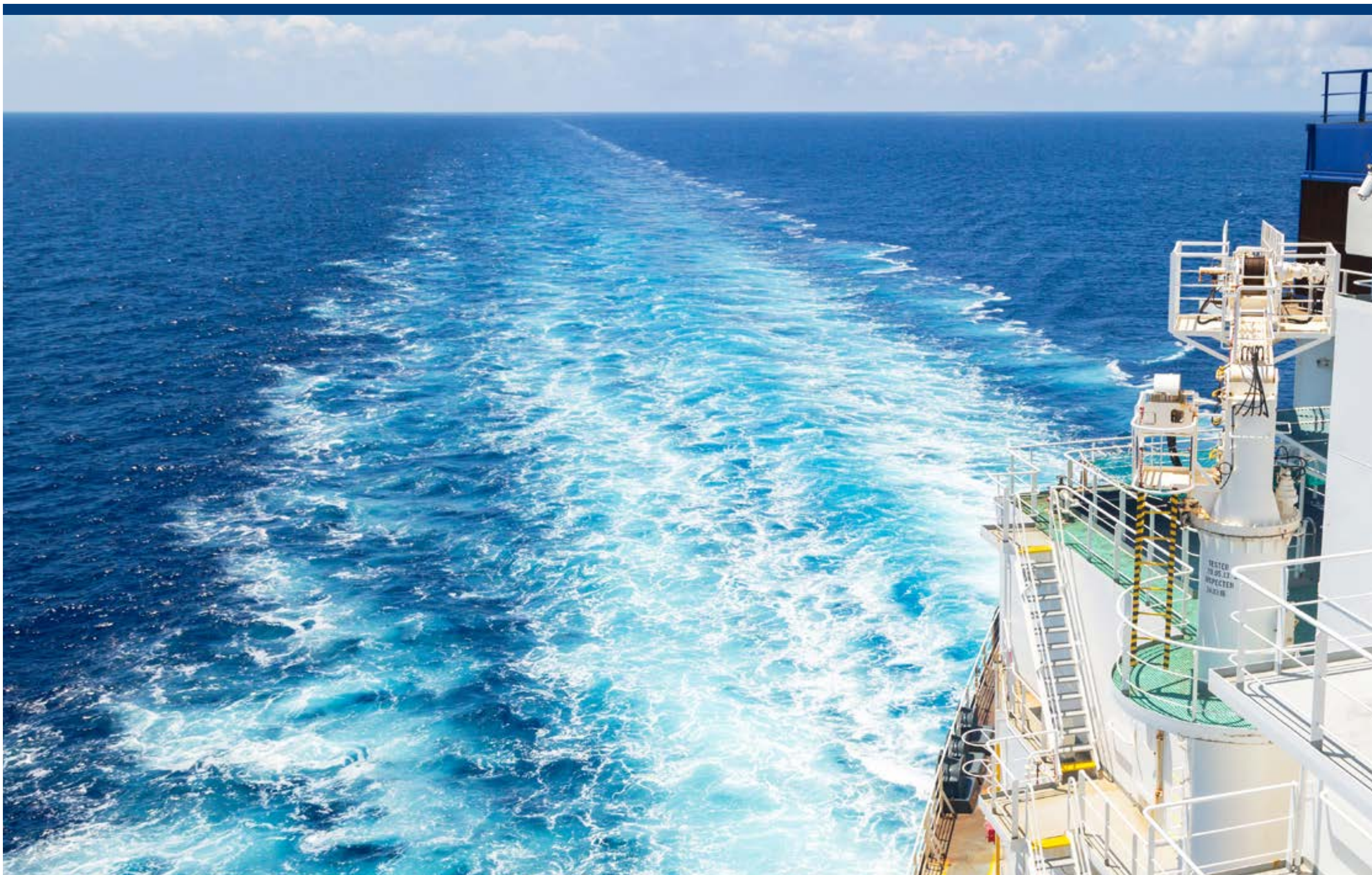
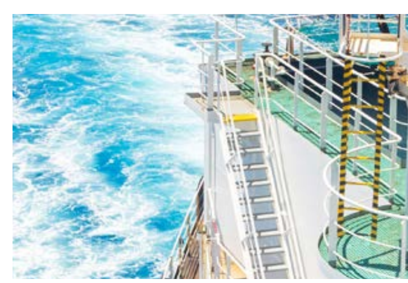
International Transport Forum



Decarbonising Maritime Transport

Pathways to zero-carbon shipping by 2035



Case-Specific Policy Analysis

OECD

Decarbonising Maritime Transport

Pathways to zero-carbon shipping by 2035

Case-Specific Policy Analysis

The International Transport Forum

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International Transport Forum
2, rue André Pascal
F-75775 Paris Cedex 16
contact@itf-oecd.org
www.itf-oecd.org

Case-Specific Policy Analysis Reports

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Executive summary

What we did

This report examines what is needed to decarbonise international shipping by 2035. Zero carbon emissions from shipping within this timeframe is one of the proposed levels of ambition in the context of the International Maritime Organization's "Initial GHG Strategy", due to be agreed in 2018. Using the ITF International Freight Model, the report provides an updated baseline scenario for the development of emissions to 2035 and gives an overview of measures that can effectively reduce shipping emissions. Using different combinations of these measures, it charts possible decarbonisation pathways and reviews the conditions for implementation. The report concludes with recommendations on policies to incentivise decarbonisation.

What we found

Maximum deployment of currently known technologies could make it possible to reach almost complete decarbonisation of maritime shipping by 2035. The four potential decarbonisation pathways for shipping identified in this report would result in a CO_2 emission reduction between 82% and 95% of the currently projected 2035 level. This reduction equals the annual emissions of approximately 185 coal-fired power plants. Remaining CO_2 emissions would be between 44 and 156 million tonnes in 2035.

This compares to a business-as-usual scenario in which carbon emissions from international shipping are projected to increase 23% to 1090 million tonnes by 2035 compared to the 2015 level. An adjusted baseline projects carbon emissions from maritime shipping of 850 million tonnes by 2035 or the equivalent to the annual emissions of 210 coal-fired power plants. The adjusted baseline scenario assumes a substantial reduction in the transport of fossil fuels and a higher share of intra-regional trade.

Alternative fuels and renewable energy can deliver much of required reductions. Advanced biofuels are already available in limited quantities. Gradually, they should be complemented by other natural or synthetic fuels such as methanol, ammonia and hydrogen. Wind assistance could reap additional reductions. The first electric ships provide transport for short-distance routes. Technological measures to improve energy efficiency of ships could yield a substantial part of the needed emission reductions. Market-mature options include, among others, hull design improvements, air lubrication and bulbous bows. Finally, operational measures such as ship speed reductions, smoother ship-port interfaces and increased ship size could achieve further important emission reductions.

Some of the measures are currently more expensive than marine propulsion using oil-based fuel, because its price does not take external effects such as climate change into account. Zero-carbon vessels are generally more expensive than conventional vessels. Retrofitting the latter requires capital that ship-owners often will not invest. Costs will come down with increased uptake of new technologies. Governments can accelerate the commercial viability and technical feasibility of certain measures. Both private and public financial institutions should offer additional financial tools and incentives to smooth the path to decarbonisation.

Certainty about the desirable decarbonisation pathway for shipping will help drive change. Clear guidance from governments is therefore essential to accelerate the transition towards zero-carbon shipping. Government intervention could make zero-carbon vessels more attractive and direct investment towards sustainable technologies and fuels, for example. Such guidance should include an ambitious decarbonisation target and a comprehensive set of short, medium and long-term measures to reach full decarbonisation. Technological innovation creates business opportunities around zero-carbon shipping, which can be a source for green growth and green jobs, not least in emerging economies. A smart phasing-in of carbon pricing for shipping could facilitate the implementation of these measures.

What we recommend

Set a clear, ambitious emissions-reduction target to drive decarbonisation of maritime transport

An ambitious absolute target for emissions reduction in the shipping sector will be a strong driver of change. This study and recent other work demonstrates that such an ambitious emission target is within reach – if radical changes are implemented quickly. Strict targets would send an important signal to industry and research that investing in decarbonisation is potentially profitable.

Support the realisation of emissions-reduction targets with a comprehensive set of policy measures

Successful decarbonisation requires a combination of measures from areas such as technology, operations and alternative energy. Ship owners play an essential role in implementing these global policies and regulations can support the uptake of low- and zero-carbon ships: through more stringent energy efficiency targets, a low-carbon fuel standard or speed limits for instance. National governments could encourage green shipping domestically by supporting research into zero-carbon technologies, their development and commercial application. Ports should provide shore power facilities, electric charging systems and bunkering facilities for alternative fuels. Shippers should assess the carbon footprint of their supply chain and target transport options with zero-carbon ships.

Provide smart financial incentives to advance the decarbonisation of maritime shipping

Financial incentives will reduce the price gap between conventional and more sustainable fuel options. They could include a carbon price for global shipping, thus leaving it to the market to allocate resources optimally. Receipts from a carbon-pricing scheme could fund further research and development in green shipping or ship retrofitting programmes. They could also help to mitigate adverse impacts of decarbonisation on trade in least developed countries and small island developing states. National or regional incentive schemes could complement carbon pricing at a global level. Governments could also provide financial incentives for green shipping e.g. via public procurement and temporary exemptions of electricity taxes for electric ships. Ports could differentiate fees based on environmental criteria. Governments might collaborate with financial institutions or encourage domestic development banks to develop targeted financial instruments for green shipping.

Introduction

Shipping's greenhouse gas (GHG) emissions and the associated climate impact are currently subject to intense debate within the International Maritime Organisation (IMO). Its member countries decided in 2016 to develop an Initial IMO Greenhouse Gas Strategy by 2018 and a Revised Strategy in 2023. This Strategy is supposed to define an ambition for GHG mitigation in maritime transport, which includes targets, guiding principles and candidate measures to reach these targets. Although global regulation on mandatory energy efficiency standards in shipping was introduced in 2013, various studies project shipping's GHG emissions to grow if additional measures are not taken. For example, the official IMO GHG study foresees an increase of shipping's GHG emissions of 50-250% by 2050 (Smith et al. 2014).

The 2015 Paris Climate Agreement formulated clear ambitions for mitigating GHG emissions. This included a long-term goal of keeping the increase in global average temperature to well below 2°C above pre-industrial levels; to aim to limit the increase to 1.5°C; and for global emissions to peak as soon as possible. Although shipping is not explicitly excluded from the Paris Climate Agreement, one could argue on the extent to which it is actually covered by it. The Agreement does not mention international shipping and – considering that international shipping is a global activity – countries have not included the sector in their Nationally Determined Contributions (NDCs) that form the backbone of the Paris Agreement.

The projected impacts of climate change are well documented, for example in the various reports of the Intergovernmental Panel on Climate Change (IPCC). These impacts include an increase in extreme weather events, sea level rise and temperature rises, with considerable impacts on global annual GDP, due to damages caused by climate change (Dellink et al., 2017). The IPCC is currently working on a report that will assess the impacts of global warming of 1.5°C above pre-industrial levels, which is planned to be released by the end of 2018. Existing research indicates the vulnerability to climate change of coastal regions, small island developing states and a range of economic sectors, including agriculture and tourism. Maritime transport will also be adversely affected by extreme weather events, such as storm surges or floods that might not only impact shipping operations and navigability, but also affect the access to seaports.

An alignment of international shipping to a 1.5°C scenario would require decarbonisation of the sector between 2035 and 2050. There are different pathways possible for such a scenario, depending on the moment at which shipping emissions would peak. If shipping emissions peak early or already start to decline, the pathway could be longer, reaching zero carbon emissions in 2050. In case of later emission peaking, a steeper decline of shipping carbon emissions would be needed, with a reduction to zero by 2035.

Decarbonisation of shipping by 2035 is one of the proposals currently discussed. In September 2017, Kiribati, Marshall Islands, Solomon Islands and Tuvalu proposed that the IMO Initial Strategy targets full decarbonisation (to zero GHG emissions) by 2035 (ISWG-GHG 2/3). This proposal was based on an earlier proposal by the Marshall Islands and Solomon Islands that an overall target for shipping GHG reductions should be consistent with a "fair share" of the global burden of reductions necessary to limit average global temperature increase to no more than 1.5°C. This also links back to a submission of Marshall Islands, in 2015, that proposed to align the shipping sector to a 1.5°C scenario.

At the other end of the spectrum a large group of countries – mostly emerging economies – are expected to support decarbonisation in the second half of this century, although they have not specified a preferred target for shipping emissions. In between are most of the OECD countries. A group of EU, Pacific countries and NGOs has proposed an absolute reduction target of 70% by 2050, pursuing efforts for 100%, and a reduction of the carbon intensity (i.e. carbon emission by tonne-kilometre) by 90% compared to 2008 (Chambers, 2017). Japan has suggested an absolute reduction target of 50% by 2060. The shipping sector itself, as represented by the International Chamber of Shipping (ICS), has officially proposed reducing carbon intensity by 50% to 2050, peaking of absolute emissions by 2008, but not suggested an absolute reduction target for GHG emissions.

This study describes what would be needed to reach the target of decarbonisation of international shipping by 2035, and as such provides some indication of the feasibility of the proposed target. In order to answer this question, the study undertakes three different exercises. First, it provides an update of baseline emissions based on new scenarios for maritime transport demand until 2035. Second, it provides an overview of the state of the art with regards to mitigation measures, the interaction of these instruments between each other and the extent to which these instruments could reduce shipping emissions. Finally, it presents the conditions under which these measures could be effectively implemented. As such, it hopes to be relevant to policy-makers in search for evidence related to shipping decarbonisation trajectories and candidate measures that might contribute to realising these trajectories.

The focus of the study is on international shipping, so the GHG emission projections in this report exclude those from domestic shipping. Domestic shipping is here defined as shipping of domestic cargo between ports within the same country. This demarcation is somewhat artificial, as there is interaction between international and domestic shipping. Yet, it reflects the fact that the International Maritime Organisation (IMO) does not have a mandate for regulating GHG emissions from domestic shipping. The interaction between international and domestic shipping is also reflected in the part of the study that deals with policy measures: innovations in domestic shipping could play an important role for international shipping as well.

This study builds on a variety of research. A first strand of research is on possible decarbonisation pathways for shipping, such as Smith et al. (2014), Smith et al. (2016), Raucci et al. 2017), DNV GL (2015), DNV GL (2017) etc. Most of these studies take 2050 as time horizon, or focus on above 1.5°C scenarios, e.g. the 1.75°C scenario outlined in IEA (2017). A notable exception is Smith et al. (2016) that also includes a zero-carbon scenario in 2035. Some studies focus on zero-carbon shipping by 2035, but only for new ships. For example, a recent study by Lloyd Register assesses the requirements for a transition to zero-emission vessels by 2030 (Lloyd’s Register, 2018). There is an extensive literature on mitigation measures and their impacts, reviewed in Bouman et al. (2017). Finally, a considerable range of literature focuses on pre-conditions for mitigation measures.

This study aims to be complementary to existing studies. While most studies reflect uncertainties with regards to future technologies applied in the shipping sector, they focus less on uncertainties related to future maritime transport demand. Our study updates existing studies by taking into account possible demand scenarios related not only to a decline in fossil fuel-related maritime transport but – unlike most of the cited studies –also considers a trend of increased regionalisation of trade. In terms of policy measures, this study aims to be comprehensive and up to date with the latest developments in the shipping sector. The study models the potential emission reductions of these measures and their interaction. Finally, the study aims to bridge research strands related to modelling, impact analysis and policy relevance.

Shipping emissions by 2035

Where might shipping's CO_2 emissions be heading without additional policy measures? In other words, what is the baseline for shipping emissions? This chapter attempts to answer this question based on projections from the ITF international freight model. In addition, the chapter will address possible shifts in demand for maritime trade not yet reflected in the model, in particular the most recent indications on declining maritime transport of fossil fuels and further trade regionalisation. We integrate these trends in the projection of maritime emissions for 2035. Finally, the chapter highlights two other possible demand shifts that do not form part of the model due to their high uncertainty, namely alternative maritime routes and potential modal shifts from ocean to rail transport.

Global shipping emissions by 2035: baseline scenario

In a baseline scenario without additional policy measures, carbon emissions from global shipping are projected to reach approximately 1 090 million tonnes by 2035. This would represent a 23% growth of emissions by 2035 compared to 2015. We base this projection on the ITF international freight model, explained in detail in the appendix. The baseline scenario incorporates the impact of existing international regulations, including on the energy efficiency of ships. A geographical representation of shipping emissions and their evolution shows that a large share of carbon emissions in the baseline scenario is generated along main East-West trade lanes (Figure 1).

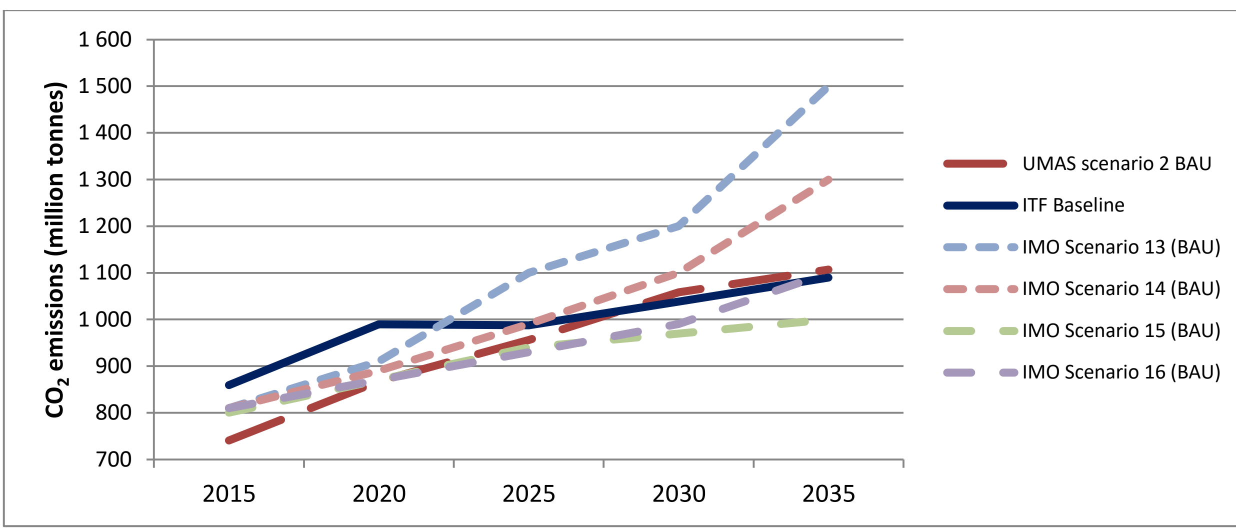
We base our projections of carbon emissions from global shipping on the ITF international freight model, designed to estimate freight transport flows for 19 commodities in all transport modes, using actual routes and related real distances, converting trade in value into freight volumes in tonne-kilometres. The model uses trade projections from the OECD ENV-Linkages model (Chateau et al. 2014), a Spatial Computable General Equilibrium Model, which accounts for the dynamic evolution of international trade, both in terms of spatial patterns and commodity composition. The carbon emission projections are the result of a confrontation of these freight flow data with energy and carbon intensity data per different ship types, as published by UMAS (Smith et al., 2016).

The main driver for the growth of global shipping emissions is the rise of international trade, projected to almost double by 2035 and growing at a rate of approximately 3% per year until 2050 (ITF, 2017). The projection reflects an outlook for international trade with a relatively lower growth rate compared to the historical values between 1950 and 2009. The GDP growth of emerging and developing economies is projected to outpace those of OECD countries, resulting in a shift of global economic weight to non-OECD countries. This would lead to a restructuration of global trade patterns. By 2035, China and India could dominate global trade with 23% of global export flows. The share of export values from Europe might be reduced to 26% of the global export flows in 2035, compared to 33% in 2015.

Our projection of baseline shipping emissions is well aligned with the outcomes of various other studies. Its results are in line with two scenarios from the IMO Third GHG Study, namely baseline scenarios 15 and 16. The IMO shipping emissions scenarios are based on so-called Representative Concentration Pathways (RCPs) projecting future demand of coal and oil transport, and Shared Socioeconomic Pathways (SSPs) estimating future economic growth. Based on these transport demand classifications, our trade projection shares similar characteristics with SSP 2 where there is a moderate growth of transport demand for all commodities due to modest global GDP growth. The IMO baseline scenario 16 is characterised by RCP 2.6 and SSP 4. In this scenario, there is a moderate growth of transport demand for non-coal bulk and dry cargo (similar to SSP 2), coupled with a decline in global energy consumption of coal and oil products. Furthermore, this scenario assumes low uptake of liquefied natural gas (LNG) as a ship propellant, the absence of emission control areas (ECAs), and low improvements in overall ship energy efficiency. Our baseline projections are also in line with the baseline projection in Lloyd's Register and UMAS study (Smith et al., 2016) (Figure 2). However, not all projections originate at the same value in 2015. The difference in the starting point of the projections is mainly due to the difference in the underlying trade projections that are used by various organisations and in the types and number of ships that are included in each study (i.e. Smith et al. (2016) include a subset of the international shipping fleet).

Figure 1. **Visualisation of CO_2 emission across global shipping routes in 2015 (top) and 2035 (bottom)**

Figure 2. **Different projections for shipping's CO_2 emissions to 2035**



Possible ranges of emissions in 2035

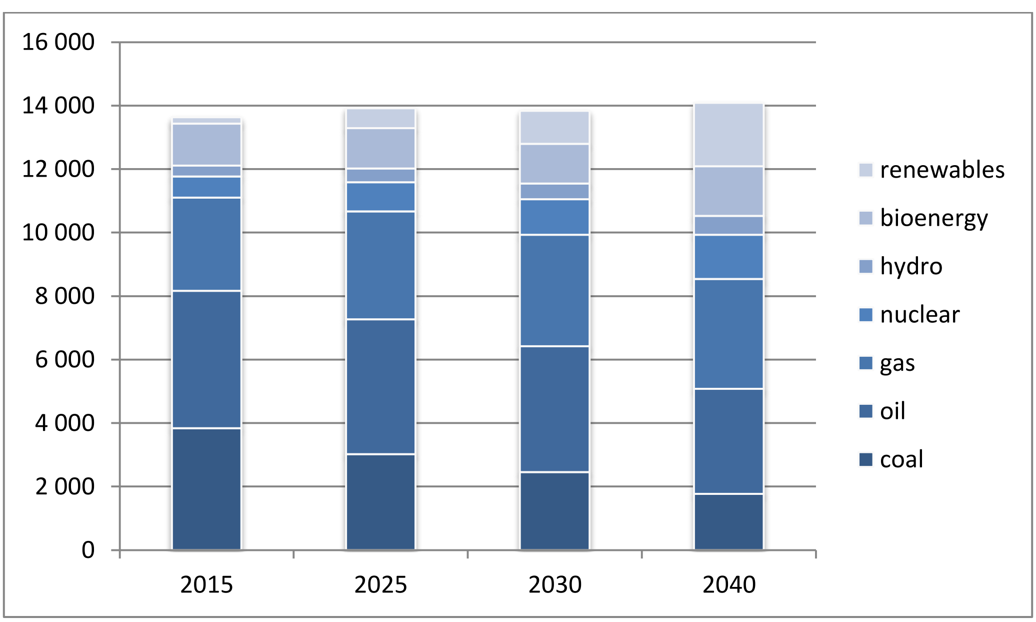
It is uncertain how future transport demand will evolve. All projections of shipping emissions are based on underlying transport demand assumptions that might not materialise. In our study we incorporate two possible developments in the baseline scenario: a strong reduction of trade in fossil fuels and further regionalisation of trade. We will show that this results in a downward adjustment of shipping emissions, when these developments are taken into account. We will also describe two other developments – alternative maritime routes and possible modal shifts – that might be relevant but that we think are relatively marginal in their impact on shipping emissions.

Less fossil fuel trade

One of the visible impacts of the Paris Agreement is the rise in commitments of countries and various sub-national governments to reduce the use of fossil fuel commodities such as coal and oil. A salient example of such commitment is the Powering Past Coal Alliance which, to date, has registered 26 countries and various, sub-national governments and businesses (PPPCA, 2018). This alliance aims at gradually phasing out the use of coal power in their jurisdictions and prohibiting the operation of any new coal power stations without operational carbon capture storage system, although no clear schedule has been given for this development to take place. Recent findings in the OECD's *Inventory of Support to Fossil Fuels* report indicate a reduction in support on the use of fossil fuel commodities in OECD countries and in their partner economies starting in 2015 (OECD, 2018). This has led to the decrease in global coal production for the first time since 1990.

This development is reflected in certain scenarios for global energy demand. E.g. the sustainable development scenario in the World Energy Outlook 2017 of the International Energy Agency (IEA) projects that global energy demand from coal will decline up to 41% and oil up to 22% by 2040 (Figure 3). Climate Analytics suggests that in order to meet the goals outlined in the Paris agreement, coal needs to be phased out by 2030 in OECD countries, by 2040 in China, and the rest of the world by 2050. In addition, other fossil fuels (such as oil and petroleum products) will also need a radical phasing out of up to 50% of consumption in 2015 (Rocha et al., 2016).

Figure 3. **World energy demand (Mtoe) under sustainable development scenarios**

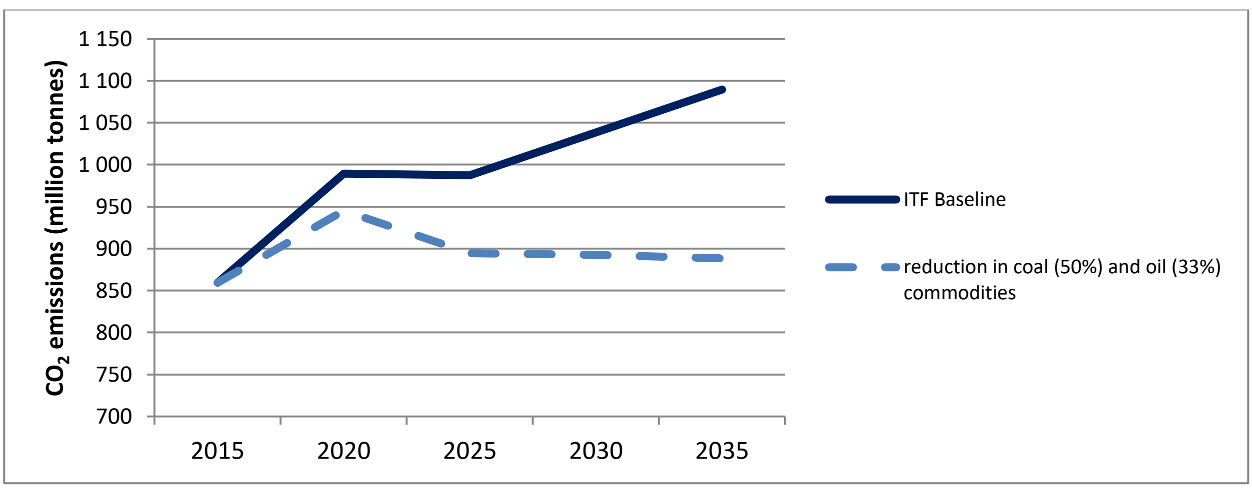


Note: Mtoe refers to "million tonnes of oil equivalent".
Source: IEA (2017)

Declining use of fossil fuels would have a significant impact on maritime trade due to the quantities of coal, oil and gas shipped over long distances. The decrease of worldwide coal production of about 2.9% in 2015 translated in a decline in seaborne coal trade of 4.3%, which represents around 50 million tonnes of cargo by sea transport (VDKi, 2018). Transport of fossil fuels represents a large share of maritime trade: in 2016, oil and gas represented 30% of the total international seaborne trade (in terms of millions of tonnes loaded) and coal represented 11% (UNCTAD, 2017).

We assume that a reduction in global coal and oil trade will take place gradually from 2015 onwards and could lead to roughly 50% and 33% reduction of coal and oil trade volume by 2035. This reduction factor is based on the IEA latest projection on global energy demand (IEA, 2017) and is similar to one of the sustainable pathways in IMO scenario RCP 2.6, which projects a decline of about 48% in transport demand for coal trade and 28% for liquid bulk trade, including oil. In our projections we assume a stronger decline for coal and oil trades since the recent observations indicate the decline to start in 2015, which is earlier than estimated in the RCP 2.6 scenario. We assume that the trade volume of these commodities will decline by 3.35% (for coal trade) and 2.1% (for oil trade) per year until 2035. This might be partly offset by a potential growth of non-fossil energy commodity trade by sea. Under these assumptions, shipping emissions towards 2035 show more moderate growth. Figure 4 presents the resulting CO_2 emission trajectories for 2035 if reduction in fossil fuel trade is taken into account.

Figure 4. **Impact of reduction in fossil fuel trade by 2035**



More trade regionalisation

Global outsourcing has driven much of the trade growth of the last decades, but current developments might indicate a more regionalised trade system in the future. With the proliferation of global value chains (GVCs) over the last decades, the direction and composition of international trade have changed significantly. Emerging economies have gained a larger share in global trade and increasingly trade with each other. One of the major trends in trade policy is the continuous increase in preferential trade agreements at a regional level. Especially in Asia, intra-regional trade has increased in relative and absolute terms (IMF, 2017). For example, the share of Chinese exports directed to emerging and developing Asian countries has grown considerably in the last decade. Such shifts in trade patterns could significantly alter the global demand for seaborne transport.

These developments are in part already reflected in our baseline projection. The baseline trade scenario, on which the ITF international freight model is based, reflects factors such as modest growth, the slowing intensity of fragmentation of global value chains, and increasing protectionism. According to the baseline projection, China and India are expected to dominate global trade with 23% of global export flows by 2035 and 27% by 2050. More importantly for the discussion on regionalisation of trade, the freight projections show much higher growth in intra-Asia and intra-African freight flows than those for intercontinental flows. Intra-Asian tonne-kilometres are estimated to grow by a factor of 4.5 between 2015 and 2050 while the growth factor is 6.5 for intra-African freight flows (ITF, 2017).

Regionalisation of trade might go further than what is currently reflected in the model. Certain technological changes will significantly alter trade patterns in the future. Robotics, automation, computerised manufacturing, artificial intelligence and other possible production modes could reduce the advantages of production in low-labour-cost emerging economies, and hence curb or even stop international fragmentation of production, which would lead to consolidation of GVCs (De Backer and Flaig, 2017). In addition, developed countries experience a trend of dematerialisation of demand, towards more service-led economies and miniaturised technological products.

The increased application of additive manufacturing, such as 3D printing, could also lead to more regionalised production patterns. As 3D printing is becoming affordable, faster and better compatible with a variety of materials including metal and ceramics, an increased use of this technology could potentially reduce trade in certain raw materials for manufacturing. The technology could shift production closer to the consumer allowing for faster prototyping and customisation, which eliminates the need for tools, moulding machines and various assembly steps. 3D printing reduces the cost of demand uncertainty and allows for more production flexibility potentially leading to a reduction of demand for spare parts from overseas suppliers (Barbieri et al., 2017). While the current application of 3D printing is limited to spare parts and certain medical applications, the range of goods is constantly expanding towards more complex industrial components and consumer items. PwC predicts that within the next 5 years, about 85% of companies in manufacturing will incorporate 3D printing into their business (PwC, 2017). Nonetheless, although the additive manufacturing sector is quickly expanding, mass production of standardised parts could well remain the norm, if technologies such as 3D printing cannot seize the same economies of scale (Weller et al., 2015). Additive manufacturing will be economically viable particularly when it reduces supply chain complexity and in situations where long lead times lead to significant real and opportunity costs. A PwC study from 2015 projected that about 37% of ocean container shipments could be threatened by 3D printing. The sectors most prone to disruption identified in this study were footwear, toys, ceramic products, electronics, and plastics (PwC, 2015).

A possible shift to a more circular economy could further reduce the global demand for raw materials and the related transport flows. A considerable share of the commodities needed for production could be sourced locally from recyclable material. In such a circular economy scenario, McKinsey estimates that consumption of primary materials could drop as much as 32% by 2030 and 53% by 2050 in Europe. While these materials include also land and water use, other inputs are tradable, e.g. car and construction inputs, synthetic fertilisers, pesticides and fuels. Europe currently imports around 60% of its fossil fuels and metal resources (McKinsey, 2016). However, a more circular economy does not necessarily mean a reduction in freight transport, because it could also give rise to trade in recycled goods or recyclable waste which gets transformed elsewhere or is returned to the point of manufacturing in global or regional loops (World Economic Forum, 2014).

In addition, maritime cost increases related to the 2020 sulphur cap might have effects on regionalisation of trade. This cap will reduce the allowed sulphur content in ship fuel from 3.50% to 0.50% (Box 1) and could translate into increases of import prices (ITF, 2016). These changes might be substantial enough to lead to changes in trade flows. Depending on price elasticities – most of which are not exactly well-known – one could assume that these cost increases lead to shortening of certain supply chains, considering that the increase in maritime costs makes nearby sourcing more attractive. We suppose this will be particularly the case for goods where transport costs make up a high share of the import value and where alternatives from nearby countries or the local market are available.

Box 1. **Global sulphur cap for ships**

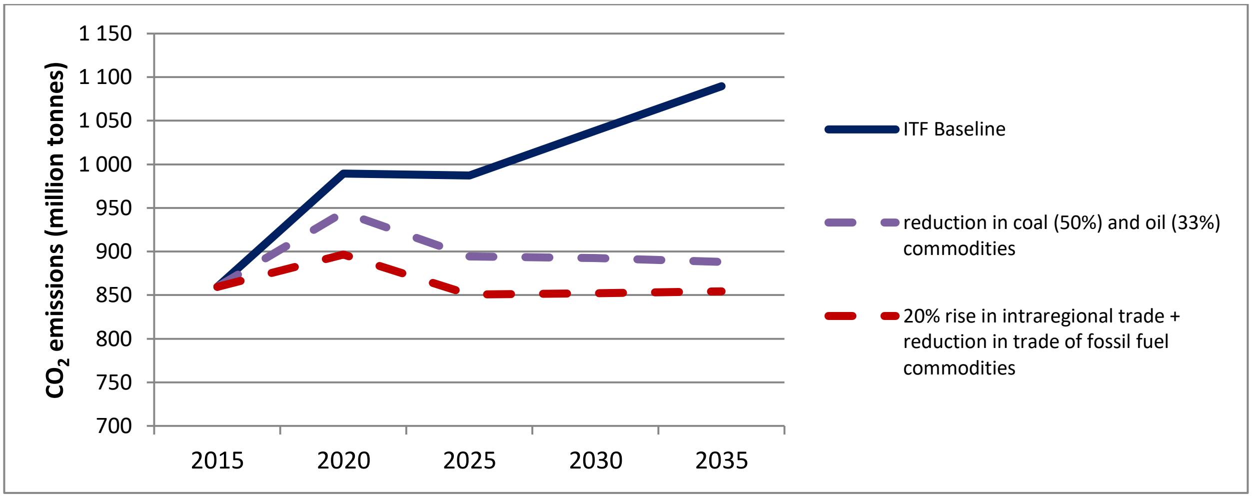
The 2020 sulphur cap will increase maritime transport costs. This global regulation will reduce the allowed sulphur content in ship fuel from 3.50% to 0.50%. This global cap complements measures already in place in emission control areas (ECA’s) in Northern Europe and North America, where the maximum sulphur content has been 0.1 since 2015. Although these regulations are focused on sulphur emissions from shipping, these will arguably also have an impact on GHG emissions from shipping, most importantly because the sulphur regulation could be considered as an implicit carbon price: it increases the costs of carbon-intensive shipping. Depending on oil price and ship size, the cost increases in container shipping costs could range between 20-85% (ITF, 2016).

These cost increases will increase the attractiveness of lower-carbon ships. This becomes apparent from order book patterns in Northern Europe since the introduction of the 0.10% limit in ECAs: LNG-powered ships have suddenly become attractive options for ship-owners that operate mostly within the ECAs, in addition to use of low-sulphur fuels, whereas the uptake from scrubbers is more limited. The use of LNG-powered ships – instead of a similar ship running on HFO/MDO – results on average in a 20% reduction of CO2 emissions, but likely increase in CH4 emissions. It is likely that such effects are incorporated in existing models on future shipping GHG emissions, via assumptions on ship fuel, although some of the studies do not explicitly mention the price effect related to the sulphur cap.

The possible impact on regionalisation of trade is in line with existing literature on carbon pricing in maritime transport. Modelling of the possible impact of a 10% increase in the bunker price due to carbon pricing found an increase of Chinese domestic iron ore production by 14-18% and a corresponding drop in the market share for seaborne imports into China, in particular from distant producers and countries with fragmented production (Vivid Economics, 2010). However, it is currently difficult to gauge the exact import substitution effects considering the lack of modelling exercises that study the trade elasticities between countries and commodities taking into account the impact of carbon pricing. However as Faber et al. (2010) conclude: it is likely that import substitution will occur in many cases. This could also be concluded from Tavasszy et al. (2014) that modelled the effects of internalisation of external effects of supply chains (increase in maritime costs) and found a 4.2% decrease of agricultural trade flows and a 1.1% decrease of coal trade to and from the Netherlands. We deduct from these references support for our assumption that the cost increases related to the 2020 global sulphur cap will lead to a certain amount of import substitution reducing the tonne-kilometres initially projected in the baseline until 2035.

More intra-regional trade, combined with a further reduction of trade in fossil fuels, could reduce baseline CO_2 emissions to around 850 million tonnes by 2035. In this projection we assume a 20% rise in intra-regional trade flows by 2035 that replace inter-continental trade flows, which results in a reduction of tonne-kilometres, as compared to the baseline scenario. The level of 850 million tonnes by 2035 will be used in this report as a benchmark of CO_2 emissions that would need to be reduced in order to reach full decarbonisation of shipping by 2035 (Figure 5).

Figure 5. **Combined impact of rise in intraregional trade and reduction in fossil fuel trade by 2035**



Uncertainties in demand projections

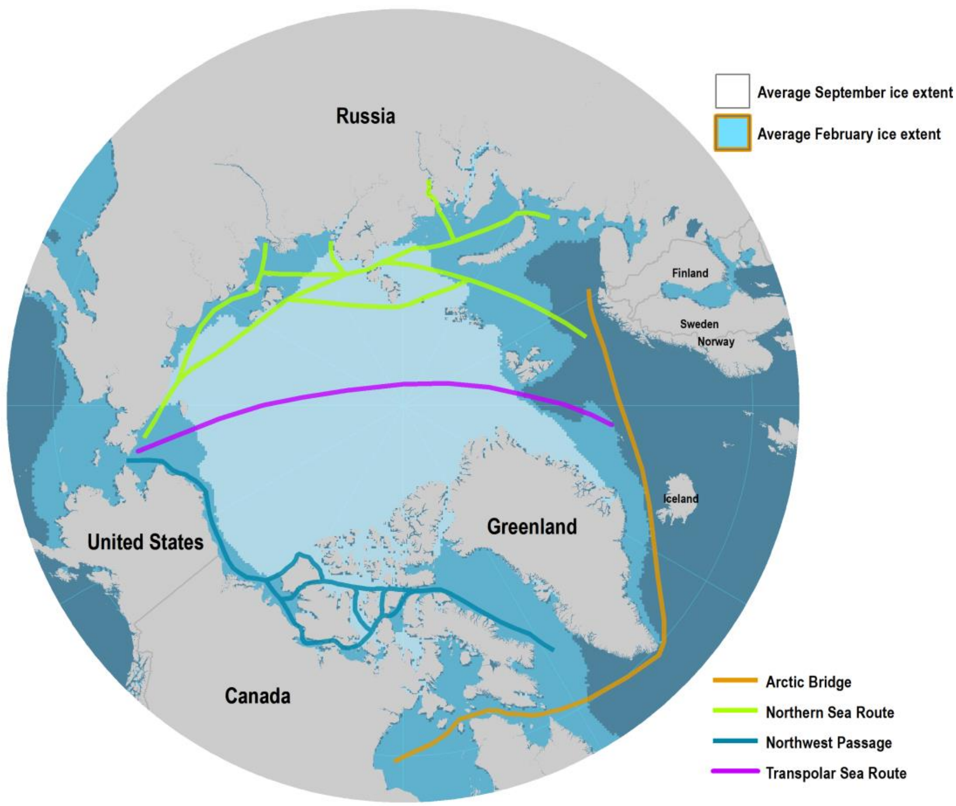
The projections presented above are subject to a range of uncertainties. Our assumptions will be subject to new developments that will likely change the demand and associated trajectories. Some of the uncertainties that change maritime transport demand and its spatial patterns are related to the use of alternative maritime routes, in particular the Arctic sea routes, and potential modal shifts, e.g. related to increased freight rail traffic between Asia and Europe. The following section presents these potential developments that might result in additional impact on maritime emissions that are not taken into account in our current modelling framework.

Alternative maritime routes

New maritime transportation routes would open possibilities to significantly reduce the distance between continents. The decrease of the ice extent in the Arctic Sea has opened up the perspectives of commercial shipping on the Northern Sea Route (including the Northeast Passage which extends the Northern Sea Route towards Europe), the Northwest Passage, and the Transpolar Sea Route (Figure 6). For ships trading between Northern Europe and Japan, using the Northern Sea Route could reduce voyage distance by 37%. Distance reductions from Northern European ports to Korea are estimated at 31%, to China at 23%, and to Chinese Taipei at 17% (Bekkers et al., 2015). Regular use of the North-West Passage could reduce voyage distance between North America and large ports located in North Eastern Asia by up to 20% (Hansen et al., 2016). For trade between South Asian countries and Southern European countries however, the conventional route via the Malacca Straits and the Suez Canal is shorter. The Northeast Passage and the

Northwest Passage are currently used seasonally and have an ice-free period during summer whereas the Transpolar Sea Route is navigable only with powerful icebreakers. The Northern Sea Route has been increasingly used also in the winter months.

Figure 6. **Arctic Sea Routes**



Note: The map serves as an illustrative purpose of Arctic Sea Routes only. The sea ice extent does not match the more current figures of seasonal ice extent which has shrunk significantly since 2010.
Source: Rodrigue (2017)

Carriers currently considering using the NSR face a trade-off between the gains of seasonal distance advantage vis-á-vis the higher costs of shipping. Beside difficult meteorological conditions and safety concerns, current barriers to increased utilisation of Arctic routes include logistical barriers, scarce infrastructure, stricter certification, as well as stricter environmental regulations, including voyage planning restrictions to protect marine ecosystems. For instance, the Polar Code provides for much stricter regulations for Arctic shipping including ship design, training, fuel tanks, discharge of sewage, etc. Stricter environmental regulations could apply to Arctic shipping in the future, e.g. restrictions on the use of HFO which is already banned in the Antarctic. These factors still affect the net economic gains resulting from a shorter transit time. While the NSR could be an economically viable option under specific circumstances mostly for bulk shipping, i.e. from the Russian Arctic, the market potential for other types of shipments remains uncertain given the scarce and inadequate infrastructure and high costs associated to specifically adapted fleet design (Kiiski, 2017).

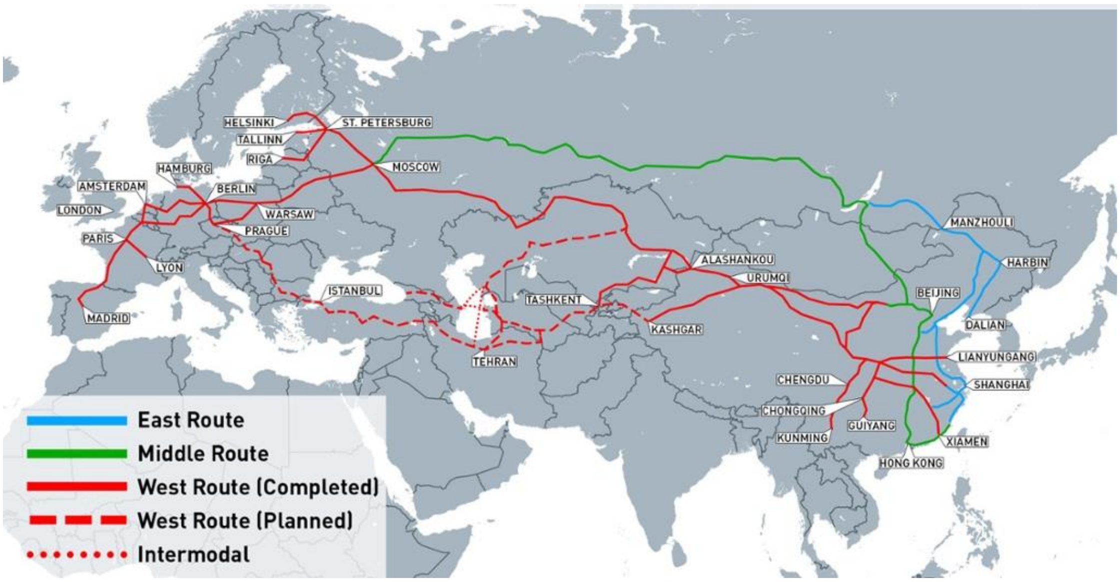
However, that trade-off might be changing fairly quickly. The ice-sea rate steadily decreases and hence the yearly duration of open water increases in the Arctic. By 2050, it is estimated that the entire Arctic coastline and most of the Arctic Ocean will experience an additional 60 days of open water each year on average, including a range of areas with more than 100 days additional days of open water (Barnhart et al., 2016). It is possible that these estimates underestimate the actual pace of Arctic warming. Meteorological conditions, infrastructure and technical solutions could allow all-year round operations already by 2030 (Bekkers et al., 2015).

In line with these expectations, traffic in the Arctic has been steadily rising and will most likely continue to do so. The Russian Federal Agency for Maritime and River Transport reported a volume of 9.7 million tonnes of goods shipped on the NSR during 2017, compared to 2 million tonnes throughout most of the 2000s. The Agency expects a six fold increase in volume over the next three years. Most goods transported along the NSR will be LNG and crude oil although container trade could also rise in the coming years (Marine Insight, 2018).This growing potential is particularly interesting for regional initiatives, such as the "One Belt One Road" initiative in China, which has included the NSR in its scope since in June 2017. In 2013, China signed a free-trade agreement with Iceland and gained observer status on the Arctic Council together with Japan and South Korea. The China Ocean Shipping Company (COSCO) has used the NSR for commercial shipping for the first time as a foreign flagged cargo ship in 2013 and is taking a more active role in the development of the route since 2016. COSCO is also active in delivering the construction materials for crude oil and natural gas extraction projects in the Russian Arctic (i.e. Yamal LNG in which China National Petroleum Corp. and China Silk Road Fund own minority stakes). Moreover, in January 2018, China released a white paper outlining its plans for a "Polar Silk Road" in the Arctic under the wider Belt and Road Initiative according to which China will encourage enterprises to build infrastructure and conduct trial voyages for commercial purposes (Reuters, 2018). Steady growth of sea traffic on the NSR could potentially lead to a reduction in transport distances by 2035. Our modelling exercise has not taken these developments into account yet.

Potential modal shifts

Regular freight trains already carry some traffic between Europe and China via the Russian Federation. Major expansion of rail cargo transport between China and Europe has gathered political momentum. As part of China's Belt and Road Initiative, three main railway corridors have been identified that span the Eurasian continent to connect China, Central Asia, Europe, South East Asia and South Asia (Figure 7). Among these corridors, the northern route – using the Trans-Siberian railways or Kazakhstan's rail system – is currently the only route with stable and reliable transport services and infrastructure (UIC, 2017). This has made the northern route – the Middle Route and completed West Route in Chinese terminology – to be the major rail freight route with the highest traffic volumes.[1] The railway option could be attractive for highly time-sensitive goods, such as fashion, electronics, car parts and perishable goods, such as food. Compared to air transport, rail transport has a cost advantage (2 times cheaper) with longer transport time (6 times longer), and compared to sea transport, it has a time advantage (1.7 times quicker) with higher transportation costs (5 times more expensive).

Figure 7. **Existing and planned Trans-Eurasian railways connecting China and Europe**



Source: Chinese Ministry of Transport

Rail freight flows between East Asia and the EU have increased significantly over the last years, from 25 000 TEU (Twenty-foot equivalent unit) in 2014 to 145 000 TEU in 2016, with an expected annual growth rate of 14% in the years to come (UIC, 2017). This significant improvement can be attributed to reductions in transit times, and increase in punctuality, which are mostly driven by the availability of better infrastructure, more efficient handling, customs and border-crossing processes. Moreover, in the past five years the China-Europe rail freight rate has dropped from 13 to 5 times of sea freight rate (Merk, 2015). This gap between rail and sea freight rate could narrow in the coming years if the ocean freight rates pick up and the cost increases of the 2020 sulphur cap be reflected in prices. On the other hand, Chinese regional governments provide considerable subsidies to the Eurasian rail services, in the order of USD 2 000 – 2 500 per TEU, which might at some point be phased out which, in turn, could threaten their viability (Rail Freight, 2017).

Despite projected future growth, shipping emission reductions due to modal shifts from sea to rail transport will likely be marginal. Whereas the Far East-Europe maritime containerised trade reached 15 million TEU in 2016, the Eurasian rail corridor is estimated to reach a traffic volume of 636 000 TEU by 2027 in a baseline scenario in (UIC 2017). Around 43% of the total volume is predicted to come from a shift from sea transport, while 5% is from air transport. This implies that there can be a slight reduction in the international shipping activities that can lead to reduction of CO_2 emissions. According to our estimation, the shift to rail freight would translate into a reduction of 90 000 tonnes of CO_2 emissions from international shipping, which is a fraction of projected current shipping emissions (0.009%). Moreover, there is considerable uncertainty on these volumes. For the northern corridor, cooperation with Russia is crucial, since the current Trans-Siberian and Baikal Amur rail links on the Russian rail network is suffering from shortage of capacity and has put a limitation on the growth for rail transit volume through Russia (Global Risk Insight, 2017).

Which measures to reach decarbonisation by 2035?

A variety of measures will be needed to reach decarbonisation of maritime transport. The first section of this report showed that shipping GHG emissions might fall by 2035 due to less transport of fossil fuels and more regionalisation of trade, but this will only result in a moderate decrease. In order to achieve full decarbonisation of shipping by 2035 significant operational and technical improvements would be needed. This section sets out what are the possible measures to achieve this objective. We distinguish between three types of measures: technological and operational measures, and measures related to alternative fuels and energy. We assess these measures on their emission reduction potential, and other impacts and conditions for implementation. We use these findings from existing research to inform our modelling of possible emission reductions. The emission reduction potentials presented in each of the sub-sections are assessed individually and cannot be cumulated without considering their potential interactions. At the end of this chapter we present an overview of maximum emission reductions that seem possible by 2035 if measures would be combined. It will show that the largest emissions reductions could be achieved via alternative fuels and energy, but technical and operational measures would also be needed to achieve full decarbonisation by 2035 (Table 1). The chapter concludes with outlining combinations of measures that could provide different decarbonisation pathways for shipping towards 2035.

Table 1. **Overview of measures to reduce shipping's carbon emissions**

Type of measures	Main measures
Technological	Light materials, slender design, less friction, waste heat recovery
Operational	Lower speeds, ship size, ship-port interface
Alternative fuels/energy	Sustainable biofuels, hydrogen, ammonia, electric ships, wind assistance

Technological measures

Improving energy efficiency via technological measures is the aim of the global regulation on the energy efficiency of ships. This regulation requires ships built after 1 January 2013 to comply with a minimum energy efficiency level: the Energy Efficiency Design Index (EEDI). The EEDI measures the CO_2 emitted (g/tonne-mile) based on ship design and engine performance data. The EEDI level is tightened incrementally every five years with an initial CO_2 reduction level of 10% for the first phase (2015-2020), 20% for the second phase (2020-2025) and a 30% reduction mandated from 2025 to 2030. This regulation is part of Annex VI of the International Convention for the Prevention of Pollution from Ships, often abbreviated as MARPOL Convention.

There are various concerns related to the effectiveness of the EEDI. Since the EEDI regulation affects only newbuild ships, it takes time for the regulation to cover the whole fleet. The average age of the shipping fleet is approximately 25 years, which means that the large majority of ships can only be considered to be covered by EEDI by 2040. Insofar as the EEDI acts as a target, it cannot be considered to be a very challenging target: the attained EEDIs of newbuild ships largely exceed the currently required EEDIs including Phase 3 requirements even though they are not mandatory before 2025, in particular containerships and general cargo ships (Transport & Environment, 2017; Faber et al., 2017b). These attained scores often do not reflect the use of innovative electrical or mechanical technology, but they are simply achieved through optimisation of conventional machinery or through changing the hull design (Faber et al., 2016). Not surprisingly, the impacts of EEDI on reductions of shipping emissions are estimated to be small: Smith et al. (2016) find only a marginal difference in CO_2 emissions between EEDI and non-EEDI scenarios. For the EEDI to have a larger impact, the mandated reductions or the reference years would need to change. The EEDI measures are already included in the baseline projections. The section below focuses on the individual technological measures that could contribute to further reductions of carbon emissions.

Technological measures cover technologies applied to ships that help to increase the energy efficiency of a ship. We distinguish here between measures related to the weight of ships (lighter materials), the design of ships, ways to reduce friction of ships (such as hull coatings and air lubrication) and ways to recover energy, such as via propeller upgrades and heat recovery (Table 2). This is just a selection of the possible measures identified in a significant body of literature. The measures described below could be considered the measures that enable the largest carbon emission reductions and are generally considered the major technological measures to increase energy efficiency of ships. The overview below assesses their potential for emission reductions. All of these technologies are available on the market, but not all options can be applied as a retrofit. It should be noted that the reduction potentials are variable throughout different ship types, weather or engine conditions and operational profiles. Moreover, estimations from industry sources may be exceedingly optimistic and should be taken with caution.

Table 2. **Main technological measures**

Measures	Potential fuel savings
Light materials	0-10%
Slender design	10-15%
Propulsion improvement devices	1-25%
Bulbous bow	2-7%
Air lubrication and hull surface	2-9%
Heat recovery	0-4%

Note: Emission reduction potentials are assessed individually. Ranges roughly indicate possible fuel savings depending on varying conditions such as vessel size, segment, operational profile, route, etc., hence limiting the possibilities for comparison. Numbers cannot be cumulated without considering potential interactions between the measures.

Sources: Bouman et al. (2017); Gilbert et al. (2014); IMarEST (2011); Lindstad (2015b); Rehmatulla et al. (2017b); Royal Academy of Engineering (2013); Smith et al. (2016); Tillig et al. (2015); Van Kluijven et al. (2013).

Slender hull designs can reduce the overall propulsion requirements of a ship. Compared to standard designs slender vessels have a lower fuel consumption ranging from 10-15% fuel savings at lower speeds to 25% per nautical mile at 15–16 knots, due to their lower block coefficient (Lindstad, 2015b). This implies altering the ship length in ship designs in order to optimise length and the hull fullness ratio, but when the ship is too long, it increases the wetted surface and frictional resistance. However, as retrofit is not possible in this case, deployment of more slender vessels to a greater extent requires fleet renovation. A greater length implies the use of more steel and hence a higher newbuilding price. The tendency of adding container capacity without adding ship length has in practice created less slender container ships over the last decades; they now operate at lower speeds so their optimum hull slenderness is now "fuller".

Further improvements can be made by using lighter materials. Some of the heavy steel used in the ship structure can be replaced by lightweight materials such as aluminium. Currently, high tensile steel is already used to some extent. The amount of weight reduction depends on the amount of replaceable heavy steel on a ship and can therefore vary quite significantly. A meta-study by Bouman et al. (2017) finds a range of potential CO_2 reductions from using lightweight construction materials between 0–10%, although more conservative estimations report energy savings not higher than 2% (Tillig et al., 2015). The cost of the material itself as well as the costs associated with building with lightweight materials such as high-tensile steel are higher, as shipyards are often not used to them (IMarEST, 2011). Furthermore, there are some technical problems associated with the use of high-tensile steel such as fatigue and welding issues, which may make this option less attractive (Tillig et al., 2015).

Reductions in propulsive requirements can also be achieved by optimisations of the ship body**. Bulbous bow** retrofits are among the most common measures. The bulbous bow has a hydrodynamic function to create a wave that cancels out the wave normally generated by the ship hull in order to reduce the wave making resistance (or drag). The measure is used across all ship types and is already relatively wide spread. In a survey by Rehmatulla et al. (2017b) implementation of bulbous bows averaged between 32% and 47% in the respondents' fleet. A bulbous bow is not always appropriate and may in some cases increase resistance. It is usually not used on smaller vessels. Other such ship optimisations can also include fore body optimisation and aft waterline extensions with quite low actual abatement potential. The installation of bulbous bows could lead to 3-7% in fuel savings on large cargo carriers (Smith et al., 2016). Other devices or retrofit to reduce resistance can reduce CO_2 emissions in a range of about 2-5% (Tillig et al., 2015). However, for slower and large ships the increase in wetted surface area due to a bulbous bow may increase the resistance of a ship. It is usually designed for a specific hull shape and speed range. While implementation of the retrofit itself is not particularly complex, the opportunity costs might outweigh the potential fuel savings at dry-docks. Therefore, the measure is mostly applied on new builds (almost 80% according to survey by Rehmatulla et al., 2017b).

Fuel savings can be realised by reducing friction through improvement of the **hull surface**. Some hull coatings have a smoother and harder surface finish, resulting in reduced friction, which typically represents some 50-80% of total resistance. Frequent cleaning of the hull can also reduce the drag and further increase the fuel reduction potential. Hull coatings can be implemented without major costs. This however does not include any maintenance or opportunity costs. For coatings, DNVGL/GloMEEP (2015) report savings in main engine fuel consumption compared to a conventional hull coating of 1-4% depending on the type of coating, vessel size, segment, operational profile, and route. Hull cleaning can generate additional fuel savings that contribute to the estimated fuel savings of maximum 5% achieved by overall skin friction reduction (Tillig et al., 2015). Significant innovation has been made with regards to coating. Nonetheless, it should be noted that surface smoothness can decrease over time, thus reducing the associated fuel savings potential.

Another technical measure to reduce resistance is **air lubrication**. In order to reduce the drag and frictional resistance between water and hull, compressed air is pumped below the ship hull, which then builds up a "carpet" of air bubbles. For this technology, Smith et al. (2016) estimate a potential fuel consumption reduction at around 3%. Good maintenance is required to actually realise the projected fuel savings, because the effectiveness of air lubrication depends highly on the smoothness of the hull. Furthermore, some pumping power is needed in addition to the propulsion power. This technology is most effective on ships with flat bottoms and certain other requirements to the hull shape and length, and is therefore often applied rather to newbuilds. Despite its drawbacks, some orders of this technology have been placed already, i.e. two AIDA cruise ships in 2016 and 2017, which are equipped with the Mitsubishi Air Lubrication System (MALS) (Mitsubishi, 2017).

Propulsion efficiency devices or energy saving devices can include different ducts, pre-swirl fins and fins on the hull, rudders, caps, contra-rotating propellers or other modifications made to the hull or propeller in order to improve efficiency. The measures with a promising fuel savings potential are propeller upgrades such as the contra-rotating propeller. The contra-rotating propeller comprises two propellers instead of a single propeller rotating in opposite directions. This can recover part of the slipstream rotational energy which would otherwise be lost in a conventional configuration (Royal Academy of Engineering, 2013). For propeller upgrades, Smith et al. (2016) cite efficiency gains between 8% and 15%. Other propulsion improving devices are stated to provide potential CO_2 reductions of around 1-25% (Bouman et al., 2017). Some indirect benefits include the increased manoeuvrability of the ship. While this technology has been applied for smaller units, mechanical issues have precluded a wider use in large-scale commercial shipping (Royal Academy of Engineering, 2013). Whereas some retrofits such as fins can be implemented with a low cost, costs of other technologies, such as contra-rotating propellers or pods are longer to recuperate. The retrofit option for contra-rotating propellers for example is costly and difficult to realise, which makes the technology more viable for newbuilds (van Kluijven et al., 2013).

Waste heat recovery recuperates thermal energy from the engine or the exhaust gas and converts it into electrical energy. The residual heat can also be used for on-board needs. Tillig et al. (2015) present a fuel savings potential in a range between 5 and 10% and Gilbert et al. (2014) state potential savings of 0-12% depending on the ship type. A more cautious estimate was made by Smith et al. (2016), expecting a reduction of maximum 4% of main engine fuel consumption. It should be noted that with improved engine efficiency and reduced speed, less waste heat is being discharged, which then also leads to a lower abatement potential.

Operational measures

Operational measures relate to the way in which ships and, more broadly, maritime transport systems are being operated. We distinguish here between four different measures: speed, ship size, ship-port interface and onshore power. Both slower speeds and larger ship sizes have over the last years contributed to a decrease in shipping emissions. The ship-port interface relates to reduction of ship waiting time before entering a port. Onshore power facilities reduce the emissions of ships whilst in port. As ship size developments refer to ship capacity utilisation, we cover these in this section, although larger ship size could arguably also be considered a technical measure. Shore power facilities are considered part of a larger set of port measures that could impact ship operations, so will be treated here rather than as a technical measure.

Table 3. **Main operational measures**

Measures	CO_2 emissions reduction potential
Speed	0-60%
Ship size	0-30%
Ship-port interface	1%
Onshore power	0-3%

Note: Emission reduction potentials concern the entire ship fleet. Numbers cannot be cumulated without considering potential interactions between the measures.
Sources: Faber et al. (2012, 2017a); Gollas et al. (2009); Kiani et al. (2006) Lindstad et al. (2011, 2012, 2013); Psaraftis and Kontovas (2014); Smith et al. (2014).

Speed limit/optimisation

Lower speeds reduce fuel consumption and emissions. A rule of thumb used in the literature states that engine power output of a ship is a third power function of speed. This means that a speed reduction of 10% translates into engine power reduction of 27%. As it takes longer to sail a given distance at a lower speed, a 10% speed reduction results in a reduction of the energy required for a voyage by 19% (Faber et al. 2012). Under an assumption of constant total transport volumes: when speed is reduced, additional vessels will be required to maintain the annual transport capacity (Lindstad et al., 2011).

There are various ways in which lower speeds could be achieved. Ship operators can have incentives to slow down as this reduces their fuel costs, in particular if fuel prices are high and freight rates or revenues are low. At the same time, they often also have contractual obligations in terms of lead times. The reduction in GHG shipping emissions over 2007-2012 was partly due to lower average shipping speeds (Smith et al. 2014). Ship speed could also be regulated. Faber et al. (2017a) indicate that regulation of speed of ships could be done globally, unilaterally as a condition of entry into a port or as a condition to navigate in coastal waters, or bilaterally between ports in two or more states. The speed limit could be absolute or average, in which case the average speed over a certain route should not surpass a certain limit – which leaves room for speed optimisation. Speed limits could be gradually lowered over time, so as to allow shipyards to add the extra ship capacity that would be needed (Lindstad et al., 2011). Speed limits could be differentiated according to vessel type or main cargo types transported. Another way that is often mentioned to achieve speed reductions is via market-based mechanisms, such as a fuel levy, which would increase fuel prices, induce slow steaming and reduce emissions (Psaraftis and Kontovas, 2014), although the link between carbon pricing and speed reductions is not undisputed (Lindstad et al., 2011).

GHG reductions from speed optimisation could range from 0% to 60% depending on the speed decrease. According to Lindstad et al. (2011) shipping's carbon emissions could be reduced by 19% with negative abatement costs and by 28% at a zero abatement cost. Currently, slowing down ship speed up to a level that would enable idle and laid-up vessels to be drawn back into operation would reduce emissions immediately by 4% (Faber et al., 2017a). If the overcapacity in shipping markets in 2009 would have been used for slow steaming, emissions by bulkers, tankers and container vessels could have been reduced by 30% compared to 2007 (Seas at Risk, 2010). Our modelling on carbon emission reductions from lower speeds follows the assumptions from Smith et al. 2016. Lower speeds are more effective if design speeds of ships are brought down as well. Slower speeds also lead to decrease of other air emissions.

Slower speeds means that more ships are needed to provide similar transport service frequency. This additional ship capacity might be available in times of overcapacity. If there is no overcapacity, it means additional investment in fleets. The highest effectiveness is found when the higher ship capacity required is accommodated by existing fleet overcapacity. Slower speeds lead to longer lead times that could mean additional supply chain costs for shippers. They also imply risks of modal shifts for time-sensitive goods to air or rail transport. This could be avoided by simultaneous introduction of niche services with high speed that could achieve equivalence in CO_2 emissions to lower speed services using technology or alternative fuels. This could help avoid modal shift to other transport modes.

Ship size

Largest vessels of all ship types emit less CO_2 per tonne-kilometre as long as the larger capacity is similarly utilised. This implies that increasing average vessel sizes can help to lower emissions. An insight from the various studies is that when the ship's cargo-carrying capacity is doubled, the required power increases with two thirds of the increase in ship size. This implies that increase in ship size fuel consumption per freight unit is reduced (Lindstad, 2013). There are economies of scale to ship-owners from larger ships, but these are decreasing with size (ITF, 2015). The relationship between ship size and emissions is not linear, but reflects a power-law relationship with diminishing marginal emission reductions as vessel increases. As dry bulk vessel size increases from 26 000 dwt to 46 000 dwt, the emissions per ton mile (nm) are reduced by 33%, while an increase from 46 000 to 72 000 dwt offers only a further 17% reduction (Lindstad et al., 2012).

CO_2 emissions could be reduced by as much as 30% at a negative abatement cost by replacing the existing fleet with larger vessels, according to Lindstad et al. (2012). In that scenario, the average ship size would amount to 106 000 deadweight tonnes (dwt) as compared to 24 000 dwt in 2007. This reduction would be gradually achieved as replacing the whole fleet might take as long as 25 years. However, there is an interaction with technical efficiency measures. As the newer (and more energy efficient) ships are often larger ships, the size-effect of larger ships could be overestimated (ITF, 2015). In our projections we assume ship size – as proxied by deadweight tonnage – to grow with the similar average growth rates per ship type as over 1996-2015, with the exception of container ships were we assume that the growth will plateau after 2025.

While deploying large ships tend to reduce energy consumption in the shipping leg, the total impact on overall door-to-door logistics performance may be negative unless such a move is complemented by smaller ships that can assist in the onward distribution of cargoes. Evidently, larger ships are not efficient when they sail only partly loaded. Net energy efficiency may be superior for a small ship with access to more ports and cargo types, being able to fill its cargo hold to capacity (Buhaug et al., 2009).

Logistics requirements and the size and costs of carrying stocks will tend to work against vessels that are too large. With constant freight volumes, the introduction of larger vessels will tend to reduce sailing frequencies, and when sailing frequencies are reduced the total lead time from factory gate to customer will be longer (Lindstad et al., 2012). There will be limitations to implementation, due to draft and port restrictions. National rules for pilotage and cost recovery via port fees will in some cases result in significant cost increases and operational disadvantages when a ship exceeds a certain size (Lindstad et al., 2012; ITF, 2015)

Ship-port interface

A smoother ship-port interface means a significant reduction of the waiting time of ships, which corresponds to the time that ships spent in port or at anchorage points before being handled. Ships use their auxiliary engines while waiting, so smoother ship-port interfaces would reduce the energy consumption during these waiting periods. We assume that smoother interfaces for a multitude of ships could be achieved by more flexible berth planning. In such a flexible system, the vessel arrival time in a port is considered a variable; it is assumed that the carrier will provide the terminal operator with a range of vessel arrival times – and that the terminal operator will schedule all vessels using these ranges, optimising for vessels' arrival time (Gollas et al., 2009). In order to achieve such flexible planning, better collaboration and data exchange would be needed by the different actors that have an influence on ship waiting time, including terminal operators, port authorities and port service providers such as pilotage and towage. Digitalisation of cargo flows and real-time schedules can enable such a smoothening of the ship-port interface and have a positive impact on service provision.

If improved ship-port interfaces would reduce ship waiting times to zero, the carbon emission reductions might amount to approximately 1% of total shipping emissions. CO_2 benefits depend on the reduction of ship waiting time. Data on this are scarce and fragmented. Examples include mean waiting times of 8.8 hours per ship in Bandar Abbas (Kiani et al., 2006) and 12 hours in Buenos Aires (Merk, 2018) Optimised berth planning could result in considerable reduction of ship waiting time (Gollas et al., 2009). Collaboration and data exchange should make it possible to reduce waiting time to zero. The most significant benefit might be voyage planning for optimal speed – e.g. slowing down to arrive ‘on time’ as opposed to the ‘hurry up and wait’ of the current system. The CO_2 reduction potential of smoother ship-port interfaces will decrease the more zero-carbon ships become available. In case of significant speed reductions, there will be more load/unload operations, and a greater need for port efficiency and accurate voyage timing, therefore the need to have an efficient ship-port interface will increase in importance.

A smoother ship-port interface would also bring other benefits. It would reduce local air pollutants, such as NO_x, SO_x and particles that have huge health impacts for citizens of port-cities. It would also potentially lead to optimal use of terminals and avoid building additional berths. The optimal number of berths in terminals maximises benefits to ship-owners (reduction in waiting time cost) and the port authority (minimizing berth construction). This represents a trade-off: adding berth capacity could reduce ship waiting time, but at the cost of new berths. Better ship-port interface planning could help to release this trade-off. For example, an analysis of the congested Manila International Container Terminal (MICT) revealed that the number of berths was adequate, but that terminal congestion would need to be dealt with in a different way than adding berth space (Saeed & Larsen, 2016).

Onshore power supply

Onshore power supply (OPS) facilities in ports – also known as cold ironing or alternative marine power – allow ships to turn off their engines and connect to the electricity grid to power ships. There are currently around a few dozen ports in the world that have such facilities. Co-benefits of shore power facilities include the reduction of other air emissions from ships and the reduction of ship noise.

OPS in ports cost USD 5-10 million per installation, mainly related to extending grid into port. Ships need to be adapted to be able to use OPS. This does not incur costs for new ships that could take this into account in design, but it might mean adaptation costs for existing ships. Financial incentives might be needed to make it an attractive option. These incentives could include exemption of energy tax for OPS and port fee reductions for ships using OPS. Certain ships (e.g. cruise ships) are very energy intensive also in port. Their energy demand might surpass local supply. Some countries do not have a stable electricity grid, which makes the application of shore power supply for ships problematic.

OPS facilities emit zero CO_2, provided that electricity is generated carbon-free. CO_2 benefits depend on the time in port. Approximately 5% of shipping’s CO_2 emissions are currently generated in ports (ITF, 2014). Part of the uptake will come from regulation already in place. For example, OPS is already mandatory in California, EU core ports will need OPS or LNG bunkering facilities in place by 2025 and other countries are following the trend. OPS can also function as a charging station for batteries of electric ships. It is likely that growing demand for electric ships will become the main driver for expansion of OPS. We suppose that financial incentives (energy tax exemptions, port fee reductions) will be used massively during the transition. We also assume that power provided by the grid will generate zero GHG emissions.

Alternative fuels and energy

Alternative fuels and energy usually have lower or zero ship emissions when used for ship propulsion. Although most alternative fuels are not derived from fossil-fuel resources, upstream emissions may arise in the production of some of them. This section covers a range of promising alternative fuel and energy options and assesses their costs and potential for emission reductions. Not all of these options have reached market maturity yet.

Table 4. **Main measures related to alternative fuels and energy**

Measures	CO_2 emission reductions
Advanced biofuels	25-100%
LNG	0-20%
Hydrogen	0-100%
Ammonia	0-100%
Fuel cells	2-20%
Electricity	0-100%
Wind	1-32%
Solar	0-12%
Nuclear	0-100%

Note: Emission reduction potentials are assessed individually. Ranges roughly indicate possible fuel savings depending on varying conditions such as vessel size, segment, operational profile, route, etc., hence limiting the possibilities for comparison. Numbers cannot be cumulated without considering potential interactions between the measures. Considering upstream emissions of synthetic fuels and electricity, an almost 100% emission reduction can occur only if produced by renewable energy sources.
Sources: See sections below.

Advanced biofuels

Biofuels are fuels produced from organic material, such as plant materials and animal waste. Traditional biofuels include unprocessed biomass (e.g. fuelwood), whereas advanced biofuels are produced by extracting biofuels from materials such as wood, crops and waste material. Biofuels can be solid, gaseous or liquid. So far, the major sources of biofuels are from plant-based sugars and oils, such as from palm, soybean, and rapeseed (Hsieh, 2017). Production of most currently available biofuels requires the conversion of agricultural land or forests, with undesirable effects such as the reduction of food supplies, deforestation and other environmental damages. Further use of these fuels should be subject to sustainability criteria taking into account broader effects on natural resources, food prices and social conditions.

Advanced biofuels offer a high potential in reducing CO_2 emissions. Depending on the quality, type and the way the bio feedstock is processed, biofuels are estimated to be able to reduce CO_2 emissions between 25% and 100% for very good biofuels. In addition, biofuels also result in very low sulphur emissions. It is technically possible to produce marine biofuels that are compatible with the existing marine engines, pipelines and bunker infrastructure, so adaptation costs are limited. It is also possible to blend sustainable biofuels with other ship fuels such as marine distillates. On the downside, one should be careful while selecting certain types of biofuels for marine application, since some specific biofuels have a tendency to oxidise and degrade when stored more than six months. This tendency heavily depends on the conversion technology from feedstock to biofuel. The ISO 8217 marine fuel standard (sixth edition) makes a clear distinction between superior and inferior biofuel grades.

However, supply of biofuels might be insufficient to power the whole shipping fleet. The current biofuels supply, which consists of both biodiesel and bioethanol, can only cover about 15% of the total demand (IEA, 2017). The IEA estimate presented here is based on what can be delivered by adapting the current agricultural and forestry production technologies without adding land use or reducing food supply. As such, it excludes the biofuels that require the conversion of agricultural land or forests. Currently, first-generation biofuels are limited to the extent that, above a certain threshold, it is impossible to produce enough biofuels without threatening food supplies and biodiversity, including problematic effects on food commodity prices. Second generation biofuels use non-food crops such as biomass and waste, whereas third-generation technologies use specially engineered crops such as algae. So both advanced biofuels from the second and third generation could, in theory, reduce problematic effects by using degraded land or residual biomass, but most of those are still in a development phase. As such, the estimate does not take into account the potential of biofuels production from expanding the agricultural area, forestation of semi-arid areas or the use of third generation biofuels such as algae, which can offer very high potential given their large availability and fast growth. Generally, in more optimistic estimates such as presented in IEA (2011) there will be sufficient biofuels for the future demand, whereas more cautious estimates such as presented in Smith et al. (2016) imply that biofuels will be able to power only a limited fraction of the global ship fleet. Governments have – via blending mandates and fuel standards – the leverage to create demand stability that could secure uptake and influence biofuel availability.

Advanced biofuels provide an emission-reducing fuel option that could become more widely available with the necessary investments and policy targets. Although more knowledge on their performance and physical properties –more testing and standardisation – might be required (Hsieh, 2017), various ships are already running on advanced biofuels. The Dutch company GoodFuels has pioneered the application of advanced biofuels – produced from feedstock that is labelled a waste or residue – for various shipping clients, including Heineken and the Dutch Coast Guard. ExxonMobil has planned to introduce algal biofuels by 2025 and other major companies such as Statoil have started to develop fuels from seaweed (Biomass Magazine, 2018). Economic opportunities of advanced biofuels have also gained growing attention in emerging economies. Production of biofuel is taking place for example in Argentina, mostly as a by-product of bean crushing for soymeal production. Brazil, considered the industry leader in biofuels, is trying to reduce emissions occurring in its large-scale ethanol production (Cantarella, 2018). The Indian government supports R&D of biomass pyrolysis, e.g. by using crop waste or algal by-products from waste water treatment. The country hosted a Conference on Sustainable Biofuels in the beginning of 2018 with main stakeholders, notably from India and countries such as China, Brazil and Canada. We assume that these could become principal producers of advanced biofuels in 2035.

Liquefied Natural Gas (LNG)

Liquefied natural gas (LNG) is formed when natural gas is cooled to -162ºC, which shrinks the volume of the gas 600 times. This makes it easier and safer to store: in its liquid state, LNG is not explosive and does not ignite. Its advantages with regards to air pollution are considered to be a major argument for using LNG as a ship fuel. Using a gas-only engine can reduce SO_x emissions and particulate matter by almost 100% compared to conventional fuel oil (IMO, 2016).

The CO_2 mitigation potential of LNG is proven to be substantial with CO_2 reduction which ranges between 5-30% compared to the heavy fuel oil (HFO) (Bouman et al., 2017). However, handling and combustion of LNG involves the release of unburnt methane, also referred as methane slip, which can diminish its overall environmental advantages depending on the volume of the methane emissions. Methane is a very potent GHG with global warming potential 28 times higher than CO_2 over a period of 100 years and 84 times higher over a 20 years period (Anderson et al., 2015). Methane emissions can differ significantly depending on ship, engine types and loads. Manufacturers claim that efficient engines can emit less than 1 g/kWh while others might have emissions close to 6 g/kWh (Verbeek, 2013). It is also important to take into account that methane slip can also occur during bunkering phase as well as upstream in the fuel production, processing and transmission, which also further lowers its GHG mitigation potential. When the methane emissions are higher than 5.8 g/kWh, the use of LNG will lose its mitigation potential and even lead to higher overall GHG emissions (Verbeek, 2013).

The uptake of LNG-powered ships remains fairly marginal, but is growing. There are currently 118 LNG fuelled vessels globally, excluding LNG carriers and inland waterway vessels. The fleet has grown exponentially since the early 2000s and currently available data on confirmed ship orders indicate that the fleet is expected to double and grow by another 123 vessels in the next years (ITF, 2018c). There is an increase in government-backed initiatives such as in Japan, Korea and China to develop LNG bunkering infrastructure as part of their commercial strategies and GHG reduction targets (DNV GL, 2017). These trends seem to indicate that the industry considers LNG as an attractive solution, in particular if LNG becomes cheaper than low-sulphur fuels. This implies that LNG might see a growing uptake in the short and medium term as part of industry efforts to mitigate CO_2 emissions. However, considering the negative impacts of LNGs due to its methane emissions and the relative CO_2 advantages of other cleaner alternative fuels such as biofuels, LNG might not be an attractive solution for longer term. As such, it is important to ensure that the investment plans for LNG infrastructure can be justified and possibly be converted for the use of alternative fuels in the longer term.

Hydrogen

Hydrogen (H_2) is another potentially attractive and viable alternative fuel since it emits zero carbon dioxide (CO_2), zero sulphur oxide (SO_x) and only negligible amounts of nitrogen oxide (NO_x). Hydrogen can be used as fuel in several different ways i.e. in fuel cells; in a dual fuel mixture with conventional diesel fuels (HFO); and lastly as a replacement for HFO for use in combustion machinery. We focus on the potentials of hydrogen as a fuel for ship propulsion both as a mixture and a complete replacement of HFO, while the potentials of hydrogen as a fuel for fuel cells is described in the fuel cells section.

The use of hydrogen as a replacement for conventional diesel fuel still requires research and development, particularly to make it commercially viable. So far, there is no standardised design and fuelling procedure for hydrogen powered ships and its bunkering infrastructure (Lindstad et al., 2015). Furthermore, remaining safety design issues with regards to the volatility of the fuel need to be resolved.

Despite the lack of rigorous commercial viability studies on hydrogen as a fuel, much research has focused on methods of sustainable hydrogen production. Nowadays, there are two common techniques that are used to produce hydrogen: by steam methane reforming and water electrolysis (Bicer, 2018). The latter has gained more attention due to its recent technological development making it possible to efficiently use renewable power to split water into hydrogen and oxygen.

The electricity needed for the production process using the electrolysis method can be generated from solar, wind and hydropower plants (future production locations of synthetic fuels are mentioned below). This significantly improves the overall mitigation potential of hydrogen taking into account its entire production life cycle. A recent assessment by Bicer (2018) has indicated that hydrogen produced by using hydropower can yield 10 times less CO_2 emissions than HFO over the entire life cycle. Furthermore, hydrogen that is used as a mixture with HFO (50% of the total fuel) can reduce CO_2 emissions up to 43% per tonne-kilometre. This shows that even when the current conventional marine fuels (HFO) are partially replaced with hydrogen, a significant reduction in CO_2 and other GHG emissions can be achieved.

Ammonia

Ammonia (NH_3) is a hydrogen carrier that can be used in fuel cells or as a fuel for direct combustion. It has the benefit of having a high hydrogen content containing no carbon atom. Ammonia hence emits zero carbon dioxide (CO_2), sulphur oxide (SO_x) and close to zero nitrogen oxide (NO_x). Unlike hydrogen, the deployment of ammonia as a marine fuel is still in a research and development phase although it has already been used successfully in land-based installations, e.g. for powering buses. To date, no ammonia powered ship is operational.

The advantage of ammonia compared to hydrogen is that its liquid form allows more hydrogen storage per cubic meter than in liquid hydrogen and without the need for cryogenic (high pressure, very low temperature) storage, which makes it a suitable hydrogen “carrier”. Although the energy density of ammonia is not very different from liquid hydrogen, capital cost savings compared to hydrogen occur with different temperatures and pressures needed. Another advantage is that it can be stored at a temperature (-33.4 C) that is easier to maintain compared to hydrogen (-252.9 C). It can be used in different ways for propulsion (e.g., in diesel engines, fuel cells, gas turbines, etc.), which makes it a very competitive option.

The life cycle assessment study conducted by Bicer (2018) shows that when ammonia is used as dual fuel with HFO, it can yield a 27% reduction of CO_2 emissions per tonne-kilometre in the overall life cycle. Furthermore, ammonia produced using wind energy that is used as dual fuel – where 50% ammonia is used in combination with 50% HFO – can reduce total CO_2 life cycle emissions up to 34.5% per tonne-kilometre. This implies that ammonia can offer an attractive short term solution in dual fuel configurations with reasonable commercial viability. In addition, further developments of ammonia as a complement or replacement for HFO can also offer a promising alternative to reduce CO_2 emissions in the long term.

Similar to hydrogen, ammonia production methods have advanced considerably in the recent years. This is partly due to the fact that ammonia is a widely traded commodity around the world and predominantly used as a fertiliser. There is already significant port loading infrastructure, handling experience and safety know-how. While production is theoretically feasible in every country, China currently produces about 31% of world total ammonia, followed by Russia (8.7%), India (7.3%), and the U.S. (7%) (U.S. Geological Survey, 2018). Other large producers are Canada, Indonesia, Saudi Arabia and Trinidad and Tobago.

The common method to produce commercial ammonia is using the Haber-Bosch process converting hydrogen and nitrogen using high temperature and a catalyst. Nowadays, this method can be performed using solar, wind or hydro power through electrolysis which gives ammonia a comparative advantage compared to the production of HFO. “Green” production of ammonia could hence easily develop where renewable energy sources are abundant. Forthcoming hydropower plants in Africa for instance may provide large excess output that provides new possibilities for local ammonia production (Philibert, 2017). Hence, ammonia can also provide an additional business case for renewable energies by generating a supplementary revenue stream. Nonetheless, in order to become viable, sustainable ammonia must become more cost competitive compared to conventional ammonia, of which 90% of production still relies on fossil fuels such as natural gas. While in the U.S., under the most favourable conditions, the cost of producing green ammonia is still about twice as high as natural-gas based ammonia, in regions where resources are especially abundant, the cost of hydro, solar and wind power can fall below USD 0.03 per kilowatt hour. According to IEA, this would include regions such as the Horn of Africa, Australia, North Africa, Northern Chile, Southern Peru, Patagonia and South Africa, as well as several regions in China. Such low electricity prices could allow a production of sustainable synthetic fuels competitive with natural gas reforming, oil-cracking or coal gasification (IEA, 2017). However, more conservative studies voice the concern that global surpluses of renewable energy could not be sufficient to cover synthetic fuel demand in the future (Bracker, 2017). Developing these energy sources would need a significant amount of additional investments. If relevant volumes of synthetic fuels, such as hydrogen and ammonia are used by 2035, it would be essential to ensure that production processes are based on renewable electricity generation. Otherwise, no improvement in CO_2 emissions compared to conventional HFO could be guaranteed.

Methanol

Methanol could be one of the future marine fuels. Today, most of the methanol is produced from natural gas and has a CO_2 emissions reduction potential of around 25% compared to HFO. Compared with HFO, methanol has an emission reduction potential of 99% for SO_x, 60% for NO_x and 95% for particle matter (PM). However, methanol can also be produced from renewable energy resources, such as CO_2 capture, industrial waste, municipal waste or biomass which significantly reduces its greenhouse impact. Methanol is available in large quantities and can be made out of a wide number of resources. Since there is a long history of transporting it, experience in handling and operation already exists. Methanol is also convenient because it requires only minor modifications to ships and bunkering infrastructure since it is similar to current fuels in several respects. It can be used in combustion engines that most ships are already equipped with. Regulation is less constraining because it is generally safer than conventional fuels and LNG. So far, methanol has been employed as a transportation fuel on a significant basis only for cars in China, where it is inexpensive and readily available since it is produced from coal thus having a negative GHG impact (IMO, 2016; Andersson and Marquez Salazar, 2015).

Sweden has been at the forefront of the development of methanol-powered ships. A pilot project was launched, with support from the EU Motorways of the Seas programme, to convert a RoPax vessel into a methanol-powered vessel and provide bunkering as well as other necessary facilities in ports. This project has led to the development of the Stena Germanica, a large passenger and car ferry operating between Gothenburg and Kiel. It is the first ship operating on methanol. Methanol used by the ship is supplied to Stena by Methanex, the world’s largest methanol supplier and is produced from natural gas so it does not achieve the full potential of CO_2 emissions it could achieve. The company partnered with Wärtsilä for engine retrofitting and installed new tanks on the bottom of the ship by seizing void spaces at the bottom. This is considered a safety concern with conventional fuel, but does not pose a risk when using methanol. A pilot fuel to ignite the methanol is needed (5% diesel and 95% methanol), which is also feasible for any large vessel. Although the conversion cost EUR 22 million, Stena expects significant cost reductions of around two-thirds of the cost once applied to several ships at the same time. Stena is currently looking into ways to develop production based on biomass so that it fully achieves its greenhouse gases emissions reduction potential. The company has identified several potential sources for bio-methanol production in Sweden already. The company has also developed a tool kit for ship conversion to methanol in order to support replication (ITF, 2018b).

Wind power

There are six main wind propulsion technologies for ships: soft sails, rigid sails and wing sails, hull sails, towing kites, rotating cylinders, and wind turbines. Soft sails resemble classical sails, which are mostly automated. Rigid or wing sails are wing shaped foils. Hull sails refer to the hull of a vessel that can be shaped like an aerofoil generating aerodynamic lift. Dynamic kites can be installed on a ship's bow to make use of high altitude winds. Vertical rotating cylinders – also called rotors – harness the propulsive force created by the pressure difference on the cylinder orthogonal to the wind direction known as the Magnus effect. Wind turbines can be installed on ships to support electric propulsion of the ship or used for direct ship propulsion. Uptake of these technologies has been fairly small so far and most wind propulsion projects are still in a test phase. To date, the technologies with the highest market maturity are kites and rotors.

Given the different operating speeds, hull, machinery, weather conditions, seasons and routes taken, there is a significant amount of heterogeneity in the fuel savings and thus some degree of uncertainty to the amount of CO_2 reductions achieved by wind propulsion technologies. The abatement potential of wind technologies on ships is estimated to be around 10–60% (Rehmatulla et al., 2015) and 1–50% of reduction in CO_2 according to a meta-study of existing estimates (Bouman et al., 2017). Rough fuel consumption reductions between 10% at 20 knots and 30% at 10 knots were calculated by Smith et al. (2016) for Flettner rotors; approximately between 10% and 50% reduction in emissions for sails dependent on speed and conditions; and for kites, a constant 5% reduction in the thrust requirement of ships. Traut et al. (2014) provide a more moderate range of 2–24% and 1–32% main engine fuel savings on dominant shipping routes for a single Flettner rotor and a towing kite, respectively. Assumedly, the fuel savings potential for a new build may be higher than for a retrofit because the ship can be constructed to meet all conditions required for optimal implementation of the technology.

Installation and operational costs vary significantly between available wind technologies. The installation of a kite is relatively superficial and easy and its cost including assembly and maintenance is notably lower than for conventional sails. Rotors are considered more effective than sails, but they are more expensive. Generally, costs are assumed to decrease with higher uptake of wind propulsion technologies. The payback time depends on a range of factors, such as the variations in fuel price as well as ship speed, type and routes of operation that are exposed to more or less wind. There can be opportunity costs and hidden costs not factored into the installation and operating cost, which could increase the payback period of the technology. This includes for instance the revenue lost from forgone cargo space, disruptions due to installation time (up to 2-7 extra dry docking days depending on technology), as well as the increased journey length to take full advantage of meteorological conditions on different routes. The increased voyage duration may also impact the number of services per year. The technical risk perceived with currently immature technologies can further drive up the capital cost to finance the implementation. A possible way around payback times is the "savings as a service" model in which technology is rented and paid for entirely out of fuel savings, avoiding up-front costs.

In most cases, wind propulsion technologies provide only partial propulsion benefits with some technologies used mainly for on-board electricity generation (wind turbines). Wind propulsion is considered most effective at slow speed (Smith et al., 2016). For example, kites work best on ships with an average speed no higher than 16 knots and are therefore most suitable for tankers and bulk carriers, but could also be applied to container ships (Traut et al., 2014). Unlike kites, rotors are not suited for container ships because of interferences with cargo handling.

Some wind power applications can be combined. E.g., the positioning and function of Flettner rotors and kites are not mutually exclusive and could harness winds coming from different directions. Wind assistance can be applied together with slow steaming and other incremental efficiency improvements. Photovoltaic technology coupled with wind propulsion is also seen as a feasible and appropriate combination (Teeter et al., 2014; Traut et al., 2014).

The uptake of wind technologies will depend on a range of factors. Calculations by Lloyd's Register show that technologies with a 10% fuel savings potential would become commercially viable only at higher fuel prices from 1 000 USD/tonne (Lloyd's Register, 2015). For instance, with the adoption of a carbon price, wind assistance could become an interesting option, especially if prices of alternative fuels are high.

There are currently two providers whose products are close to marketability for commercial ships, although a range of technologies that are currently being tested will be marketable before 2035. The German company SkySails has equipped two multi-purpose ships and a bulk carrier with auxiliary towing kites. Rotor cylinders have also been tested by the shipping company Bore, who has installed cylinders on a Ro-Ro cargo ship between Rotterdam and Teesport in the United Kingdom (Bore, 2015). Norsepower, a Finnish start-up has signed an agreement with the shipping company Viking Line in 2017 to install its Rotor Sail Solution on board a cruise ferry in the second quarter of 2018 (Norsepower, 2017a). The company will also fit a Maersk tanker with 30m high and 5m wide in diameter Flettner rotor sails in 2018, which will be tested at sea until the end of 2019 (Norsepower, 2017b). Simulations have been conducted between 2012 and 2015 testing viability and fuel reduction potential of a container ship "Ecoliner" equipped with sails (SAIL project, 2015). Nelissen et al. (2016) anticipate the market potential to amount to around 3,700-10,700 installed systems on bulkers and tankers by 2030. Smith et al. project a gradual uptake of wind propulsion systems from 2025 despite the relatively low level of market maturity and few applications in practice that nonetheless show an interesting potential.

Fuel cells

The fuel cell directly converts electrochemical energy by transforming the chemical energy from certain compounds into electric power without combustion involved. It thus releases both electrical energy and some thermal energy in the process. Hydrogen is most frequently used in fuel cells. It can be produced conventionally from methane steam reforming, fossil fuel or biomass gasification, or water electrolysis (see above). Possible alternative fuels are methanol, LNG, liquid organic hydrogen carriers (LOHC) and ammonia. The most promising technologies are the Proton Exchange Membrane fuel cell (PEMFC) functioning with hydrogen, the High Temperature PEMFC and the Solid Oxide fuel cell (DNV GL, 2017). High-temperature fuel cells could become suitable as sources of on-board energy for larger vessels such as cruise ships and container ships. Existing fuel cell solutions favour smaller vessels of short range where storage of compressed hydrogen is more viable.

The PEMFC's maturity is highest among the three fuel cell types and is therefore less costly compared to other fuel cells. The High Temperature PEMFC has a higher cost and is more space-demanding incurring an opportunity cost of foregone cargo space. The SOFC still has a relatively high cost compared to other fuel cells which, however, could be reduced with broader use of the technology.

If fuelled with hydrogen, the only exhaust product is water. SOFCs can also be used with hydrocarbon fuel, which generate CO_2 and NO_x emissions. Although burning hydrogen does not release CO_2, indirect emissions need to be accounted for, including fuel manufacturing (Gilbert et al., 2015). Green hydrogen generated using renewable energy would be the most sustainable solution in this context. The fuel efficiency is estimated at 50-60% for PEMFCs and 60% for SOFCs (85% with the use of heat recovery).

The major drawbacks of the PEMFC technology are their sensitivity to impurities in the hydrogen as sulphur and CO, a complex water management system (both gas and liquid) (Van Biert et al., 2016). The High temperature PEMFC could be an alternative as the higher temperature reduces the sensitivity towards impurities and simplifies the water management since water is only present as gas phase. Excess heat can be used for heat recovery for different on-board purposes. SOFCs can pose a safety concern because of the high operating temperatures (it operates at 800-1000 °C). Despite their benefits, fuel cells still have a low maturity, and are expensive and space demanding. PEMFCs for example are more suitable for auxiliary engines and can contribute to the electricity demand but not fully cover it. In its current state of development, fuel cell technology is viable mainly in auxiliary, hybrid and low power machinery (Royal Academy of Engineering, 2013). An estimated 2–20% CO_2 reduction potential was therefore reported in a meta-study by Bouman et al. (2017).

One possible combination could be hybrid systems that combine SOFC, heat recovery and high-performance batteries. One concept of this type is operated in the steamers on Hamburg’s Alster Lake. A different hybrid system could combine fuel cells with diesel engines or gas turbines to achieve higher efficiencies while using more energy dense fuels.

Fuel cells can be used with different types of fuels. If used with hydrogen, the low energy density requires very sizeable fuel tanks, which increases the capital cost and reduces cargo space. Generally, the storage of hydrogen is still challenging, given the lack of the infrastructure and insufficient coverage of regulations and standards (DNV GL, 2017). IMO regulations are currently being adapted to anticipate future uptake of fuel cells in shipping. In September 2017, further progress was made in developing safety provisions for ships using fuel cells, including a proposed new part E on fuel cell power installations to the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code). Different governments have begun to develop infrastructure for hydrogen (i.e. in Japan and the European Union), or have incentivised research on fuel cells (i.e. Germany).

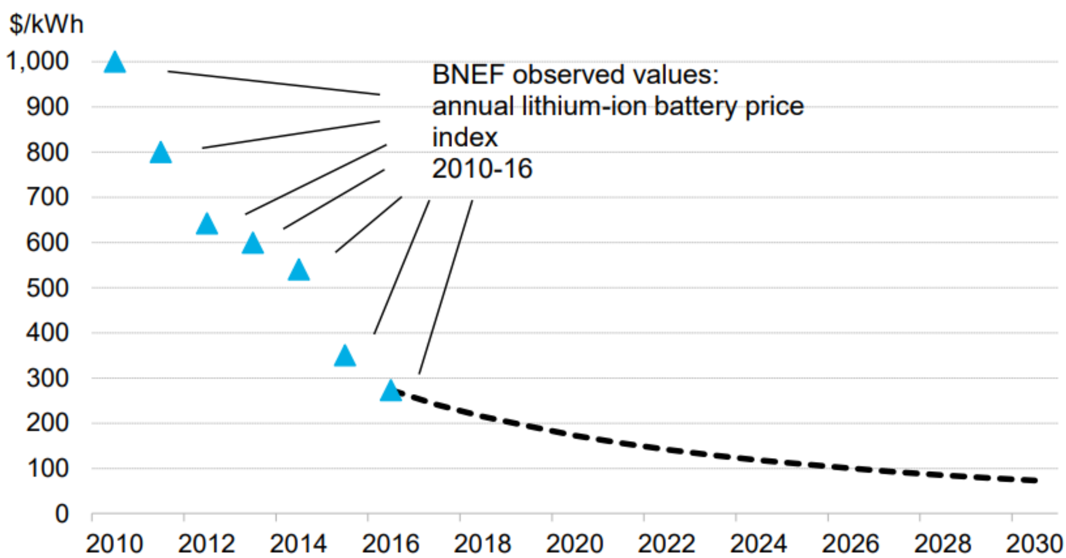
Electric/hybrid propulsion

Power supply for zero-carbon electric propulsion can come from energy storage systems such as batteries, flywheels or super capacitors, which, compared to batteries, can store and release large amounts of electricity very quickly. Energy storage systems remain a relatively costly technology. Electric motors are assumed to be cheaper than conventional engines, but the cost of batteries per unit of energy and their accommodation on ships makes it a very expensive option. Throughout different scenarios, the electric vessel has been estimated to be the least profitable technology compared to alternative fuel options such as hydrogen, ammonia and biofuels (Lloyd’s Register/UMAS, 2018).

In a trial of a hybrid ferry including battery power supply, Fuel savings of 35% were demonstrated. The overnight charge of batteries lead to 24% of fuel savings and the remaining 11% were attributed to optimising the use of the engine and the battery through better energy management. Hybridisation of some ships may provide fuel savings of 10-40% and payback times as low as one year (DNV GL, 2016). Hybrid propulsion also allows design flexibility to enable a ship to be configured to balance financial constraints and environmental considerations (Royal Academy of Engineering, 2013). The most environment friendly alternative would be full electric propulsion. All-electric ships emit almost no emissions although one needs to factor in possible upstream emissions from electricity generation. Producers of Norwegian car ferry Elektra report a reduction of CO_2 emissions by 95% and operating cost by 80% (Elektra, 2018).

Rapidly falling costs of battery technology for electric vehicles suggest that the technology might become a more viable and readily available option also for other transport sectors such as shipping. A study shows that forecasts prior to 2014 have repetitively underestimated the actual observed price reduction of the technology (Nykvist & Nilsson, 2015). Bloomberg New Energy Finance (2017) estimates a learning rate (price decrease for every doubling of capacity) of 19% based on annual industry average battery prices between 2010 and 2016 for electric vehicles and stationary storage. By 2030 they estimate that lithium-ion battery pack prices would fall to as little as \$73/kWh compared to \$273/kWh in 2016. Currently, intense competition forces manufacturers to innovate on their materials and processes and significant improvements in energy density, safety and cycle life are continually being realised. This illustrates the potential for broader use of batteries in the shipping segment although large improvements still need to be made in terms of battery capacity for longer voyages.

Figure 8. **Annual lithium-ion battery price developments 2010-2030**



Source: Bloomberg New Energy Finance (2016)

Solar energy

Photovoltaic energy can deliver electricity for the on-board power demand. Solar panels can either be installed horizontally on deck or vertically in an arrangement with certain sail types. The technology can be applied jointly with wind technology (mast-like structure) to increase the available area for energy capture from the sun. Given their limited capacity to satisfy power demand of ships, photovoltaic installations are currently only suited for auxiliary power demands. Like currently available wind propulsion systems, this technology is expected to leave a requirement for a liquid fuel source. Similar to wind energy, the efficiency of this technology also depends on meteorological conditions. In zones close to the equator, solar energy production reaches higher values makes this a more viable investment for ships operating in these zones.

Potential reductions from solar energy are fairly limited. Smith et al. (2016) assume a reduction of around 0.1–3% of auxiliary engine fuel consumption. The potential CO_2 reduction reported in different studies range from 0.2–12% according to Bouman et al. (2017). Another major constraint is the need for a large deck surface area which does not interfere with cargo handling (although it can be used with RoRo car carriers). Operators of Nichioh Maru, a Japanese car carrier running with solar assistance, state that the ship allows a reduction of 1 400 tonnes of diesel per year implying a yearly reduction of 4,200 tons of CO_2.

Technology for solar propulsion systems is still very expensive and implementation is complicated (Glykas et al., 2010). The cost of solar power may however decrease in the future when the technology is mature and applied on a larger scale. As for batteries, cost reductions are likely to arise from R&D and cumulative production experience gained in other sectors which are developing equivalent or similar technology. Uptake can be expected in the medium to long term, although this would apply only for certain ship types allowing deck space to be covered with an extensive array of photovoltaic panels.

Nuclear propulsion

Nuclear propulsion of ships has been used since 1955 mostly for military and submarine purposes. Despite a small number of commercial vessels being built since, the technology has not progressed beyond usage in the military or for ice-breakers (mostly Russian icebreaker classes). “Savannah”, a nuclear propelled container ship operated in the U.S. 1970 to 1977. One ore carrier and one cargo ship operated in Germany and Japan but were decommissioned in 1982 and 1995 (Hirdaris et al., 2014).

Nuclear ship propulsion during operation emits no CO_2, NO_X, SO_X, or particulate emissions. Another advantage of nuclear power is that it enables the vessel to run for long periods of time without the need to refuel, which increases its autonomy and removes exposure to fuel price fluctuations. There are however significant environmental and health risks. The use of radioactive fuel poses risks such as environmental hazards and challenges including safe storage for spent nuclear fuel and decommissioned on-board power plants. This means that the conventional methods of design, planning, building and operation of merchant ships would need complete overhaul, since for a nuclear propelled ship the process would be dominated by a safety rather than an efficiency case. Main difficulties stem from design execution and planning, operation, training of crews and shore staff, nuclear regulation, security, public perception, disposal, etc. Operating nuclear propelled vessels requires stringent crew selection, education and training regimes. This would require an up-to-date and sensitive regulatory framework on an international level. E.g. the IMO Code of Safety for Nuclear Merchant Ships, Resolution A.491(XII) would need to be updated for current use of nuclear technology in shipping (Royal Academy of Engineering, 2013). A range of other regulatory issues, such as safety, insurance, damage compensation, etc. remain despite international nuclear liability conventions in place. This also relates to the fundamental issue of nuclear propulsion: a majority of countries would not allow these vessels to enter their ports unless a multilateral treaty covers this case. It is hence likely that international nuclear fuelled shipping would need to start on a bilateral level based on a specific treaty.

The cost of uranium has been relatively cheap in comparison to conventional marine fuels. Operation costs however have been excessively high in former commercial trials so that the ships were finally decommissioned. With the building, operation, maintenance of the ship and decommissioning of used fuel being sensitive features, complex safety analysis and compliance are principal factors driving up the cost of the technology. Moreover, financing this technology implies that the initial cost of the on-board plant is paid up front (including the nuclear fuel).

While no broad uptake is expected for nuclear fuels in the short-term, some safer and less risky nuclear fuels could be considered for propulsion in the long run. So-called molten salt reactors fuelled with thorium are one option.[2] Thorium reactors are considered safer and have a lower proliferation risk than traditional naval reactors fuelled with highly enriched uranium, although commercial use would require considerable R&D investment (World Nuclear Association, 2017). Thorium-based reactors, depending on their configuration, may only produce some 3% of the high level waste developed by current nuclear reactors (Royal Academy on Engineering, 2013). However, there is a lack of clear drivers and economic incentives to the deployment of thorium fuels and only a few industrial projects are being considered in this direction. Such projects face a very high capital cost and very little public support. The prospects for industrial use before 2050 are therefore relatively limited (OECD, 2015). While there has been almost no public investment in this domain since the 1970s, interest from governments and researchers is slowly rising again. In late 2017, the Chinese government has decided to spend USD 3.3 billion on two prototype molten salt nuclear reactors, which will be developed for use in aircraft carriers, drones and military aircrafts, as well as a potential commercial use in the future (Chen, 2017).

Measures included in our modelling

Our modelling includes the main measures described above, but not all of them. Table 5 provides an overview of different technologies, operational measures and alternative fuels that are included in our modelling exercise. We take the technological, operational and alternative fuels measures that are assessed in the UMAS study (Smith et al., 2016) as the base input for our modelling study and add several relevant additional measures, such as ship size and port-ship interfaces. The technological measures listed in the table do not represent an exhaustive set of measures. A full set of these measures and their assessments can be found in the appendix of the study by UMAS (Smith et al., 2016).

Table 5. **Main types of measures to reduce shipping's carbon emissions**

Type of measures	Main measures
Technological (based on Smith et al., 2016)	Contra rotating propeller, Air lubrication, Main engine turbo compounding propeller, Aux turbo compounding series, Organic Rankine Cycle WHRS, Flettner rotors, kites, Engine derating, Speed control of pumps and fans, Block coefficient improvement
Operational	Lower speeds, ship size increase, ship-port interface
Alternative fuels/energy	Liquefied natural gas (LNG), Advanced biofuels, hydrogen, ammonia, electric ships, wind assistance

Decarbonisation pathways: which combination of measures?

The previous sections provided an overview of the possible measures to reduce CO_2 emissions from international shipping. While the individual measures can deliver a significant reduction on CO_2 emissions, it is unlikely that one single measure on its own would be the most cost-effective way to achieve decarbonisation of shipping by 2035: a combination of measures would be needed, which generate different decarbonisation pathways. This section sets out these possible pathways to decarbonise international shipping by 2035.

The implementation of one measure might be incompatible with other measures. This is especially the case for the possible technologies that can be combined in a particular ship, for instance between different wind and solar technologies. More detailed information on the possible combination of technologies that can be installed on a ship is provided in a compatibility matrix by Smith et al. (2016).

To estimate the carbon emissions for both baseline and adjusted demand scenarios, we use the carbon intensity data obtained from UMAS (Smith et al., 2016), Lloyd's Register study (Lloyd's Register, 2017) and the 3rd IMO GHG study. Specifically, we use ships' carbon intensity evolution of scenario 2 from the study by UMAS and Lloyd's Register for 3 major ship types (container, tanker, bulk) and we use IMO data for other ship types such as roll on-roll off-ships (RoRo). The carbon intensity trajectory is used in combination with ITF transport demand projection to compute CO_2 emissions for the baseline. This scenario reflects the relevant trends in ship's efficiency improvements, which already take into account the impact of the EEDI regulation, but not any of the measures listed in Table 5. Appendix A provides a more detailed overview for this computation.

The projections for the possible decarbonisation pathways are based on the results of the Whole Ship Model that is reported by Smith et al. (2016). Specifically, we use the table that provides the reduction in ships' carbon intensity associated with the application of operational, technological and alternative fuel measures as the starting point that form the input of our modelling exercise. Furthermore, we studied the impact of additional operational and alternative fuels measures such as those listed in the table 5 above on the possible further reduction of ship's carbon intensity. In this way, we focus on the reduction in carbon intensity levels (EEOI) that can be achieved by combining all possible technical, operational, and alternative fuel measures without explicitly considering the cost-effectiveness of the measures. In order to estimate the impact of the individual additional measures, we apply the "ASIF" (Activity, Structure, Intensity, Emission Factor) framework (Schipper and Marie 1999; Schipper, Gorham and Marie 2000), inspired by the implementation of this framework in IEA's Mobility Model (IEA, 2017). The relevant data required to apply this approach, such as ships' energy intensity, fuel mix, ships' load factor, emission factors for different fuel types, are obtained from UMAS (Smith et al., 2016) and IEA (IEA, 2017). Furthermore, we do not include the dynamic feedback that might exist between measures, due to their interactions. This allows us to assess the maximally possible carbon emission reductions by 2035. The commercial viability of these pathways will be considered in the next chapter.

Different pathways to reach carbon emission reductions can be constructed by combining the operational, technical and the use of alternative fuel measures at different times and degrees. On the operational side, we consider speed reduction as a major measure that can reduce carbon intensity of ships. We consider two possible alternatives for implementing speed reduction: moderate and maximum speed reduction. Moderate speed reduction implies a reduction of 6% (for container ships) and 9% (for tankers and bulk carriers) of the standard operational speed for different ship types, which was assumed to be 12.8 knots for bulk carriers and tankers and 18.4 knots for container ships, in line with the study by Smith et al. (2016).

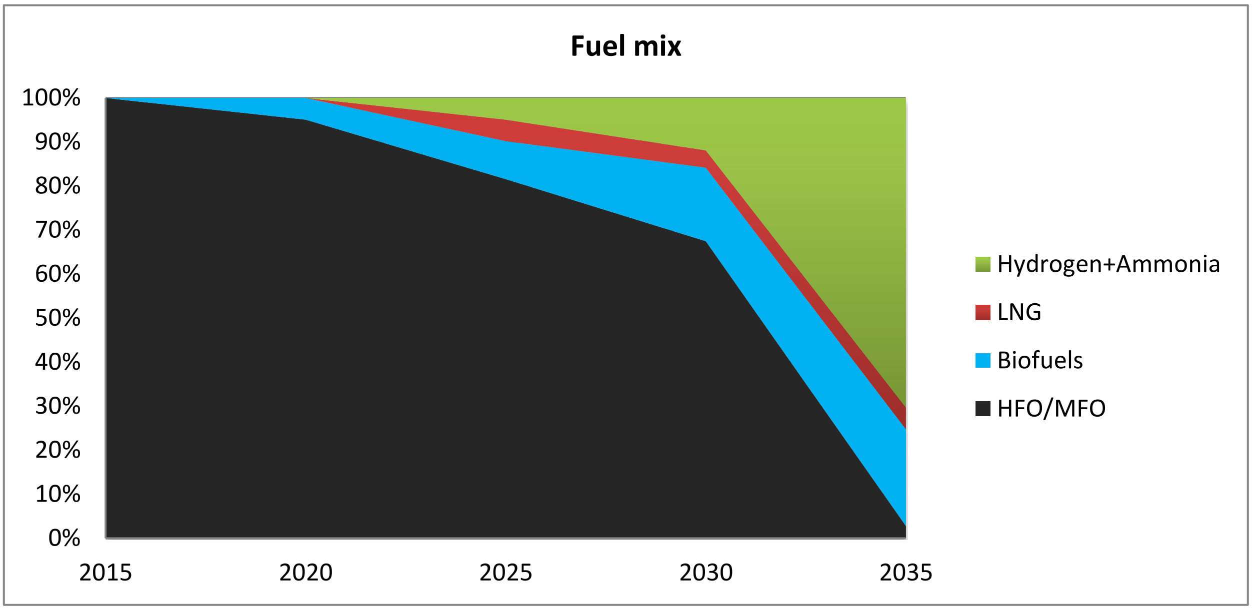
In the case of maximum speed reduction, we consider a strong speed reduction that is technically possible, which is 26% (for container ships) and 30% (for tankers) and 65% (for bulk carriers) of the standard operational speed. Even though it is technically possible to attain such low operating speeds, navigators will prioritise safety and manoeuvrability, e.g. operating with higher speed in difficult weather conditions. Another operational measure that has been integrated in this modelling framework is optimised ship-berth planning. This relatively low-cost measure is aimed at reducing the waiting time of ships at port before berthing. According to our estimation, this measure could deliver around 1% reduction of the total CO_2 emissions. We assume that the operational measures, especially speed reductions, could be implemented from 2020 onwards to yield maximum potential by 2030, which would require decision making by 2018.

In terms of technical measures, we apply maximum ship design specifications that can lead to the highest reduction in ship's carbon intensity, taking into account the speed reduction measures described above. This maximum specification entails the implementation of a series of technologies encompassing ship engine design and hydrodynamic improvements that can increase a ship's energy efficiency as described in Smith et al. (2016). This pathway includes a range of technological measures such as wind assistance and block coefficient improvements to reduce resistance in which case can help delivering higher CO_2 reduction (up to 30%). When speed reduction is implemented, the energy efficiency savings gained from measures such as block coefficient and wind assistance will diminish. We take this interaction into account and assume that the increase in energy efficiency will be taking place gradually (in linear fashion) between 2020 and 2035, which would require decision-making in 2018.

Furthermore, we also apply two additional measures: the uptake of electric ships and Onshore Power Supply (OPS). We include a scenario in which the pace of innovation in battery technology will sharply reduce battery costs, which could drive electrification of around 10% by 2035. Most of these electric ships will be used to serve international short-distance shipments between countries. In such a scenario the penetration rate of electric ships is assumed to see a gradual increase from 1% in 2025 to 10% in 2035. The second additional measure is Onshore Power Supply (OPS) which can help to reduce the carbon emissions from ships at berth during the loading and unloading process. OPS is already fairly widely used and is likely to be expanded due to favourable regulation, e.g. in the European Union where it will become mandatory by 2025 for European "core ports". As OPS could also be used as charging facilities for electric ships, we assume that uptake of electric ships and OPS go hand in hand. This would be facilitated by a market-based mechanism to commence by 2025.

Three different levels of reduction in the fuel carbon factor are considered as possible pathways: 50%, 75%, and 80%. While the first two are taken from Smith et al. (2016), the third reduction level is estimated by taking into account the uptake of potential alternative fuel such as ammonia. The level of carbon factor reduction presented here indicates the average reduction in carbon content of the fuel (gram of carbon dioxide per mega-joule of energy) that can be achieved due to the use of alternative fuels compared to the baseline. As such, high carbon factor reduction here is used to indicate high uptake of alternative fuels such as advanced biofuels, hydrogen, and ammonia. In the case of 80% carbon factor reduction, it is assumed that hydrogen and ammonia will form around 70% of the mix of ship. This, along with the increase in the uptake of biofuels (22%) and LNG (5%), could diminish the use of oil-based fossil fuels significantly to around 3% by 2035 (Figure 9).[3] While the gradual increase in uptake of these fuels starts from 2015, zero-carbon alternative fuels such as hydrogen and ammonia are expected to see a stronger uptake after 2025, when we assume the adoption of a market-based measure. We assume that this high uptake could be possible via a low-carbon fuel standard or carbon pricing.

Figure 9. **Fuel mix evolution between 2015-2035 for 80% carbon factor reduction**



Another measure that is included in this pathway is the increase in ship size that will lead to higher ship capacity. Unlike other measures which might require additional incentives and stimulus, the changes in ship size already form part of the shipping industry's strategy to seize economies of scale. We assume that the trend of ship size increases over 1996-2015 (per different ship types) and can be extrapolated towards 2035.[4]

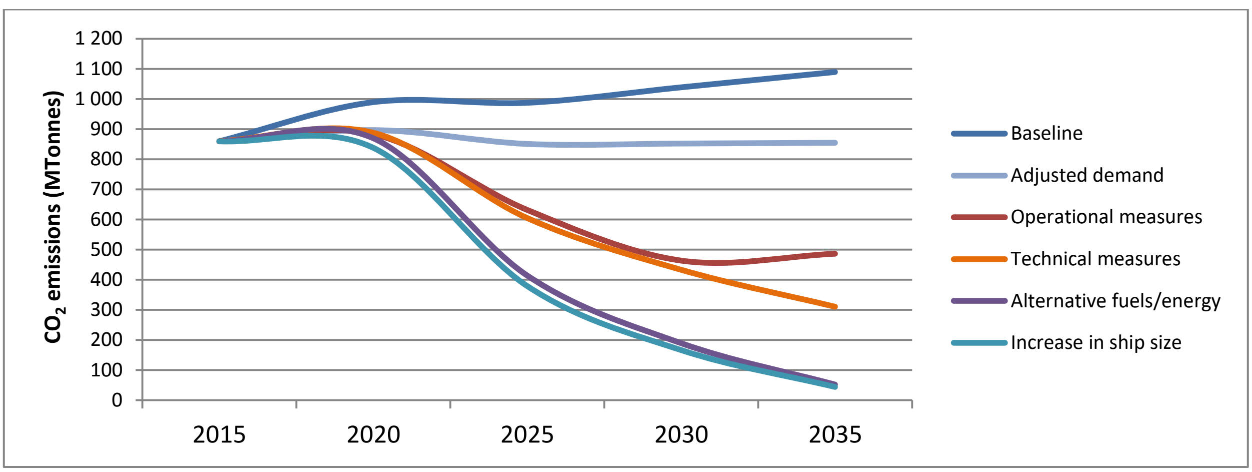
We consider four different pathways based on the possible combinations of the measures considered in this study (Table 6). All pathways assume maximum application of the possible technical measures. The main differences between the pathways are related to speed reductions (moderate or maximum) and the application of zero-carbon fuels and electric ships, ranging from very high to more moderate assumptions.

Table 6. **Four potential decarbonisation pathways and their components**

Pathway	Operational measures	Technical measures	Carbon factor reduction due to alternative fuels	Electric ship penetration
"Maximum intervention"	Maximum	Maximum	80%	10%
"Zero-carbon technology"	Moderate	Maximum	80%	10%
"Ultra-slow operation"	Maximum	Maximum	50%	-
"Low-carbon technology"	Moderate	Maximum	75%	-

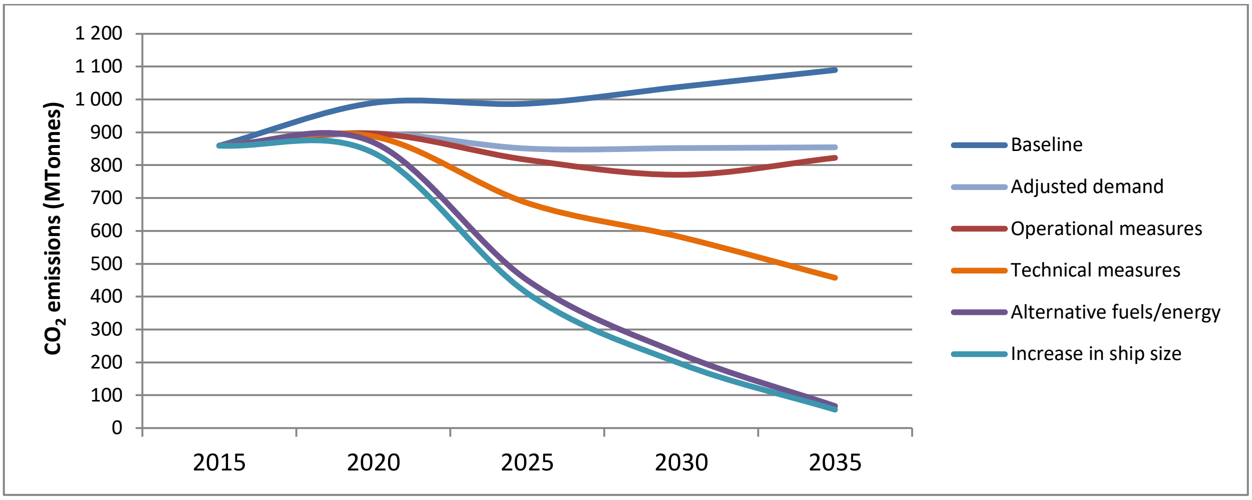
The "maximum intervention" pathway represents the most ambitious reduction trajectory to reach zero emissions, where maximum speed reduction will be implemented starting from 2020 and reaching its maximum reduction level by 2030, while the other measures such as energy efficiency improvements and zero-carbon fuels are implemented gradually (Figure 10). If we disregard the possible negative impact on international trade (such as increased time to transport goods), drastic speed reduction could reduce CO_2 emissions by 43% by 2030. However, the effect of speed reduction alone is not going to be sufficient to reach zero carbon emissions by 2035. The estimated growth in international trade will offset the reduction impact of this measure starting by 2030. On the other hand, the application of technical measures will help to maintain a downward trend in the emissions between 2030 and 2035. The additional reduction that can be delivered by energy-saving technologies will be relatively low when the ship is operating with ultra-low speed. The increase in ship size together with the application of zero-carbon fuels, especially from 2025 onward, will help to reduce CO_2 emissions further by 95% from the adjusted demand level, which leads to remaining emissions of 44 million tonnes by 2035. However, to achieve this level of decarbonisation by 2035, zero-carbon fuels such as hydrogen, ammonia will have to see a rapid uptake and constitute the majority of the fuel mix by 2035 (more than 70%). Additionally, we assume that electric ships could constitute around 10% of the global ship fleet by 2035, which contributes to the reduction in the total CO_2 emissions.

Figure 10. **"Maximum intervention" pathway**



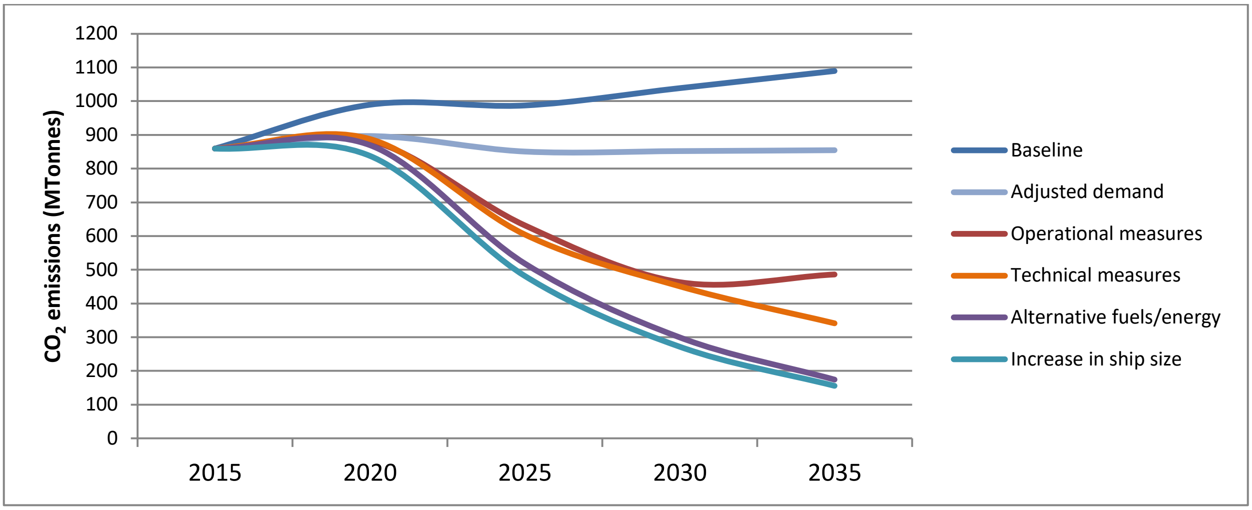
The "zero-carbon technology" pathway is as ambitious as the previous scenario with regards to zero-carbon technologies but assumes only a moderate speed reduction that helps to reduce emissions in the short run (Figure 11). Reducing speed will lower emissions by 4% in the short-term and the implementation of technical measures can help reducing the emission in medium to long term by 46%. Similar to the "maximum intervention" pathway, the use of electric ships and zero-carbon fuels will be the key measure to reach a 92% emission reduction by 2035. The combination of these measures will help to bring CO_2 emission levels down to 56 million tonnes, which is equivalent to a 93% emissions reduction from the adjusted demand level. Both the "maximum intervention" pathway and the "zero-carbon technology" pathway will allow a strong reduction in CO_2 emissions by 2035.

Figure 11. **"Zero-carbon technology" pathway**



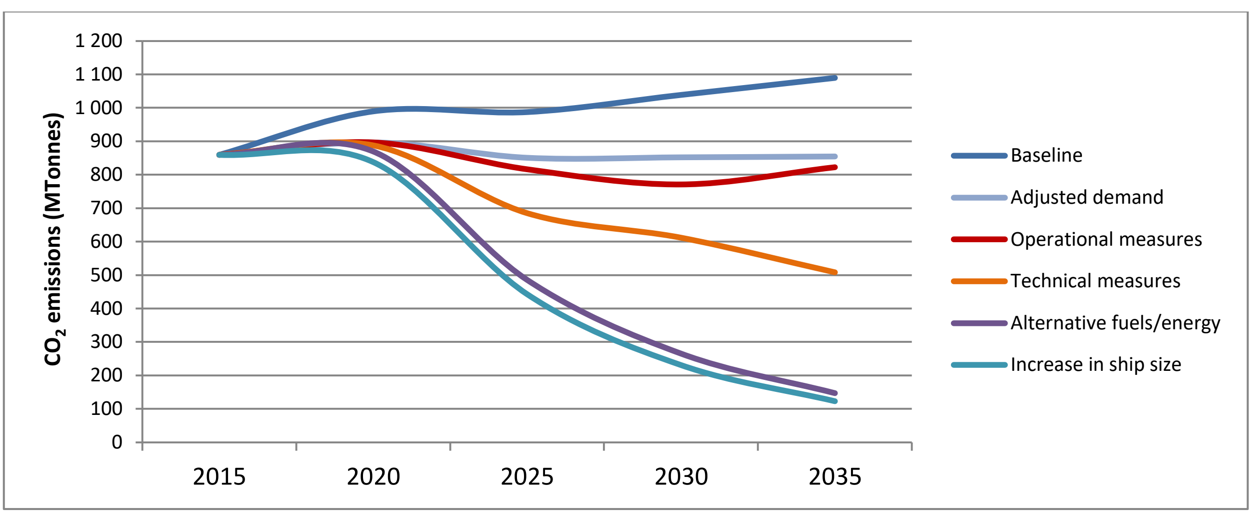
The "ultra-slow operation" pathway represents a scenario that relies heavily on speed reduction and sets a less ambitious target on energy-saving technologies and zero-carbon fuel adoption (Figure 12). The overall pattern of this pathway is similar to the "maximum intervention" pathway where most of the reduction comes from reducing speed drastically, which is followed by the gradual implementation of other measures. In this pathway, we assume that electric ships will fail to penetrate the global ship fleet and might serve only domestic purposes. The uptake of zero-carbon fuels in this scenario is also foreseen to be less strong as in the other pathways, which could reflect insufficient investments and commitments to ensure sufficient availability of biofuels, hydrogen, and ammonia to replace the conventional fuels. This pathway would lead to 82% emissions reduction from the adjusted demand level to reach around 156 million tonnes in 2035.

Figure 12. **"Ultra-slow operation" pathway**



The "low-carbon technology" pathway represents a scenario that aims to balance moderate speed reductions with the use of zero-carbon fuels. This scenario reflects a strong uptake in zero-carbon fuels in the medium to long term, but with a less optimistic view on the penetration rate of electric ships and the uptake of ammonia. With the application of moderate speed reductions, the overall trajectory of this pathway resembles that of the "zero-carbon technologies" pathway, with a less rapid emissions decline to 2035 (Figure 13). This pathway will result in an 86% reduction of CO_2 emissions from the adjusted demand level, reaching 123 million tonnes by 2035.

Figure 13. **"Low-carbon technology" pathway**



In conclusion, we have assumed four different pathways that could lead to the decarbonisation of maritime transport with CO_2 emissions approaching zero by 2035, with remaining shipping emissions ranging from 44 to 156 million tonnes by 2035 (Figure 14). These pathways demonstrate that targeted interventions using combination of possible measures can reduce CO_2 emissions from international shipping between 82% ("ultra-slow operation") to 95% ("maximum intervention") from the adjusted demand level. Table 7 presents the total CO_2 emissions reduction for the four pathways by 2035. At the aggregate level, it is observable that two similar initial trajectories can be distinguished based on the application of speed reduction measures in the short term. The "maximum intervention" and "ultra-slow operation" pathways represent an extreme reduction in speed, while the "zero-carbon" and "low carbon technology" pathways represent a more moderate speed reduction. Furthermore, the level of decarbonisation in these pathways by 2035 depends on the extent to which zero-carbon fuels and technologies are applied. As demonstrated by the nearly-zero-carbon pathways ("maximum intervention" and "zero-carbon technology"), the use of zero-carbon fuels and technology is indispensable to achieve full decarbonisation.

Figure 14. **Four different decarbonisation pathways for shipping**

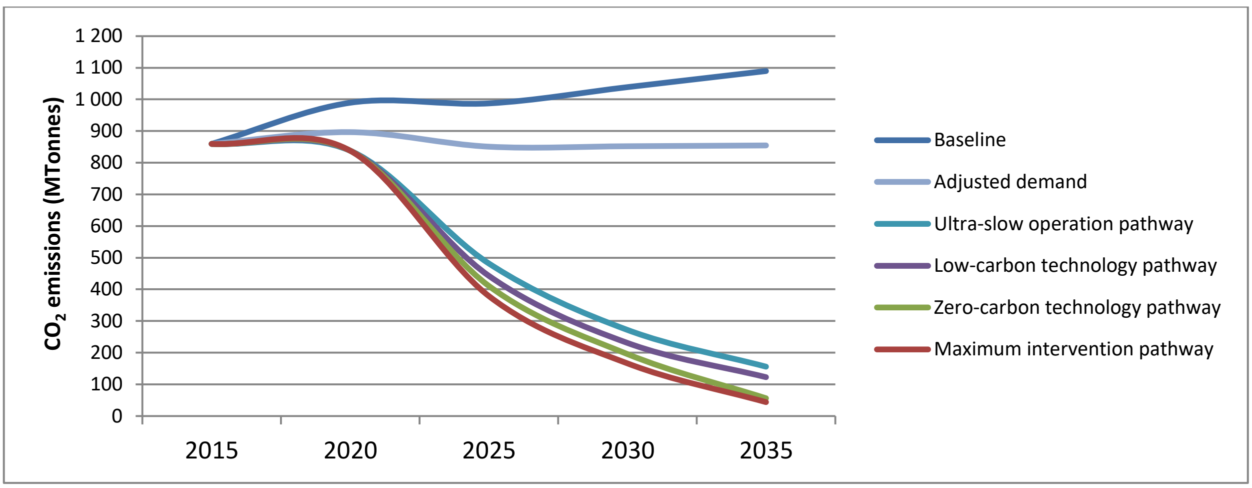


Table 7. **Total CO_2 emissions reduction by 2035 for the four decarbonisation pathways**

Pathways	CO_2 reduction (in million tonnes)	Reduction percentage (%)
Maximum intervention	810	95
Zero-carbon technology	798	93
Ultra-slow operation	698	82
Low-carbon technology	731	86

Decarbonisation by 2035: Under which conditions?

Decarbonisation of maritime transport should be technically possible by 2035, as shown in the previous chapter, but what would be needed to realise it? This chapter spells out the drivers and barriers of decarbonisation and the conditions under which it could be achieved. One of these conditions is strong financial incentives, such as carbon pricing. The chapter concludes with implications for regulation.

Market forces driving decarbonisation

The vision of a trade-off between environment and competitiveness has been blurred over the recent years. Several actors in the industry have identified economic advantages in adopting more energy efficient technologies and are able to shift constraints through innovation. Furthermore, an increasing number of shippers have been demanding higher environmental standards in sea transportation, and charterers, insurers and investors might become more and more risk adverse with regards to stranded carbon assets, in line with the emerging consciousness on stranded assets in the wider economy.

Technology push and the business case for zero-carbon shipping

Fuel cost savings are an essential motivation for implementing technical measures and other eco-innovations. Studies have shown that current levels of energy efficiency have not been driven by regulations, but rather by market conditions and fuel costs (Smith et al., 2016; Faber et al., 2015). Furthermore, while some companies have considered the necessity of CO_2 reductions an annoying cost or postponable threat, others have proactively engaged in the development of greener technologies and identified a clear business case for doing so. Combined with a perceived likelihood for future regulation, it can have an even stronger effect, as announcements for stricter regulation reduce the uncertainty that investments to address environmental impacts will be profitable. Greater certainty encourages investment and regulation, which then creates pressure that motivates innovation (Porter, 1995).

Applying emerging technologies in the maritime industry creates new business opportunities. Norwegian companies for example aim to acquire a first-mover advantage in developing autonomous all-electric cargo vessels. The development of the cargo ship Yara Birkeland is a collaboration between the Norwegian agricultural company Yara, maritime technology firm Kongsberg, DNV GL, Marin Teknikk naval design, test laboratory SINTEF Ocean, and Norwegian maritime authorities. First testing and operations are expected in early 2019, and fully autonomous operations are supposed to start in 2020. Chinese ambitions in the clean tech-sector are also driving some of their innovative initiatives in shipping, such as the development of a full-electric inland barge.

Other companies whose main activities are based on onshore applications are moving into the shipping sector to offer propulsion technology on a different scale. ABB, the Swiss-Swedish conglomerate, is expanding its activities in electrification, robotics and industrial automation towards uses in the maritime segment, particularly in hybrid propulsion and optimised efficiency of electrical power systems and fuel cells. Operating between Helsingborg in Sweden and Helsingør in Denmark, the HH Ferries Tycho Brahe and Aurora are powered with battery technology from ABB and supplied by automated shore-side charging stations using an industrial robot (Box 2).

Box 2. **Electric ferry between Sweden and Denmark**

The project consists of both converting two diesel-electric HH Ferries (Tycho Brahe and Aurora) into the world's largest fully electric ferries to date and equipping the ports of Helsingør (Denmark) and Helsingborg (Sweden) with the first automated shore-side charging arms. The ferries operate on a 4-kilometre long route and can accommodate 1 100 and 1 250 passengers and 240 cars respectively, sailing around the clock, with an average journey time of 20 minutes. The investment amounts to SEK 300 million and the EU's INEA (Executive Agency for Innovation and Network) has provided a grant of SEK 120 million to the project, the rest being funded by HH Ferries. The Swedish-Swiss conglomerate ABB was in charge of supplying the complete power and propulsion systems. At both ends of the route ABB also supplied the automated shore-side charging stations using an ABB industrial robot, to optimise the connection time and therefore maximise the charging period. PBES designed the energy storage system to be integrated within ABB's solutions.

The project was successfully developed with the Tycho Brahe tested to start operations in mid-2017 and the Aurora to follow later in 2017. The two ships are the largest 100% electricly-powered Ro-Pax ships in the world. Both are hybrid: diesel-electric with the diesel engine from Wärtsilä as a backup for the electric engine. It is supplied by 640 lithium batteries placed in four 32-foot containers on top of the vessel between the two chimneys. The combined battery power of 8 320 kWh (4 610 kWh each) for the two ferries is the equivalent of 10 700 car batteries. The batteries must be charged with approximately 1 200 kWh every time the ferries are at port. This requires both automated charging and a unique cooling system for the lithium batteries. In Helsingør they have 5.5 minutes and in Helsingborg nine minutes to charge which is why the charging process has been fully automated in order to save time. The energy storage system embedded with a liquid cooling system is meant to provide a higher level of safety for customers and the ships have also been modernised to include energy storage control systems and on-board DC grid technology. The thermal management system constantly maintains optimal internal temperatures to maximise the lifespan of the battery.

Source: ITF (2018a)

A different case is the LNG industry, which, faced with oversupply, is pushing the development of LNG as a bunkering fuel for ships. Some major LNG importers such as Japan are currently seeking new revenue sources related to LNG by developing the necessary bunkering infrastructure (ITF, 2018c). Technology push has also been observed in the biofuels sector. The Finnish firm UPM uses wood residues for making biofuels by treating crude tall oil, a waste from pulp production. The company has formed a partnership with Wärtsilä for engine tests and Boskalis, a dredging company, has used their biofuel blends for their dredging vessel EDAX in the Netherlands.

Shippers greening their supply chains

Shippers (cargo owners) increasingly ask for higher environmental performance. Based on consumer demand, reputation concerns and pressure from investors, regulators or NGOs, cargo owners have developed strategies to green their supply chains and increasingly monitor their carbon emissions. It is part of a greater awareness and willingness to reduce pollution, waste, and the risk of hazards and spills. This trend has increased in recent years, as evidenced by the creation of a number of industry initiatives. Beside compliance concerns, industry actors also expect to increase their visibility and see a competitive advantage by showcasing transparency on performance. Voluntarily adopting higher standards and eco-innovations in many cases also represent a first-mover advantage for firms, which have been well documented in a range of industry sectors (Porter, 1995).

Demand-side factors also play a role. In an oversupplied market, a ship might not be chartered in the first place if it has low energy efficiency levels. For instance, 25% of shippers in the dry bulk and wet bulk market use the RightShip GHG emissions rating although a clear effect of a use of more A-B rated ships across the global fleet has not been observed yet. There is a range of other initiatives, such as the Sustainable Shipping Initiative (SSI), the Clean Cargo Working Group (CCWG), Green Marine, Green Ship of the Future, Shippingefficiency.org, and the Clean Shipping Project. The Clean Cargo Working Group (CCWG) has 45 members including various large multinational shippers and about 85% of the container carriers. The Group releases yearly environmental performance data of the member carriers verified by third parties, which aims to help shippers review and compare their environmental performance when reporting and making logistics procurement decisions. The United States Environmental Protection Agency (EPA) has developed a similar approach to assess carriers' environmental performance. Their programme SmartWay produces a ranking each year to inform shippers and freight forwarders. Smart Freight Centre established a group of industry stakeholders, experts, governments and others, called the Global Logistics Emissions Council (GLEC), in order to harmonise emissions accounting and consistent data collection.

Corporate responsibility initiatives are particularly advanced in countries such as Sweden (ITF, 2018a). Many of Swedish leading companies, such as Volvo, IKEA, H&M and Tetra have formulated targets to reduce their carbon footprint. This ambition also covers the decarbonisation of their supply chains and the transport movements that are related to these. Various large shippers monitor the CO_2 emissions related to the transport activities for which they are responsible. Some large Swedish shippers have been driving the development of the Clean Shipping Index (CSI). The CSI is an online tool that provides a rating to each registered ship based on a range of environmental criteria to compare vessels' environmental performance (Box 3). Carbon emissions from shipping will become more important to shippers with target dates for their zero carbon footprints approaching.

Box 3. **Clean Shipping Index**

The Clean Shipping Index (CSI) was introduced in 2007 by the shipping industry and shippers in Gothenburg and western Sweden. The CSI is an online tool that provides a rating to each registered ship based on a range of environmental criteria to compare vessels' environmental performance. The scheme enables shipping companies and shippers to gain recognition for their environmental performance but also to secure economic opportunities on that basis. It is operated by the Clean Shipping Network which is composed of companies from a variety of sectors that make sure it develops and is applied properly. Members of the network are charged EUR 2 700 and meet several times per year to discuss strategic orientations and a full-time secretariat handles the daily operation and administration of the index.

The CSI is mainly directed at shippers and carriers, not as much to ports. As of 2017, 31 cargo owners (among which companies such as H&M, Philips, Volvo, Tetra Laval) are registered as well as 56 shipping companies with over 2 200 ships having a CSI rating. Companies from around the world use it though most remain based in Europe. Banks and investors can also use the rating to assess environmental performance when approving loans for the building of new ships. Though the scheme was not designed specifically as a tool for ports to develop incentive schemes, some do provide discounts on its base: the Port of Gothenburg in Sweden, the ports of Vancouver and Prince Rupert in Canada. The Swedish Maritime Administration will also use it to environmentally differentiate the national fairway dues from 2018 onwards.

Ship-owners have to answer a set of 25 questions about their operational environmental impacts that relate to five environmental impact categories: NO_x, SO_x and PM, CO_2, chemicals, water and waste. Information is recorded on a ship-by-ship basis and aggregated to a total carrier fleet score to determine average ratings per ship owner as well (also weighted in function of the number of registered ships). Third-party verification by accredited Classification Societies (such as DNV-GL, Bureau Veritas, Lloyd's Register) is required that for at least two vessels per carrier. Ship-owners bear theses costs themselves, as well as the ones related to providing data.

In 2017 a new scoring system was introduced. The CSI now gives each registered ship a rating ranging between 1 (CSI 1) and 5 (CSI 5) stars based on a number of points achieved. A total 150 points can be obtained with a maximum of 30 points for each of the environmental impact categories. The scheme is designed in such a way that ships only obtain points by going beyond existing IMO requirements.

- NO_x scores calculated based on how NO_x emissions from main and auxiliary engines relate to the standards (Tier I to Tier III) as set in the revised IMO MARPOL Annex VI, with the exception that between Tier II and III, two extra levels (respectively NOx performance 30% or 40% below Tier II levels) are included to reward different NO_x reduction techniques. Both pre- and post-combustion reduction techniques are rewarded and in case OPS is installed and used at all equipped ports a maximum score for auxiliary engines is granted.

- For SO_x and PM, the basis for scoring is the average SO_x content in fuels for main and auxiliary engines used during a running year (or the measured PM emissions for PM only). Scores can be obtained if the SO_x content in fuel, or in the treated exhaust gases, is lower than the global (IMO) standards for both main and auxiliary engines. Extra points are awarded to ships for using low-sulfur fuel in main engines, auxiliary engines, and/or boilers when navigating in port areas outside ECAs.

- For CO_2 emissions, scores are calculated by how well a vessel performs compared to a reference ship; the better it does, the higher the CSI score granted. Information required is the cargo carried, the distance travelled and the fuel consumption over 12 months. Operational factors are accounted for through estimates of engine load and payload factors. Depending on ship types there are several options for submitting CO_2 data: in grams/tonne-nm, in grams/passenger-nm for cruise and passenger ships and in grammes per year/(transport work for freight + 0.7 × transport work for passengers) for Ro-Pax ships according to IMO's EEOI Guidelines; in grammes/TEU-km for container vessels according to the calculation formula of the Clean Cargo Working Group.

Source: ITF (2018a)

Avoiding stranded assets

Currently, there is a risk premium to implement innovative technologies and ship-owners therefore face high barriers to upgrade to a more energy efficient fleet. Ship-owners need to convince financiers that the additional costs of greener technology will be recovered. A study by UMAS and Carbon War Room (2017) looked at implications of climate mitigation policies for ship-owners and financiers under different market conditions and identified several actions that would need to be taken to understand and manage these risks. This could include for example integrating risks associated to evolving climate regulations into financing decisions and identifying opportunities that environmentally responsible investments represent for financiers, for instance a substantial expected demand for capital for vessel modifications.

There is a growing awareness on fossil fuel-related stranded assets, that is: assets that have lost their value more quickly than foreseen due to the declining attractiveness of fossil fuels within the light of climate change agreements. Such a risk would translate into more difficulties to finance ships powered by fossil fuels, as banks and financial institutes will ask a risk premium to provide for the eventuality that their loans for these ships become worthless. Although the general awareness amongst shipping financiers of climate-related stranded asset risks is rising, only very few are actively managing those risks (Mitchell and Rehmatulla, 2015). In the longer term however, the conditions for loans for zero-carbon ships could become more favourable than for ships powered on fossil fuels, considering their risk to become stranded assets once stricter regulation is enforced.

Confronting climate risks in ports and port-cities

Climate change will increasingly affect fixed assets and infrastructure, especially at ports and in port-cities. Coastal zones are particularly vulnerable to sea-level rise and extreme weather conditions such as storms and high waves. Extreme hazards and rising sea levels can negatively impact the provision of goods and services in coastal zones through events such as storm surge and associated flooding, submergence, salt-water intrusion and coastal erosion. In ports, financial risks are associated with severe climate effects on ship movements causing disruptions or delays in operation, and even land and capital loss under extreme circumstances. According to OECD (2015) estimates, South and South East Asia will be the most affected by sea level rise, with highest impacts in India, and other developing countries in the region. Hanson et al. (2011) estimated the monetary value of assets exposed to a 1 in 100 year extreme water level to be USD 3 000 billion globally (assuming strongly growing asset exposure in the future), with the highest asset value at risk located in Asia. The importance in global trade of the biggest port cities implies that failure to develop effective adaptation and mitigation strategies would inevitably have local, national and wider economic repercussions. Ports and supply chains make strong economic contributions, and hence, inaction would be paid by a wide range of sectors of the economy. In addition to these, ports and port-cities often face high levels of pollution from shipping (ITF, 2014).

Citizens in port-cities have become increasingly vocal on the impacts of shipping. In Venice this took the form of vocal opposition against the visible and environmental impacts of very large cruise vessels (ITF, 2016). In Vancouver there is considerable local opposition against the port’s coal terminals and the related traffic of coal carriers. In several port-cities, concerns about local air pollution have pushed local port administrations to develop policies on pollution mitigation. A significant part of ports is controlled by local governments (ITF, 2017), so most citizens can actually have a direct influence on the direction of their port via their local government representatives.

As a result, ports have become more active stakeholders in mitigating climate change. Not only do ports increasingly adapt to climate change and invest in the protection of vulnerable infrastructure; they have also started to play a more fundamental role to pressure shipping companies towards decarbonisation pathways through the use of incentives. An increasing number of ships and ports are covered by green port fees and similar schemes. Green berth allocation policies, green procurement and carbon pricing schemes have also been applied in some ports (ITF, 2018b). Recognising their responsibility to contribute to the reduction of GHG emissions, fifty-five of the world’s key ports have founded the World Ports Climate Initiative, which has tried to develop port strategies to reduce GHG emissions and to facilitate good practices related to climate change mitigation.

Potential market failures and barriers

If complying with environmental regulation can be profitable, in the sense that a company can more than offset the cost of energy efficient technologies, then why would further regulation be necessary? The answer is that certain conditions prevent firms to take optimal choices: there is a range of market barriers and market failures – highlighted in this section - that lead to a delay in adoption of technologies with a higher environmental performance.

Sunk costs and path dependence

The average life of a ship is approximately 25 years, which means that a significant share of current ships will still be in operation by 2035. Even if all ship-owners would from now on order zero-emission vessels, there would still be a considerable share of ships that would not be zero-emission. Decarbonisation of the sector will depend to an important extent on the level of fleet renewal that is possible, which depends on the extent of scrappage of old vessels and the capacity to retrofit existing vessels. So, there are sunk costs that cannot be ignored. The potential for fleet renewal is larger if maritime trade is expanding and could also be subject to policy interventions to speed up the process and mitigate excessive economic harm that sudden changes could cause.

Significant use of the CO_2 mitigation measures also assumes sufficient adaptation of infrastructure and production capabilities to future demand of alternative fuels and energy that might not take place immediately, considering the path dependence in the shipping sector. Choices made on the basis of temporary conditions can persist long after these conditions change, especially when the capital has a high life span. This durability of invested capital makes major changes particularly impractical and costly. Examples of far-reaching adaptations that might be needed include the wider energy infrastructure and production capabilities related to advanced biofuels, hydrogen, ammonia and other zero-carbon fuels. In addition, ships would require the relevant facilities for bunkering and energy provision, e.g. charging systems for electric ships. There might be two distinctive concerns in this respect: first, concerns about the maximum supply potential within a given time period (e.g of advanced biofuels); and second, how to reach sufficient scale for measures to become commercially viable, e.g. with regards to hydrogen and electric ships.

Carbon emissions as negative externality: the climate as unpriced public good

A negative externality arises when an individual or a firm takes an action but does not bear the costs imposed on a third party. In the case of the shipping industry, pollution imposes health, environmental and economic costs on the whole society without bearing the cost of it. Since costs are never borne entirely by the emitters and they are not obliged to compensate those who lose out because of climate change, they face little or no economic incentive to reduce emissions. Human-induced climate change and associated GHG emissions have been described as the greatest market failure in history (Stern, 2006). A particular challenge with this “market failure” is the uncertainty about the exact size, timing and location of the effects on environment, society and the economy. Furthermore, climate change is a global phenomenon in both its causes and consequences and is therefore politically extremely challenging to address.

Climate change risks are clearly not internalised in the price of maritime transport, especially since ship fuel is not taxed, in contrast for example to fuels for the road sector. Taxing fuels would be a way to internalise the externalities of carbon emissions. This lack of taxation is also hampering the uptake of alternative ways to power ships: heavy fuel oil (HFO) for ships is not taxed but generates huge negative externalities, whereas some of the alternative energy sources (e.g. electricity) with much less of these externalities are actually taxed. This complicates a massive transition from HFO to alternative technologies and fuels.

Split incentives

Split incentives represent a type of principal-agent problem and occur when participants in an economic transaction do not have the same priorities and incentives. A classic example is the split incentive between charterer and ship-owner in the time charter market, where the ship-owner provides a vessel, but the fuel costs are borne by the charterer as part of the operational costs. The difference between the actual level of energy efficiency and the higher level that would be cost-effective from the firm’s point of view is often referred to as the efficiency gap (IEA, 2007). Usually, minimising the capital cost of the vessel, the ship-owner does not have an incentive to choose the most energy efficient technology, which often leads to suboptimal investment choices.

Whether time charter is used depends on the shipping segment. They are most prevalent in the container and dry bulk sector where about 70% and 60% of ships respectively are run under time charter agreements whose duration mostly does not exceed one year, which is too short to amortise green investments (Rehmatulla et al., 2017). However, charterers may also decide to reward owners for their investments in clean technologies or engage in longer charter contracts to allow for a sufficient payback time for these technologies. For example, the LNG bunkering vessel Coralius from Sirius Shipping was facilitated by Skangas (part of the Finnish state-owned Gasum Group) who agreed to a 15-year charter agreement. Preem and ST1 were willing to engage in long-term charters making it possible for Terntankers to order LNG-powered vessels. Shippers have also been supportive as regards the conditions of charters. Preem agreed to pay higher charter rates to compensate for higher costs related to greener vessels (ITF, 2018a).

Imperfect information and information asymmetry

Imperfect, insufficient or incorrect information can cause firms to make suboptimal investments in energy efficiency. This type of market failure is particularly relevant in this case, as it contributes to preventing the uptake of greener technologies. Previous research has shown that the quality of knowledge and the level of technological know-how acquired through R&D activities are found to be vital for the diffusion of technologies (Constantini et al., 2014). There is however a shortage of detailed and audited performance data of new technical measures with a low market maturity, which acts as a barrier to their uptake. The lack of reliable information on performance in actual operating conditions then leads to a typical chicken-and-egg problem in which no firm is ready to adopt a technology – or no financier ready to finance a zero-carbon ship - because there is a lack of clear proof of its efficiency and commercial viability.

This deficiency can be explained by the wide array of factors that influence fuel consumption of ships, namely weather conditions, draught, machinery conditions or operational aspects, which lead to highly variable performance data even for a single ship. In some cases, ship-owners may have an incentive to make overly optimistic efficiency claims towards the charterer. Finally, the quality of measurement might also vary, although the industry is gradually shifting towards more frequent and reliable data collection methods, including continuous monitoring systems, which could potentially also discourage misrepresenting performance data (Rehmatulla et al., 2017). The shortage of fuel efficiency data under real operating conditions also highlights the considerable market failure of a suboptimal level of resources allocated to technological and scientific knowledge. Subsidies to R&D, or partnerships between government, research and industry would be a possible solution where this can produce more evidence supporting or discarding a certain technology, or develop alternative, non-incremental options.

The need for incentives

The barriers that prevent the market from spontaneously moving towards decarbonisation pathways might require incentives. The section below will cover different sorts of incentives that might help to increase the scalability of measures – overcoming sunk costs and path dependence – to internalise externalities and to increase transparency on potential effects of measures for the different maritime stakeholders. The section below will focus on carbon pricing, public and private finance.

Carbon pricing

Carbon pricing would be a way to incorporate the costs of shipping's carbon emissions into ship-owners' decision-making. Put differently: it would help to internalise negative externalities associated with carbon intensive shipping. This would make zero-carbon ships a more attractive option vis-à-vis conventional ships: some measures highlighted in this report will become commercially viable more quickly if accompanied by carbon pricing, or other measures, such as regulation, e.g. via low-fuel standards. This is especially the case if heavy fuel oil for ships would remain untaxed and alternatives (e.g. electricity for electric ships) would continue to be subject to taxation. So, carbon pricing would be one of the building blocks for achieving decarbonisation pathways. Lloyds Register and UMAS (2018) indicates that zero-emission ships using biofuels only become competitive (in comparison with conventional vessels) with carbon prices in the order of USD 250 per tonne. Synthetic fuel options, such as ammonia and hydrogen, would become competitive at a carbon price of approximately USD 500 per tonne in a low cost of capital scenario and slightly higher in a high cost of capital scenario.

Carbon pricing for shipping could take different forms. The two basic ways to implement carbon pricing are via a carbon tax or an emission trading scheme. Under a carbon tax, firms are taxed according to the amount of carbon that they emit. Under an emission trading scheme, each firm acquires emission rights; if it wants to emit more it would need to buy additional emission rights from other firms that would be willing to sell these rights and they emit less than they are allowed to. Common to both approaches is the incentive it gives to firms to reduce their carbon emissions: it becomes their interest to decarbonise. Since the 1990s a wide range of generic carbon pricing mechanisms have been introduced in dozens of countries.

Yet, it has proven difficult to reach international consensus on carbon pricing for shipping. Discussions within the IMO on market-based mechanisms – as carbon pricing is commonly called within the global shipping policy community - during the late 1990s resulted in political stalemate, due to fundamental differences over desired design, perceived economic impacts and potential use of revenues of the mechanism. In those discussions, both carbon taxes, emission trading schemes and hybrid forms were proposed, to no avail. Discussions on IMO's GHG Strategy and advances in fuel data collection provide a window of opportunity to re-open the discussion on carbon pricing in maritime transport, which would facilitate the realisation of a strong decarbonisation ambition.

A global carbon pricing mechanism for shipping would need to be delicately balanced in order to overcome the various concerns raised by different groups of countries and stakeholders. In order to be effective, it would need to be clearly linked to carbon emissions and to be simple in design and implementation. Possible adverse effects on country's trade, in particular for least developed countries and small island developing states, would need to be assessed and to some extent compensated for. A global carbon pricing mechanism for shipping could raise a substantial amount of revenues, part of which could be earmarked to stimulate further decarbonisation of the sector, e.g. via research and development.

Global application would mirror the global reach of the shipping sector and would create a "level playing field" in particular for ports, some of which might be affected by a lack of global coverage. However, a collection of regional and national mechanisms could also provide necessary incentives. China has introduced an emissions trading scheme in which shipping is involved (Box 4). At the EU level a proposal has been formulated to include shipping in the Emission Trading Scheme of the EU (EU-ETS) that will be implemented by 2023 if no comparable scheme at the global level would be introduced. The need for carbon pricing would be less imminent if strong standards would be developed. For example, low-carbon fuel standards could be developed for the shipping sector, similar to the fuel standards that have been developed for road transport in many countries.

Box 4. **Shanghai emission trading scheme**

Shanghai was the second Chinese region, after Shenzhen, to start a pilot ETS in 2013 as part of the step-by-step development of the China national ETS scheme. The pilot covers more than half of the city's emissions, sixteen sectors in total, including power, industrial and non-industrial sectors like building, aviation and shipping. 368 entities were liable as of 2016 and its coverage is expanding. The Shanghai Development and Reform Commission (DRC) regulates the scheme and the Shanghai Environment and Energy Exchange was designated as the trading platform. Companies are required to monitor and report their CO_2 emissions every year and to have it verified by a third-party. The DRC has developed released guidelines for monitoring and reporting per industry sectors included.

Shanghai is the only pilot region that includes the aviation and port sectors in its ETS. It is also the only pilot ETS region that adopted different inclusion thresholds for industrial and non-industrial sectors. The inclusion thresholds for transport companies are 10 000t CO_2/year (or 5 000 tce/year) for aviation and ports, and 100 000t CO_2/year or (50,000 tce/year) for shipping, considering both direct and indirect emissions. There are free allocations based on sector-specific benchmarks (power, heat, car glass manufacturers), historic emissions intensity (industry, aviation, ports, shipping, and water suppliers, generally based on 2013-15 data) or historic emissions (buildings and commercial sector, generally based on 2013-15 data).

Penalties for failing to submit emission reports or verification reports on time or providing fraudulent information range from EUR 1 309 to EUR 6 544 (CNY 10 000 to 50 000). Penalties for non-compliance range from EUR 6 544 to 13 088 (CNY 50 000 to 100 000). On top of the financial sanctions, further sanctions may be imposed. The system achieved full compliance for three years in a row. In 2016 Shanghai further expanded its ETS coverage. Assessment of the impacts it has had on each business sector still to be produced. There is no data on the overall GHG emissions per sector but the target of the scheme is to reduce the overall CO_2 emissions by 20.5% compared to 2015 levels (originally -19% in 2015 compared to 2010 levels) with an absolute cap of 155 million tonnes of CO_2 equivalents for 2016. The current price per tonne per CO_2 equivalent approximates USD 1.08.Initially, the seven Chinese pilot ETS were scheduled to end after three compliance years and be replaced by the national ETS in 2016. However, as the national ETS should start in second half of 2017, the pilots will continue operating until then and probably also beyond. Shanghai has indicated a second 3-year phase to run until 2018, with the announcement of the transition plan for the Shanghai Emissions Allowances (2013–15) to be banked to Phase II 2016–18 (ITF, 2018b).

Public finance

Public subsidies to shipping could be targeted to stimulate decarbonisation. Some countries explicitly subsidise their shipping sector. Although one could wonder why governments should subsidise a private sector, there might be arguments for temporary support to help sectors move from one pathway to another pathway. Subsidies could then help to create the critical mass needed to move shipping to a zero-carbon pathway. This support should be designed in such a way that it has an actual impact on moving towards decarbonisation, rather than being a disguised form of state aid.

Favourable tax treatment to shipping could be leveraged to decarbonise the sector. Various countries provide favourable tax treatment for their shipping sector, often in the form of tonnage taxes, a tax that uses fleet size rather than corporate income as a tax base. In exchange for this form of state aid, countries frequently ask their shipping corporations for guarantees with regards to seafarer training and employment for their nationals. Countries could also consider defining decarbonisation as one of the conditions for tonnage taxes. This could be coordinated by countries, for example at the EU level. Electric ships would be helped with exemptions from electricity taxes, similar as those provided in relation to onshore power supply for ships, e.g. in Sweden (Box 5).

Box 5. **Exemptions of electricity tax for onshore power supply**

Onshore power supply (OPS) in Sweden is exempted from the electricity tax that is applied for electricity uses that are not for business use, as it considers that ships using shore power does not constitute business use. These tax rates that should normally be paid are SEK 293 (EUR 33.94) per MWh or SEK 185 (EUR 21.43) per MWh in Northern Sweden. Instead, Swedish authorities apply SEK 50 (EUR 5.79) per MWh of electricity tax to shore-side electricity. So the reduction from the tax is about 98%. At the request of Sweden to provide an incentive for shipping companies to adapt ships and ports to develop shore power facilities, the European Union agreed to allow these exemptions on the grounds that it does not distort competition.

The Swedish authorities apply SEK 50 (EUR 5.79) per MWh of electricity tax to shore-side electricity. This tax rate is above the minimum rate of taxation for electricity as laid down in European Directive 2003/96/EC. Sweden will apply the reduced rate of electricity taxation to all supplies of shore-side electricity of at least 380 V to vessels used for commercial shipping of at least 400 gross tonnage. The limit is considered appropriate by the Swedish authorities so as to ensure that the absolute majority of vessels used in international traffic and larger vessels used in national traffic will be covered by the proposed reduction.

Source: ITF (2018a)

Country's development banks and sovereign wealth funds could also target decarbonisation of shipping. Some of these state-owned entities are active in ship finance, but not always explicitly promoting decarbonisation of shipping. Very recently, Norway's Government Pension Fund Global (GPFG) announced that they will introduce environmental requirements for their participations in the shipping sector.

Carbon emissions could also be a criterion in the public procurement of shipping services. Various countries provide public service contracts, for example for shipping services to remote islands. These contracts hardly ever take carbon emissions into account, despite the huge potential (Rehmatulla et al. 2017c). There are exceptions: the public procurement procedure for the maritime connection between Stockholm and Gotland incorporated GHG emissions; this – in combination with the 10-year duration of the contract – facilitated the order of LNG-powered vessels by Rederi Gotland AB that won that procurement that will decrease CO_2 emissions with around 20% (ITF, 2018a). Such practices could be rolled-out. Although this might mainly affect domestic shipping, decarbonisation of national shipping activities will provide spillovers to fleets that operate internationally and would provide an important arena for piloting and developing zero-emission technologies and their associated infrastructure.

Port-based incentives could also be more effectively focused on reducing shipping’s carbon emissions. A considerable share of world ports (28 out of the 100 largest ports) reductions of port fees for ships with better environmental performance (ITF, 2018b). Most of these port fee reductions have been focused on reducing local air pollutants. Now that most of these local pollutants have been covered in global regulation, there might be room to extend port incentives to reduction of carbon emissions from shipping. The uptake of electric ships could benefit from reductions on port fees, particularly if applied in many ports and if the reduction is substantial. Governments can also stimulate the private financial sector to provide green ship finance instruments, e.g. create favourable conditions for financial instruments such as “Blue Bonds” that aim to channel private finance towards green shipping.

Implications for regulation

Creating certainty with an ambitious target

The global debate on an emissions target for shipping has so far focused on which target could be realistic. One of the main reasons why the IMO and its Marine Environmental Policy Committee (MEPC) did not explicitly and immediately express adherence to the ambitions of the Paris Climate agreement was hesitance to commit to targets that might prove difficult to realise. The decision in IMO’s MEPC in 2016 to engage in a process to define an Initial GHG Strategy by 2018 and a Revised Strategy by 2023 can be interpreted as a way to find bottom-up agreement on possibilities to underpin shipping’s contribution to reduction of GHG emissions.

Our study and other recent studies show the range of options that would be possible to reach full decarbonisation of shipping. We demonstrated that getting close to zero carbon emissions by 2035 is possible, in line with findings of Smith et al. 2016, even if it would require radical changes quickly. There is still a huge gap between what is technically possible and business as usual, and public policies - some of which highlighted below - can play a role in bridging that gap. Although there is evidence of potentialities, there are also uncertainties regarding the upscaling of alternative fuels, the production capabilities needed for this, shipyard capacity and retrofit docks and trade impacts for countries. Government intervention could help to minimise these uncertainties.

An ambitious target for decarbonisation of shipping would provide more certainty to the market as to the direction the sector is going to take. This would stimulate market actors to take their responsibility. It would provide ship-owners and financiers with more certainty that investing in conventional ships is increasingly risky. It would provide shippers with more confidence that they can select shipping firms with low carbon footprints. It would ensure citizens of port-cities that they could indeed expect their ports to be stringent on the sort of ships they would like to attract to their ports. An ambitious target would also stimulate the innovation necessary to reach that target. It is the target that will drive change, not the other way around, as there is a large amount of path dependence in shipping related to fossil fuels. However, a target alone would not be sufficient for the investment that is needed. It would be helped by a package of measures.

A package of measures

Our study shows that no measure in isolation will be able to realise full decarbonisation, so a mix of measures would be needed. Possible combinations should include measures that cover technological and operational innovations, as well as alternative fuels and energies that can be included in the short, medium and long term. Smart phasing in of carbon pricing could facilitate the implementation of these measures. Possible combinations should ideally also provide possibilities for the different market stakeholders – such as the maritime industry, shippers and ports – to play their part. Although these combinations will be composed as part of a global effort to decarbonize shipping, it could also contain national measures to facilitate the transition, e.g. with respect to infrastructure and research and development.

Taking short term measures would be needed to ensure early emission reductions. Measures that could help in this respect are related to ship speed, low-carbon fuel standards and more stringent energy efficiency measures. Full decarbonisation can only be realised by transitioning towards zero-carbon ships; this transition can take some time but policy measures could help to advance this. Despite the global character of the shipping industry and the need for global regulation, there is also room for national initiatives to stimulate zero-carbon shipping. Many innovations depend on favourable national and local circumstances and policies, as has been be illustrated by the case of Sweden (ITF, 2018a). Good practices and effective national policies could be shared more widely to the benefit of other countries that would like to advance on decarbonisation of maritime transport. This could help to reduce some of the highlighted barriers, such as split incentives and imperfect information. The importance of the national level has been underlined by China’s proposal for national action plans for decarbonizing shipping that could be submitted to the IMO, mirroring NDCs submitted to the UNFCCC. Relevant responsibilities at the national level are not limited to maritime administrations, but could also include ministries of infrastructure, e.g. for charging and alternative bunkering facilities, and research institutes.

Conclusion

Would it be possible for international shipping to decarbonise by 2035, and what would be needed to achieve that? This is the central question that this report examines, by providing modelling of emissions, measures and an assessment of conditions under which this could happen. We projected that carbon emissions from international shipping could amount to 1 090 million tonnes by 2035, a growth of 23% compared to its 2015 level. We also modelled an adjusted baseline, which takes into account a substantial reduction in the transport of fossil fuels and a higher share of intra-regional trade, as compared to the modelling assumptions for the baseline. When these developments are incorporated, carbon emissions are projected to amount to 850 million tonnes by 2035.

Our study illustrates that maximum deployment of technologies that are currently known could make it possible to reach almost full decarbonisation by 2035. We formulated four possible decarbonisation pathways for shipping, which foresee remaining carbon emissions ranging from 44 to 156 million tonnes by 2035 with CO_2 emission reduction ranging from 82-95% of the projected 2035 level. A major part of the required reductions could be realised via alternative fuels and renewable energy. Technological measures are available to increase the energy efficiency of ships and could yield a substantial part of emission reductions. Finally, operational measures could also achieve a considerable share of the required emission reductions. The report gave an overview of a selection of these measures in detail.

Government intervention can help to accelerate the commercial viability and technical feasibility of certain measures. An essential role can be played by ship-owners, some of which are already pioneering with low- and zero-carbon ships. Various policies or regulations could support their uptake, including more stringent energy efficiency targets, a speed limit and a low-carbon fuel standard. These policies could be introduced globally and by IMO member states. Governments and ports could provide necessary infrastructure, e.g. for shore power facilities, electric charging systems and bunkering facilities for alternative fuels. Governments could also encourage green shipping domestically, stimulate research and development on zero-carbon technologies, and design programmes to increase commercial viability of these technologies. Financial institutions could develop green finance programmes to stimulate sustainable shipping. Shippers could be further encouraged to assess the carbon footprint of their supply chain and target zero-carbon shipping options.

Financial incentives are essential to reduce the price gap between conventional and more sustainable fuel options. These incentives could include adopting a carbon price for global shipping, leaving it to the market to allocate resources to maximum effect. Receipts from such a scheme could also be used (in part) for further decarbonisation of the sector, e.g. to facilitate research and development in green shipping, facilitating ship retrofit programmes, and compensation for potential adverse trade impacts in least developed countries and small island developing states. Carbon pricing at a global level could be complemented with incentive schemes at the national or regional level. Governments could also provide financial incentives for green shipping, e.g. greening the procurement of maritime transport falling under public service agreements, temporary exemptions of electricity taxes for electric ships, etc. Ports could also provide financial incentives for green shipping via differentiation of their port fee tariffs based on environmental criteria. Governments might partner with financial institutions or encourage domestic development banks to develop targeted financial instruments for green shipping.

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Appendix: The ITF International Freight Model

The model projects international freight transport activity and related CO_2 emissions up to 2050 based on global trade projections. The model includes six main components, each feeding into the next calculations (Figure A2):

- A general equilibrium model for international trade, covering 26 world regions and 25 commodities of which 19 require transport (see Château, et al., 2014 for more details);
- A global freight transport network model based on 2010 data;
- Global production/consumption centroids;
- An international freight mode choice model calibrated using Eurostat and ECLAC data;
- A weight/value model to convert trade in value into weight, calibrated for each commodity and transport mode;
- An international shipping route choice model calibrated using observed port throughput data for 400 major global ports; and
- CO2 intensities and technology pathway by mode.

The final outputs of the model are freight tonne-kilometres by transport corridor by mode and related CO_2 emissions. Each of the model components are described in more detail below. For technical details of the earlier version of the international freight transport model, as well as some validation results see Martinez, Kauppila, Castaing (2014).

Transport network model

The model consolidates and integrates all freight transport networks based on open GIS data for different transport modes. Seaports and airports are physically connected to road and rail networks with data on intermodal dwelling times. Travel times by type of infrastructure and dwelling times between transport modes are estimated using average speeds based on available information by region. The model then computes the shortest paths between each production/consumption centroid for each transport mode (for the modes available for each link), generating two main inputs:

- The average travel time and distance by mode for each origin destination pair. For countries with multiple centroids, a weighted average of all centroid pairs is used;
- The shortest path between each centroid for each transport mode.

Centroids

The underlying trade projections are done with a regional aggregation of 26 zones. This introduces significant uncertainties from a transport perspective as it does not allow a proper discretisation of the travel path used for different types of product. Therefore, we disaggregate the regional origin-destination (OD) trade flows into a larger number of production/consumption centroids. The centroids were identified using an adapted p-median procedure for all the cities around the world classified by United Nations in 2010 relatively to their population (2,539 cities). The objective function for this aggregation is based on the minimisation of a distance function which includes two components: GDP density and geographical distance. The selection was also constrained by allowing one centroid within 500 km radius in a country. This resulted in 294 centroids globally, with spatially balanced result also for all continents.

Freight mode choice model

The mode share model (in value) for international freight flows assigns the transport mode used for trade between any origin-destination pair of centroids. The mode attributed to each trade connection represents the longest transport section. All freight will require intermodal transport both in the origin and destination. This domestic component of international freight is usually not accounted in the literature, but is included in our model. The model is calibrated using a standard multinomial logit estimator including a commodity type panel term, variables on travel times and distances taken from the network model while two geographical and economic context binary variables are added, one describing if the OD pair has a trade agreement and the other for the existence of a land border between trading partners.

Weight/value model

We used a Poisson regression model to estimate the rate of conversion of value units (dollars) into weight units of cargo (tonnes) by mode, calibrated using Eurostat and Latin American data on value/weight ratios for different commodities. We use the natural logarithm of the trade value in millions of dollars as offset variable, a panel terms by commodity, travel time and distances, and geographical and cultural variables: the binary variables for trade agreements and land borders used above and a binary variable identifying if two countries have the same official language. Moreover, economic profile variables were included to describe the trade relation between countries with different types of production sophistication and scale of trade intensity. The resulting dataset was then divided according to each transport mode, leading to different calibrations by mode.

Route choice model

We used path size logit model in combination with path generation method to estimate the volume of freight transport across all possible international shipping routes between all origins and destinations. The model does this by using a shortest path algorithm and choice set creation algorithm to identify the sub-segments of the complete shortest route for each port-to-port segment of a shipping line. The model accounts for both maritime connections between two countries as well as overland connections between the centroids. The route and port choice algorithms use a path-sized logit model which takes overlaps between the alternative routes into account and distinguish the transport costs associated with these alternatives properly. The basis of this model can be found in (Ben-Akiva and Bierlaire, 1999). The model is calibrated by minimizing the difference between observed and modelled port throughputs for more than 400 major ports in the world. A detailed description on the model can be found in (Halim et al., 2015) or in (Tavasszy et al., 2011)

Estimation of CO_2 Emissions for different decarbonisation pathways

We applied the “ASIF” (Activity, Structure, Intensity, Emission Factor) framework (Schipper and Marie 1999; Schipper, Gorham and Marie 2000) to assess the impact of the maximum possible technical, operational, and alternative fuels measures on the total CO_2 emissions of international shipping (Figure A.1). The implementation of the framework is inspired by ASIF framework implemented in the shipping model of Momo (IEA, 2017).

The international freight transport model produce output with the value, weight and distance travelled (with path specification) between 2010 and 2050, for each centroid pair, mode, type of commodity and year, stemming from international trade. This data is used to compute the tonne-kilometres for different commodities (Activity) and the projections for future transport demand scenarios (Figure A.3). Afterwards, the activity (in tonne-kilometres) for each commodity is assigned to possible ship types to estimate the activities for each ship type. We consider 6 ship types: dry bulk, container, oil tanker, gas, wet product and chemical, general cargo in our model. Together with ship's capacity and load factor data, the vehicle-kilometre for each ship type can be estimated (Structure). The data for ship's load factor is obtained from the 3rd IMO GHG study and the projection for the changes in ship size is estimated based on the historical pattern of ship size (Figure A.4). Furthermore, we compute the fuel consumptions of all ship types using engine efficiency improvement pathways obtained from UMAS study (Smith et al., 2016). The resulting fuel consumption for each ship type is then used to estimate the total CO_2 emissions using carbon factor and energy content data of different fuel types obtained from the International Energy Agency's Mobility Model (IEA, 2017). Table B1 presents the emission factor for different fuel types used in this study.

To compute CO_2 emission for the baseline, we use both the carbon intensity data from LR/UMAS study (Lloyd's Register, 2017) and IMO 3rd GHG study (Smith et al., 2014). Figure A5 provides carbon intensity trajectories for 5 different ship types used in the model. In comparison with the other projections such as those from the IMO 3rd green house study and from UMAS, ITF BAU projection starts with higher CO_2 emissions in 2015 and reaches an emission level comparable to UMAS study. This is particularly because in the period of 2010-2015, the global shipping sector has seen an upward trend in total transport demand activities (12 %) while this is not accompanied by strong reduction in carbon intensity for various ship types (4-17 %). Furthermore, tanker ship – considerably carbon intensive ship, is reported to have seen an increase in its carbon intensity during this period by 13%. From 2020 until 2025, the reduction of carbon intensity/EEOI for different ship types is projected to happen more rapidly due to the compliance to ship energy efficiency design regulations. These trends will, in turn, stagnate the rise of CO_2 emissions for a short period of time until the rate of reduction in carbon intensity starts to slow down from 2025 onwards. Given that transport activities will keep on increasing, CO_2 emissions will continue to rise from 2025 until 2035.

Figure A.1. **ASIF framework used to estimate international shipping CO_2 emissions**

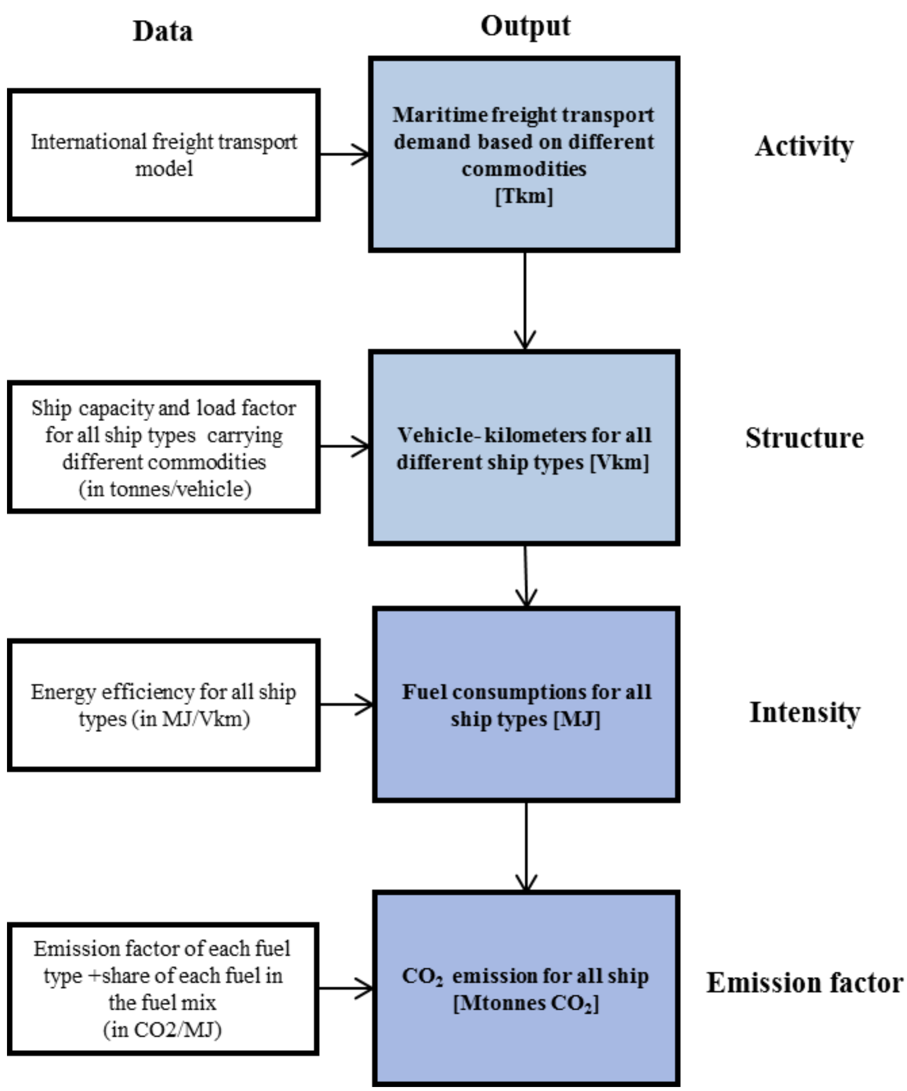


Figure A.2. **Schematic description of the ITF international freight model**

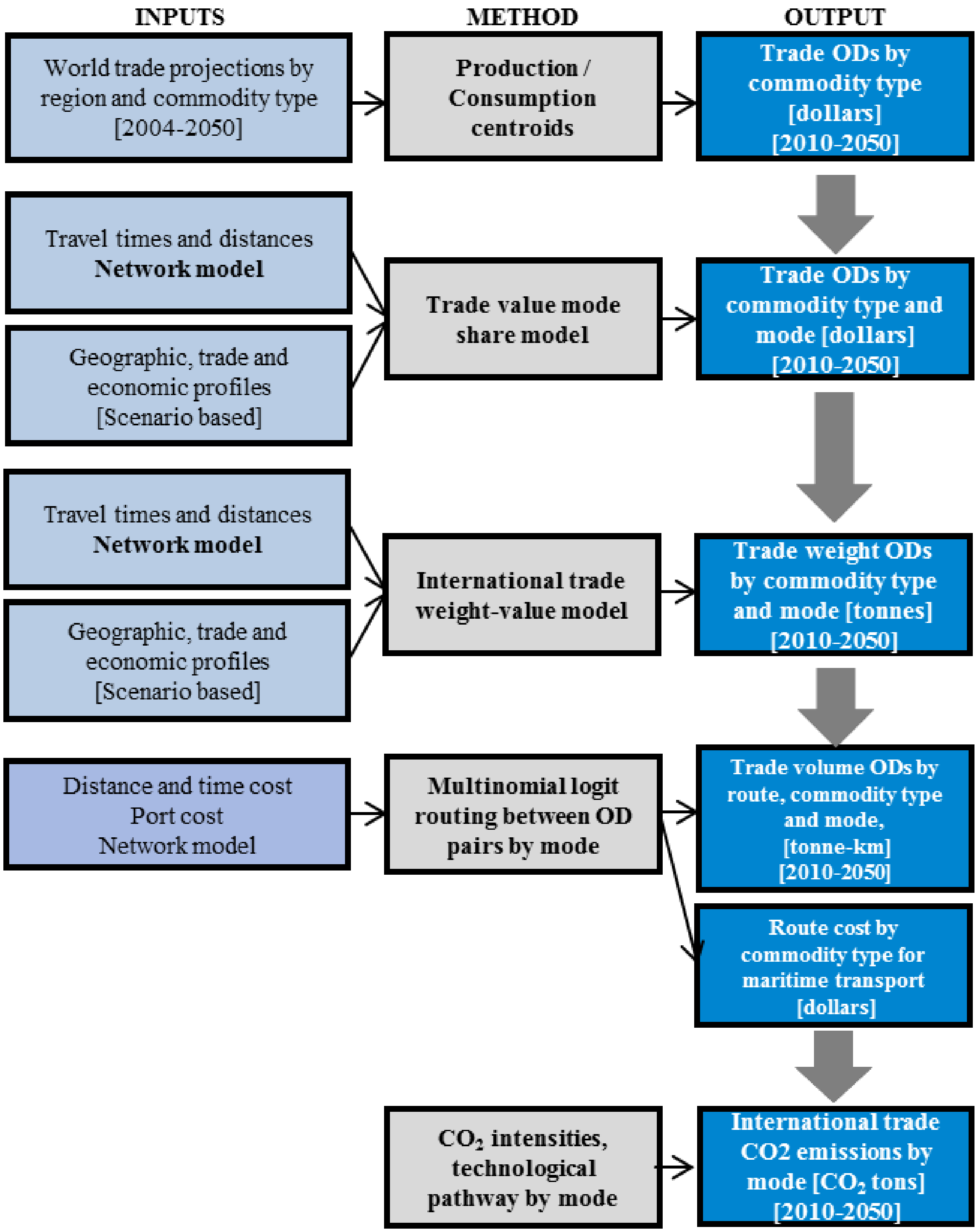


Figure A.3. **Transport demand scenarios estimated using international freight transport model**

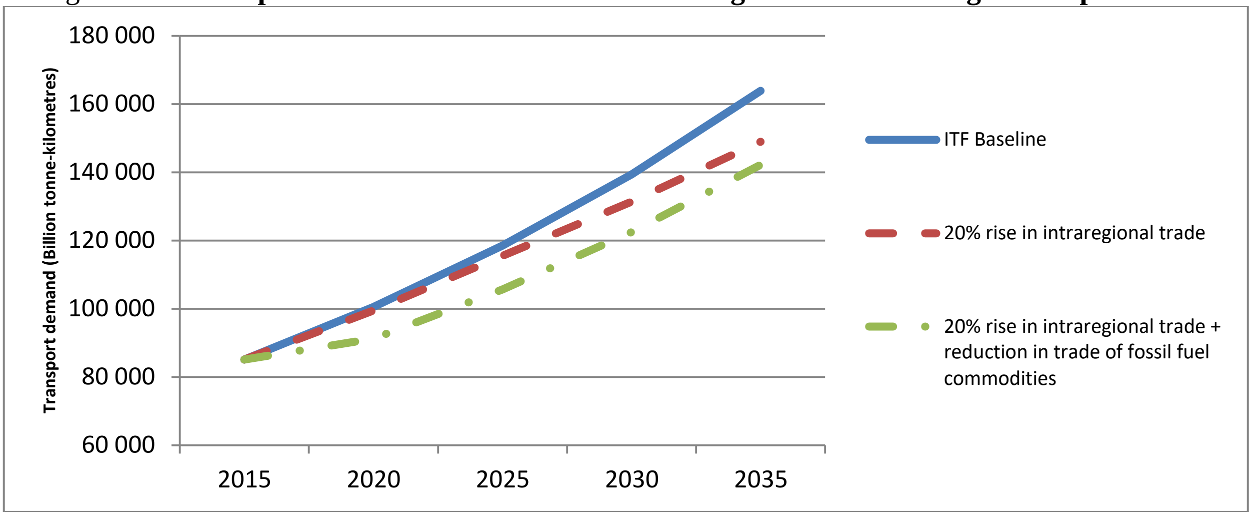


Table A1. **Emission factor of different fuel types**

Fuel type	Emission factors (kgCO2/MJ)
HFO	0.081
MDO/MFO	0.072
LNG	0.810
Hydrogen	0
Biodiesel	0.522
Ammonia	0

Figure A.4. **Historical (1996-2015) and estimated (2016-2035) changes in ship size**

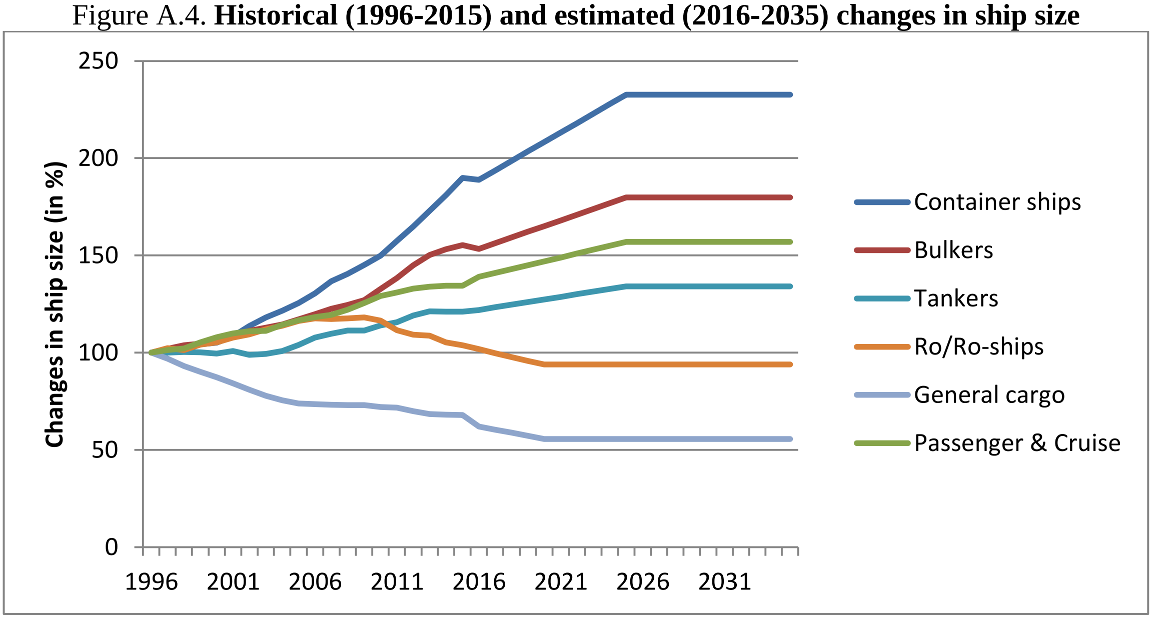
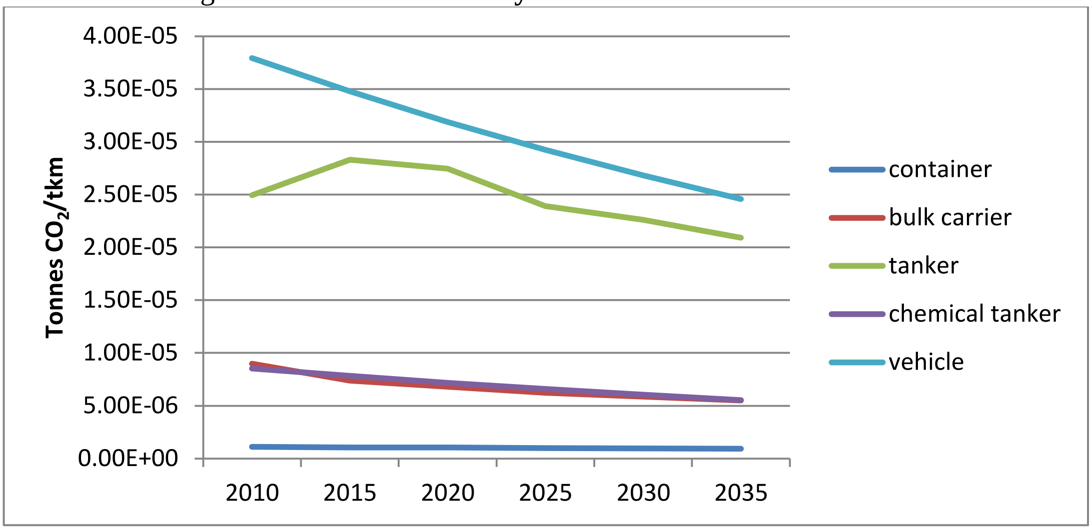


Figure A.5. **Carbon intensity evolution for baseline scenario**



Freight transport network: A detailed representation

Assessing potential capacity constraints with precision is made possible within our modelling framework through the inclusion of a detailed global freight transport network based on data from Geographic Information Systems (GIS). This allows the model, although global, to describe network conditions at a detailed scale. Our main contribution is the consolidation and integration of all different modal networks into a single, routable freight network, and the association of capacity constraints to links and nodes. The freight network comprises links and nodes for all four main modes: a global road network, containing the primary and secondary road networks (i.e. motorways, main roads and trunk roads); a rail network; an air network, including all commercial air links between international airports; a maritime network; and a global inland waterways system with navigable rivers (see Figure A.6). In order to estimate travel times for the different types of infrastructure, as well as dwelling times between transport modes, we use average speeds based on available information by region.

GIS data for the global network model are available online:

- The road network information integrates two main sources: Global Roads Open Access Data Set (gROADS) (http://sedac.ciesin.columbia.edu/data/set/groads-global-roads-open-access-v1) and OpenStreetMap (www.openstreetmap.org).
- The rail network was collected from the Digital Chart of the World (DCW) (http://www.princeton.edu/~geolib/gis/dcw.html) project, integrated and updated with the OpenStreetMap data on rail lines and rail stations as intermodal points of connection between road and rail.
- The actual maritime routes are taken from the Global Shipping Lane Network data of Oak Ridge National Labs CTA Transportation Network Group (http://www-cta.ornl.gov/transnet/Intermodal_Network.html), which generates a routable network with actual travel times for different sea segments. We connect this network to ports, based on data

from the latest World Port Index Database of the National Geospatial-Intelligence Agency (http://msi.nga.mil/NGAPortal/MSI.portal).

- The commercial air links between international airports were integrated using data from OpenFlights.org database on airports, commercial air links and airline companies (www.OpenFlights.org).
- The inland waterways network was obtained from the CIA World DataBank II (https://www.evl.uic.edu/pape/data/WDB/), and combined with information on the navigability for each river.

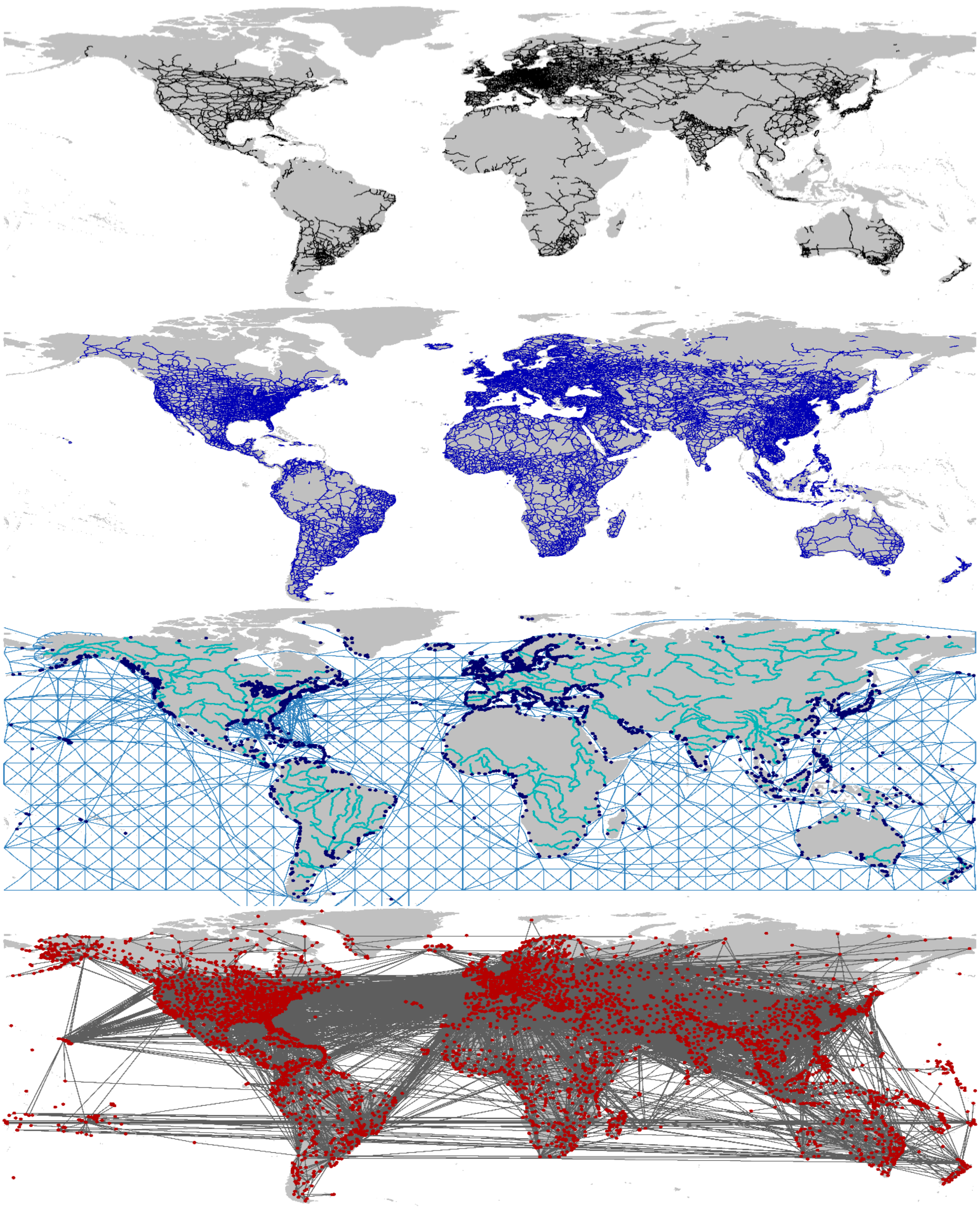
The different networks are consolidated into a single, routable network, and connected to the centroids using the road network and rail stations.

Port capacity

To assess future port infrastructure needs, the ITF built a detailed database of current port capacity, along with planned capacity increases. The data come from the combination of several sources: Drewry (2014), Dynamar (2015), OSC (2012a, 2012b, 2012c) and Clarkson port database. These publications are complemented with data from national port authorities for the United States, Australia, New-Zealand and Brazil, as well as data from Eurostat for European ports.

For each port, we differentiate five types of cargo: containerised cargo, liquid bulk, dry bulk, break bulk and Ro/Ro. Each commodity is associated to one cargo type. The capacity figures introduced in the model are in TEU for containerised goods and in tonnes for non-containerised goods. The data collection focuses mainly on large ports (above 500 KTEU) for which data is freely available. The global coverage is 75% in terms of TEU, with numbers ranging from 53% in Scandinavia, where small and medium ports make the bulk of port capacity, to close to 100% in regions of the world such as North America or China where large ports are predominant for international freight movements.

Figure A.6. **Rail, road, sea (waterways) and air networks (top to bottom)**



Notes

[1] The Chinese classification of the routes is based on how these routes are connected to the railways within China. In this classification, Chinese geographical regions are used as reference instead of the whole Eurasian continent. East route for the railways are in the eastern region of China and connected to the TSR network, West route for railways in the western region, etc. The Northern, central and southern corridors as used in the text is a categorisation based on how the railways are situated on the Eurasian continent.

[2] Instead of using solid rods containing enriched uranium, molten salt reactors use liquid (molten) fuel salts. They are considered safer than conventional reactors, because the following mechanism prevents them from overheating: rising temperature would cause a plug at the bottom of the reactor vessel to melt and the liquid would flow into a cooling tank where it solidifies and hence prevents release of radioactivity into the environment. No plutonium by-products are generated, which reduces weapon proliferation risks when using thorium.

[3] The scenarios with 80% carbon factor reduction are complemented with 10% uptake of electric ships. The 80% carbon factor reduction refers in those cases to the carbon intensity of the 90% of the fleet that runs on fuels.

[4] With the exception of containerships where the ship size increase rate between 1996-2015 has been very large. We assume that the additional returns to scale have decreased to such an extent that ship-owners will no longer see benefits from upsizing from 2025 onwards.

International Transport Forum

Decarbonising Maritime Transport

Pathways to zero-carbon shipping by 2035

This report examines what would be needed to achieve zero CO2 emissions from international maritime transport by 2035. It assesses measures that can reduce shipping emissions effectively and describes possible decarbonisation pathways that use different combinations of these measures. In addition, it reviews under which conditions these measures could be implemented and presents concrete policy recommendations.

This report is part of the International Transport Forum's Case-Specific Policy Analysis series. These are topical studies on specific issues carried out by the ITF in agreement with local institutions.

International Transport Forum
2 rue André Pascal
F-75775 Paris Cedex 16
T +33 (0)1 45 24 97 10
F +33 (0)1 45 24 13 22
Email: contact@itf-oecd.org
Web: www.itf-oecd.org