CONSEQUENCES FOR NSA MEMBERS FROM CO2 REGULATIONS

Navigating a low-carbon future

Norwegian Shipowners' Association

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Objective:

This study is commissioned by the Norwegian Shipowners' Association (NSA) with the purpose to:

- explore and analyze the CO_2 pathways available to meet a 2-degree emission trajectory for international shipping towards 2100
- outline robust strategies for NSA members on meeting the requirements

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1 EXECUTIVE SUMMARY

What we did

The shipping industry is under increasing pressure to act upon the Paris Agreement and reduce greenhouse gas (GHG) emissions. IMO's Marine Environment Protection Committee (MEPC) has taken actions, recently agreeing on a Roadmap for developing a comprehensive IMO strategy on reduction of GHG emissions from ships. The initial GHG reduction strategy is expected to be adopted in 2018. This study is commissioned by the Norwegian Shipowners' Association (NSA) with the purpose of:

- explore and analyze the CO_2 pathways available to meet a 2-degree emission trajectory for international shipping towards 2100
- outlines robust strategies for NSA members on meeting the requirements

A baseline trajectory was developed for international shipping, applying realistic growth rates for the main ship types. The differences between the 2-degree target – corresponding to 33 GT accumulated CO_2 emissions between 2010 and 2100 – and the baseline trajectory represents an increasing gap, which needs to be covered by emission reductions towards 2050. A high-level Pathway Model has been developed to determine whether a set of CO_2 reduction measures can bridge the gap and achieve the targets set by the 2-degree trajectory. Possible CO_2 reduction measures have been identified from four broad categories:

1. technical and operational energy efficiency measures
2. alternative low carbon fuels
3. improved logistics and speed reduction
4. offsetting emissions

Six distinct CO_2 pathways have been **developed** (see table below) which meet the 2-degree targets. Each pathway has been **evaluated** on **barriers, costs, emission reduction and needs for offsets**. The pathways have different pros and cons, balancing the different **risks**: where the *Fossil-ship* pathway relies on offsets and mature technologies, the two *Bio-ship* pathways require biofuels to large extent, the two *Slow-ships* pathways relies on significant speed reduction and *Space-ship* is a balance between using offsets and relying on non-mature novel technologies and measures.

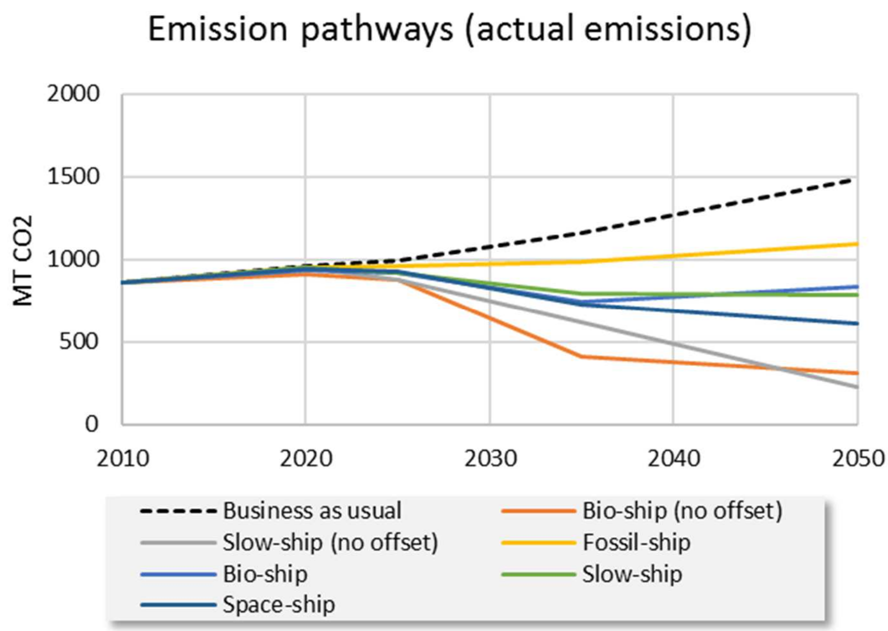
Pathway	Description
Bio-ship (no offset)	Focus on biofuels; moderate electrification; no offsetting
Slow-ship (no offset)	Extensive slow steaming; electrification, hydrogen and bio-LNG, no offsetting
Fossil-ship	Continue using fossil fuels, rely on offsetting; extensive energy efficiency
Bio-ship	Focus on biofuels; moderate slow steaming and energy efficiency; moderate electrification
Slow-ship	Extensive slow steaming; electrification, hydrogen and LNG
Space-ship	Moderate use of biofuels, speed reduction and offsets; extensive energy efficiency including measures on idea stage

The pathways are designed to cover possible ways to reach the emission targets towards 2100. We have not identified which pathway is the most likely, indeed all are possible ways to reach the targets. Having described and analyzed a set of pathways, the findings from all pathways are synthesized. Based on these, a **long-term strategy is formulated**, with the ambition to successfully navigate the rocky waters of societal expectations, possible CO_2 regulations and non-mature abatement options which lie ahead.

What we found

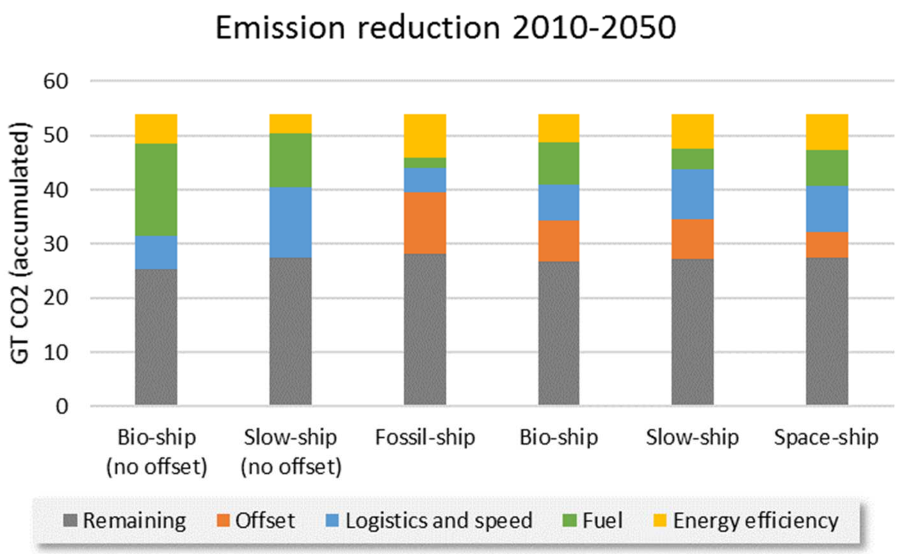
The six CO_2 pathways which meet the 2-degree targets

The six CO2 pathways consistent with the 2-degree targets are shown in the figure below. The modelling results shows that reaching the reduction targets without offsetting is possible but difficult. Without offsetting, 70-80 % emissions reduction in 2050 is needed to reach the targets and not exceed the 33 gigaton (GT) carbon budget. In the pathways relying on offsets in this study, 30 to 50 % of emissions must be offset by 2100, corresponding to a volume of between 14 to 33 GT. Offsets will mitigate costs and reduce reliance on immature measures. However, offsetting is also an immature solution and the cost and availability is uncertain. Shipping is part of the global effort to reduce emission and other sectors will compete for the same low carbon energy and offsets.



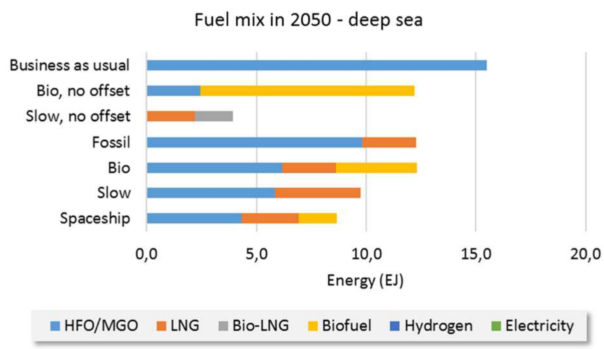
The most important CO_2 reduction measures

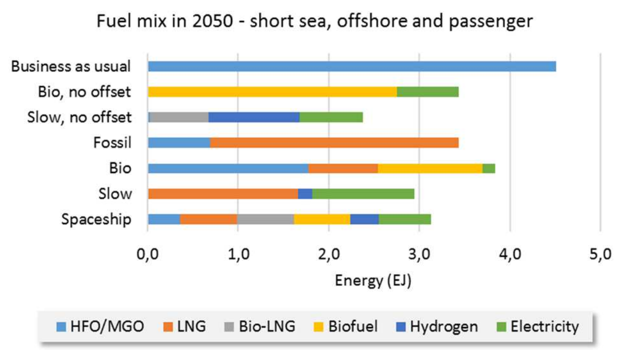
Energy efficiency is not enough in itself to reach the targets, and extensive use of speed reductions and alternative fuels are needed in addition (see figure below). Biofuels or more specifically, low carbon, sustainable fuels for marine use is a key element to reach the ambitious emission reductions. Hydrogen and electrification are solutions for the short sea, offshore and passenger segment. They are an important supplement and have other benefits such as reducing local pollution. Nuclear power has not been analysed in this study, but could provide substantial emission reductions.



Energy mix

The figure below shows the fuel mix for the different pathways. Between 2.4 to 12.5 EJ (about 57 to 300 MTOE) of biofuels, and up to 5.6 EJ (about 134 MTOE) of LNG will be needed. LNG and biofuel will be used in all segments. The deep-sea segment is more dependent on fossil fuels, compared the non-deep-sea segments. Electricity and hydrogen are only used for the non-deep-sea segments. Use of LNG is significantly higher for the non-deep-sea segments.

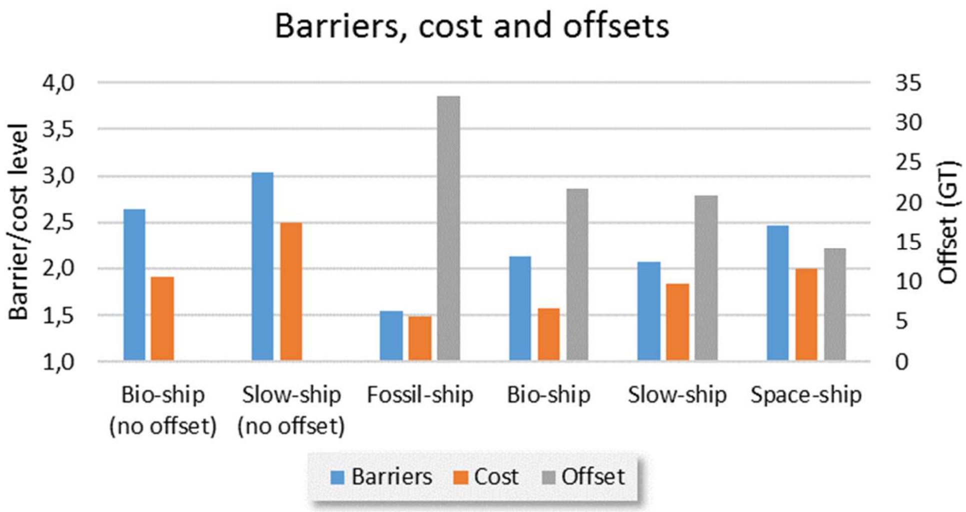




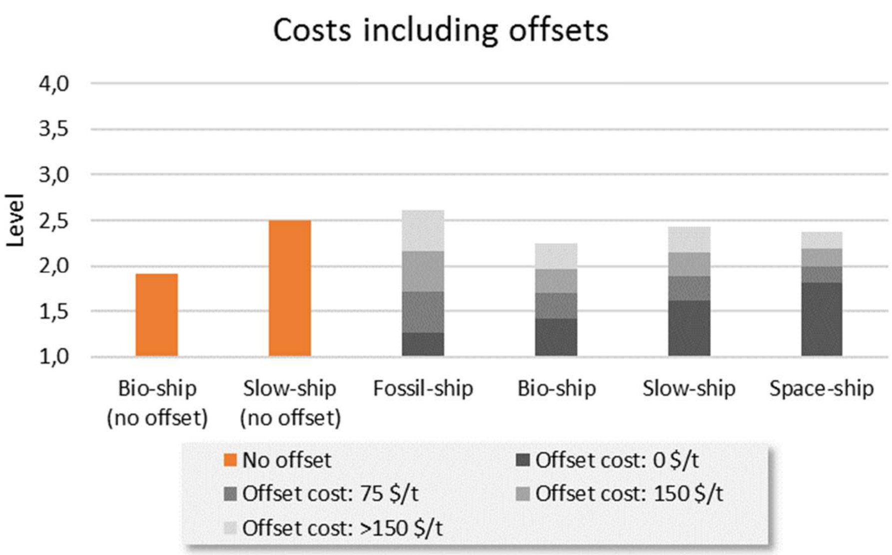
Evaluation of pathways

The figures below evaluate each pathway on barriers, cost, and offset needs. A high **barrier** score indicate that this pathway comes with a high uncertainty, and costs could be even higher. Slow-ship (no offset) has the highest barrier and cost level, followed by Bio-ship (no offset). Even if the barrier level for the individual measures may be high, by relying on several of these measures, the robustness increases and the overall risk is reduced.

Costs are estimated when the solutions are assumed to become mature and the barriers are overcome. The set of solutions applied in the pathways aggregates to an increased cost of shipping of between 10 to 25 %. As this is an aggregated estimate, costs will vary between ship segments, (i.e. for implemented solutions, upfront investment needs and potential for savings in operation) and time periods (e.g. the low-hanging fruits will be implemented first). This is a substantial increase, requiring significant investments. The financial strength of many ship owners will be challenged, i.e. whether they can raise the needed capital to *invest* in the technologies and solutions which may be required. This can be mitigated through financial support mechanisms.



The reliance on **offsets** can be translated into a price on carbon set in a global market. The cost of offsetting is very uncertain given that there a no global market in place, and the figure below illustrates the overall cost level for each pathway under various carbon price assumptions. The highest offset needs are for the fossil ship. The pathways without offsetting, have the highest score on barriers reflecting the need for high uptake of immature measures.



What we recommend

A robust strategy for navigating the uncertainties

In addition to the extensive use of energy efficiency improvements (pushing the envelope in all segments), the pathways identified meeting the 2-degree targets rely on **at least one** of the following solutions being implemented at a scale which seems daunting today;

- Alternative fuels (sustainable biofuels in deep sea, electricity and hydrogen in other segments)
- Moderate to extensive speed reduction (20-50% reduction)
- Offsetting of emissions (internally in shipping or externally)

Should any one of the above solutions be ‘off the table’ at a given point in the coming three decades, the relevant pathways to reach the emission targets will be closed – limiting the room for ship owners to manoeuvre. Thus, in **a robust strategy**, where reliance on a single solution should be avoided, actions should be taken to increase the likelihood of the above **solutions being available** to the industry at sufficient quantities and at competitive prices. Ship-owner associations (SA) and ship owners (C) can take actions on different levels, and key actions identified in this study are presented in the table below.

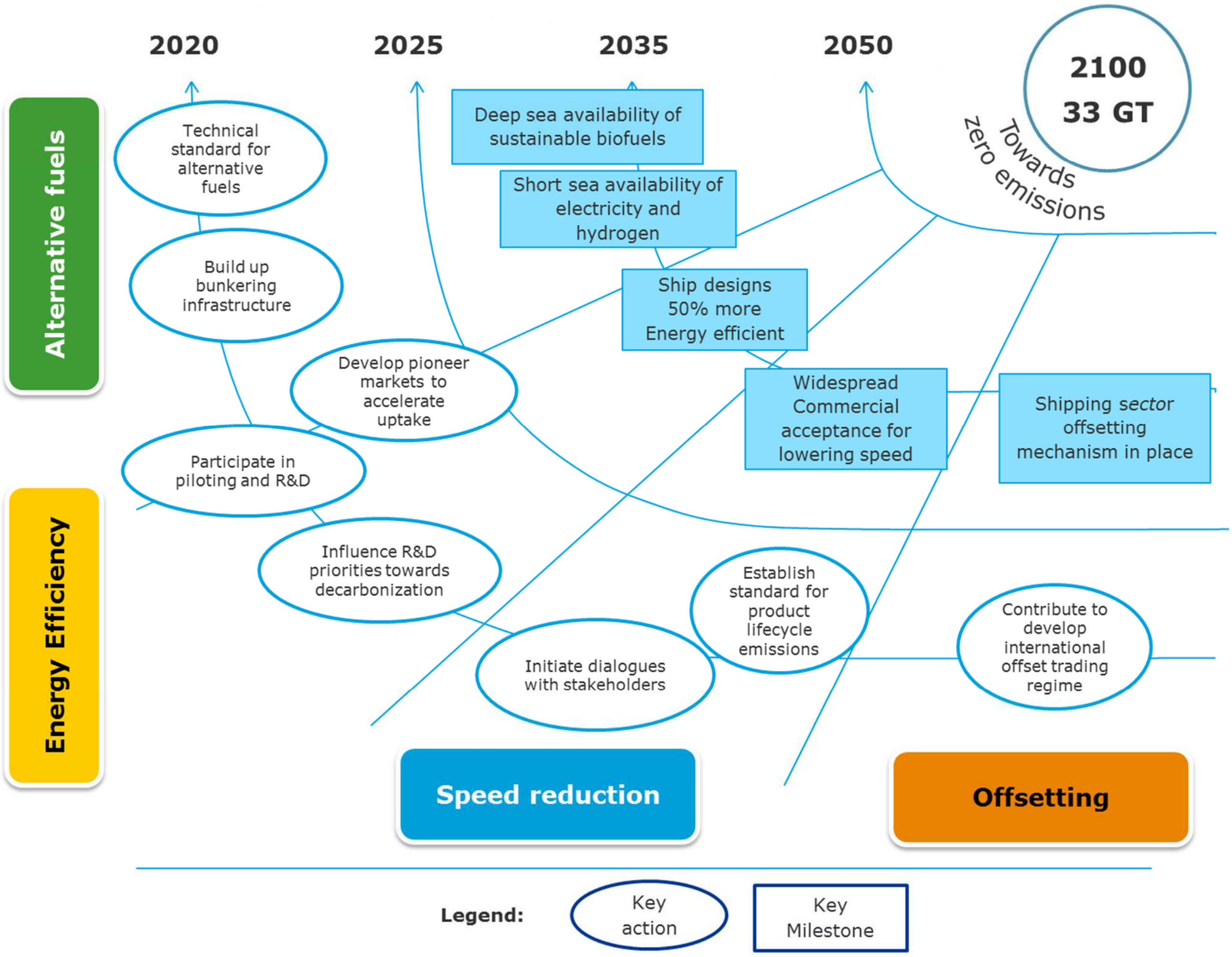
Strategy chart towards 2100

The *Strategy chart towards 2100,* illustrated below, is an extract of the table above. It points towards concrete actions needed to be taken to overcome barriers for the mitigation solutions presented in this study, along with important milestones. Only the most important key actions and milestones are presented. For meeting the long terms targets and reducing risks, efforts are needed to be taken within all mitigation categories, and delays should be avoided. Implementing the proposed strategy, the members of NSR is expected to maintain and strengthen their competitiveness, through operating fuel and speed flexible low emission ships, and avoiding potential “stranded assets” (e.g. ships with high operational costs or incapable of running on low carbon fuels). This will challenge the way ships are designed and operated today. The overall key recommendations from this study are:

- Build up availability and infrastructure for alternative low carbon fuels/energy carriers
- Develop stakeholder acceptance for substantial speed reductions
- Establish an offsetting mechanism for international shipping
- Influence national and regional R&D priorities, to strength effort on decarbonization of shipping

Solution	Barriers	Actions
Alternative fuels (biofuels in deep sea, electricity and hydrogen in other segments)	Price, production and availability Risk – safety and reliability, complexity	• Stimulate demand for biofuels by working towards and enforcing national and regional requirements to blending drop-in biofuels. (SA) • Push for incentives and arrangements promoting uptake of alternative low carbon fuels/energy carriers. (SA) • Build industry competence and experience through piloting (fuel cell, hydrogen). (C) • Design ships with fuel flexibility (e.g. dual fuel, LNG/battery readiness). (C) • Push for development rules for safe and effective introduction of alternative fuels. (SA) • Develop national and regional home-markets as to create local demand (e.g. electrification, uptake of hydrogen), as a stepping stone for later international expansion[1]. (SA)
	Bunkering infrastructure	• Develop a technical industry standard for shore connection for electricity. (SA) • Build up shore-based infrastructure for biofuels, hydrogen and electrification. (SA)
	Different types and qualities of fuels Engine compatibility issues Ship-shore compatibility issues	• Develop a technical industry standard for marine biofuel and hydrogen quality, incl. shore based electrification (energy mix/carbon intensity). (SA) • Ensure engine compatibility with marine biofuels, including ship-shore compatibility. (SA)/(C)
	Sustainability of fuels (lifecycle emissions) – and documentation hereof	• Support the creation of an international standard for life cycle carbon intensity and sustainability of possible fuels (biofuels, bio-LNG, hydrogen, electricity). (SA)
Speed reduction (moderate to extensive)	-Complex global transport chains with high value cargo -Cargo owners have low knowledge and acceptance of speed reduction impacts -Not allowed due to charter party clauses -Financial and economic constraints – uncertain business case	• Initiate dialogues and partnerships to challenge conventional wisdom relating to the necessity of speed; on sector level (SA) and on company level (C). • Educate internally in ship owner organisations about benefits of speed reduction (to bridge the communication gap between technical and commercial department). (C) • Create an industry standard for a consistent carbon efficiency index and start reporting to create transparency on product lifecycle emissions. (SA) • Dialog and workshops with cargo owners. (SA)
	More ships are needed, and current ships are not efficient at low speeds	• Order ships designed and built to be efficient within a broader speed range (hull, propellers and machinery). (C)
Offsetting	No regulatory framework in place	• Influence the development of a IMO offset regime, including a standard for defining an offset/credit (SA)
	-Low availability of offsets -Fragmented carbon markets limits access to offsets	• Develop shipping specific carbon markets/offset sources such as a contribution fund/levy. (SA) • Connect shipping to an international carbon market. (SA)
Energy efficiency (push the envelope in all segments)	-Technical uncertainty – maturity, reduction effect, system integration -Financial and economic constraints- cost of implementation, access to capital, cost of operation -Risk – safety and reliability, complexity -Behavioural barriers- lack of information and awareness	• Develop national and regional home-markets to create local demand, as a stepping stone for later international expansion. (SA) • Participate in selected R&D and large scale demonstration projects. (C) • Prioritize piloting and experience accumulation of novel solutions. (C) • Influence national and regional R&D priorities. (SA) • Build "Best in class"- energy efficient newbuilds (C) • Focus on energy managements systems and energy culture (C)

[1] E.g. as described for the Norwegian domestic fleet, in the Roadmap developed by the Green Coastal Shipping Programme: https://www.rederi.no/aktuelt/2016/sjokart-for-gronn-skipsfart/


2020
2025
2035
2050
2100
33 GT
Towards zero emissions
Alternative fuels
Energy Efficiency
Technical standard for alternative fuels
Build up bunkering infrastructure
Deep sea availability of sustainable biofuels
Short sea availability of electricity and hydrogen
Ship designs 50% more Energy efficient
Develop pioneer markets to accelerate uptake
Participate in piloting and R&D
Widespread Commercial acceptance for lowering speed
Shipping sector offsetting mechanism in place
Influence R&D priorities towards decarbonization
Establish standard for product lifecycle emissions
Contribute to develop international offset trading regime
Initiate dialogues with stakeholders
Speed reduction
Offsetting
Legend:
Key action
Key Milestone

2 INTRODUCTION

The shipping industry is under increasing pressure to act upon the Paris Agreement and reduce greenhouse gas (GHG) emissions. In the agreement[2], all countries agreed to work to limit global temperature rise to well below 2°C, and to strive for 1.5°C. Implementation of the Paris Agreement is essential for the achievement of the recently adopted UN Sustainable Development Goals[3]. Although the shipping industry isn't directly covered by the Paris agreement, it is largely accepted that keeping global warming below the given temperature limits places a responsibility on all sectors of the global economy, including international shipping. It is considered likely that if the IMO doesn't address climate pollution from shippers, the industry could face "unwelcome" regional and local regulations from the European Union, the US, Canada, and others. With such regulations, there is potential for serious market distortion and disruption to operation, as shipping is a truly global industry requiring global rules. IMO's Marine Environment Protection Committee[4] (MEPC) has taken actions, recently agreeing on a Roadmap for developing a comprehensive IMO strategy on reduction of GHG emissions from ships. The initial GHG reduction strategy is expected to be adopted in 2018.

The Norwegian Shipowners' Association (NSA) invited DNV GL to carry out the study "Operational and economic consequences from existing and proposed future CO_2 Regulations". The overall ambition of the project was to:

- explore and analyze the CO_2 pathways available to meet a 2-degree emission trajectory for international shipping towards 2100
- outlines robust strategies for NSA members on meeting the requirements

This study has used a 2-degree emission trajectory for international shipping, based on input from NSA. The 2-degree trajectory entails a carbon budget of 33 GT CO_2-eq from 2010 to 2100 and an emission trajectory peaking in 2025 and with 50% of reduction of emission levels in 2050 (relative to 2010). A baseline trajectory is developed, applying realistic growth rates for the main ship types. The differences between the 2-degree and the baseline trajectory represents an increasing gap, which needs to be covered by emission reductions towards 2050.

A high-level Pathway Model has been developed to determine whether a set of solutions can bridge the gap and achieve the targets set by the 2-degree trajectory. The solutions cover CO_2 reduction measures from four broad categories; energy efficiency; alternative fuels; logistics and speed; and offsetting of emissions. A CO_2 measure database for the main ship segments has been established to this end. With the CO_2 measure database as input, the model was used to construct and evaluate the most relevant pathways.

The relevant pathways or scenarios in which measures within the four categories have been implemented, have been evaluated based on the emission reductions achieved, but also on the *cost level* associated with the applied measures, as well as the barrier level. The cost and barrier levels have a substantial impact on the likelihood of given measures being implemented. The model was designed to calculate the potential emissions reductions in 2025, 2050 and 2100. A fundamental issue with this pathways-approach is that there are a very large number of different pathways available for analysis –

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[2] The Paris Agreement: http://unfccc.int/paris_agreement/items/9485.php
[3] UN Sustainable Development Goals: http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E
[4] IMO: http://www.imo.org/en/OurWork/environment/pollutionprevention/airpollution/pages/ghg-emissions.aspx

more than practically feasible. Thus, it becomes necessary to apply a practical approach to selecting the most relevant pathways.

This report starts with establishing reductions targets towards 2100, followed by description of the pathway modelled used in this study to establish the CO_2 baseline and the mitigation pathways. The result section elaborates around the most promising abatement pathways, and highlight to which extent they bridge the gaps. Having selected, described and analyzed a set of pathways, the findings from all pathways are synthesized and based on these possible strategies for ship owners to follow, to successfully navigate the rocky waters of CO_2 regulation and abatement which lies ahead, are formulated.

The introduction continues with a separate section highlighting some major historical shifts in the world fleet.

2.1 Major historical shifts in the historical world fleet

To understand the future, it is important to understand that major changes in the shipping industry in the past have been slow and, to a large extent, economically motivated. This section highlights some of the major historical shift related to fuel types and main engines, building on work published by DNV GL (e.g. Eide et al 2007, OECD 2010).

The ocean going civil world fleet gradually shifted from sail around 1870 to a full engine powered fleet around 1940. Steamships, burning coal, dominated up to around 1920 (Fletcher, 1997). Coal was thereafter gradually replaced by marine oils due to shift to diesel engines and oil fired steam boilers (Table 1). Table 1 illustrates how the transition from coal to oil fuel as the preferred maritime fuel occurred in the period 1914-1935. It took about 20 years before internal combustion (diesel) engines reached a 20% share of the fleet. This contrasts with the 6 years required for oil to get a 20% share of the fuel market (Table 1). The shift to modern marine diesel engines has been a slow process taking more than 100 years. In 1961 there were still over 10,000 steam engine powered ships and 3,536 steam turbine powered ships in operation (36% by number), (LR, 1961). This indicates that switching fuels on existing hardware, can be achieved more swiftly than the implementation of new hardware (main engines).

Figure 1 shows the relationship between motor ships (diesel) and steamships in a thirty-year period from 1950. The relative number of motor ships (Figure 1, right) increased much faster than the relative tonnage of motor ships (Figure 1, left). In this period, the market share for steamships dropped by 60% measured in tonnes, but 90% in numbers. This indicates that the switch to motor ships occurred first within the smaller segments in the fleet.

As scrapping of ships are economically motivated, future periods could for example look like the period 1970 to 1985, when the fuel price increased by a staggering 950%. Because of rising fuel prices, the tankers fitted with inefficient steam turbines were among the first to go to the scrap yards in the 1970s (Stopford, 1997; Wijnolst & Wergeland, 1997).

It is plausible to assume that the price of oil – and other fuels - will significantly influence future trends of shipping as we have seen in the past. In addition to fuel prices, a strict future CO_2 regime will drive introduction of low emission and competitive ships through innovations and technology development. Similar development has already been seen associated with the Ballast Water Convention.

Table 1: Percentages of World's total merchant fleet (exclusive of Sailing Ships) using the specified form of motive power (from Fletcher, 1997).

Year	Coal	Oil fuel for boilers	Internal combustion (diesel) engines
1914	96.6	2.9	0.5
1922	74.1	23.4	2.5
1924	68.9	27.9	3.2
1927	63.9	29.3	6.8
1929	60.8	29.2	10.0
1935	51.0	31.2	17.8

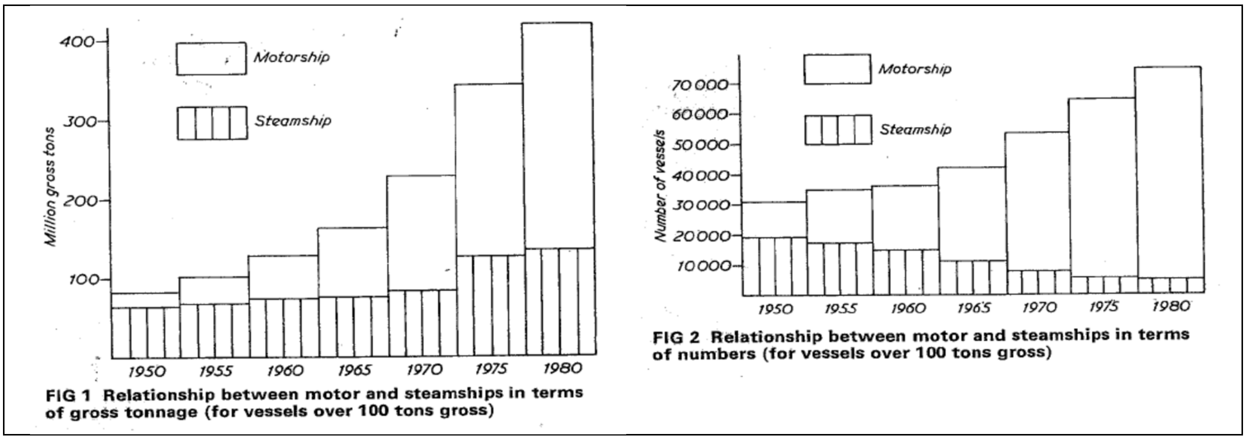


Figure 1: Past relationship between motor ships and steam ships (Thoma, 1981).

3 A 2-DEGREE EMISSION TRAJECTORY FOR SHIPPING

This study has used a 2-degree emission trajectory for international shipping, based on input from NSA. The trajectory is illustrated in Figure 2, and builds on:

- The RCP2.6 (Representative Concentration Pathways) mitigation scenario and the SSP3 (Shared Socioeconomic Pathways) scenario for economic growth, described in the IPCC fifth assessment report[5], aiming to limit the increase of global mean temperature to 2°C.
- The "fair share" of shipping's contribution to global emission reduction should be based on the responsibility principle in the UMSA/DSA study with a carbon budget of 33 GT from 2010 to 2100 (Smith et al 2016).
- The emission level should peak in 2025, and the 2050 emission level should be 50% of the 2010. It further assumes a gradual reduction until 2100.

[5] IPCC: https://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf

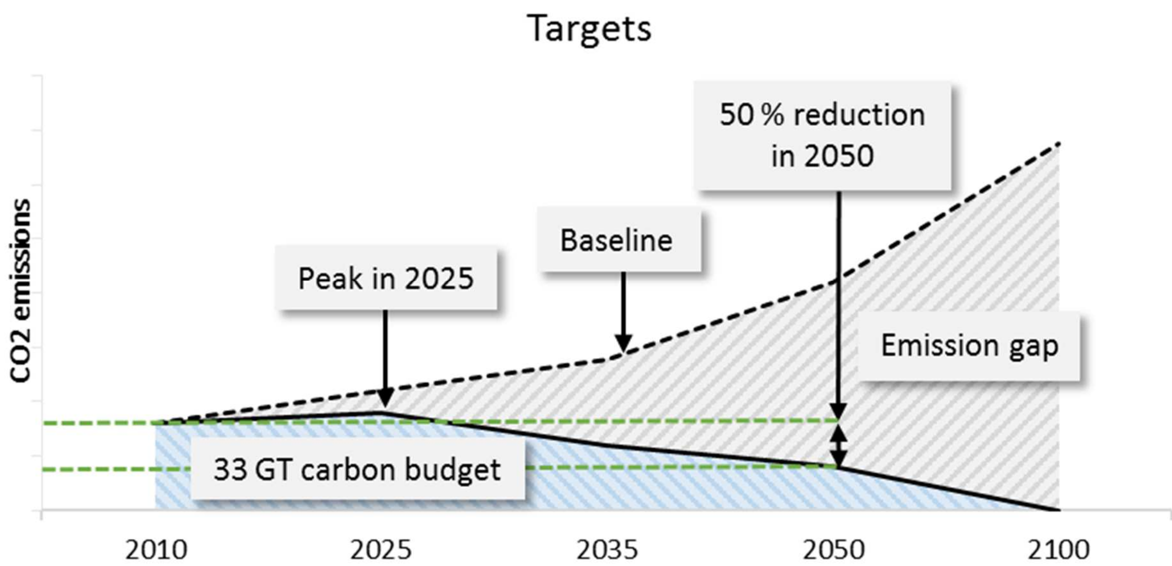


Figure 2: Illustrative emission trajectory for 2010 to 2100 (variable time scale). The carbon budget and necessary emission reductions are based on the Norwegian Shipowners' Association's target. The baseline emission is based on a combination of SSP3 and RCP2.6 scenarios, without any emission reduction or efficiency increase (see Section 4.2).

This study looks at emission reduction options until 2050, and assumes that the emission level will gradually be reduced to zero in 2100. Given a 50% reduction in 2050 relative to 2010, a carbon budget of 9.5 GT is needed to cover remaining emissions from 2050 to 2100, leaving 23.5 GT for the period from 2010 to 2050.

A higher reduction rate achieved in 2050 or a faster reduction to zero emission, gives a higher available carbon budget before 2050. This can allow for a slower implementation of emission reduction measures towards 2030-2040. Table 2 shows the available carbon budget for four scenarios: reaching 50% or 80% reduction in 2050 compared to 2010 and zero emissions in 2080 or 2100.

The modelling in this study will assume at least 50% reduction in 2050, including offsets, and gradually reducing to zero emissions in 2100. This gives an available budget of 23 to 29 GT CO_2 in 2010 to 2050. The figures used throughout will only show the emissions to 2050.

Table 2: Available carbon budget from 2010 to 2050, and from 2050 onwards, given a 33 GT total budget and varying emission levels in 2050 and target year for zero emissions.

Reduction in 2050 (compared to current levels)	Zero emission in 2080		Zero emission in 2100	
	2010-2050	2050-2080	2010-2050	2050-2100
50 %	27.2 GT	5.8 GT	23.5 GT	9.5 GT
80 %	30.7 GT	2.3 GT	29.2 GT	3.8 GT

4 PATHWAY MODEL

Several activity-based models have been developed to provide long term outlooks of GHG emissions from shipping (e.g. Eyring et al. 2005; Buhaug et al, 2009; Eide et al 2009; 2013; Smith et al 2014; 2016). Recently, also top down energy system based models have reported long term outlooks for the energy mix for the world fleet (e.g. Hansson et al 2016, Raucci et al 2014, Grahn et al 2013; Fulton et al. 2015). Common to these studies, is the large span of baselines and reduction scenarios, which illustrates the large uncertainty in CO_2 projections.

The sections below describe the Pathway Model developed for this study, including assumptions made for establishing the baseline and promising mitigation trajectories.

4.1 Modelling approach

The high-level model developed in this study is inspired by previous bottom up activity-based models, and in particularly a simplified model developed by Eide et al (2009). In the new Pathway Model, the main features are the capabilities to:

- Analyze the uptake of reduction measures within specific ship segments;
- Calculate total CO_2 reduction, and average barrier and cost levels;
- Evaluate whether a set of solutions can achieve the given targets, and to which extent offsetting is needed to bridge the gap.

An outline of the modelling approach is given in Figure 3, indicating the different calculation steps. For a given reference year the activity-based model calculates the emissions per segment based on transport work, energy efficiency and carbon intensity. CO_2 reduction measures are defined with impact on one or more of these three factors, in addition to a barrier and cost level. For example, measures can potential improve the energy efficiency (e.g. hybridization, speed reduction), lowering carbon content in marine fuels (e.g. LNG, biofuel), and reducing demand in transport work (e.g. shorter routes such as across the Arctic). The measures can then be applied in different scenarios with specific uptake rates per segment and reference year, and the model calculates the resulting CO_2 emissions. Aggregating over the segments gives the CO_2 emissions for the fleet. The measures are applied in no particular order (e.g. fuel before speed reduction) and the contribution of each measure is the weighted average relative to the total reduction.

Offsetting is kept separate in the model. It keeps control over the aggregated carbon emission, and can calculate the need for carbon offsets to keep within the given carbon budget.

The following equation reflects the calculations made in the pathway model:

$$M = W \cdot E \cdot C \quad (1)$$

Where

M: CO_2 emissions, in tonnes CO_2

W: Transport work, in tonne-miles

E: Energy efficiency, in kWh per tonne-mile

C: Carbon intensity, in tonnes CO_2 per kWh

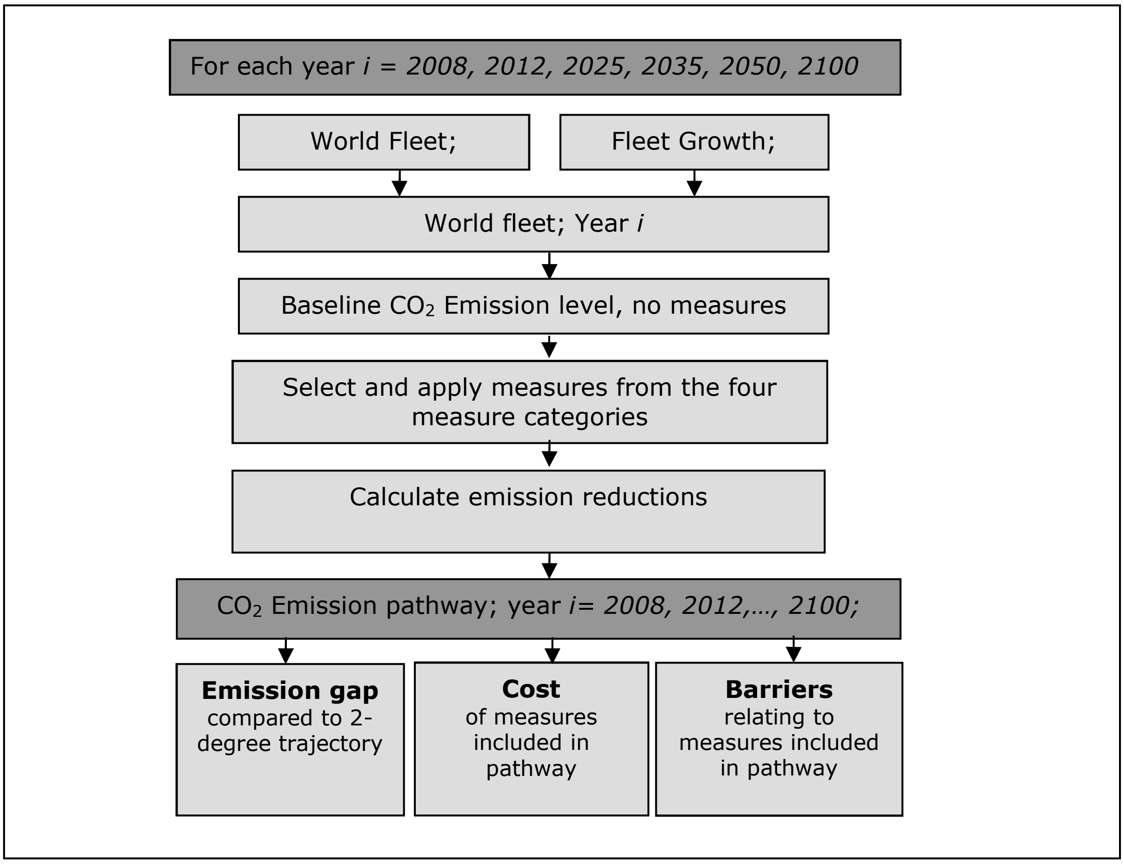


Figure 3: Model outline. The fleet growth rates produce the baseline CO_2 emissions through an activity based modeling approach. The introduction of abatement measures produces alternative emissions pathways.

4.2 Modelling of baseline CO_2 emissions

The baseline CO_2 emission in 2010 is developed based on fleet data from IMO GHG study 2014 providing the number of ships, transport work, fuel consumption, CO_2 emissions, average speed, average dwt and average days at sea per segment, for 2008 and 2012 (Smith et al 2014). The emission level for 2010 (about 860 MT CO_2) is assumed to be the average of the emissions in 2008 and 2012.

The data for the IMO GHG study segments are aggregated into the segments used in this study. The number of segments are kept at a minimum and represents the most typical ship types and operational patterns where measures will typically have a similar application and effect. Table 3 shows the selected segments trading internationally.

Table 3 also reflects the share of activity in domestic and international trade, as the scope of this study is international shipping. The vessels within the tanker, bulk and container/roro deep sea segments are all assumed to operate internationally, while in the short sea, passenger and offshore segments 75% of activity is assumed to be international. Other service vessels such as tugs are assumed to only operate domestically. This share is set so that the total emission corresponds with the emission level for 2012 in the IMO GHG study 2014.

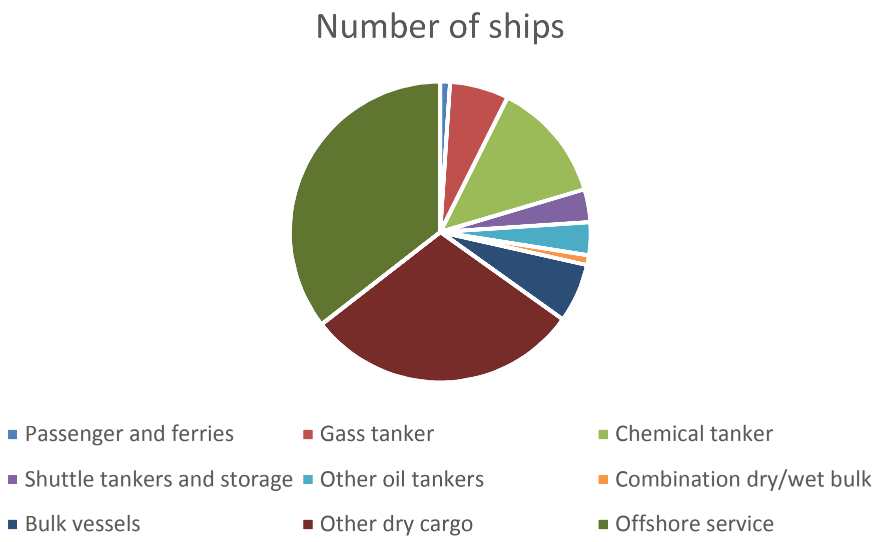
Energy efficiency and carbon intensity are calculated, reversing equation (1), from the emissions and fuel consumption in the baseline years, assuming a split between MGO and HFO of 15%/85%, and using the carbon and energy content per fuel given in the EEDI calculation guidelines (IMO, 2014).

The baseline emissions for 2020, 2025, 2035, 2050 and 2100 are derived by applying segment specific growth rates on the transport work and then calculating the emission using the same energy efficiency and fuel carbon content as for 2008/2012. Table 3 presents the applied segment growth rates that builds on Smith et al (2016). The transport demand projections are based on the SSP3 and RCP2.6 scenarios.

Table 3: Definition, growth rate and share of activity in international trade for each segment.

Segment	Vessels included	Share of activity in international trade	Annual growth rate (2010 to 2050)
Tank	All gas tankers, oil tankers above 20 000 dwt; and chemical tankers above 10 000 dwt	100%	-1.8 %
Bulk	Bulk carriers and general cargo above 10 000 dwt	100%	2.5 %
Container/roro	All container vessels above 1000 TEU; vehicle carriers above 4000 vehicles; roro vessels above 5000 dwt; and all reefers	100%	4.0 %
Short sea	All tank, bulk and container/roro below the above size limits	75%	1.6 %
Offshore	All offshore service vessels	75%	2.0 %
Passenger	All passenger ships, ferries, cruise and ro-pax vessels	75%	2.0 %

Note that the Norwegian controlled fleet in international trade is represented in all the segments in the world fleet, except for container vessels. Figure 4 shows that the cargo carrying capacity of the Norwegian controlled fleet in international trade have substantial contributions from six segments of roughly comparable size; gas tankers, chemical tankers, shuttle tankers, other tankers, dry bulk ships, and other cargo ships (general cargo). In numbers, the main contribution is from other cargo ships (general cargo). However, the offshore service segment is the largest segment in terms of numbers.



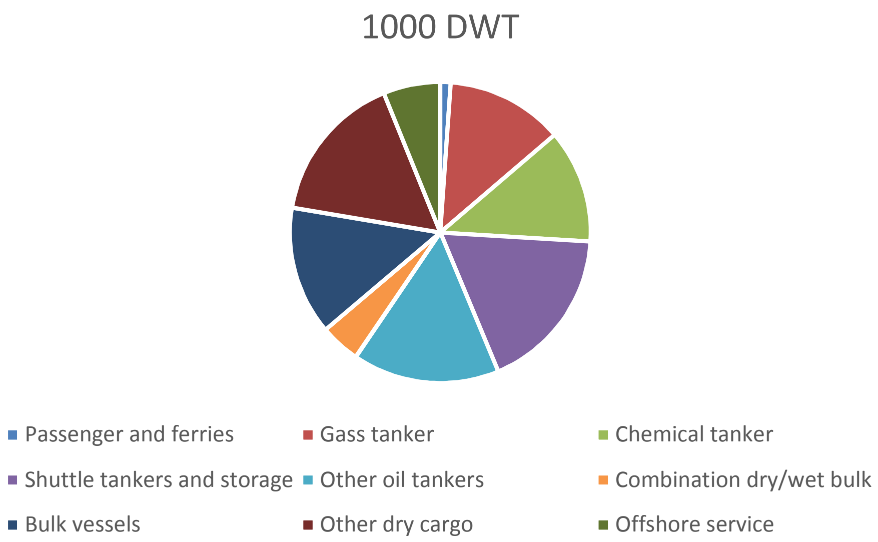


Figure 4: Norwegian controlled fleet in international trade, as of January 2016. In number of ships (top) and cargo capacity (bottom). From the Norwegian Shipowners' Association Annual report 2015[6].

4.3 Modelling of CO_2 emission pathways

This study evaluates mitigation measures within four categories: operational and technical energy efficiency, alternative fuels, logistics/speed, and offsetting (see Section 5). The model is developed to handle uptake of the measures based on the impact on energy efficiency, carbon intensity and transport work. For each mitigation measure the following parameters are assigned, based on litterateur review, DNV GL work, and expert judgement:

- Reduction potential per ship segment (impact on energy efficiency, carbon intensity and transport work). The reduction potential reflects both applicability for the segment and current

[6] https://www.rederi.no/om-oss/arsrapporter/

uptake of the measure, i.e. no reduction potential where the measure is not applicable and reduced potential if it is partly applied.

- Barrier level (1-4), as outlined in Section 4.3.1.
- Cost level (1-4), as as outlined in Section 4.3.1.

The high-level modelling approach allows evaluation of various pathways – or scenarios – in which measures are implemented to varying degrees in the fleet. A pathway is defined by setting uptake rates per ship segment and reference year. If the measure cannot be applied on existing vessels, the uptake rate is limited to the fleet renewal rate of 5% per year, assuming a 20-year vessel lifetime.

The CO_2 emission reduction for the fleet (or segments) can be modelled selecting measures only within one category or from combined categories. Figure 5 illustrates how example pathways A through D to a varying degree will implement measures within the four categories. In "extreme" scenarios (A, B) only one type of measure is allowed. In other pathways (C, D) combinations of measures are applied.

Pathways consistent with target

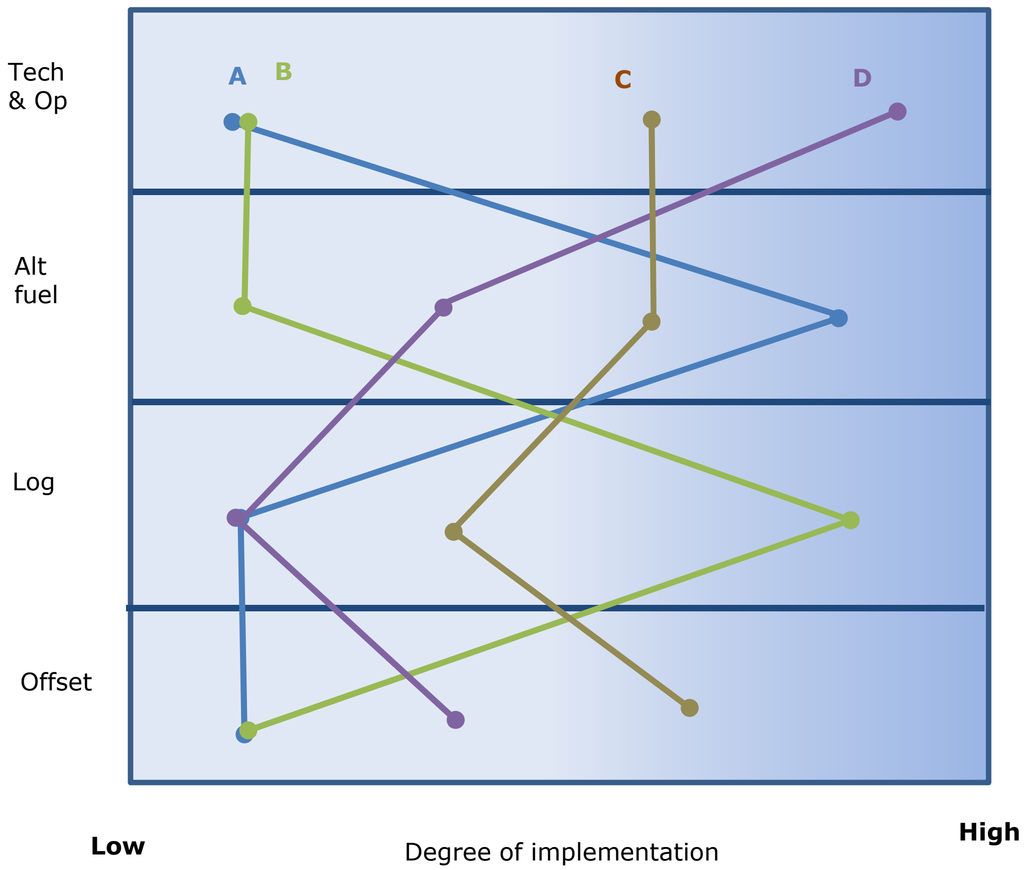
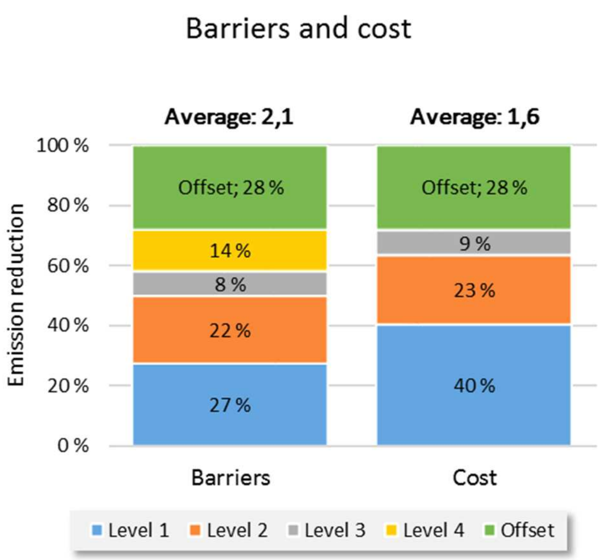


Figure 5: Illustration of different pathways. In each pathway measures from each of the four categories are applied to varying degree (from low to high). In "extreme" scenarios (A, B) only one type of measure is allowed. In other pathways (C, D) combinations of measures are applied.

Using the model developed in this study, each pathway will be evaluated based on the emission reductions achieved, but also on the *cost level* which can be associated with the applied measures; the *barrier level* of the same measures; and finally, the offset needed to keep within the carbon budget.

Applying only well-known measures will give low barrier and cost levels, but a high need for offsetting. Similarly, an aggressive reduction strategy can eliminate the need for offsets, but the barrier and cost levels will be high, indicating a higher risk. This is important as the barrier level has a substantial impact on the likelihood of given measure being implemented, and a simple cost optimization approach to emission reduction is deemed insufficient.

Figure 6 illustrates two options for how this evaluation can look for two pathways A and B (for barriers and cost only). Barriers and cost are both evaluated on a four-point scale, and the figures show the percentages of emission reduction achieved by measures within each of the four levels. Both pathways are assumed to achieve the required emission reduction, and differences in barrier, cost and offset levels are illustrated. For the two example pathways shown, the results indicate that the Pathway A has a higher barrier and cost level than Pathway B, but that more offsetting is required in the latter. The higher barrier level indicates a higher exposure to challenges of a practical, legislative, organizational, technological, or logistical nature.



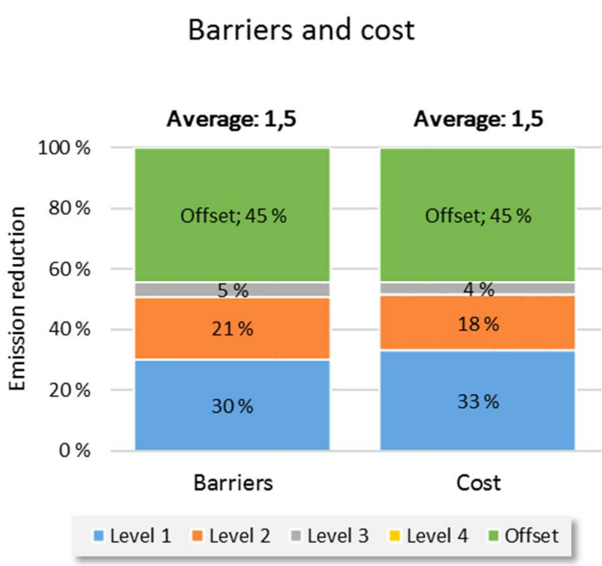


Figure 6: Illustrations of how pathways are evaluated in the model.

4.3.1 Assigning barrier and cost level

Quantifying and comparing the costs and uptake, including projections 30-40 years into the future is challenging. The measures evaluated in this report are very different in nature, both on impact of the cost level and how mature they are with regards to uptake in the fleet:

- Energy efficiency measures can be applied considering only aspects relating to the ship itself. However, new solutions need testing and maturing. Technologies start out as expensive, but after testing and early implementation, as production rates increase, costs usually go down.
- New types of fuel require availability (production and distribution), bunkering infrastructure and in many cases, extensive on-board ship modifications. Building up fuel infrastructure need significant support from society before it becomes a viable alternative.
- Logistics and speed measures may impact the transport system, thus involving stakeholders such as cargo owners, port operators and other actors down in the chain. It can take years before they can be implemented as they require cooperation and coordination across many stakeholders. Logistics measures are typically not based on technology solutions and do not follow the same cost development.
- Offsetting requires administration and a source for purchasing emission units, possibly connected to a global market.

For barriers, the study applies a 4-level scale based on years to maturity. A barrier level of 1 indicate high maturity and a measure that is commercially available, and 4 indicate low maturity and a measure that is not even on a pilot stage. The barrier level reflects technological, practical, legislative, organizational, or logistical challenges implementing the measure. The barrier level is evaluated per the status today.

Similarly, the study does not model costs in detail, but uses a qualitative 4-level scale based on a cost range. The scale is based on a simple model of shipping costs, given a fuel price of 500 $/tonne which will be the base cost, after the introduction of the 0.5% sulphur limits in 2020. The cost split is assumed to be 35% for capital costs, 50% for voyage costs of which 70% are fuel costs and 15% for other operational costs (Stopford, 2009). The percentages will vary significantly between different ships types and sizes, but this is an approximation made to be able to simplify the cost impact.

A score of 1 indicate that a measure will not increase costs, while 4 indicate a cost increase of more than 35 % per ton transported. The cost level reflects the difference between cost of implementing a measure (both capital costs and operational costs) and the benefit from the measure (includes fuel cost savings and increased revenue). Table 4 describes the cost assessment levels. All measures on the same level have about the same cost impact on the transportation cost per tonne. Offset costs are included as a benchmark level with level 1 set at no cost of carbon. Cost of logistics measures are not included, but speed reduction is evaluated in the same way as energy efficiency measures.

Table 4: Cost assessment levels. Costs are evaluated at maturity.

Level	Fuel cost	Capital costs	Energy efficiency	Offset
1 Current	Current MGO price level: 500 $/t (~45 $/MWh)	No increase in capital costs	Cost-effective at 500 $/t fuel price over 10 years	0 $/t CO2
2 +5-15 %	Fuel price: 750 $/t (~65 $/MWh)	40 % increase in capital costs	Cost-effective at 750 $/t	75 $/t CO2
3 +15-35 %	Fuel price: 1000 $/t (~90 $/MWh)	100 % increase in capital costs	Cost-effective at 1000 $/t	150 $/t CO2
4 +35- %	Fuel price above 1000 $/t (~90 $/MWh)	More than 100 % increase in capital costs	Not cost-effective at 1000 $/t	>150 $/t CO2

Table 5 describes the barrier levels. The barriers and cost of a technology are typically interlinked and they drive each other. In its early stages technologies are on a research stage and very expensive. It will then start to be piloted, and as more experience is gained, barriers are removed and the cost goes down. When implementation picks up, scale of economies reduces costs even more. However, the implementation does not pick up if the cost is too high, and this is a critical stage for any technology. If this gap is not bridged, the implementation stops. The barrier level thus reflects the risk of a measure not being applied.

We assume that any measure that is applied in a pathway will become mature. This again will have an impact of costs as we expect a significant learning effect and cost reduction. Thus, the costs of the measures are evaluated at maturity, *when the barriers are overcome* and the solutions are in common use.

Table 5: Barrier assessment levels. The barrier level is evaluated per the status today. A higher barrier level indicates more uncertainty or risk and a longer time to market and maturity.

Level	Barrier aspects			
	Regulations and organisation	**Infrastructure**	**Technology**	**Logistics**
1 Current	Measures that can be applied without involvement across stakeholders and under current regulations	Fuels that are readily available world-wide, and can be used with conventional mature engine technology	Measures that are off the shelf and commonly used on new ships	No changes to transport systems
2 2-5 years to maturity	Measures that need limited involvement across stakeholders; minor changes to regulations needed	Fuels that are generally available, but in a limited number of locations; needs technology that are commercially available but not fully mature	Measures are commercially available, but not fully mature	Minor changes to transport systems, but can be applied by ship owner (in isolation)
3 5-10 years to maturity	Measures that need significant involvement across stakeholders; major changes to regulations, but scope is known	Fuels that are only available in specific locations and must be specifically sourced; needs technology that are not previously used in the marine sector; pilots underway	Measures that are under piloting, and/or with only a few commercial applications	Major changes to transport systems, but minor impact on value chain of cargo owners
4 More than 10 years to maturity	Measures that need significant involvement across stakeholders over time; regulations needed but scope not know	Fuels that are only available in very limited amounts and must be specifically sourced; needs technology that has not been scaled up for marine use; no piloting are underway	Measures that have not been tested in full scale and no piloting or full-scale testing underway	Major changes to transport systems and value chain of cargo owners

5 AVAILABLE MEASURES FOR CO_2 REDUCTION

A large number of measures are available for reducing CO_2 emissions from shipping (e.g. Eide et al 2013, DNV GL 2016b, IMO 2016; Maritime Knowledge Centre, TNO & TU delft, 2017). In this study, the available measures for CO_2 reduction are grouped into four main categories:

- operational and technical energy efficiency measures;
- alternative fuels (incl. batteries and other energy carriers)
- logistics and speed reduction; and
- offsetting

This section gives a brief overview of measures applied within these categories. As outlined in Section 4.3, the applicability for each segment; barriers; expected cost; and reduction potential are determined for each measure.

5.1 Technical and operational measures

The fuel saving and CO_2 emission reduction measures are typically divided into measures for reducing propulsion energy demand, and measures reducing the onboard energy use of other consumers. The mitigation measures ranges from easily achievable operational opportunities to capital intensive technical solutions.

In this section, a brief overview of the technical and operational measures applied is given. The work is based on a DNV GL report for Enova (DNV GL, 2016a) and Marginal Abatement Cost Curve (MACC) studies (e.g. IMO 2011, OECD, 2009; Eide et al 2011, 2013; Longva et al 2010; Hoffmann et al 2012), assessing the cost-effective and maximum reduction potential in 2030 (and 2050). The results indicate cost-effective reduction potential for technical and operational measures (not including fuels) in the range of 20-30 %, and up to around 50-60 % if including the more expensive and novel technologies and solutions.

As the purpose of this study is to evaluate possible long term emission reductions, the measures are grouped per barrier level, indicating at which time the measures can be applied, rather than by functional area such as hull, machinery and operations. The measures applied are grouped as:

- **Quick wins:** measures that are mature today and in common use for new builds.
- **Up and coming:** measures that are tested and well known, but are still 3-5 years from being commonly applied.
- **Next generation:** measures that are being piloted today and are between 5-10 years from becoming mature.
- **Black swans:** measure that are only at an idea stage. The impact and applicability of these measures are highly uncertain.

The estimated reduction potential of the measures is reflecting the potential on future new builds relative to the average of the fleet in 2012. For simplicity, retrofitting measures are not included, as this has limited impact on the results towards 2050 because of the fleet renewal rate.

The use of batteries supplementing auxiliary engines (battery hybridisation) are included as an energy efficiency measure in this section, while batteries charged from shore power are considered an alternative fuel.

5.1.1 Quick wins

The quick wins include measures that are 'off the shelf' and commonly used on new ships, but that still have potential for increased applicability and effectiveness relative to 2012. The category includes all measures on hull and propeller efficiency, including operational measures such as hull coating and cleaning. Further, it includes all voyage execution measures such as trim/draft optimization, weather routing, combinator optimization and autopilot use. Finally, the category includes improving auxiliary engine load and cargo operations.

The reduction potential of the quick wins is estimated to 13-20 % depending on ship type. The highest effect will be on ships with a high share of time in cruising mode such as tank, bulk, container/roro and short sea. The barrier and cost levels are set to 1.

5.1.2 Up and coming

Up and coming technical and operational measures are well known, but there are still challenges to applying them for maritime use and for expanding the applicability to more ships types and sizes. The technologies behind these measures are focused on improving the machinery and electricity system. The category includes optimization of auxiliary system; use of direct current (DC) power; hybridization (peak load shaving in conjunction with batteries); use of shore power; shaft generators and waste heat recovery.

Advanced process modelling tools is expected to improve the overall energy performance for ships, promoting tighter overall system/heat integration (e.g. boilers, heat exchangers, piping), optimized waste heat recovery system (incl. low temperature), and higher degree of flexibility (e.g. Dimopoulos et al 2012, 2014, 2015). The effectiveness and applicability are dependent on the operational mode of the vessel, and the solutions must be customized to some degree.

The introduction of batteries enables selection of smaller engine sizes that can operate at optimal loads for a larger portion of the time, due to additional power being obtained from the batteries when required (peak loads). When power requirements are low, the batteries can be charged using the excess energy generated by running the engine still at the optimal load. Also, for vessels with electric cranes and other cargo equipment with transient peak loads and options for regenerating power, batteries can introduce significant benefits. The introduction of a hybrid system is expected to reduce the fuel consumption of up to 20% depending on the ship type and its operational profile. Hybrid operations with batteries for a supply ship have shown in practice 15% fuel consumption and CO_2 emission reduction (the FellowShip project).

The reduction potential of the up and coming measures is estimated to 12-24 % depending on ship type. The highest effect will be on ships with variable operational modes and engine loads, such as offshore and passengers. The barrier and cost levels are set to 2.

5.1.3 Next generation

The next generation technical and operational measures are solutions still in a piloting stage, or with only a handful commercial applications. It includes use of wind power and air cavity lubrication.

The first commercial application of an air lubrication system is expected in 2017[7], while others are under consideration[8]. Such systems can have saving potentials around 5% or higher, depending on speed and ship type.

[7] http://shipandbunker.com/news/emea/709523-first-commercial-silverstream-air-lubrication-system-installed-on-norwegian-cruise-ship

[8] AIDA Cruise ships along with few other shipping companies have already confirmed of plans to

Various actual sail arrangements (e.g. sail, kite, fixed wing, Flettner rotors) have been tested out on merchant vessels over the years (e.g. DNV, 2010a). Large scale experiments were carried out using fixed wing sails during the oil crises in the late 1970s and early 1980s, and the reported fuel saving was 30% under optimal wind conditions (e.g. bulk/log carrier Usuki Pioneer), (UNCTAD[9], Brett 1984). Promising wind concepts have also recently been reviewed[10]. A new Delft study estimated significant saving potentials for wind powering and found that the larges tank and bulk ships had the largest potential. An overall CO_2 reduction for the world fleet of 3.7% was projected in 2050 (Delft, 2017). Currently three ships (Research, ro-ro, ro-lo vessel) have installed wind rotors and one is under planning (Delft, 2017). In addition, three ships (two multi-purpose, one bulk carrier) are equipped with a towing kite. It is also reported[11] that the first modern auxiliary wind propulsion technology will be retrofitted onboard a ferry in 2018. More radical concepts[12] are also reported, claiming large fuel and emission savings.

Figure 7: The first deep sea merchant ship designed and outset for sail-assisted propulsion, a 26000 dwt bulk/log carrier Usuki Pioneer (Brett, 1984).

The reduction potential of the next generation measures is estimated to 6-10 % for deep sea vessels going long distances, depending on ship type. The barrier and cost levels are set to 3.

5.1.4 Black swans

Black swans and technologies are solutions that we only have an idea about, but may be developed into workable solutions towards 2050. For example, wave powering[13] of ships have been researched for decades, and could emerge as an applicable solution.

Increased uptake of solar power could also emerge. Solar power on ships is not very common at present, but some installations have been done recently. This has been in the form of solar panels installed on a vehicle carrier. The solar panels installed will only be used to "small" supplement to the diesel generators and thus reduce the power required from these units. The solar power units can produce energy both at

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implement Air Lubrication Systems on their ships http://www.marineinsight.com/green-shipping/how-air-lubrication-system-for-ships-work/

[9] Low Carbon Shipping Module: http://unctadsftportal.org/wp-content/uploads/2016/08/PRINT-2b-Case-Studies-of-Previous-PacificTrials.pdf

[10] http://www.marineinsight.com/green-shipping/top-7-green-ship-concepts-using-wind-energy/
http://www.nsrsail.eu/wp-content/uploads/2015/12/Wind_powered_shipping-Lloyds-Register.pdf

[11] Viking Grace: http://worldmaritimenews.com/archives/211233/viking-grace-to-become-1st-ship-with-wind-propulsion-system/

[12] Vindship: http://www.ladeas.no/

[13] The history of wave-powered boats: http://www.wavepropulsion.com/ and
http://www.bluebird-electric.net/wave_powered_ships_marine_renewable_energy_research.htm

sea and in port, but only during daylight. It is reported[14] that Auriga Leader, a ro-ro ship, is fitted with over 300 solar arrays. An innovative hybrid concept[15] has been proposed, that incorporates a variety of elements including solar panels, energy storage modules, a computer control systems and an advanced rigid sail design, claiming fuel savings of 40% or more.

Avoiding ballast water and the required treatment can reduce the energy consumption and emissions. Innovative ballast free ships concepts proposed[16] include continuous flow concepts (ships which allow for the continuous flow of sea water through specifically designed tanks and/or trunks) and no ballast water concepts (ships that do not use water ballast at all) such as the DNV GL Triality concept ship.

Looking to 2050 we can even expect to see new solutions that we have not thought of today. The reported savings are also to a large degree based on theoretical calculations and optimistic claims. This makes it inherently difficult to include them in a model. They are included to show the potential impact of such technologies and as a reminder that novel technologies and solution may see large scale implementation in the fleet. As such they are given a flat reduction potential of 15 % with barrier and cost levels set to 4.

5.1.5 Summary

Table 6: Summary of technical and operational measures.

Measure	Applicable for	Barrier level	Cost at maturity	Potential reduction
Quick wins (incl. propulsion, voyage execution, auxiliary load)	All segments, various impact	1	1	13-20 %
Up and coming (incl. advanced machinery, hybridization, waste heat)	All segments, various impact	2	2	12-24 %
Next generation (incl. renewables, air cavity lubrication)	Tank, bulk, container	3	3	6-10 %
Black swans (incl. ballast-free ships, wave power)	All	4	4	15 %

14 Auriga Leader, a RoRo Ship: http://www.marineinsight.com/types-of-ships/auriga-leader-the-worlds-first-partially-propelled-cargo-ship/
15 Aquarius Eco Ship: http://www.ecomarinepower.com/en/aquarius-eco-ship
16 http://www.maritime-executive.com/article/moving-towards-a-ballast-free-future

5.2 Alternative fuels

For marine applications, the fuel alternatives to bunker fuel oils and diesels include LPG (Liquefied Petroleum Gas), LNG (Liquefied Natural Gas), Methanol, Ethanol, DME (Dimethyl ether), synthetic fuels, biodiesel, biogas, electricity (i.e. battery) and hydrogen and nuclear fuel (e.g. IEA, 2014; Chryssakis et al 2014). The potential for marine applications will depend on factors related to meeting emission requirements, physical and chemical characteristics, availability, cost, safety, and environmental and overall GHG footprint (e.g. Chryssakis et al 2013; 2014, 2015).

LNG powered vessels have already been introduced (currently 102 ships in operation and 108 confirmed newbuilds), biofuels (incl. renewable) and methanol [17], [18] are available in certain ports, and full electrical/hybrid ships are emerging in the short sea, offshore and passenger segments. The recently introduced two-stoke dual fuel engines has increased significantly the fuel flexibility, as they use fuels such as methanol, ethanol and LPG (or LNG/NG, Ethan), in addition to HFO/MGO. Marine fuel cells are also emerging, providing a higher efficiency and thereby lower fuel consumption and associated emissions.

Nuclear propulsion has been used only within a limited number of merchant ships (Savannah (USA), Otto Hahn (Germany), Mutsu (Japan), Enrico Fermi (Italy)), and on a few Russian ice-breakers. Nuclear power could cut emissions if applied on large ships (e.g. Eide et al 2013). However, the need for a special infrastructure to deal with radioactive waste, the requirements of scientific personnel on board, and societal fears surrounding this technology (particularly nuclear proliferation concerns) have precluded widespread use of nuclear propulsion in the civilian fleet. As such, on-board nuclear reactors are not expected to be used commercially in shipping towards 2050 and are not considered further in this study. Nuclear power can however, be used to produce electricity, hydrogen and other low carbon fuels that can be applied by ships.

Previous studies (e.g. Eide et al. 2013) have shown that achieving large CO_2 reductions will require a shift to low carbon fuels or energy carriers. In this study the following alternative low-carbon fuels are described in more detail, and used in the modelling:

- Liquids biofuels (diesel engines)
- LNG/Bio-LNG (diesel engines)
- Electricity (shore power/battery storage, diesel engines)
- Hydrogen (marine fuel cell)

The selection of alternative fuels is based on studies pointing toward the most promising candidates for shipping (e.g. Chryssakis et al 2013, 2014, 2015; DNV GL 2016a, b, c, d; IEA 2014; Royal Academy of Engineering 2013; Energy Research Partnership 2016).

The life cycle emissions vary from very low to high deepening of factors such as the energy source and supply chain. Common for these energy carriers/fuels are the need for infrastructure and technology development. Challenges also relates to factors such as availability, fuel price (Table 7), engine and fuel system cost, indirect cost (e.g. reduced range, reduced cargo space), (e.g. IEA 2014). An updated review of global production of alternative fuels is given by Maritime Knowledge Centre, TNO & TU delft

[17] Stena Germanica bunkering in Gothenburg is the only example of methanol bunkering to a ship being carried out presently, http://www.bunkerindex.com/news/article.php?article_id=18047

[18] Seven 50,000 dead weight tonne vessels are built with the first-of-its kind MAN B&W ME-LGI 2-stroke dual fuel engine that can run on methanol, fuel oil, marine diesel oil, or gas oil. https://www.methanex.com/about-methanol/methanol-marine-fuel#sthash.oW84bYPp.dpuf

(2017). For example, it is reported 53 MT hydrogen produced per year, 32 MT biodiesel produced per year, and 170 Mt straight vegetable oils produced per year (SVO).

In the following sections, each of the four alternatives are described.

Table 7: Historical and expected price ranges (€/MWh) for potential marine fuels (Source: Taljegård et al 2015).

Heavy fuel oil	17-43
Marine gas oil	32-68
Rapeseed methyl ester	90-140
Fischer-Tropsch biodiesel[a]	50-97
Liquefied natural gas	11-43
Liquefied biogas	40-180
Methanol (from natural gas)	18-54
E-methanol[a,b]	80-140
Hydrogen gas (from electrolysis)[a,b]	75-90

[a]The figure represent expected production cost range and not price
[b]The low range is for a future (optimistic) scenario of investment cost and electricity-to-methanol efficiency (see 2.4) and high range represents estimates from the base case scenario assuming an investment cost and efficiency of the production process as of today. In both calculations, a capacity factor of 70% is assumed.

5.2.1 Liquid biofuels

Biofuels derived from biomass or biomass residues are commonly divided into first-, second, and third-generation biofuels. As described by the European Biofuels Technology platform the definition of conventional (first generation) or advanced biofuels (second and third) depends on source of carbon used[19]. The CO_2 reduction potential of biofuels varies widely, depending on the specific feedstock and generation biofuel (IEA 2011, Ecofys 2012). Bengtsson et al. (2012) report CO_2 reductions of up to 80-90% for certain types of biofuels, based on lifecycle assessments. Advanced biofuels (diesel replacement) have a GHG reduction (compared to petroleum-based diesel fuel) between 20% and 120% (savings over 100% reflects use of bioproducts), (IEA 2011). The reduction potential is set to be 10-90% in this study, depending on generation biofuel and % blending.

Depending on biodiesel type the use of biofuels take the form of drop-in fuels (i.e. substitute for conventional fossil fuels and compatible with existing infrastructure and engine system) or through modification of infrastructure and engine systems. Challenges reported for first-generation biofuels includes fuel instability, corrosion, susceptibility to microbial growth, and poor cold flow properties. These technical challenges are largely resolved for the next generation biofuels. Still, widespread use of biofuel in shipping will depend on production cost, incentives for use (including CO_2 regulation), and availability in sufficient volumes. Currently, volumes available for shipping is limited[20].

Several demonstration projects have been carried out over the years, and are listed in Appendix D of Ecofys, (2012), and more recent by IRENA (2015). In Amsterdam[21] and Rotterdam biofuels are available replacing premium MGO, and it is reported to be "considerable uptake" (e.g. Dutch coastguard). In

[19] the European Biofuels Technology platform: http://www.biofuelstp.eu/advancedbiofuels.htm#whatare
1st Generation - the source of carbon for the biofuel is sugar, lipid or starch directly extracted from a plant. The crop is actually or potentially considered to be in competition with food.
2nd Generation - the biofuel carbon is derived from cellulose, hemicellulose, lignin or pectin. For example this may include agricultural, forestry wastes or residues, or purpose-grown non-food feedstocks (e.g. Short Rotation Coppice, Energy Grasses).
3rd Generation - the biofuel carbon is derived from aquatic autotrophic organism (e.g. algae). Light, carbon dioxide and nutrients are used to produce the feedstock "extending" the carbon resource available for biofuel production. This means, however, that a heterotrophic organism (using sugar or cellulose to produce biofuels) would not be considered as 3G.

[20] http://www.fathomshippingevents.com/uploads/2/5/3/9/25399626/dnv_gl_presentation.pdf

[21] Biofuels are already available in Amsterdam and Rotterdam: http://www.seatrade-maritime.com/news/americas/will-biofuels-become-significant-alternative-fuel-for-shipping.html

Norway ferries and smaller passenger vessel (Ruter and Fjord1) are already[22, 23] using advanced renewable biodiesel, and it is also available at marinas[24] (e.g. Tofte, Norway). The third-generation algae based biofuels has also recently been tested on the container ship Maersk Kalmar (Ecofys 2012, IEA 2014). IRENA (2015) report that algae based fuels may be promising candidate for shipping, as the production could occur close to ports and coastal areas, less reefing is needed and the large diesel engines can run on lower grad HFO fuel. It is expected increased production and availability towards 2050 (e.g. Ecofys 2012, Smith et al. 2016).

Biofuel is evaluated as relatively mature at its current technology level, except for third generation. This study therefor has assumed a barrier level in the range of 2 to 4, depending on generation biofuel. It is recognized that game changes for the industry could occur, e.g. widespread, cheap extraction, or breakthroughs in biofuel production technologies.

Biofuels will in most cases be more expensive[25, 26] than fossil fuels, and particularly for advanced renewable biofuel (e.g. Ecofys 2012, MAN 2016). This is due to higher production costs and lower economics of scale. The potential for reducing fuel costs is expected to be higher for second generation fuels, compared to first generation where a major part is already taken (Festel et al. 2014; Van Eijk et al. 2014). This development is supported by reported price projections (IEA, 2011, their Figure 13). Additional costs related to modifications of the ship's engines and infrastructure for running on conventional biofuel are estimated by engine manufacture to be less than 5% of the engine cost (Ecofys 2012). For advanced biofuels, no additional cost is expected for engine and infrastructure. The above data indicate a cost level at maturity of 2 to 3, depending on generation biofuel.

5.2.2 LNG/Bio LNG

Liquefied Natural Gas (LNG) is a fossil fuel and its CO_2 emission reduction potential is estimated at around 10–20% compared to HFO/MDO (Bengtsson et al 2011, 2012; Verbeek et al 2011), from a lifecycle perspective. LNG has already been used since around 2000, and mostly by small sized short sea ships. As of March 2017, there are 102 LNG powered vessels in operation (excluding LNG Carriers and inland waterways vessels), and 108 confirmed orders for vessels that will be built in the next five years (see Figure 8). Large volumes of natural gas are available today and the next decades, but there is still a lack of a global infrastructure and bunkering facilities for shipping. This is reflected by using a barrier level of 2**.**

It is expected that strict regulations on NOx and SOx emissions, combined with a more competitive gas price, will drive the uptake of gas as a marine fuel. Based on recent experience, the new-building cost of LNG-fuelled ships is about 10–30 % higher than for equivalent diesel-fuelled ships (Æsoy et al, 2011; Chryssakis et al 2015). The extra investment needs to be compensated in operations, and will depend on oil and gas prices. The recent drop in oil price seems to have an impact on uptake of LNG ships, as the payback time increases. This study assumes a future gas price that is competitive with MGO, and the cost levels is set to 2.

Bio-methane/LNG could be an attractive low carbon alternative to LNG, that could use the existing and upcoming LNG infrastructure. This fuel has gained increasing interest in the shipping sector. In Norway

[22] Ruter: https://ruter.no/om-ruter/miljo/gassdrevne-passasjerferger/
[23] TU: http://www.tu.no/artikler/de-blir-verdens-tre-forste-ferger-pa-kun-biodrivstoff/275609
[24] 2G marin: http://eco-1.no/2g-marine-fornybar-diesel-til-fritidsbater/
[25] Nets: https://www.neste.com/en/corporate-info/investors/market-data/biodiesel-prices-sme-fame
[26] NP: http://www.np.no/aktuelle-saker/biodrivstoff-i-budsjettforliket-article1031-140.html

MS Prinsen, operating in Oslofjorden, is probably the first in the world to sail on biogas[27]. In addition, the Samsø ferry in Denmark is planning to sail on biogas in 2018.

The cost level for bio-LNG is set to 3, based on the assumed higher fuel price relative to LNG (Table 7). The barrier level is set to 3 to 4, depending on generation.

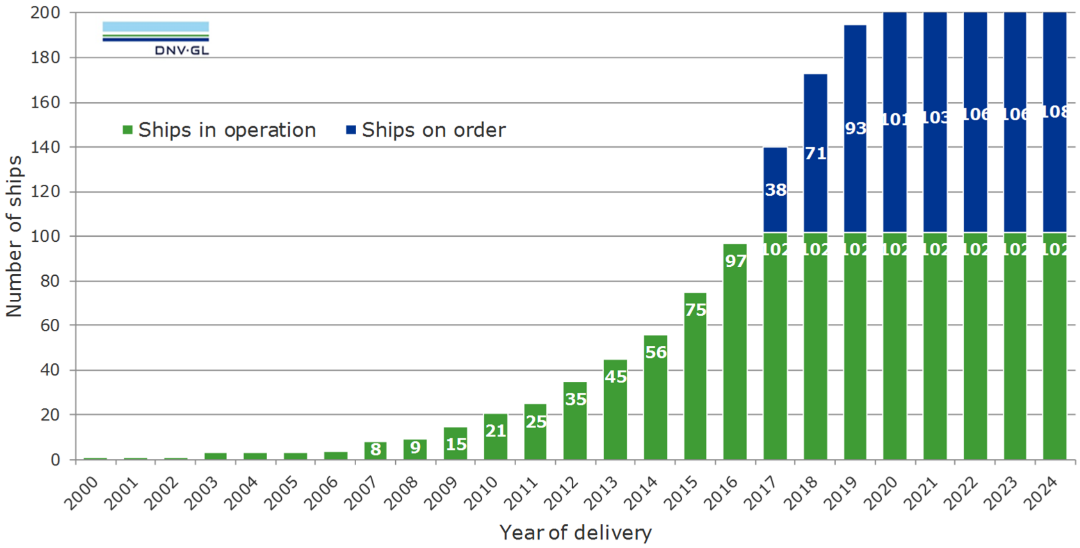

Figure 8: LNG ships in operations and on order as of March 2017.

5.2.3 Electricity

On a *full-electric* ship, all the power, for both propulsion and auxiliaries, comes from batteries which are charged from an on-shore connection to the electric grid while at berth. A *plug-in hybrid* ship, like a plug-in hybrid car (PHEV), can charge its batteries using shore power and has a conventional engine in addition. The ship can operate on batteries alone on specific parts of the route, e.g. when manoeuvring in port, during stand-by operations. A *conventional hybrid* ship uses batteries to increase its engine performance and does not use shore power to charge its batteries. This study has considered *full-electric* and *plug-in hybrid* ship as alternative fuels, with an assumed CO_2 reduction potential increasing up to 90% in 2050. Conventional hybrids are covered in the section on Technical and Operational measures (Section 5.1). Limited shore based infrastructure is available today for charging, but progress is made in certain regions[28,29] (e.g. Ecofys, 2015).

The first full electrical ferry Ampère[30] has been in service between Lavik-Oppedal on the west coast of Norway for around two years. The next full electrical ferry[31] will be in service between Pargas og Nagu in Finland from summer 2017. There are also several electrical ferries under construction[32], intended to

[27] TU: https://www.tu.no/artikler/kapteinen-om-bord-pa-verdensnyheten-jeg-kjenner-ingen-forskjell/363685

[28] First for Shore Power in India: http://www.maritime-executive.com/editorials/first-for-shore-power-in-india

[29] Shore power, Norway: http://www.tu.no/artikler/havner-vil-fa-hurtigruten-over-pa-landstrom/193818 http://www.mynewsdesk.com/no/enova-sf/pressreleases/140-millioner-til-landstroem-1689508

[30] Teknisk ukebald:http://www.tu.no/artikler/denne-fergen-er-revolusjonerende-men-passasjerene-merker-det-knapt/222522

[31] Teknisk vekeblad: http://www.tu.no/artikler/eksporterer-batteriteknologi-til-finland/278058

[32] http://www.fjord1.no/ferje/byggjer-tre-el-ferjer, https://www.tu.no/artikler/e39-far-to-tyrkiskbygde-el-ferger/348601

operate at the west coast of Norway. Several plug-in-hybrid ferries are on order, and there are plans[33] for building short sea ships with plug-in capabilities. A new plug-in hybrid ferry on biodiesel will be operating between Tjøtta-Forvik in Helgeland (North of Norway) from spring 2017[34]. In addition, the first hybrid cruise ships[35,36] (Hurtigruten) will be delivered in 2018 and 2019. They will be installed with a battery of 1.36 MWh sufficient for 30 minutes full electrical powering in transit. Later it is planned to extend it to a 5 MWh battery pack, reported sufficient for 3-4 hours of full electrical powering in transit. The above status is reflected by a barrier level of 3.

Installing battery systems (incl. replacement after typically 8-10 years) on board is significantly costlier, compared to traditional diesel engines. In addition, infrastructure investments on land is required to provide electricity. The electricity production from hydropower is reported to be price competitive (e.g. Hansson et al 2016, DNV GL 2015) with MGO. However, considering the uncertainty about future electric prices and the large geographical variations (IEA 2015), it is expected to be challenging to pay back the investments (thorough only the price difference). Reflecting this, the cost level is set to 3**.**

5.2.4 Hydrogen

Hydrogen is a potential energy carrier, produced in different ways such as by reforming natural gas and electrolysis. When used in combination with a marine fuel cell the CO_2 emission could be reduced, probably in the range of 10-90%. The highest reduction relates to production based on renewable/nuclear energy, while the lowest reduction relates to reforming from natural gas (Chryssakis et al 2014). However, future use of carbon capture and storage (CCS) technology could strenghten the case for reforming. Hydrogen is available[37], but it is lack of a global infrastructure and bunkering facilities. Increased production and availability is expected towards 2050. For example, a mobile production units already exists - the Hydrogen Challenger[38], a 66-metre tanker for mobile hydrogen production.

Until recently fuel cells have been applied only for special purposes, such as space application and submarines. Fuel cells provide higher efficiencies and thereby lower fuel consumption and associated emissions. At optimal load efficiency of 45-50% is expected, slightly higher than state-of-art marine diesel generators (DNV, 2012). When including the significant potential for heat recovery, the efficiency increase to 55-60% (DNV, 2012). Noise and vibrations are insignificant and in addition fuel cells require less maintenance compared to conventional combustion engines and turbines. The challenges include the need for clean low carbon fuel, relatively short lifetime in addition to the need for reductions of size and weight.

The fuel cell convert the chemical energy of the fuel to electric power through electrochemical reactions. The process can be similar to battery, but with continuous fuel and air supplies. Different fuel cell types are available, and their names reflect the materials used in the membrane. The properties of the electrolyte membrane affect the allowable operating temperature, the nature of electrochemical reactions and fuel requirements (Larminie 2003, DNV 2012). DNV GL (2016d) recently evaluated seven fuel cell technologies, and concluded that the Solid oxide fuel cell, the PEM (Proton Exchange Membrane) fuel cell and the high temperature PEM, are the most promising for marine use. Depending of fuel cell

33 Teknisk ukeblad http://www.tu.no/artikler/disse-fem-prosjektene-skal-gjore-norsk-skipsfart-mer-miljovennlig/275588

34 NRK: https://www.nrk.no/nordland/forst-i-verden-1.12843626

35 Speifikasjoner: http://www.tu.no/artikler/na-er-det-like-for-slik-skal-hurtigrutens-ekspedisjonsskip-seile-miljovennlig-i-arktiske-strok/364004

36 https://www.cruiseindustrynews.com/cruise-news/15765-new-hurtigruten-ships-will-be-first-hybrid-cruise-ships.html

37 The global hydrogen industry is well established and produces more than 50 million tonnes of hydrogen per year http://www.chfca.ca/education-centre/what-is-hydrogen/

38 It is stationed in the German Bight or near Helgoland (where there is most wind) and docks in Bremerhaven where the produced hydrogen is delivered to the market. A vertical axis wind turbine generates electricity for the electrolysis of water to fill the hydrogen storage tanks. https://en.wikipedia.org/wiki/Hydrogen_Challenger

type they can be powered by low carbon fuels such as natural gas (reducing particularly NOx, SOx, PM) and hydrogen. If hydrogen is generated from renewables, zero emission ships are introduced.

Driven by the expected improved performance and efficiency, fuel cells for ships have become a subject of development and large scale testing during the last decade, but application in shipping is still in its infancy. Several demonstration projects have been carried out, and is described in DNV (2016d). One of the largest demonstration project was Fellowship that successfully prepared, implemented and tested hybrid systems on a supply ship (use of marine Molten Carbonate fuel cell (MCFC) and energy storage/battery).

Norway has an ongoing development, with ambitions of putting in service a new ferry on hydrogen in 2021[39]. If success, it is expected that national regulations will be developed to secure safe and effective introduction of hydrogen. Several demonstration projects have been carried out testing marine fuel cell fuels on LNG and methanol (e.g. DNV 2012; DNV GL 2016d). According to Motorship, two vessels are to be built for Royal Caribbean Cruise Lines featuring new generation of LNG-fueled cruise ships with LNG propulsion and fuel cells for power generation. The aim is to develop fuel cells for powering the ship's hotel functions, converting from fuels such as diesel or LNG. The two 200,000 GT ships are to be delivered in 2022 and 2024. Several Scandinavian companies[40] have entered an agreement to develop hydrogen projects that will initially focus on the maritime area. Based on the above, barrier level is set to 4. Considering expected future prices of hydrogen (Table 7), (Raucci et al 2014), as well as the costs of fuel cells, cost is set to 4.

5.2.5 Summary

Table 8 summaries the selected fuels and belonging converters (Appendix A. It also reflects per measure cost, barriers and applicability (segment relevant for use). For example, full electricity ships with battery are assumed used only for the small passenger, small short sea, and offshore segments, due to the energy storage limitations. For deep sea segments, marine application of fuel cell on hydrogen is not assumed applicable, as storage tank capacity is 10-15 times (depending on the pressure) larger than for marine bunkers (e.g. Chryssakis et al 2015, Maritime Knowledge Centre, TNO & TU delft 2017). Biofuels are expected to develop significantly from today’s first generation fuel, and 3 generation biofuel has been included with decreasing carbon intensity, but higher barrier levels.

In this study gas turbines are not included, as they are less efficient and more costly.

[39] Norge kan i 2021 bli verdens første som tar i bruk en hydrogenferge
https://www.tu.no/artikler/i-2015-ble-norge-forst-ut-med-elferge-na-skal-ny-milepael-nas/358972

[40] Generating electricity via fuel cells: http://www.bunkerindex.com/news/article.php?article_id=18479

Table 8: Summary of alternative fuels.

Family	Fuel types	Converter	Applicable for	Barrier level	Cost at maturity	Potential reduction
1.Liquid fuels	A. Biofuel 1. gen (20% blend)	Diesel/Dual fuel engine	All	2	3	10%*
	B. Biofuel 2.gen (100%)		All	3	3	80%
	C. Biofuel 3.gen (100%)		All	4	2	90%
2.Gaseous fuels	A. LNG/LPG	Diesel/Dual fuel engine	All	2	2	20%
	B. Bio-LNG/LPG (30% blend)		All	3	3	35%
	C. Bio-LNG/LPG (100%)		All	4	2	90%
3.Electro-chemical fuels	A. Full electric	Battery	Small passenger, small short sea, offshore	3	4	Dependent on carbon intensity of electricity in 2050 50-90%
	B. Plug-in hybrid (30%)	Diesel/Dual fuel engine/ Battery	Passenger, offshore, short sea	3	4	20-35%
	C. Hydrogen (renewables/ nuclear)	Fuel Cell	Passenger, offshore, short sea	4	4	80%

*Assumes consistency between maturity, cost and reduction

5.3 Logistics

There is a significant potential to improve efficiencies throughout the transport networks aligning the transport demand with size, operations and functionality of ships and with land-based infrastructure and logistics systems. The industry and related stakeholders must work together to realise on this potential.

The options to reduce CO_2 emissions through logistics have two aspects:

- Increasing the transport system efficiency: is the current network the most efficient way to move the cargo?
- Increasing the fleet efficiency: given the transport network, is the fleet utilised in the most effective way?

Increasing the transport system efficiency is a more complex matter that includes modal shifts and integration of value chains. This study assumes a transport demand scenario, but structural changes to the transport modes can shift cargo from land to sea, increasing the demand and emissions for shipping, but still reduce the overall global emissions. This should be addressed on a strategic level, and in this study, no specific options are further described.

Fleet efficiency is a wide term that includes all efforts that can be made to increase the fleet efficiency in a transport system. The efficiency can be measured in energy per tonne-mile of transported goods. In general, improving fleet efficiency is the consequence of measures that realises the following effects on a ship:

- Increased utilisation, such as reducing ballast legs
- Using larger vessels, and assuming the increased capacity is utilised
- Alternative sea routes that can be sailed with shorter distances
- Speed reduction

5.3.1 Increased utilisation

The high-level measurement of fleet or ship utilisation is the annual transport work per deadweight. On a short term this can vary based on fluctuation in demand and supply, for example when it is not sufficient cargo available to fill the ship to capacity.

Over time, structural changes such as reducing ballast legs or repositioning of the vessel and increasing the average cargo load, will increase the productivity. This change is expected to be driven further by digitalisation and improved control over cargoes and ship movements.

The barrier and cost levels are set to 1, however, it should be noted that these are incremental improvements. The efficiency improvement is estimated from 4 % to 25 % in 2050 depending on ship type (Smith et al 2014).

5.3.2 Larger vessels

A larger vessel uses more fuel but is more efficient relative to the cargo amount (Lindstad and Eskeland, 2016). This is however, dependent that the vessel is fully loaded, and the transport demand must be sufficient to justify the vessel size. This can for example be achieved by restructuring the transport system where cargo is fed into ports to fill larger vessels. The recent expansion of the Panama Canal increases the maximum size of the ships allowed to use the route, which facilitates the use of larger vessels.

The IMO GHG study 2014 (Smith et al, 2014) projects an increase in average size for three segments: 44 % increase for gas tankers; 30% increase for container; and 10 % increase for bulk. The barrier and cost levels are set to 1.

5.3.3 Alternative sea routes

Alternative sea routes can become available due to building canals, such as the Panama Canal. Note that the expansion of the canal is covered under “larger vessels”, or by reduced ice coverage, as in the case of the Northern Sea Route (e.g. DNV, 2010b, Smith and Stephenson, 2013). Alternative routes, also exists on a microlevel, where sailing distances can be reduced by adjusting sea lanes or even dynamically through improved information flows (Andersson and Ivehammar, 2016).

Alternative routes enable ships to sail shorter distance while still fulfilling the transport demand. The reduced voyage costs must be weighed up against increased other expenses such as insurance, ice strengthening and traffic management.

The only concrete new sea route covered here is the Northern Sea Route (NSR). The NSR is expected to be passable during summer months and potentially reduce emissions by 13 to 35 % CO_2 for ships using the route (Furuichi and Otsuka, 2013). The potential is estimated to 5 % of the global traffic in 2050 (Corbett et al, 2010).

The barrier level is set to 3. The Northern Sea Route see some traffic today, and is increasing, but use of this alternative is not assumed to be common practice during the summer month within the next 3-5 years. The cost level is set to 1, as the cost is not expected to increase as new routes will not be developed and used if they are not cost effective.

5.3.4 Speed reduction

In general, the fuel consumption of a vessel increases exponentially with the speed. By reducing the speed, significant emission reductions can be realised (Lindstad and Eskeland, 2016). The reduced potential transport work per ships must be compensated, either by building more ships or reducing time spent waiting or in port.

Speed reduction can be achieved by improving port and cargo operations and using the extra time for slow steaming, or by explicitly changing the time tables and schedules.

Part of the speed reduction can be absorbed in the current transport systems through reduced time in port and improved coordination and synchronisation between ship and port to avoid waiting in port, and use the extra time to slow steam (Longva, 2011, Andersson, 2017). The highest potential is in non-liner shipping – tank, bulk and short sea. The costs are related to investments in the port, but the main barrier is to coordinate among stakeholders.

Further speed reduction can be achieved by explicitly changing the time tables and schedules of the transport system. This can be done with different degrees of ambitions from a moderate reduction to an extensive speed reduction. In general, speed reduction beyond 50 % of today’s level will not reduce emissions further.

Extended speed reduction requires major changes to transport systems and logistics chains, and more ships to cover the demand. Cargo owners must accept a doubling of the lead time if the speed is halved.

Moderate speed reduction can more easily be absorbed, also in the transport system. For example, with the high fuel prices experienced from 2008 to 2015, the average speed of container vessels was reduced. However, with the drop and current low fuel prices, the speed has not increased in the same way.

After a while new designs optimised for lower speeds has entered the fleet. Extensive speed reduction will require different designs to be optimal, and the reduction potential for the hull and propeller measures will be lower. However, the reduced energy need will also enable other solutions such as use of electricity and batteries or hydrogen.

Extensive speed reduction is a very complex measure and the barrier level is set to 4. It will take more than 10 years to prepare logistics chains and to provide more vessels. Legacy industry practices, culture, and established supply chains resist a quick fix, and for a system that involves so many stakeholders, coordinated action or synchronised behaviour represents a significant challenge (Røsæg, 2009), however digital technologies are expected to facilitate an improved information flow (Andersson, 2017). Moderate speed reduction of 20% is easier to manage and is set to barrier level 2 for cargo vessels and level 3 for passenger vessels.

The cost of the measure is dependent on the fuel cost, time/charter rates (i.e. demand for ships) and value of the cargo (i.e. inventory cost for cargo owners). Cargo owners would like to reduce time to market for new products and stocks. Optimal speed for an Aframax tanker is around 13 knots under the current MGO fuel prices from an economic perspective, and about 7 knots from an emission perspective. The cost is about 15% higher in the latter case (Lindstad and Eskeland, 2015). The cost is set to level 1 for any speed reduction up to 20% and to level 3 for a 50% reduction which is the optimal from an emission perspective, but not for costs.

The applicability varies between the segments. Short sea shipping is more exposed to alternative transport modes and reducing speed may move cargoes from ships to other transport modes. For deep sea ships, there are few if any alternatives for most cargoes.

Passengers are in general not inclined to spend longer time for transportation, and the potential for speed reduction is limited. Service vessels that transport cargo has the same potential as deep sea vessels as there are few alternatives, while work vessels have limited impact of speed reduction.

5.3.5 Summary

Table 9 summaries the selected logistic and speed reduction measures, reflecting cost, barrier level, reduction potential and applicability (segment relevant for use).

Table 9: Summary of logistic and speed measures.

Measure	Applicable for	Barrier level	Cost at maturity	Potential reduction
Moderate speed reduction (20% of current speed)	All segments	2-3	1	35 %
Extensive speed reduction (50% of current speed)	Container, bulk, tank	4	3	75 %
Increased utilisation	Container, bulk, tank, short sea	1	1	4-25 %
Larger vessels	Container, bulk	1	1	3-15 %
Alternative sea routes	Container, bulk, tank	3	1	20 %

5.4 Offsetting

While not reducing actual emissions in shipping, offsetting can be an option to reach a sector emission target, where the actual reduction is enforced in other sectors/nations on their carbon budget. The intention behind allowing for trading credits in a carbon market is that this will ensure that the emission reduction is done where it is the cheapest. The World Bank estimates a potential cost saving of 54% for having an international trading market in 2050 (World Bank, 2016).

In this study, offsetting is assumed to be available as an alternative means to achieve the emission targets. This assumes that a market for carbon credits is established where shipping actors (either a centralized body, or each ship owner) can purchase credits.

There is currently no global system, but there are local or regional offset mechanisms and trading systems in place. These are very different in nature, with various scopes, and mechanisms. Currently very few trading systems acknowledge emission units from other systems. This is expected to change, with more linking between the systems allowing for trade.

The Paris Agreement makes provisions for market-based mechanisms, but does not provide any detailed rules on how they should work beyond a framework for accounting rules (Article 6).[41] The Agreement covers cooperative approaches where Parties can collaborate to meet their nationally determined contributions (NDCs) by using internationally transferred mitigation outcomes (ITMOs). However, the precise nature of ITMOs has not yet been defined. ITMOs should follow accounting principles approved by the COP to avoid double counting.

5.4.1 Volumes and current prices

It is vital to understand the current carbon markets, as surplus allowances from these systems are needed for the shipping sector to buy. Two aspects of relevance are the volumes of tradable emission credits, and the likely cost.

The current cap-and-trade emission trading systems (ETSs) in operation cover approximately 4,500 MT CO2eq where the EU ETS is by far the largest. Potential inclusion of a Chinese national ETS and Ontario ETS in 2017 would potentially increase the total cover to an estimated 6 800 MT CO_2. In comparison, international shipping emitted an estimated 810 MT CO_2 in 2012 (World Bank, 2016).

In addition, domestic and international offset systems are developed by various jurisdictions, mainly to supply offsets for their domestic climate mitigation programs. Examples of programs generating only domestic offsets include the development of offset protocols for the ETSs being implemented in California and Quebec, China CER and Switzerland's offset programs. Programs generating international offsets include Japan's Joint Crediting Mechanism (JCM) - a bilateral offset credit scheme between Japan and 16 partners - which issued its first credits in 2016.

International demand for Kyoto credits – Certified Emission Reduction (CER) and Emission Reduction Unit (ERU) – is almost exhausted and only 50 million primary CER were traded in 2015. The EU, which historically has been the largest source of demands, has likely fulfilled is demand (World Bank, 2016). No other substantial source of demand currently exists. The World Bank estimates the CDM pipeline to have the potential to issue 3500 MTCO2-eq[42] between 2016-2020, however, a more realistic estimate considering the effect of actual demand on issuance levels is about 300-600 MtCO2eq (World Bank, 2016). Looking beyond 2020, the outlook is uncertain as the role of CDM alongside the new mechanism established in the Paris agreement has not yet been defined.

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41 Paris Agreement: https://unfccc.int/files/meetings/paris_nov_2015/application/pdf/paris_agreement_english_.pdf

42 Based on registered portfolio without considering the effect of actual demand on issuance levels

There is also a market for voluntary credits and potential credits from programs such as Carbon Capture and Storage (CCS), Reduction of Emission from Deforestation and forest Degradation (REDD+), and destruction of HCFC (Hydro Chlorofluorocarbons) and CFC (Chlorofluorocarbons). Voluntary standard credits are developed and implemented by mostly non-government entities, and function outside of the compliance market. The two main standards are the 'Gold Standard' which is endorsed by numerous environmental charities and the Voluntary Carbon Standard which is being developed by the International Emissions Trading Association (IETA), The Climate Group and the World Economic Forum[43]. In 2015, 84 MtCO_2eq of carbon offsets worth 279 million $ were purchased on the voluntary market (World Bank, 2016).

In total, carbon pricing mechanisms, including taxes, currently cover about 7 GT CO_2-eq, or 13% of the world total emissions (World Bank, 2016). This is expected to increase in the coming years, with more linkages between the systems.

The carbon price varies from 1 to 15 $/tonne $CO_{2\text{-eq}}$ in the trading systems while in the tax systems the highest level is 131 $/tonne. The total market value for carbon pricing initiatives, including taxes are estimated to 50 billion $. To reach the 2°C target the IPCC indicates a carbon price of 70 to 150 $/tonnes in 2030, increasing to 150 to 300 $/tonne in 2050 (IPCC, 2014). In a survey by OECD, internal carbon pricing was reported being used in some countries when evaluating investments, with an average price of about 150 $/tonne for long term investments towards 2050 (World Bank, 2016).

5.4.2 Summary

Table 9 summaries assumptions regarding offset, reflecting cost, barrier level, reduction potential and applicability (segment relevant for use). Given the uncertainty of the volumes and price, and whether the credits are available for purchase, the offsetting is modelled separately. Instead of assuming an uptake of offsetting, the model calculates the necessary offsetting needed to reach the targets after the other measures are applied. This volume can be compared with the barrier and cost level of the applied measures.

A shipping carbon market, and links to other markets are likely to emerge in the next 10 years, giving a barrier level of 3. The price is also highly uncertain, and can range from 2 to 4 on the cost scale used.

Table 10: Summary for offset.

Measure	Applicable for	Barrier level	Cost at maturity	Potential reduction
Offset	All	3	2-4	100 %

[43] http://www.icao.int/Meetings/GLADs-2015/Documents/ENV_Report_MBMs_2013.pdf and http://www.ieaghg.org/docs/general_publications/Carbon%20Offsetsweb.pdf

5.5 Solutions not included

It is recognized that in a 30 to 40-year perspective, there is significant uncertainty in our projections. The further we look into the future, the larger the uncertainty span will be. In addition to the uncertainty of the costs, applicability and reduction potential inherent in our evaluation of measures, we anticipate that other reduction measures will appear not included in this study. Examples are:

- Carbon capture and storage (CCS) onboard ships
- Onboard nuclear reactors
- Synthetic fuels
- Innovative light materials
- Radical propulsion technologies.

Major events such as breakthroughs in biofuel production technologies, slowdown in economy, increased regionalization, use of 3D printers, accelerated uptake of land-based CCS, fast transformation to a hydrogen economy, cheap unconventional/synthetic oil and gas, are potential game changers for the industry, impact both the transport demand and energy availability. In such cases, the accuracy of our projections could be challenged.

In addition, other structural changes, such as new routes and geographical trade patterns can have a large impact on transport demand. For example, Eide et al. (2007) and Mangset et al. (2011) considers new energy routes (fossil) and biofuel routes, emerging cargo routes, need for water transportation, and demand for rock, gravel and sand materials (e.g. related to dams and dikes). OECD/ITF (2016) has also projected large changes in global traffic patterns towards 2050, based on comprehensive global freight modelling. They also discussed new sea routes.

It is also a vast potential to improve the level of recycling of industry input factors. Increased recycling leads to less need for imports of raw materials used in production of steel, plastics etc., thus reduced volumes of seaborne trade (OECD, 2010).

Alternative propulsion technologies may also emerge. A demonstration ship[44] YAMATO 1 has been built and tested, demonstrating superconducting electro-magnetohydrodynamic propulsion. Other alternatives future power/propulsion is reported by for example Royal Academy of Engineering (2013). For example, successful land based testing of a 36.5 MW high temperature superconductor ship propulsion motor has also been carried out (Royal Academy of Engineering 2013). In 2013, the electric ferry *Ar Vag Tredan* was delivered with energy storage based on super-capacitors[45]. The energy storage capacity is today enough for making short voyages for the ferry (around 2.5 nm), (Royal Academy of Engineering 2013).

[44] Info about YAMATO 1: http://www.jime.jp/e/publication/bulletin/english/pdf/mv23n011995p46.pdf
https://en.wikipedia.org/wiki/Yamato_1
[45] STX: http://www.stxfrance.com/UK/stxfrance-reference-23-AR%20VAG%20TREDAN.awp

6 RESULTS

A very large number of different pathways are available for analysis. This section presents the results from the “extreme” pathways modeling. Pathways combining elements from the “extreme” pathways are also presented. These pathways are constructed on the condition that they meet the overall ambitions for emission reductions. Furthermore, they are selected keeping the importance of both barriers and cost in mind, as well as a realistic implementation and uptake rate.

For comparison, two basic pathways are developed: The Reference pathway projects the expected emissions, considering activity growth, but without any improvements. The Business-as-usual pathway is set up to cover all reductions that are expected as part of normal efficiency improvements without any further effort on CO2 emission reductions. The measures in the Business-as-usual pathway is expected implemented in all other pathways.

6.1 Extreme pathways

In the first set of “extreme” pathways we want to examine how far it is possible to come towards the emission targets by looking only at one group of measures. For each pathway, we apply the main measures to the full technical potential, regardless of cost, fuel availability and infrastructure. The measures are phased in on newbuilds as soon as they are mature.

Table 11 describes the eight selected extreme pathways, compared to the reference and business-as-usual pathways and evaluated against the targets on keeping within the 33 GT carbon budget from 2010 to 2100, halving the annual emissions in 2050 and peaking the annual emissions in 2025.

The “extreme” modelling results show:

- In addition to the biofuel pathways (E4 and E6), only extensive speed reduction (E3) can by itself reduce emissions close to the targets.
- Liquid biofuels are the only pathway which can reach the targets on its own but the measure scores high on barriers, indicating that realisation will be challenging. The pathways assume an early availability of fuels.

Table 11: Results from modelling of extreme pathways. The barriers and cost scores are the weighted average of all measures given the reduction and uptake for all segments.

Pathways	Description	2010-2100 accumulated emissions (GT CO2)	2050 emissions relative to 2010	Peak year	Barrier level	Cost
Reference	No emission reduction	191.4	144 %	No peak	1.0	1.0
Business as usual	BAU energy and fleet efficiency improvements	81.7	73 %	No peak	1.0	1.0
E1 Energy efficiency	Full uptake of energy efficiency measures	68.7	32 %	No peak	1.6	1.6
E2 Moderate speed reduction	20 % speed reduction on all vessels	62.1	21 %	No peak	1.5	1.0
E3 Extensive speed reduction	50 % speed reduction on all vessels	42.0	-57 %	2020	2.9	2.3
E4 Biofuels	Full uptake of liquid biofuels	27.1	-83 %	2020	2.9	2.0
E5 LNG	Full uptake of LNG	69.5	39 %	No peak	1.4	1.4
E6 Bio-LNG	Full uptake of LNG and then bio-LNG	33.4	-83 %	2020	2.9	1.8
E7 Electricity	Full uptake of full-electric and hybrid solutions in non-deep sea segments	77.4	60 %	No peak	1.5	1.7
E8 Hydrogen	Full uptake of hydrogen in non-deep sea segments	71.5	42 %	No peak	2.4	2.4

6.2 Balanced pathways

The balanced pathways combine elements from the "extreme" pathways, with assumptions made about technology shifts and uptake of alternative fuels. These pathways are constructed on the condition that they meet the overall target for emission reduction (i.e. 33 GT carbon budget from 2010 to 2100), either directly or by offsetting. Each pathway focus on one or two key reduction options. Additional measures are added to reach the overall emission target, keeping in mind barriers and cost and applying a relatively relaxed implementation rate.

The first two pathways assume that no offsetting is available and shipping must reach the targets by applying own measures. In the other four pathways, offsetting is available, making it possible to balance it with own measures, keeping in mind the uncertainty of availability and price of offsets. It is noted that the low carbon fuels pathways are sensitive to assumed carbon intensity of the applied alternative fuels (lifecycle emissions).

6.2.1 Bio-ship (no offset)

In this pathway, no offsetting is possible and shipping must reach the targets by an aggressive implementation of biofuels. The total need for biofuels are mitigated by moderate energy efficiency and speed reduction, as well as electrification of the short sea, offshore and passenger segments. Table 12 outlines in more detail the assumptions made for this pathway. Key assumptions are:

- **Aggressive** use of biofuels
- No offset market

Table 12: Reduction measures selected in the Bio-ship (no offset) pathway.

Segment	Logistics	Fuel	Energy efficiency	Offset
Tank	Fleet efficiency; Moderate (20 %) speed reduction for 33% of fleet	80 % biofuel; 20 % MGO	Full uptake of quick wins; 70% uptake of up and coming	No offsetting
Bulk				
Container/roro				
Short sea		10 % electric; 35 % hybrid (30% electricity, 70% biofuel); 55 % biofuel		
Offshore				
Passenger				

Figure 9 shows the resulting emission trajectories; barriers and cost; and energy mix. The following observations are made:

- The main bulk of reduction comes from low carbon fuels, followed by speed reduction and energy efficiency.
- Biofuel dominates the energy mix, with contribution from also MGO/HFO and electricity.
- Moderate cost, but high barrier score. The main challenges include availability in sufficient volumes and global infrastructure of biofuel, and the carbon intensity of the fuel (lifecycle emissions).

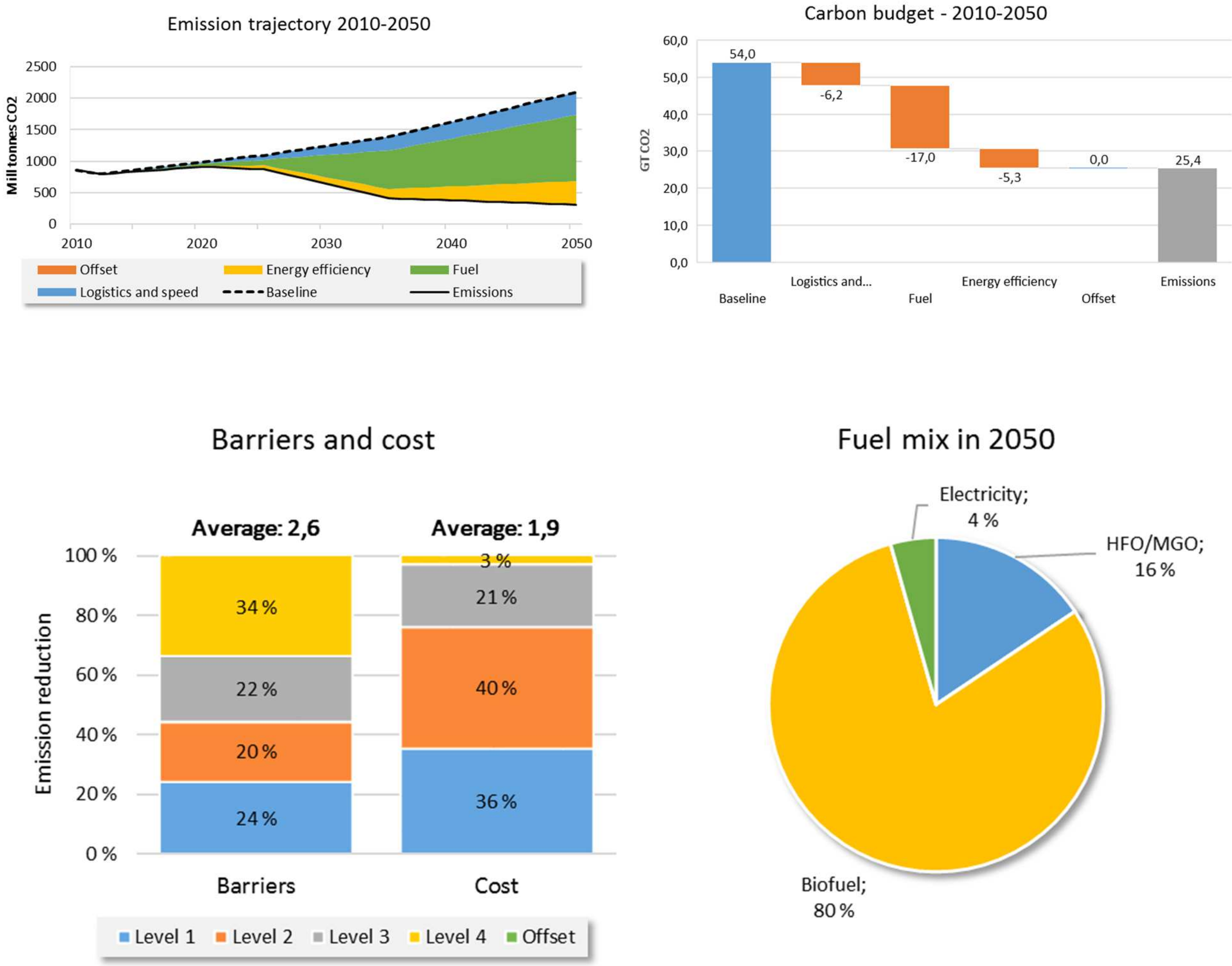


Figure 9: Main results for the *Bio-ship-no-offset*, with heavy reliance on biofuels and no offsetting. *Upper left:* Emission trajectory towards 2050, *Upper right:* Resulting fuel mix in 2050: *Lower left:* Carbon budget per category, *Lower right:* Resulting score for Barriers and Costs.

6.2.2 Slow-ship (no offset)

In this pathway, no offsetting is possible and with limited availability of biofuels, shipping must reach the targets by significantly reducing speed. The limited biofuel available is blended in as gas, using a global LNG infrastructure. In addition, electrification and use of hydrogen must be extensively used in the short sea, offshore and passenger segments. Reduced speed will increase the potential applicability of batteries and hydrogen as the necessary energy need is reduced, but will also reduce the effect of energy efficiency measures related to propulsion and resistance. Table 13 outlines in more detail the assumptions made for this pathway. Key assumptions are:

- **Extensive speed reduction**, particularly in the deep-sea segments
- No offset market

Table 13: Reduction measures selected in the Slow-ship (no offsetting) pathway.

Segment	Logistics	Fuel	Energy efficiency	Offset
Tank	Fleet efficiency; Extensive (50 %) speed reduction for 100% of fleet	80 % LNG/Bio-LNG (30% blend); 20 % Bio-LNG	Full uptake of quick wins (reduced effect); 60% uptake of up and coming	No offsetting
Bulk				
Container/roro				
Short sea	Fleet efficiency; Moderate (20 %) speed reduction for 50% of fleet; Extensive (50%) speed reduction for rest	20 % electric; 80 % hydrogen		
Offshore				
Passenger	Fleet efficiency; Moderate (20 %) speed reduction for 100% of fleet	40 % electric; 60 % bio-LNG		

Figure 10 shows the resulting emission trajectories; barriers and cost; and energy mix. The following observations are made:

- Speed reduction is the main contributor to the reduction, followed by low carbon fuels (mix).
- LNG/Bio-LNG dominates the energy mix, but hydrogen and electricity also contributes.
- Moderate cost, but high barrier score. Main challenges include practical issues related to aggressive speed reduction and the impact on the global transport systems; as well as availability and global infrastructure of (Bio) LNG, hydrogen and electricity.

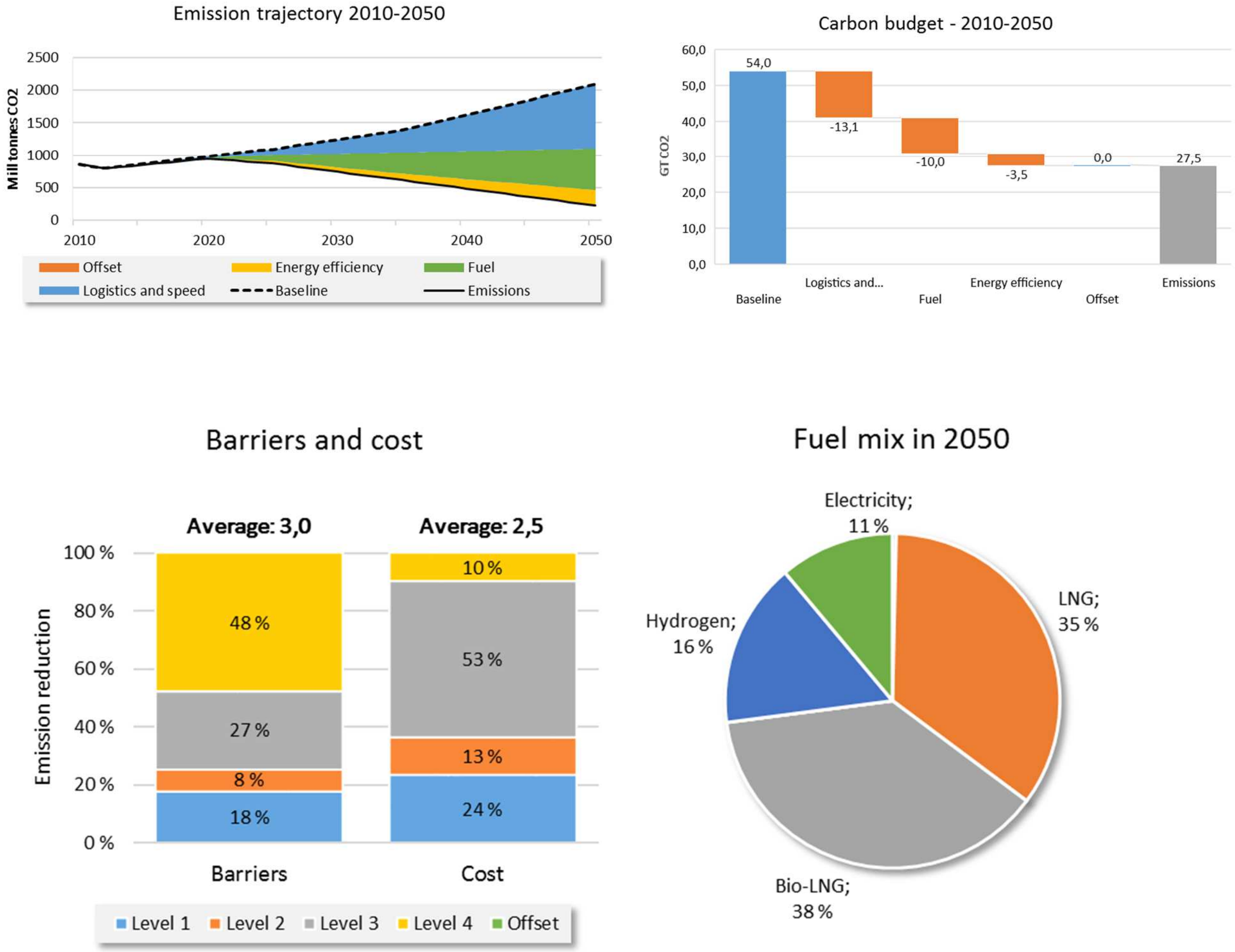


Figure 10: Main results for the Slow-ship scenario, with heavy reliance on speed reduction. *Upper left:* Emission trajectory towards 2050, *Upper right:* Resulting fuel mix in 2050: *Lower left:* Carbon budget per category, *Lower right:* Resulting score for Barriers and Costs.

6.2.3 Fossil-ship

In this pathway, shipping will continue to use fossil fuels and rely on offsetting to reach the targets. There will be a high focus will be on energy efficiency in all segments and a moderate speed reduction in the container/roro segment. In addition, moderate use of LNG in the deep-sea segments and more extensive in the short sea, offshore and passenger segments. Table 14 outline in more detail the assumptions made for this pathway. Key assumptions are:

- **Extensive energy efficiency** improvements
- Very extensive use of offsets

Table 14: Reduction measures selected in the Fossil-ship pathway.

<table>
<tr><th>Segment</th><th>Logistics</th><th>Fuel</th><th>Energy efficiency</th><th>Offset</th></tr>
<tr><td>Tank</td><td rowspan="2">Fleet efficiency</td><td rowspan="3">80 % MGO/HFO,
20 % LNG</td><td rowspan="6">Full uptake all energy efficiency measures, except Black Swans</td><td rowspan="6">50 % to 2100
45 % to 2050</td></tr>
<tr><td>Bulk</td></tr>
<tr><td>Container/roro</td><td>Fleet efficiency
20 % speed reduction for 40% of fleet</td></tr>
<tr><td>Short sea</td><td rowspan="3">Fleet efficiency</td><td rowspan="3">20 % MGO/HFO,
80 % LNG</td></tr>
<tr><td>Offshore</td></tr>
<tr><td>Passenger</td></tr>
</table>

Figure 11 shows the resulting emission trajectories; barriers and cost; and energy mix. The following observations are made:

- Energy efficiency is the main contributor for reduction, and a high level of offsetting is needed.
- In the energy mix, HFO/MGO will still be the main fuel source, but also relying on LNG.
- Moderate cost, but high barrier score. Main challenges include lack of global infrastructure for LNG, but also a functioning offsetting scheme, with sufficient volume of allowances available at acceptable cost. The actual decarbonization challenge is postponed to after 2050.

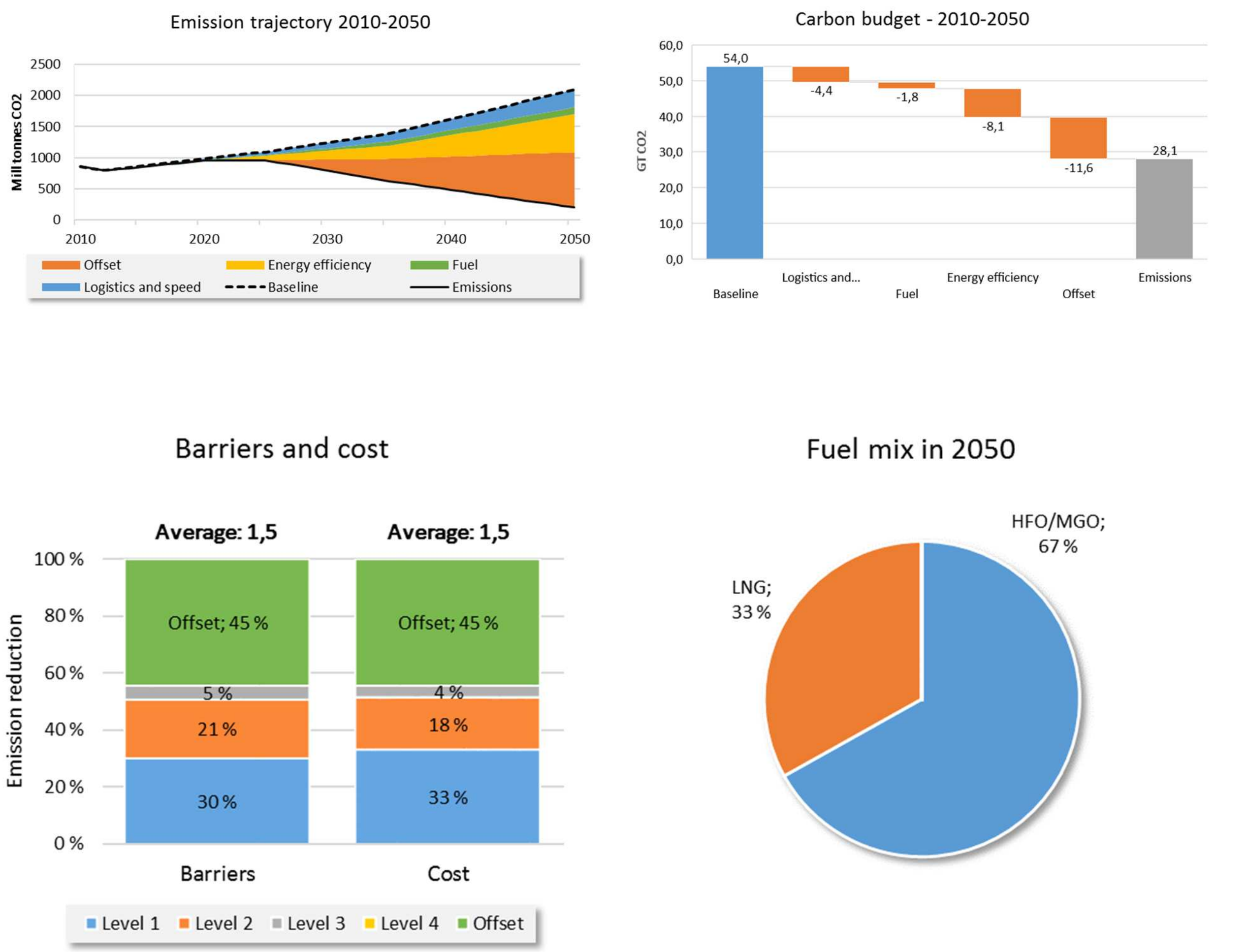


Figure 11: Main results for the Fossil-fuel ship scenario, with heavy reliance on fossil fuels and on offsetting. *Upper left:* Emission trajectory towards 2050, *Upper right:* Resulting fuel mix in 2050: *Lower left:* Carbon budget per category, *Lower right:* Resulting score for Barriers and Costs.

6.2.4 Bio-ship

In this pathway, shipping will gradually replace fossil fuels with a moderate uptake of biofuels. The short sea, offshore and passenger segments will use electricity. There will be moderate use of LNG in all segments. In the deep sea and short sea segments moderate speed reduction will be applied. In addition, moderate energy efficiency improvements will be implemented. Offsetting is still needed to reach the targets. Table 15 outlines in more detail the assumptions made for this pathway. Key assumptions are:

- Moderate use of biofuels (and LNG)
- Extensive use of offset

Table 15: Reduction measures selected in the Bio-ship pathway.

Segment	Logistics	Fuel	Energy efficiency	Offset
Tank	Fleet efficiency; 20 % speed reduction for 40% of fleet	30 % biofuels; 20 % LNG	Full uptake of quick wins; 50% uptake of up and coming measures	40 % to 2100 28 % to 2050
Bulk				
Container/roro				
Short sea		30 % biofuels; 20 % LNG; 10 % hybrid (30 % electric; 70 % MGO/HFO)		
Offshore	Fleet efficiency			
Passenger				

Figure 12 shows the resulting emission trajectories; barriers and costs; and energy mix. The following observations are made:

- The main contributor to reduction is fuels, followed by logistics and speed. The reduction measures stabilize the emission level, and offsetting is to reach the carbon budget target.
- The fuel mix changes towards 2050, with increased use of biofuels (1/3 of fuel used in 2050) and LNG.
- Low cost, but medium barrier score. Main challenges include availability of biofuel in sufficient volumes, lack of global infrastructure for LNG and biofuel, but also a functioning offsetting scheme, with sufficient volume of allowances available at acceptable cost. The actual decarbonization challenge is postponed to after 2050.

Note that in this scenario, the sector is vulnerable to a dwindling supply of offsets post 2050, where one must assume that all sectors will need to de-carbonize. This makes the post 2050 task of decarbonizing the shipping sector more challenging than in other scenarios.

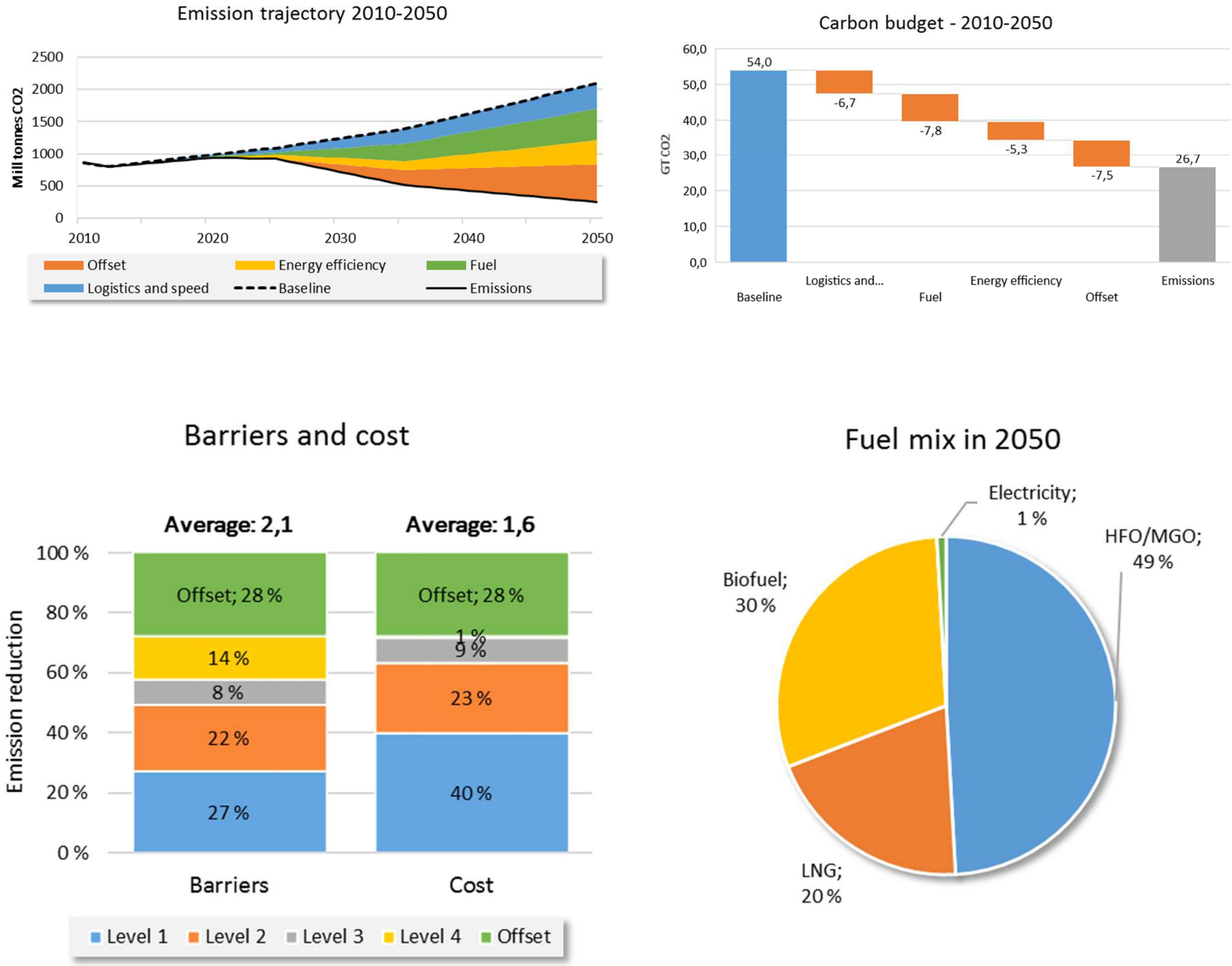


Figure 12: Main results for the Bio-fuel ship pathway, with heavy reliance on biofuels and on offsetting. *Upper left:* Emission trajectory towards 2050, *Upper right:* Resulting fuel mix in 2050: *Lower left:* Carbon budget per category, *Lower right:* Resulting score for Barriers and Costs.

6.2.5 Slow-ship

In this pathway, shipping will still rely on fossil fuels, but LNG is phased in in all segments. Speed is reduced considerably, except in the passenger segment. Hydrogen and electricity are moderately used in the short sea, offshore and passenger segments. There will be moderate use of biofuel and energy efficiency improvements. Offsetting is still needed to reach the targets. Table 16 outlines in more detail the assumptions made for this pathway. Key assumptions are:

- Considerably **speed reduction**, except for the passenger segment
- Extensive use of offsets

Table 16: Reduction measures selected in the Slow-ship pathway.

<table>
<tr><th>Segment</th><th>Logistics</th><th>Fuel</th><th>Energy efficiency</th><th>Offset</th></tr>
<tr><td>Tank</td><td rowspan="5">Fleet efficiency;
50 % speed reduction for 20% of fleet;
20 % speed reduction for 40% of fleet</td><td rowspan="3">60 % MGO/HFO;
40 % LNG</td><td rowspan="6">Full uptake of quick wins (reduced impact due to speed reduction) and up and coming, 50% uptake of next generation</td><td rowspan="6">39 % to 2100
27 % to 2050</td></tr>
<tr><td>Bulk</td></tr>
<tr><td>Container/roro</td></tr>
<tr><td>Short sea</td><td rowspan="2">10 % electric;
10 % hydrogen;
50 % hybrid (30% electricity; 70% LNG);
30 % LNG</td></tr>
<tr><td>Offshore</td></tr>
<tr><td>Passenger</td><td>Fleet efficiency;
20 % speed reduction for 40% of fleet</td><td>40 % electric;
50 % hybrid (30% electricity;
70% LNG);
10 % LNG</td></tr>
</table>

Figure 13 shows the resulting emission trajectories; barriers and costs; and energy mix. The following observations are made:

- The fuel mix change towards 2050, with increased use of LNG, Hydrogen, and electricity.
- The main contributor to reduction is speed reduction, followed by energy efficiency and fuels.
- Moderate barrier and cost score. Main challenges include practical issues related to aggressive speed reduction. In addition, challenges relate to availability and global infrastructure of LNG, hydrogen and electricity.

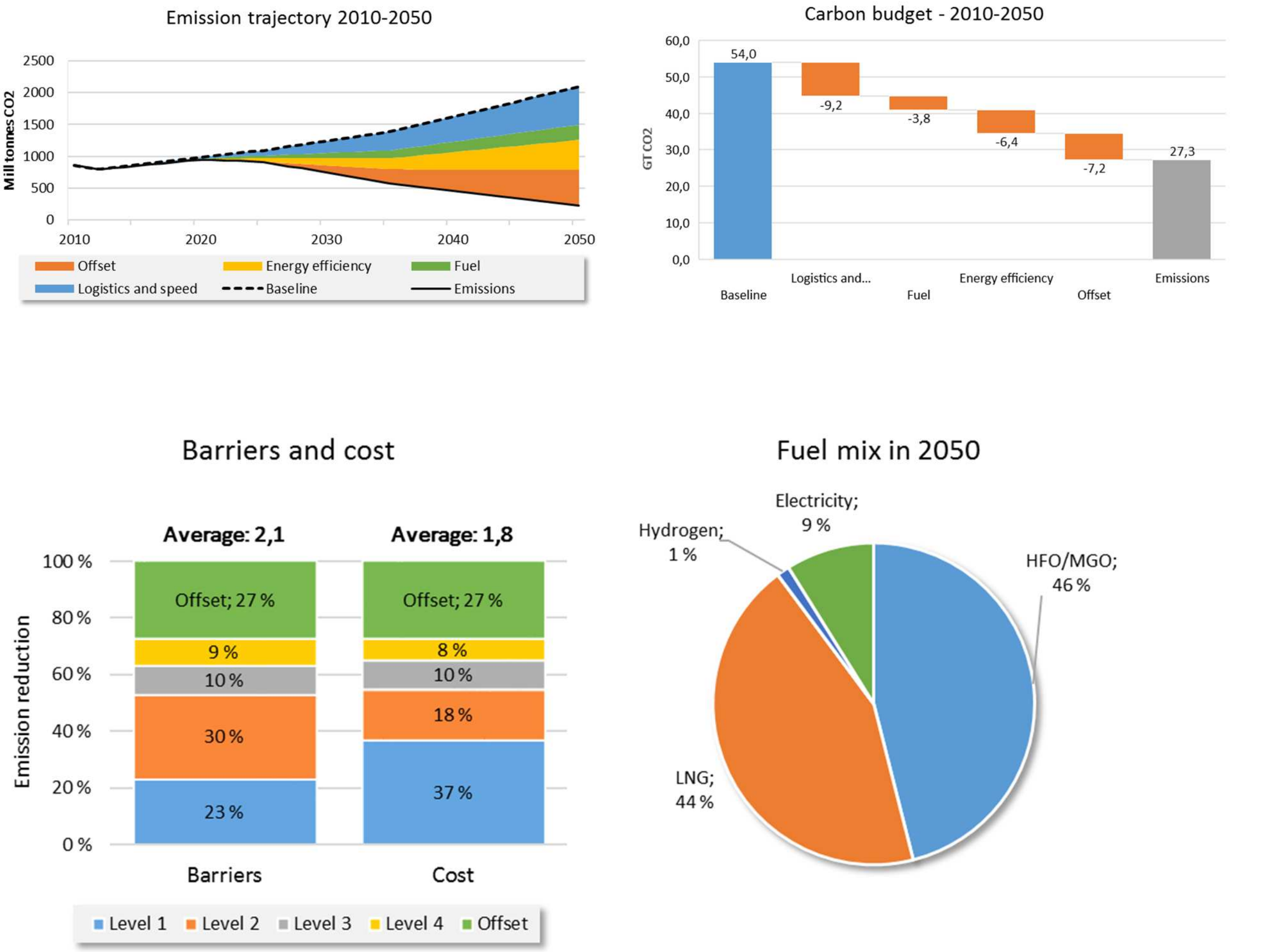


Figure 13: Main results for the *Slow ship* scenario, with heavy reliance on speed reduction and on offsetting. *Upper left:* Emission trajectory towards 2050, *Upper right:* Resulting fuel mix in 2050: *Lower left:* Carbon budget per category, *Lower right:* Resulting score for Barriers and Costs.

6.2.6 Space-ship

This pathway balances the need for biofuel (liquid and LNG), speed reduction and offsetting. Novel technologies and concepts such as those described in Section 5.1.4 "Black Swans" are assumed to be realised towards 2050. Shipping will still rely on fossil fuels, but LNG (supplemented with bio-LNG) is extensively used in the short sea, offshore and passenger segments. Offsetting is still needed to reach the targets. Table 17 outlines in more detail the assumptions made for this pathway. Key assumptions are:

- Extensive energy efficiency improvements, including novel technologies and concepts
- Moderate use of offset

Table 17: Reduction measures selected in the Space-ship pathway.

Segment	Logistics	Fuel	Energy efficiency	Offset
Tank	Fleet efficiency Moderate to extensive (20-50% speed reduction for 30 % of fleet	50 % MGO/HFO, 30 % LNG 20 % biofuel	Full uptake all energy efficiency measures including "Black Swan" technologies	30 % to 2100 19 % to 2050
Bulk				
Container/roro				
Short sea	Fleet efficiency Moderate (20 %) speed reduction for 30 % of fleet	20 % LNG 20 % bio-LNG 10 % hydrogen 5 % fully electric 45 % hybrid (70 % HFO/MGO, 30 % electricity		
Offshore				
Passenger				

Figure 14 shows the resulting emission trajectories; barriers and costs; and energy mix. The following observations are made:

- The fuel mix changes towards 2050, with increased use of LNG, biofuel, hydrogen, and electricity.
- The main contributor to reduction is speed reduction, but also energy efficiency improvements and alternative low carbon fuels.
- Moderate costs, but high barrier score. Main challenges include practical issues related to aggressive speed reduction. In addition, challenges relate to availability and global infrastructure of LNG, biofuel, hydrogen and electricity.

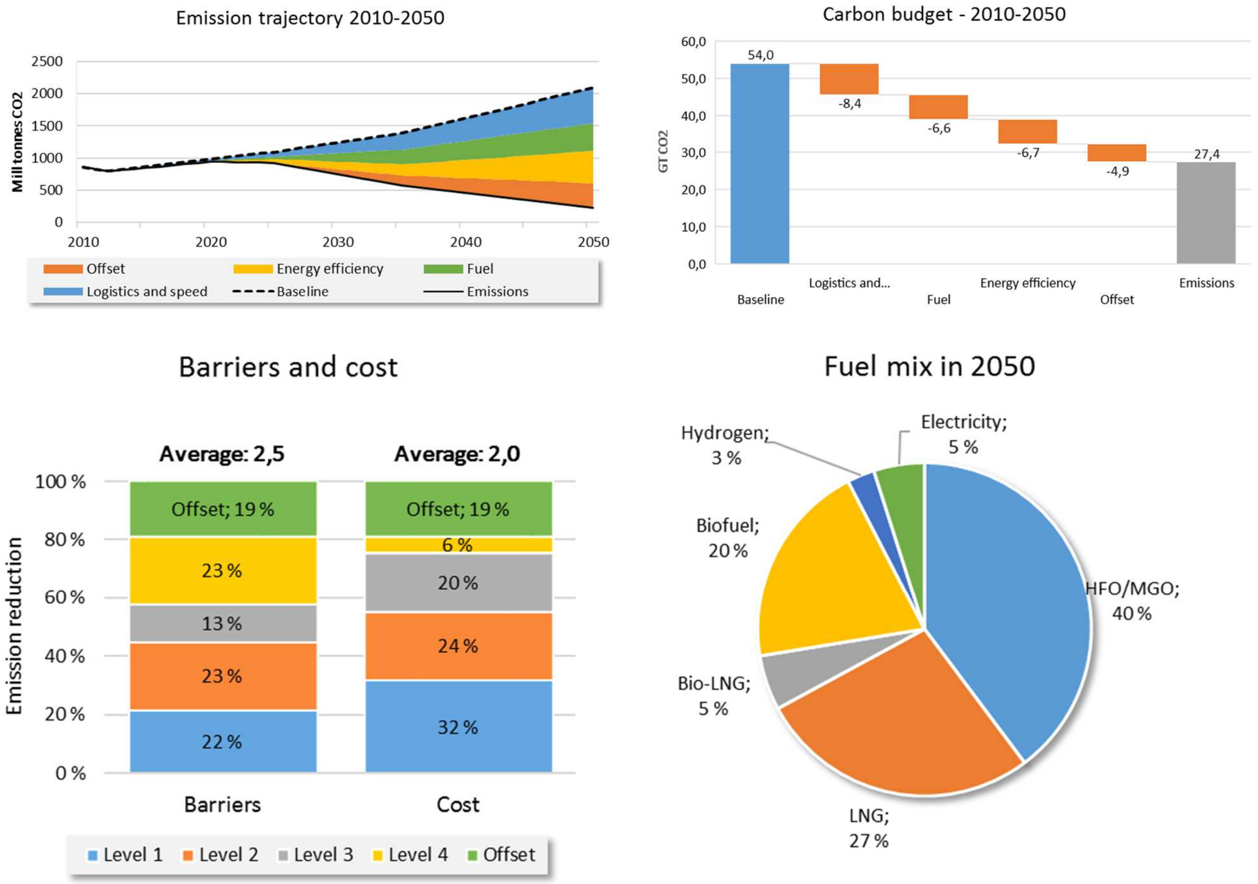


Figure 14: Main results for the *Space-ship* pathway, with heavy reliance on novel emerging technologies/concepts. *Upper left:* Emission trajectory towards 2050, *Upper right:* Resulting fuel mix in 2050: *Lower left:* Carbon budget per category, *Lower right:* Resulting score for Barriers and Costs.

6.3 Summary of pathways

6.3.1 The most important CO_2 reduction measures

The modelling results show that reaching the reduction targets without offsetting is possible but difficult (Figure 15). Without offsetting, 70-80 % emissions reduction in 2050 is needed to reach the targets. In the pathways relying on offsets in this study, 30 to 50 % of emissions must be offset by 2100, corresponding to a volume of between 14 to 33 GT.

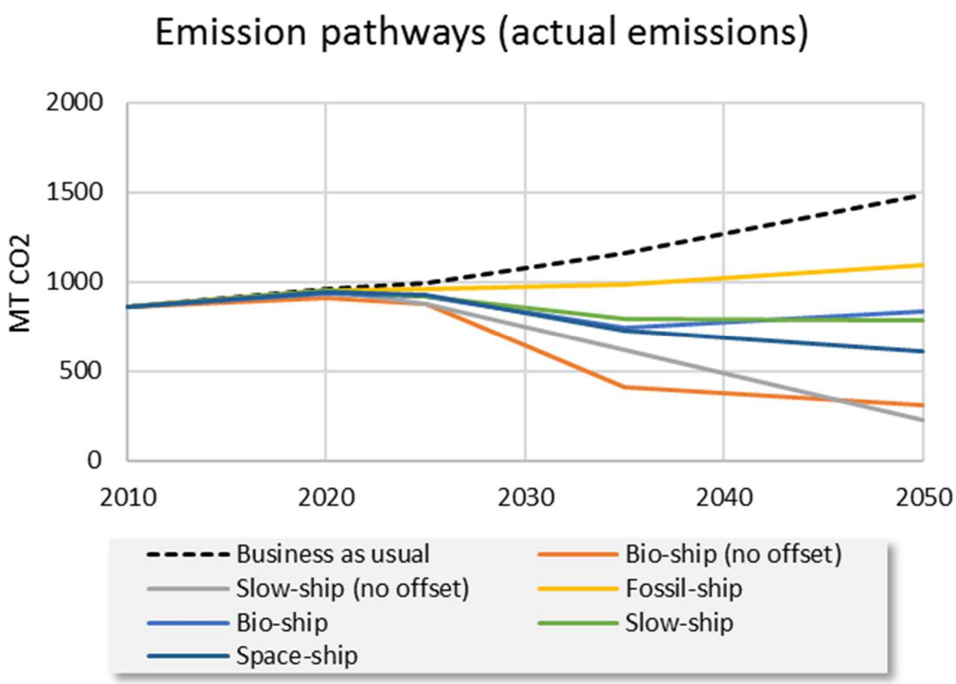


Figure 15: Emission pathways (CO_2 emissions per year) from 2010 to 2050. Offsetting is not included.

Energy efficiency is not enough in itself to reach the targets (Figure 20), and extensive use of speed reductions and alternative fuels are needed in addition. Technical and operational energy efficiency measures is not sufficient to stabilise emissions at 2010 levels, even including novel technologies and solutions.

Biofuels or more specifically, low carbon, sustainable fuels for marine use is a key element to reach the ambitious emission reductions. Hydrogen and electrification are niche solutions for the short sea, offshore and passenger segment. They are an important supplement and have other benefits such as reducing local pollution.

While the targets can be met with measures applied in shipping alone, offsets will mitigate costs and reduce reliance on highly immature measures. However, offsets are itself an immature solution and the costs and availability are uncertain. Similarly, for biofuel and other low carbon fuels, the shipping industry will rely on a global production and supply. Shipping is part of the global effort to reduce emission and other sectors will compete for the same low carbon energy and offsets.

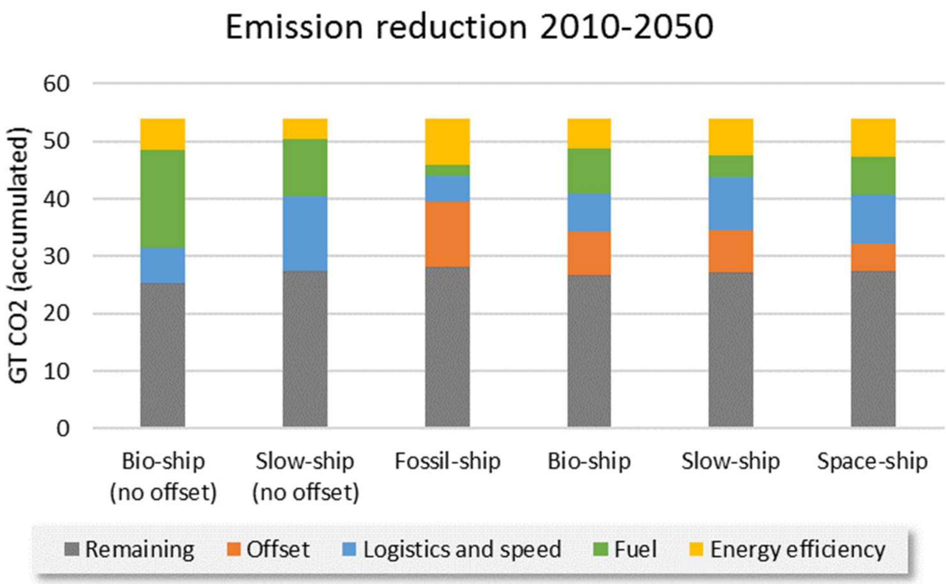


Figure 16: Emission reduction per category.

Note, that while nuclear power has not been considered in this study, the technology could provide substantial emission reductions in the fleet (e.g. Eide et al 2013). However, concerns regarding radioactive waste, nuclear proliferation, and safety must be overcome in a fashion sufficiently reassuring society to allow widespread use.

The carbon intensity of the pathways developing over time is shown in Figure 17. The figure illustrates how the pathways without offsetting require that the carbon emitted per unit of transport work must be reduced by 80 % by 2050. While the other pathways (with offsetting) have less stringent demands on carbon efficiency, they have less resilience towards potentially high CO_2 costs.

Figure 18 further shows the variation in carbon intensity between segments in 2050. The figure illustrates that although different measures and fuels are applied in each segment, the overall results on carbon intensity varies only slightly.

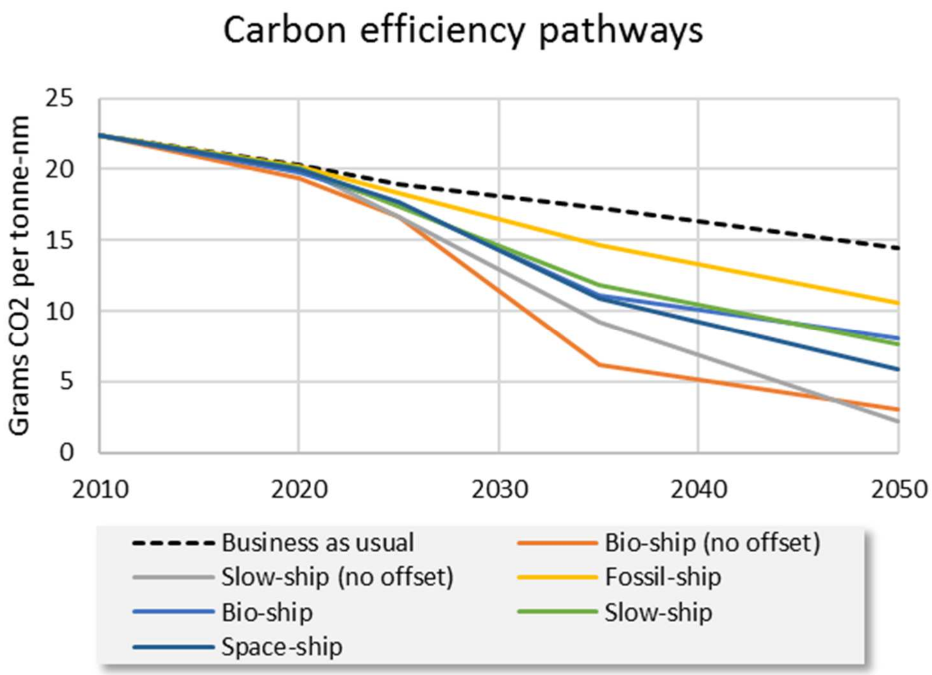
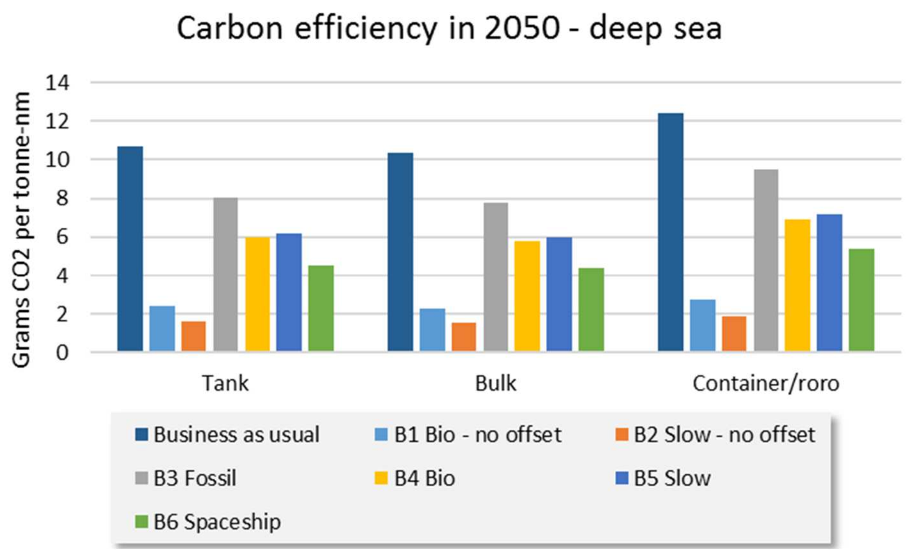


Figure 17: Development in overall carbon efficiency for each pathway (CO_2 emissions per transport work) from 2010 to 2050.



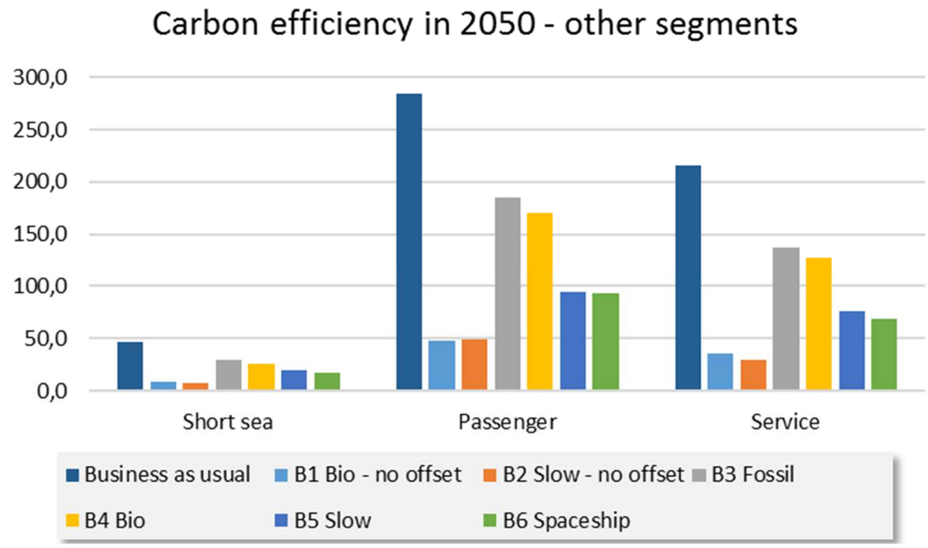


Figure 18: Carbon efficiency in deep sea segments (top) and non-deep sea segments (bottom). Note that the scales vary between the figures.

6.3.2 Energy mix in 2050

Biofuels or more specifically, low carbon sustainable fuels for marine use is a key element to reach the ambitious emission reductions. Energy efficiency is not enough in itself to reach the targets, but are important to reduce the energy and fuel need.

Figure 19 shows the fuel mix for the different pathways. Between 2.4 to 4.8 EJ (about 57 to 114 MTOE) of biofuels will be needed, except for the Slow-ship pathways where no biofuels are included and in the Bio-ship pathway without any offsetting where 12.5 EJ of biofuels are needed.

LNG is also a relevant fuel, even if it has limited impact on CO_2 emissions. Up to 5.6 EJ of LNG will be needed (about 134 MTOE). The LNG and biofuel will be used in all segments. Hydrogen and electricity are relevant fuels for the non-deep-sea segments, with up to 1 EJ of hydrogen and 1.1 EJ of electricity needed.

Figure 19 also shows that the deep-sea segment is more fossil, compared the non-deep-sea segment. Electricity and hydrogen are only used for the non-deep-sea segment. Use of LNG is significantly higher for the non-deep-sea segment.

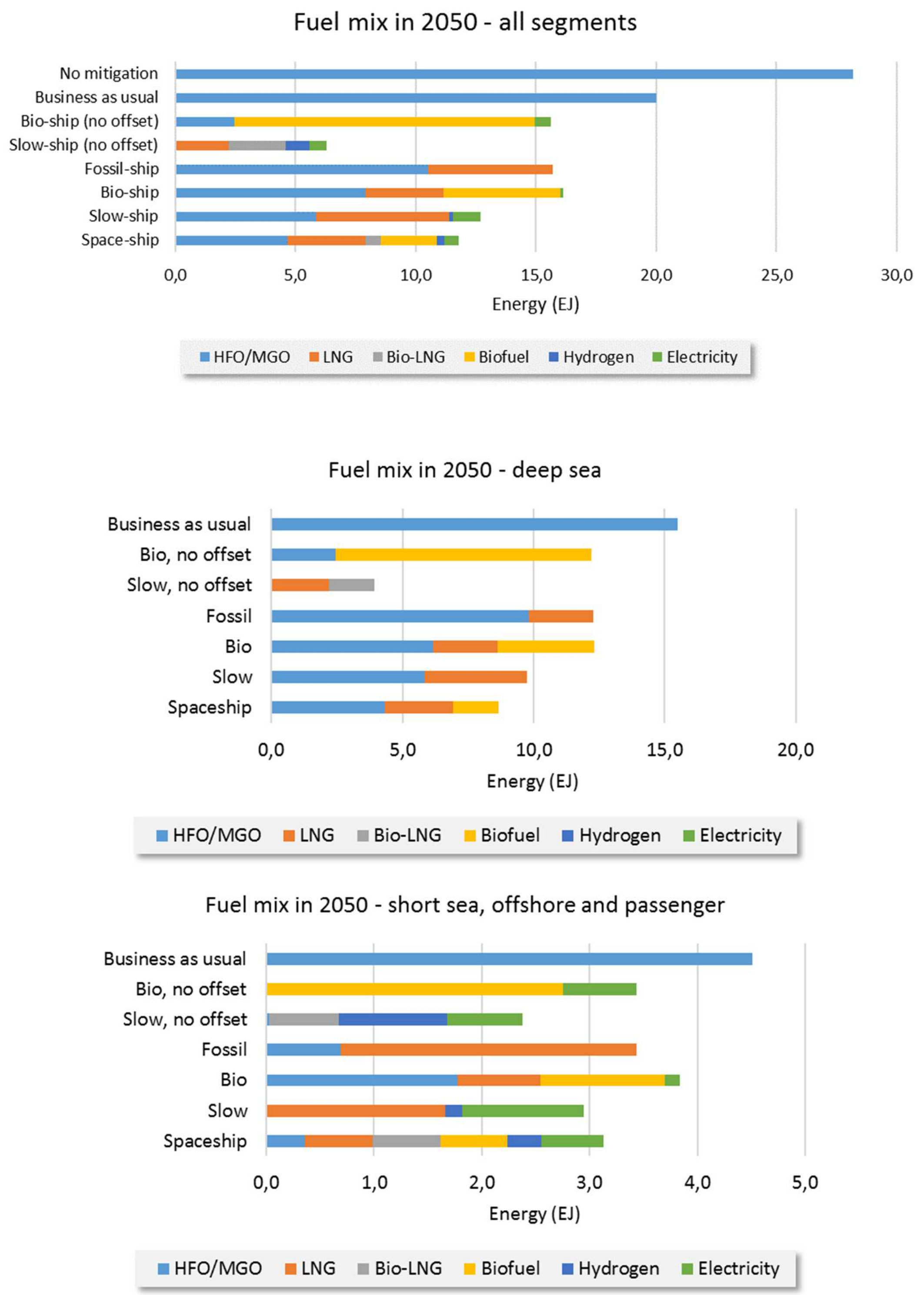


Figure 19: Fuel mix per pathway for all, (top panel), deep sea (middle panel) and non-deep-sea segments (bottom panel) in 2050. 1 EJ equals about 24 million tonnes of oil equivalents (MTOE).

6.3.3 Evaluation of of pathways

The figure below evaluates each pathway on barriers, cost, and offset needs. The barrier levels vary from a score of 1.7 to 3.1, while cost levels range from 1.2 to 1.8. A high barrier score indicates that this pathway comes with a high uncertainty, and costs could be even higher. Slow-ship (no offset) has the highest barrier and cost level, followed by Bio-ship (no offset). Even if the barrier level for the individual measures may be high, by relying on several of these measures, the robustness increases and the overall risk is reduced. The reliance on offsets translates into a price on carbon set in a global market. The highest offset needs are for the Fossil-ship pathway.

The pathways without offsetting, have the highest score on barriers reflecting the need for high uptake of immature measures. Extensive speed reduction can have a significant impact but is expected to be expensive and difficult to implement.

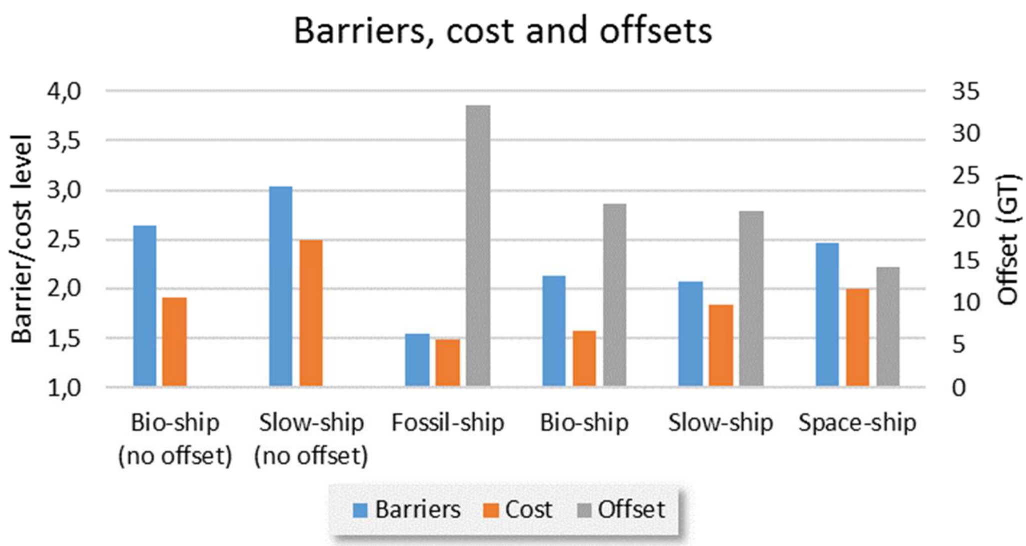


Figure 20: Ranking of barriers and cost per pathway, including required offset volumes (2010 to 2100).

The costs of offsetting is very uncertain given that there a no global market in place. For example, the Fossil-ship relies heavily on offsetting, and is very exposed to variation in the offset costs. Figure 21 shows the cost level, assuming different levels of costs for offsets.

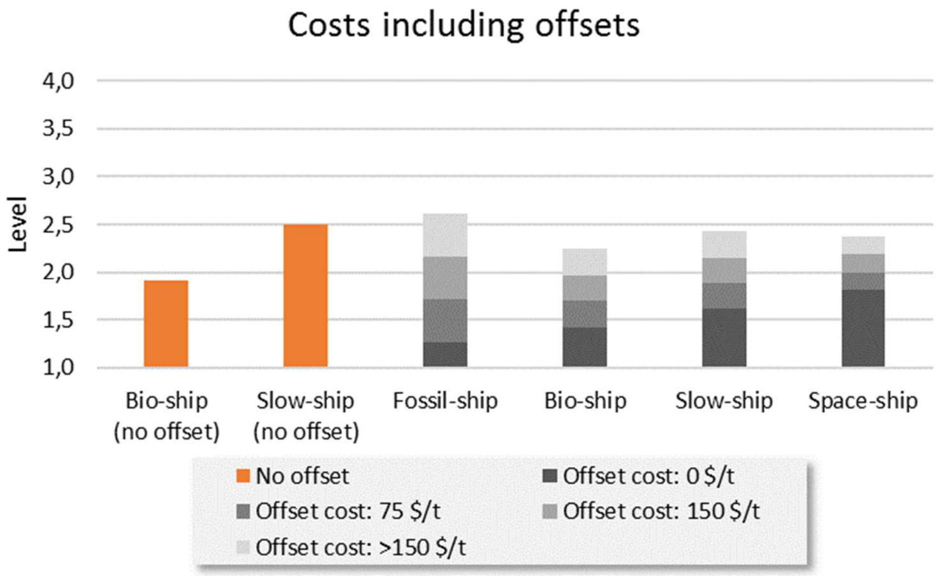


Figure 21: Ranking of cost per pathway with different levels of offset cost.

The set of solutions applied in the pathways aggregates to an increased cost of shipping of between 10 to 25 % (see Table 4, Section 4.3). This is a substantial increase – although the cost hike is not larger than what has been experienced in the past e.g. following steep increases in fuel prices.

There is a substantial uncertainty associated with the cost estimates and maturity of these. Furthermore, as previously noted, these costs are estimated assuming the solutions become mature. The high barrier scores for the pathways indicate that this comes with a high uncertainty, and costs could be even higher. Should – for instance – the current biofuel prices be assumed valid for the Bio-ship pathway, the cost would be significantly higher.

The cost of shipping is expected to increase, but all sectors must decarbonize. The cost of GHG emissions will over time be internalized, providing a level playing-field both inside and outside the sector.

The pathways are designed to cover possible ways to reach the emission targets towards 2100. They have different pros and cons, balancing the different risks: where the Fossil-ship relies on offsets and mature technologies, the two Bio-ship pathways require biofuels to a large degree, and the Space-ship is a balance between using offsets and relying on non-mature novel technologies and measures. We have not identified which pathway is the most likely, indeed all are possible ways to the targets. The next chapter will outline a strategy for navigating this uncertainty and ensure that the targets are met by the shipping industry.

7 STRATEGY

The following section describes a robust strategy for navigating the uncertainties and preferences, and balancing the different risks outlined in the pathways. The strategy is based on the conclusions in this study which has been presented and discussed with members of the Norwegian Shipowners' Association (NSA).

The purpose of the strategy is to outline a way forward for shipping companies within the different segments and their industry organizations such as NSA, to ensure that the targets are achieved as effectively as possible. The strategy should be robust in the sense of avoiding putting all the eggs in one basket and locking shipping to one solution. The targets cannot be met by one single measure and a broad range of initiatives must be employed, retaining also a flexibility to adapt to initiatives and developments outside the sector. Further, the strategy should enable the industry to be forerunners for uptake of energy efficiency technologies and low carbon fuels. It should identify areas where the industry can influence development of sound and effective regulations and policies and to encourage innovation.

The strategy for individual companies will vary based on their segment and operations, but the core content of this strategy should be relevant for all companies. Inspiration for developing more specific company based strategies and ambitions, addressing aspects such as emissions mitigation strategies and activities, can be found in the Climate Change Reporting Framework to IPIECA[46].

The strategy centres on a set of suggested *actions* which can be performed by individual ship owners or a collective organisation such as the NSA. These actions aim to mitigate or remove a given *barrier* to the widespread use of a set of core CO_2 mitigation *solutions*. The core solutions are derived from the analysis of the emission pathways described in the previous sections. The relationship between *solutions*, *barriers* and *actions* are illustrated in Figure 22. Barriers to be mitigated depends of measures considered and has been investigated through questionnaires (e.g. Acciaro et al 2013; Rehmatulla & Smith, 2015). Findings indicate the importance of technical barriers, but also managerial practices and legal constraints.

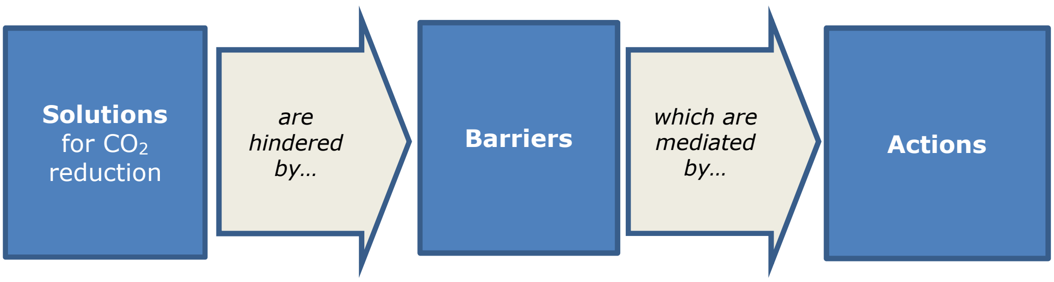


Figure 22: Derivation of actions.

4646 http://www.ipieca.org/news/ipieca-releases-pilot-climate-change-reporting-framework/

The analysis presented in the sections above clearly show how each of the pathways identified rely on at least one of the following solutions being implemented at a scale which seems daunting today;

- Alternative fuels (sustainable biofuels in deep sea, electricity and hydrogen in other segments)
- Moderate to extensive speed reduction (20-50% reduction)
- Offsetting of emissions (internally in shipping or externally)

In addition, all pathways rely on the extensive use of

- Energy efficiency; push the envelope in all segments

Should any one of the above solutions be ‘off the table’ at a given point in the coming three decades, the relevant pathways to reach the emission targets will be closed – limiting the room for ship owners to manoeuvre. Thus, in a robust strategy, where reliance on a single solution should be avoided, actions should be taken to increase the likelihood of the above solutions being available to the industry at sufficient quantities and at competitive prices. Ship-owner associations (SA) and ship owners (C) can take actions on different levels, and key actions identified in this study are presented in Table 18.

It is noted that ship owner actions are mostly effective in response to barriers relating to *Energy Efficiency* and *Speed reduction*. For *Alternative fuels* and *Offsetting*, many of the barriers are out of reach for individual owners, and must therefore be overcome though the influence exerted by the Ship-owner associations.

Table 18: Barriers and mitigating actions. Actions have been labelled *C* for company-level actions, and *SA* for ship-owner-association level actions.

Solution	Barriers	Actions
Alternative fuels (biofuels in deep sea, electricity and hydrogen in other segments)	Price, production and availability Risk – safety and reliability, complexity	• Stimulate demand for biofuels by working towards and enforcing national and regional requirements to blending drop-in biofuels. (SA) • Push for incentives and arrangements promoting uptake of alternative low carbon fuels/energy carriers. (SA) • Build industry competence and experience through piloting (fuel cell, hydrogen). (C) • Design ships with fuel flexibility (e.g. dual fuel, LNG/battery readiness). (C) • Push for development rules for safe and effective introduction of alternative fuels. (SA) • Develop national and regional home-markets as to create local demand (e.g. electrification, uptake of hydrogen), as a stepping stone for later international expansion[47]. (SA)
	Bunkering infrastructure	• Develop a technical industry standard for shore connection for electricity. (SA) • Build up shore-based infrastructure for biofuels, hydrogen and electrification. (SA)
	Different types and qualities of fuels Engine compatibility issues Ship-shore compatibility issues	• Develop a technical industry standard for marine biofuel and hydrogen quality, incl. shore based electrification (energy mix/carbon intensity). (SA) • Ensure engine compatibility with marine biofuels, including ship-shore compatibility. (SA)/(C)
	Sustainability of fuels (lifecycle emissions) – and documentation hereof	• Support the creation of an international standard for life cycle carbon intensity and sustainability of possible fuels (biofuels, bio-LNG, hydrogen, electricity). (SA)
Speed reduction (moderate to extensive)	-Complex global transport chains with high value cargo -Cargo owners have low knowledge and acceptance of speed reduction impacts -Not allowed due to charter party clauses -Financial and economic constraints – uncertain business case	• Initiate dialogues and partnerships to challenge conventional wisdom relating to the necessity of speed; on sector level (SA) and on company level (C). • Educate internally in ship owner organisations about benefits of speed reduction (to bridge the communication gap between technical and commercial department). (C) • Create an industry standard for a consistent carbon efficiency index and start reporting to create transparency on product lifecycle emissions. (SA) • Dialog and workshops with cargo owners. (SA)
	More ships are needed, and current ships are not efficient at low speeds	• Order ships designed and built to be efficient within a broader speed range (hull, propellers and machinery). (C)
Offsetting	No regulatory framework in place	• Influence the development of a IMO offset regime, including a standard for defining an offset / credit (SA)
	-Low availability of offsets -Fragmented carbon markets limits access to offsets	• Develop shipping specific carbon markets / offset sources such as a contribution fund/levy. (SA) • Connect shipping to an international carbon market. (SA)
Energy efficiency (push the envelope in all segments)	-Technical uncertainty – maturity, reduction effect, system integration -Financial and economic constraints- cost of implementation, access to capital, cost of operation -Risk – safety and reliability, complexity -Behavioural barriers- lack of information and awareness	• Develop national and regional home-markets to create local demand, as a stepping stone for later international expansion. (SA) • Participate in selected R&D and large scale demonstration projects. (C) • Prioritize piloting and experience accumulation of novel solutions. (C) • Influence national and regional R&D priorities. (SA) • Build "Best in class"- energy efficient newbuilds (C) • Focus on energy managements systems and energy culture (C)

[47] E.g. as described for the Norwegian domestic fleet, in the Roadmap developed by the Green Coastal Shipping Programme: https://www.rederi.no/aktuelt/2016/sjokart-for-gronn-skipsfart/

The *Strategy chart towards 2100,* illustrated in Figure 23 is an extract of the table above. It points towards concrete actions needed to be taken to overcome barriers for the mitigation solutions presented in this study, along with important milestones. Only the most important key actions and millstones are presented. To meet the long-term targets and reducing risks, efforts need to be taken within all mitigation categories, and delays should be avoided. Implementing the proposed strategy, the members of NSR is expected to maintain and strengthen their competitiveness, through operating fuel and speed flexible low carbon emission ships, avoiding being a potential “stranded asset” (e.g. to high operational costs). This will challenge the way ships are designed and operated today. The overall key recommendations from this study are:

- Building up availability and infrastructure for alternative low carbon fuels/energy carriers
- Develop stakeholder acceptance for substantial speed reductions
- Establishing an offsetting mechanism for international shipping
- Influence national and regional R&D priorities

The actions outlined above should help develop the availability and reduce the risks associated with each of the four solutions needed. This forms a robust strategy in the sense of avoiding putting all the eggs in one basket and locking shipping to one solution. However, it is dependent on a regulatory environment which leaves sufficient room for maneuvering; in other words, that the IMO implements a goal-based regulation which leaves the specific solutions for compliance up to the ship owners.

A goal-based regulatory reduction mechanism should translate a shipping sectors ambitions for GHG emissions and societal expectations into a required CO_2 emission level for a vessel. By using CO_2, and not for example energy efficiency, the regulation would drive all types of measures, from speed reduction to biofuels, and the most cost effective solution can be applied by each stakeholder. Any goal-based regulation should not prescribe specific measures.

The development of a goal-based mechanism should not be taken for granted, as more specific prescriptive regulations can also be implemented. This reduces flexibility, but can likely be implemented quicker and with predictable effects. For example, a speed limit would directly impact energy use and emissions. Other prescriptive regulations could take form of a maximum carbon intensity of fuels, like the current maximum sulphur content limit.

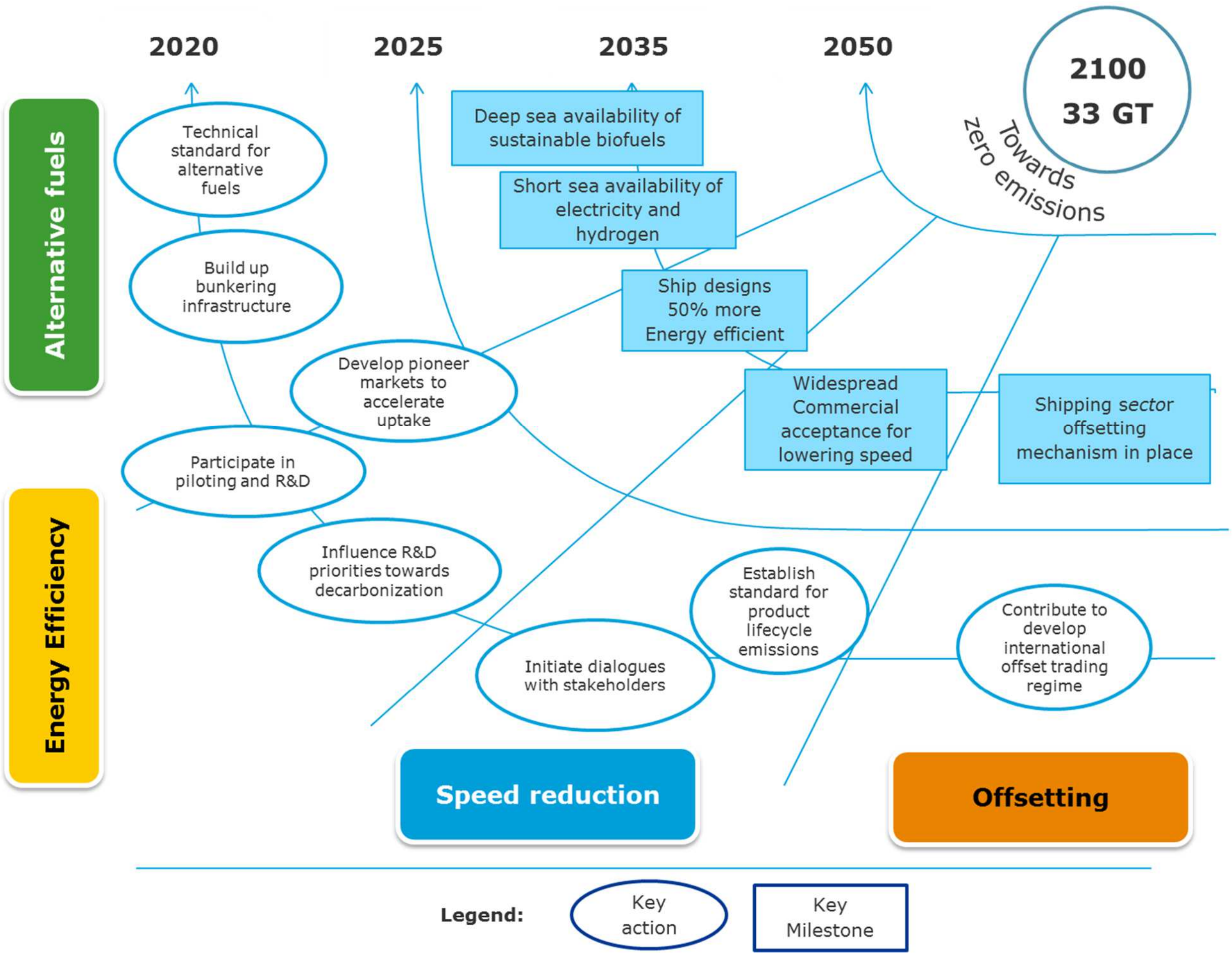


Figure 23: Strategy chart towards 2100.

8 REFERENCES

Acciaro M., Chryssakis, C., Eide, M.S., Endresen, Ø. "Potential CO_2 Reduction from Energy Mix Changes in the World Fleet", 2012 International Association of Maritime Economists (IAME) Conference, Taipei, Taiwan, 2012.

Acciaro et al (2013). The Energy Efficiency Cap in Maritime Transport. Journal of Shipping and Ocean Engineering 3 (2013) 1-10.
http://www.davidpublishing.com/davidpublishing/Upfile/3/3/2014/2014030371606417.pdf

Andersson, P. (2017): Green approaches at sea – The benefits of adjusting speed instead of anchoring, Transportation Research Part D: Transport and Environment Volume 51, March 2017, Pages 240–249.

Andersson, P. and Ivehammar, P. (2016): Cost Benefit Analysis of Dynamic Route Planning at Sea, Transportation Research Procedia, Volume 14, 2016, Pages 193–202.

Bengtsson S, Fridell E, Andersson, K. Environmental assessment of two pathways towards the use of biofuels in shipping. Energy Policy, 44, 451-463 (2012).

Bengtsson S, Andersson K, Fridell E. A comparative life cycle assessment of marine fuels; liquefied natural gas and three other fossil fuels. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment. 225, 97-110 (2011).

Buhaug, Ø., Corbett, J.J., Endresen, Ø., et al., Second IMO GHG study 2009, International Maritime Organization (IMO), London, UK, April 2009.

Chryssakis C., O. Balland, H.A. Tvete, A. Brandsæter: "Alternative fuels for shipping", DNV-GL strategic research and innovation position paper 1-2014.

Chryssakis C., H.W. Brinks, T. King, "The fuel trilemma: Next generation of marine fuels", DNV-GL strategic research and innovation position paper 03-2015.

http://production.presstogo.com/fileroot7/gallery/DNVGL/files/original/9fef597280b44480b6455332c7886d74.pdf

Chryssakis C., S. Stahl, Well-To-Propeller Analysis of Alternative Fuels for Maritime Applications, Paper No. 265, CIMAC Congress 2013.

Corbett et al. (2010). Arctic shipping emissions inventories and future scenarios, Atmos. Chem. Phys., 10, 9689–9704, 2010.

Dimopoulos G. G., C. A. Georgopoulou and N. M. P. Kakalis. (2012), The introduction of exergy analysis to the thermo-economic modelling and optimisation of a marine combined cycle system, Proceedings of 25th ECOS, Italy.

Dimopoulos G.G., Georgopoulou C.A., Stefanatos IC, Zymaris A.S., Kakalis N.M.P. (2014), A general-purpose process modelling framework for marine energy systems. Energy conversion and management. 2014; 86(0):325-39.

Dimopoulos G. G., I. V. Stefanatos and N. M. P. Kakalis (2015), Exergy analysis and optimisation of a marine molten carbonate fuel cell system in simple and combined cycle configuration. Energy conversion and management.

Eide, M.S., Chryssakis, C., and Endresen, Ø., CO_2 abatement potential towards 2050 for shipping including alternative fuels (2013), Carbon Management, June, Vol. 4, No. 3, Pages 275-289, 2013.

Eide, M., Longva, T., Hoffmann, P., Endresen, Ø., Dalsøren, S. Future cost scenarios for reduction of ship CO_2 emissions (2011), Maritime Policy & Management, 38:1, 11-37, 2011.

Eide M., Endresen Ø., and Longva T. (2009), Future CO2 Emissions: Outlook and challenges for the shipping industry, Proceedings of the 10th International Marine Design Conference (IMDC), Trondheim, Norway, 2009.

Eide et al. (2007), EU project QUANTIFY delivery: Ship emissions of the future, Report No 2007-1325, Det Norske Veritas AS, Høvik, Norway.

DNV GL (2016a), Teknologier og tiltak for energieffektivisering av skip, DNV GL report 2016-0511.

DNV GL (2016b), Reduksjon av Klimagassutslipp fra Norsk innenriks skipsfart, utreding for Klima og miljødepartementet. Rapportnr. 2016-0150.

https://www.regjeringen.no/contentassets/b3df5ceb865e42b48befdf132a95a8be/skipsfart-klimagasser-dnvgl.pdf

DNV GL (2016d), Fuel Cell in Shipping, utredning for EMSA, DNV rapportnr. 111M9MGA-1

http://emsa.europa.eu/main/air-pollution/alternative-fuels.html

DNV GL (2016c), Beregning av kostnad og nytte av investeringer i infrastruktur for alternative drivstoff i Norske havner, Utredning for Kystverket, Rapportnr.2016-1040.

DNV GL (2015), Vurdering av tiltak og virkemidler for mer miljøvennlige drivstoff i skipsfartsnæringen, Utredning for Klima- og miljødepartementet, Rapportnr. 2015-008.

DNV (2013), Hybrid ships, position paper 15, 2013.

DNV (2012). Fuel cell for ships, position paper 13, 2012.

DNV (2011), Alternative fuels for Maritime applications, DNV report 2011-1449.

DNV (2010a), Wind assisted propulsion in maritime transport, DNV rep no 2010-0595.

DNV (2010b), Shipping across the Arctic Ocean, DNV Position paper no. 4, 2010.

DNV (1984), A fair wind for sail-assisted merchant ships, Veritas November/December 1984.

Ecofys (2012), Potential of biofuel for shipping, January 2012, BIONL11332, http://www.ecofys.com/files/files/ecofys_2012_potential_of_biofuels_in_shipping_02.pdf

Ecofys (2015), Potential for Shore side electricity in Europe http://www.ecofys.com/files/files/ecofys-2014-potential-for-shore-side-electricity-in-europe.pdf

Energy Research Partnership (2016), Energy Options for transport: Overview of options, April 2016 http://erpuk.org/wp-content/uploads/2016/04/54541_ERP_Transport_Report_Annex-18-Apr-16.pdf

Eyring VK, Köhler HW, Lauer A, Lemper B. Emissions from international shipping: 2. Impact of future technologies on scenarios until 2050. *J. Geophys. Res.*, 110 (2005).

Festel, G. et al. (2014). Modelling production cost scenarios for biofuels and fossil fuels in Europe. Journal of Cleaner Production 66: 242-253.

Fletcher, M. (1997), From coal to oil in British shipping, in The World of Shipping, edited by D. M. Williams, section 10, pp. 153–171, Ashgate, Brookfield, Vt.
Lloyd's Register of Shipping (LR) (1961), Statistical Tables, 1961, United Kingdom.

Fulton et al (2015), The need for biofuels as part of a low carbon energy future. DOI: 10.1002/bbb.1559; Biofuels, Bioprod. Bioref (2015). http://bioenergycenter.org/besc/publications/fulton_biofuels_yr8.pdf

Furuichi, M., Otsuka, N. (2013): Cost Analysis of the Northern Sea Route (NSR) and the Conventional Route Shipping, Proceedings of the IAME 2013 Conference July 3-5 – Marseille, France.

Grahn et al (2013), Cost-effective choices of marine fuels under stringent carbon dioxide targets, 3rd international conference on technology, operations, Logistics and modelling in low carbon shipping, London, 9-10 September 2013.
http://fy.chalmers.se/~np97magr/Grahn_et_al_2013_LCS_conference.pdf

Hoffmann, P., Eide, M.S., Endresen, Ø. Effect of proposed CO2 emission reduction scenarios on capital expenditure, Maritime policy & Management, DOI:10.1080/03088839.2012.690081, 2012.

Hansson et al (2016), The potential role of electro-fuels as marine fuel: A cost-effective option for the future shipping sector, Shipping in Changing climates (SCC), Newcastle, 10-11 Nov 2016. http://publications.lib.chalmers.se/records/fulltext/245468/local_245468.pdf

IEA (2011), Technology Roadmap, Biofuel for transport.
https://www.iea.org/publications/freepublications/publication/Biofuels_Roadmap_WEB.pdf

IEA (2014), Alternative Fuels for Marine Applications, http://www.iea-amf.org/app/webroot/files/file/Annex%20Reports/AMF_Annex_41.pdf

IEA (2015), World energy outlook 2015, Released on 10 November 2015 (page 327).

IMO (2011), Reduction of GHG emissions from ships, Marginal Abatement Cost and Cost Effectiveness of Energy-efficiency measures. MEPC 62/INF.7.

IMO (2014), 2014 Guidelines on the Method of Calculation of the Attained Energy Efficiency Design Index (EEDI) for New Ships, Resolution MEPC.245(66), adopted on 4 April 2014.

IRENA (International Renewable Energy Agency) (2015), Renewable energy options for shipping, TechnologyBrief.
http://www.irena.org/DocumentDownloads/Publications/IRENA_Tech_Brief_RE_for%20Shipping_2015.pdf

Lindstad. H and Eskeland, G.S. (2015): Low carbon maritime transport: How speed, size and slenderness amounts to substantial capital energy substitution, Transportation Research Part D 41, 2015, 244–256.

Longva, T. (2011): A New Queuing Policy in Ports, Proceedings of MTEC2011, 13-15 April 2011, Singapore.

Longva, T., Eide, M. S., Skjong, R. A cost–benefit approach for determining a required CO2 index level for future ship design. Maritime Policy and Management, 37(2), 129–143, 2010.

Mangset, L. E., Acciaro, M., and Eide, M. S.: A Global Seaborne Trade Pattern Forecasting Method for Shipping Emissions Modeling, IAME, Santiago De Chile, 25 - 28 October 2011.

MAN (2016), Costs and Benefits of alternative Fuels for an LR1 Product Tanker, Key results from a DNV GL and MAN Diesel & Turbo joint study, June 2016.

http://marine.man.eu/docs/librariesprovider6/test/5510-0196_alternative-fuels-low.pdf?sfvrsn=24

Maritime Knowledge Centre, TNO & TU delft (2017), Framework CO_2 reduction in Shipping, 16-01-2017.

OECD (2009), Greehouse gas emissions reduction from potential from International shipping, Paper no 2009,-11, may 2009, http://www.itf-oecd.org/sites/default/files/docs/dp200911.pdf

OECD/ITF (2016), Capacity to grow, http://www.itf-oecd.org/sites/default/files/docs/future-growth-transport-infrastructure.pdf

OECD (2010), Globalisation, Transport and the Environment, ISBN 978-92-64-07919-9.

Rehmatulla, N., and Smith, T., (2015). Barriers to energy efficiency in shipping: A triangulated approach to investigate the principal agent problem. Energy Policy, Volume 84, September 2015, Pages 44–57.

Raucci et al (2014), A framework to evaluate hydrogen as fuel in international shipping, Shipping in changing Climates, Liverpool 2014.

http://www.lowcarbonshipping.co.uk/files/ucl_admin/SCC/A-framework-to-evaluate-hydrogen-as-fuel-in-international-shipping.pdf

Royal Academy of Engineering (2013), Future ship Powering options, July 2013, http://www.raeng.org.uk/publications/reports/future-ship-powering-options

Røsæg, E.: A System For Queuing In Ports, Scandinavian Institute of Maritime Law Yearbook 2008, Sjørettsfondet 2009.

Smith et al (2014), Third IMO GHG Study 2014; International Maritime Organization (IMO) London, UK, June 2014.

Smith, T., Raucci, C., Haji Hosseinloo S., Rojon I., Calleya J., Suárez de la Fuente S., Wu P., Palmer K. CO2 emissions from international shipping. Possible reduction targets and their associated pathways. Prepared by UMAS, October 2016, London.

Smith and Stephenson (2013), «New Trans-Arctic shipping routes navigable by mid-century. http://www.pnas.org/content/110/13/E1191#_methods=onPlusOne%2C_ready%2C_close%2C_open%2C_resizeMe%2C_renderstart%2Concircled%2Cdrefresh%2Cerefresh%2Conload&id=I1_1380621063143&parent=http%3A%2F%2Fwww.pnas.org&pfname=&rpctoken=76325118

Stopford, M. (2009), Maritime Economics, 3rd ed., Routledge, London and New York.

Taljegård et al (2015), Electrofuels- A possibility for shipping in a low carbon future? Conference Shipping in changing climates, Glasgow, November 2015. http://www.lowcarbonshipping.co.uk/files/Ben_Howett/SCC2015/ELECTROFUELS__A_POSSIBILITY_FOR_SHIPPING_IN_A_LOW_CARBON_FUTURE.pdf

van Eijck, J., Batidzirai, B., Faaij, A. (2014). Current and future economic performance of first and second generation biofuels in developing countries. Applied Energy 135: 115-141.

Verbeek R, Kadijk G, van Mensch P, Wulfferts C, van den Beemt B, Fraga F. Environmental and Economic aspects of using LNG as a fuel for shipping in The Netherlands. TNO Report, TNO-RPT-2011-00166 (2011).

Wijnolst, N., and T. Wergeland (1997), Shipping, Delft Univ. Press, Delft, Netherlands.
Thoma, R.F. 1981. Trans. I. Mar. E., 1981 vol 93 paper 9.

World Bank; Ecofys; Vivid Economics (2016): State and Trends of Carbon Pricing 2016. Washington, DC: World Bank.

Æsoy V, Einang PM, Stenersen D, Hennie E, Valberg, I. LNG-Fuelled Engines and Fuel Systems for Medium-Speed Engines in Maritime Applications. *SAE Technical Paper* 2011-01-1998, (2011).

APPENDIX A ALTERNATIVE FUELS

The most promising alternative fuel candidates and converters are indicated in Table 19.

Table 19: Fuel and converter matrix applied in this study (bold "X" indicates considered)

		Converters							
Energy carriers		Diesel engine	Dual fuel engine	Hybrid propulsion	Battery main	Fuel cell AUX	Fuel cell ME	Renewa-bles (part)	Nuclear
Liquefied fuel	Liquefied fossil fuels	**X**	**X**	**X**	-	-	-	-	-
	Methanol	-	X	X	-	X	X	-	-
	1st gen. biofuel	**X**	**X**	**X**	-	-	-	-	-
	2rd gen. biofuel	**X**	**X**	**X**	-	-	-	-	-
	3rd gen. biofuel	**X**	**X**	**X**	-	-	-	-	-
	Synthetic/Bio-Methanol	-	**X**	**X**	-	**X**	**X**	-	-
Gaseous fuels	Gaseous fossil fuels, LNG	**X**	**X**	**X**	-	**X**	**X**	-	-
	Bio gas	**X**	**X**	**X**	-	**X**	**X**	-	-
	Synthetic	-	-	-	-	-	-	-	-
Electrochemical (part)	Full electric, land based charging	-	-	-	**X**	-	-	-	-
	Plug in hybrid, land based charging	**X**				-	-	-	-
	Hydrogen	-	-	-	-	**X**	**X**	-	-
On board renewables	Sail, kites, turbines, solar	-	-	-	-	-	-	X	-
Nuclear	Thorium, Uranium, plutonium	-	-	-	-	-	-	-	X

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