emissions, expressed in CO_2 equivalent.

The power of the main engines is estimated using a regression based on ship type, main dimensions, speed, and capacity. Specific fuel consumption and emission factors are based on the latest literature data.

The table below represents emissions and efficiency of ships for the year 2018. For the following years, the number of ships will evolve in line with the expected demand for transport work.

Tipo nave	Capacità		Unità	Numero di navi	Potenza MMPP media (kW)	Velocità di progetto media	Media giorni di navigazione	Consumo medio MMPP (kt)	Consumo medio ausiliari (kt)	Conusmo medio caldaie (kt)	Totale emissioni GHG (millioni t	Totale emissioni CO2 (millioni t)
Bulk carrier	0	9.999	dwt	1.446	1.796	11,8	178	1,0	0,3	0,1	3,8	3,7
	10.000	34.999	dwt	2.014	5.941	13,8	177	2,8	0,3	0,1	20,3	20,0
	35.000	59.999	dwt	3.391	8.177	14,3	184	3,7	0,4	0,2	46,4	45,7
	60.000	99.999	dwt	3.409	9.748	14,4	214	4,9	0,7	0,3	63,9	63,0
	100.000	199.999	dwt	1.242	16.741	14,5	252	9,2	0,7	0,2	39,6	39,0
	200.000	+	dwt	516	20.094	14,6	258	12,7	0,7	0,2	22,3	22,0
Chemical tanker	0	4.999	dwt	6.067	987	12,2	168	0,8	0,3	0,9	15,0	14,8
	5.000	9.999	dwt	862	3.109	12,9	185	1,6	0,8	0,7	8,2	8,1
	10.000	19.999	dwt	1.088	5.101	13,8	190	2,7	0,8	1,0	15,6	15,3
	20.000	39.999	dwt	706	8.107	14,7	202	4,5	1,2	1,3	15,6	15,3
	40.000	+	dwt	1.289	8.929	14,6	201	4,7	1,2	1,2	28,7	28,2
Container	0	999	teu	1.027	5.077	16,0	196	2,6	0,7	0,4	10,2	10,0
	1.000	1.999	teu	1.271	12.083	19,0	210	5,1	1,5	0,4	28,5	28,0
	2.000	2.999	teu	668	20.630	21,1	220	7,9	1,5	0,6	21,2	20,9
	3.000	4.999	teu	815	34.559	23,1	246	12,7	2,4	0,5	40,1	39,4
	5.000	7.999	teu	561	52.566	24,6	258	20,3	2,4	0,5	41,3	40,7
	8.000	11.999	teu	623	57.901	23,9	261	26,4	2,9	0,5	58,8	57,9
	12.000	14.499	teu	227	61.234	23,8	246	27,2	3,3	0,6	22,3	22,0
	14.500	19.999	teu	104	60.202	20,2	250	26,7	3,7	0,6	9,9	9,7
	20.000	+	teu	44	60.240	20,3	240	21,0	3,6	0,9	3,5	3,5
General cargo	0	4.999	dwt	13.296	1.454	11,1	170	0,6	0,1	0,0	19,2	18,9
	5.000	9.999	dwt	2.245	3.150	12,7	176	1,4	0,3	0,2	13,0	12,8
	10.000	19.999	dwt	1.054	5.280	14,0	192	2,8	0,8	0,2	12,9	12,7
	20.000	+	dwt	793	9.189	15,0	197	4,5	0,8	0,2	14,0	13,7
Liquefied gas tanker	0	49.999	cbm	2.685	2.236	14,2	190	2,4	0,4	1,1	16,1	15,8
	50.000	99.999	cbm	308	12.832	16,4	229	8,9	3,0	0,8	12,3	12,1
	100.000	199.999	cbm	436	30.996	19,0	271	22,2	4,4	1,0	41,3	37,5
	200.000	+	cbm	46	36.735	19,2	252	26,3	11,7	1,9	5,8	5,7
Oil tanker	0	4.999	dwt	9.692	966	11,4	135	0,5	0,4	0,7	23,5	23,2
	5.000	9.999	dwt	779	2.761	12,1	142	0,9	0,6	0,9	6,0	5,9
	10.000	19.999	dwt	235	4.417	12,9	136	1,4	0,9	1,4	2,8	2,8
	20.000	59.999	dwt	615	8.975	14,6	166	3,4	1,0	2,8	14,0	13,8
	60.000	79.999	dwt	429	11.837	14,8	194	5,2	1,0	2,8	12,2	12,1
	80.000	119.999	dwt	1.029	13.319	14,8	195	5,4	1,2	3,1	31,5	31,1
	120.000	199.999	dwt	597	17.446	15,1	220	8,0	1,8	3,5	25,1	24,7
	200.000	+	dwt	755	27.159	15,5	252	14,5	1,7	3,1	46,0	45,3
Other liquids tankers	0	3.999	dwt	533	687	9,6	98	0,1	0,6	2,1	1,5	15,0
	4.000	+	dwt	106	2.034	13,6	207	4,8	0,9	1,2	0,7	0,7

Tipo nave	Capacità		Unità	Numero di navi	Potenza MMPP media (kW)	Velocità di progetto media	Media giorni di navigazione	Consumo medio MMPP (kt)	Consumo medio ausiliari (kt)	Conusmo medio caldaie (kt)	Totale emissioni GHG (millioni t	Totale emissioni CO2 (millioni t)
Ferry-pax only	0	299	gt	10.680	1.152	19,3	162	0,4	0,3	0,0	8,6	8,4
	300	999	gt	666	3.182	26,2	161	0,7	0,3	0,0	2,1	2,1
	1.000	1.999	gt	51	2.623	14,5	135	0,6	0,3	0,0	0,1	0,1
	2.000	+	gt	55	6.539	16,2	199	3,5	0,9	0,0	0,8	0,8
Cruise	0	1.999	gt	812	911	12,7	93	0,1	0,4	2,2	1,7	1,7
	2.000	9.999	gt	110	3.232	13,8	148	0,5	0,8	1,8	1,1	1,1
	10.000	59.999	gt	105	49.378	49,0	206	5,0	6,4	1,4	4,3	4,2
	60.000	99.999	gt	98	54.548	24,8	256	16,1	20,3	1,0	11,6	11,4
	100.000	149.999	gt	61	67.456	24,3	250	24,4	20,0	1,0	8,8	8,6
	150.000	+	gt	21	73.442	22,0	236	23,2	19,8	1,2	2,9	2,9
Ferry—RoPax	0	1.999	gt	2.854	1.383	13,0	165	0,6	0,2	0,5	5,7	5,6
	2.000	4.999	gt	400	5.668	17,4	167	1,8	0,6	0,4	3,5	3,5
	5.000	9.999	gt	227	12.024	21,6	155	3,2	1,2	0,5	3,5	3,4
	10.000	19.999	gt	231	15.780	20,3	190	7,9	1,9	0,6	7,6	7,5
	20.000	+	gt	282	28.255	22,6	219	15,2	3,3	0,5	17,1	16,7
Refrigerated bulk	0	1.999	dwt	1.371	793	12,1	147	0,4	1,0	0,5	1,9	1,9
	2.000	5.999	dwt	213	3.223	14,7	149	1,2	2,1	0,5	2,6	2,5
	6.000	9.999	dwt	182	6.206	17,4	150	2,6	2,8	0,5	3,4	3,3
	10.000	+	dwt	157	11.505	20,2	218	7,1	5,3	0,3	6,3	6,2
Ro-Ro	0	4.999	dwt	2.174	1.618	11,2	129	0,7	0,9	0,5	6,8	6,7
	5.000	9.999	dwt	202	9.909	17,6	201	6,1	1,4	0,4	5,0	4,9
	10.000	14.999	dwt	135	15.939	19,6	218	10,0	1,9	0,5	5,3	5,2
	15.000	+	dwt	89	19.505	19,1	199	11,1	1,8	0,5	3,8	3,7
Vehicle	0	29.999	gt	175	7.264	17,3	213	4,6	0,9	0,4	3,2	3,1
	30.000	49.999	gt	189	11.831	19,4	254	7,1	1,0	0,3	5,0	4,9
	50.000	+	gt	487	14.588	19,9	281	10,4	0,9	0,2	17,8	17,5
Yacht	0	+	gt	10.121	1.116	16.7	78	0,4	0,0	0,0	4,9	4,9
Service - tug	0	+	gt	76.266	1.086	11,9	80	0,3	0,2	0,0	41,0	40,3
Fishing	0	+	gt	36.530	983	11,7	164	0,3	0,3	0,0	40,7	40,0
Offshore	0	+	gt	16.893	2.040	13,9	80	0,6	0,5	0,0	20,9	20,5
Service - other	0	+	gt	9.565	1.620	13,6	96	0,6	0,4	0,0	14,3	14,1
Miscellaneous	0	+	gt	249	15.301	18,2	102	2,1	0,4	0,2	1,3	1,3

Figure 1-8: Fourth IMO Study, Emissions by Ship Type and Size

2 Regulatory framework

Both the International Maritime Organization (IMO) and the European Union (EU) are developing their own strategies and measures to effectively mitigate greenhouse gas (GHG) emissions and reduce the effects of global warming. These measures can be independently applied.

The IMO Strategy on Reduction of GHG Emissions from Ships (2023 IMO GHG Strategy), recently adopted by the Marine Environment Protection Committee (MEPC 80), sets ambitious goals for the shipping industry:

- Reduce CO_2 emissions per transport work, on average in international shipping, by at least 40% by 2030 compared to 2008.
- Reduce GHG emissions by at least 20%, aiming for 30%, by 2030 compared to 2008.
- Reduce GHG emissions by at least 70%, aiming for 80%, by 2040 compared to 2008.
- Achieve zero GHG emissions impact around 2050, taking into account individual national contexts.
- Adopt zero or near-zero GHG emission technologies, fuels, or energy sources representing at least 5%, aiming for 10% of energy used in international shipping by 2030.

In parallel, on July 9, 2021, the European Commission (EC) adopted the European Climate Law, which sets two highly ambitious goals for the EU:

- Reduce GHG emissions by at least 55% compared to 1990 levels by 2030.
- Achieve climate neutrality, meaning a 90% reduction in greenhouse gas emissions from the transport sector by 2050.

To achieve their respective targets by 2030, both the IMO and the EU have proposed significant legislative measures that have already come into effect, such as the IMO's short-term measures, or will soon come into effect, such as the EU's new requirements.

2.1 IMO Regulations

Short-term measures to achieve the IMO's 2030 targets, as defined in the initial IMO GHG Strategy, introduce new requirements to Annex VI of MARPOL, significantly impacting both new and existing ships with regards to:

- The calculation and verification of the new Energy Efficiency Existing Ship Index (EEXI).
- Strengthening the Ship Energy Efficiency Management Plan (SEEMP).
- An energy efficiency assessment mechanism linked to the new Carbon Intensity Indicator (CII).

Bulk carriers, combination carriers, container ships, unconventional propulsion cruise ships, gas carriers, general cargo ships, refrigerated cargo ships, LNG gas carriers, Ro-Ro cargo ships, vehicle carriers, Ro-Ro passenger ships, and tankers of 400 GT and above engaged in international voyages have to calculate the attained EEXI. This should be equal to or lower than the required EEXI, calculated based on a reference line and specific reduction factors for each ship type.

Verification of the attained EEXI must be conducted at the first annual, intermediate, or renewal survey of the IAPP Certificate or the initial IEEC Certificate, whichever is first, starting from January 1, 2023.

By January 1, 2023, the ship types mentioned above, along with conventional propulsion cruise ships with a gross tonnage of 5,000 GT or more engaged in international voyages, must include in the SEEMP:

- The methodology used to calculate the ship's attained annual operational index CII and reporting this value to the Flag Administration.

- An implementation plan to meet the required annual operational index CII for the following three years.
- A self-assessment and improvement procedure.

Confirmation of compliance is be provided by the Flag Administration or its Recognized Organization (RO) before January 1, 2023, and kept on board. The SEEMP will be subject to verification during Company audits.

For ships subject to the new SEEMP requirements:

- Starting from 2023, at the end of each calendar year, the attained annual operational CII is be calculated over a 12-month period and electronically communicated to the Flag Administration /RO by the following March.
- The required annual operational CII is reduced by the same percentage each year for all ship types (5% for 2023; 7% for 2024; 9% for 2025; 11% for 2026, with percentages yet to be decided for 2027-2030).

The Flag Administration /RO is to verify the attained annual operational CII against the required annual operational CII to determine the energy efficiency class A, B, C, D, or E. The required annual operational CII is the midpoint of the range corresponding to the C-rating level.

A ship classified as D for three consecutive years or E for any year must develop a corrective action plan to achieve the required annual operational CII. This plan must be included in the SEEMP and submitted to the Flag Administration /RO for verification.

It's worth noting that the CII has been heavily criticized for its inability to accurately describe a ship's efficiency. As a simple metric with few elements, it fails to accurately describe a ship's efficiency in terms of:

- Anchored ships
- Ships in port
- Ships under repair
- Ships manoeuvring
- Ballast voyages compared to laden voyages.
- Actual cargo carried.

Given these shortcomings, the revision of the CII within the context of short-term measures planned by 2026 will be of great importance. It will be an opportunity to study and propose modifications and improvements to the CII, both as the Italian Administration and in collaboration with European Member States. This should consider challenges such as strikes, port congestion, technical stops, and include increased data granularity resulting from the revision of data submission to the DCS.

Regarding mid and long-term measures to achieve the 2050 target defined in the 2023 IMO GHG Strategy, these will include a combination of technical measures (goal-based marine fuel standards) and economic measures (MBMs - market-based measures).

For economic measures, it may be desirable to impose a direct tax on fossil fuels to reduce the "green premium"[9], aimed at promoting the adoption of sustainable fuels, as discussed, and proposed during MEPC 80.

Funds collected could be used, for example, to incentivize first movers, promote R&D projects, and finance alternative fuel infrastructure.

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[9] The term "green premium" refers to the additional cost of using cleaner technology compared to one with higher emissions.

2.2 EU Directives and Regulations of Major Impact

The EU requirements have been incorporated into the so-called "Fit for 55 Package," a package of rules that cover all sectors of the EU economy, including maritime transport, and aim to achieve the 2030 climate target of reducing GHG emissions by 55%. The most significant legislative proposals for shipping are:

- The revision of Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading (ETS Directive).
- The new FuelEU Maritime Regulation, aimed at incentivizing the use of low or zero carbon emissions alternative fuels.

2.2.1 Directive (EU) 2023/959 – ETS

Directive (EU) 2023/959, amending the ETS Directive, will be implemented by European Member States and by Iceland and Norway, which are part of the European Economic Area (EEA), and will apply from January 1, 2024, to emissions from ships, regardless of their flag, exceeding 5,000 GT. From January 1, 2027, it will also apply to offshore units exceeding 5,000 GT. The regulation covers:

- 100% of GHG emissions in European/EEA ports and for voyages between European/EEA ports.
- 50% of GHG emissions for voyages arriving in European/EEA ports from non-European ports or vice versa.

Where GHG emissions include CO_2 emissions from January 1, 2024, and CO_2, methane (CH_4), and nitrous oxide (N_2O) emissions from January 1, 2026.

According to the Directive, from 2025 onwards, every shipping company operating in Europe has to:

- Report aggregated and verified emission data for the previous year (by March 31 of each year).
- Surrender the following allowances (by September 30 of each year):
  - 40% of the reported aggregated verified emissions for 2024.
  - 70% of the reported aggregated verified emissions for 2025.
  - 100% of the reported aggregated verified emissions for 2026 and each subsequent year.
- Pay a penalty of EUR 100 for each ton of emissions for which allowances have not been surrendered. Payment of the penalties does not exempt the Company from surrendering the allowances. If a Company fails to comply with the ETS Directive for two consecutive years, its ships may be denied entry to European ports until the Company fulfils its obligations.

The Directive also provides the following exemptions until December 31, 2030:

- Ships with ice class (IA or IA Super or equivalent) may surrender 5% less allowances than the required amount for their reported aggregated verified emissions.
- GHG emissions do not need to be counted in the following cases:
  - Voyages made by passenger ships (other than cruise ships) or passenger ro-ro ships to/from European islands with a population of fewer than 200,000 permanent residents.
  - Voyages made by passenger ships or passenger ro-ro ships as part of a transnational public service contract.
  - Voyages between a port located in the remote regions of a European state and a port in the same state.

It is essential to note that these exemptions are not automatic, and it is the responsibility of the Member State to communicate any exemption to the Commission.

Considering the emissions data from the publicly available MRV database, it's worth noting that the types of ships used in Motorways of the Sea services will be most affected by the ETS system, as:

- At the European level, ro/pax and ro/ro ships represent approximately 20% of the ETS emissions quota.
- At the national level (Italy), ro/pax and ro/ro ships represent approximately 60% of the ETS emissions quota.

2.2.2 FuelEU Maritime Regulation

The FuelEU Maritime Regulation, which is likely to be implemented by the Member States of the European Economic Area (EEA) (i.e., Norway, Iceland, and Liechtenstein), applies to ships with a gross tonnage (GT) of 5,000 or more that transport passengers or goods for commercial purposes, regardless of their Flag. The regulation covers the following:

- 100% of the energy used in European/EEA ports and for voyages between European/EEA ports.
- 50% of the energy used for voyages arriving in European/EEA ports from non-European ports or vice versa, and for voyages to and from remote regions of the EU.

The Regulation requires that:

- Starting from 2025, an annual average greenhouse gas (GHG) intensity index must be calculated for each ship, which must not exceed a target value that will decrease significantly over the years (from 2% in 2025 to 80% in 2050). The calculation of the GHG intensity index requires to divide the total emissions of CO_2, CH_4, and N_2O by the energy used by the ship during the reference year. If the GHG intensity index exceeds the target, the company must pay a penalty proportional to the cost of renewable and low-carbon emission fuels that the ship should have used to comply with the regulation. However, the regulation allows for the borrowing or baking of a ship's compliance surplus between two reference periods and for the pooling of two or more ships, even from different Companies. Compliant ships (i.e., with a GHG intensity index below the target or with paid penalties) must have a FuelEU Document of Compliance on board.
  It is important to note that the possibility of forming ship "pools" promotes the use of alternative fuels, particularly biomethane or other biofuels that, when used on a limited number of ships, can still meet the standard, or mitigate the impact on the entire fleet.
- Starting from 2030, container ships and passenger ships berthed in EU/EEA ports subject to the "Alternative Fuels Infrastructure Regulation" (under development) must connect to onshore power supply (OPS) systems and use them to meet all energy needs while at berth unless:
  - They stay at the quay for less than two hours.
  - They use zero-emission technology (definition still subject to working groups).
  - They cannot connect due to compatibility/unavailability of connection points.
  - They need to carry out maintenance/functional tests.
  - There are safety/emergency reasons.

  If this requirement is not met, the company is required to pay a penalty calculated based on the hours spent in port and the total electricity demand of the ship while berthed.

EU/EEA Member States may exempt:

- Ice-class ships (IA or IA Super or equivalent) until December 2034.
- Passenger ships (other than cruise ships) when traveling between ports of the same EU/EEA State to/from islands with a population of fewer than 200,000 permanent residents, until December 2029.
- Specific routes between ports located in remote regions, until December 2029.
- Voyages (and related stay in port) undertaken by passenger ships as part of transnational public service obligations, until December 2029.
- Until December 2029, specific routes between EU continental ports and ports on an island of the same Member State operated by passenger ships providing maritime transport services under a public service obligation/contract and operating before the Regulation comes into force.

2.3 Considerations on Regulations

The decarbonization measures of the IMO and the EU are independent of each other and are based on two different approaches: while the IMO currently requires ships to comply with the mandatory requirements of the MARPOL Annex VI Convention (otherwise, the ships will not be allowed to operate), the EU imposes payment for equivalent CO_2 emissions and penalties for non-compliance on the principle of "polluter pays."

This difference in approach makes it extremely difficult for both shipbuilders and shipowners to identify a ship platform that can meet the needs of both regulations. It is urgently necessary to harmonize both regulations in order to have a single global objective that makes the performance index on which the ship platform should be developed unequivocal. The current dichotomy makes the decarbonization process difficult and significantly slows it down due to the high level of uncertainty it generates.

It should be noted that European measures are regional and only affect traffic to/from and within Europe. In this sense, these measures risk creating market distortions and a loss of competitiveness for the European maritime sector, industry, and related sectors. For this reason, it is of utmost importance that if an international agreement (at IMO level) is reached on issues already regulated at the EU regional level, European rules should be revised to align with it. This is in line with what has already been clarified by European institutions and would prevent duplication of obligations and administrative burdens for ships traveling in Europe.

It should be emphasized that the application of regional rules imposes a managerial burden on shipping companies and, more importantly, market distortion.

Furthermore, in both regulations (IMO and EU), there are many implementation aspects that are still unclear or leave room for interpretation, preventing a clear understanding for both shipbuilders and operators. It is also crucial to develop and prepare rules for the training and education of crews who will operate on ships powered by alternative fuels. Almost all alternative fuels, in order to be managed safely, require a much higher level of preparation and competence than current fuels. The risk is to have technologies and alternative fuels available but not enough maritime personnel trained to handle them.

The uncertainties mentioned above are limiting the propensity to invest in research on new technologies. In particular, to avoid the risk of having different rules and regulations regarding the same "tools" used and recognized for the calculation and measurement of:

- LCA (Life Cycle Assessment)
- GHG saving calculation.
- Sustainability criteria
- Certification systems

both IMO and European regulations should achieve the same objectives and use the same tools. This would allow for a homogeneous and easily applicable regulatory framework. Otherwise, operability would be unnecessarily penalized.

Therefore, it is necessary for all aspects to be considered as soon as possible so that all stakeholders (shipowners, operators, fuel producers, ports, Recognized Organizations, verifiers, and Flag Administrations) have a clear understanding of how to comply with their obligations.

Furthermore, regarding international regulations, it is essential that there is a uniform approach agreed upon at the IMO level to avoid each Administration making different decisions, introducing disparities in treatment for ships flying different flags, such as calculating CII values differently, making them incomparable. In this regard, it would be advisable for unified interpretations and circulars approved by the MEPC to be consistently applied internationally.

It should be noted that, for example, at the last MEPC 80, the "I*nterim guidance on the use of biofuels under Regulations 26, 27 and 28 of MARPOL Annex VI (DCS and CII)*" was approved to try to overcome, pending the definitive application of the LCA Guidelines, different approaches by Flags, such as France, which in its document ISWG-GHG 15/5 "*Information document on the first steps of implementation of the CII regulation by the French flag Administration*," shared its unique approach to biofuels in the context of CII.

However, given the advisory nature of the document, it is hoped that it will be adopted by all Administrations (IMO Member States).

Moreover, as highlighted in several documents submitted to the MEPC, any technical and/or economic measure alone or as part of a basket of measures is ineffective in achieving decarbonization goals unless the availability of future fuels, new technologies, engines at affordable prices, and onboard personnel trained for their safe use are guaranteed.

Finally, both at the regional and international levels, funds collected through economic measures can be used, for example, to incentivize first movers, promote R&D projects, and finance infrastructure for alternative fuels. It should be emphasized that in the drafts of the delegated acts, the European Commission has provided that a portion of the Innovation Fund funded by the proceeds from the EU ETS be allocated to support the decarbonization of the maritime sector.

3 Possible Solutions for Compliance and Cost Reduction

3.1 Alternative Fuels

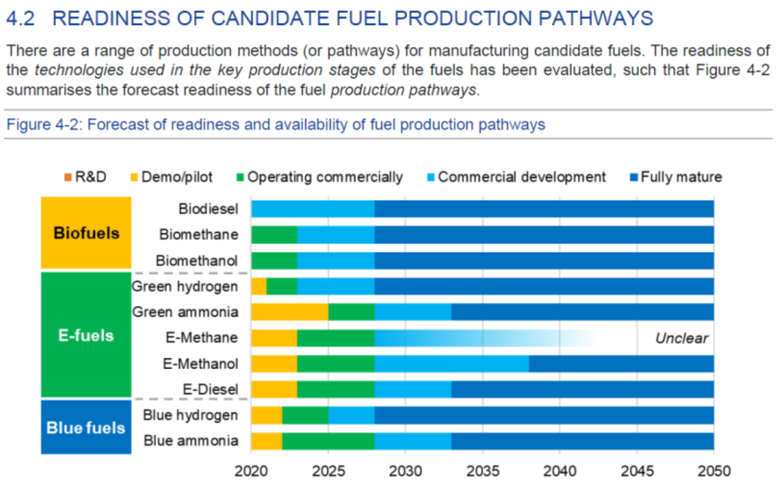
3.1.1 Availability

The IMO Secretariat presented a study on the "readiness" and availability of low and zero-carbon emission technologies and fuels in the maritime sector at MEPC 80[10]. The study considered the following "candidates" as fuels:

- Biofuels derived from biomass (algae, waste) such as bio methanol, biomethane, and biodiesel.
- Synthetic fuels or non-biological renewable origin fuels (RFNBO subset of e-fuels) based on hydrogen produced by electrolysis using renewable or nuclear energy, including carbon-free fuels such as synthetic hydrogen, synthetic ammonia, or direct carbon capture from biogenic sources, such as synthetic methanol, synthetic methane, or synthetic diesel.
- "Blue fuels" based on hydrogen from fossil sources and carbon capture greater than 90%, such as blue hydrogen and blue ammonia.
- Electricity from the grid, produced from both fossil and renewable sources and made available as shore power.
- Fossil fuels blended with certified sustainable biofuels with onboard carbon capture greater than 70% (similarly for synthetic fuels).

In addition to what was analysed in the study, a promising solution worthy of further investigation is the use of nuclear power, although it is still in the research and experimentation phase.

Below is a table from the same study indicating the readiness and technological maturity for each type of fuel:



4.2 READINESS OF CANDIDATE FUEL PRODUCTION PATHWAYS

There are a range of production methods (or pathways) for manufacturing candidate fuels. The readiness of the *technologies used in the key production stages* of the fuels has been evaluated, such that Figure 4-2 summarises the forecast readiness of the fuel *production pathways*.

Figure 4-2: Forecast of readiness and availability of fuel production pathways

Figure 3-1: Forecast of readiness and availability of different types of fuel for the maritime sector.

The study highlights that biofuels are currently in the commercial development phase and are expected to be fully mature by 2030. It is worth noting that biodiesel already has production and logistical maturity that makes it usable immediately, and it is already widely used in road transport and, more recently, in small quantities for maritime transport, blended with conventional fuel.

Biomethane and bio methanol are also in use today. Commercial development requires an increase in production plants and the supply of waste raw materials; this may be partly determined by use in other sectors, although this could lead to competition for these fuels and/or their raw materials.

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[10] MEPC 80/INF.10 “Report on the study on the readiness and availability of low- and zero-carbon ship technology and marine fuels”

The critical issue related to the use of these fuels is mainly related to the regulatory and certification scheme, which is currently extremely complex, varied, and far from international harmonization, making it extremely difficult to identify the real contribution in terms of global emissions that these fuels can provide.

Synthetic fuels are transitioning from the demonstration phase to commercial availability and are expected to reach full maturity by 2030. From a purely technical point of view, there are no technical barriers to the production of green hydrogen and ammonia, although ammonia production plants are currently still in the pilot phase and high cost.

There are investments in both production plants and renewable energy to commercialize their production in the next 5-10 years. In the case of more ambitious decarbonization goals, greater investments would increase the rate of commercialization and their availability.

Current and planned pilot plants for synthetic fuels with carbon content (e-methane, e-methanol, and e-diesel) typically use CO_2 from biogenic sources, but it is likely that increased production will require direct air capture technology, which should be ready by around 2030 and therefore able to support full-scale e-fuel production.

The commercial development of e-diesel up to full maturity expected by 2030 could be driven by demand from the road sector, which could also compete with the maritime sector itself.

For "blue" fuels, the production routes for blue hydrogen and blue ammonia are expected to reach full maturity before 2030 and the middle of the next decade, respectively.

For large-scale methane reforming plants for blue hydrogen production, current CO_2 capture technologies have proven to be challenging and costly.

The development of alternative reforming technologies for hydrogen and ammonia production may guarantee the capture of more carbon and, therefore, greater production of these types of fuels, although new plants may be required rather than the modification of existing reforming plants.

Ambitious decarbonization targets for 2050 could be achieved and not limited by the technical and commercial readiness of candidate fuels and technologies, nor by the readiness of infrastructure and shipyards, as long as there is clear guidance from national, regional, and international institutions on how to proceed and regulatory constraints depending on the adopted technologies or fuels.

Finally, given the high investment costs involved for all parties in this process (fuel producers, shipyards, shipowners), the development of dedicated funds, for example, derived from the "polluter pays" scheme, is desirable to enable the large-scale development of these technologies and fuels.

Considering the new targets adopted with the 2023 IMO GHG Strategy (5% energy from alternative fuels/technologies by 2030), the demand for alternative fuels/technologies could accelerate planned investments and announced projects for their production.

Considering that the planned investments and announced projects to produce candidate fuels by 2030 are still conservative, achieving a more stringent target for 2030 in greenhouse gas reduction could be very challenging. Therefore, clear demand signals and more ambitious policies are needed by 2025 to achieve stricter goals by 2030.

At the European level, studies have also been carried out, such as by EMSA. The study acknowledges that among the wide range of technologies and fuels available, biofuels potentially offer a medium- and long-term solution that can enter the maritime market in relatively short timeframes.

Regarding availability, the study analysed both technological maturity and potential for greenhouse gas reduction and other aspects of sustainability, such as the availability of raw materials, suitability, and cost trends. These aspects were used to identify the most promising biofuel options, evaluated on a five-point scale (--, -, 0, +, ++) and these symbols were translated into numerical representation as in the table below:

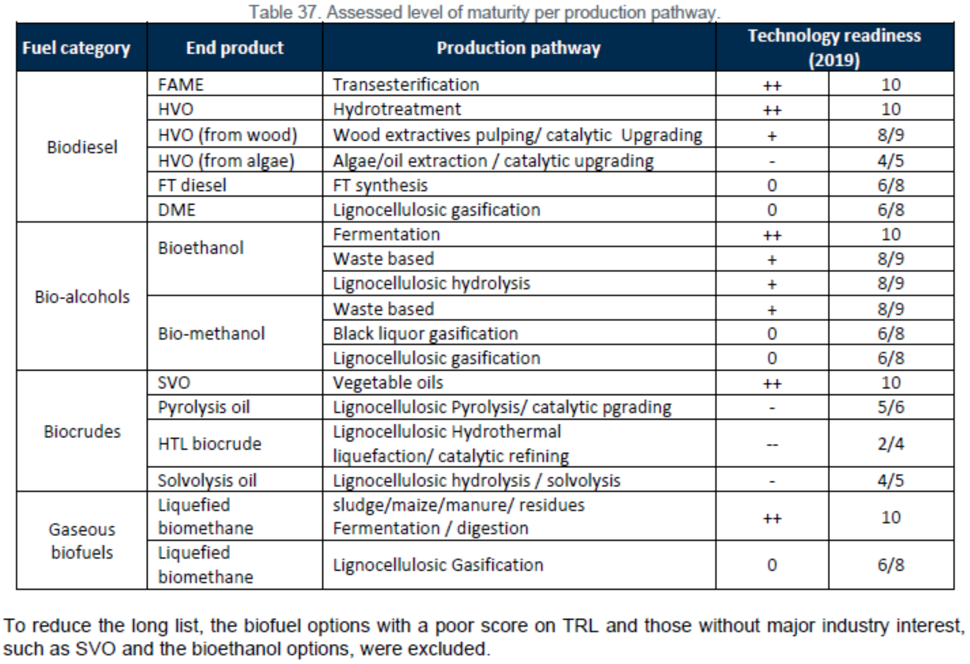

Table 37. Assessed level of maturity per production pathway.

Fuel category	End product	Production pathway	Technology readiness (2019)	
Biodiesel	FAME	Transesterification	++	10
	HVO	Hydrotreatment	++	10
	HVO (from wood)	Wood extractives pulping/ catalytic Upgrading	+	8/9
	HVO (from algae)	Algae/oil extraction / catalytic upgrading	-	4/5
	FT diesel	FT synthesis	0	6/8
	DME	Lignocellulosic gasification	0	6/8
Bio-alcohols	Bioethanol	Fermentation	++	10
		Waste based	+	8/9
		Lignocellulosic hydrolysis	+	8/9
	Bio-methanol	Waste based	+	8/9
		Black liquor gasification	0	6/8
		Lignocellulosic gasification	0	6/8
Biocrudes	SVO	Vegetable oils	++	10
	Pyrolysis oil	Lignocellulosic Pyrolysis/ catalytic pgrading	-	5/6
	HTL biocrude	Lignocellulosic Hydrothermal liquefaction/ catalytic refining	--	2/4
	Solvolysis oil	Lignocellulosic hydrolysis / solvolysis	-	4/5
Gaseous biofuels	Liquefied biomethane	sludge/maize/manure/ residues Fermentation / digestion	++	10
	Liquefied biomethane	Lignocellulosic Gasification	0	6/8

To reduce the long list, the biofuel options with a poor score on TRL and those without major industry interest, such as SVO and the bioethanol options, were excluded.

Figure 3-2: Readiness of different types of biofuels in the EU.

3.1.2 Costs

Next-generation fuels will be more expensive than current ones, so the industry needs even more certainty to adopt them, considering the necessary investments for their use.

A document [11] submitted to MEPC 80 highlights the significant price difference between conventional and alternative fuels in current market scenarios. Based on available market data for alternative fuels, the document shows indicative prices for various types of fuel, comparing energy content, emissions on a well-to-wake basis, and the equivalent cost of alternative fuels to replace one ton of conventional fuel:

Data	Conventional	Future ready fuels				
	VLSFO	Methanol grey	Bio methanol	Ammonia grey	LNG grey	Biofuel
Indicative Price Per Tonne (USD) (March 2023)	524.3	789.3	2767	1356	644.5	1625
Energy Content per MT in GJ	40.2	19.9	19.9	18.6	48.0	38.8
Tank-to-Wake C_f	3.151	1.375	0	0	2.75	0
Tank-to-Wake C_f without Methane Slip	3.151	1.375	0	0	0	0
Multiple times of Future Fuel required for Eq. energy content per tonne of VLSFO		2.055	2.055	2.161	0.8375	1.036
Price of Fuel based on Eq. Energy Content used as replacement (USD)		1,622.0	5,686.2	2,930.3	539.8	1,683.5
Times costlier in comparison with conventional fuels		3.09	10.84	5.59	1.03	3.21

Figure 3-3: Hypothetical fuel cost and key characteristics

Actually, in the study, the price of methanol appears to be rather overestimated compared to the prices found on the market.

The EMSA study also analyses cost projections limited to different types of biofuels by 2030 and 2050 and recognizes that ships powered by alternative fuels are currently not cost-competitive compared to ships operating with conventional VLSFO.

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[11] MEPC 80/7/14 “Comments on documents MEPC 80/WP.6 and MEPC 80/INF.10” submitted by India.

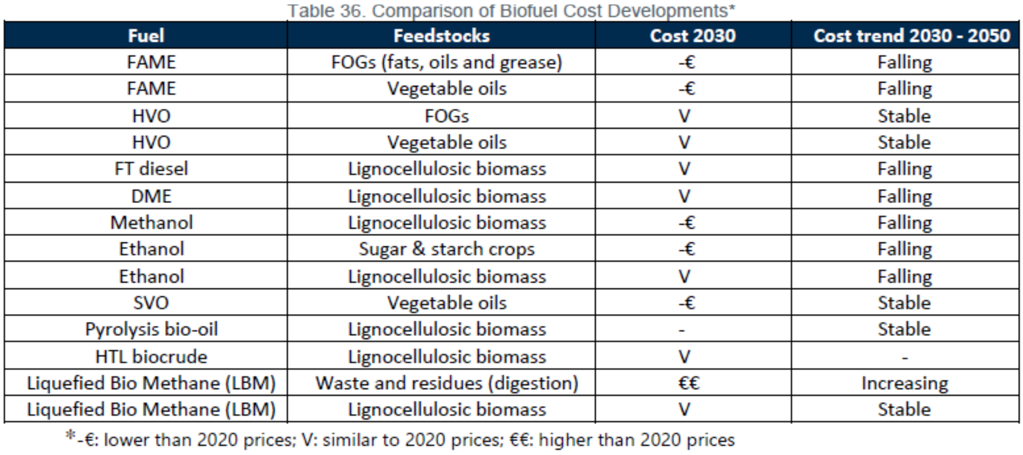

Table 36. Comparison of Biofuel Cost Developments*

Fuel	Feedstocks	Cost 2030	Cost trend 2030 - 2050
FAME	FOGs (fats, oils and grease)	-€	Falling
FAME	Vegetable oils	-€	Falling
HVO	FOGs	V	Stable
HVO	Vegetable oils	V	Stable
FT diesel	Lignocellulosic biomass	V	Falling
DME	Lignocellulosic biomass	V	Falling
Methanol	Lignocellulosic biomass	-€	Falling
Ethanol	Sugar & starch crops	-€	Falling
Ethanol	Lignocellulosic biomass	V	Falling
SVO	Vegetable oils	-€	Stable
Pyrolysis bio-oil	Lignocellulosic biomass	-	Stable
HTL biocrude	Lignocellulosic biomass	V	-
Liquefied Bio Methane (LBM)	Waste and residues (digestion)	€€	Increasing
Liquefied Bio Methane (LBM)	Lignocellulosic biomass	V	Stable

*-€: lower than 2020 prices; V: similar to 2020 prices; €€: higher than 2020 prices

Figure 3-4: EMSA study, biofuel cost projection

In 2030, additional costs for shipowners are presumed to be higher for ships powered by bio methanol and biomethane, with a slight long-term advantage.

Bio methanol shows a significant cost reduction, although with absolute costs about 35-40% higher than VLSFO in 2050.

Depending on the actual price of fuel oil (including ETS and excise duties), costs for the use of hydrotreated vegetable oil (HVO) and fatty acid methyl esters (FAME) could be higher or lower than fuel oil. Alternative fuels like FT-diesel (Fisher-Tropsch (FT) diesel) show promising trends from 2030 onwards, with annual costs 3-7% lower than VSLFO in 2050.

Regarding synthetic fuels, their cost currently appears higher than that of their respective biofuels and clearly fossil fuels. This cost comes from the amount of energy needed for their synthesis and mass production. As a result, the "green premium" required to make these fuels competitive is too high.

Other additional costs to consider are those related to CAPEX, such as engines, fuel systems, and storage, as shown in the table below:

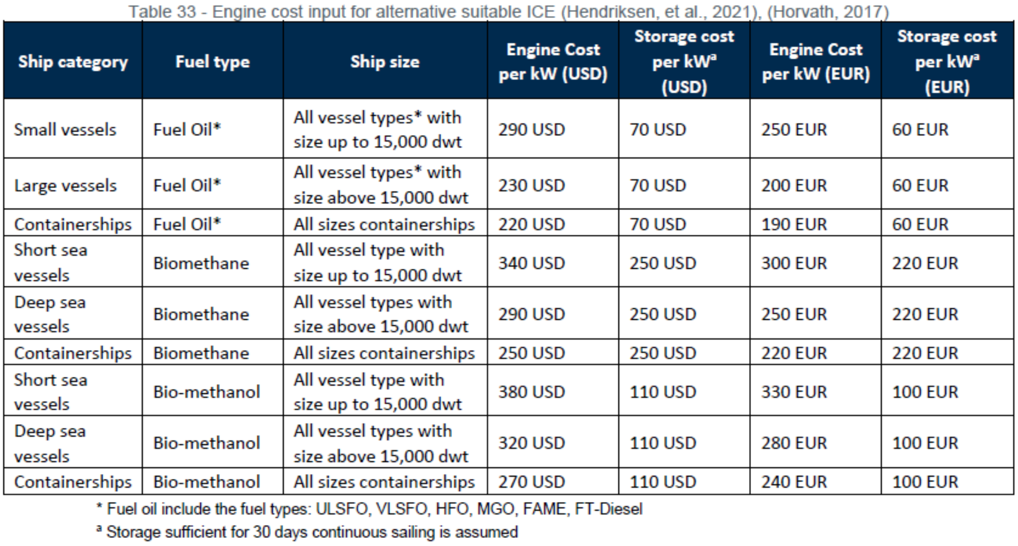

Table 33 - Engine cost input for alternative suitable ICE (Hendriksen, et al., 2021), (Horvath, 2017)

Ship category	Fuel type	Ship size	Engine Cost per kW (USD)	Storage cost per kW^{a} (USD)	Engine Cost per kW (EUR)	Storage cost per kW^{a} (EUR)
Small vessels	Fuel Oil*	All vessel types* with size up to 15,000 dwt	290 USD	70 USD	250 EUR	60 EUR
Large vessels	Fuel Oil*	All vessel types* with size above 15,000 dwt	230 USD	70 USD	200 EUR	60 EUR
Containerships	Fuel Oil*	All sizes containerships	220 USD	70 USD	190 EUR	60 EUR
Short sea vessels	Biomethane	All vessel type with size up to 15,000 dwt	340 USD	250 USD	300 EUR	220 EUR
Deep sea vessels	Biomethane	All vessel types with size above 15,000 dwt	290 USD	250 USD	250 EUR	220 EUR
Containerships	Biomethane	All sizes containerships	250 USD	250 USD	220 EUR	220 EUR
Short sea vessels	Bio-methanol	All vessel type with size up to 15,000 dwt	380 USD	110 USD	330 EUR	100 EUR
Deep sea vessels	Bio-methanol	All vessel types with size above 15,000 dwt	320 USD	110 USD	280 EUR	100 EUR
Containerships	Bio-methanol	All sizes containerships	270 USD	110 USD	240 EUR	100 EUR

* Fuel oil include the fuel types: ULSFO, VLSFO, HFO, MGO, FAME, FT-Diesel

[a] Storage sufficient for 30 days continuous sailing is assumed

Figure 3-5: MSA study, estimated additional CAPEX costs for using biofuels.

3.1.3 State of Technology for Deployment

To achieve decarbonization goals, not only the fuels but also the various technologies for their use, whether current or in development, could play a crucial role.

- Shore-based electrical power supply: This technology is ready, but there is a lack of onshore infrastructure. High energy costs result from significant investment requirements.
- Use of biofuels: The technology is ready, but there are significant impacts. Regulations are not uniform among various regulatory instruments (TtW - WtW approaches), and validation by engine manufacturers is needed for their use.
- Use of fossil LNG in internal combustion engines: The technology is ready, with a moderate impact on emissions.
- Use of methanol in internal combustion engines: The technology is ready for almost all engines, with a moderate impact on emissions. There is a growing demand for dual-fuel (diesel - LNG) engines that can be converted to methanol during the ship's operational life. A strong push toward methanol as a new maritime fuel is expected in some segments as early as 2023. By 2025, all engine manufacturers will offer methanol-powered engines, and some will provide conversion solutions allowing diesel engines and dual-fuel engines to use methanol.
- Use of methanol fuel cells: This technology is in progress and ready only for small-scale applications.
- Use of ammonia in internal combustion engines: This technology is in progress, with two-stroke engines in the most advanced stage. Lack of regulations. There is a growing, albeit minimal, demand for dual-fuel (diesel - LNG) engines that can be converted to ammonia during the ship’s operational life. A plausible scenario envisions substantial growth in fleets equipped with ammonia-powered engines. By 2025, all engine manufacturers will offer some series of ammonia-powered engines and conversion solutions for diesel engines and dual-fuel engines.
- Use of ammonia in fuel cells: This technology is not ready.
- Use of hydrogen in internal combustion engines: This technology is in progress, with laboratory tests underway to burn varying amounts of hydrogen. Lack of Regulations.
- Use of hydrogen in fuel cells: This technology is ready and progressing for large-scale applications. Lack of Regulations.
- Use of CO_2 capture and storage systems onboard, pre-, and post-combustion: This technology is in progress, with a lack of regulations.
- Use of nuclear energy: This technology is not ready and lacks regulations.

3.1.4 State of Logistics for Distribution

The IMO Secretariat presented a study to MEPC 80 [12] on the maturity and availability of low and zero carbon emission technologies and fuels in the maritime sector, emphasizing the need to adapt existing infrastructure to meet the demands of alternative fuels. The study provides a high-level screening, as shown in the figure below:

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[12] MEPC 80/INF.10: Report on the study on the readiness and availability of low- and zero-carbon ship technology and marine fuels

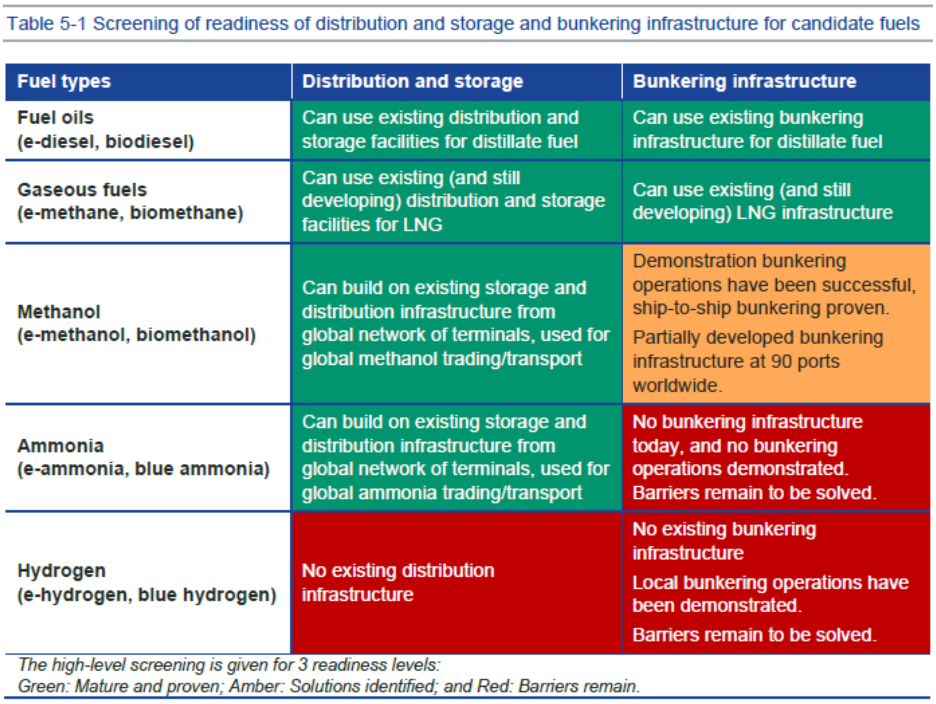


Table 5-1 Screening of readiness of distribution and storage and bunkering infrastructure for candidate fuels

Fuel types	Distribution and storage	Bunkering infrastructure
Fuel oils **(e-diesel, biodiesel)**	Can use existing distribution and storage facilities for distillate fuel	Can use existing bunkering infrastructure for distillate fuel
Gaseous fuels **(e-methane, biomethane)**	Can use existing (and still developing) distribution and storage facilities for LNG	Can use existing (and still developing) LNG infrastructure
Methanol **(e-methanol, biomethanol)**	Can build on existing storage and distribution infrastructure from global network of terminals, used for global methanol trading/transport	Demonstration bunkering operations have been successful, ship-to-ship bunkering proven. Partially developed bunkering infrastructure at 90 ports worldwide.
Ammonia **(e-ammonia, blue ammonia)**	Can build on existing storage and distribution infrastructure from global network of terminals, used for global ammonia trading/transport	No bunkering infrastructure today, and no bunkering operations demonstrated. Barriers remain to be solved.
Hydrogen **(e-hydrogen, blue hydrogen)**	No existing distribution infrastructure	No existing bunkering infrastructure Local bunkering operations have been demonstrated. Barriers remain to be solved.

The high-level screening is given for 3 readiness levels:
Green: Mature and proven; Amber: Solutions identified; and Red: Barriers remain.

Figure 3-6: Availability and distribution of alternative fuels

The use of new fuels raises questions about the quantity of available fuels that can be allocated to the maritime sector, the adaptability of existing infrastructure where possible, and the need for new infrastructure development.

It should also be noted that both biological and synthetic fuels are produced in certain regions of the world with abundant biomass, waste, and renewable energy sources, which may not always align with the final distribution infrastructure, complicating the logistics and transportation cost chain.

The availability of a distribution chain for new fuels will be one of the key challenges to address for their development. Fuel producers and suppliers are often distinct and unrelated entities. Therefore, investments in the production of a biofuel or alternative fuel like methanol will need to go hand in hand with complementary investments to upgrade coastal storage facilities and vessels for distribution.

3.1.5 Pros and Cons of Considered Fuels

Each new fuel has its pros and cons in terms of availability, environmental impact, safety, and costs.

Safety is one of the most important factors. New fuels like LNG, methanol, and hydrogen have a low flashpoint, so precautions must be taken regarding possible leaks, and furthermore especially for methanol and, more importantly, for ammonia due to their toxicity.

Another important factor is the volumetric energy content. LNG, ammonia, methanol, and hydrogen have lower energy content compared to conventional fuels, requiring more onboard space and different storage methods to reduce their volume, such as low-temperature liquefaction and high-pressure compression.

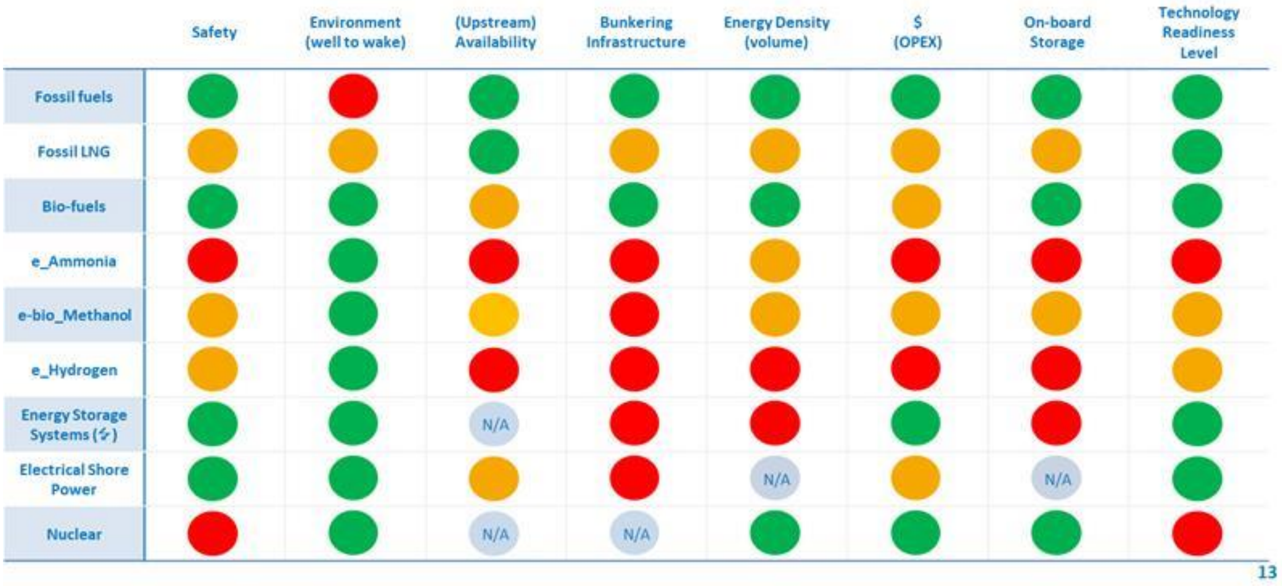
For example, liquid methane, without considering fugitive emissions, results in a 25% reduction in emissions, while methanol reduces emissions by about 8%.

Additionally, some fuels may improve CO_2 emissions but worsen emissions of other potent greenhouse gases like methane and nitrogen oxides.

Lastly, each fuel should be evaluated in terms of emissions throughout its lifecycle, from production, transformation, transportation, distribution, to combustion onboard.

LNG, methanol, ammonia, and hydrogen, if derived from fossil sources, have a higher CO_2 emissions impact throughout their well-to-wake (WtW) lifecycle compared to directly using fossil fuels.

Below is a summary table of the main pros and cons for each primary fuel.



	Safety	Environment (well to wake)	(Upstream) Availability	Bunkering Infrastructure	Energy Density (volume)	$ (OPEX)	On-board Storage	Technology Readiness Level
Fossil fuels	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟢
Fossil LNG	🟠	🟠	🟢	🟠	🟠	🟠	🟠	🟢
Bio-fuels	🟢	🟢	🟠	🟢	🟢	🟠	🟢	🟢
e_Ammonia	🔴	🟢	🔴	🔴	🟠	🔴	🔴	🔴
e-bio_Methanol	🟠	🟢	🟡	🔴	🟠	🟠	🟠	🟠
e_Hydrogen	🟠	🟢	🔴	🔴	🔴	🔴	🔴	🟠
Energy Storage Systems (⚡)	🟢	🟢	N/A	🔴	🔴	🟢	🔴	🟢
Electrical Shore Power	🟢	🟢	🟠	🔴	N/A	🟠	N/A	🟢
Nuclear	🔴	🟢	N/A	N/A	🟢	🟢	🟢	🔴

Figure 3-7: Pros and Cons of Main Alternative Fuels

An important aspect to consider for green fuels is the availability of renewables. In a study presented at the IMO[13], an interesting analysis was conducted on the quantities involved in the production of green fuels, particularly green ammonia.

Starting with the current quantity of fossil fuel used by international shipping, approximately 200 million tons, it's essential to consider the equivalent amount of ammonia required in terms of energy content, which is about 450 million tons.

The production of 450 million tons requires approximately 80 million tons of hydrogen, accounting for 66% of the total current production of hydrogen from any source.

To achieve this quantity, around 5,500 TWh/year of renewable energy is needed, equivalent to 54% of all renewable energy currently generated worldwide.

Therefore, the challenges of making this result realistic in the short term are evident.

3.1.6 Clarifications on the Meaning of "Ready" Ship

In a constantly changing technological and regulatory landscape, the shipping industry faces challenges in defining the right choice for an asset, the ship, for which the design, construction, and utilization times are significantly long. During this time frame, a technology or fuel may emerge as the dominant choice in an unpredictable manner.

Hence, there is a regulatory and design need to build "ready" ships. These are ships that are already designed to be able to use new technology or a new fuel and are delivered with the capability to easily install components and systems for their immediate use.

There are, indeed, ships for which a design has been developed for the use of an alternative fuel, and these are referred to as "ready" designs, encompassing both structural and systems aspects. Subsequently, these

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[13] MEPC 79/7/3 Analysis of fuel options to meet the levels of ambition in the Initial IMO Strategy on reduction of GHG emissions from ships - INTERTANKO.

ships will undergo a retrofit, for example, for the installation of fuel storage, distribution systems, and final utilization of the new fuel.

In the development of a "ready" ship project, some components, such as dual-fuel engines or structures necessary for accommodating fuel containment systems, might already be installed on board. However, it is often preferred to defer or avoid such installations to prevent aging and unnecessary initial installation and maintenance costs.

Nevertheless, the absence of a regulatory framework issued by the IMO—currently, there are only guidelines available for methanol[14] – necessitates the approval of the onboard ship system design through an alternative design process, as required by IMO Circular MSC.1/Circ.1455[15]. This makes the work more cumbersome and uncertain, as each Administration may express different opinions on the same design. An acceleration by the IMO in this regard would be necessary.

Regardless of whether the "ready" class notation is assigned, when the ship is converted to use the alternative fuel, it will be necessary to re-verify the approvals already issued based on the statutory and class rules applicable at the time of the conversion contract signing.

3.1.7 Considerations on the Use of Alternative Fuels

When analysing the use of alternative fuels in the maritime sector, some of the key considerations are as follows:

- An increasing number of ships under construction will be powered by alternative fuels.
- The number of shipyards constructing ships powered by alternative fuels is diversifying.
- The production of new fuels will increase once the demand becomes clear.
- There will not be a single dominant fuel in the maritime landscape, but rather diversification based on the type of ship.
- The production of alternative fuels will follow geo-economic scenarios regardless of the maritime sector.

3.2 Carbon Capture

Carbon capture on board is the only technology capable of making conventional maritime fuels compatible with emissions reduction targets and could be one of the transitional solutions in the coming years.

Although it is a mature technology on land, there are still some challenges, such as the space required on board for both the capture and storage of CO_2, the increased onboard energy demand depending on the various technologies, certification of the system, management and "ownership" of the CO_2 once discharged from ships, and clear regulations defining the criteria and limits for the commercialization of CO_2 delivered to land.

It is expected that investments in carbon capture on board will increase in the next decade as carbon regulations become more stringent.

3.2.1 Carbon Capture Before Combustion

Among the solutions aimed at reducing ship emissions of CO_2, there are also fuel treatment solutions before combustion or use.

For example, it is possible to combine LNG and steam in a gas reformer to convert LNG molecules into hydrogen and CO_2. The hydrogen stream is used to power internal combustion engines or fuel cells, and CO_2

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[14] MSC.1/circ.1621 Interim guidelines for the safety of ships using methyl/ethyl alcohol as fuel.

[15] Guidelines for the approval of alternatives and equivalents as provided for in various IMO instruments.

is captured directly from the reformer's output stream, making the process simpler compared to capturing CO_2 from the engine exhaust gases.

The energy for this process comes from extra fuel consumption, but the emissions are offset by the capture of CO_2 at the end of the process as described below.

Using this technology, it is possible to produce hydrogen directly on board in the necessary quantities, bypassing the significant challenges of hydrogen storage.

Two process stages are required to convert methane into hydrogen and CO_2. The first stage of the process converts methane into hydrogen and CO:

CH4 + H2O ⇌ CO + 3H2

To increase the hydrogen yield of the process, the water gas shift reaction occurs in the subsequent phase of this chemical process:

CO + H2O ⇌ CO2 + H2

The significant advantage is that the cryogenic temperature of LNG as a fuel can liquefy the CO_2 from the reformed gas stream, which can then be collected and stored in a dedicated tank. It can be delivered to shore for further use or storage, or on-board tanker ships as inert gas.

3.2.2 Carbon Capture After Combustion

The separation and capture of CO_2 from exhaust gases are usually carried out using the following methodologies:

- Chemical absorption
- Physical adsorption
- Membrane separation
- Cryogenic distillation and other cryogenic capture methods
- CO_2 concentration using electrochemical devices.

It is worth noting that the exhaust gas cleaning systems currently installed on board and used for sulphur oxide and particulate matter removal are not suitable for CO_2 capture. However, pre-treatment of exhaust gases, especially those from fuels such as HFO, VLSFO, and MGO, may be necessary to enable better operation or longer lifespan of CO_2 capture technology. In practice, post-combustion CO_2 capture technologies need to work on exhaust gases already cleaned of particulates and sulphur oxides, making the installation of a scrubber often a prerequisite for the optimal functioning of the technology.

Another promising technology that involves a chemical and physical process of the CO_2 molecule is represented by molten carbonate fuel cells (MCFC). MCFCs are not only highly efficient in CO_2 capture but also generate additional electricity.

Ship engine exhaust gases can be treated with these devices, capturing up to 90% of CO_2 and producing a CO_2-rich captured stream that can be easily separated through a specific purification step applied at one order of magnitude lower flow rate than the original exhaust gases.

Examples of chemical absorption include technologies based on processes where a fluid is dissolved by a liquid or solid (absorbent). The assimilation of molecular species through a mass of a solid or liquid solvent is defined as absorption.

Among the chemical absorption processes used in the industry to capture CO_2 from exhaust gases, amine and calcium hydroxide washing are well-established technologies.

Amine solutions are capable of reversibly absorbing carbon dioxide. Exhaust gases are washed with these solutions to reduce the amount of emitted CO_2. The CO_2-rich amine solution is subsequently regenerated through the combined action of vacuum and heat, releasing gaseous CO_2 that, in an onshore facility, should be liquefied and stored.

Experience shows that tertiary amines perform well in terms of load capacity, energy requirement for regeneration, and corrosiveness. These compounds/solutions may have components classified as Group T according to the IBC code for bulk transport, requiring a series of provisions for storage. However, the shipbuilding industry is believed to be prepared to handle these chemicals properly.

A suspension of calcium hydroxide in water with a solid content between 10% and 30% is known as lime milk. Since the solubility of calcium hydroxide is very low (about 1.7 g/L at room temperature), water suspensions are often used to increase the concentration of the reactant. Calcium hydroxide reacts with CO_2 to form calcium carbonate, which is only slightly soluble in water; hence, it will form a solid product or suspension.

The result of the chemical process is an inert inorganic compound, which is basically a suspension of calcium carbonate $CaCO_3$, also known as limestone, calcite, or aragonite, which are the main components of mollusc shells in nature.

The evaluation of the initial compound and the final product in relation to IMO international conventions (MARPOL, IMSBC, IBC) shows that:

- If stored on board as dry powder and mixed on board with seawater, the initial chemical product is classified as Group B according to the IMSBC code for bulk transport, and the main hazard is the exothermic reaction when dry slaked lime comes into contact with water.
- Both in suspension and in solid form, calcium carbonate poses no identified hazards, resulting in Group C in solid form according to the IMSBC code for bulk transport.

Since it is not among the prohibited wastes according to Annexes I and II of the London Convention, the possibility of disposing of calcite (calcium carbonate) at sea could be comparable to a geological deposit of CO_2 in an inert inorganic substance that is not harmful in suspension and/or deposited on the seabed, obtaining a general discharge permit based on the assessment provided in Annex III of the same convention.

However, the possibility of its discharge, based solely on technical assessments, is not admissible unless supported at the level of individual Administrations and possibly at the IMO level.

3.2.3 Considerations on Carbon Capture Techniques

In a study presented at MEPC 80[16], it is emphasized that the development of CO_2 capture technology is at an advanced stage, but there are risks that need to be mitigated before the widespread application of such technology.

The main risks include logistical difficulties related to onshore reception facilities, increased onboard energy demand, potential cargo losses due to the volumes required for plant installation and end-process storage, and delays in the development of the regulatory framework to recognize CO_2 reduction credits.

In addition to what was analysed in the study, it is worth noting the additional costs of any chemical additives required for the process.

It is necessary that a receiving and reuse or permanent storage chain is available and regulated. Only when there are signals of infrastructure availability and appropriate regulations can this technology be adequately considered.

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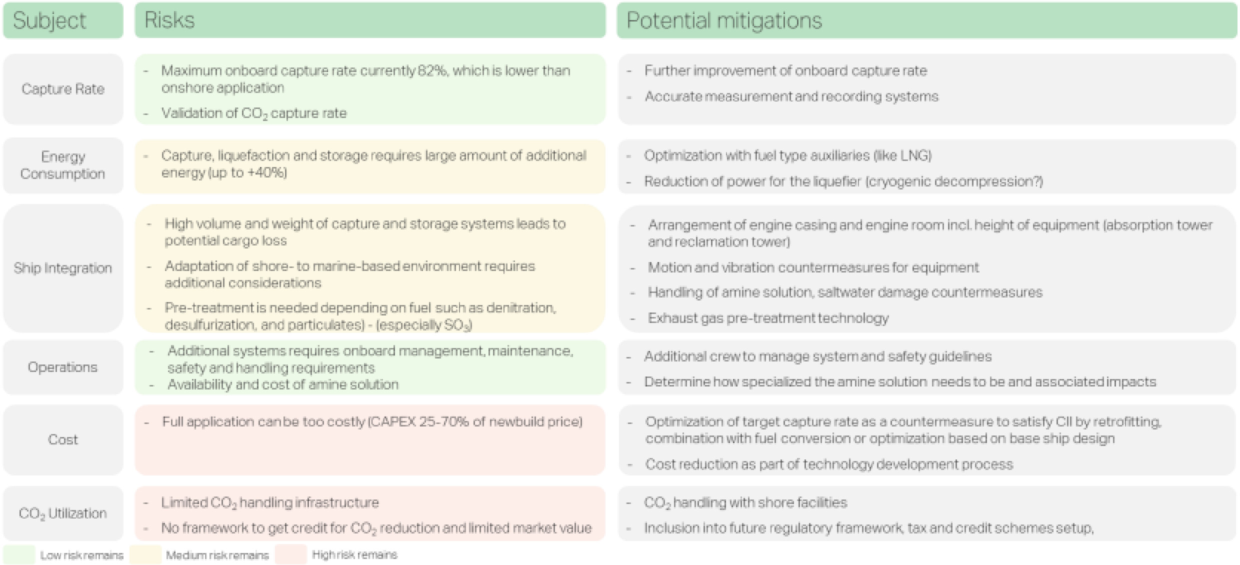
[16] MEPC 80/7 e MEPC 80/INF.14 Onboard carbon capture del Royal Institution of Naval Architects



Subject	Risks	Potential mitigations
Capture Rate	🟩 - Maximum onboard capture rate currently 82%, which is lower than onshore application - Validation of CO_2 capture rate	- Further improvement of onboard capture rate - Accurate measurement and recording systems
Energy Consumption	🟨 - Capture, liquefaction and storage requires large amount of additional energy (up to +40%)	- Optimization with fuel type auxiliaries (like LNG) - Reduction of power for the liquefier (cryogenic decompression?)
Ship Integration	🟨 - High volume and weight of capture and storage systems leads to potential cargo loss - Adaptation of shore- to marine-based environment requires additional considerations - Pre-treatment is needed depending on fuel such as denitration, desulfurization, and particulates) - (especially SO_3)	- Arrangement of engine casing and engine room incl. height of equipment (absorption tower and reclamation tower) - Motion and vibration countermeasures for equipment - Handling of amine solution, saltwater damage countermeasures - Exhaust gas pre-treatment technology
Operations	🟩 - Additional systems requires onboard management, maintenance, safety and handling requirements - Availability and cost of amine solution	- Additional crew to manage system and safety guidelines - Determine how specialized the amine solution needs to be and associated impacts
Cost	🟥 - Full application can be too costly (CAPEX 25-70% of newbuild price)	- Optimization of target capture rate as a countermeasure to satisfy CII by retrofitting, combination with fuel conversion or optimization based on base ship design - Cost reduction as part of technology development process
CO_2 Utilization	🟥 - Limited CO_2 handling infrastructure - No framework to get credit for CO_2 reduction and limited market value	- CO_2 handling with shore facilities - Inclusion into future regulatory framework, tax and credit schemes setup,

🟩 Low risk remains 🟨 Medium risk remains 🟥 High risk remains

Figure 3-8: RINA Study - Risks Related to CCS

In addition to these risks, there is a lack of applicable requirements for CO_2 capture systems regarding installation, testing, monitoring, and certification. Currently, Annex VI to MARPOL does not regulate this technology.

From the perspective of principles established for testing, monitoring, and certification, there may be similarities with scrubbers (exhaust gas cleaning systems for sulphur oxides), such as the quality of discharge water, documentation, monitoring, and certification, which could potentially be applied to CO_2 capture systems.

The same study analyses the performance, design integration, and financial impacts of integrating a CO_2 capture system on board (OCC) a VLCC, a LR2 long-range tanker, an 82,000 DWT bulk carrier, a 205,000 DWT bulk carrier, and a 15,000 TEU container ship powered by low sulphur fuel oil (LSFO), LNG, and methanol (MeOH). While most of the case studies involve new building integration, the VLCC case study also includes retrofitting a CO_2 capture system to an existing vessel.

The study's conclusions indicate:

- CO_2 capture through chemical absorption is technically feasible and should reach commercial availability by 2030.
- Additional energy requirements result in higher total fuel consumption and a greater amount of installed power on board (up to a 45% increase for a maximum carbon capture rate of 82%).
- The potential application of CO_2 capture systems shows the most promise for new building, as retrofits are costly and may require significant modifications.
- The installation of CO_2 capture systems requires space and may result in cargo space loss, depending on the type and size of the vessel.

Considering the above, there is a strong need for clear and applicable regulations so that this technology can also be included among those capable of providing a concrete response to the challenges posed by decarbonization. It is expected that the MEPC Committee will develop specific requirements or establish a dedicated working group to facilitate the introduction of these technologies.

3.3 Technologies for Reducing the Amount of Consumed Fuel with a Focus on Efficiency

To achieve decarbonization goals, not only alternative fuels but also various energy efficiency technologies, whether existing or in development, can play a crucial role. Some shipowners have already implemented or are implementing emission reduction policies that are more stringent than those required by regulations, using some of the solutions listed below.

Whether it's hydrodynamic optimizations or renewable energy sources, each solution should be evaluated in terms of its contribution to reducing greenhouse gas emissions, technological maturity, and cost.

3.3.1 Hydrodynamic Improvements

- Propulsion Optimization: This involves optimizing the propeller-rudder coupling, changing blade designs for a new operating point, modifying hubs, using counter-rotating propellers, and employing flow-conveying fins to improve the hydrodynamic performance of the ship. This technology is ready, has a moderate impact, and involves design and dry-docking costs.
- Hull and Propeller Maintenance: This includes monitoring performance, cleaning through brushing, high-pressure hull cleaning, and sandblasting. The technology is ready, has a moderate impact, and may incur additional costs for dry-docking. Underwater cleaning is not authorized in all ports.
- Air Lubrication Systems: These systems cover the hull's surface in contact with water with air bubbles to reduce frictional resistance. This technology is ready and has a moderate impact.
- High-Performance Hull Paint: The use of high-performance paints containing biocides or silicones can reduce frictional resistance. This technology is ready and has a moderate impact.
- Optimization of Hull Openings: Minimizing water flow resistance through hull openings. This technology is ready and has a low impact.
- Lightweight Ship Design: Using new materials to reduce the weight of ships. This technology is in progress, has a low impact, and is applicable only to certain types of ships (e.g., small fast passenger ships).

3.3.2 Speed Reduction

Speed reduction is recognized as a technology with significant CO_2 reduction potential. It's important to acknowledge its actual effectiveness and challenges, including costs.

The fuel consumption per hour (tonnes per hour) of a main engine is proportional to the cube of the speed. Therefore, the total fuel consumption (tonnes) of the engine during a voyage is proportional to the square of the ship's speed, assuming constant consumption of auxiliary engines and a boiler.

However, it's important to note that reducing a ship's speed can often lead to incremental CAPEX (capital expenditure) due to the need for additional ships to maintain the same annual transportation capacity as a fleet. It can also potentially lead to an increase in the prices of transported goods if an equivalent total transportation capacity is not restored after the speed reduction.

3.3.3 Thermodynamic Improvements

- Engine optimization: This involves optimizing combustion parameters, using common-rail technology, and implementing electronic control. This technology is ready and has a low impact.
- Steam plant optimization: This includes monitoring and regulating boiler performance and improving boiler operation (applicable primarily to tankers, chemical carriers, and gas carriers). This technology is ready and has a low impact.

3.3.4 Energy Efficiency

- Electric load optimization: This entails using low-consumption lighting and automatic shutdowns to optimize electrical load. This technology is ready and has a low impact.

- Auxiliary system optimization: It involves using frequency converters and controlling the speed of pumps and fans to optimize auxiliary systems. This technology is ready and has a low impact.

3.3.5 Shore Power Supply (OPS - Cold Ironing)

One of the most effective technologies for reducing, even eliminating, emissions of local pollutants such as SO_x, PM (smog), and NO_x is the ability to power the ship with electricity from the shore when in port. This allows the ship's engines to be turned off. Additional benefits of this solution include the reduction of CO_2 emissions, especially if the shore-based energy is entirely or partially from renewable sources, and the reduction of noise pollution from ship machinery.

Many ships are already equipped to be powered from shore, so it is important to invest in port logistics for this solution, which, as mentioned above, offers several environmental advantages. Considering that, as defined by FuelEU Maritime, starting from 2030, container ships and passenger ships moored in EU/EEA ports, to which the "Alternative Fuels Infrastructure Regulation" (under development) will apply, must connect to shore power supply (OPS) facilities, the urgency of investing in suitable infrastructure appears more than necessary.

3.3.6 Batteries

The use of batteries for energy storage is a technology that is ready, and it's in progress for larger vessel sizes. Regulations are already in place.

As of today, propulsion based solely on batteries, due to technological limitations (size and weight), is only feasible for medium-small-sized vessels (both merchant and passenger ships) that operate short routes and require systematic recharging through shore power connections (cold ironing). For such vessels, what's achievable is known as "full electric" propulsion.

Batteries play a crucial role in hybrid applications with PTO/PTI electric machines for all merchant and passenger ships, as they allow for operating cost savings for internal combustion engines, thus reducing overall fuel consumption. The use of batteries can, in some conditions, eliminate the need to start additional auxiliary generators, support the main propulsion during rapid power demands due to weather conditions, prevent onboard blackouts, and, if properly sized, enable zero-emission manoeuvres or port stays for a defined period. Of course, all this needs to be considered during the ship and propulsion system design phase.

Lastly, it's worth noting the need for batteries to manage load peaks and transients when fuel cells are used for power generation, given their limited capacity to handle load variations and absorb impulse loads.

3.3.7 Waste Heat Recovery

Waste heat recovery systems capture residual heat from engines to generate steam or hot water, which can then be used to drive steam turbines for electricity generation or be utilized in auxiliary engine exhaust gas boilers to generate steam or hot water. This technology is ready with a moderate impact.

3.3.8 Wind Assisted Propulsion

Harnessing wind power through sails, rigid sails, or rotors to reduce propulsion power is another option. Directly transforming renewable wind energy into propulsion skips several steps and associated energy losses, making it an area worth focusing on.

In some cases, contribution levels exceeding 25% have already been achieved, with various projects aiming for even higher values.

This technology is in progress, and its impact depends on the vessel type, routes, and operational profile.

3.3.9 Renewable Energies

The use of solar energy through solar panels to convert sunlight into electricity is a ready technology with a low impact.

3.3.10 Considerations on the Use of "Fuel Saving" Technologies

There are many technologies and procedures that can be defined as "fuel-saving" because they consequently reduce the impact of CO_2 emissions.

The shipbuilding industry has been developing and applying energy efficiency technologies for many years, driven by the need to reduce fuel costs and, more recently, by regulatory measures (e.g., EEDI, EEXI, CII).

Various ship design technologies are already mature and applied to many new ships, including weight reduction, hull size optimization, bulb optimization, bow thruster tunnel optimization, ballast, and trim optimization.

There is still potential for a broader adoption of these technologies, leading to greater fuel savings for the fleet in the future. Many of the energy efficiency measures listed in the previous paragraphs can also be implemented in the existing fleet. Among the various technologies for efficiency and reducing the energy required by ships, there are some that are not yet fully ready, and their expected technological maturity is illustrated in the figure below:

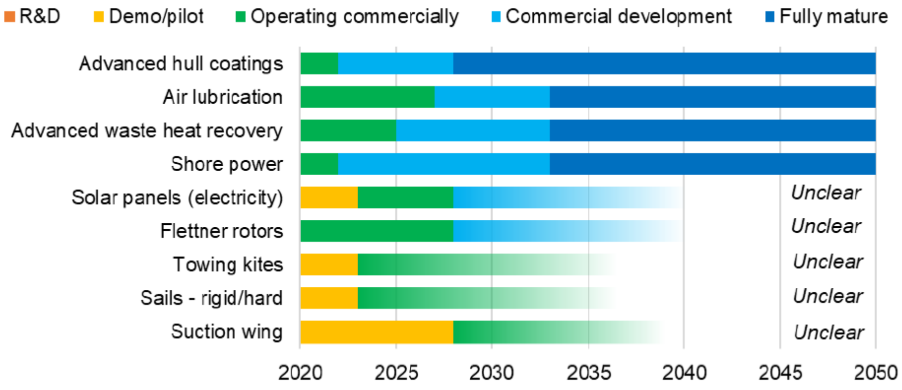


Figure 3-9: IMO Study - Maturity of Some Energy Efficiency Solutions

The adoption of onboard fuel-saving technologies requires optimization studies and an assessment of the return on investment based on the remaining useful life of the existing ship.

3.4 Changes in Ship Operations

3.4.1 Contribution of Digitalization

Performance monitoring systems and weather routing that assist in voyage optimization have seen recent developments and are already mature.

Autonomous navigation is currently in a research and development phase, requiring demonstrations of correct and safe functionality in all operational and weather conditions, as well as the availability of appropriate regulations and laws governing responsibilities in this new context.

While regional experiments are underway, fully autonomous international navigation ships may not be ready for another 10 years, and full maturity may not be achieved until 2050.

Furthermore, like many other technologies, this one can initially be applied to certain types of ships with simple operational profiles that do not require the presence of experienced operators on board.

In the meantime, a reduction in onboard personnel and a reorganization of onboard activities are expected following the adoption of increasingly advanced automation, gradually moving toward autonomous ships.

3.4.2 Bunkering

The current order book for alternative fuel ships will drive the demand for bunkering facilities.

Various port and bunkering investment projects are expected, including green maritime corridors, which could potentially be instrumental in ensuring the availability of specific types of green fuels on predetermined routes, with the collaboration of ports and fuel producers.

In the context of green corridors, it would be desirable for Italy to guarantee the possibility of supplying alternative fuels or at least one alternative fuel for ships traveling, for example, between the Far East and Europe. This possibility would also allow smaller ports to benefit from fuelling, serving ships engaged in cabotage.

Biodiesel, e-diesel, and bio-methane can utilize existing bunkering infrastructure.

Ammonia and hydrogen will require the construction of new refuelling infrastructure. To avoid any potential constraints on the use of these fuels, assuming their availability, bunkering infrastructure, distribution, and storage capacities need to be sufficiently developed.

As methanol is a fuel with a flashpoint below 60°C, current bunkering infrastructure may need adjustments in this regard, although such adjustments do not involve modifications related to cryogenic aspects or high pressures.

Assuming the availability of these fuels, bunkering infrastructure, distribution, and storage capacities will be sufficiently developed to avoid any potential constraints on introduction.

3.4.3 Considerations on Changes in Vessel Operations

There is a strong connection between decarbonization and digitalization.

Fuel savings are the primary way to reduce carbon emissions. Some shipowners have already implemented real-time fleet performance monitoring systems to obtain information on the ship's energy efficiency, collecting data from onboard sensors and transmitting it to shore via satellite communication.

For this trend to continue and evolve, it is necessary for satellite data transmission systems to become more reliable, efficient, and, above all, accessible at market prices, both in terms of CAPEX (Capital Expenditure) and OPEX (Operating Expenditure).

This information will be valuable for real-time assessment of the Carbon Intensity Indicator (CII) to evaluate the amount of emissions subject to the ETS (Emissions Trading System) trip by trip, both for forecasting and managing contractual relationships with charterers, as well as assessing potential penalties for non-compliance with FuelEU regulation requirements.

4 Considerations on the Application of Possible Solutions

4.1 New buildings

4.1.1 Type of Vessel and Size

According to analyses by Clarksons[17] and information from other sources, the order book still predominantly features LNG as an alternative fuel type, followed closely by methanol and ammonia. The numbers for batteries and fuel cells remain relatively low.

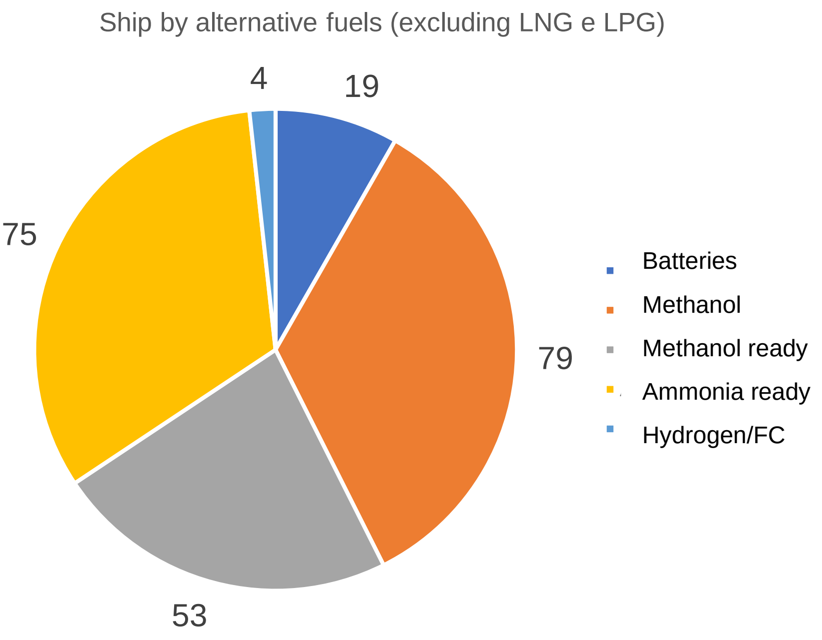


Figure 4-1: New buildings by alternative fuels (Clarksons and other sources)

	Tanker	Bulk	Container	PCC	Methanol Bunkering	Chem & Oil	CSOV	LPG	Pass/Car F.
Metanolo	0	4	63	2	6	2	2	0	0
Metanolo ready	2	0	20	12	0	6	13	0	0
Ammonia ready	0	12	20	29	0	1	4	9	0
Batterie	0	0	4	0	0	2	11	0	2
Idrogeno/FC	0	0	4	0	0	0	0	0	0

Figure 4-2: Number and type of new constructions on order based on alternative fuels.

4.1.2 Operational Profile

The operational profile plays a crucial role in choosing the right fuel or innovative solution.

Short-voyage ships such as ferries, passenger ships, and ships involved in STS operations can use low-volumetric-energy-content fuels, as they can make frequent refuelling or battery recharging stops, both onboard and onshore.

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[17] Shipbuilding Market_What's Been Ordered – 2023 – 20/06/2023.

Long-voyage cargo vessels can benefit from renewable energy sources (wind, solar), although these are highly variable depending on the operating area and time of year, route optimization based on weather and sea conditions, and speed reduction.

4.2 Existing ships

4.2.1 Type of Vessel and Size

Converting an existing ship to use an alternative fuel or installing a new solution requires a careful technical and economic evaluation based on the age of the ship and its remaining lifespan.

Regarding new fuels, it's necessary to find onboard space for new tanks and modify or replace the engines.

Among the major conversions, noteworthy are modifications to ferries for the use of LNG, with tanks on open decks and the conversion of engines to dual fuel. This type of ships has proven particularly suitable, as it allows for the installation of relatively small systems that use the boil-off of LNG without complicated installations.

Equally noteworthy are hydrodynamic and propulsion efficiency improvements made to existing vessels, which allow for a substantial reduction in emissions. Specific studies based on the new operational conditions must be conducted, and these conditions should be clearly defined during the design phase and maintained to achieve the corresponding benefits in terms of fuel consumption and emissions. Numerical calculation tools now allow for reliable predictions without the absolute need for tank tests, although tank tests remain the principal validation tool.

Cargo ships, such as large container vessels designed for high speeds, have benefited greatly from changing bulbs and propellers optimized for the new low-speed operational profile.

4.2.2 Operational Profile

All solutions for monitoring and optimizing operational profiles can be easily implemented on existing vessels and across all types of ships.

Adapting a ship with a fuel cell propulsion system is more complex than converting an engine to use an alternative fuel, as it involves modifying fuel storage and supply systems. However, building new ships with potential future conversions in mind, such as using an electric propulsion system (a well-established technology), might make the transition from engines to fuel cells a more practical proposition.

Installing fuel cells on board still requires significant modifications compared to retrofitting an engine. Unless specific safety concepts for the fuel cell are in place, the compartment containing the fuel cell must be categorized as "hazardous," and precautions must be taken to prevent the formation of pockets of explosive mixtures, especially in the upper part of the compartment.

Certainly, the ability to install new technologies or alternative fuels on existing ships, especially "drop-in" options like biofuels, can accelerate the process. In this case, as mentioned earlier, it is essential to consider any requirements and limitations recommended by engine manufacturers to avoid voiding the engine warranty.

Financial support mechanisms to cover these additional costs are encouraged in this regard.

5 Possible future scenarios

5.1 Nuclear

Meeting climate goals to reduce greenhouse gas emissions can be achieved through various solutions, and nuclear power appears to have significant potential. While nuclear power is not currently an option for merchant ship propulsion, it is undoubtedly one of the technologies capable of reducing greenhouse gas emissions by nearly 100%.

Additional advantages of nuclear power, aside from its environmental footprint, include the extremely long autonomy of a single "bunkering," a compact propulsion system relative to the power output, and the absence of exhaust gases. Economically, the initial investment must be evaluated in relation to the entire lifespan of the ship, as this upfront investment includes all costs related to fuel purchase.

However, today, forms of leasing have been devised to overcome or reduce the issue of very high initial capital expenditures (CAPEX). Still, this unfortunately introduces other contractual and legal issues during the operational phase of the ship.

One of the most critical aspects, as with all alternative fuels but especially for nuclear power, is public acceptance and the risk associated with potential acts of terrorism that may arise from its application on board.

Nuclear energy is not a new concept for maritime transport. Nuclear submarines and other naval vessels, such as aircraft carriers, have been built since the 1950s, particularly in the United States and the Soviet Union. Nuclear power has also been applied to merchant ships, albeit to a lesser extent than in the naval sector.

The most famous nuclear-powered merchant ships are the NS Savannah, the first nuclear-powered merchant ship funded by U.S. government agencies and launched in 1959, and the Otto Hahn, built in Germany and launched in 1964. The Russian merchant ship Sevmorput, built in 1988, is currently the only nuclear-powered merchant ship in service. A small fleet of Russian-flagged icebreakers is also in service.

The race for nuclear ships never really started. In the last century, the climate crisis was not a primary concern, and the oil crises occurred later. Compared to traditional fuel-powered ships, nuclear-powered ships have entailed higher maintenance and operational costs. Concerns about end-of-life disposal processes also played a significant role. Furthermore, nuclear technology is a matter of national security and subject to multi-governmental approvals. Finally, nuclear energy often fails in terms of general societal acceptance.

However, despite no recent construction of nuclear-powered merchant ships and the general sentiment against this technology, the idea has not been entirely abandoned. In recent decades, research has been conducted on both the general application of nuclear energy for marine propulsion and more detailed work on conceptual ship designs.

New reactors, such as molten salt reactors, are currently undergoing experimentation for naval uses. If installation on board these plants prove challenging, technological development could lead to the use of this technology to deploy nuclear reactors in the middle of the sea to produce alternative fuels such as hydrogen or synthetic ammonia, addressing the issue of limited renewable resources on the planet.

5.2 Power to X

Power-to-X refers to the conversion of electrical energy from renewable sources into something else (X), such as hydrogen and synthetic liquid fuels. In this case, electrical energy could be converted into hydrogen through the process of water electrolysis. This hydrogen can then be used directly or in combination with other elements, such as CO_2, to produce low-carbon synthetic fuels or chemicals.

Power-to-X processes and technologies are essential in the green transition, especially in cases where the only viable solution to achieve decarbonization targets involves the use of synthetic fuels. This is certainly the case for maritime transport, which holds much promise for the use of synthetic methanol in the not-so-distant future.

6 Final considerations

The analysis has highlighted that when considering the right solution for decarbonizing shipping, several aspects need to be considered. There is no one-size-fits-all solution for every ship throughout its entire lifespan, especially considering that emission limits will become increasingly stringent over time.

Each ship is differentiated by its type, installed power, and type of navigation. Therefore, the optimal solution should be considered based on the combination of these characteristics.

In analysing the composition of the global fleet, as shown in the latest IMO study on greenhouse gases ("Fourth IMO GHG Study 2020"), ships can be categorized based on the characteristics, and the results can be highlighted as shown in the table below:

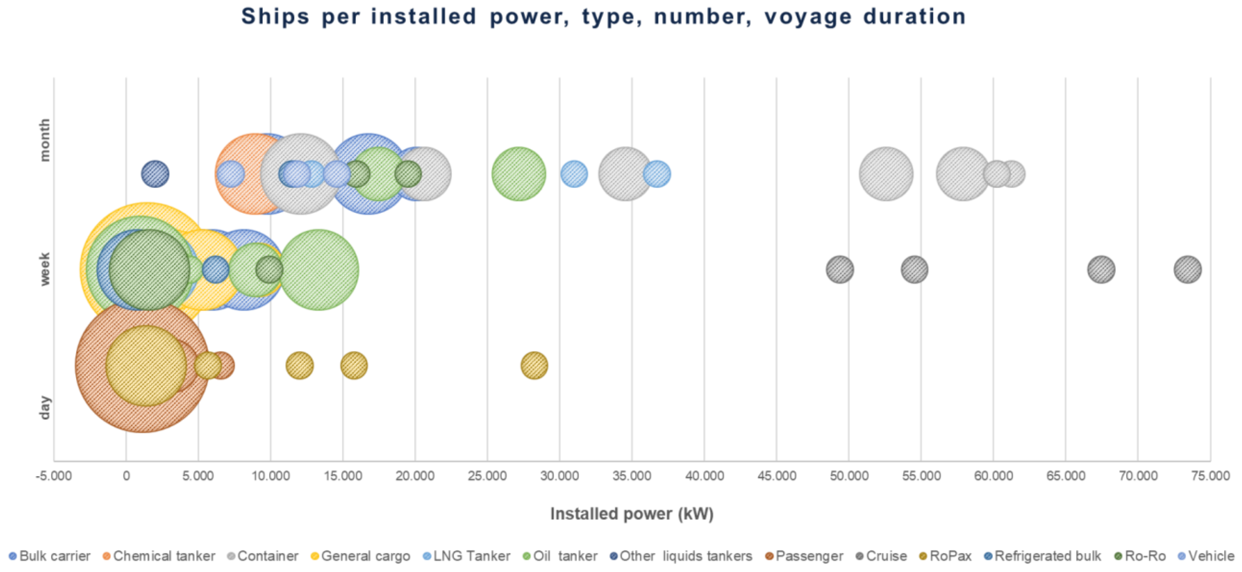

Figure 6-1: Number of ships categorized by type (colour), number (circle size), days of navigation (on the ordinate), installed power (on the abscissa).

In the table below, simplified results by category are presented without quantification of the number of ships.

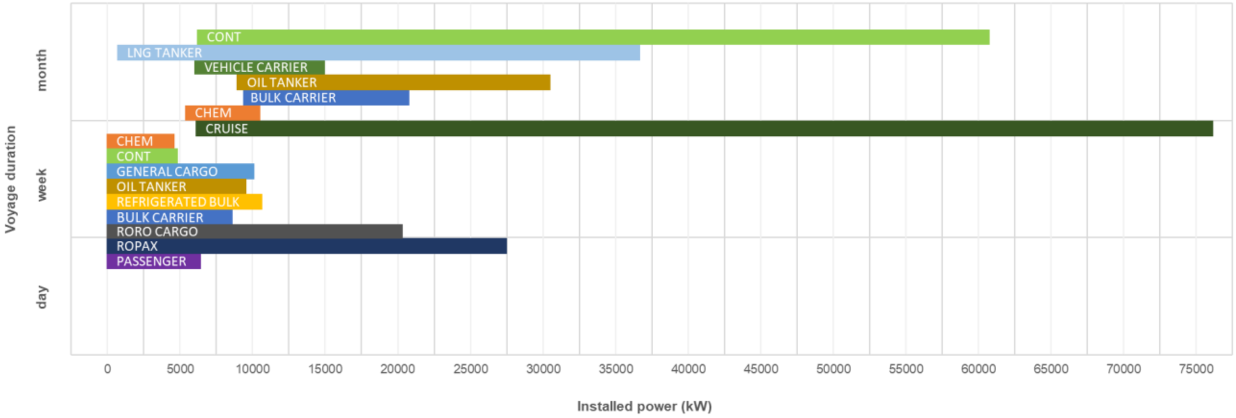

Figure 6-2: Simplified representation of ship distribution by type, navigation, and installed power

Similarly, it is possible to categorize fuels based on their potential use depending on the days of navigation and installed power on board.

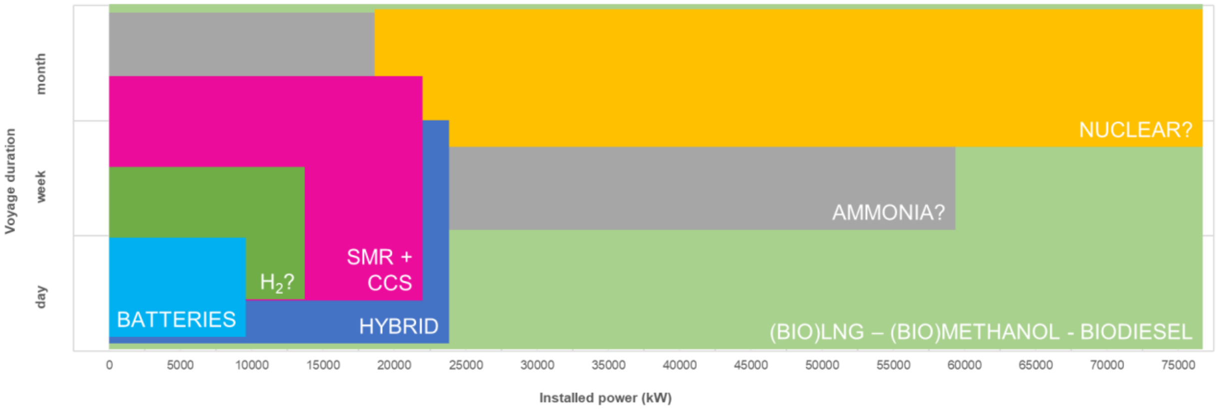

Figure 6-3: Qualitative representation of fuels for navigation duration and installed power.

By combining the characteristics of ships and fuels, it is possible to make some projections as follows concerning new constructions:

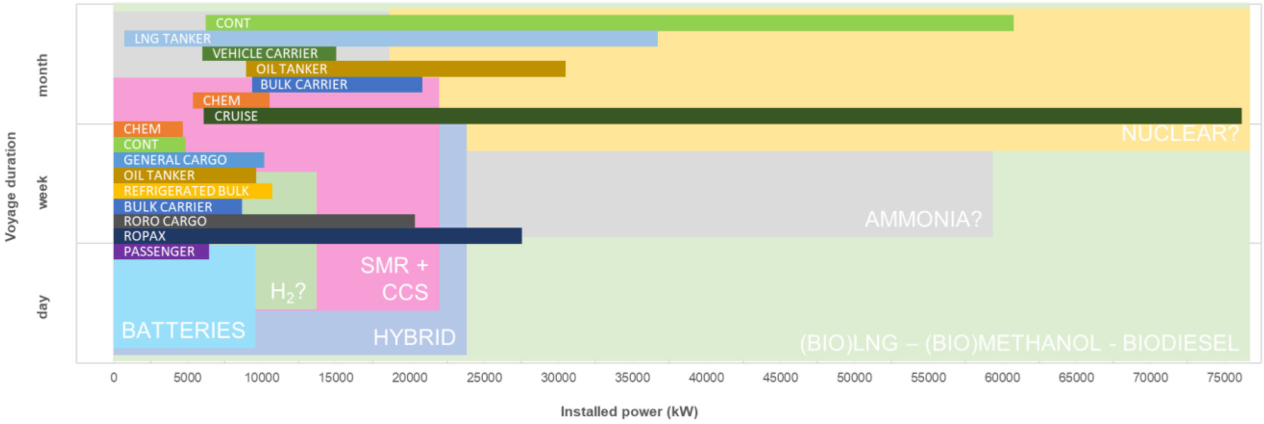

Figure 6-4: Fuel and ship type combination for key characteristics.

- Cruise ships with weekly rotation and high installed power are expected to gradually adopt LNG (available fossil, possibly bio) and then transition to bio-methanol, with the possibility of nuclear adoption in the distant future (keeping in mind the need for social acceptability of such technology).
- Long-distance container ships may follow a similar path to cruise ships due to similar power characteristics.
- Short-range passenger ships are already transitioning to LNG and may start electrification with batteries, although it depends on the evolution of energy costs.
- Medium and long-range cargo RoRo ships could drive the development of hybrid propulsion with batteries and alternative fuels.
- Tramp cargo ships will gradually transition to LNG and may explore steam reformer solutions with CO_2 capture for onboard hydrogen production.
- All other types of ships may use drop-in alternative fuels like biodiesel with the introduction of electric propulsion for short-distance vessels.
- Finally, it is not excluded that the use of CO_2 capture could gain ground for small to medium-sized ships with not excessively high installed power, using fuel cell types like MCFC, which act as CO_2 concentrators, making the process more energy-efficient.

Considering that the future fuel landscape, especially over a ten-year horizon, though not fully defined, does not rule out the possibility of developing synthetic fuels such as e-methanol and e-ammonia. It is important that there are no barriers to research, development, production, and distribution of such fuels, even at the national level, to maintain an adequate level of competitiveness for the national fleet.

Acknowledgments

We would like to express our gratitude to all the members of the RINA Decarbonization Committee who participated in the meeting on July 13th, and in particular, to the Companies and associations to which these members belong for their valuable contributions to the preparation of this document:

The Chairman of the Committee:

Dr. Salvatore d'Amico, Fleet Director of d'Amico Società di Navigazione S.p.A.

Participants from the Companies and associations who contributed with comments (in alphabetical order):

- Alphatrading
- Assarmatori
- Confitarma
- Ecospray
- Fincantieri
- Fratelli d'Amico Armatori
- Grimaldi Group
- Naos ship & boat design
- Rosetti Marino

From RINA SERVICES SPA:

- Giovanna Carosi
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