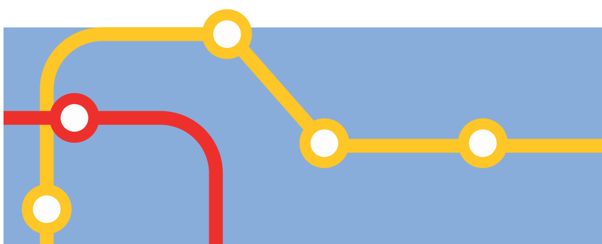
Decarbonising European Shipping

Technological, operational and legislative roadmap

TRANSPORT & ENVIRONMENT



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Executive Summary

Europe has set ambitious goals to regulate EU-related shipping, i.e. all ships calling at EU ports and carrying EU trade, in order to ensure the sector contributes to the Union's climate goals. The Commission proposal on the European Climate Law requires all emissions regulated in the EU, including shipping, to be reduced to net zero by 2050 at the latest. In addition, EC communication on the European Climate Plan for 2030 argues that all sectors, including maritime transport, should contribute to the revised 2030 climate goal of -55% emissions reductions below 1990 levels.

Such ambitious political goals raise an important question as to how EU-related shipping could cut its GHG emissions in order to contribute its fair share to the said EU climate goals. With that in mind, this study aims to analyse technical, operational and fuel options that could help cut EU shipping emissions in line with the EU's economy-wide targets. To enable that, T&E built a tailor-made shipping stock model, which takes account of technology review and transport work demand from the 4th IMO GHG study, EU THETIS-MRV database and relevant literature review, in order to identify potential decarbonisation pathways for EU shipping. We analysed three scenarios that investigated the impact of different levels of energy efficiency improvements along with an ambitious but sustainable uptake of green e-fuels. According to the findings of this analysis:

1. To contribute its fair-share to the EU's -55% 2030 target, EU shipping must slash about 90 Mt CO_2 emissions by 2030 compared to 2018 emissions. A combination of large energy efficiency improvements and zero-emission enabled vessels (ZEEVs) deployment get the closest to attaining this target but still miss it by 35 Mt CO_2/year.

2. EU-related shipping could cut up to a third of its emissions in 2050 (Figure E.1) by simply improving its technical and operational energy efficiency (i.e. fuel economy). This can be achieved, inter alia, by installing energy saving devices such as wind-assist, but also through operational changes including optimising/reducing operational speed. In general, up to 41% fuel economy (i.e. fuel consumption per transport work) improvements are possible between now and 2030.

3. Among the sustainable electro-fuels, green ammonia appears to be the cheapest fuel to decarbonise the EU-related shipping with green liquid hydrogen gradually catching up by 2050. However, given the superior energy density and lower storage costs green ammonia is likely to remain the cheapest e-option for ocean-going vessels from the total cost of operation perspective.

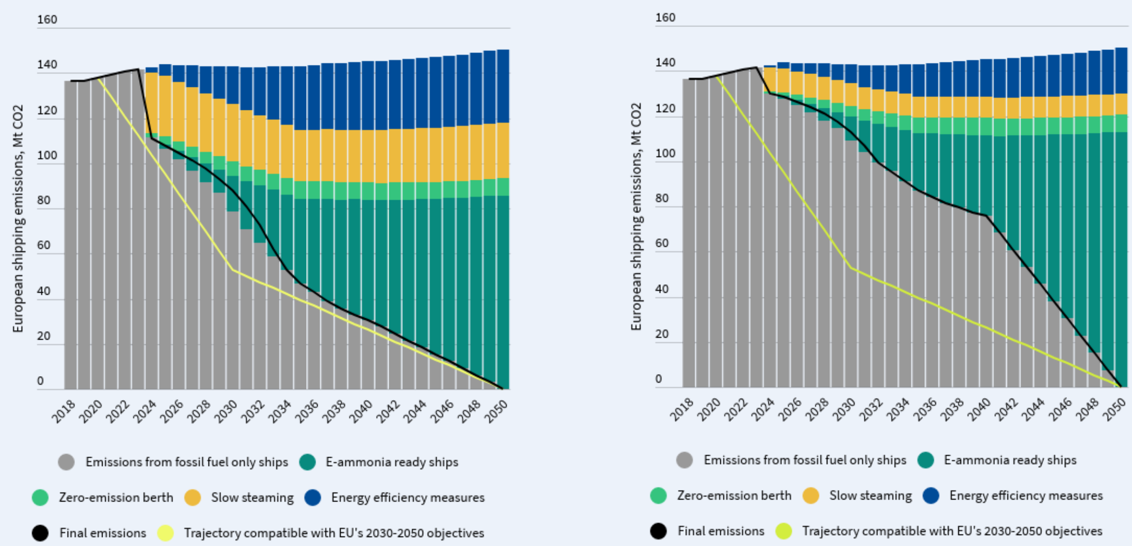
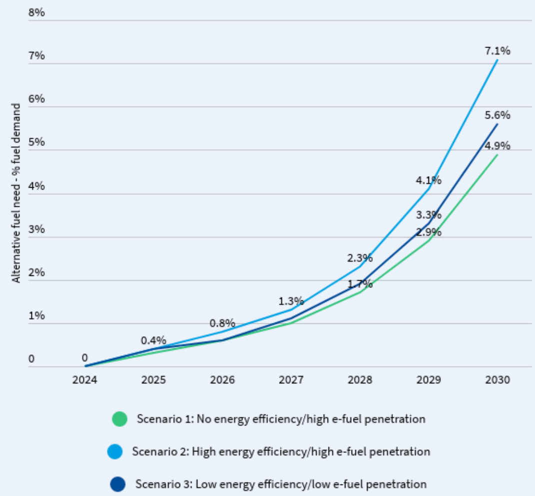


Figure E.1: Decarbonisation pathways for EU-related shipping: high and low energy efficiency scenarios.

4. To fully decarbonise by 2050, EU-related shipping needs to deploy green fuels as soon as possible. We analysed what a sustainable uptake of green ammonia in EU territory could be, and found that around 4.6Mt e-ammonia, or 85 PJ, could be feasibly made available for shipping by 2030. To produce such amounts of green ammonia, Europe would need to install about 14.6 GW of additional renewable electricity and about 7.5 GW of electrolyser capacity by 2030.

5. When combined with maximum energy efficiency improvements including rapid uptake of shore side electrification, the e-ammonia could reach a maximum 7% share in the fuel mix by 2030. This would deliver equivalent (i.e. 7%) improvement in on-board fuel/energy carbon intensity reduction by 2030 compared to the current fossil baseline (Figure E.2, left). If less stringent energy efficiency measures are implemented in parallel, or none at all, the 4.6 Mt e-ammonia would correspond to a lower share of shipping's fuel demand.



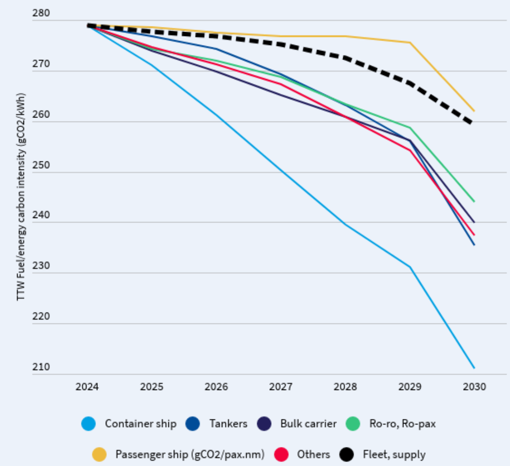


Figure E.2: Green fuels uptake pathways for European shipping, left. Demand for e-ammonia by ship type, right.

6. In order to consume the supply of e-ammonia, and to create the demand for it, shipping companies would need to start deploying zero-emission enabled vessels from 2025 onward. The demand for e-ammonia will vary by ship type (Figure E.2, right). If all of this demand to consume this amount of green ammonia were to come from containerships alone, about 120 large (14500-+ TEU) ammonia-power vessels would need to be deployed by 2030 under the EU MRV scope to consume 4.6Mt ammonia. This compares to an analysis of new build ship order books showing that the equivalent of at least 130 new LNG or LPG-powered vessels of the same total capacity (by DWT) will be deployed in the next 3 years alone.

7. Combined energy efficiency and zero-carbon fuel deployments would also save industry up to €12 billion in costs in 2050 to fully decarbonise (Figure E.3). As a result, EU regulations driving both energy efficiency and green carbon-free fuels deployments would deliver 6 times more cost-effective carbon reduction in 2030 and about 2 times more cost-effective carbon reduction in 2050.

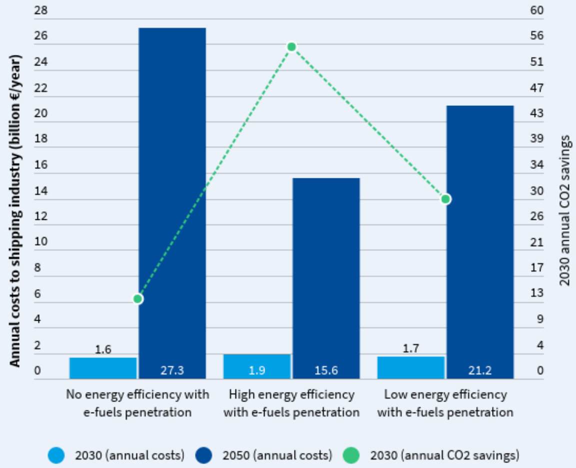


Figure E.3: Cost-effectiveness of EU ship CO_2 abatement under different decarbonisation scenarios

Based on these findings, T&E makes the following policy recommendations to the EU legislators:

1. Shipping sector has enough technical, operational and fuel options to cut its emissions in-sector without undue burden for other sectors. Therefore, the EU should include the largest scope of EU-related maritime emissions in its 2030 climate target and the forthcoming maritime ETS and FuelEU Maritime initiatives.

2. The EU should mandate a 7% (equivalent to 4.6Mt of e-ammonia or 85PJ of other e-fuel) sustainable electrofuel deployment by 2030 for the entire EU-related shipping as an ambitious but realistic waypoint to achieve full decarbonisation by 2050. This would mean that in a goal-based fuel carbon standard, the 2030 target should be -7% compared to the current fossil baseline. This target is only possible with high energy efficiency measures including rapid uptake of shore side electrification; otherwise the target should be revised down to 5% to avoid crop-based biofuels. The mandate should be expressed in energy terms, as opposed to volumetric terms and be accompanied with a credit-exchange mechanism to incentivise operators to start deploying full ZEVs as opposed to incrementally improving existing fleet via unscalable biofuels. Ideally, all biofuels should be excluded from the eligibility list. Alternatively, crop/feed-based biofuels should be banned and sustainable advanced biofuels should be capped at e.g. 1%. Lastly, all eligible fuels should comply with a -70% sustainability criteria.

3. Improvement of ships' fuel economy is also an effective tool, which can both speed up emissions cuts in the near future but also reduce transition costs of deploying sustainable alternative marine fuels. Therefore, the EU should either include energy efficiency in the scope of FuelEU Maritime initiative or complement it with a stand-alone energy efficiency regulation. The ongoing revision of the EU MRV Regulation provides a good opportunity, as proposed by the European Parliament, to implement energy efficiency requirements for EU shipping.

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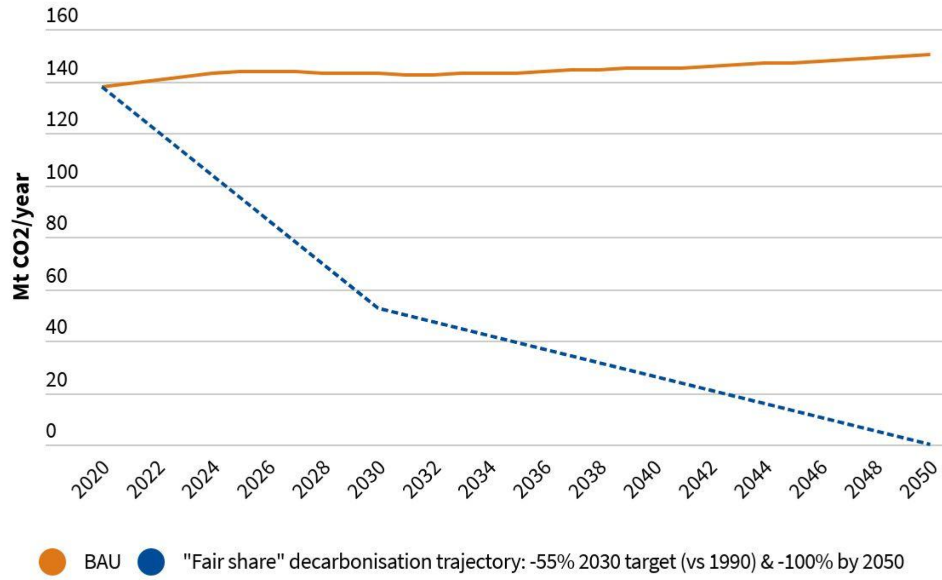
1. Introduction: political and regulatory context

Maritime shipping plays a major role in European freight and passenger transport. It accounts for 75% of the EU's external trade, 36% of intra-EU trade flows by volume and more than 400 million passengers per year[1]. Even though an energy-efficient mode of transport, European shipping is still a very large source of greenhouse gas emissions and air pollution. EU related ship CO_2 emissions reached 145 Mt in 2019[2]. In 2018, maritime emissions represented 3.7% of total EU CO_2 emissions, making its climate impact comparable to that of Belgium, and 13% of the EU's transport emissions[1]. Due to projected growth in global seaborne trade, shipping's global emissions are also expected to increase by up to 50% between now and 2050[3].

In this context, the salience of shipping's climate impact in Europe's political debate has been rising over the past couple of years. While the negotiations at the International Maritime Organisation (IMO) - shipping's international regulator, have intensified over the past couple of years, the IMO has failed to achieve substantial progress in emissions reduction[4]. Against that background, shipping remains the only economic sector that is not contributing to the EU's emissions reduction efforts. By signing the Paris Agreement, the European Union has committed to 'economy-wide' greenhouse gas (GHG) emission reduction efforts. While ships have been required to monitor and report, among others, their EU-related CO_2 emissions and operational efficiency since 2018, to this day shipping is the only transport sector in the EU not subject to GHG emission reduction targets or measures. Figure 1 shows the challenge that EU-related shipping faces: business as usual CO_2 emissions[1] are projected to increase by at least another 10 Mt CO_2 by mid-century. On the other hand, the European Commission's communication on the European Climate Plan for 2030 argues that all sectors, including maritime transport, should contribute to the revised 2030 climate goal of 55% emissions reductions below 1990 levels[5]. This is equivalent to around 52.6 Mt CO_2 by 2030 compared to 1990 emissions, or around a 90 Mt CO_2 reduction from 2018 emissions[2], and should have a goal of full decarbonisation by 2050. This target is part of the Commission proposal on the European Climate Law[6] and is also a requirement for Europe to achieve its Paris Agreement obligations.

[1] More details in Section 2.

[2] This is based on an approximation of MRV scope emissions in 1990, where UNFCCC emissions, based on fuel sales, are scaled to the 2018 difference between fuel sales and activity data, resulting in 1990 emissions of 117 Mt CO_2.



Note: "Fair share" trajectory envisages a -55% 2030 target (vs 1990) & -100% by 2050, compatible with the EU's overall climate goals. "Fair share" assumes that shipping's share in the overall EU emissions/ decarbonisation remains constant.

Figure 1: European shipping emissions business-as-usual (BaU) compared with EU climate targets.

Partially dismayed by the lack of progress by the IMO, but also encouraged by the domestic pressure to increase Europe's climate ambition, the European Commission eventually committed as part the European Green Deal, among others, to include shipping in the EU Emissions Trading Scheme (ETS) and deploy alternative sustainable marine fuels.[3] Such a high ambition was later confirmed by the European Smart and Sustainable Mobility Strategy (SSMS), which additionally set a goal to have the first zero-emission ocean-going vessel in the water by 2030[8]. Furthermore, the draft European Climate Law set an overarching goal of European climate-neutrality by 2050[9], which under Article 2 includes emissions of international shipping.[4] Last but not least, the European Parliament voted in September 2020 as part of the revision of the MRV Regulation to include shipping in the EU ETS, mandate 40% vessel carbon intensity improvements by 2030 compared to 2018 and achieve

[3] The European Green Deal is a set of policy initiatives by the European Commission with the overarching aim of making Europe climate neutral by 2050. See: [7]
[4] Article 2 puts the focus on *"Union-wide emissions and removals of greenhouse gases* ***regulated*** *in Union law"*, which includes international shipping emissions regulated under the EU MRV Regulation 2015/757. Highlights in the quoted text belong to T&E.

zero-emission berth operation by 2030[10]. Before any of these become a binding law, EP's recommendations will need to be first negotiated with the Council of the EU representing the EU.

The following section provides a more detailed overview of the possible policy pathways to regulate shipping, including the forthcoming FuelEU Maritime initiative[11], that will be fundamental to shipping's technological transition.

1.1. Purpose of this study

The European Commission is keen to incorporate shipping in its 2030 and 2050 targets and has committed to make several legislative proposals during the course of 2021. These new objectives do not only set a new long-term target for shipping, but also raise important questions on the needed *pathway* to achieve them. This encouraged T&E to have a fresh look at our original *Roadmap to Decarbonising European Shipping[12]*, which despite the title provided only a snapshot of the European shipping's likely energy/fuel needs in 2050 and the available technologies to deploy to decarbonise. The current study aims to fill that gap in several respects:

- To chart the emissions reduction potential of different technological options, including both energy efficiency and fuels/energy switch. In particular, we address 2030 reduction potential in order to feed into the current EU regulations
- In the absence of ambitious and detailed zero emission vessels (ZEVs) deployment plans by the industry or the governments, the study aims to imagine a radical but broadly achievable timeline for the deployment of alternative marine fuels in European shipping by 2030. In doing so, the analysis takes into account the latest announcements by the original equipment manufacturers (OEMs), fuels suppliers and pioneer shipping companies and aims to chart out the pathway to fleet-wide uptake of ZEVs compatible with the EU's 2050 carbon-neutrality objective.
- Informed by these technical analyses, the study provides policy recommendations to the EU and Member States to take on board as part of the decision-making process on the forthcoming FuelEU Maritime, ETS and other relevant legislations.

To achieve these, the study develops three modelling scenarios described in further detail in Section 2. The first scenario relies only on ambitious e-fuels uptake, the second combines the e-fuels uptake with ambitious energy efficiency measures, while the third simulates a slightly less ambition in the coming decades in energy efficiency uptake and e-fuels uptake. With these guiding scenarios, this study:

- Analyses and describes the effect of CO_2 abatement technologies available to the shipping sector;

- Calculates the amount of the cumulative GHG that can be saved with energy efficiency vs. fuel switch (and in combination) between 2020 - 2050, compared to a business as usual scenario with the ultimate goal of mid century decarbonisation;
- Models achievable improvements in energy intensity (fuel economy) for EU shipping;
- Models an energy carbon intensity roadmap for EU shipping, both for new vessels and retrofits;
- Estimates the net costs of energy efficiency and the net costs of fuel switch, both separately and in combination, in order to shed light on the cost-effectiveness of the 3 analytical scenarios explored;

1.2. Possible regulatory pathways for decarbonising shipping

As this study will demonstrate in the following chapters, decarbonisation of shipping will require both improvements in vessel fuel economy (i.e. energy efficiency) and change in fuels used for propulsion and other onboard energy use. From the regulatory perspective, there are different ways to bring about this change. Those include economic measures such as ETS, but also command & control mechanisms such as operational vessel carbon intensity and/or operational fuel carbon intensity standards. So long as the targets on operational fuel carbon intensity and fuel carbon intensity standards are sufficiently high, absolute emissions can be placed on a downward trajectory. As the recommendations of the current study will concentrate on the latter two plus a hybrid system, the following paragraphs will describe these operational standards in further detail.

Goal-based operational vessel carbon intensity standards refer to a regulator setting annual targets for maximum allowed GHG emissions per unit transport work[5] and letting the shipping companies decide on the methods of meeting those standards in operation. These operational vessel carbon intensity standards (a.k.a. operational CO_2 standards) could be set using a variety of operational metrics, including AER ($gCO_2eq/DWT \cdot nm$), EEOI ($gCO_2eq/t \cdot nm$), cgDIST ($gCO_2eq/GT \cdot nm$), etc. To comply with such standards, vessels could improve their energy efficiency (i.e. fuel economy) via e.g., slow steaming or wind assist technologies and/or switch to alternative sustainable fuels. However, beyond a certain point energy efficiency would reach its physical limits and fuel switch would be the only option of compliance.

Goal-based operational energy carbon intensity standards refer to a regulator setting annual targets for maximum allowed GHG emissions per unit of energy consumed on board for propulsion and auxiliary power needs. The units of the standard could be gCO_2eq/kWh or gCO_2eq/MJ, etc. Such a standard would give enough flexibility to shipowners to choose their preferred method of compliance,

[5] Transport work for shipping refers to the product of total cargo carried over total total distance sailed during a specific period of time, usually a year. Sometimes, instead of cargo carried, a vessel's cargo capacity (either by volume, by mass or unitised metrics such as TEU) is used to calculate proxy transport work.

which could include blending of carbon-neutral fuels, such as biofuel and synthetic hydrocarbons and alcohols, co-combustion of green hydrogen and ammonia together with pilot fuels in internal combustion engines (ICE) or using fuel cells to power the vessels alone or in combination with other energy sources. However, in order to provide equal opportunities for new, yet to be deployed fuels, such as hydrogen and e-ammonia, the standard needs to be set at the company/operator level and complemented with a credit-exchange mechanism. The former would enable shipping companies to comply with the set targets by deploying new full zero-emission vessels as opposed to marginally improving existing ones. The latter would also allow shipping segments with predictable schedules and itineraries to deploy ZEVs at a faster rate while ensuring that the costs of over-compliance can be socialised via credit purchasing by the under-performing companies/ship types.

The standard would need to be progressively tightened to increase the share of alternative fuels in the overall energy consumption of vessels. Unlike operational CO_2 standards, energy carbon intensity standards won't give credits to fuel economy improvements and if based on the current EU MRV (or IMO DCS) systems, which only require fuel-based energy monitoring, they would also exclude alternative energy sources such as wind power or on-shore electricity.

INFO BOX 1 - Fuel uptake mandate - opportunities and risks

Mandating ships to uptake advanced alternative marine fuels is an important necessary legal mechanism to create predictable demand, boost supply chains, to give investment certainty, and allows ship builders to access the right fuel technologies. Although it is not as flexible as the operational CO_2 standard, whereby the market can choose to adopt the most cost effective technologies to abate CO_2, a fuel mandate can ensure the early uptake and adoption of clean fuels. On the surface of it, if designed properly with strong sustainability safeguards, a higher target would translate to higher CO_2 savings. The type of target (energy or volume based) is also crucial to take into account.

However, the FuelEU Maritime legislation is unlikely to dictate the type of fuel to be supplied: it is expected that alternative renewable fuels covered in the Renewable Energy Directive (the RED II) will be allowed. The implication is that, if nothing is done, cheaper fuels, such as crop-based biofuels, could quickly enter the market to meet a fuel target before long-term scalable and renewable technologies based on green hydrogen. Although this risk exists regardless of the target, a target that exceeds a realistic uptake of e-ammonia would likely only be met by an additional uptake of biofuels. Too low a target would not give the clear signal to the market for large investments. The target should exclude all crop based biofuels.

Goal-based carbon and energy intensity standards (CEIS) takes the goal based operational vessel carbon intensity standards above and splits it into a combination of a vessel energy intensity (VEI) standard (i.e. energy per transport work), and energy carbon intensity (ECI) standard (emission per unit of energy consumed), see Equation 1. Each component has its own target, at a granularity of ship type and size, see Equation 2:

$$CEIS\ [\frac{gCO2}{t \cdot nm}] = Energy\ Intensity\ [\frac{kWh}{t \cdot nm}]\ *\ fuel\ CI\ [\frac{gCO2}{kWh}] \quad \text{Equation 1}$$

$$CEIS_{yc} = [VEI_{y0}\ *\ (1 - a_{yc})]\ *\ [ECI_{y0}\ *\ (1 - b_{yc})] \quad \text{Equation 2}$$

Where $CEIS_{yc}$ is the required vessel carbon & energy intensity in the compliance year *yc*, VEI_{y0} is the average energy intensity of vessels of the same type and size in the baseline year *y*0, ECI_{y0} is the average energy carbon intensity, a_{yc} is the required V*EI* reduction target, e.g. 30% improvement target gives $a_i = 0.3$, and b_{yc} required *ECI* reduction target.

Unlike the previous two standards, CEIS would allow the regulator to set separate and targeted objectives for vessel energy efficiency/intensity (i.e. fuel economy) and on-board energy carbon intensity improvements. The main difference with the operational CO_2 standards would be that the regulator would be able to speed up the deployment of alternative fuels without resorting to higher targets for the total vessel's carbon intensity (i.e. through AER or EEOI).

CEIS could be implemented both at the vessel and fleet levels and combined with a credit-exchange mechanism as explained above. While the European Parliament proposal in the context of shipping MRV revision is based on the operational CO_2 standard concept, the European Commission seems to be prioritising operational energy carbon intensity standards according to the publication consultation on FuelEU Maritime initiative.

If the European Commission chooses the latter for its FuelEU Maritime proposal in the coming months, it could be complemented with CEIS in the future revisions of the legislation in order to incentivise vessel energy efficiency (fuel economy) improvements which would otherwise be left out in the FuelEU Maritime initiative.

1.3. EU Shipping climate performance and the MRV regulation

In 2019, T&E analysed the EU shipping's climate performance using the 2018 MRV data[13]. The report looked at some of the biggest shipping companies, and found that the containerships owned and operated by the Mediterranean Shipping Company (MSC) emitted 11 Mt CO_2, equivalent to the emissions of the largest coal power plants on the continent. Emissions attributed to some member states by activity were in some cases larger to or equivalent to their national passenger car fleets. It also found that the operational performance of shipping consistently underperformed compared to the design efficiency of ships, and thus called into question the premise of design energy efficiency indices as effective measures to improve the performance of shipping.

But the most important conclusion of that analysis was that the information provided by the MRV was crucial to assess the optimal ways to reduce emissions in the sector and MRV data was of high enough quality to make relevant policy decisions.

2. Summary of options to decarbonise shipping

This section investigates the technical options available to ships and ports in order to decarbonise EU-related shipping by 2050. It draws on the Fourth IMO GHG Study 2020[3] and in-house analysis. The inhouse analysis was based on building a shipping stock model for the ships that call at European ports. More details can be found in the Section 3.1 and the Appendix. Table 1 shows the technological and operational options and the maximum CO_2 abatement potentials considered. For more detailed information on each group of measures, see the Appendix.

2.1. CO_2 abatement technologies used in this study

For efficiency measures, we used the CO_2 abatement potential from the IMO's maximum abatement potential applied to operational emissions only (i.e they are not applied to energy consumption and thus CO_2 emissions at berth). For wind assist, the abatement potential was assessed for each ship type based on a review of the literature. For speed reduction, a 20% speed limit below the average speed for each ship type and size was applied to ships for which such a measure would result in lower emissions. As it could be impractical for cruise ships, ro-ros, ro-pax and vehicle carriers to reduce their speed, we did not apply any speed reduction to these ship types. For zero-emission berth operation, the maximum abatement potential is the share of CO_2 at berth over total CO_2 emissions. 2030 CO_2 abatement is derived using a linear adoption rate on the maximum abatement potential. See the Appendix for more detailed discussion. The marginal abatement costs (MAC) show that optimising the hull and propeller saves money (i.e. the amount invested is more than paid back in saved fuel costs).

Table 1: CO_2 abatement technologies and their maximum potential in Europe in 2030 and 2050, compared to IMO calculations for the global fleet. *Abatement potential or MAC from IMO4 not used in this study; potential based on uptake, not final max potential. §e-ammonia abatement in 2030 limited by supply and figure for high energy efficiency scenario only; potential excludes berth emissions.

Measure [IMO technology group, table 77 p278]	2030			2050		
	IMO 4th GHG study MAC (USD/ tonne -CO_2)	IMO 4th GHG study CO_2 abatement potential (%)	CO_2 abatement (%), this study	IMO 4th GHG study MAC (USD/tonne -CO_2)	IMO 4th GHG study CO_2 abatement potential (%)	CO_2 abatement (%), this study
New ship main and auxiliary engine improvements [12,2,1,7]	25.4	2.8%	1.0%	18.2	4.9%	4.0%
Propeller optimisation [6,5]	-54.2	3.6%	3.4%	-56.6	6.3%	5.7%
Hull optimisation [10,9,8]	-89.5	5.3%	4.8%	-88.8	9.2%	7.8%
Wind assist [13]*	6.0	0.9%	2.5%	2.0	1.7%	4.0%
Speed reduction [16]*	43.0	7.4%	17.5%	26.0	7.5%	16.5%
Zero-emission berth (plug-in at port) [-]*	5.4		4.7%	-33.4		5.0%
Use of e-ammonia [-]*,§	280.0		7.0%	221.8		100.0%

For e-fuels, we chose e-ammonia as a "placeholder". This was done for three reasons. Firstly, adding multiple e-fuel options would create additional complexity to the model. E-ammonia requires green hydrogen, which would be a feedstock for all e-fuels. This makes it easy to make further calculations in the future if other e-fuels see higher uptake. Secondly, e-ammonia presents the cheapest e-fuel option for shipping as Figure 2 below illustrates. Lastly, there is growing consensus among the world's largest shipyards that e-ammonia might be the "closest alternative to an ideal fuel" for shipping[14]. Despite its inferior energy density to e-hydrocarbons and e-alcohols, such as e-diesel, e-methanol or e-methane, the total cost of operation of ocean going e-ammonia appears to be the lowest even when taking on board the opportunity costs of space loss[15]. This however, doesn't mean that other e-alternatives aren't technically feasible. For example, DFDS and Viking Cruises are aiming to build a compressed and liquid hydrogen ferry and cruise ships, respectively.[6]

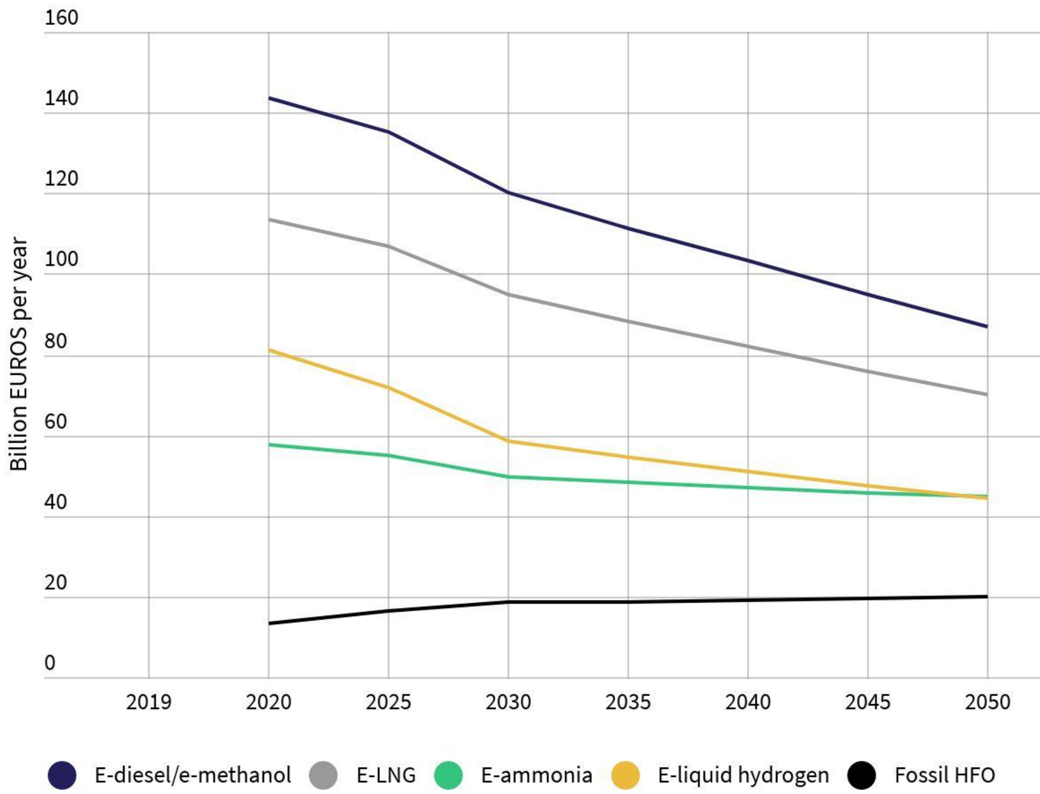


Figure 2: Potential energy costs for European shipping under different e-fuel options.

2.2. Abatement technologies not taken into account and why

We did not consider super light ship designs or solar panels as viable CO_2 abatement technologies, as their impact is very limited and the projected small impact on the fleet. Liquified natural gas (LNG) is often touted as a bridging fuel to decarbonisation, however many studies show that it only has marginal climate benefits (Figure 3) over existing marine fuels[18–20]. LNG will cause a lock-in effect of carbon fuels extraction and infrastructure. An uptake in this technology will at best lead to stranded

[6] Partnership aims to develop hydrogen ferry for Oslo-Copenhagen [16]; Europe: $3.7 million funding for Norwegian maritime liquid hydrogen supply chain [17]

assets with a switch to zero-emission technologies or at worse exacerbate climate change. Biomethane is sometimes referred to as a replacement for LNG, however there is little evidence that there would be capacity to sustainably produce sufficient biomethane to provide more than a small fraction of shipping's fuel needs (Figure 4).[21]

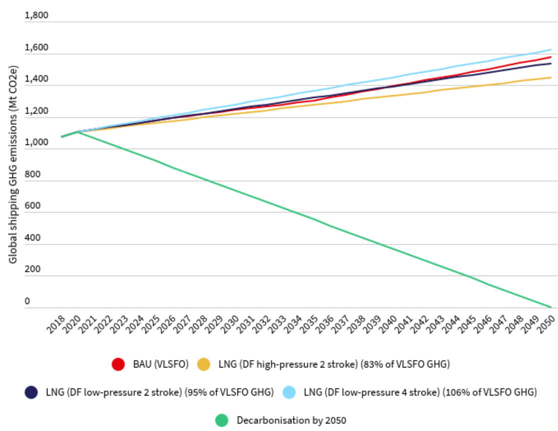


Figure 3: Visualisation the impact on GHG reduction of hypothetical large-scale switch to LNG in shipping.

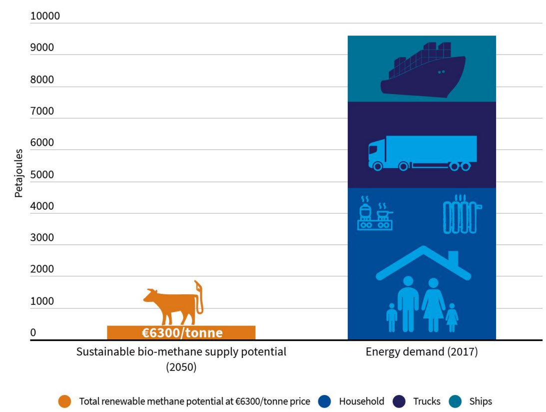


Figure 4: The limits of sustainable biomethane supply potential compared to large demands from competing sectors.

3. Shipping emissions model and results of the analysis

This section describes the techno-economical shipping model developed, the scenarios and their assumptions in greater detail. The model allows for the application of technological uptake, efficiency improvements, and fuel uptake, as described in the following sections.

3.1. T&E's shipping model

For this work, T&E built a shipping fleet turnover model, as shown schematically in Figure 5. The basis of the model draws on the shipping activity and operational performance as reported in the 2018 MRV as a baseline. The Clarkson database for the ships' characteristics, such as size/capacity (for example DWT and GT) and age, was combined with the ships in the MRV so that 87% of ships, responsible for 96% of EU MRV emissions (i.e. ships greater than 5000 GT), were assigned characteristics. We were then able to class ships into size and type categories, and their average annual transport work calculated. Knowing the age of the ships enabled us to determine their expected retirement year, and it also enabled us to define the efficiency of new ships, which were taken to be equivalent to the average of the ships built in the last 5 years, for each class.

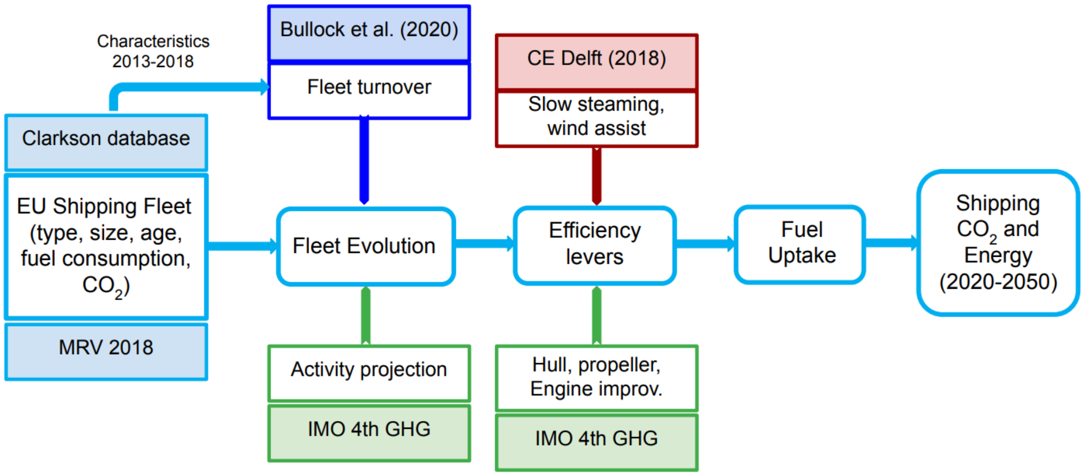


Figure 5: Schematic of the shipping energy and CO_2 emissions model developed for this study

Projections for activity are taken from the IMO 4th GHG study (the SSP2_RCP2.6_G growth scenario, which is deemed to be compatible with the well-below 2°C target of the Paris Agreement). New ships enter the fleet to meet the combined increase in projected new transport demand as well as to cover the transport activity of retired ships. This enables us to keep track of both the number of ships in the fleet and of new ships by year of introduction. Technologies are then applied to either new vessels, retrofitted to the fleet of existing vessels, or a combination of both. We assume technology penetration increases linearly between the year of introduction of the technology, taken to be 2024 as the assumed date of entry of the relevant EU regulations (with the exception for e-ammonia, 2025) and the year when it has been fully adopted. More details on the assumptions related to technology penetration can be found in the Appendix.

3.2. Scenarios and summary of assumptions for modelling

In this study we develop three technology roadmaps, or scenarios, to assess the benefits of different strategies for reaching zero-emissions in 2050 as detailed in Table 2. We first assess an ambitious but probable e-fuels deployment speed, and then we apply this uptake to cover a range of scenarios: the first scenario considers only operational e-fuels and berth electrification deployment to achieve mid century decarbonisation; the second scenario applies maximum technical-operational efficiency first before electrofuel and berth electricity deployment; the third scenario roughly halves the efficiency measures of the second scenario. These scenarios also allow us to see the potential emissions reductions in 2030, an important milestone for setting the trajectory of emissions of toward zero and also for the cumulative emissions of the sector over the next three decades. All three scenarios are compared to a business as usual scenario, which assumes no climate mitigation technology adoption through lack of policy or incentive.

Table 2: Scenarios investigated in this study.

Scenario	Efficiency measures	Zero emission berth operation via electricity shore-side connection	E-fuel demand
Business as usual	Efficiency improvements due to new, larger (and thus more efficient - AER the average of the last 5 years) vessels entering the fleet.	No zero berth emission uptake	No e-fuel uptake
Scenario 1: fuels only	As per business as usual	Achieved by cruise, ro-ro, ro-pax by 2025, container, oil tanker, ref-bulk by 2030, and remaining vessels by 2035.	From 2025, all new vessels co-combust at 70:30 ratio of NH_3 and pilot diesel; from 2030 old vessels progressively retrofitted for 50:50 NH_3 and pilot diesel co-combustion; from 2040 the remaining fossil diesel is eliminated from the fleet via mono-fuel technologies or NH_3 co-combustion with e-diesel/biofuel/hydrogen.
Scenario 2: high energy efficiency with e-fuels	As per scenario 1, and additionally all vessels improve their technical and operational efficiency and carry out regular vessel maintenance, as per Table 1 in Section 2.		
Scenario 3: low energy efficiency with e-fuels	Half of the technical, operational, and maintenance levels of Scenario 2. Speed limit 10% below average speed for each ship type, applied by 50% of the vessels in the fleet.	Achieved by cruise, ro-Ro, ro-pax, container, oil tanker, ref-bulk by 2030, and remaining vessels in 2035.	Half of the new (from 2025) and half of the retro-fitted (from 2030) ships for co-combustion until 2040 compared to Scenarios 1 and 2, whereafter rapid technology shifts to achieve zero emissions.

An important differentiation is made in this study on the ship uptake of new technologies that enable co-combustion with e-ammonia (driving demand for this fuel) and the sustainable and economically plausible supply of e-ammonia. Although the supply of e-ammonia could technically match the demand from ships, it is ultimately down to the level of government policy to drive demand and fiscal support to ensure a rapid and coordinated roll-out of renewable electricity generation, electrolyzer and ammonia synthesis plants deployment.

INFO BOX 2 - Determining a potential sustainable e-ammonia supply

There are many uncertainties in the costs, market uptake, and sustainable availability of new technologies and energy vectors. Thus predicting or modelling an available fuel supply in a decade's time can be forlorn, particularly as many factors can evolve rapidly, most importantly government financial and political support. We undertake the task of determining a sustainable uptake of green e-ammonia cautiously for reasons discussed in INFO BOX 1. Further, we base the supply of e-ammonia as being produced only within EU territory. We do not set out to model the available quantity from a bottom up approach or through economic analysis. Rather, we compare the quantity of e-ammonia in 2030 against several metrics to determine whether the uptake is feasible and could be done sustainably.

The main assumption underpinning the e-ammonia supply is based on the demand curve from the uptake of new LPG and LNG ships with build years from 2014 to 2023, from the IHS Markit shipping database. In lieu of direct policy, but likely spurred on by the regulated change in the sulfur content of fuel signed in 2016, new LNG-powered ships have had, and looking at the upcoming builds in the next couple of years, will continue to see a rather striking uptake.[7] This is a useful indicator, as the global deployment of LNG ships led to the EU significantly ramping up its natural gas supply to ships, where in 2016 it supplied 0.09 PJ while in 2019 this rose to 6.0 PJ[8]; this compares to 14 000 PJ of gross inland consumption in the EU. European ports were thus able to rapidly deploy a new marine fuel and associated infrastructure for ships.

We manually fit an S-curve to the share of the DWT ingress of LPG and LNG ships of the shipping fleet. It should be noted that fitting an S-curve to relatively few data points increases the uncertainty of the projections. We argue that with a direct and clear policy outlook, ammonia powered ships could more than double the rate of deployment of LNG ships; we assume by a factor of 2.5. Figure 6 shows the real and extrapolated LNG curves as well as the assumed e-ammonia curve. Without knowledge of which ships would switch to ammonia first, we apply the anticipated share of ammonia powered vessels to the energy demand of the business as usual fleet. Note that the e-ammonia supply curve is eventually limited by the shipping demand (after approximately 10 years), as explained further in Section 3.3. Based on these parameters, we approximate that about 4.6 Mt of green e-ammonia[9], or 85 PJ, could be deployed in shipping by 2030. Although achieved in a very short time, this is an order of magnitude greater than the LNG supply in 2019; hence the requirement for strong, clear, and early policy support for e-ammonia to ensure that it is realised.

[7] T&E has argued that this is not a solution for the climate, see for example [20]
[8] Eurostat tables nrg_bal_s
[9] This compares to the EU27+UK ammonia production capacity of 21 Mt. See [22]

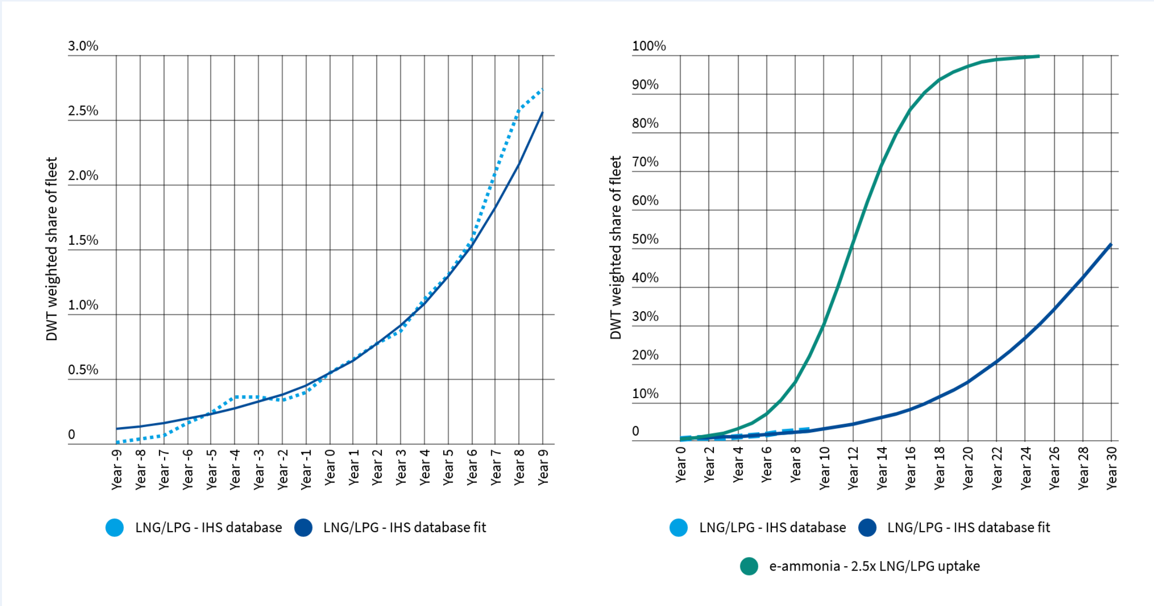


Figure 6: Projection of e-ammonia uptake in 2030, based on DWT share of LPG and LNG ships in the total fleet. For LNG/LPG, Year 0 corresponds to 2014, whereas we assumed Year 0 to be 2025 for e-ammonia.

To produce such amounts of green ammonia, the EU would need to install about 14.6 GW of additional renewable electricity; this compares to 14.7 GW of total wind capacity installed in Europe in 2020 and 220 GW total installed capacity by 2020 [23].[10] The EU would also require around 7.5 GW of electrolyser capacity by 2030, which compares to Hydrogen Europe forecasts and ambitions of 40 GW electrolyser capacity in 2030 [26]. The EU would also need to commission around 10 dedicated ammonia producing installations, compared to the 42 installations that are on the continent (total in 2013)[22]. If all of this demand came from containerships alone, to consume this amount of green ammonia, about 120 large (14500+ TEU) ammonia-power vessels would need to be deployed by 2030 under the EU MRV scope. This deployment rate seems reasonable when comparing to the future deployment of LNG/LPG-powered vessels. Indeed, analysis of the IHS Markit shipping database demonstrates that the total LNG/LPG-powered ship capacity that has already been ordered for the next 3 years is equivalent to the ship capacity of 130 large (14500+ TEU) containers.

Given the uncertainties, we recommend that 85 PJ of e-ammonia should be the maximum estimate for uptake of fuel produced in the EU by 2030 to be used in the EU shipping sector. This quantity can be produced sustainably in EU territory provided that the required dedicated renewable electricity generation capacity, ammonia installation construction, and electrolyser capacity are met.

[10] Forecasts for 2030 are 323 GW installation of wind turbines [24] and 563 GW of solar capacity [25].

3.3. CO_2 reduction pathways

This section shows the CO_2 savings and contributions of the scenarios investigated. A 55% reduction on 1990 emissions, in line with the European Commission's Climate Target Plan, would mean that shipping emissions would be capped at 52.6 Mt CO_2 in 2030.[11] We use this value as a benchmark for near term emissions savings. In all scenarios, the zero berth emission standards reduce total emissions by 7.5 Mt CO2 in 2050. The application of the measure is slower in Scenario 3 (4.9 Mt CO_2 reduction in 2030) than in the other scenarios (6.7 Mt CO_2 reduction in 2030). All scenarios adopt the same uptake of e-ammonia. All results are then summarised in Table 3 at the end of this subsection.

Scenario 1: fuels only

Figure 7 shows the results for Scenario 1. With no technical or operational energy efficiency measures, emissions are only reduced through e-fuels. The uptake of ammonia ready ships begins in 2025, with on average 380 new ships per year (of all types and sizes) entering the European fleet in the second half of the 2020s. From 2030, around 5% of the EU fleet is retrofitted per year, equivalent to around 600 vessels per year, in addition to the new ships, which is also on average 600 vessels per year. Initially the demand for e-ammonia exceeds the supply, however by 2035, it is anticipated that supply will largely meet demand. From 2040 onwards, we assume that ammonia will be co-combusted with an e-diesel as a pilot fuel, or that technology will be developed to allow full ammonia combustion.

In 2030, we project that emissions would be 129.5 Mt CO_2 compared to 142.9 Mt CO_2 in the business as usual scenario. E-ammonia will make up for around 4.9% of the non-port energy consumption of the shipping fleet. In total, the fuels only pathway represents a reduction in emissions of approximately 6.9 Mt CO_2 compared to 2018, or 5.1.3%. This corresponds to emissions 10.9% higher than 1990 emissions, far from the 55% reduction target.

[11] As described in the introduction. This assumes that the EU target covers the full MRV scope.

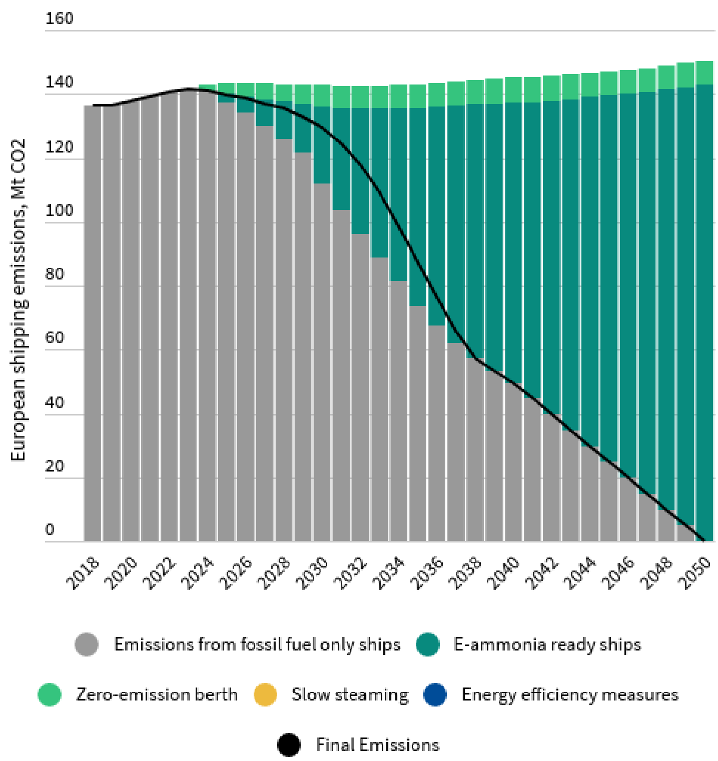


Figure 7: CO_2 results for scenario 1: fuels only

Scenario 2: high energy efficiency with e-fuels

Figure 8 shows the results for Scenario 2. Technical and operational energy efficiency options and e-fuels uptake in combination reduce CO_2 emissions by 41.8 Mt CO_2, or 29%, in 2030 compared to the business as usual and 57 Mt CO_2 in 2050, or 36%. As per scenario 1, the uptake of ammonia ready ships begins in 2025, and from 2030, around 5% of the EU fleet is retrofitted per year. In 2030, e-ammonia makes up for 7.1% of the non-port energy consumption. Together, high energy efficiency including rapid uptake of shore side electrification and e-fuels measures still miss the -55% 2030 target by 35.1 Mt CO_2.

In 2030, we project that emissions would be 87.7 Mt CO_2 compared to 142.9 Mt CO_2 in the business as usual scenario. In total, this pathway represents a reduction in emissions of approximately 48.7 Mt CO_2 compared to 2018, or 36%. As technical and operational efficiency measures can be applied in a much shorter time frame than an equivalent ramp up of green hydrogen for e-ammonia, significant gains can be made this decade. This plays an important role in reducing cumulative emissions in the sector, and thus for climate change mitigation.

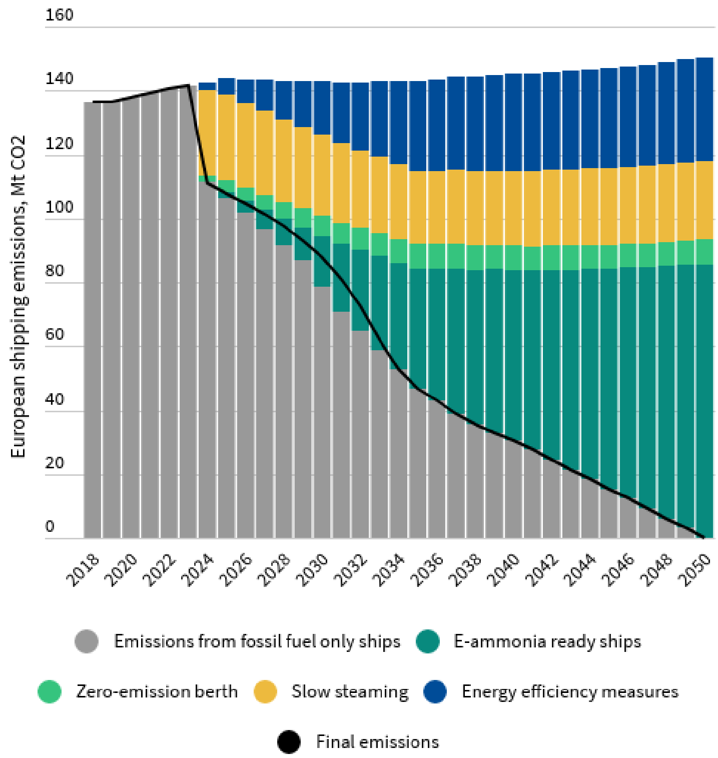


Figure 8: CO_2 results for scenario 2: high energy efficiency with e-fuels

Scenario 3: low energy efficiency with e-fuels

Figure 9 shows the results for Scenario 3. Technical and operational energy efficiency options and e-fuels uptake combined reduce CO_2 emissions by 18.3 Mt CO_2, or 13%, in 2030 compared to the baseline and 29.7 Mt CO_2 in 2050, or 20%. In 2030, we project that emissions would be 112.9 Mt CO_2 compared to 142.9 Mt CO_2 in the business as usual scenario. In total, this pathway represents a reduction in emissions of approximately 23.4 Mt CO_2 compared to 2018, or 17%. The results show that even if vessels were not to attain all of the high technical and operational energy efficiency options of scenario 2, the emission savings could still be in the order of three times as great as the fuels only scenario.

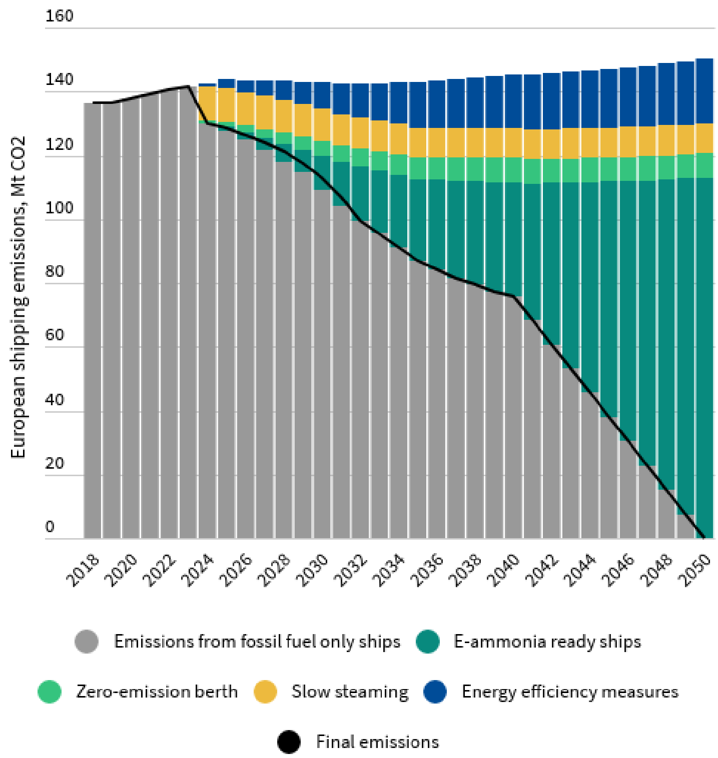
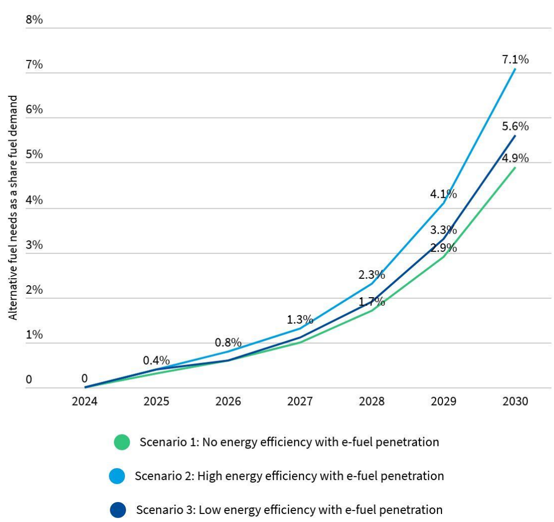


Figure 9: CO_2 results for scenario 2: low energy efficiency with e-fuels

Results summary: Scenario 2 closest pathway to -55% CO2 reductions by 2030
Table 3 summarises the CO_2 savings results for the three scenarios. Compared to 2018 emissions in the scope of our study amounting to 136.4 Mt CO_2, all scenarios reduce emissions. With the 55% target of 52.5 Mt CO_2, scenario 2 with its biggest emissions cuts comes closest to achieving this. Figure 10 (left) provides a visualisation of the e-ammonia uptake in each scenario in terms of share of final. Figure 10 (right) shows how the supply of e-ammonia is eventually limited by the demand of e-ammonia ready ships, for scenario 2. In this scenario, where all new builds are ammonia enabled from 2025, potential demand of the fuel outstrips supply until 2034. The demand curtails the maximum supply from 2034 on. As described in Info Box 2, the supply potential of e-ammonia is highly uncertain; this is especially true for the steep ramp up in supply after 2030.

Table 3: Summary of CO_2 results. [*]1990 emissions approximated scaling the MRV 2018 CO_2 emissions with the UNFCCC navigation emissions, equal to 117 Mt CO_2.

	BaU	**Scenario 1**	**Scenario 2**	**Scenario 3**
Emissions in 2030 (Mt CO_2); compared to emissions in 1990[*]	142.9; +22.4%	129.5; +10.9%	87.7; -24.9%	112.9; -3.2%
Cumulative emissions, 2021 to 2030 inclusive (Mt CO_2); vs business as usual	1423; 0%	1375; -3%	1124; -21%	1281; -10%
Cumulative emissions, 2021 to 2050 inclusive (Mt CO_2); vs business as usual	4332; 0%	2437; -44%	1758; -59%	2502; -42%
e-ammonia supply, 2030 (Mt); e-ammonia share in terms of operational energy demand	N/A	4.6; 4.9%	4.6; 7.1%	4.6; 5.6%
e-ammonia supply, 2050 (Mt)	N/A	99	59.5	78.4
SSE 2030 (TWh)	N/A	13.0	13.0	9.5



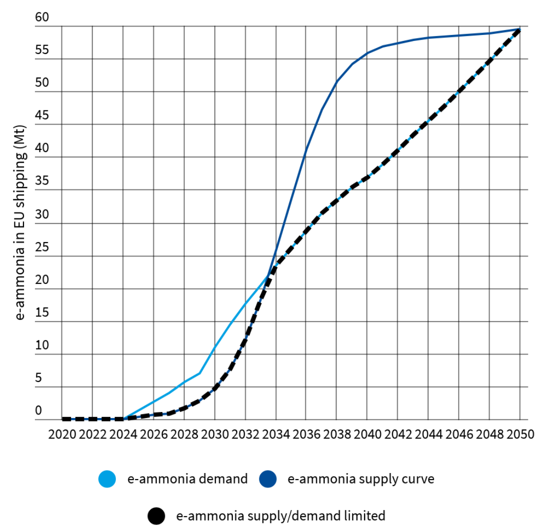


Figure 10: Green e-ammonia uptake for the 3 scenarios, left. Demand limited supply, example from scenario 2, right.

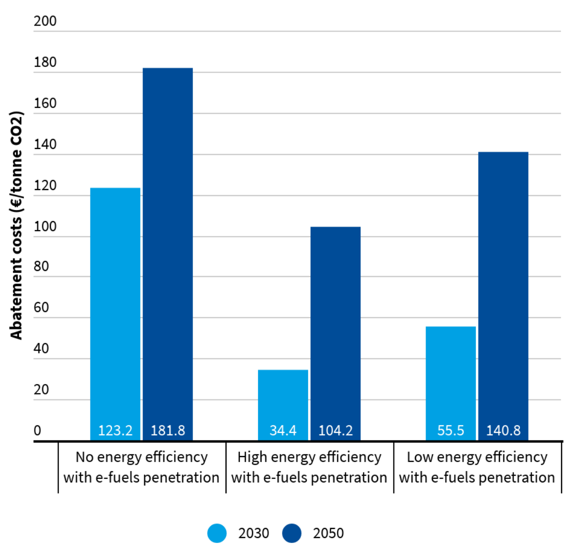
3.4. Costs and energy demand

As shown in the previous section, the three scenarios all reach zero emissions in 2050. Where the marginal abatement cost (MAC) values are not taken from the IMO, we generated our own MACs from equation 3.2 p.225 in the 4th IMO GHG report, as described herein. For zero emission berths, the fuel consumption at ports was converted into energy consumption. The efficiency difference of direct electrification was considered to be 94% (accounting for transmission losses), whereas for a diesel generator we took 51%. Table 4 lists the key input parameters for the zero-emission berth MAC calculation. Retrofitting costs were deemed negligible in regard to infrastructure costs and were not included in the calculation. Given the total calculated electricity consumption at port and the utility factor of the chargers, the total installed power required is calculated to be 2480 MW in 2030 (in the high energy efficiency and fuels only scenarios), and 2780 MW in 2050. With these assumptions and a constant HFO price of €326/t, we calculate zero-emission berths to have a negative MAC in 2050, i.e. sparing more fuel cost than the required infrastructure and electricity costs. For e-ammonia, we consider only the fuel cost as the marginal difference for the engine modifications and onboard storage are relatively small compared to the price of fuel itself, which is largely dictated by the price of electricity and the cost of electrolysers. We took the prices for e-ammonia directly from Ricardo[27], which were €501 per tonne in 2030 and €429 per tonne in 2050, corresponding to CO_2 abatement costs of €243 and €193 per tonne CO_2, respectively.

Table 4: key inputs for zero emission birth MAC calculation

Input	Value	Units	Source/comment
Charging infrastructure cost	400 000	€/MW	T&E[28]
Utilisation factor	0.6	--	Assumption
Service life	25	years	IMO4GHG
Annual operational cost, of CAPEX	1%	--	Assumption
Annual interest rate paid on CAPEX	4%	--	IMO4GHG
Infrastructure cost (with interest)	25 605	€/MW/year	IMO4GHG
Electricity cost, 2030	60	€/MW	Eurostat, 2020 prices
Electricity cost, 2050	40	€/MW	Wind Europe
HFO cost	326	€/t	IMO4GHG

The chart on the left of Figure 11 shows the MAC results for the three scenarios in 2030 and 2050, a result of applying the abatement technologies and their associated costs from Table 1. The fuels only scenario (i.e. scenario 1) has abatement costs around €120/t CO_2 and €180/t CO_2 in 2030 and 2050, respectively. This compares to scenario 2 with high energy efficiency measures that has abatement costs of €34/t CO_2 and €104/t CO_2 in 2030 and 2050, respectively. It is also of interest to compare the quantity of CO_2 abated in the different scenarios, as shown in Figure 12. In 2030, thanks to technical and operational energy efficiency options, more than four times the amount of CO_2 emissions will be saved in scenario 2 compared to scenario 1, with a cost-effectiveness three times higher; in 2050, the efficiency measures reduce the cost of total CO_2 mitigation by 43%. In scenario 3, where lower efficiency measures are adopted, mitigation costs increase in 2030 by €21.1/t CO_2 compared to scenario 2 with 25.3 Mt CO_2 emissions not abated; compared to scenario 1, abatement and total mitigation costs are significantly less than a fuels only approach. The chart on the right of Figure 11 shows the annual total cost to the shipping industry for the deployment of the abatement technologies. By 2050, the European shipping industry would save over €5 billion per year by deploying more efficiency measures as defined in scenario 2, compared to scenario 3. Scenario 1 would cost the industry €11.7 billion more per year in 2050 than scenario 2.



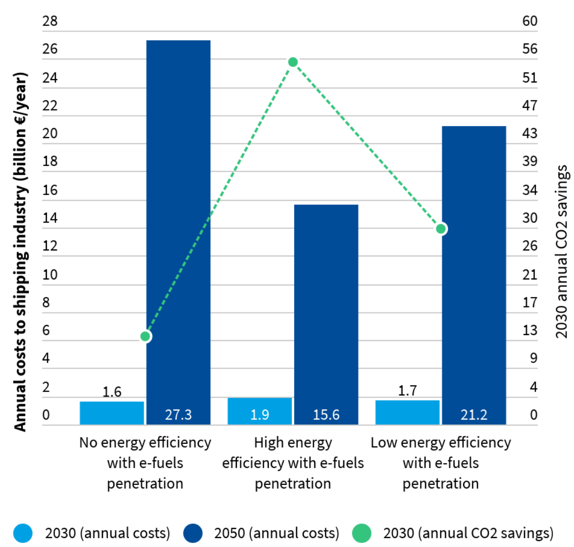


Figure 11: Abatement (left) and total (right) costs for the three scenarios

Additionally, Figure 12 compares the costs of achieving the same CO_2 reduction with fuels only (via a sensitivity analysis dubbed scenario 4 in the figure) as with efficiency measures (i.e. scenario 2), for 2030. This results in an extra cost of €10bln (€12bln vs. €2bln) for the fuels only approach to achieve the same 55Mt CO_2 reduction that year.

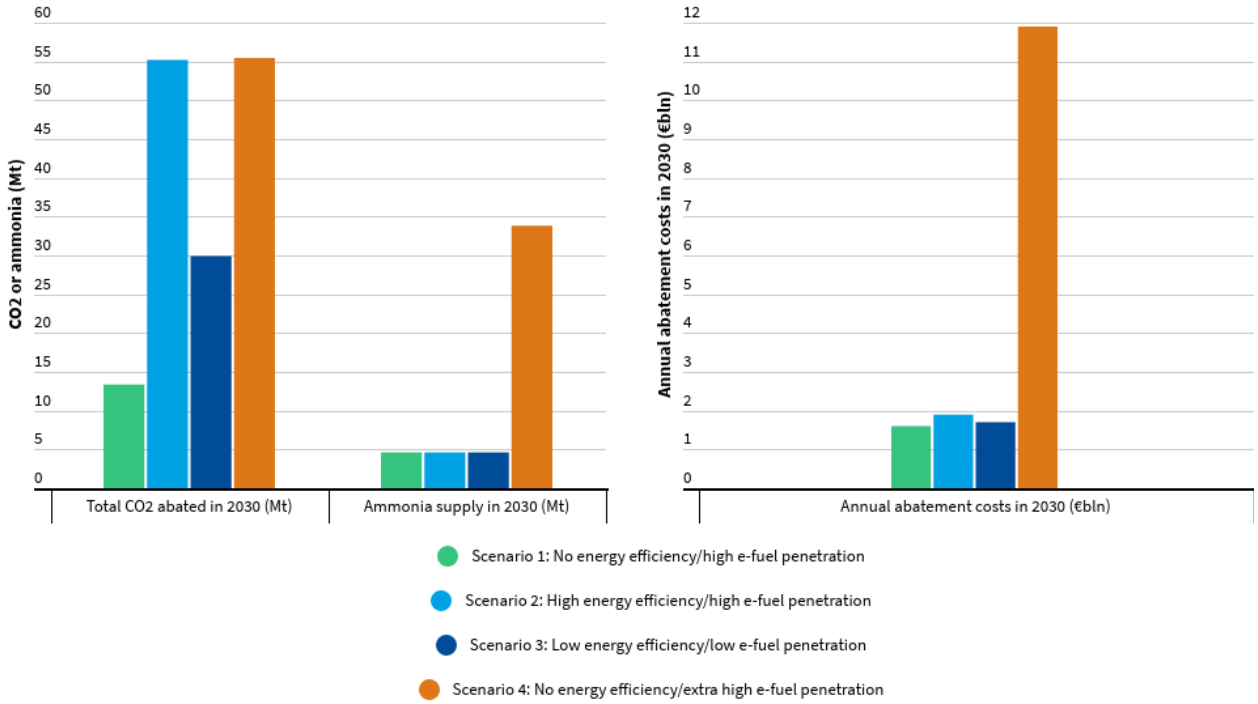
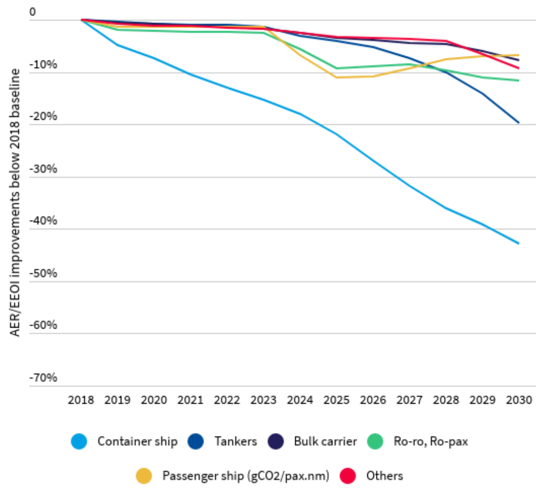


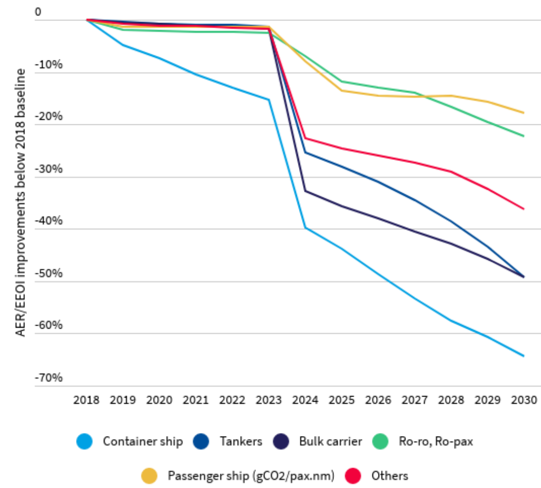
Figure 12: CO_2 abated, quantity of ammonia required and abatement costs for different scenarios in 2030. Scenario 4 assumes a hypothetical e-fuel uptake at much higher level in order to deliver the same total CO_2 savings as the high energy efficiency scenario (i.e. scenario 2).

3.5. Improvements in vessel carbon intensity per transport work

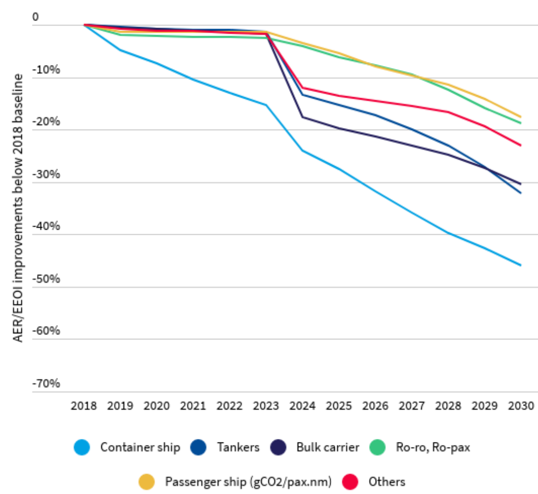
This section analyses the impact of the efficiency and fuel measures on the operational carbon intensity of shipping. The objective is to provide guidance to lawmakers on feasible targets for 2030 based on a 2018 baseline. AER, cgDIST and EEOI metrics chosen for each ship type are detailed in the Appendix. Figure 13 shows the results for the fleet, separated in 6 ship groups. In all scenarios, containerships have the most potential for steep improvements, ranging from 43% in Scenario 3 to 64% in Scenario 2. This clearly shows the effectiveness of energy and operational efficiency improvements to reducing the transport work intensity of the sector. Passenger (cruise) ships and ro-ros have less potential, from 14% to up to 22% in the highest energy efficiency scenario.



Scenario 1: fuels only



Scenario 2: high energy efficiency with e-fuels

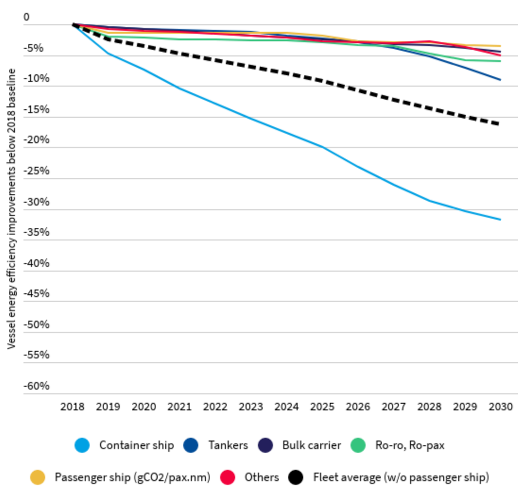


Scenario 3: low energy efficiency with e-fuels

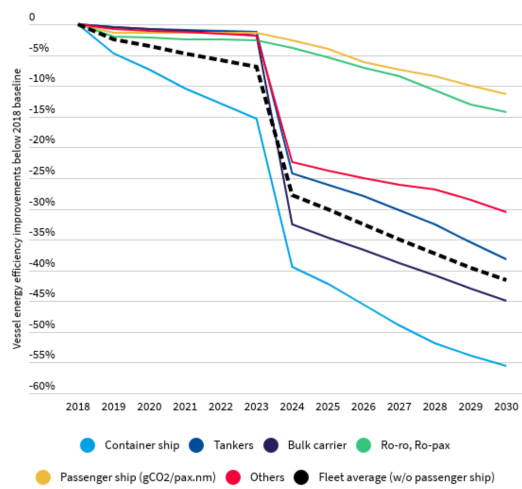
Figure 13: Operational carbon intensity per ship type, improvement of AER (gCO_2/dwt.nm), cgDIST (gCO_2/gt.nm) and EEOI (gCO_2/t.nm or gCO_2/pax.nm). Different ship types are using different formulas and units; see Appendix 5.9 for the formulas per ship type.

3.6. Improvements in vessel fuel economy per transport work

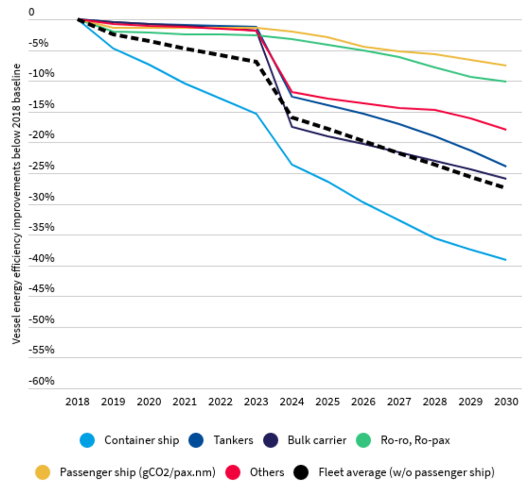
This section looks into the first term of Equation 1, the fuel economy (or energy consumption) per unit of transport work, with the results of all scenarios shown in Figure 14. The energy consumption improvements shown in Scenario 1 (the fuels only scenario) are a result of fleet renewal, as described in Section 3.2; this is equivalent to the business as usual case. In this scenario, the containership fleet is projected to improve its efficiency by over 30% thanks to the shift towards bigger, more efficient ships; all other ship types are in the range of 4% to 9% improvement. Scenarios 2 and 3 show the clear efficiency gains to be made by slow steaming, underscored by the stepwise drop in 2024, the year of policy implementation. Passenger ships and ro-ros are assumed not to slow down, but with additional measures have the potential to more than double their efficiency in scenario 2 compared to scenario 1. The fleet averages are also shown in each figure, excluding passenger ships as their vessel fuel economy metric has different units from other ship types. By implementing all efficiency measures discussed previously, fleet-wide fuel economy can improve by 41% by 2030. This target, differentiated per ship type and size categories, should be mandated by the EU to ensure the adoption of efficiency measures within the European fleet.



Scenario 1: fuels only



Scenario 2: high energy efficiency with e-fuels



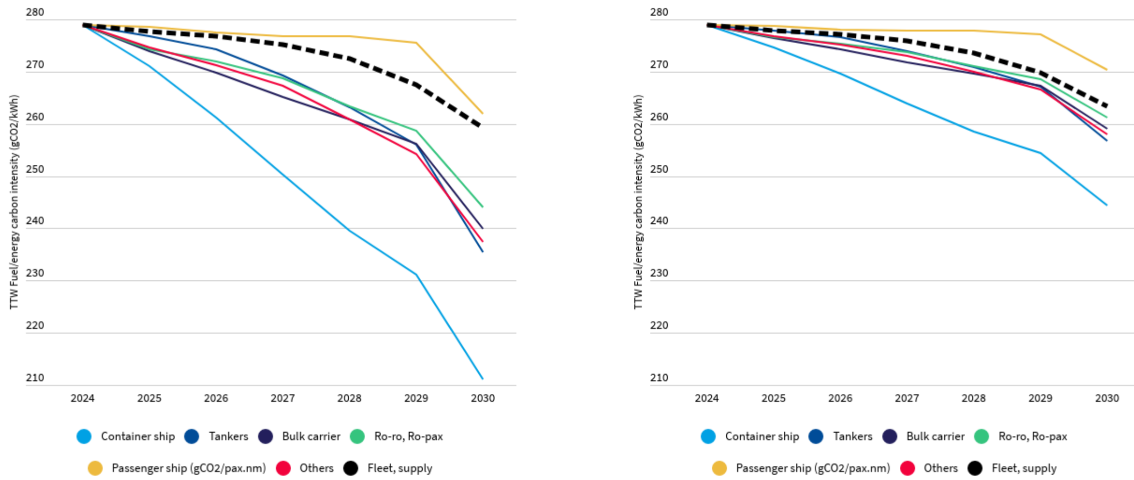
Scenario 3: low energy efficiency with e-fuels

Figure 14: Vessel energy efficiency improvements (kWh/t.nm or kWh/pax.nm). Different ship types are using different formulas and units; see Appendix 5.9 for the formulas per ship type.

3.7. Improvements in carbon intensity of the on-board energy use

Figure 15 shows the results of the fuel carbon intensity improvement, the second term of Equation 1. These results do not include emissions reductions from zero-emission berth mandates. The curves for each ship group are based on demand, i.e. what would happen if enough ammonia could be supplied to all new ships up to 2030. In other words, the lines plotted for each ship type show a hypothetical fuel carbon intensity based on the ammonia enabled ships. Varying levels of carbon intensity reductions are largely affected by different renewal rates per fleet type. These results show that in particular containerships would be the fastest to be able to reduce their fuel carbon intensity, by up to 25% should the supply meet the demand[12]. The "fleet, supply" curve shows the average fleet carbon intensity when the e-ammonia is supplied equally across all ship types, as shown in Figure 10. In all scenarios, the demand of e-ammonia is supply limited, so the fleet curves show the impact of the e-ammonia share of final energy.. From the mid 2030s, we calculate that the fuel carbon intensity would be limited on the demand side, i.e. the number of ships that are ammonia enabled. It is important therefore that retrofitting rapidly ramps up from the 2030s in order to reach 2050 decarbonisation.

[12] Analysis was not conducted to determine the outcome if the e-ammonia supply was mandated for only one ship type.



Scenario 1 and scenario 2, with fleet supply of scenario 2

Scenario 3

Figure 15: Reductions in onboard energy carbon intensity (gCO_2/kWh)

4. Conclusions and policy recommendations

The EU shipping sector needs to slash in the order of 90 Mt CO_2 emissions by 2030 to meet the European Green Deal target of 55% below 1990 emissions, followed by full decarbonisation by 2050. In this study, we investigated 3 scenarios that show pathways for mid-century decarbonisation of EU shipping. We developed an EU shipping stock model that allows us to model the deployment of different energy efficiency technologies on different ship types and sizes, in order to quantify the potential CO_2 emission savings from each measure. Each scenario looks at a different level of energy efficiency measures along with an ambitious uptake of e-ammonia.

The EU needs to rapidly deploy renewable electricity production, hydrogen electrolysers, and ammonia production installations in order to ramp up supply of green fuels such as e-ammonia. We estimate that the EU could produce up to 4.6 Mt of e-ammonia, or 85 PJ, sustainably on its territory for use in shipping. Zero emission vessels need to be deployed from 2025 at the latest, while existing vessels need to be retrofitted to run on green hydrogen(-based fuels) from 2030 on, in order to meet mid-century decarbonisation.

This paper shows the significant benefits of mandating high energy efficiency. Although no scenario is able to reach the 55% reduction below 1990 level target, deploying the maximum potential of technology and operational efficiency measures, including rapid uptake of shore side electrification, with an ambitious but sustainable uptake in e-ammonia could reduce shipping emissions by 25% compared to 1990 emissions. Reducing the ambition of efficiency measures would reduce the CO_2 cuts compared to 1990 to 3.2%, while a lack of energy efficiency measures would result in emissions around 11% above the same baseline.

In 2030, high energy efficiency measures can deliver 4 times the CO_2 reductions and be three times more cost-effective than a fuel only scenario. To achieve the same CO_2 reductions with fuels only would increase costs sixfold compared to using energy efficiency measures. In 2050, the yearly cost to the European shipping sector would be almost halved by including the maximum energy savings potentials, many of which save money when deployed.

Policy recommendations:

Based on the findings of this analysis, Transport & Environment strongly recommends the following for the forthcoming EU regional measures for international maritime transport:

1. The EU should rapidly deploy green e-fuels for shipping. With sufficient policy and investment, the EU could produce up to 85 PJ of sustainable e-ammonia. If ambitious energy efficiency measures are legislated, including shore side electrification, the EU could set a maximum 7% sustainable e-fuels target for the FuelEU Maritime initiative under the full shipping MRV scope. This would equal to improving the carbon intensity of energy (i.e. gCO_2eq/kWh energy consumed) by EU shipping by 7% between now and 2030. If no energy efficiency legislation is introduced, the EU should revise the target down, to around 5%.

2. This analysis concluded that up to one third of the EU's shipping's GHG could be eliminated by energy efficiency alone. This includes both technical options (e.g. wind-assist, hull air lubrication, etc) but also operational measures (most notably slow steaming). With this in mind, in order to have a 7% e-fuels goal, the EU should in parallel set a fleet-wide energy efficiency (i.e. kWh/t-nm) reduction target of 41% by 2030 vis-a-vis 2018. This target will however need to be differentiated per ship type and size categories as different vessels have varying degrees of potential to improve their energy efficiency (i.e. fuel economy).

3. The fuel energy carbon intensity target by 2030 can be uniformly implemented across all ship type and size categories. It is also possible to differentiate the target across different ship types. Two facts would favour such an approach: firstly, it is likely that new propulsion technologies (based on hydrogen or e-ammonia) will be deployed initially on newbuilds, and secondly, fleet turnover differs

across different ship types. Therefore, the ship types that have a higher turnover rate could have a higher mandated target than those with lower turnover.

4. The EU should mandate zero-berth emissions for cruise vessels, ro-ro cargo and ro-pax vessels by 2025. These vessels consume the largest amount of energy at berth. This should be followed by a zero-berth emissions standard for container, oil tanker and refrigerated-bulk carriers by 2030, and the remaining vessels by 2035. This would be achieved through a rapid deployment of shore side electrification. Not only would it reduce CO_2 emissions, but also the SO_x and NO_x emitted at port.

5. The regulation needs to start from 2025, be goal-based enabling new sustainable technologies as they appear and come of age. The target should be ambitious but dependent on parallel legislation on energy efficiency and shore side electrification.

6. Sustainable alternative fuels (i.e. e-hydrogen, e-ammonia but also battery electric whenever feasible) are more likely to be initially taken up by newbuild vessels. To enable this, a “credit” or “pooled compliance” system needs to be established in order to incentivise shipowners to order hydrogen/ammonia/battery capable vessels when renewing their fleet.

7. A simple goal-based regulation would strongly favour unsustainable crop based biofuels, which are much cheaper to produce than sustainable e-fuels. Advanced biofuels from wastes and residues have limited feedstocks, and thus limited potential. About 50% of the EU’s used cooking oil (UCO) biodiesel is imported for use in land-sectors, which signals a saturation of domestic EU supply potential. Biofuels also pose a significant enforcement problem. About one third of the Netherland’s UCO biodiesel for road is suspected to be virgin oil. This problem would be further aggravated if shipping draws in significant voluments of biofuels and “fuel cheating” is much easier and more widespread in maritime transport. We, therefore, recommend:

a. To exclude all crop and feed-based biofuels from eligibility list for shipping;

b. To cap the contribution of advanced biofuels at maximum 1 percentage point of meeting the 2030 target, or set a sub-target for sustainable e-fuels complemented with high multipliers for e-fuels and direct use of electricity.

5. Appendix - Detailed methodology

For this work, T&E built a shipping turnover model. The basis of the model draws on the shipping activity and operational performance as reported in the 2018 MRV as a baseline. The Clarkson database for the ships' characteristics, such as size/capacity (for example DWT and GT) and age, was combined with the ships in the MRV so that 87% of ships, responsible for 96% of emissions, were assigned characteristics. We were then able to class ships into size and type categories, and their average annual transport work was calculated. We used the data from Bullock[29] to model average ship class retirement ages. We defined the efficiency of new ships as the average AER of ships built in the last 5 years, for each class and size bin. From 2024, all new ships had inbuilt improvements (for example, to the auxiliary system, reduced auxiliary power usage, engine-related measures and air lubrication) that resulted in a further 4.9% reduction in energy per transport work delivered.

Projections for activity are taken exogenously from the IMO 4th GHG study (the SSP2_RCP2.6_G growth scenario). New ships enter the fleet to meet the combined increase in projected shipping demand as well as to cover the transport activity of retired ships. This enables us to keep track of both the number of ships in the fleet and of new ships by year of introduction. Technologies are then applied to either new vessels, retrofitted to the fleet of existing vessels, or a combination of both. We assume technology penetration increases linearly between the year of introduction of the technology, taken to be 2024 (with the exception of e-ammonia, 2025) and the year when it has been fully adopted. The following subsection describes the technological groups applied in the model, and their emissions savings.

5.1. Main engine and auxiliary engine improvements

New and existing engines have several technological options that can increase their efficiency. These include, among others, engine tuning, common rail systems and electronic engine control, where fuel consumption is optimised through engine mapping, variable valve timing, and fuel injection by controllers from the high pressure fuel accumulator; reduced auxiliary power usage, through energy efficiency measures on board, such as LED lighting or energy efficient air conditioning. We don't take into account steam plant improvements owing to their conflict with zero-emission berth measures or waste heat recovery as it conflicts with slow steaming.

5.2. Propeller optimisation

Propellers convert the engine or motor's rotational energy into thrust in the axial direction, and thus have an important impact on the overall efficiency of the vessel. Propeller performance monitoring ensures optimal servicing, such as propeller polishing to reduce roughness and to remove organic matter. New propeller designs or systems, such as nozzles, tip winglets, boss cap fins and contra rotating propellers, reduce tangential flow and hub vortex losses. Finally, an integrated propeller-rudder with a rudder bulb can reduce drag.

5.3. Hull optimisation

As water passes over a ship's hull, it generates drag. Hulls that become rough (from the accumulation of organic matter, known as fouling) create more drag, and negatively impact fuel consumption. Hull optimisation includes technologies that optimise or facilitate regular de-fouling (by brushing or hydro-blasting) of ships' hulls, and technologies such as low-friction coats or air lubrication, resulting in lower drag and thus improved fuel efficiency. These approaches are described in further detail below.

All ships accumulate organic matter and sea life on their hulls. This affects the roughness of the hull, and in turn increases drag or resistance as the ship is in motion. The impact of defouling for a bulker ship can be up to 9% reduction in CO_2 emissions (after defouling whilst at berth), a process that occurs around twice per year[30]. If conducted in a dry dock, the reduction in emissions can be up to 17%. Innovative technologies in the form of autonomous robots are being employed to make this process less labour intensive, cheaper and with good results, thus potentially enabling essentially continuous defouling that can occur whenever the ship is stationary. Thus, this option for ship owners and operators could on average reduce CO_2 emissions, and thus the CO_2 intensity of their operations, by around 5%.[13]

Hull air lubrication is an emerging albeit old technology[31] that reduces the drag on the hull of a ship by providing a constant stream of bubbles or an air film on the surface of the hull. Rather than the form drag friction being water on the hull, a portion of the surface of the hull will be dragging through air. The main mechanism for reducing the friction is because the local effective density of water is reduced, diminishing the Reynolds' stresses, but there may also be an effect of reducing the effective viscosity of the water due to an increasing void ratio.[32] Different types of hull air lubrication are possible and may be applicable to different ship types depending on the hull form. While theoretical savings may be as high a 16%, net energy savings have been reported that range from 1%-3%[32], indicating the technology is still in its infancy.[14]

5.4. Wind assist

Wind-assist technologies (WAT) have been identified as an additional way to effectively reduce the carbon intensity of ships. The term encapsulates a series of distinct technologies, some of which can be retrofitted, such as towing kites, Flettner rotors, wingsails and turbines. The power harvested by

[13] This is assumed to be compared to a ship being defouled every 6 months, and that the change in drag increases linearly during that time.
[14] For more, see for example[31, 33]

these devices from the wind is almost fully used to overcome water resistance, since it does not involve all the losses associated with regular propulsion. WAT such as wingsails and rotors combine well with slow steaming, as they provide higher relative savings at lower speeds. They can also act as range extenders, which could be particularly useful when associating such technologies with a fuel switch on the vessel. They also have the advantage to be an OPEX-independent measure. Today, the first commercial projects are being developed and the expected savings for retrofits are expected to range from 5 to 20%, and up to 30% for certain ship types. For new builds, improvements of the order of 20% to 40% are expected on the short term, and up to 50% on the long term[34]. These improvements however, are not applicable to all ships and actual savings heavily depend on ship size and operational characteristics. Table A.1 details the ship types and sizes and the WAT CO_2 reduction potential modelled in our study. We drew on CE Delft's 2016 study on the potential of WAT for containers, tankers and bulkers and interpolated their results for the different ship size bins below.[35]

Table A.1: Wind assist technologies (WAT) emission savings for ship types and sizes

Ship type and size	WAT CO_2 savings potential	Ship type and size	WAT CO_2 savings potential
Container ship 0-1999 TeU	4%	Bulk carrier 0-9999 DWT	7%
Container ship 2000-2999 TeU	3%	Bulk carrier 10000-34999 DWT	12%
Container ship 3000-4999 TeU	2%	Bulk carrier 35000-59999 DWT	16%
Container ship 5000-7999 TeU	1%	Bulk carrier 60000-99999 DWT	21%
Oil tanker 0-4999 DWT	8%	Bulk carrier 100000+ DWT	24%
Oil tanker 5000-9999 DWT	8%	Chemical tanker 0-4999 DWT	8%
Oil tanker 10000-19999 DWT	9%	Chemical tanker 5000-9999 DWT	8%
Oil tanker 20000-59999 DWT	10%	Chemical tanker 10000-19999 DWT	9%
Oil tanker 60000-79999 DWT	12%	Chemical tanker 20000-39999 DWT	10%
Oil tanker 80000+ DWT	13%	Chemical tanker 40000+ DWT	11%

5.5. Slow steaming - speed limit

Speed reduction in ships, also called slow steaming, is a viable short term measure that has been shown to have the potential to reduce the carbon emissions of the global shipping fleet from 13% (by capping average speed at 2012 levels)[36] to 33% with a 30% speed reduction[37]. This is due to the approximate cubic relationship between fuel consumption of the main engines (which is proportional to CO_2 emissions for a given fuel) and the sailing speed. That means a 10% reduction in speed would lead to around a 33% reduction in the instantaneous main engine fuel consumption.

In reality, the reduction in CO_2 will be somewhat more modest for several reasons. First, as a given journey would take longer to complete the engines would be running for a longer time to complete each journey. Secondly, the auxiliary engine and boiler behaviour would not change significantly, and would also be required to run longer for a given journey for a ship that slows down. Additionally, ships would need some modifications to their front bulb, propeller and potentially the engine itself in order that the engine still operates at its optimal speed. Despite this, as described above the reduction in total ship CO_2 emissions from slow steaming could be significant. In this study, for the optimistic scenario, a 20% speed limit below the average speed for each ship type was applied to ships for which such a measure would result in lower emissions. For the pessimistic scenario, a 10% speed limit was chosen, applied to half the ships of the fleet. Table A.2 shows the savings per ship type.

Table A.2: Slow steaming emission savings for ship types and sizes

MRV ship type	**Mt CO_2 saved from slow steaming (% of total)**	
	Scenario 2	**Scenario 3**
Passenger ship	0.00 (0.0%)	0.00 (0.0%)
Ro-pax ship	0.00 (0.0%)	0.00 (0.0%)
Container/ro-ro cargo ship	0.48 (29.1%)	0.20 (11.8%)
General cargo ship	1.63 (26.8%)	0.88 (14.3%)
Vehicle carrier	0.00 (0.0%)	0.00 (0.0%)
Container ship	10.27 (23.2%)	3.33 (7.5%)
Other ship types	0.19 (31.3%)	0.15 (24.3%)
Gas carrier	0.76 (29.3%)	0.53 (20.4%)
Bulk carrier	4.61 (29.0%)	2.31 (14.5%)
Chemical tanker	1.74 (21.1%)	0.95 (11.6%)

Refrigerated cargo carrier	0.23 (13.0%)	0.09 (5.2%)
Ro-ro ship	0.00 (0.0%)	0.00 (0.0%)
Oil tanker	3.73 (21.2%)	1.66 (9.5%)
Combination carrier	0.01 (14.7%)	0.01 (8.9%)
LNG carrier	1.37 (23.6%)	0.37 (6.4%)
Total	25.04 (18.3%)	10.48 (7.7%)

5.6. Zero-emission berth mandate

At present, there are very few ships that plug in at berth, although this technology has been discussed for quite some time[15]. Any emission reductions from a strategy that makes use of plugging it at port would be additional to the reduction of CO_2 intensity. All ship types could technically make use of ship-to-shore plug in options. The results show that total fleet CO_2 emissions could be reduced by 5.8%. Passenger ships (cruise ships), oil tankers, chemical tankers, and ro-pax ships in particular could save the most CO_2 relative to their total operations; oil tankers in particular would be an ideal candidate for port-side plugging in as the total emissions saved is the highest of all ship types. Table A.3 shows the maximum potential for each ship type in 2018. These figures evolve slightly over time, whereby the total savings in 2030 are 7.88 Mt CO_2 and 7.54 Mt CO_2 in 2050 .

Table A.3: Wind assist emission savings for ship types and sizes

MRV ship type	**Mt CO_2 at port (saving)**
Passenger ship	0.70 (10.8%)
Ro-pax ship	1.01 (7.2%)
Container/ro-ro cargo ship	0.09 (5.3%)
General cargo ship	0.29 (4.8%)
Vehicle carrier	0.21 (4.2%)

[15] For example, 10 years ago in Rotterdam: https://new.abb.com/news/detail/48794/abbs-shore-to-ship-power-solution-for-rotterdam

Container ship	1.63 (3.7%)
Other ship types	0.03 (4.9%)
Gas carrier	0.18 (7.0%)
Bulk carrier	0.66 (4.2%)
Chemical tanker	0.82 (9.9%)
Refrigerated cargo carrier	0.05 (2.9%)
Ro-ro ship	0.30 (4.8%)
Oil tanker	1.84 (10.5%)
Combination carrier	0.01 (15.8%)
LNG carrier	0.15 (2.7%)
Total	7.99 (5.8%)

5.7. Zero-carbon fuels

The above technologies are able to reduce the fossil fuel consumption of ships to varying degrees. To achieve full decarbonisation of the shipping sector requires a new source of sustainable and renewable fuel. Fuels produced by additional renewable electricity (e-fuels or electrofuels) are the only scalable solution that fits the requirements of energy dense, deployable, and clean fuels. In a recent study, Ricardo Energy & Environment assessed the levelised cost of synthetic hydrocarbon fuels (such as e-methane and e-diesel) with e-hydrogen and e-ammonia. They found that e-ammonia was the cheapest technology, particularly considering the cost uncertainties surrounding direct air capture, required for synthetic hydrocarbons and still a nascent technology. E-ammonia has advantages over e-hydrogen, such as its higher volumetric density, significantly higher boiling point and its technological maturity (from it's extensive use in fertilizers). This results in smaller, cheaper tanks with less boil-off to store the same amount of energy.

For this study, we assume that e-ammonia will be the only renewable fuel used to decarbonise shipping. From 2025 (the assumed date of commercialisation[38]) to 2040, it will mainly be used with a diesel fuel pilot fuel for combustion, and in the last decade before mid-century, either fuel cells or spark ignition engines capable of running on 100% e-ammonia will be available and retrofitted. More details on the uptake of this technology on the ships (demand) and assumptions on the fuel readiness (supply) are discussed in the next section.

5.8. Application of different abatement technologies

All CO_2 abatement measures but the speed limit have a reduction potential that can be achieved progressively as ships get equipped with the corresponding technologies. We modeled technology penetration linearly:

$R_{y,m} = 0 \; for \; y \leq y_{start,m}$

$R_{y,m} = R_{max,m} * (y - y_{start,m} + 1)/(y_{end,m} - y_{end,m} + 1) \; for \; y_{start,m} \leq y < y_{end,m}$

$R_{y,m} = R_{max,m} \; for \; y \geq y_{end}$

where:

- $R_{y,m}$ is the CO_2 reduction thanks to measure *m* on year *y*
- $R_{max,m}$ is the maximum CO_2 reduction potential of measure *m*
- $y_{start,m}$ is the year when technology *m* enters the fleet
- $y_{end,m}$ is the year maximum CO_2 reduction potential of measure *m* is achieved

Table A.5 shows the assumption we made for each abatement measure. For speed reduction, the measure is applied to the whole fleet starting in 2024. This could be achieved by mandating a type and size-based speed limit on the ships, entering into application in 2024.

Table A.4: Wind assist emission savings for ship types and sizes

Measure	Scenario 1 (last two rows only) and scenario 2			Scenario 3		
	Year start	Year end	Reduction potential on operational CO_2 of 2018 MRV fleet	Year start	Year end	Reduction potential on operational CO_2 of 2018 MRV fleet
New ship main and auxiliary engine improvements	New ships: 2024	New ships: 2024	4.9%	New ships: 2024	New ships: 2024	2.45%
Propeller optimisation	2024	2035	6.3%	2024	2035	3.15%

Hull optimisation	2024	2035	9.2%	2024	2035	4.6%
Wind assist	2024	2035	4.9%	2024	2050	2.45%
Speed reduction	2024	2024	19.4%	2024	2024	8.0%
Zero-emission berth (plug in at port)	2024	Cruise, ro-ro, ro-pax: 2025, container, oil tanker, ref-bulk: 2030 remaining vessels: 2035	5.9% of 2018 MRV emissions (100% of port CO_2)	2024	Cruise, ro-ro, ro-pax, container, oil tanker, ref-bulk: 2030 remaining vessels: 2035	5.9% of 2018 MRV emissions (100% of port CO_2)
Use of e-ammonia	New ships: 2025 Retrofits: 2030	New ships: 2025 Retrofits: 2040	New ships: 70% Retrofits: 50%	New ships: 2025 Retrofits: 2030	New ships: 2025 Retrofits: 2040	New ships: 70% Retrofits: 50% Half of the ships

5.9. Vessel carbon intensity metrics

Table A.6 shows the metrics and formulae used to analyse the energy efficiency of vessels, in terms of CO_2 emissions per transport work. Most ship types use a form of the annual efficiency ratio (AER), an indirect measure based on a vessel's annual CO_2 emissions divided by the product of the vessel size and distance travelled. The vessel size, whether in gross tonnage (GT) or deadweight tonnage (DWT) is constant for a vessel and does not directly consider how much transport work is actually done. For passenger ships and container ships, the energy efficiency operational index is used, a direct measure of a ship's performance in that the sum of passengers or cargo is used in the denominator, respectively.

Table A.6: Wind assist emission savings for ship types and sizes

MRV ship type	Metric	Formula
Passenger ship	EEOI (tCO_2/pax.nm)	total_CO2/(pax*total_dist) - direct
Ro-pax ship	AER (tCO_2/dwt.nm)	total_CO2/(GT*total_dist) - indirect
Container/ro-ro cargo ship	AER (tCO_2/dwt.nm)	total_CO2/(dwt*0.7*total_dist) - indirect
General cargo ship	AER (tCO_2/dwt.nm)	total_CO2/(dwt*0.7*total_dist) - indirect
Vehicle carrier	AER (tCO_2/dwt.nm)	total_CO2/(dwt*0.7*total_dist) - indirect
Container ship	EEOI (tCO_2/t.nm)	total_CO2/(cargo*total_dist) - direct
Other ship types	AER (tCO_2/dwt.nm)	total_CO2/(dwt*0.7*total_dist) - indirect
Gas carrier	AER (tCO_2/dwt.nm)	total_CO2/(dwt*0.7*total_dist) - indirect
Bulk carrier	AER (tCO_2/dwt.nm)	total_CO2/(dwt*0.7*total_dist) - indirect
Chemical tanker	AER (tCO_2/dwt.nm)	total_CO2/(dwt*0.7*total_dist) - indirect
Refrigerated cargo carrier	AER (tCO_2/dwt.nm)	total_CO2/(dwt*0.7*total_dist) - indirect
Ro-ro ship	cgDIST (tCO_2/gt.nm)	total_CO2/(GT*total_dist) - indirect
Oil tanker	AER (tCO_2/dwt.nm)	total_CO2/(dwt*0.7*total_dist) - indirect
Combination carrier	AER (tCO_2/dwt.nm)	total_CO2/(dwt*0.7*total_dist) - indirect
LNG carrier	AER (tCO_2/dwt.nm)	total_CO2/(dwt*0.7*total_dist) - indirect

6. References

1. European Commission. (2020). *2019 Annual Report on CO2 Emissions from Maritime Transport*. Retrieved from https://ec.europa.eu/clima/sites/clima/files/transport/shipping/docs/c_2020_3184_en.pdf
2. THETIS-MRV. (n.d.). Retrieved 2020, from https://mrv.emsa.europa.eu/#public/emission-report
3. Faber, J., Kleijn, A., Hanayama, S., Zhang, S., Pereda, P., Comer, B., … Xing, H. (2020). *Fourth IMO Greenhouse Gas Study*. Retrieved from https://docs.imo.org/Shared/Download.aspx?did=125134
4. Degnarain, N. (2020). Global Shipping's UN Climate Talks Fail Amid Threats Of A Walkout. *Forbes*. Retrieved from https://www.forbes.com/sites/nishandegnarain/2020/10/24/global-shippings-un-climate-talks-fail-amid-threats-of-a-walkout/?sh=5b65ae6c3897
5. European Commission. (2020). *Stepping up Europe's 2030 climate ambition. Investing in a climate-neutral future for the benefit of our people - Impact Assessment*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020SC0176
6. European Commission. (2020). *Proposal for a European Climate Law*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020PC0080&from=EN
7. European Commission. (2019). *The European Green Deal* (No. COM(2019) 640). Retrieved from https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF
8. European Commission. (2020). *Sustainable and Smart Mobility Strategy – putting European*

transport on track for the future (No. SWD(2020) 331). Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020SC0331

9. *Regulation of the European Parliament and of the Council establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law)* (No. COM(2020) 80 final). (2020). Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020PC0080&from=EN
10. EP. (2020). *Decision by Parliament, 1st reading/single reading*. Retrieved from https://oeil.secure.europarl.europa.eu/oeil/popups/ficheprocedure.do?reference=2019/0017(COD)&l=en
11. European Commission. (2020). *Public consultation on FuelEU Maritime initiative*. Retrieved from https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12312-FuelEU-Maritime-
12. Transport & Environment. (2018). *Roadmap to Decarbonising European Shipping*. Retrieved from https://www.transportenvironment.org/publications/roadmap-decarbonising-european-shipping
13. Transport & Environment. (2019). *EU Shipping's climate record*. Retrieved from https://www.transportenvironment.org/sites/te/files/publications/Study-EU_shippings_climate_record_20191209_final.pdf
14. Guisheng, P. (2021). *Green Technology Development Alternative Fuel*. Presented at the IMO Alternative Marine Fuels Symposium. Retrieved from https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Symposium%20

2021/Presentations/First%20day%20-%20Blocks%201%20and%202/Symposium%20presentations%20-%20First%20Day/Block%202.1%20-%20Peng%20Guisheng_Green%20Technology%20Development-Ammonia%20Fuel.pdf

15. UMAS & Lloyd's Register. (2020). *Techno-Economic Assessment of Zero-Carbon Fuels*. Retrieved from https://www.lr.org/en/latest-news/lr-and-umas-publish-techno-economic-assessment-of-zero-carbon-fuels/
16. Jakobsen, G. (2020, November 26). Partnership aims to develop hydrogen ferry for Oslo-Copenhagen. *DFDS*. Retrieved from https://www.dfds.com/en/about/media/news/hydrogen-ferry-for-oslo-copenhagen
17. Taylor, I. (2019, December 17). EUROPE: $3.7 MILLION FUNDING FOR NORWEGIAN MARITIME LIQUID HYDROGEN SUPPLY CHAIN. *Bunkerspot*. Retrieved from https://www.bunkerspot.com/europe/49564-europe-3-7-million-funding-for-norwegianmaritime-liquid-hydrogen-supply-chain
18. Lindstad, E., & Rialland, A. (2020). LNG and Cruise Ships, an Easy Way to Fulfil Regulations—Versus the Need for Reducing GHG Emissions. *Sustainability*. https://doi.org/10.3390/su12052080
19. Lindstad, E., Eskeland, G. S., Rialland, A., & Valland, A. (2020). Decarbonizing Maritime Transport: The Importance of Engine Technology and Regulations for LNG to Serve as a Transition Fuel. *Sustainability: Science Practice and Policy*, *12*(21), 8793.
20. Transport & Environment. (2018). *Natural gas-powered vehicles and ships – the facts*. Retrieved from

https://www.transportenvironment.org/publications/natural-gas-powered-vehicles-and-ships-%E2%80%93-facts

21. Searle, S., Baldino, C., & Pavlenko, N. (2018). *What is the role for renewable methane in European decarbonization?* ICCT. Retrieved from https://theicct.org/sites/default/files/publications/Role_Renewable_Methane_EU_20181016.pdf

22. Egenhofer, C., Schrefler, L., Rizos, V., Infelise, F., Luchetta, G., Simonelli, F., … Colantoni, L. (2014). *FOR A STUDY ON COMPOSITION AND DRIVERS OF ENERGY PRICES AND COSTS IN ENERGY INTENSIVE INDUSTRIES: THE CASE OF THE CHEMICAL INDUSTRY - AMMONIA* (No. Ref. Ares(2014)174362). CEPS. Retrieved from https://ec.europa.eu/docsroom/documents/4165/attachments/1/translations/en/renditions/pdf#:~:text=The%20EU%2D27%20has%20a,to%20about%2021%20million%20tonnes.&text=The%20remaining%20ammonia%20production%20facilities,Czech%20Republic%2C%20Estonia%20and%20Greece.

23. Komusanac, I., Brindley, G., Fraile, D., & Ramirez, L. (2021). *Wind energy in Europe: 2020 Statistics and the outlook for 2021-2025*. WindEurope. Retrieved from https://windeurope.org/intelligence-platform/product/wind-energy-in-europe-in-2020-trends-and-statistics/

24. Nghiem, A., & Pineda, I. (2017). *Wind energy in Europe: Scenarios for 2030*. WindEurope. Retrieved from https://windeurope.org/wp-content/uploads/files/about-wind/reports/Wind-energy-in-Europe-Scenarios-for-2030.pdf

25. SolarPower Europe increases 2030 ambition with new EU renewables target of at least 45%. (2021, February 10). *SolarPower Europe*. Retrieved from https://www.solarpowereurope.org/solarpower-europe-increases-2030-ambition-with-new-eu-renewables-target-of-at-least-45/

26. van Wijk, A., & Chatzimarkakis, J. (2020). *Green Hydrogen for a European Green Deal A 2x40 GW Initiative*. Hydrogen Europe. Retrieved from https://static1.squarespace.com/static/5d3f0387728026000121b2a2/t/5e85aa53179bb450f86a4efb/1585818266517/2020-04-01_Dii_Hydrogen_Studie2020_v13_SP.pdf

27. Ash, N., Davies, A., & Newton, C. (2020). *Renewable electricity requirements to decarbonise transport in Europe with electric vehicles, hydrogen and electrofuels*. Ricardo Energy & Environment. Retrieved from https://www.transportenvironment.org/sites/te/files/publications/2020_Report_RES_to_decarbonise_transport_in_EU.pdf

28. Transport & Environment. (2020). *How to decarbonise the UK's freight sector by 2050*. Retrieved from https://www.transportenvironment.org/publications/how-decarbonise-uks-freight-sector-2050

29. Bullock, S., Mason, J., Broderick, J., & Larkin, A. (2020). Shipping and the Paris climate agreement: a focus on committed emissions. *BMC Energy*, *2*(1), 1–16.

30. A new robot may help keep ships' bottoms clean. (2020). *The Economist*. Retrieved from https://www.economist.com/science-and-technology/2020/05/28/a-new-robot-may-help-keep-ships-bottoms-clean

31. Alex Abolfazl Shiri, M. W. (2018). Hull air lubrication: future and challenges. *SSPA*. Retrieved September 2020, from https://www.sspa.se/ship-design-and-hydrodynamics/hull-air-lubrication-future-and-challenges
32. ABS. (2019). *Air Lubrication Technology*. Retrieved from https://ww2.eagle.org/content/dam/eagle/advisories-and-debriefs/Air%20Lubrication%20Technology.pdf
33. Kawabuchi, M., Kawakita, 1. Chiharu, Mizokami, 2. Shuji, & Kodan, 3. Yoichiro. (2011). CFD predictions of bubbly flow around an energy-saving ship with Mitsubishi air lubrication system. Retrieved March 31, 2021, from http://www.rexresearch.com/mals/e481053.pdf
34. International Windship Association. (2020, June 29). *No title [PowerPoint presentation]*. Presented at the European Sustainable Shipping Forum.
35. Faber, J., Nelissen, D., Traut, M., Köhler, J., & Mao, W. (2016). *Study on the analysis of market potentials and market barriers for wind propulsion technologies for ships*. CE Delft. Retrieved from https://www.cedelft.eu/publicatie/study_on_the_analysis_of_market_potentials_and_market_barriers_for_wind_propulsion_technologies_for_ships/1891
36. CE Delft, UMAS, Oeko Institut, Lloyd's Register. (2019). *Study on methods and considerations for the determination of greenhouse gas emission reduction targets for international shipping*. Retrieved from https://www.cedelft.eu/en/publications/2297/study-on-methods-and-considerations-for-the-determination-of-greenhouse-gas-emission-reduction-targets-for-international-shipping
37. Faber, J., & Nelissen, D. (2017). *Regulating speed: a short-term measure to reduce maritime GHG*

emissions. CE Delft. Retrieved from https://www.cedelft.eu/en/publications/2024/regulating-speed-a-short-term-measure-to-reduce-maritime-ghg-emissions

38. Yonhap. (2020). Daewoo wins approval for ammonia-fired ship from Lloyd's Register. Retrieved January 2021, from http://www.koreaherald.com/view.php?ud=20201006000301