Marine Mobility and the Dilemma of Low Carbon Emissions. A technical and societal impact review

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ABSTRACT

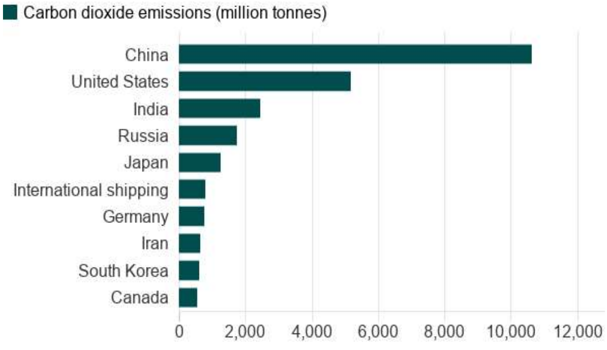
Shipping may be seen as a “barometer” of the world economy. If shipping was to be considered as a nation, it would be the 6th bigger CO_2 polluter in the world. However, dividing those CO_2 emissions by the amount of cargo transported, one can see it is one of the environment’s friendliest modes of transportation. As shipping is extremely dependent on the markets and their geographical location, vessel variables like speed, dimensions and energy efficiency, that have been well defined for decades, will need to be reviewed quickly, and with these technical changes, societal changes should also be expected. Such changes, will have a strong impact on the societies but also on the praxis of the design of marine propulsion plants, even though the support to the vessels that the ports can offer also has a strong impact on the carbon footprint of the vessel operation. One obvious way to improve the carbon footprint of the vessels, is through the improvement of the energy efficiency. Therefore new concepts of propulsion plants need to be designed, calling for new energy technologies like hybrid systems, extensive waste heat recovery, renewables and the use of new fuels with lower carbon intensity. The paper, also focuses on the comparison of future fuels and their respective carbon foot print. Finally it is presented a forecast of the future marine fuels until 2050, and some recommendations in what concerns the required research and innovation.

1. Introduction

It is well known, that the environment is not as it was some years ago, and those changes are impacting negatively most of the countries, with storms of unprecedented force, and desertification. While emissions on land are generally falling, shipping emissions are expected to increase by 5% due to the growth of international ship traffic in the Northern Hemisphere. The 7% (or €58.4 billion) contribution of shipping emissions to the total health costs in Europe in 2000 is likely to increase to 12% (or €64.1 billion) in 2020 [1].But, how to solve the problem of global heating, and what is the contribution of shipping to it? The answer is simple, through Climate regulation. In fact, it is extremely important that shipping emissions are quantified and characterized not only in terms of CO_2 emissions and other pollutants, but also in terms of the shipping segments. The IMO [2] addressed this problem in 1997 based on the Kyoto Protocol requirement to understand the climate impact of shipping and arrange possible solutions. However, despite many deadlines for action by the EU, IMO progresses were very slow and almost negligible to implement mandatory deep GHG reduction actions. Finally, after 21 years of talks between the EU and IMO, the former agreed in 2018 to a GHG strategy, even though it was a non-binding resolution recognizing the need for an eventual decarbonization of shipping. Unfortunately, IMO’s efforts have resulted in very small advances. Since the adoption of the resolution of a strategy in 2018 GHG, IMO has been pursuing a long and slow process of limited results, based on discussions on how to implement such decarbonization policies, resulting in very few advances, and a number of intentions.

Frustrated with the results obtained, the European Parliament and civil society increased calls for EU to regulate international shipping. The recently elected President of the European Commission, Ursula von der Leyen [3] expressed the wish to extend the EU Emissions Trading Scheme (ETS) or a CAP and TRADE system to maritime transport as one of the top political priorities of her upcoming tenure. This ETS was seconded by the executive vice-president nominee Frans Timmermans in charge of the European Parliament's climate action unit.

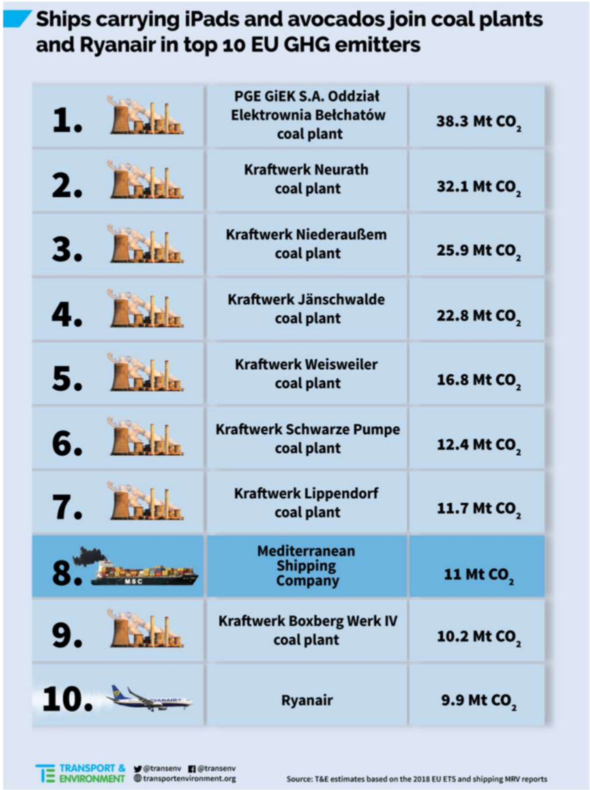
IMO Marine Environment Protection Committee (MEPC) announced that member state delegates have agreed on a target to cut the shipping sector's overall CO_2 output by 50 % by 2050, despite the fact that global shipping is not the major responsible for CO_2 emissions as it is responsible for about 2.2% of all global greenhouse gas emissions, and 2.1% of global CO_2 according to UN International Maritime Organization's most recent data as per figure 1.



Sources: International Council on Clean Transportation, Netherlands Environmental Assessment Agency

Figure 1 - International shipping emissions compared to countries in 2015.

According with the study by Transport & Environment published in 2019, the CO_2 emissions of some European shipping companies are considerable (particularly from container vessels). Figure 2, lists the top 10 CO_2 emitters, mainly Coal Power Plants, and amongst them, is MSC (Mediterranean Shipping Company) in the 8th position. One must give special attention to the type of cargo these container ships carry, namely high added value products from Asia to Europe. MSC, is the world's second largest container shipping company, releasing over 11 million tonnes of CO_2 in the atmosphere in 2018 in all journeys falling under the scope of the EU MRV. Fact that places it at the 8th position on the ranking of the most polluting companies in Europe, next to some of the most CO_2 intensive coal power plants. Another important information is that, containerized transportation of goods has more than tripled since the year 2000, and this trend is only growing*.



Ships carrying iPads and avocados join coal plants and Ryanair in top 10 EU GHG emitters

1.	PGE GiEK S.A. Oddział Elektrownia Bełchatów coal plant	38.3 Mt CO_2
2.	Kraftwerk Neurath coal plant	32.1 Mt CO_2
3.	Kraftwerk Niederaußem coal plant	25.9 Mt CO_2
4.	Kraftwerk Jänschwalde coal plant	22.8 Mt CO_2
5.	Kraftwerk Weisweiler coal plant	16.8 Mt CO_2
6.	Kraftwerk Schwarze Pumpe coal plant	12.4 Mt CO_2
7.	Kraftwerk Lippendorf coal plant	11.7 Mt CO_2
8.	Mediterranean Shipping Company	11 Mt CO_2
9.	Kraftwerk Boxberg Werk IV coal plant	10.2 Mt CO_2
10.	Ryanair	9.9 Mt CO_2

TRANSPORT & ENVIRONMENT @transenv @transenv transportenvironment.org

Source: T&E estimates based on the 2018 EU ETS and shipping MRV reports

*Figure 2 - *UNCTAD, Review of Maritime Transport in 2018, p. 8.*

2. The EEDI and the EEOI

A commonly used transport energy efficiency indicator is the dubbed transportation work, that basically relates the energy, and therefore the emissions with the mass of cargo transported through a distance. This indicator known as EEOI Energy Efficiency Operational Index, that is usually expressed in terms of ($gCO_2/tonne\ mile$), was defined by the MEPC Cir. 684 of 17 August 2009 and has many particularities to understand.

As the use of the EEOI was suggested and not compulsory, its use has been somehow neglected by the maritime industry. In order to complement a possible monitoring mechanism, a new index was introduced, the Energy Efficiency Design Index (EEDI) also defined in ($gCO_2/tonne\ mile$), and was made mandatory for new ships, as well as the enforcement of the Ship Energy Efficiency Management Plan (SEEMP) for all ships at MEPC 62 (July 2011) with the adoption of amendments to

MARPOL Annex VI (resolution MEPC.203(62)), by Parties to MARPOL Annex VI. This was the first legally binding climate change treaty to be adopted by IMO since the Kyoto Protocol.

The EEDI for new ships is an important technical measure and aimed to promote more energy efficient (less polluting) equipment and engines. The EEDI requires a minimum energy efficiency level per capacity mile (e.g. tonne mile or passenger mile) for different ship types and size segments. Since 1 January 2013, following an initial two-year phase zero, new ship designs need to meet the reference level for their ship type. This level is to be narrowed incrementally every five years, and so the EEDI was expected to stimulate continued innovation and technical development of all the components influencing the fuel efficiency of a ship early in its design phase. The EEDI is a non-rigid, performance-based mechanism that leaves the choice of technologies to use in a specific ship design to the industry.

A great difference, of about 30%* has been observed, between the EEOI (Energy Efficiency Operational Index) and the expected EEDI (Energy Efficiency Design Index) mainly due to two facts: the first is related to the difference between the ship operation in the real world conditions, weather, fouling, power level, wear and tear of machinery, but also on the port operations; the second is due to the promises EEDI figures by the ship builders that cannot be achieved, but that can be a sales argument to sell their projects.

By using the EEOI as an indicator of energy efficiency, it is possible to rank the ships in operation according to their type and tonnage. Knowing this, and considering that CO_2 will have a market cost (presently around 24€/tonne) all the ship operators must be aware of the extra cost related to their emissions and therefore their energy inefficiency. Based on the ship operational efficiency, ship CO_2 intensity is an important tool to have impact both on the environment, as well as on the economics of maritime operations.

Table 1 - Most container ships have their EEOI much higher than their declared EEDI.

THEORETICAL DESIGN EFFICIENCY				**REAL WORLD OPERATIONAL EFFICIENCY**			
Ranking*	Companies	#of ships EEDI**	(gCO_2/DWT nm)^t	Ranking*	Companies	#of ships EEOI **	EEOI (gCO_2/t nm)
1	COSCO Group	82	13.74	1	COSCO Group	85	13.24
2	Yang Ming	3	16.2	1	ONE (Ocean Network Express)		14.59
3	MSC	169	16.31	3	MSC	347	19.92
4	CMA CGM Group	175	16.33	4	CMA CGM	205	20.40
5	Evergreen Line	33	16.49	5	Evergreen	47	20.70
6	APM-Maersk	249	17.03	6	Hapag-Lloyd	123	21.13
7	ONE Ocean Network Express	47	17.96	7	Yang Ming	26	21.35
8	Hapag-Lloyd	65	18.29	8	APM -Maersk	261	22.07
9	UniFeeder	16	29.24	9	UniFeeder	30	39.02
10	X-Press Feeders Group	14	29.36	10	X-Press Feeders Group	21	43.05

** The higher position an operator holds in the ranking, the more efficient their ships/operations were.*

*** Some ships did not report their EIV OR EEDI and/or EEOI. This explains the discrepancy in the number of vessels for the design and operational efficiency scores.*
† Estimations of EIV OR EEDI for containerships assume 70% load-factor under the relevant IMO guidelines.

*According to the Transport & Environment study

Table 2 - CO2 intensity metrics for different ship types under the EU MRV Regulation

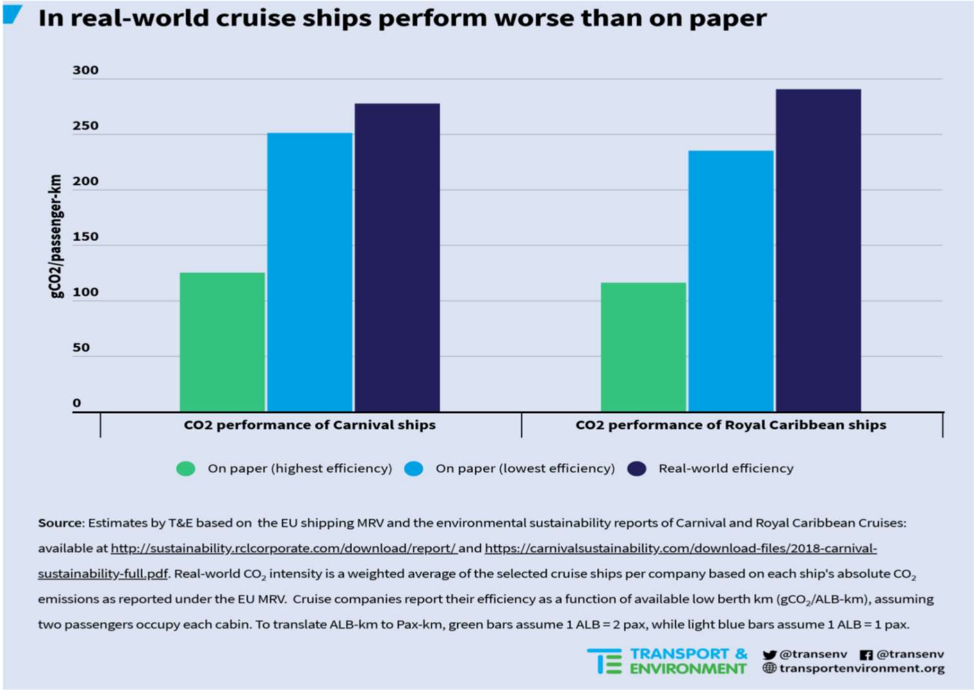
SHIP TYPES	**CO_2 INTENSITY INDEXES**	**NOTES**
Passenger, Ro-Pax	gCO_2/Pax-nm	Based on the number of passengers carried. Ro-Pax vessels also report transport work for freight by mass.
Oil tankers, chemical tankers, bulk carriers, refrigerated cargo ships, vehicle carriers, gas carriers, combination carriers, container ships, Ro-Ro, Ro-Pax	gCO_2/tonne-nm	Based on the mass of the actual cargo carried
LNG carriers, container/ro-ro cargo ships	gCO_2/m_3-nm	Based on the volume of the actual cargo carried
General cargo ships, other ship types	gCO_2/DWT-t-nm	Based on ship deadweight for laden (i.e. loaded) voyages and as zero for ballast voyages

Transport work is defined as the total amount cargo or passengers carried multiplied by the total distance sailed. Given that different ships carry different types of cargo, the units of transport work also change, i.e. tonnes NM, to passengers NM, or m^3 NM.

Another consideration regarding container ships, their EEOI is usually defines in gCO2/m3NM, this is making their EEOI not sensitive to mass transportation, as many of these vessels do their voyages, with high percentages of empty containers, i.e., not carrying weight but empty boxes. Similar problems may occur with oil tankers which usually do the return trip, empty or in ballast condition.

Cruise ships, are also important vessels in what regards the CO_2 emissions, namely, because these are high energy consumers, and their EEOI deviation in reference to their declared EEDI is even bigger.

Figure 3, represents the CO_2 performance of cruise ships of the bigger cruise companies in the world.



In real-world cruise ships perform worse than on paper

Source: Estimates by T&E based on the EU shipping MRV and the environmental sustainability reports of Carnival and Royal Caribbean Cruises: available at http://sustainability.rclcorporate.com/download/report/ and https://carnivalsustainability.com/download-files/2018-carnival-sustainability-full.pdf. Real-world CO_2 intensity is a weighted average of the selected cruise ships per company based on each ship's absolute CO_2 emissions as reported under the EU MRV. Cruise companies report their efficiency as a function of available low berth km (gCO_2/ALB-km), assuming two passengers occupy each cabin. To translate ALB-km to Pax-km, green bars assume 1 ALB = 2 pax, while light blue bars assume 1 ALB = 1 pax.

Figure 3 - Gap between EEOI and EEDI.

Finally, it is important to mention the existing use of very doubtful passenger vessels indicators, which make the use of information dubious, not allowing for direct comparisons of cruise vessels energy efficiencies with that of other vessels. In fact, the cruise industry has a peculiar index to report their energy efficiency, (gCO_2/ ALB km), being ALB that assumes two passengers per cabin. So, to understand the graph above, to compare with (gCO_2/ pax km), the value declared must be corrected as 1 ALB = 2 Passengers, but even so, the operational index is well above the lowest indicator value calculated based on 1 ALB.

3. How can shipping be less harmful to the environment?

Considering that the shipping activity includes many processes, one can say that it is important to have all the shipping processes optimized, in view of their environment impact and not only in view of profit. Therefore this question has a number of answers, namely, by having more energy efficient vessels, by using more environmentally friendly fuels, sailing at reduced speeds, and having more environmentally friendly ports, not doing half voyage loaded and the other half empty, arriving to the ports on time and also minimizing long voyages. The vision is of a ‘smart marine ecosystem’, whereby shipping stakeholders should work together using cutting-edge technologies to drive inefficiency from the entire logistics chain.

In fact, the matter is as much about the impact of shipping on the societies as it is about the impact of societies on shipping, for the shipping responds to the world economy that by itself reflects the interests of the societies. So, one possible way, would be the relocalization of manufacturing to locations nearer the consumers. This measure would have a strong impact on the container shipping emissions, as most of these vessels perform the transportation of manufactured products, mainly from Asia to the Western world, returning to Asia almost empty. The rethinking of the world economy based on the sustainability would bring more jobs to the Western countries (fighting with high youth unemployment) creating more social sustainability, but also a better “justice” in what concerns the emissions of the exporting countries, as Asia manufacturing countries are paying a high cost with the degradation of their environment. So, the rules of the global economy and the markets must be reviewed to consider the environment sustainability and the social impacts as trade variables.

4. Regarding the propulsion plants, what can be done?

Remembering that a vessel propulsion power is approximately proportional to its speed through the water to the cube, and that speed is a market request, therefore the propulsion plant must be capable of delivering such power, to allow the vessel operation in the desired market. If one looks into the propulsion plant of any commercial vessel (or any other type of vessel) it is easy to conclude that the power of such plants is ranging from hundreds of kW for very small vessels to hundreds of MW for cruise and container vessels. As a consequence, vessels, need to be fueled by a high energy density fuel, as hull volume is limited for any other good than cargo, i.e., a comprehensive quantity of energy to volume ratio must be provided, which is only possible by using hydrocarbon-based fuels or nuclear power so far. Other types of propulsion technologies, namely wind propulsion, may be considered as well, but the levels of speed would not be the same as they are presently, and the predictability of deliveries is not the same, as wind may not blow all the time.

Despite of the nowadays technical advances on ship systems, most of the ship-owners are still ordering their vessels with a minimum of energy saving systems as they are usually looking at the cheaper and not necessarily the most efficient ships, or being deceived by shipyards and ship designers. In fact, the cost of not investing on ship energy systems, can cost many times their investment throughout the ships life. On the other hand, market freight rates are not helping ship owners to order energy efficient ships, by the contrary, they push for cheap vessels while constraining their profits to a minimum, making it so that no money for investment is available. Finally, despite of all the technological advances in the main and auxiliary machinery, the thermal efficiency of a slow speed two stroke engine is just about 50%, which means 50% of the energy in the fuel is wasted. The overall thermal efficiency of a typical small feeder vessel of 6000 TDW equipped with a four stroke, medium speed main engine is only about 33% efficient, translating to a waste 67% of the energy used!

Summarizing, it can be said that the solution does not fall over the ship-owners, but also over the market players, freighters and authorities that must implement a CO_2 trading scheme, similar to the one existing for the shore industry, therefore pushing the industry players as a whole.

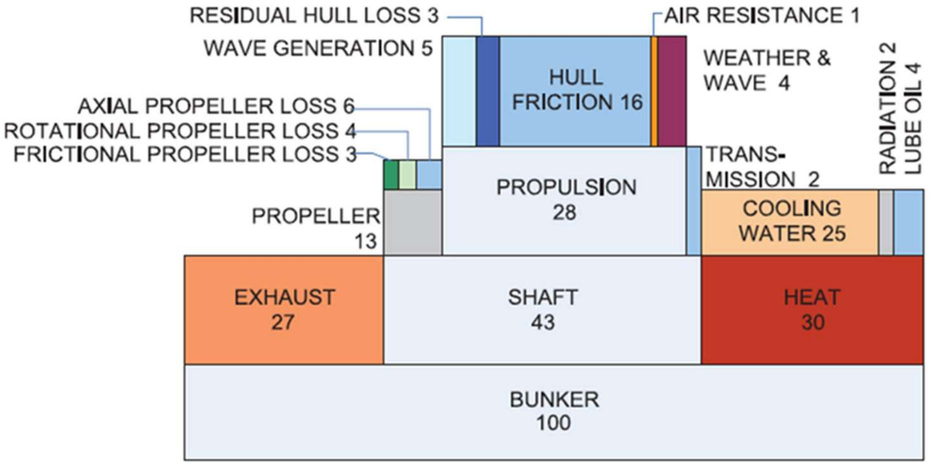


Figure 4 - Energy segregation of a small cargo vessel head sea, Beaufort 6.

During the recent years, ships have been scrapped due to their alleged impossibility of being sufficiently efficient in terms of energy, and have been replaced by vessels that unfortunately have only slightly higher energy efficiency. In fact, since about one and a half century ship energy efficiency have been just around 25 to 35%, this means that in the best, 65% of the energy is wasted in its heat form. Only a fraction of the fuel energy used by the ship's main engines actually ends up generating propulsion thrust.

This is illustrated in Figure 4, which represents a small well-maintained short sea container ship moving at about at 15 knots in Beaufort 6 head weather condition. The bottom bar in this diagram represents the energy input to the main engine from the fuel to which one needs to had the energy used on auxiliary boilers and generators. In this case, 43% of the fuel energy is converted into shaft power while the remaining energy is lost in the exhaust or cooling systems and radiation. Due to further losses in the propeller and transmission system, only 28% of the energy from the fuel that is fed to the main engine generates propulsion thrust in this example. The rest of the energy ends up as heat, dumped into the atmosphere and sea, and as transmission and propeller losses. The majority of these remaining 28% are spent to overcome hull friction, while the remaining energy is spent in overcoming wave resistance, air resistance, as well as residual resistance. Additionally, to the consumption of the main engines, one must add the fuel for the operation of the auxiliary engines and boilers.

5. Energy requirements of a ship and its consumption structure

Total energy consumed in a ship E_t is expressed as follows:

$$E_t = E_p + E_a \qquad (1)$$

Where, E_p is propulsive energy and E_a is energy for auxiliaries and miscellaneous uses. E_a is divided into heat (thermal energy) and electric energy in respect of energy form, and each of these forms is further divided into the energy for supporting the main engine operation and the energy for other miscellaneous services in respect of the use, being the Ea proportional to the power of the propulsion plant, such that:

$$\begin{aligned} E_a &= E_{aT} + E_{aE} = \\ &= (a_{T1} + a_{T2} \cdot P_m) + \\ &\quad +(a_{E1} + a_{E2} P_m) \end{aligned} \qquad (2)$$

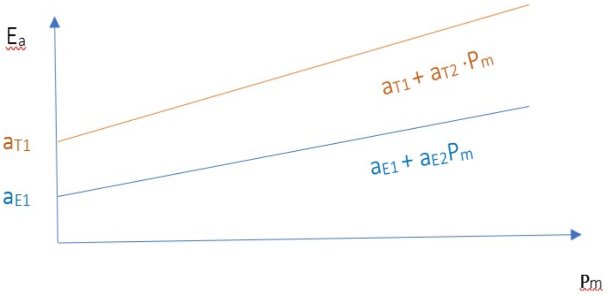


Figure 5 - Ship auxiliary power components .

Where:

E_{aT} – Auxiliary thermal energy (kW);

E_{aE} – Auxiliary electric energy (kW);

P_m – Main engine installed brake power (kW);

a_{T1}, a_{E1}, – constants corresponding to the minimum of energy requirements (kW).

a_{T2}, a_{E2}, - constants of proportionality of the energies to the installed power of main engines.

If the energy efficiencies of the main engines, the auxiliary engines and the boilers are respectively η_m, η_{aE} and η_{aT}, the total energy consumption of a ship equals to:

$$\left(\frac{E_P}{\eta_m} + \frac{E_{aT}}{\eta_{aT}} + \frac{E_{aE}}{\eta_{aE}}\right) \qquad (3)$$

Now, introducing the transportation energy performance e_t, expressed in (kJ/t km) or (kJ/t NM) as defined above, it can be expressed as follows:

$$e_t = e_p + e_a =$$

$$= \frac{3600}{WV}\left(\frac{E_P}{\eta_m} + \frac{E_{aT}}{\eta_{aT}} + \frac{E_{aE}}{\eta_{aE}}\right) \quad (4)$$

Where:

e_p - energy consumption rate of main engine in (kJ/ t·km);

e_a - energy consumption rate of auxiliaries and miscellaneous services in (kJ/ t·km);

W - cargo holding capacity, that is expressed as dead weight (ton);

V - ship speed over ground (VOG) (km/h or NM/h = knots);

Ep/WV in the equation is also expressed as follows,

$$\frac{E_P}{WV} = \frac{P_m}{WV} = 2.72\,\frac{1}{\eta_t}\frac{1}{\eta_p}\frac{RV}{W_T V}\frac{W_T}{W} \quad (5)$$

(kw·h/t·km) or (kw·h/t·NM)

Where:

η_t - transmission efficiency;

η_p -propulsion efficiency $\eta_p = \eta_{p0}\,\eta_r\,\frac{(1-t)}{(1-w)}$

η_{p0} – open water propeller efficiency;

η_r – relative rotative efficiency;

t – thrust deduction friction;

w - wake fraction;

R – Total of hull and appendages;

W_T – displacement (ton).

The term W_T/W in the right side of equation (5) is considered as representing the cargo holding performance, of which reciprocal W/W_T is defined as the cargo holding efficiency η_C· As a result the transportation energy performance e_t can be expressed by the following equation (6),

$\eta_t\ \eta_p\ \eta_{p0}\eta_r t\ wRW_T$

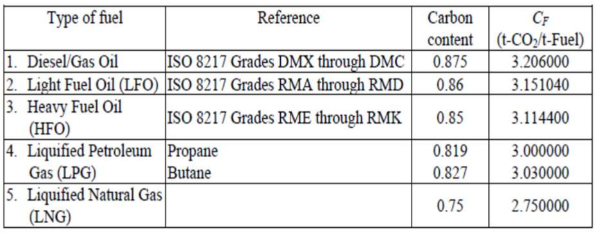
$$e_t = \left[9800\left(1 + \frac{\eta_m}{\eta_{aT}}\,a_{T2} + \frac{\eta_m}{\eta_{aE}}a_{E2}\right)\frac{1}{\eta_m}\,\frac{1}{\eta_t}\,\frac{1}{\eta_p}\,\frac{R}{W_T}{}' + 3600\left(\frac{a_{T1}}{\eta_{aT}} + \frac{a_{E1}}{\eta_{aE}}\right)\frac{1}{W_t V_c}\right]\frac{1}{\eta} \quad (6)$$

(kJ/tonkm, or kJ/tonNM)

Therefore, it is evident, that transportation energy performance depends on the efficiency of all the main and auxiliary equipment's, largely on the installed power of the propulsion plant, that ultimately is a consequence of the desired operational peed of the vessel, but also on the vessel's displacement and its cargo holding efficiency. Therefore, vessels should operate at their rated cargo capacity, which is not happening with most container vessels, as well as in other types of vessels, that are loaded only for half of their courses.

Also important to note, is the fact that energy is dependent on the speed through the water (and therefore on the weather conditions) and that energy can be easily translated into emissions by using simply using the emissions factors as defined in the IMO Cir.684 (see table 3).

Table 3 - Fuel mass to CO_2 mass conversion factors (CF)



Type of fuel	Reference	Carbon content	C_F (t-CO_2/t-Fuel)
1. Diesel/Gas Oil	ISO 8217 Grades DMX through DMC	0.875	3.206000
2. Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	0.86	3.151040
3. Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	0.85	3.114400
4. Liquified Petroleum Gas (LPG)	Propane Butane	0.819 0.827	3.000000 3.030000
5. Liquified Natural Gas (LNG)		0.75	2.750000

C_F is a non-dimensional conversion factor between fuel consumption measured in g and CO_2 emission also measured in g based on carbon content. The value of C_F is as per table 3, that summarizes the CO_2 emissions factors (as per

MEPC Cir.684 for the calculation of EEDI and EEOI) and the respective calorific values and emissions factors of some candidate fuels for the marine transportation.

6. The future marine fuel path.

In order to make a decision for a new fuel, there are a number of criteria that have to be fulfilled. There is no "best fuel", but a fuel that is more advantageous considering a number a variables to the ship owner and its ships and their respective operation.

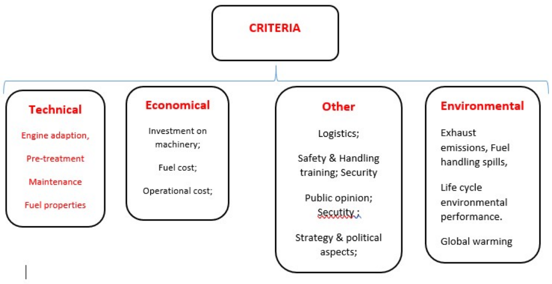


Figure 7 - Possible considerations criteria for the decision of a marine fuel

Regarding the marine fuel pathways, it may be important to understand that carbon foot print of the fuel must be considered "*from well to ship*", and that can be very different from fuel to fuel but not negligible. Figure 8 below, represents possible pathways from source to propulsion plant.

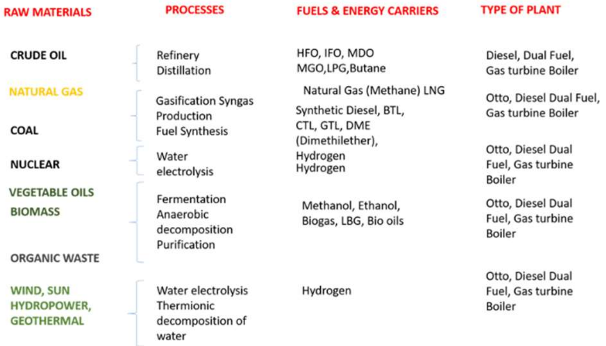


Figure 8 – Carbon foot print path ways.

For example, the use of LPG, may have a lower carbon footprint that natural of gas, as LPG, is a byproduct of the refining process, therefore its carbon footprint, is shared by other fuels obtained from the distillation of crude. The same applies to other refinery by products such as the marine fuels. By opposition, LNG has an extensive carbon foot print, if its not obtained as a byproduct, and considering the energy required for liquefaction and transportation. As it can be seen on figure 8, there are a number of propulsion plant technologies that are flexible, namely Dual fuel engines based on Diesel cycle, Boilers, Gas turbines, each one of them being more adequate to certain types of fuels and vessels than others. So, a criterious choice of propulsion plant technology is a very important step towards the CO_2 emissions and quantities required by the vessel operation.

The extensive use of Diesel or (natural gas fueled Otto) electric propulsion plants, in particular of variable frequency may mitigate inherent efficiency difficulties of operation in part load conditions or non-standard operation, making easier an optimized energy management, as well as plant reliability.

7. The fuel mix, the difference between the theory and the practice.

As there is always a difference between the practice and the theory, and as the shipping industry will not change from one day to another, there will be a transition time, towards the decarbonization of shipping, that is the same to say, that in the future there will the same marine fuels as before plus some new fuels, resulting in a fuel mix.

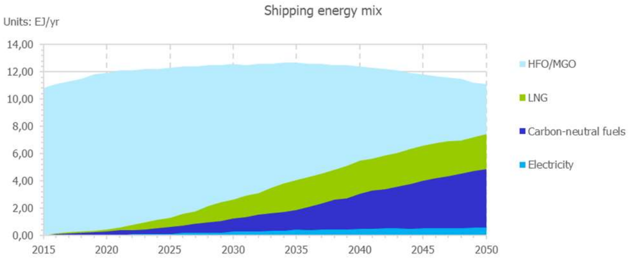


Figure 9 – Shipping energy mix forecast until 2050

(1EJ=278 TWh)

Based on figure 9, it is evident that marine hydrocarbon fuels like HFO and MGO, will be dominant by 2050, although reaching their maximum by 2035, after which a slow decay of their use will take place. This is so, in a "business as usual" environment, and considering the technologies as they are at the present, having the carbon neutral fuels, by 2050 a quota of about 39%.

8. Green fuels and CO_2 neutral fuels which are the solutions and forecasts.

The options regarding marine fuels, are not many, but there are some considerations regarding the marine fuels or energy carriers that are worthwhile to expose, and these are summarized as follows.

Table 4 - CO_2 emissions factors and the respective net calorific values for the most common marine fuels. **The emissions associated to ammonia production are quite high, due to natural gas reforming, as well as the energy required for the process. ** If hydrogen is produced by electrolysis using renewable, or nuclear power, its CO2 emissions are virtually zero.*

Fuels	Emissions Factor	Net Calorific Value
Natural Gas (LNG)	2.7500 Ton CO_2/ Ton	48.75 MJ/ kg
HFO (RME-RMK)	3.1151 Ton CO_2/ Ton	41.20 MJ/ kg
Diesel Gasoil (MGO)	3.2060 Ton CO_2 / Ton	42. 20 MJ /kg
Methanol (CH_3OH)	1.3865 Ton CO_2 /Ton	20.10 MJ/kg
Ammonia (NH_3)	0.0000 Ton CO_2/ Ton*	119.93 MJ/kg
Hydrogen (LH_2)	0.0000 Ton CO_2/ Ton**	120.00 MJ/kg

As can be deduced from Table 4, Natural gas, the promised marine fuel, is not so different, in terms of CO_2 emissions, from the blackest fuel on the list, the HFO (RME-RMK), being even worst if the emissions related to extraction, its production and transportation are considered, namely, liquefaction and transportation, this considering that HFO is a refinery byproduct. The other options, like Methanol may be considered, but the extensive use of methanol may not be possible due to its availability worldwide and because its massive production would require considerable use of natural resources.

Hydrogen, stands out as the stronger candidate, as it is burnable in most reciprocating engines, namely diesel engines (that do not need high purity hydrogen), and may be produced virtually in any port (or nearby) by using renewable energy, or by using the excess of energy in the grids occurring mainly during the night, in particular in energy networks where nuclear power is available in excess. However, hydrogen will be most certainly produced by reforming of natural gas, with the capture of the carbon resulting from this chemical process. As so, CO_2 capture technologies will have a strong role to play in a near future, in particular to make hydrogen available for propulsion purposes. Hydrogen, can be dubbed as “green” or “black”, depending on the process used to obtain it, namely through the use of renewable energies, by using dedicated renewable energy plants (wind power, solar, photovoltaic, biological or nuclear), or making use of natural gas reforming, or simply using electricity produced by power plants using hydrocarbons.

The low energy density of compressed hydrogen gas makes storage and transportation expensive, consuming considerable quantities of energy for production, liquefaction and storage. Liquefied hydrogen is more energy dense than compressed hydrogen gas but a significant amount of energy must be expended to liquefy hydrogen and keep it refrigerated because its boiling point is –253 ºC. Liquefaction requires about 30% of the energy content of liquid hydrogen while compression to 800 bar requires about 10-15% of energy carried by the hydrogen depending on the compression technology. Hydrogen's molecules are very small and difficult to contain. Hydrogen also causes embrittlement of metals.

A plan to facilitate the transition from fossil to renewable and nuclear sources, would first replace fossil with renewable fuels (hydrogen, or fuels that are carbon neutral). The strategy stipulates that all energy sources (fossil, renewable, and nuclear) will be most efficiently monetized by conversion to three energy vectors: electric, power and two liquid renewable fuels, all compatible with existing infrastructure, enabling global carbon emissions to be reduced significantly early in the transition, perhaps by as much as an order of magnitude by 2030. At completion of the transition, fossil sources will be replaced by renewable (and perhaps nuclear) sources.

Considering this plan of action there are many discussions about the use of Ammonia as an interesting energy carrier.

Is the use of anhydrous ammonia rather than hydrogen better?

Using ammonia (NH_3) as an energy carrier is not a novelty as such possibility has been discussed for the last 40 years. Ammonia has several distinct advantages over hydrogen gas. It can be stored at much lower pressures, typically is liquid at 25ºC at a pressure of 25 bar, or as compressed gas at 5 to 10 bar, it is already distributed in millions of tonnes a year, it is liquid at ambient temperature and pressure, and as so high energy density may be achieved, and can be used as a fuel in internal combustion engines. However, ammonia poses serious technical and environmental challenges, in particular due to its production.

Most of the production of ammonia is based on the Haber-Bosch process, and this process is based on the reforming of natural gas to produce the hydrogen rich gas that is combined with nitrogen at high temperature (350-550ºC) and pressure (100-250 bar) to yield ammonia, while consuming a considerable quantity of energy per kg, between 30 and 38 MJ/kg of ammonia. Also, the Haber-Bosch process requires a considerable quantity of hydrogen, produced from natural gas reforming, therefore resulting in considerable production of carbon that must trapped somehow. While carbon trapping technology, is not economically available, the mass production of ammonia is compromised.

Ammonia's advantages as an energy vector are: its boiling point being -33.35 °C, the small rates of leakage being easily detectable by the humans, producing no embrittlement of metallic parts. Leakages dissipate into the atmosphere where it is eventually destroyed through photodissociation although the consequence of ammonia emissions, apart of being harmful to people, will produce eutrophication and acidification of soils and waters. Ammonia is also a promoter of particulate matter $PM_{2.5}$ through a mechanism where NH_3 becomes NH_4 resulting in ammonium salts which are themselves the Particulate Matter.

According to 2018 report by the UN's Intergovernmental Panel on Climate Change (IPCC) [4], nuclear power is "essential" if the world is to keep global warming to below its 1.5C temperature rise target, as laid out in the 2015 Paris Agreement. Using nuclear power stations, cheap electricity may be used in large quantities virtually without the emissions of CO_2, and therefore making possible the extensive use of hydrogen.

9. Conclusions

The emissions, may be decreased by taking operational actions namely making the use of energy more efficient, some of these actions have been put in place by the industry already; like the slow steaming, just in time, or by increasing the vessels sizes, and by revamping the vessels systems. Although the results are not sufficient to respond to the environment urgency, and it will be certain that a "CAP and Trade" system, will put in place making shipowners to pay the cost of their energy inefficiencies.

The decarbonization of shipping, do not rest only with the shipowners, but also with the ports, as the markets, call for faster deliveries, of the goods produced far a way of the markets.

The use of new fuels must be very well evaluated, in order to keep the carbon footprints lower that they are presently, in particular it is important to understand the fuels "well to propeller" carbon footprint.

The higher is the power of the propulsion the higher the power the corresponding auxiliary machinery, originating a proportional emission in particular in port, but also, deteriorated energy efficiencies all the time they operate far from their optimized matching point. So, energy recovery systems, and systems integration should be installed to recover the energy from high and low temperature dumping systems. This energy can be stored, for example as hydrogen to run the generators in port, therefore reducing drastically the port emissions.

The shipping industry emissions, are not limited to CO_2, but also to many other pollutants, like Particulate Matter, which is responsible for many deaths in Europe and elsewhere with costs to the populations and countries. Although the particulate matter as other pollutants are not regulated.

In a “Business as Usual” scenario, HFO and Marine Diesel, will be onboard most ships beyond 2050, but their decline will be around 2035, as other fuels will take place on the market, but these are dependent on the maturity of the required technologies.

Decarbonization of shipping is the bigger and probably the tougher step the shipping industry must consider in a near future.

The impact of decarbonization will be much stronger, than the impact of ultra-low Sulphur fuels (commenced in 1st January 2020) as it is more difficult to solve requiring the implementation of global strategies, having very well defined pathways, in order to avoid extremely costly mistakes.

Decarbonization, has a strong positive impact on the world population, by promoting local or regional manufacturing instead of overseas manufacturing generating unemployment in consuming countries (importers).

Decarbonization will call for innovation in technology, which already exists, but needs to be improved and stimulated in order to use new fuels. There is no doubt, that hydrogen in its various forms and nuclear power will be hand in hand and will be a solution for the shipping of the future, at least while carbon trapping technologies are not available at reasonable cost. In any case, there is an urgent need of developing cost-efficient hydrogen production, storage and handling systems, as well as develop and improving the technology to overcome the possible embrittlement of metals, as well as the optimization of combustion systems to operate with hydrogen, such as reciprocating engines and turbines.

If the objectives of the decarbonization are to be achieved within the time set by EU and UN, only hydrogen can be the solution to the problem, making virtually impossible the close down of nuclear power stations, for the production of electricity at a very low cost, without CO_2 emissions.

The power in use onboard most commercial deep sea vessels, is not compatible with the use of Fuel Cells, although, these can be used concomitantly with higher power systems, like Diesel engines and Turbines.

References

[1] E. Commission, “Science for Environment Policy,” SCU, The University of the West of England, Bristol, 2013.

[2] I. I. M. Organization, “Low carbon shipping and air pollution control,” IMO International Maritime Organization, 2018. [Online]. Available: http://www.imo.org/en/MediaCentre/HotTopics/GHG/Pages/default.aspx. [Accessed 2 2020].

[3] E. F. f. T. &. E. AISBL, “EU Shipping Climate Report - Maritime CO2 emissions and real-world ship efficiency performance,” Transport & Environment, Brussels, 2019.

[4] V. P. Z. H.-O. P. D. R. J. S. P. S. Masson-Delmotte, “IPCC, 2018: Global Warming of 1.5°C.An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of clim,” In Press., 2019.

[5] D. G. AS, “Maritime Forecast to 2050 Energy Transition Outlook 2018,” DNV GL, 2018.

[6] R. M. A. P. R. J. M. Gomes Antunes, “Conversion of large-bore diesel engines for heavy fuel oil and natural gas dual operation,” in *UK. Motorship Gas Conference 2012*, Rotterdan, 2012.

[7] G. M. Kimball, “Ammonia for Renewable Energy Systems,” *Department of Chemistry, California Institute of Technology.*

[8] J. M. G. Antunes, R. Mikalsen and A. P. Roskilly, “An investigation of hydrogen-fuelled HCCI engine performance and operation,” *International Journal of Hydrogen Energy,* no. 33, pp. 5823-5828, 2008.

[9] J. M. G. Antunes, R. Mikalsen and A. P. Roskilly, “An experimental study of a direct injection compression ignition hydrogen engine,” *International Journal of Hydrogen Energy,* no. 34, pp. 6516-6522, 2009.

[10] J. M. G. Antunes, J. Correia, P. Ribeiro and T. , “Retrofitting older vessels, a sustainable approach and a sounder economic sense,” in *Motorship Propulsion & Emissions Conference*, Hamburg, May 2014.

[11] J. M. G. Antunes, “Tools for the control of ship emissions and energy and the new IMO regulations”.

[12] S. Maritime and E. Engineering, “Energy Management ECA Retrofit Technology - Scrubber Retrofit Description,” 2011.

[13] S. Maritime and E. Engineering, “ECA Retrofit Technology - LNG Retrofit Description - Steel work on upper deck,” 2011.

[14] L. Register, “Design Review of Scrubber Option & LNG as a Fuel Option,” 24 November 2011.

[15] M. B&W, “Green Ship of the Future, SECA Project - ME - GI retrofit description,” in *4th Annual Asia Green Shipping Conference*, Singapore, 2014.

[16] J. Antunes, “Ship Benchmarking,” Tecnoveritas, 2012.

[17] J. Antunes, “Ship Energy Performance Monitoring,” Tecnoveritas, 2012.

[18] J. Antunes, “Monitoring & Targeting a Tool for Lean Management of Energy,” Tecnoveritas, 2008.

[19] J. Antunes, “Ship Key Performance IndicaTORS,” Tecnoveritas, 2012.

[20] J. Antunes, “Voyage analysis and in service monitoring,” Tecnoveriats, 2012.

[21] J. Antunes, “Hull roughness and power increments,” Tecnoveritas, 2011.

[22] MAN, “Improved Efficiency and Reduced CO2”.

[23] MAN, “SFOC Optimisation Methods for MAN B&W Two-strokes IMO Tier II Engines”.

[24] MAN, “Waste Heat Recovery Systems for Reduction of Fuel Consumption, Emission and EEDI”.

[25] MAN, “Basic Principles of Ship Propulsion”.

[26] A. Bhatia, “Improving Energy Efficiency of Boiler Systems,” *Course No: M06-022; Credit: 6 PDH.*

[27] H. TC., “Waste heat recovery of organic Rankine cycle using dry fluids,” *Energy Convers Manage,* no. 539, pp. 42-53, 2001.

[28] O. P. P. R. S. Badr O, “Rankine-cycle systems for harnessing power from low-grade energy sources,” *Appl Energy,* no. 36, pp. 263-92, 1990.

[29] A. G. K. I. Erickson DC, “Heat activated dual-function absorption cycle,” *ASHRAE,* no. 110, pp. 515-25, 2004.

[30] S. IK., “Power plant cycles and processes - Profiting fron low-grade heat, thermodynamic cycles for low-temperature heat sources,” Crook AW, London, 1994.

[31] M. M., Availability analysis: a guide to efficient energy use, 2nd ed, New York: ASME, 1989.

[32] K. G. W. M. F. J. Saleh B, “Working fluids for low temperature organic Rankine Cycles,” *Energy,* no. 32, pp. 1210-21, 2007.

[33] T. W. C. o. Energy, “Profiting from low-grade heat,” No 26, London.

[34] W. J. Tucker R, “Identifying and quantifying energy savings on fires plant using low cost modelling,” *Appl Energy,* no. 89, pp. 127-32, 2011.

[35] T. D. B. D. H. G. T. B. G. A. e. a. Linnhoff B, “A user guide on process integration for the efficient use of energy,” Institution of Chemical Engineers, Rugby, England, 1994.

[36] ExxonMobil, “ExxonMobil releases new outlook for energy: a view to 2030,” 2007.

[37] W. J. G. L. Dai Y, “Parametric optimization and conparative study of organic Rankine cycle (ORC) for low grade waste heat recovery,” *Energy Convers Manage,* no. 50, pp. 576-82, 2009.

[38] T. a. T. R. Department of the Environment, “Waste Heat Recovery in the Process Industries. Good practice guide.,” Didcot (Oxfordshire), 1996.