Is new emission legislation stimulating the implementation of sustainable and energy-efficient maritime technologies?

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Is new emission legislation stimulating the implementation of sustainable and energy-efficient maritime technologies?

Abstract

There is a significant increase in the attention given to green maritime ship technologies due to the growing importance of sustainable operations. The driving force behind this development is the implementation of several new legislative actions taken by the International Maritime Organisation (IMO) and the European Union (EU). One of the main questions that arises is whether this new emission legislation stimulates the implementation of sustainable energy-efficient maritime technologies.

In this paper, a framework is developed that allows linking the different emission legislation initiatives in different countries with the technical energy-efficient solutions that could be used to comply with the legislation. Based on this framework, the main research question can be answered. It turns out that the EEDI (Energy-Efficient Design Index) does not in the first place stimulate the introduction of new ship engine technologies nor the use of alternative fuels, but rather makes shipping companies order ships with a reduced design speed. SEEMP (Ship Energy Efficient Management Plan) on the contrary makes companies shift to bi-fuel engine systems, rather than fully to alternative energy systems. The findings are of relevance both to policy-makers and to shipping companies.

Keywords: Energy efficiency, emission legislation, maritime technologies, retrofitting, maritime pollution policies

1. Introduction

There is a significant increase in the attention given to green maritime ship technologies due to the growing importance of sustainable operations (see for instance Rizet et al., 2014, Aluvinen et al., 2014, Blinge et al., 2014, Evangelista, 2014). The driving force behind the increase of this importance is the implementation of several new legislative actions taken by the International Maritime Organization (IMO) and the European Union (EU).

Policies by different international organizations and institutions impose international environmental limits on their member states to restrict the emission of greenhouse gases. Business as usual could have a direct and short-term impact on human life and health and it will have a global and long-term impact on climate change (Laffineur, 2012). As a consequence, limiting exhaust emissions has become an important item for these organizations. There is even not any regulation for PM emissions despite the health issues and consequential costs related to these emissions.

Shipping is one of the sectors hit by such stricter legislation. New vessel designs are often a specific answer to a specific logistics problem. Its size, main dimensions (quay length, draughtt), design speed (preferable crossing time often maximum eight hours) and cargo type (cassettes and/or trucks) can have large influences on their profitability in a certain trade. As a consequence, the policies imposing specific solutions can jeopardize specific trades due to the limitations in installed power. The consequence for existing ships could be that the really fast vessels will stay longer in service. This is the case for all ship types, including passenger transport, general cargo and container ships.

The question is how shipowners will react to this new legislation. More specifically: are ship-owners going to implement new innovative technologies in either their new building projects or are they going to retrofit their existing ships due to this new legislation?

In order to answer this main research question, first, a literature review is made in section 2 of the severity of emission problems by shipping and the outlook for the future. Next, section 3 gives an overview of the emission legislation. This overview was constructed based on a literature review. Furthermore, an additional overview is drafted in section 4 with the possible technical solutions to reduce emissions either due to a reduction of fuel consumption or only by pure emission-reducing techniques. This overview was constructed via desk research, comprising various reports, studies and scientific articles. For each of these technologies, it is indicated whether it is only applicable to newbuildings or whether it can be installed as a retrofitting effort (installed on an existing ship). After these two overviews, a framework is developed in section 5 to link the previously mentioned policies with the new maritime technologies. This framework is applied in section 6 to analyse the applicability of these new technologies to either newbuilding projects or retrofitting projects, through quantification of the observed impacts. The paper ends in section 7 with a number of conclusions and recommendations for policy makers and sector members.

2. Literature review on shipping and related emissions

In order to frame international shipping from an environmental perspective, it can be stated that it contributes to about 3% of global CO_2 emissions (Eide *et al.*, 2009), while it transports almost 90% of the world trade (Laffineur, 2012). IMO (2015) reports for the year 2012 total shipping CO_2 emissions at approximately 938 million tonnes. International shipping emissions for 2012 are reported to be 796 million tonnes CO_2, whereby it represents 2.2% of global CO_2 emissions.

IPCC (2013) reports that, for the period 2007–2012 on average, shipping accounted for approximately 3.1% of annual global CO_2 emissions, using 100-year global warming potential conversions. Their multi-year average estimate for all shipping using bottom-up totals for 2007–2012 is 1,015 million tonnes of CO_2. International shipping in their calculations accounts for approximately 2.6% of CO_2 emissions, with a total for 2007–2012 of 846 million tonnes of CO_2. These multi-year CO_2 comparisons are just slightly smaller than the 3.3% and 2.7% of global CO_2 emissions reported by IMO (2010b) for total shipping and international shipping in the year 2007, respectively.

From this perspective, the contribution of international shipping to environmental pollution is small. However, there are more emissions than only CO_2. Maritime shipping is a large contributor to NOx and SO_x emissions: IMO (2015) reports 961 million tonnes CO_2 equivalents for GHG's combining CO_2, CH_4 and N_2O by global shipping. International shipping contributes by 816 CO_2 equivalents, representing 2.1% of global GHG emissions. Multi-year (2007–2012) average annual totals are at 20.9 million and 11.3 million tonnes for NOx and SOx from all shipping, respectively, corresponding to 6.3 million and 5.6 million tonnes converted to elemental weights for nitrogen and sulphur, respectively. International shipping is estimated to produce annually approximately 18.6 million and 10.6 million tonnes of NOx - and SOx, respectively, which converts to totals of 5.6 million and 5.3 million tonnes of NOx and SOx. Methane (CH4) emissions from ships increased over the 2007-2012 period due to increased activity associated with the transport of gaseous cargoes by liquefied gas tankers, particularly over 2009–2012.

IPCC (2013) gets to an approximate 2.8% share of annual GHG's on a CO_2 equivalent basis for shipping. Their multi-year average estimate for all shipping using bottom-up totals for 2007–2012 is 1,036 million tonnes CO_2 equivalents for GHG's combining CO_2, CH_4 and N_2O. International shipping in their calculations accounts for approximately 2.4% of GHG emissions, totalling 866 million tonnes of CO_2 equivalents for GHG's. Global NOx and SOx emissions from all shipping represent about 15% and 13% of global NOx and SOx from anthropogenic sources; international shipping NOx and SOx represent approximately 13% and 12% of global NOx and SOx totals, respectively.

According to IMO (2015), over the period 2007–2012, average annual fuel consumption ranged between approximately 247 million and 325 million tonnes of fuel consumed by all ships, reflecting top-down and bottom-up methods, respectively. Of that total, international shipping fuel consumption ranged between approximately 201 million and 272 million tonnes per year, depending on whether consumption was defined as fuel allocated to international voyages (top-down) or fuel used by ships engaged in international shipping (bottom-up), respectively.

Fleet activity during the period 2007–2012 shows widespread adoption of slow steaming. The average reduction in at-sea speed relative to design speed was 12% and the average reduction in daily fuel consumption was 27%. Many ship type and size categories exceeded this average. Reductions in daily fuel consumption in some oil tanker size categories was approximately 50% and some container ship size categories reduced energy use by more than 70%. Generally, smaller ship size categories operated without significant change over the period, also evidenced by more consistent fuel consumption and voyage speeds. A reduction in speed and the associated reduction in fuel consumption do not relate to an equivalent percentage increase in efficiency, because a greater number of ships (or more days at sea) are required to do the same amount of transport work. (IMO, 2015)

The decision for VLCC's transporting fuel to go for slow steaming or not sailing at all is largely linked to the bunker fuel price, as shown by Devanney (2015). He observes that when prices are very low, vessels will choose not to sail. When prices go up, they may start doing so, but under a slow-steaming regime. However, one has to take into account that for a conventional long-stroke diesel engine, it is technically difficult to operate below about 50% power.

Moreover, over the period 2010-2050, OECD/ITF states that regionally, more specifically in Asia and the Northern-Pacific, the CO_2 emissions in absolute terms will increase largely. This is confirmed by IMO (2015), whose BAU scenario's, depending on future economic and energy developments, project an increase by 50% to 250% in the period to 2050. Further action on efficiency and emissions can mitigate the emissions growth, although all scenarios but one project emissions in 2050 to be higher than in 2012. Among the different cargo categories, IMO (2015) projects demand for transport of unitized cargoes to increase most rapidly in all scenarios.

Emissions projections as reported in IMO (2015) demonstrate that improvements in efficiency are important in mitigating emissions increase. However, even modelled improvements with the greatest energy savings could not yield a downward trend. Compared to regulatory or market-driven improvements in efficiency, changes in the fuel mix have a limited impact on GHG emissions, assuming that fossil fuels remain dominant.

Most other emissions increase in parallel with CO_2 and fuel, with some notable exceptions. Methane emissions are projected to increase rapidly (albeit from a low base) as the share of LNG in the fuel mix increases. Emissions of nitrogen oxides increase at a lower rate than CO_2 emissions as a result of Tier II and Tier III engines entering the fleet. Emissions of particulate matter show an absolute decrease until 2020, and sulphurous oxides continue to decline through 2050, mainly because of MARPOL Annex VI requirements on the sulphur content of fuels. (IMO, 2015)

Bows-Larkin et al. (2014) develop and apply three scenario's for the evolution of future shipping emissions in the UK: a Big-World scenario (S1), a Full-Speed-Ahead scenario (S2), and a Small-Ships-Short-trips scenario (S3). The resulting forecasts for 2030 and 2050 are shown in figure 1.

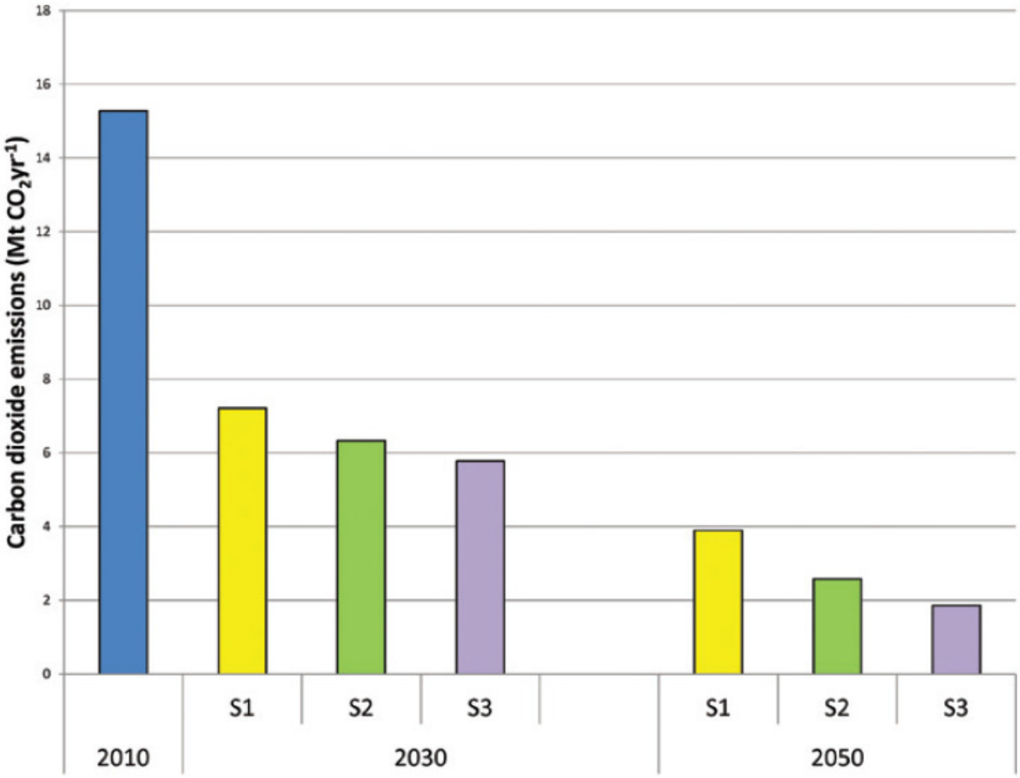

Figure 1: UK shipping emissions under three scenario's
Source: Bows-Larkin, 2014

Expectations by Wrobel et al. (2013) of trends in dry bulk shipping flows to 2050 highlighted drivers including Arctic ice melt, canal upgrades, piracy and mode splits. Globally, expected doubling of raw materials shipments to Western economies and quadrupling elsewhere will be partially offset by expectations of shorter hauls. Moderate annual expected tonnage growth globally compares with rapid annual growth in coal shipments, although more localized and multi-sourcing will shorten global coal hauls. Predicted changing patterns of maritime oil freight flows to 2050 were conservative. Local sourcing, new Arctic seaways and fossil fuel intolerance will tend to reduce oil freight work but ship re-routing to avoid ECAs and piracy would lengthen hauls. In advanced industrial nations, reducing energy intensities and diminishing social tolerance of fossil fuels imply reducing maritime oil shipments.

Artuso et al. (2015) apply a scenario approach too to address the uncertainties in future developments in an explicit manner. The scenarios include the main drivers affecting the outlook and prosperity of the EU maritime industry. The outlook and prosperity of the maritime industry is influenced by exogenous drivers outside the sector, like macro-economic or demographic developments, and sector specific developments for the maritime industry, such as environmental, labour or security regulations for the maritime sector. The authors distinguish among three scenario's.

- A sustainability scenario, that describes a world that is making relatively good progress towards sustainability.
- A fragmented world scenario, characterised by the world being separated into regions with extreme poverty, pockets of moderate wealth, and a bulk of countries that struggle to maintain living standards for a strongly growing population.
- The conventional development scenario is oriented toward economic growth, that is a high economic growth scenario with an energy system dominated by fossil fuels, resulting in high GHG emissions.

Table 1 shows the implications of each of the three scenarios with respect to among others environmental issues, which will translate also in the level of emissions that shipping will produce. Related to emissions are technological developments and incentives/subsidies.

Table 1: Implications of different scenarios on emission levels

	Sustainable	Fragmented	Conventional
Maritime drivers			
Maritime trade growth	Medium	Low	High
Shipping market developments	Competitive	Less competitive	Competitive
Technological developments	High, alternative fuels and propulsion, less labour intensive Low resources intensity, shift to clean energy	Low technological progress Medium energy demand, local resources (shale gas, tar oil)	Optimizing existing systems, less labour intensive High energy demand , Fossil fuels (Oil, gas, coal)
Environmental requirements	Internationally arranged, high priority and strict regulations	Standards by country and region – internationally low but higher for Europe	International cooperation but little priority for the environment
Employment	Increased international standardization	Standards by country and region	Increased international standardization
Safety and security	Internationally arranged	Standards by country and region	Internationally arranged
Incentives and subsidises	Medium	high	Low
New intercontinental routes and ports	No/ high investment and transformation	No/modest investments	Yes/ high investments

Source: Artuso, et al., 2015

Given all the above, it is necessary that the maritime sector should improve its efforts to reduce these emissions. The next section presents what regulatory measures are taken to try and achieve so.

3. Emission legislation for international shipping

Four large developments regarding emission legislation in international shipping can be distinguished among, namely MARPOL ANNEX VI, the Energy-Efficient Design Index (EEDI), the Ship Energy Efficient

Management Plan (SEEMP) and the White paper of the EU (European Commission, 2011). These four regulation initiatives are discussed in more detail in this section.

3.1. MARPOL Annex VI developments of emission legislation in international shipping

Annex VI, which contains the regulations regarding sulphur emissions by ships, is the newest addition to the MARPOL convention[1]. The revised Annex VI (into force since 1 July 2010) has been adopted by 72 member states, representing 94.3% of the total world tonnage. Regulation 14 of MARPOL Annex VI states that the sulphur content of any fuel used on board a ship must be reduced to 0.5% from 1 January 2020. Inside an Environmental Control Area (ECA), however, the limits for SO_x and particulate matter must be further reduced from 1% (since 1 July 2010) to 0.10 %, effective from 1 January 2015[2] (IMO, 2013).

Next to studies of classification societies (for instance DNV, 2009 and 2012) and engine manufacturers (for instance MAN Diesel A/S, 2011; Wärtsilä, 2009), the subject also attracted the attention of (academic) researchers (for instance the EC Framework 7 project RETROFIT[3]). Initial studies focussed on short sea shipping (among others Entec, 2009; Kalli et al., 2009; Notteboom et al., 2010). All these studies were commissioned by specific maritime actors. Corbett et al. (2003), Karim (2010) and Sys et al. (2012) emphasize deep sea shipping and pay attention to the modal and economic impact of the emission legislation. Cullinane and Bergqvist (2014) and Jiang et al. (2014) address the decision concerning what measures and strategies to implement and the timing of such decisions from the perspective of private operators.

3.2 EEDI and SEEMP

The Marine Environment Protection Committee (MEPC), a committee of the IMO, did make amendments to the MARPOL 73/78. From 1 January 2013, the EEDI and the SEEMP will be mandatory for all vessels over 400 gross tonnes (IMO, 2011; Laffineur, 2012; Harrison, 2012). These systems attempt at further enhancing the reduction of greenhouse gas emissions.

Due to the long lifespan of a vessel, up to thirty years, the replacement of engines will only happen in the long run. It is to be said that old engines are much bigger polluters than the newer engines (Van Laer, 2012). By making EEDI and SEEMP regulation mandatory, a further reduction of exhaust greenhouse gases will be reached. The additional commitment of the IMO could reduce the emission of greenhouse gases to between 180 and 240 million tons on an annual basis as a consequence of the EEDI regulation alone (IMO, 2011).

The EEDI is a benchmark on the energy efficiency set to reduce exhaust gas on newly-built vessels. It is a non-prescriptive measure that helps the industry decide which technologies should be installed on a specific ship design. When the emission of CO_2 is above this benchmark, the design of the vessel has to be changed. As long as the energy efficiency is below the target, the ship designers and builders are free to choose the most cost-efficient technologies to comply with the regulations (IMO, 2010). The formula to calculate the EEDI is given here below.

In order to interpret Equation 1, the formula can best be split into four main blocks. First of all, in the numerator of formula 1, the first two factors in between brackets represent the CO_2 emissions produced by the main and auxiliary engines respectively; while the third factor denotes the emissions produced by the shaft generators. The last part in the numerator represents the energy saving technologies. The denominator of the formula refers to the work (unit known from physics) that is performed by the ship in tonne.nm.

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[1] For an overview of the developments: see Harrison (2012).

[2] Depending on the outcome of a review, to be concluded in 2018, as to the availability of the required fuel oil, the date may be postponed to January, 1st 2025.

[3] www.retrofit-project.eu.

$$EEDI = \frac{\left(\prod_{j=1}^{M} f_i\right)\left(\sum_{i=1}^{nME} P_{ME(i)}.C_{FME(i)}.SFC_{ME(i)}\right) + \left(P_{AE}.C_{FAE}.SFC_{AE}\right)}{f_i.Capacity.V_{ref}.f_w} +$$

$$\frac{\left(\prod_{j=1}^{M} fi.\sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)}.P_{AEeff(i)}\right).C_{FEA}.SFC_{AE} - \left(\sum_{i=1}^{neff} f_{eff(i)}.P_{eff(i)}.C_{FME}.SFC_{ME}\right)}{f_i.Capacity.V_{ref}.f_w} \quad \text{Eq. (1)}$$

where
EEDI = Energy Efficient Design Index (g CO_2/ tnm)
nME = number of main engines installed in the ship (-)
nPTI = number of shaft engines (-)
P_{ME}, P_{AE} , P_{PTI} = power of the main, auxiliary and shaft engines respectively (kW)
P_{MEeff},P_{AEeff},$P_{PTTIeff}$ = the main, auxiliary and shaft power which is generated by innovative technologies (kW)
$C_{F\ ME}$,C_{FAE} ,$C_{F\ SE}$ = CO_2 emission factor for the main, auxiliary and shaft engines (g CO_2/g fuel)
$SFC_{ME,AE\ or\ SE}$ = specific fuel consumption of main, auxiliary and shaft engines (g/kWh)
f_i = the capacity factor for any technical/regulatory limitation on capacity (-)
f_j = a correction factor to account for ship-specific design elements (-)
f_w = the coefficient for decrease of speed in enhanced weather conditions (-)
Capacity = deadweight capacity ($0.7 \cdot DWT_{Summerloaddraft}$ for container vessels) (tonne)
V_{ref} = reference speed (knots)
$f_{eff(i)}$ = the availability factor for each innovative energy efficiency technology (-)
m = the number of applied correction factors (-)

The benchmark will be progressively reduced in the future compared to a reference value, consequently decreasing the emission of greenhouse gases. Table 2 represents this progressive reduction of the EEDI for the different vessel types and dimensions (IMO, 2011; Laffineur, 2012).
Currently, the Marine Environment Protection Committee (MEPC) of the International Maritime Organization (IMO) is reviewing the targets. The historical development of design efficiency can provide relevant information to answer this question in three ways (Faber and ‘t Hoen, 2015).

- It can elucidate how the design efficiency in the reference line period 1999–2008 compares to other periods.
- It can show what the timeframe for market-driven efficiency improvements has been.
- It can show which design changes have resulted in efficiency changes.

The analysis of Faber and ‘t Hoen, (2015) showed that the design efficiency of new ships improved significantly in the 1980’s, was at its best in the 1990’s and deteriorated after that. One of the reasons why the fuel efficiency deteriorated after the 1990’s is, according to Faber and ‘t Hoen, the deteriorated designs. Also changing market conditions (low fuel price or higher freight rates) contributed to vessels that are fuller (higher block coefficient). These ships will have a higher resistance and also a lower fuel efficiency. Based on this analysis, the EEDI should be used to ensure a constant improvement of the fuel efficiency of the ship.

Table 2: Progressive reduction of EEDI (in %)

Ship type	Size	Phase 0	Phase 1	Phase 2	Phase 3
		1 Jan 2013-31 Dec 2014	1 Jan 2015- 31 Dec 2019	1 Jan 2020 - 31 Dec 2024	1 Jan 2025 onwards
Bulk carrier	20.000 dwt and above	0	10	20	30
	10.000-20.000 dwt	n/a	0-10*	0-20*	0-30*
Gas tanker	10.000 dwt and above	0	10	20	30
	2.000-10.000 dwt	n/a	0-10*	0-20*	0-30*
Tanker	20.000 dwt and above	0	10	20	30
	4.000-20.000 dwt	n/a	0-10*	0-20*	0-30*
Container ship	15.000 dwt and above	0	10	20	30
	10.000-15.000 dwt	n/a	0-10*	0-20*	0-30*
General cargo ship	15.000 dwt and above	0	10	20	30
	3.000-15.000 dwt	n/a	0-10*	0-20*	0-30*
Refrigerated cargo carrier	5.000 dwt and above	0	10	20	30
	3.000-5.000 dwt	n/a	0-10*	0-20*	0-30*

Source: own composition based on Laffineur (2012) and MEPC (2011)
*: Reduction factor depends on vessel size, n/a: no EEDI applies

The EEDI is not a technology but an attempt to force ship-owners to use state of the art technology. The spread in the energy performance of ships is large (Chen et al., 2010, Kruger, 2004). Longva et al. (2010) present an approach where a required index level (IR) can be determined through a cost-effectiveness assessment of the available reduction. They show that there is no agreement on a mandatory application or on how to set the required targets. Zheng et al. (2013) identify the characteristics of energy consumption in shipping and the stakeholders involved in the EEDI application process, they analyse the relationships among stakeholders in the shipbuilding industry in China, and point out the drivers and barriers in the implementation. Again, the implementation of EEDI is not easy given the number of stakeholders involved, the split incentives and the lack of technical knowhow in some of the major shipbuilding countries such as China. This all means that the designs have to improve and/or alternative energy saving technologies have to be applied.

The SEEMP is an operational measure that helps the shipping company improve the energy efficiency of its operations in existing vessels (IMO, 2010; Laffineur, 2012). The SEEMP shows how energy savings can be made in four steps: planning, implementation, monitoring and self-evaluation (MEPC, 2011).

In the SEEMP, the current performance of the ship has to be determined. Also a plan for improvement must be developed. This improvement can be reached through a large list of possible options (such as speed optimization, weather routing, etc.) which all should be examined. The energy efficiency of the ship should be monitored in a quantitative way. Here, the EEDI could be used (MEPC, 2011).
The MEPC also discusses other possibilities of reducing the greenhouse gas emissions, such as market-based mechanisms. These mechanisms put a price on greenhouse gas emissions, consequently giving economic incentives to the industry to invest in vessels and technologies with low exhaust of emissions. The generated revenue can be used to limit climate change (IMO, 2011).These mechanisms could include:

- A levy on vessels that do not meet the EEDI standard.
- A levy on all greenhouse gas emissions coming from all types of vessels.
- A global emission trading system.
- A penalty on trade and development.
- A rebate mechanism for a market-based instrument for international shipping.

(IMO, 2010; Laffineur, 2012).

3.3 EU White paper 2011

Finally, the 2011 Transport White Paper of the European Commission (2011) states that the European Union wants to diminish its greenhouse gas emissions to limit climate change to 2°C. To reach this goal, the European Union must attain a reduction in greenhouse gas emission levels by 80-95% below 1990 levels by 2050. For the transport sector in particular, the greenhouse gas emissions must be reduced by 20% by 2030 and by 40% by 2050 compared to their level in 2008. The White Paper emphasizes that decisions that are taken today will influence future decisions and actions. That is why the implemented measures must be well thought through.

The next section provides an overview of technologies that have been developed for the shipping sector to comply with the above-mentioned legislation.

4. Alternative sustainable maritime technologies

. In order to categorize the different technical solutions to make a vessel more energy-efficient, first the propulsion system of a ship must be understood. This system consists of four main elements: the propulsion plant (engine), the propulsor (propeller), the hull (resistance) and the operation of the ship (the captain). In figure 2, a diagram is given on how four of these main elements are related to each other.

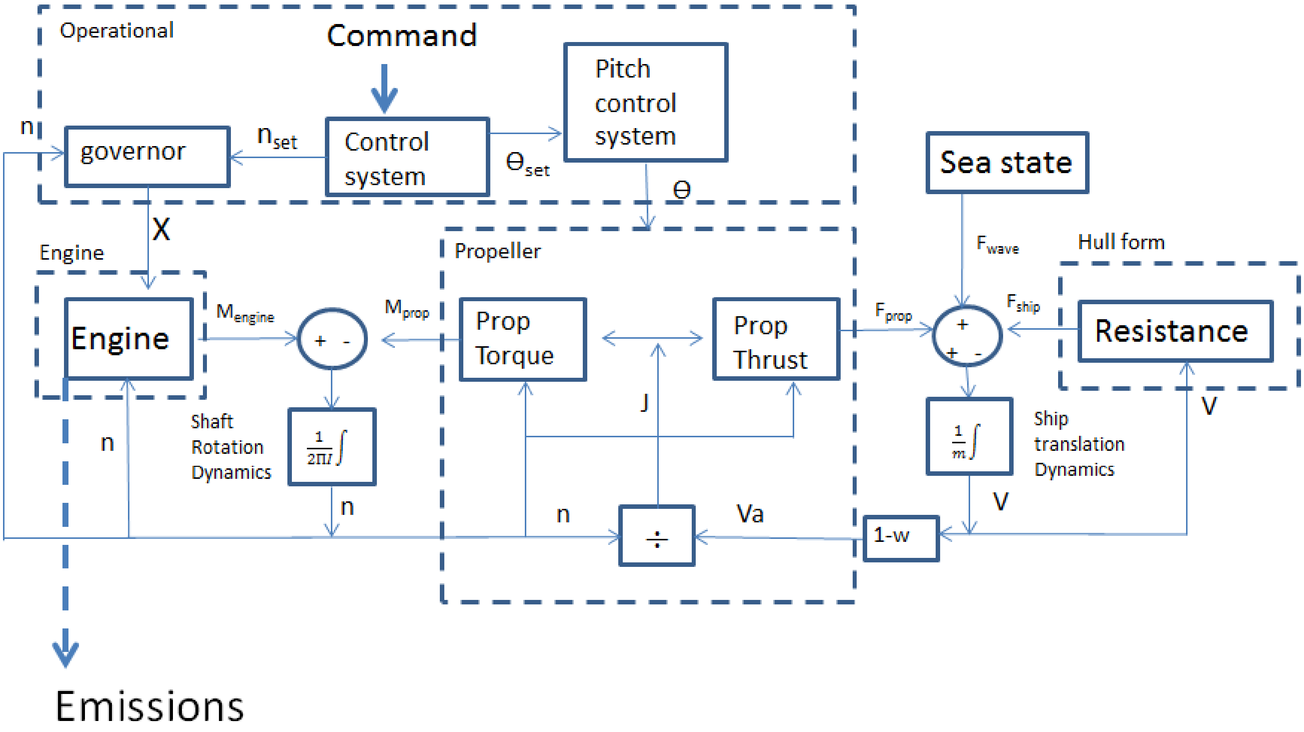

Figure 2: Block diagram of propulsion dynamics
Source: own composition based on Stapersma, 2004

On the left hand side of figure 2, there is the engine. The engine will consume fuel (denoted as X) and generate RPM (n, the revolutions per minute), torque (M_{engine}) and emissions. The torque generated by the engine will be transferred to the propeller. On the basis of the difference between the needed propeller torque (M_{Prop}) to sail at a certain speed (V) and the generated torque of the engine, the propeller RPM can be calculated by integrating the torque difference over time and dividing it by the product of 2π and the moment of inertia of the propeller (I)[4]. The engine RPM will be influencing the propeller RPM and it will be used to control the speed of the ship.

In the middle of figure 2, the ships' propeller is given. The propeller is in between the engine and the hull of the ship. There are two main components of the propeller, namely the torque and the propeller RPM. Based on the advanced ratio (the non-dimensional speed) of the propeller (J[5]), which is determined by the undisturbed

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[4] $n = \int M_{total}/2\pi I.\partial t$
[5] $J = V_a/n.D$ in which D is the propeller diameter

axial velocity upstream of the propeller (V_a[6]), the propeller torque and thrust, the working point of the propeller can be determined as well as the efficiency of the propeller.

On the right hand side, there is the hull form. The hull form will determine, along with the speed of the ship, the draft (which relates to the payload) and the weather conditions (wave heights), what the resistance is. The added resistance due to waves (F_{waves}) is determined by the sea state in which the ship is sailing. In order to overcome this resistance, the propeller must generate thrust. Based on the difference between the propeller thrust (F_{prop}), the added resistance due to waves (F_{wave}) and the resistance of the ship (F_{ship}), the speed of the ship can be calculated. The speed is calculated by integrating the resulting forces acting on the hull of the ship (F_{total}) over time and dividing it by the mass of the ship (m)[7]. The speed of the ship is then influenced by the resistance (hull form and loading, with which there is an iterative relation), the sea state and the propeller.

On the topside of figure 2, the control system is given (operational part). In this block, the captain can set a certain ship speed. This can be done either by changing the engine's RPM, which can be adjusted by changing the fuel injection of the engine (n_{set}) or, when the ship has a controllable pitch propeller, adjusting the pitch of the propeller (θ). Changing the pitch of the propeller affects also the efficiency of the propeller.

From figure 2, it can be concluded that there are a lot of dynamic links between the different elements of the ship's drive train. This is important to realise when one is discussing the reduction of marine emissions, because reducing marine emissions is not only related to the engine, although it is the engine that is producing these emissions, but it relates to the total system. Fuel consumption (and thus emissions) relates to the complete and dynamic system of engine, propeller, hull form, external influences (such as sea state) and control systems (the captain).

The main objective of this section is to come to a list of potential alternative technologies that could reduce the fuel consumption, therefore reducing the emission of carbon dioxide and other pollutants, or of technologies purely to reduce the level of emissions. These different technologies can be classified into five main classes. All the alternative technologies (and operational changes) and their corresponding classes can be identified in table 3.

Table 3: Overview of the maritime technologies and operational measures

1. Hull	**2. Propulsion**	**3. Machinery**	**4. Alternative Energy Sources**	**5. Operation/maintenance**
Air lubrication (N)	Contra-rotating propellers (N+R)	Advanced power management (N+R)	Fuel type: Bio fuel (N+R)	Autopilot adjustment
Bulbous bow (N+R)	Optimization of the propeller blade sections (N+R)	Automation (N+R)	Fuel type: Low-sulphur fuel (N+R)	Hull cleaning
Ducktail waterline extension (N+R)	Propeller boss cap with fins (N +R)	Common rail (N+R)	Fuel type: LNG (N+R)	Increasing cargo load factor
Hull surface / Hull coating (H+R)	Propeller nozzle (N+R)	Cooling water pumps, speed control (N+R)	Solar Power (N+R)	Increasing energy awareness
Interceptor trim plates (N+R)	Propeller tip winglets (N+R)	Delta tuning (N+R)	Wind Power: Flettner Rotor (N)	Optimization of trim and ballast
Minimizing resistance of hull openings (N+R)	Propeller-rudder combination (N+R)	Engine derating (N+R)	Wind assisted: Kites (N+R)	Propeller polishing

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[6] $V_a = V.(1-w)$ in which w is the wake factor of the ship

[7] $V = \int F_{total}/m.\partial t = \int a.\partial t$

Efficiency of scale (N)	Rudder resistance (R)	Part load operating optimization (N+R)	Wind Power: Sails (N)	Reducing ballast
Lightweight construction (N)	Constant versus variable speed reduction	Reducing onboard power demand (N+R)		Reducing port time
Optimal propeller hull interaction (N)	Optimization of propeller and hull interaction (N)	Scrubber (N+R)		Reducing speed
Optimization of skeg shape (N)	Propeller efficiency measurement	Selective catalytic reduction (N+R)		Optimizing voyage optimization
Shaft line arrangement (N)	Pulling thruster (N)	Waste Heat Recovery (N)		Weather routing
	Wing thrusters (N)	Diesel-electric machinery (N)		
		Hybrid Auxiliary Power generation (N)		
		Low loss concept for electric network (N)		
		Variable speed electric power (N)		

Source: own composition, mainly based on Crist, (2009), MEPC, (2008 and 2010), Wärtsilä, (2009) and Stevens (2012)

The first three classes are based on figure 2 and are measures to adjust the hull of the ship, the propulsor and the installed machinery respectively. The additional class that was added is the class of alternative energy sources (class 4). The class of alternative energy sources is in-between the classes of propulsor and machinery. In this class, the technical solutions such as wind propulsion (sails) and alternative fuel types (low-sulphur and LNG) are categorized. The fifth class is the operation (and maintenance) of the ship. This class is not related to different technological solutions but only to the way the ship is being operated hence representing the topside of figure 2.

The technologies are now also classified as newbuilding technologies or retrofitting technologies. The measures followed by (N) are the technologies that can only be built into new ships (hull optimization or installing a waste heat recovery system). (N+R) is used when measures can both be installed in new vessels or that can be retrofitted into existing vessels (installing scrubbers or optimizing the bulbous bow). The measures without brackets are measures that can be used to reduce the fuel consumption of a vessel by changing one of the parameters in their operational activities. For example, by reducing the speed of a vessel or by changing the route of the vessel due to weather conditions, a fuel reduction can be reached (last column).

The list of 55 measures is based on a study of different reports, studies and presentations. Measures that are not yet operational or not widespread are not included into table 3. Therefore, other measures could have been added into the list. For a detailed description of these and other technologies, reference is made to Stevens (2012). Wrobel et al. (2013) apply a number of policy scenarios to calculate the likelihood of energy-efficient and sustainable shipping measures. The main types they distinguish among are: slow steaming, technologies and ship design, ship and propulsor hydrodynamics, wind assistance, internal combustion technology and electrical propulsion, alternative fuels, fuel cells, raising crew awareness, ship hull and propeller maintenance and voyage optimisation. The same authors call on a number of factors that create substantial uncertainty in the measurement of the way in which shipping energy-use and abatement will evolve. Rehmatulla (2015) presents the results of a survey that was held early 2015 among shipping associations and committees on the actual uptake of energy-efficient and sustainable technologies. The author distinguishes among 6 categories of possible measures: design-related measures, hydrodynamic measures, machinery measures, alternative energy sources, maintenance measures and after-treatment measures. Overall, from figure 3, it can be observed that newbuilding and retrofitting are by far the preferred ways by which energy-efficient technologies get introduced.

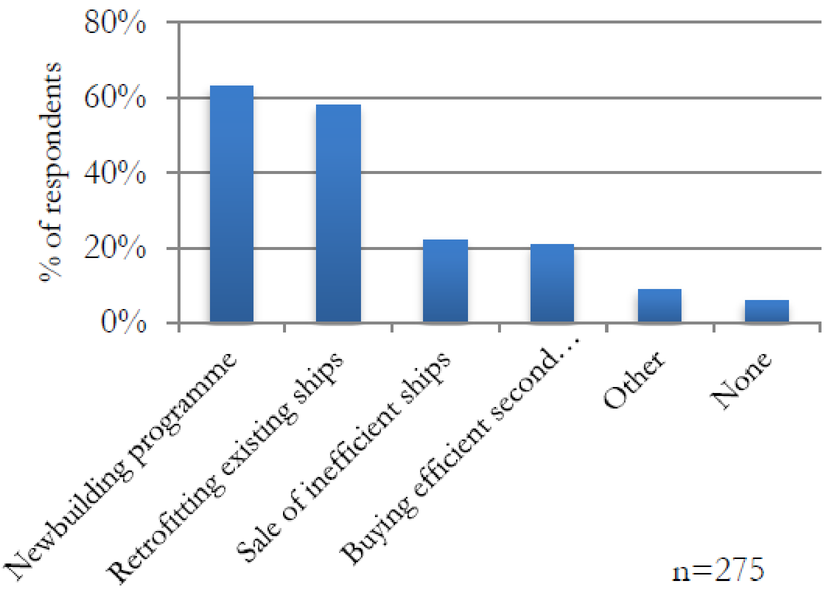

Figure 3: Shipping energy efficiency strategy
Source: Rehmatulla, 2015

The next section will combine the legislative framework (section 3) with the technological options (section 4) to comply with it.

5. Development of a framework to link emission policy to maritime technologies

In figure 4, the different links between legislation and technology can be observed. The figure is split in two main parts: a shipowner part, where the interest is in the fuel cost of the ship, and a policy maker part, where the interest is in the emissions part of the ship.

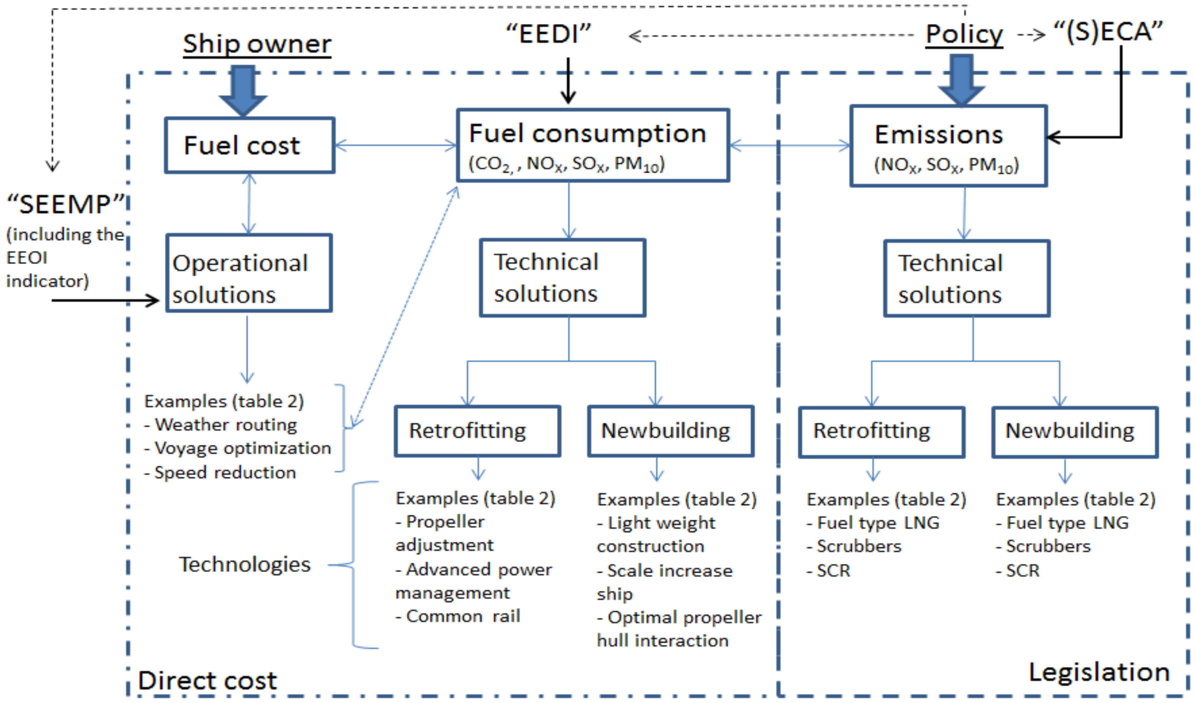

Figure 4: Linking emission policy to maritime technologies
Source: own composition

Figure 4 shows that there is no direct link between fuel cost, which is of interest for the shipowner, and the emissions. There is only an indirect link via the fuel consumption. This is a key element in the framework which is developed in figure 4. The shipowner is very much interested in reducing the fuel cost of the vessel.

The fuel costs are one of the dominant cost components of the total cost of maritime transport. At the historic price of 135 USD per ton bunker fuel, costs represented about half the operating cost of larger containerships (Notteboom, 2006). When the oil price approached 150 USD per barrel bunker fuel, price exceeded 750 USD per ton. When bunker fuel price hovers around 500 USD per ton, it constitutes about three quarters of the operating cost of a large containership. (Ronen, 2011)

In figure 5, the historic trend of heavy fuel bunker prices (180cst) at Rotterdam is given. The bunker price increased to over 700 USD per tonne in 2008, decreased to 250 USD per tonne in 2009, to increase again to over 700 USD per tonne in 2011. In 2015, the bunker price decreased again to 340 USD per tonne.

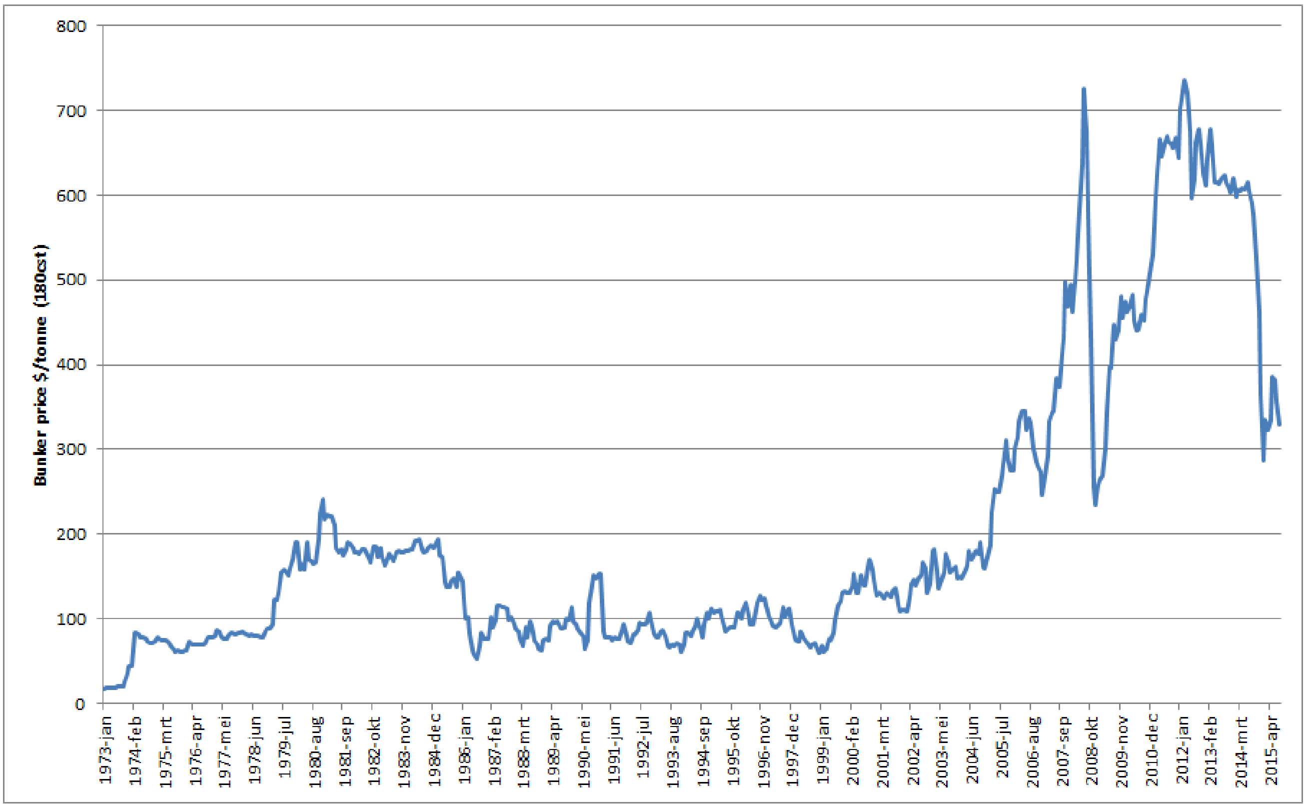

Figure 5: Rotterdam bunker price 1973 – 2015 (heavy fuel oil,180cst)
Source: Shipping Intelligence Network (2015)

The bunker prices were in the period 2007 to 2015 at an all-time high, but also the drops in bunker prices were very large. The volatility and the spread in the volatility were never as high. These high bunker prices and the very high volatility in the bunker prices will affect the shipowners. Reducing the fuel cost of a shipowner can be done in two ways, namely by financial or operational means or by reducing the (design) fuel consumption. It can be seen, in figure 4, that two different policies are targeting these aspects (SEEMP and EEDI). The policy to implement the (S)ECA's, for instance, is directly related to the emissions which is not directly related to the fuel costs of the shipowner.

The financial way of reducing the fuel cost is by hedging the fuel price. In this way, it is possible to reduce the fuel cost even without implementing any technical solution. If a large spread in the bunker price is observed like in figure 5, this strategy can be very useful. An operational way to reduce the fuel cost is to change the route of the vessel (either by voyage optimization or by weather routing). A third operational way to reduce the fuel cost is to reduce the speed of the vessel. By reducing the speed of a ship, also the fuel consumption will be reduced, and as a result, also the emissions. The impact of reducing speed is very high, especially at high speeds, because the fuel consumption of a vessel is related to the speed of the ship to the power 3. All the operational measures (column 5) mentioned in table 3 can be placed in this left part of the diagram.

There are also technical ways of reducing the fuel consumption of a ship. This can be split into two different ways, namely adjusting (retrofitting) an existing ship or buying a new ship with the latest technologies. Several possible solutions are given in the middle part of figure 4. The examples given here come from the first four columns of table 3 without the grey shading. These types of technology are very much in the interest of the shipowner because they can be beneficial by means of a reduced fuel bill. The cost-effectiveness of different technical options depends very much on the bunker prices. If the bunker prices are very high, the cost-effectiveness of technical solutions such as waste heat recovery systems, wind power assistances technologies (kites) or alternative fuel sources (LNG) will be high. But at low fuel prices, the cost-effectiveness will decrease. And due to the high volatility of the bunker prices, the decision of the shipowners to opt for these technologies will become very difficult.

Another element that needs to be taken into account is that determining the fuel consumption of a ship is rather complex (see figure 2). This means that in order to determine the effectiveness of a certain technology, a complete simulation must be made in order to determine the cost effectiveness of all the possible technologies. Due to the fact that there are a serval external influences on the system (payload of the vessel, sea state, etc.), it is even more difficult to assess the cost effectiveness. Therefore, it is highly plausible that a shipowner will opt for the technology or measure that has the highest probability of being the most cost-effective.

The right part of figure 4 shows the technical measures that will only reduce the emissions (NOx, SO_x and PM_{10}) and not the fuel consumption. Examples of these types of technology are scrubbers and using low-sulphur fuels. The implementation of these technologies comes at a cost while there is no direct economic benefit for the shipowner. Therefore, the implementation of these technologies is not in the main interest of the shipowner but is rather forced by legislation. It can therefore be expected that if a shipowner is forced to take measures to fulfil to new criteria, he will opt for the solutions that are the least costly. In table 3, these technologies are marked with a grey colour. All these technologies relate to the policy of introducing (S)ECA zones.

The legislation's main interest is in reducing emissions. This can be done by reducing fuel consumption but can also be forced by law. This can be seen at the top side of figure 4, where the different policies are shown. The SECA legislation is an example where the shipowner is forced to think about implementing additional technologies, such as scrubbers or using low-sulphur fuel, in order to be able to sail to a specific port region. On 1 January 2015, the North Sea was established as an ECA zone with a severe 0.1% sulphur-content limit. A relevant policy-related question then is why the Mediterranean Sea is not a sECA, and eventually could become one. A first argument is that a proposal for an ECA zone implies a perseverance, conviction and will of the Member States. Furthermore, the recent political turmoil within the Southern border of the Mediterranean Sea leads towards unstable and perhaps unreliable partners. Interviews confirm that it is not inconceivable that an expansion of the sulphur regime in the Mediterranean rises. Most respondents keep this in mind, but no one could put a timing on it. (Sys, et al., 2015b)

Moreover, some legal literature has drawn attention to the fact that an enforcement regime such as the one governing MARPOL Annex VI, could lead to compliance problems and threaten the competitiveness of complying shipping companies. Also, the industry notifies that some shipping lines may ignore the new regulation, particularly when it is considered that penalties in certain countries are estimated to be lower than the increased cost of using the more expensive fuel. In contrast to the Northern-American ECA requirements, the industry points out that the enforcement of the Northern-European ECA requirements is rather weak. (Sys, et al., 2015b)

The EEDI is a type of legislation the aim of which is to reduce the emissions by reducing the fuel consumption of the ship. This is a type of legislation which could be of interest to the ship because it is also in its interest that the fuel consumption will be reduced. The technologies which can do that are the unmarked items in table 3. The operational measures all relate to the SEEMP legislation mentioned in section 3 .

The next section applies the developed framework to three potential solutions: EEDI, (S)ECA zones and SEEMP.

6. Application of the developed framework

In this section, it is analysed whether the three mentioned policies of section 3 are stimulating the implementation of the new technologies.

6.1 EEDI

In order the determine the effectiveness of stimulating the implementation of new technologies via the EEDI, first, the EEDI has to be examined more in depth. When the EEDI is simplified and the admiralty constant[8] is inserted into the formula, the EEDI becomes as in Equation 2.

$$EEDI = \frac{(C_{CO_2}.sfc - f).C_{ad}.\Delta^{2/3}.V^2}{dwt} \qquad \text{Eq. (2)}$$

Where C_{ad} is the admiralty constant, Δ the displacement of the ship, *DWT* the deadweight, C_{CO2} the CO_2 emission coefficient, *sfc* the specific fuel consumption, *f* the reduction factors of green technologies and *V* the design speed of the ship.

In table 2, an overview was given of the future reduction of the EEDI. In order to do this, the shipowner has several options. He can reduce the fuel consumption by applying the new techniques mentioned in table 3 or he can increase the dwt of the ship (mainly by reducing the lightweight) or he can reduce the speed of the ship. There are three reasons why it could be argued that investing in new technologies, to reduce the EEDI, could be problematic due to too high uncertainty.

- The effectiveness of the new technology is unknown or not yet proven (i.e. factor "*f*" in Equation 2 is unknown)
- The actual fuel consumption of a ship is related to the total propulsion system including external effects. Therefore, the effectiveness of the technologies might be reduced in the total propulsion system and by external effects.
- The high volatility in the bunker fuel price and the unknown development of the bunker price make investments in new technologies more uncertain.

Reducing the speed is a much more efficient measure because the EEDI relates to the squared speed of the ship. So, if the effectiveness of the implementation of the new technologies is not clear for the shipowner, the shipowner will be forced to reduce the design speed of the ship. In this respect, the EEDI is not stimulating the implementation of the technologies mentioned in table 3.

The characteristics of newly built ships seem to confirm the observation that the choice for lower design speeds is indeed more and more preferred over time. That observation is certainly true for the 6,000-8,000 TEU ships (figure 6), and to a large extent also for the 10,000-18,000 TEU ships (figure 7).

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[8] $P = C_{ad}.\Delta^{2/3}.V^3$ in which: C_{ad} = admiralty constant, Δ = Displacement, *V* = Speed and *P* = power

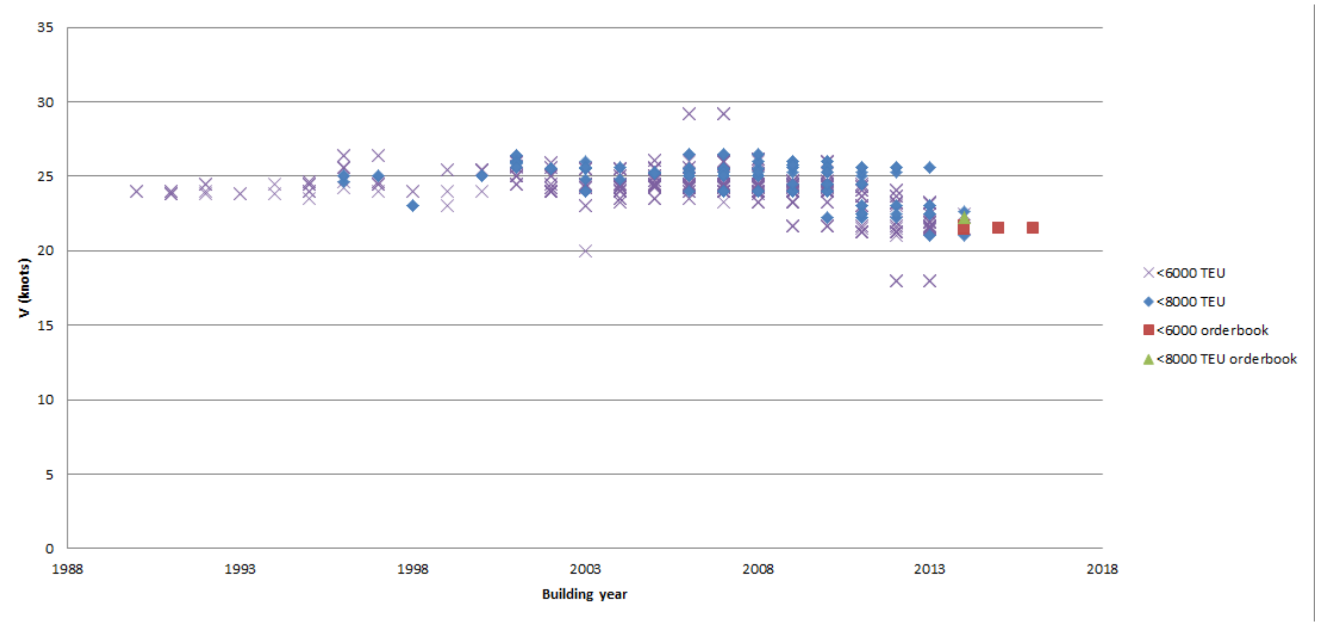

Figure 6: Design speed 6,000-8,000 TEU container ships
Source: own composition based on Clarksons (2014) data

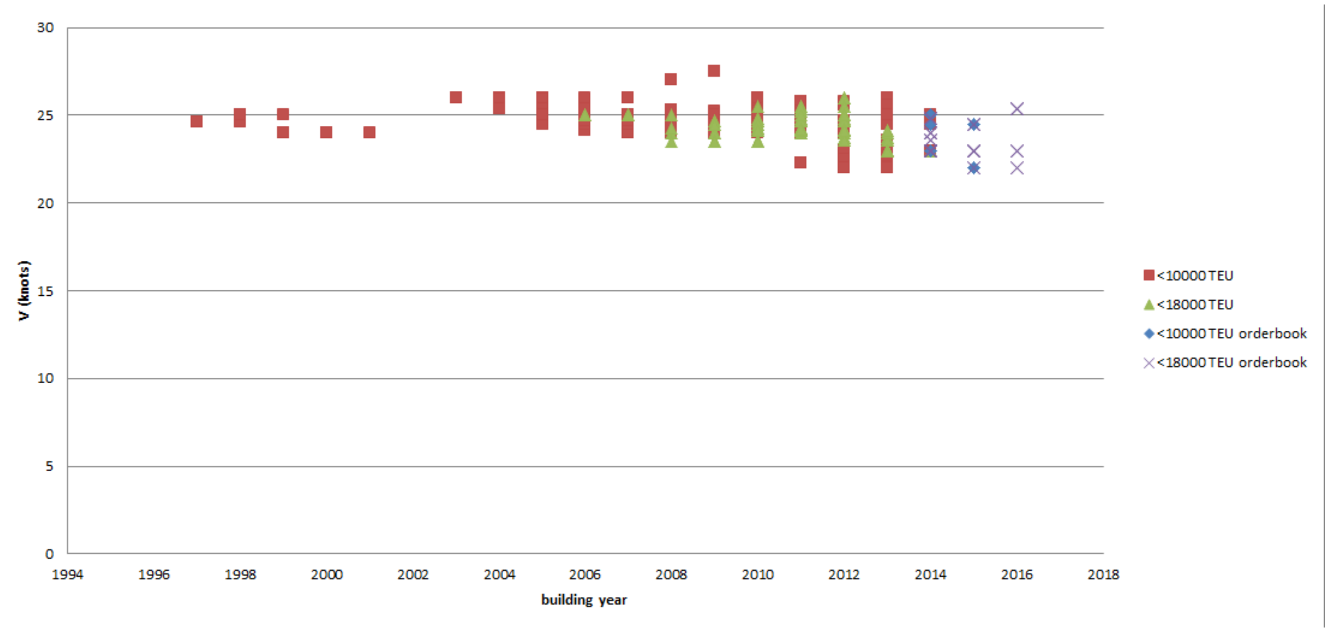

Figure 7: Design speed 10,000-18,000 TEU container ships
Source: own composition based on Clarksons (2014) data

To solve this problem, the direction of the regulations should be more towards a propulsion performance index based on the state of the art which should not be influenced by the shape, main dimension ratio's and speed (Frouws, 2014). These parameters are often determined by the trade and or the geographic situation. Speed can be the unique selling point of a certain line service. It cannot be the intention of a rule to "kill" a shipping line service by reducing the service speed, for example, with a better energy performance than an alternative truck service. Devanney (2015) comes to similar findings. EEDI induces owners to use smaller bore, higher RPM engines. These engines have a higher specific fuel consumption and more importantly require a smaller, less efficient propeller. This means the EEDI-compliant VLCC consumes more fuel when the market is not in oom, which is 90% of the time. For existing vessels, the answer can be the SEEMP. Although obliged to introduce, there is not any hard requirement in terms of fuel savings.

6.2 (S)ECA-zones

With respect to the implementation of the (S)ECA zones in the world, it can be concluded that the pure goal of this policy is to reduce the SO_X emissions in parts of the world (coastal regions). First of all, this will force the shipowner to reduce the emissions in these controlled areas and not outside these areas. It is recognized that the harmful impact of SO_X and PM_{10} emissions in coastal regions is much higher than on the high seas due to the fact that a lot people are living in coastal regions. This is thus a measure which is forced upon the shipowner. As a result, he will opt for the easiest (most cost efficient) way to fulfil these criteria. For this type of legislation, we can distinguish among two types of ships: ships that can "escape" the (S)ECA zones (deepsea shipping) and ships that are "trapped" inside the (S)ECA zones (short sea ships, ro/ro ferries, etc.).

For the first group of ships, the most efficient way to deal with the current (S)ECA legislation is to use a bi-fuel system. This means that one uses HFO outside the (S)ECA zones and distillate fuel inside the zone (Greenship, 2012). Due to the high volatility of the fuel prices, the choice for alternative technologies to comply with the regulations of the (S)ECA zone, will become more uncertain. Also in Yang *et al.* (2012) it was recognized that the most cost-effective way of reducing the SO_x (and PM_{10}) emissions is to use segregated tanks (bi-fuel option).

For the second group of ships (the ones that cannot "escape" the (S)ECA zones), scrubber technology and LNG propulsion are serious alternatives (Greenship, 2012) to fulfil the current day requirements of the (S)ECA-zones besides using low-sulphur fuel. Also for this group of ships, the high volatility and the uncertain development of the bunker prices will make the investments in new technologies such as scrubbers more uncertain.

6.3 SEEMP

The introduction of the SEEMP will not contribute to the introduction of new green technologies because this type of legislation only relates to the operation of the ship and not directly to the fuel consumption. The SEEMP will impact on the operation of the ship and will influence the control system in figure 2. The impact of the control system of the ship may have a very strong impact on the fuel consumption of the ship. This type of legislation is a good supplement to the other two types because now all the possible parameters that could impact on the fuel consumption and the emission production are addressed.

7. Conclusions and discussion

Due to the significant increase in attention for the reduction of the marine emission such as CO_2, NO_X, SO_X and PM_{10}, several new legislative actions are taken by the IMO and EU, namely EEDI and (S)ECA zones. In this paper, different technical solutions are presented to fulfil these new legislation initiatives. Also, a framework was developed to link these new technologies to the legislation.

It was shown with the framework developed in this paper that the fuel consumption of a ship is a highly dynamic process which involves the engine, the propeller and the hull of the ship. So, measures to reduce fuel consumption (and thus also emissions) have to take this into account. Just changing or adjusting the engine is not enough! Also the impact of the bunker price on the cost effectiveness of new technologies must be recognized. The high volatility of the bunker prices make it very difficult for the shipowner to project the development of the fuel prices and the cost-effectiveness of the considered technologies.

Implications for managerial practice

With the developed framework, the likelihood of specific sustainability measures to be taken up and being successful, can be simulated.

When the EEDI is applied, it will not stimulate the use of new technologies but it will push the ship designer into the direction of reducing the design speed (due to the fact that the EEDI relates to squared speed) or to further minimize the light weight of the ship rather than to apply new techniques.

With respect to the (S)ECA zones, it can be concluded that the installation of those zones is by itself very useful. The harmful PM_{10} and SO_X emissions near coastal regions are to be minimized to protect the population from these harmful emissions. However, the implementation of the (S)ECA will not stimulate, in the short run, the implementation of new technologies for ships that will sail in and out of these areas. But it will most likely stimulate the implementation of bi-fuel, hybrid types of propulsion systems which can be switched to (S)ECA mode in the control areas and switched off outside these areas. By using this solution, shipowners can buy some time to further analyse potential solutions to fulfil the necessary requirements of the (S)ECA zones.

Applying the developed framework shows that measures should be introduced with care, after having analysed potential reaction patterns, and stepwise, so as to avoid a radical switch with unpredictable outcomes. After the agreement back in 2011 on the EEDI and the SEEMP, discussions within IMO have focused on further measures to reduce CO_2 emissions from existing vessels. Wide-ranging proposals have been submitted to the IMO resulting in complicated discussions. The last couple of IMO meetings, these discussions have culminated in proposals for a more step-wise approach:

1. Data collection
2. Testing
3. Full implementation.

Moreover, IMO will update its Greenhouse Gas (GHG) study, resulting in up-to-date information on shipping emissions. (Sys, et al., 2015)

Meanwhile, the European Commission proposed its scheme for monitoring, reporting and verification (MRV) of CO_2 emissions in July 2013 and informal discussions on which steps should be taken first are ongoing internationally. This proposal was based on earlier commitment to take action in the Climate and Energy Package adopted on April 23rd, 2009 . The mentioned deadline has passed without sufficient international action as the EEDI, despite its utility, is not expected alone to deliver absolute emission reductions compared to base years if the forecast growth in traffic will materialize. According to European Commission (2013), "*the precise amount of CO_2 and other greenhouse gas emissions of EU-related maritime transport is not known due to the lack of monitoring and reporting of such emissions.*" The introduction of an MRV system is considered a pre-requisite for any market-based measure or efficiency standard, whether applied at EU-level or globally.

The Commission proposes that the MRV system apply to shipping activities carried out from 1 January 2018. The main lines of the Commission proposal are:

1. The proposed EU system of MRV for shipping emissions is designed to contribute to building an international system. First steps in this direction have already been taken at the IMO, with active support from the EU and partner countries. By yielding further insights into the sector's potential to reduce emissions, an MRV system will also provide new opportunities to agree on efficiency standards for existing ships.
2. The proposal would create an EU-wide legal framework for collecting and publishing verified annual data on CO_2 emissions from all large ships (over 5,000 gross tons) that use EU ports, irrespective of where the ships are registered.
3. Shipowners would have to monitor and report the verified amount of CO_2 emitted by their ships on voyages to, from and between EU ports. Owners would also be required to provide certain other information, such as data to determine the ships' energy efficiency.
4. A document of compliance issued by an independent verifier would have to be carried on board ships and would be subject to inspection by Member State authorities.
5. Calculate annual CO_2 emissions based on fuel consumption and fuel type and energy efficiency using available data from log books, noon reports and bunker delivery notes.
6. Use existing structures and bodies of the maritime sector, in particular recognized organisations to verify emission reports and to issue documents for compliance;
7. Exclude small emitters (ships below 5000 GT) which represent about 40% of the fleet, but only 10% of the total emissions.

(European Commission, 2013)

Contribution to scholarly knowledge

The developed framework provides theoretical insights into the potential effectiveness of specific environmental measures in shipping. It provides a basis for further monetary quantification of the encountered relationships in further research. Furthermore, it allows determining the levels of compensation or incentives that is to be provided to operators in order to make them apply a specific measure if it turns out that private benefits do not outweigh costs. In this way, it can build further on for instance Sys et al. (2015). Finally, the framework can be applied to other types of environmental measures, so as to provide a full picture of potential conceptual impacts.

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