Evaluating scenarios for alternative fuels in international shipping

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Abstract
Whilst oil derivatives (heavy and intermediate fuel oils and marine diesel oil and marine gasoil) have been the principle shipping fuels in recent decades, higher crude oil prices, lower gas prices, technology developments and environmental regulation could all create drivers for this to change, and precipitate a switch to "alternative" fuels. Liquid Natural Gas (LNG) burnt in internal combustion engines has been one of the primary alternative solutions which has gained significant attention followed by biofuels, both of them mainly due to the compatibility that they present with the current infrastructure and machinery. However a number of other fuels e.g. Methanol and Hydrogen, and machinery technologies such as fuel cells also represent options that could see take up in the next few decades. This paper presents the method and assumptions used and the analysis conclusions from a study conducted using GloTraM (Global Transport Model) to estimate scenarios for the future of international shipping out to 2050. The analysis follows previous scenario definitions produced in the study "Global Marine Trends 2030" and applies these within the techno-economic framework of GloTraM to explore the robustness of a number of different potential 'futures' of the shipping industry. The broader impacts of the take up of different alternative fuels (for example on the take-up of different energy efficiency technologies and operational interventions) is also considered and discussed, as well as the consequences on the trajectory of the industry's emission.

Keywords: Alternative fuels, shipping, GloTraM

1 Introduction and Context

The shipping industry, common to other transport sectors (road, aviation), is a significant user of oil derivative liquid fossil fuels, most commonly distillate fuels such as Marine Diesel Oil (MDO) and residual fuels such as Heavy Fuel Oil (HFO). Bauhaug et al. (2009) consensus estimate for 2007 is 257 million tonnes of residual fuel and 76 million tonnes of distillate fuel [A].

Shipping, pushed on one side by tighter regulations on efficiency and air pollution, and on the other by the increases in oil prices, produces speculation that alternative fuels could prove superior to these conventional fuels in the near future (e.g. 2015-2025). More specifically, MARPOL Annex VI on SOx regulation poses a particular challenge for residual fuels, composed by the heavier oil refined fractions and containing high sulphur levels, while the NOx regulation poses a challenge both for MDO and HFO since these emissions are significant from the current specification of marine diesel engines, the current dominant main and auxiliary machinery used by shipping. MARPOL Annex VI's inclusion of mandatory EEDI for newbuild ships incentivizes the use of fuel and machinery combinations, which halve a low specific carbon intensity (e.g. low CO2 emissions per kWh of power produced). Oil prices have remained at approximately $100 per barrel for a number of years resulting in sustained high residual fuel prices. Demand side pressure on distillate fuels, particularly in response to fuel switching anticipated in response to MARPOL's SOx regulation is expected to maintain these high prices in the near future, if not lead to them becoming even higher. The combination of these factors and the lower air pollutant emissions of LNG and Methanol has led to debate about their future role in shipping, and orders for a limited number of newbuilds and conversions capable of their use (particularly for the former, LNG).
Further in the future (e.g. 2025 +), there is speculation about the effects on international shipping of:

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- Further rising and uncertain oil and gas prices due to their finite supply and increased demand side pressure from a growing global economy
- The price and availability of bio energy resources
- Increased stringency on GHG emissions, particularly CO2, imposed through a Market Based Measure or equivalent in order to meet global targets and commitments to manage the risk of dangerous climate change
- Other environmental regulations (e.g. on black carbon, PM etc)

Such developments could see comparative advantage switching to a new mix of bio, synthetic and fossil derived fuels (e.g. biodiesel, SVO and hydrogen), and integration of these fuels with a range of new propulsion and auxiliary architectures.
To place these potential developments in the context of international shipping, it is useful to think in terms of the life span of a ship. Ocean going merchant ship designs have typically had an economic life of 25-30 years (IMO MEPC 61 Inf. 18) [B]. Assuming this continues, ships ordered in the next few years could be active out to 2050, which encompasses both the potential switch to LNG and Methanol, and the more uncertain switch to an increased bio fuel and synthetic scenario. For ships designed with no flexibility either to convert to suit fuels, which provide a competitive advantage, or change their operation to suit a modified market, this could result in significant premature obsolescence (premature scrappage or loss of second hand value), price volatility and uncertainty.

Despite the significance of these risks to the industry, little rigorous and in-depth evaluation of the broad spectrum of possible future marine fuels, their interaction with energy efficiency technical and operational interventions, and the growth and dynamics of the shipping markets, has been carried out to date.

The aim of this study is to undertake an assessment using the whole systems model GloTraM (Global Transport Model), developed in the project "Low Carbon Shipping – A Systems Approach". The model requires the definition of a number of exogenous factors that set the context for global economic and policy development over the next 40 years. To provide some exploration of the range of possible future scenarios, this is taken from the recent study Global Marine Trends 2030 [C], published by Lloyd's Register, University of Strathclyde and QinetiQ.

2 Literature review/state of the art

There are a number of models that attempt to illustrate the characteristics of the international shipping industry with the aim of predicting its evolution and role in the future of the economy. One can find along the literature that several organizations, private and public, national and international, have identified energy, and in particular fuel used in the shipping industry as a key factor. Although fuel use is influenced by the regulations, supply availability and market prices, it is the main driver controlling key components of the shipping industry structure, e.g. technology used and in the end is responsible of the marine emissions.

On the one hand, cost-optimisation energy systems type of models being used for exploring the fuel choices in the shipping industry as in the work developed by Taljegard, M [D] seem an attractive option for providing a useful picture of the role of the marine industry and its energy consumption implications in the wider economy, however their simplistic representation of the shipping sector can lead to conclusions that underestimate the potential of alternative solutions within the sector.

Other types of models more detailed for the oil refining sector such as the work developed by EPA [E] can give very accurate short term projections of the developments of the system, but only for the conservative and well known current perspective of technologies. More recent works that aimed specifically at exploring alternative futures for the shipping industry have adopted a scenario or pathways analysis framework to discuss the impacts of the implementation of non-conventional energy and machinery solutions within the marine sector, see [F] and [A]. Although these frameworks are the most accepted within the general public, given their logic and intuitive evolution-based approach, they severely rely on the specific views and stakeholder inputs provided, therefore limiting the capabilities of computer technologies of providing alternative solutions that might seem unexpected and not intuitive a priori.

2.1 Cost optimization energy systems models

In an attempt to define cost-effective choices for the marine industry, Chalmers University of Technology used the Global Energy Transitions (GET) model developed. GET is an energy systems model, which uses linear relationships to provide an aggregated representation of the economy. The modeling framework is based on a cost optimization formulation. In the work developed by Maria Taljegard [D], in addition to the conventional fossil fuels used in the shipping industry (MGO and HFO), biofuels, coal-to-liquid, gas-to-liquid and hydrogen are included as fuel shipping options. The results from the model show a shipping industry dominated mostly by LNG up to 2050, although several sensitivity analyses prompt on further alternative fuels uptake when storage costs, oil derived product supply or CO2 concentration levels change. While the model is able to provide a useful picture of the role of the shipping industry and its energy consumption in the economy, it fails in providing detailed insights on the interactions between feedstock choice, emission levels and shipping technologies that at this point concern decision makers for investing in technologies able to maintain and increase the competitiveness of the shipping industry.

A detailed modeling exercise for global trade and marine fuels assessment was developed by EPA [E] using the WORLD bottom-up oil refining logistics and demand simulation model, including 4 categories of HFO, 2 categories of MDO and MGO as fuel options for 20 different regions. In this work, although biofuel consumption is included in the model, the only alternative fuel considered for the marine industry is LNG. In this work the world biofuel consumption projections are based on IEA World Energy Outlook 2006 reference scenario, no market based instruments or carbon price effect is considered and energy efficiency design index regulation is neglected. The advantages of this model lie principally on its ability to produce accurate forecasts of product demand and supply relatively short-term projections. Nevertheless, this framework is not capable of projecting the introduction of alternative fuels in the marine industry, neither of analysing the drivers for such changes.

2.2 Scenario analysis

IMO 2nd GHG [A] is a very detailed work, where expert input and judgment from the shipping industry plays a big role and therefore constitutes one of its main advantages. It is based on a scenario construction type of model, where the storylines defined in IPCC 2007 [G] are taken as a basis. While it provides a clear and very detailed picture of the possible outcomes and critical thinking major views, it essentially fixes fuel penetrations and therefore would not be the preferred modeling framework to provide insights of non-expected possibilities of fuel uptake. In this work seven fuel categories are considered, from which the alternative fuel options are LNG, LPG, biodiesel, fischer-tropsch diesel and other renewable sources. Although one could argue the assumptions taken for the different penetration levels or fuel production pathways, it is not possible to analyse non-expected solutions or interactions using this type of framework.

DNV 2050 [F] is an Engineering-Economic model to assess the potential technical reduction in CO_2 emissions arising from bunkering fuels and alternative fuels including technical and operational measures for energy efficiency and emission reduction. The model is built using expert judgment assumptions and scenario sampling techniques to represent fuel prices uncertainty. Although being a valuable contribution as an economic exercise, the model alternative fuel options are implemented in three generic group types being presented as LNG, biofuels and nuclear energy. The lack of details on the production processes assumed for the alternative fuels makes unclear the accuracy of the results or the wider variability to which the emission reductions might be exposed.

The LNG Model in [H] is a spreadsheet based Engineering-Economic simulation model forecasting LNG demand in deep sea shipping out to 2025. In this framework the decision to adopt LNG is made at the ship building stage as no retrofitting is allowed. LNG adoption is based on a propensity figure, which is itself based on the amount of time spent in the ECAs (varying across routes mentioned above) and on a cost comparison between LNG, MDO and HFO options. Fuel prices need to be provided as an input to the model. Inputs to the model include the technological specification of each ship type including cost of standard engines, exhaust gas treatment system (scrubber), average reference engine power, LNG storage tank costs and interest rate. More specifically this type of model can produce valuable results to assess the LNG potential in the shipping industry, but has further obvious limitations to include different alternative fuels at the same level of detail given the lack of data for fuels that have still not been implemented.

2.3 Scope of this study

The aim of this work is therefore to explore profitable optimal pathways for the shipping industry by feeding the modeling framework, GloTraM with specific and detailed assumptions on fuel and technological choices for the international marine industry. In particular, the main advantage of this work lies on the stylized representation of the fuel characteristics, such as feedstock used, operational and life cycle emissions and its connections to market prices and resource supply availability within a hybrid optimization-simulation solution approach in an engineering-economic based model. Accordingly, it can be ensured that the assumptions taken in each of the model modules are consistent across the whole modelling framework.

In this work the conventional marine fossil fuels are represented by one category representing marine distillates (MDO/MGO) and two categories representing residual fuel of different sulphur contents (HFO and LSHFO). The alternative fuel choice implemented for this work includes LNG, methanol, hydrogen and biomass derived products equivalent or substitutes for the options mentioned. Table 1 shows the fuels considered in the study, their technology specification and their reasons for being included.

Table 1 Conventional and alternative fuel options modelled in GloTraM

Fuel name	**Fuel type**	**Feedstock**	**Production technology**	**Comments**
MDO	Marine distillate including marine diesel and gas oil	Oil	Refinery	It is composed of lighter distillate fractions than residual fuel, and has lower sulphur content.
Bio_MDO	Biodiesel (1st generation) Biodiesel (2nd generation)	• Rapeseed oil (1st generation) • Lignocellulose/Wood (2nd generation)	• Trans esterification Gasification	It is commercially available, can be blended with marine distillates and be fully compatible with the engines, it has the potential of reducing GHG emissions
HFO	Marine residual oil	Oil	Refinery	It is the main marine fuel used, is very competitive in price, has high environmental impacts
Bio_HFO	Straight vegetable oil (SVO)	Rapeseed oil	Pressing	It is an easily accessible fuel able to substitute HFO to reduce GHG emissions
LSHFO	Low sulphur fuel oil	Oil	Refinery	Still competitive in price as HFO and lower sulphur emissions (<1.5%), assumed to meet 0.5% sulphur limit from date of global sulphur
Bio_LSHFO	Straight vegetable oil (SVO)	Same as Bio_HFO	Same as Bio_HFO	Same as Bio_HFO
LNG	Liquefied natural gas	Natural gas	Extraction and liquefaction	It has lower GHG emissions than oil derived fuels, is competitive in prices, and is already used in part of the fleet.
Bio_LNG	Biogas	Lignocellulose/ wood biomass	Gasification	It has the same benefits as LNG but with the additional life cycle environmental impact reductions.
H2	Hydrogen	Methane	Steam methane reforming with CCS	It has no carbon emissions in the point of operation
Bio_H2	Hydrogen	Lignocellulose/ wood biomass	Gasification	It has the potential of being a carbon negative fuel.

MeOH	Methanol	Methane	Reforming and synthesis	It has lower carbon content on a mass basis and has good compatibility with
Bio-MeOH	Methanol	Lignocellulose/ wood biomass	Gasification	It has the potential of being a carbon negative fuel and its liquid physical form gives it an advantage from the storage point of view. It can be used as feedstock for other alternative fuels production (DME) and as additive for conventional fuels.

3 Scenario specification

The shipping industry is a service provider to the global trade. Major drivers such as economic and population growth, resource demand, accelerated technological advances, rise of consumers and cities in large emerging countries [C] will therefore shape the future of the shipping industry. GMT 2030 discusses how these drivers interact and creates three possible outcomes, namely Status Quo, Global Commons and Competing Nations:

Table 2 Key characteristics of GMT 2030 scenarios

Scenario	Description
Status Quo	Business as usual, economic growth at the current rate, short term solutions, rapid regulatory change. In this scenario, shipping will develop but in a controlled rate
Global Commons	More economic growth, more international cooperation, regulation harmonisation, international trade agreements, emphasis on environmental protection and climate change, expansion of globalisation. Shipping will be greatly favoured in this scenario.
Competing Nations	Dogmatic approaches and regulatory fragmentation, protectionism, local production and consumption, trade blocks, brake in globalisation. Shipping will suffer in this scenario.

GMT 2030 scenarios are mainly qualitative in nature. This paper follows the philosophy of these three scenarios and translates them into specific inputs, which may influence the rate of adoption of alternative fuels and technologies in the shipping industry.

Table 3 Key characteristics of GMT 2030 scenarios derived for GloTraM

Scenario	Oil price trajectory	Gas price trajectory	Trade scenario	Technology scenario	Economic assumptions	Regulation scenario	Bio energy (2050)
Status quo	DECC central oil price	DECC central gas price	BAU - IPCC A1B	BAU – LCS data	0% inflation, 50% barriers, 10%/3 years	2025 global sulphur switch, $40/t carbon price from 2030	1 EJ
Global commons	DECC central oil price	DECC – central gas price, lower hydrogen price	BAU	BAU	0% inflation, no market barriers, 5%/15 years	Global, carbon price from 2030, no ECAs. 2025 sulphur switch	1EJ
Competing nations	DECC high oil price	DECC – high gas price	BAU	BAU	2% inflation, 75% barriers, 10%/3 years	2030 sulphur switch, lots of ECAs, no carbon price	11EJ

It is acknowledged, both in this paper and in [C], that disruptive events may cause divergence from these scenarios. Although it is not always possible to predict (or model) such events, they would create step changes in the marine industry and, in our case, affect the outlook of alternative fuels. They may also render some of the above assumptions less relevant. A long period of instability in Egypt and subsequent disruption/closure of the Suez Canal is an example.

4 Method and assumptions

The model used to analyse the role and demand for different fuels, is GloTraM, a bottom-up model for estimating the CO_2 emissions trajectories of the shipping industry. The model applies time-domain simulation to calculate evolution over time of the global fleet. The two main drivers of the CO_2 emissions trajectories are:

- the transport demand (e.g. t.nm) over time
- the transport carbon intensity (e.g. gCO_2/t.nm) over time

Transport carbon intensity is a function of the evolution of a fleet's composition (ships) and their technical and operational specifications. These are determined by combining consideration of regulation, economics and technology performance, availability and cost and applying to models of how the fleet evolves both through stock turnover (newbuild and scrappage) and existing fleet management (lay up, retrofit and operation). The choices that are made to determine technical and operational specifications of new build and existing ships are driven by the profit maximization of the ship's owner, and regulatory compliance. An important feature of the model is its representation of the interaction between technical and operational specifications and the inclusion of technology additionality and compatibility. These interactions are an important feature of the model and can be the cause of take-back effects that create unintended consequences, for example as described in [I]. These interactions are often overlooked using conventional marginal abatement cost curve based approaches [B].

As shipping is a derived demand, the fleet turnover is driven by transport demand (the transport work demanded by the economy to satisfy the trade in goods between origin-destination pairs). The nature of the transport demand (e.g. flows of commodities and passengers between countries) determines:

- which ships are allocated to which routes
- the number of ships that are laid up
- the number of newbuilds in any one year

A transport demand scenario is selected at the beginning of the simulation, and is considered external to the system's dynamics. The IPCC SRES A1B derivative scenario described in [J] is used for all scenarios studied in this paper, because of its consistency with the work in [A].

Transport demand and its supply are broken down into a number of component shipping markets. Each shipping market has a specified commodity type and ship type (defined in [J]). The ship type is matched to the commodity type and there is not assumed to be any substitution outside of the market. In this paper, for clarity and simplicity, only the dry bulk sector is modelled.

The fleet's activity servicing this transport demand is calculated on an annualised basis and statistics produced for the average ship in each type, size and age category (fuel consumption, carbon emissions, transport supply etc). From the allocation of ship types and sizes to specific trade flows and routes, national and regional statistics can be obtained for CO_2 emissions according to different allocation philosophies.

A more complete description of the method can be found in [K], and the derivation of the model's baseline input data can be found in [L]. An overview of the assumptions and method details most pertinent to the comparative analysis of alternative fuel choices can be found below, these are explained in greater detail in [M].

4.1 Bioenergy

In this work, the term biofuels refers to liquid and gaseous fuels produced from biomass. Given the complexity associated to the multiple choices of production pathways that can arise from joining the different elements, specific production pathways are selected for each fuel type considered in the study.

In this work global biomass availability was reviewed from [N] and the critical research report published by [O], in which the methodological approaches to size the biomass resource availability were classified as:

- Resource focussed studies, based either on simple estimation rules or on spatially explicit assessments.
- Demand driven studies, focused on the competitiveness of bioenergy as an alternative to other conventional energy sources.

  Integrated studies, aiming at combine resource and demand assessments into a unified modelling framework.

As can be expected, most of the studies in the area lie within the resource focused category, and most of the models used are integrated assessment models. Nonetheless, for the scope of this work, demand driven studies provide the competitiveness angle that this work aims to lighten. The demand driven studies identified in [O] are studies published by the IEA and by FAO. The second source is oriented to a country basis study. Whereas IEA Energy Technology perspectives uses an energy systems model that takes biomass availability potentials from resource focused studies to provide the shares of biofuel consumption for the shipping industry in 2050 for a set of scenarios. The Table 4 summarizes the global biomass resource sizes reported.

Table 4 Global biomass resource sizes

Source	Definition	Value in 2050	Classification
IEA	Maximum technical potential	1500 EJ	High band
IEA	Low risk potential	475 EJ	Medium band
TIAM-UCL	High scenario	236 EJ	Medium Band
GET Chalmers	Base-case	200 EJ	Medium Band
IEA Roadmap	BLUE Map Scenario	145 EJ	Medium Band
TIAM-UCL	CCC estimate	38 EJ	Low Band
TIAM-UCL	Limited scenario	9 EJ	Low Band

Slade et al (2011) [O] concluded that most of the studies agreed on assuming that the levels will fluctuate somewhere between the medium band estimates. Therefore, as a reference for this study the projections given for biomass share in the shipping industry in 2050 by the demand driven ETP Blue Map scenario developed in [N] were taken as a reference case.

In this scenario the international shipping fleet is assumed to adopt biofuels in a similar way as the road transport sector is already doing given the blending targets and mandates for fossil fuels. The final share of the international shipping industry in this scenario is expected to be 3.52 EJ, that is to say 2.42% of the global share in 2050. Variations around this value, derived from [N] study, the following biofuel penetration levels in the marine sector have been defined:

- Status Quo →1 EJ in 2050. This number is consistent with the CCC estimated low band biomass availability for TIAM-UCL. In this case short-term focused solutions, rapid regulatory changes and overlapping jurisdictions and conflicting laws act as a barrier for alternative fuel penetration in the international fleet.
- Global Commons → 1 EJ in 2050. A more sustainable and globally harmonised biofuel penetration, built-in security and compliance certification is envisaged, along with rapid regulatory changes, leading to a similar, low, amount of bioenergy availability for shipping.
- Competing Nations → 11.5 EJ in 2050. Under a dogmatic and protectionist scenario, consistent with the low risk potential published in [N] the biofuel use increases exponentially. Considering the existing policies enforcing biodiesel blends, and given that biofuels can help increasing energy security for each individual nation and reducing their GHG emissions, the

solution adopted leads to a less sustainable scenario where more biofuels are used due to their price and accessibility competitiveness and other alternative fuels use is affected.

In this case study, dry bulk's share of the shipping industry's demand for bioenergy is calculated on the basis of a business as usual scenario, but when modeling the whole fleet is found through successive iteration until an equilibrium solution is reached.

4.2 Main machinery assumptions

Different type of fuels can be used in different type of main machinery technology; in this study the model GloTraM uses the main machinery and fuel type compatibility matrix in Table 5. Alternative fuels such as LNG and methanol were matched with both fuel cell and 4 stroke spark ignition technologies, while hydrogen was considered only in combination with fuel cell technology.

Table 5 Main machinery and fuel type compatibility matrix

Main machinery	**Fuel types**					
	HFO	**MDO**	**LSHFO**	**LNG**	**H2**	**MeOH**
2 stroke diesel	✓	✓	✓			
4 stroke diesel		✓				
Diesel electric	✓	✓	✓			
4 stroke spark ignition				✓		✓
Fuel cells				✓	✓	✓

Each of these main machinery and alternative fuel combinations may have different concept designs; the viability of each concept designs is driven mainly by capital cost, efficiency, loss of cargo carrying capacity, environmental performance and safety aspects. Accordingly with GloTraM input data the following performance and costs parameters for each concept design were estimated:

- Unit procurement cost (UPC) or upfront capital cost
- Through life cost (TLC) excluding fuel costs. For concepts design options with fuel cells, it depends from the fuel cell stack changes and other maintenance requirements. For concepts design options with ICE, TLC has been neglected.
- Specific fuel consumption at 75% MCR (sfc), which enshrines both the efficiency of the technology and the energy density of the fuel
- Dead weight tonnes loss (dwt_loss) to estimate the effect of the alternative fuel on loss of cargo carrying capacity e.g. due to lower energy volumetric density of fuel storage compare to the current storage tanks.

A summary of the estimated variables is provided in Table 6, while details of their derivations and assumptions used can be in found in [E].

Table 6 Costs and performance parameters for each concept design

Concept design description	**Costs**		**Performance**	
	UPC	**TLC**	**sfc (@75% MCR)**	**dwt_loss**
	($/MW)	**($/MW)**	**(g/kWh)**	**(te/MWh)**
H2+Fuel cells + electric motor	5.30E+06	1.70E+05	57	0.26
LNG + Reformer + Fuel cells	2.40E+06	1.70E+05	153	0.09
CH4O + Reformer + Fuel cells	1.70E+06	1.70E+05	389	0.07
LNG +4 stroke spark ignition	1.65E+06	-	150	0.09
CH4O +4 stroke spark ignition	9.50E+05	-	381	0.07

4.3 Fuel price scenarios

Forecasts for the price of shipping fuels considered in this study were obtained with different approaches. We assumed a relationship with the oil price for oil-derived fuels (HFO, LSHFO, MDO, MGO, Methanol) and a relationship with the gas price for gas-derived fuels (LNG and hydrogen). The low and central scenarios of oil and gas prices projections from [P] were used in order to derive forecasts of these shipping fuels coherent with the context provided by the global common, status quo and competing nations in [C]. The trajectories of the fuel price forecasts for the three GMT 2030 scenarios used are shown in **Error! Reference source not found.**, a detailed description of the different approaches and assumptions used can be found in [M].

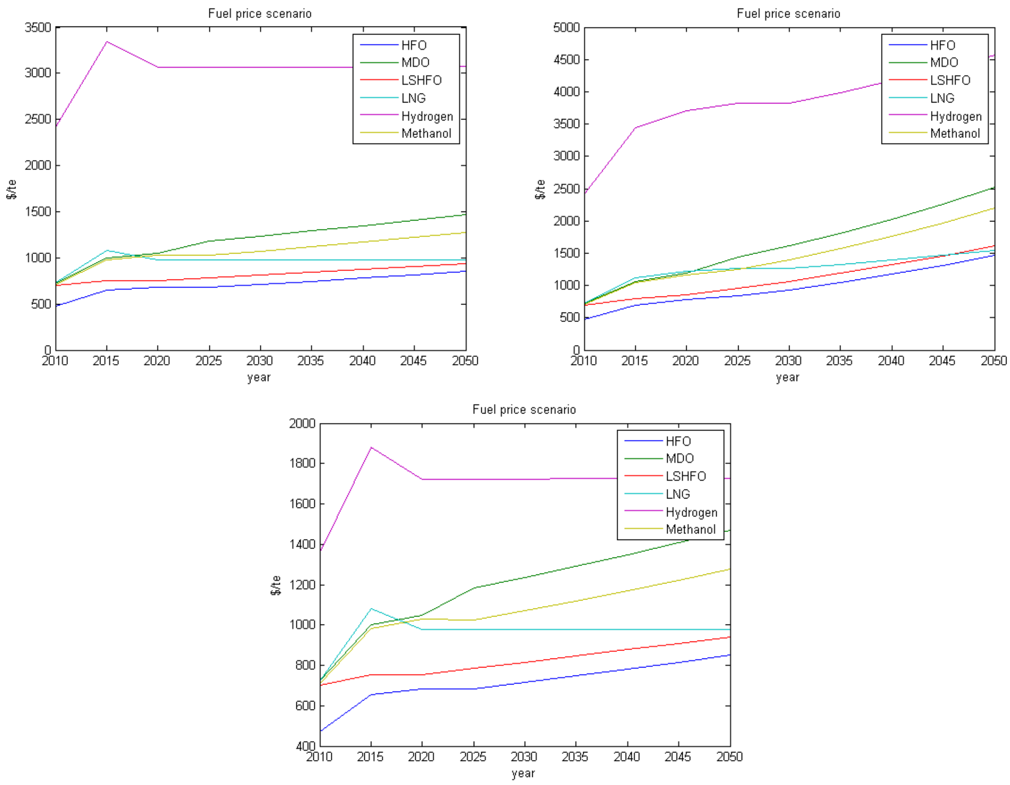


Figure 1: Status Quo (top left), Global Commons (top right) and Competing Nations (bottom) fuel price forecasts

Price forecasts of light fuel oil and heavy fuels oil were obtained based on historical trend and on assumptions on the response of ship operators to the policy drivers. In particular, up to 2020 prices of MGO , LSHFO and HFO were obtained by multiplying historical ratios between the fuels prices and the Brent price by the oil price forecasts from [P]. After 2020 prices are largely a function of how the market is expected to deliver the emission reductions. We envisaged a hypothesis in which MGO and LSHFO would have a more marked departure from the values we have observed in the past. Forecasts for fossil fuel derived methanol can be obtained with a similar approach used for MGO and IFO 380. We assumed a constant relationship between methanol and IFO 380 prices.

LNG price forecasts were obtained with a simple model of LNG infrastructure for shipping taken from [J]. The system goes from terminal to terminal; in the importer country, we have the receiving terminal, in the exporter the shipping terminal where LNG is liquefied. In between there is the infrastructure for storing (barges) and transporting the liquefied gas. Given the annual quantity consumed, the investment costs, the cost of gas, the annuity factor and the production level, the annualized cost and the cost per unit is calculated.

Hydrogen price forecasts for shipping were obtained by a spread sheet that uses the logic from [J]. It provides a techno economic analysis of a basic hydrogen infrastructure with the following assumptions: hydrogen production at a centralized location from gas through steam methane reforming with CSS technology, transport through a short pipelines (20 km) to the delivery point, liquefaction for off-shore and on-board storage. Details of both models and assumptions used can be found in [M].

4.4 Emissions accounting framework for GloTraM

In this study, CO2 emissions from the fuel combustion activities at the point of operation are modelled through the use of carbon factors based on the carbon content of the fuels and fuel blends. Therefore the main hypothesis lies on assuming that most of the GHG emissions come from the CO2 released in fuel combustion activities of the vessels during their operation. The other main assumption made in this work is that all the carbon from the fuel is converted into CO2, assuming that no other harming green house gases arising from incomplete combustion are released. Despite being simplistic, these assumptions can be accepted as being statistically representative, since it can be demonstrated that in most cases CO2 emissions constitute more that 99% of the GHG released in fuel combustion processes, and that combustion is usually performed in the presence of enough oxygen excess to avoid incomplete combustion.

The carbon factors used for conventional marine fuels are taken from IMO, due to its role as the regulating authority, and are reported on a mass basis for the fuel consumed from shipping activities. The carbon factor of the biofuel blends is calculated through a mass balance based on the carbon factor and energy content of each fuel as follows:

$$ED_{blend}\left[\frac{MJ}{ton}\right] = BF_{bio}^{mass} \times ED_{bio} + BF_{foss}^{mass} \times ED_{foss} \quad (1)$$

$$CO_{2,blend}^{op}\left[\frac{ton}{ton}\right] = ED_{blend} \times \left(BF_{bio}^{mass} \times \frac{CO_{2,bio}^{op}}{ED_{bio}} + BF_{foss}^{mass} \times \frac{CO_{2,foss}^{op}}{ED_{foss}}\right) \quad (2)$$

Where ED is the energy density of the biofuel and fossil fuels, CO_2^{op} is the carbon emission factor at the point of operation for each fuel and BF is the mass fraction of each fuel in the blend. In this case study the criteria for biofuel GHG emissions at the point of operation are considered to zero. It is worth to note that in this work different biofuel penetration projections are assumed, these are explained in greater detail in [M].

5 Results and discussion

The section displays the GloTraM output for the three scenarios. A large number of variables are monitored within GloTraM to help diagnose the underlying trends and drivers for the evolution of the industry, only a few of the key variables are displayed here, greater detail for the results can be found in [M].

5.1 Outputs for the aggregate fleet (all size categories)

Figure 2 displays the fuel mix for the three scenarios, and an interesting contrast for the mix of fuels employed by the fleet. The main drivers for the differences are:

- Regulations
- Price and price differential
- Availability of bioenergy

In Status Quo, the favourable price of LNG (relative to oil derivative fuels) and the MARPOL Annex VI regulations on air emissions drives the majority of ship sizes to adopt LNG. Further incentivisation comes from the EEDI regulation, due to the carbon factor benefit of LNG as a fuel and the analysis that according to GloTraM and its inputs assumptions, this is a more cost-effective way of meeting the regulation than either speed or technology on its own. That said, there remain some larger ships, which, for an interim period find that LSHFO or HFO and scrubbers remain a more profitable solution. The general trend for energy demanded by mass is an increase over the period 2010 to 2050 due to the underlying growth in trade and therefore transport demand, as depicted in the IPCC A1B scenario [G].

Global Commons sees a different solution. LNG is the fuel of choice for newbuilds initially (e.g. 2015), however this soon switches to a preference for hydrogen and fuel cells (initially for small ships and then for all ship size categories). In addition to the regulation scenario, this is driven both by the lower differential between the gas and hydrogen price and by the higher carbon price which incentivizes the consumption of a fuel which at least in terms of operational CO2 emissions is carbon neutral. An additional driver is the longer time-horizon over which the return on the investment is assessed. This benefits the fuel cell and hydrogen combination, which has a higher capital cost than the internal combustion machinery for LNG and oil derivative fuels, but a lower operational cost (the fuel cost and associated carbon cost), although only in combination over a long enough "life" will the operational cost savings payback the higher initial investment.

Contrasting with both the Status Quo and Global Commons solutions, Competing Nations sees continuation in the use of oil derivative fuels. Sulphur regulation incentivizes a switch to LSHFO. Some of the smaller ship size categories see take-up of LNG from 2025. This is partly to do with the difference in the oil and gas price scenarios, which do not provide sufficient incentive for a more wide-scale switch to gas, and partly due to the lack of a carbon price which does not provide the extra "push" present in Status Quo which in that scenario incentivizes the push to lower carbon fuels.

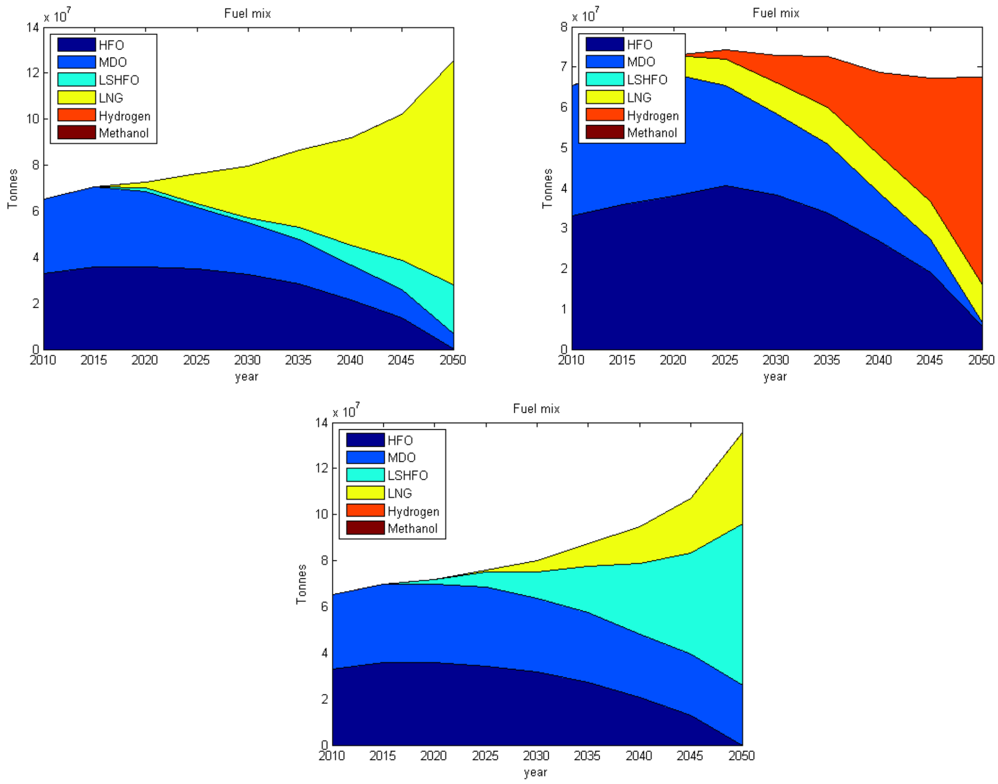


Figure 2 Status Quo (top left), Global common (top right) and Competing Nations (bottom) demand for different fuel types (2010-2050)

Figure 3 displays the consequence of each scenario on the Dry bulk sector's CO2 emissions. All scenarios are significantly different. Status Quo sees slow growth in CO2 as rapid uptake of LNG and some technology and speed reduction mitigate growth in annual emissions created by growth in transport demand. By 2030, the rate of carbon intensity reduction across the aggregate fleet has reduced as these options reach a plateau and so the growth in emissions becomes dominated by that transport demand growth. In Global Commons, the switch to hydrogen as a fuel can be seen to have a dramatic impact on the emissions trajectory, effectively decarbonizing the industry by 2050. It might seem counterintuitive that in Competing Nations, the most dramatic decarbonisation occurs. This can be explained due to the high penetration of bioenergy (availability increases at a rate faster than the fossil energy demand growth) and so bioenergy forms an increasing share of the fuel mix. This carries on until 2045 when the growth rate of energy demand exceeds the available bioenergy supply growth rate and a significant share of fossil derived fuel is required once again.

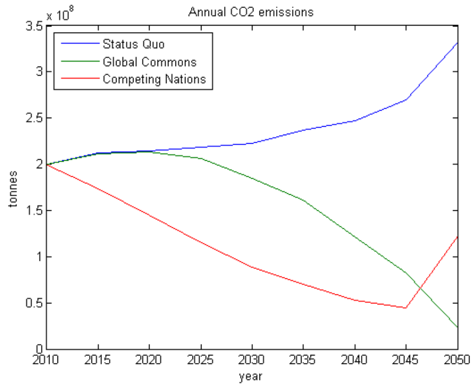
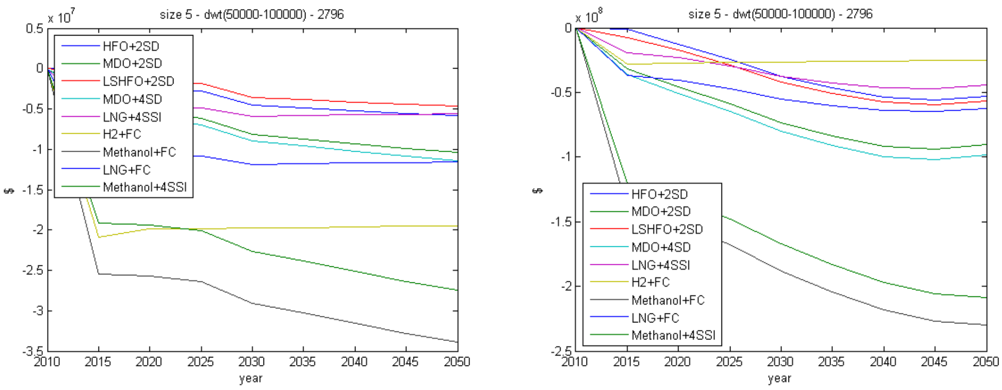


Figure 3: Status Quo, Global Commons and Competing Nations total annual emissions for dry bulk carriers (all sizes)

5.2 Outputs for specific ship size categories

A more detailed explanation for the fuel and machinery selection can be found from Figure 4, which shows the profitability of a range of fuel and machinery choices considered by GloTraM. Only ship size 5 (50-100,000 dwt) is displayed, for clarity and simplicity reasons and there is some differentiation between ship size, due to differences in the size (and therefore costs) of different engines and the impact of increase fuel storage volume (e.g. hydrogen) on the ship's payload capacity and therefore revenue. The profitability changes over time because of the evolution over time of the individual fuel prices and the carbon price. The plots are displayed for a baseline design of ship (the technical and operational specification of the 2010 fleet). All else being equal, GloTraM should select the most profitable fuel choice, and some clear switch overs can be seen (e.g. hydrogen switches over from HFO in 2025 to become the most profitable choice) in the Global Commons scenario. However, all else is not equal as for each time-step the ship's technology and operational specification is also varied. The global profit maximization for all three parameters (fuel/machinery choice, speed and take-up of technical and operational abatement and energy efficiency interventions) can result in a different fuel/machinery being selected than those for the baseline ship. Therefore these results are only intended to be indicative of the relative advantages of the fuel/machinery options modelled.



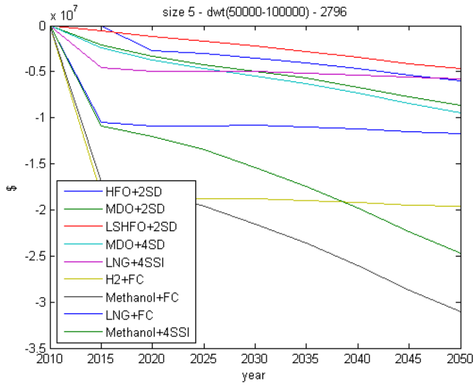


Figure 4: Status Quo (top left), Global Commons (top right) and Competing Nations (bottom) evolution over time of annualized cost (capex and opex) for different alternative fuel and machinery combinations applied to the baseline (2010) design of ship for size 5 (50-100,000 dwt)

One consequence of the fuel, machinery and technology selection in GloTraM is that this can result in the incentivisation of different ship speeds. If everything else is equal, higher fuel and carbon costs will drive lower speeds, however in practice there is an interaction with the technical efficiency of the ship e.g. in a given market, ships with better technical efficiency (e.g. EEDI) can maximize their profit by travelling faster than less efficient ships. This helps to explain the differences in the three scenarios observed in Figure 5, which might otherwise also be counter-intuitive. Global Commons sees, in general, higher ship speeds than the Status Quo and the Competing Nations scenarios.

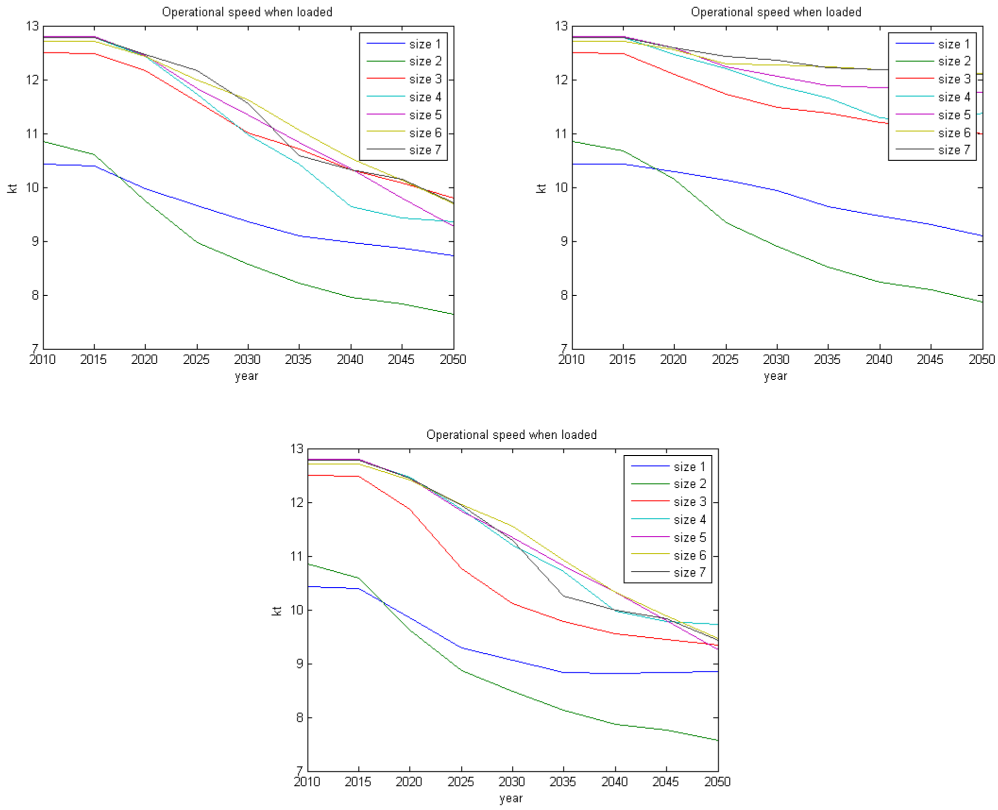


Figure 5: Status Quo (top left), Global Commons (top right) and Competing Nations (bottom) fleet average (new builds and existing ships) operating speeds and their evolution over time

Figure 6 depicts the EEDI of the average fleet over time. In all three cases, the most dramatic increases in efficiency appear to be occurring in the smallest ship sizes (due to a combination of alternative fuels with lower carbon factors, take-up of energy efficiency technology and lower design speeds). Status Quo sees only limited improvement in EEDI over time, with a ‘plateau’ occurring for some of the larger ship sizes from approximately 2030, demonstrating the challenge to improve the carbon intensity fundamentals of these ship sizes, as long as they remain powered by conventional oil derivative fuels. The take-up of hydrogen has a marked impact on the EEDI scenarios in Global Commons, as does biofuel (with the assumption that this is allowed to modify C_f in the EEDI formula) in the case of Competing Nations.

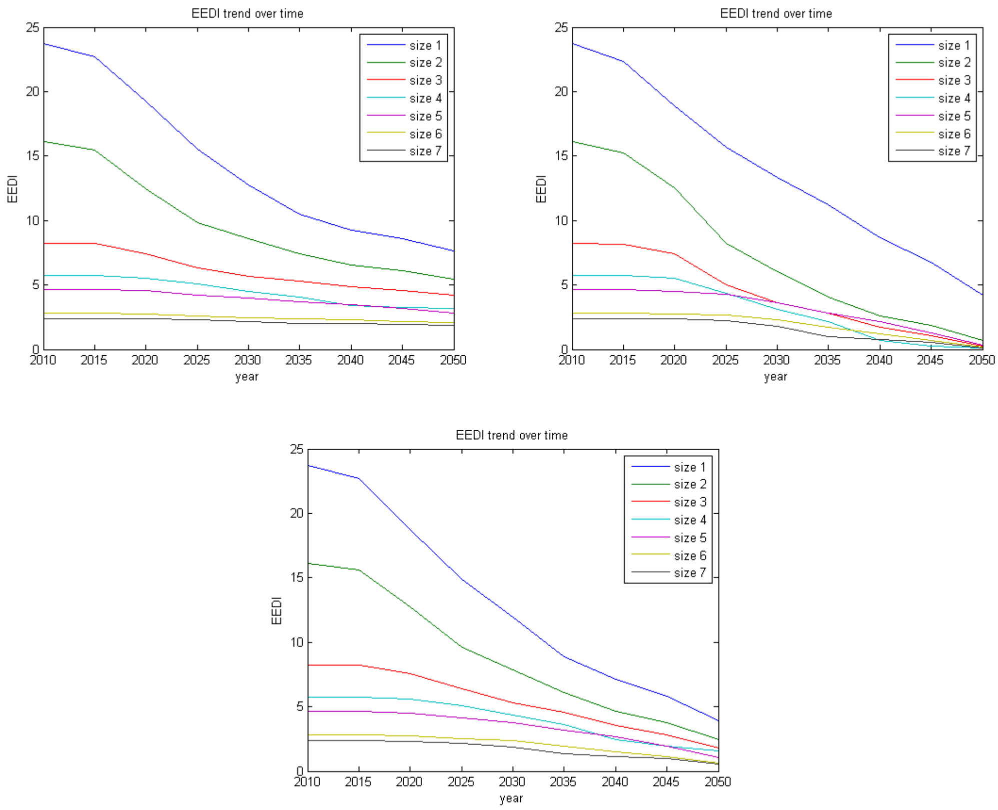


Figure 6: Status Quo (top left), Global Commons (top right) and Competing Nations (bottom) Fleet average (newbuilds and existing ships) EEDI and their evolution over time

6 Concluding remarks

The take up of different alternative fuels in shipping is complicated by the large number of interactions involved. This complexity can be investigated by exploring different scenarios. Although these scenarios can be qualitative, the modeling framework helps to highlight the main interactions. The choices that are made to determine technical and operational specifications of new build and existing ships are driven by the profit maximization of the ship's owner, and regulatory compliance. Under this assumption the results for the aggregate fleet (all size categories) show that the fuel mix is generally driven by regulations, price and price differential and availability of bioenergy. Although there are specific solutions for individual ship size categories studied, some macro behaviour can be identified in all scenarios. Despite the model's opportunity to select scrubbers and SCR type solutions, a switch to a fuel that meets the MARPOL Annex VI regulations can be observed in all scenarios. Sulphur regulation is the first incentive to this switch, the presence of a carbon price provides an extra "push" to fuels with low/zero carbon content e.g. hydrogen in Global Commons. Differences in the fundamental oil and gas price have an effect on the competitiveness of oil-derived fuel versus gas-derived fuels, which command the wide-scale switch to gas derived fuels. The same mechanism can be seen when a lower differential between the gas and hydrogen price is applied in global commons. The trajectories of the industry's emission are very different between the three scenarios demonstrating a high sensitivity to the fuel mix take up. Whilst in Status Quo they seem to depend on transport demand growth, in Global Commons the introduction of hydrogen as fuel has a dramatic impact, as well as the high penetration of bioenergy in Competing Nations.

Other interactions can be observed for specific ship size categories. The profitability of a fuel/machinery option varies with the size of ships due to the impact of increase fuel storage volume on the ship's payload capacity and therefore revenue. This profitability changes over time because of the evolution over time of the capital costs and operational costs differential. Whilst operational costs change due to the fuel prices and the carbon price trajectories, capital costs of the machinery are considered constant for each size category. The fuel/machinery selection cannot be explained only with this variation over time as the ship's technology and operational specification for each time-step and size category change and this has an effect on the global profit maximization. For example ships with better technical efficiency (e.g. EEDI) can maximize their profit by travelling faster than less efficient ships. The increases in efficiency appear to be occurring in the smallest ship sizes, whilst larger ship sizes have difficulty to improve their carbon intensity, as long as they remain powered by conventional oil derivative fuels. The take-up of hydrogen in global commons and biofuel in competing nations has a remarkable impact on the EEDI evolution over time also for larger ships.

The analysis underlined that the system may be very difficult to predict because of its extreme sensitivity to small variations and change occurrences (the butterfly effect) so even small changes in input assumptions can create large changes in the alternative fuels mix.

Future areas of work include a more complex representation of the marine fuels supply demand balance in order to identify the dynamics of fuels prices and their differential, quantifying upstream emissions, supply infrastructure and the interaction with shipping's energy demand. Other scenarios and input assumptions can be investigated exploring different concept designs of ships, as well as market conditions under which a switch to alternative fuels becomes an attractive option. Due to the nature of infrastructure and supply chains, fuel prices are not globally homogenous and the regional differences could increase with the advent of alternative marine fuels. Furthermore, there are emerging and deepening differences in regulation between regions. Future work that deals with the regional specifications is suggested.

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8 References

[A] Buhaug, Ø., Corbett, J.J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D.S., Lee, D., Lindstad, H., Markowska, A.Z., Mjelde, A., Nelissen, D., Nilsen, J., Pålsson, C., Winebrake, J.J., Wu, W.–Q., Yoshida, K. (2009). Second IMO GHG study 2009 London: International Maritime Organization (IMO).

[B] IMO MEPC 61 Inf. 18 (2010) Formal safety assessment. Available from: http://www.rina.org.uk/hres/mepc%2061_18.pdf [Accessed August 2013].

[C] QinetiQ, Lloyd's Register, University of Strathclyde (2013). Global Marine Trend 2030. Available from: http://www.lr.org/sectors/marine/GTC/gmt2030.aspx [Accessed August 2013].

[D] Taljegard, M. (2012). Cost-effective choices of marine fuel under stringent carbon dioxide targets Results from the Global Energy Transition (GET) model. GET Chalmers. Available from: http://www.gu.se/digitalAssets/1375/1375340_maria-taljeg--rd.pdf [Accessed August 2013].

[E] Enviromental Protection Agency EPA (2008). Global trade and fuels assessment – future trends and effects of requiring clean fuels in the marine sector. Available from: http://www.epa.gov/nonroad/marine/ci/420r08021.pdf . [Accessed August 2013].

[F] Eide, M., Chryssakis, C., Alvik, S., Endresen, Ø. (2012) Pathways to Low Carbon Shipping - Abatement Potential Towards 2050 DNV Position Paper 14 - 2012. Available from:

http://www.dnv.com/binaries/position%20paper%20from%20dnv%20pathways%20to%20low%20carbon%20shipping_tcm4-535306.pdf [Accessed August 2013].

[G] IPCC, 2007: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[H] Aagesen, J., Ajala L., Nicoll S., (2012). LNG-fuelled deep sea shipping. The outlook for LNG bunker and LNG-fuelled newbuild demand up to 2025. August 2012. Lloyd's Register

[I] Smith T.W.P., Technical energy efficiency, its interaction with optimal operating speeds and the implcations for the management of shipping's carbon emissions. Carbon Management (2012) 3(6), 589-600.

[J] Smith, T.W.P. O'Keeffe, E. Haji, S. Agnolucci, P. GloTraM external factors, UCL, London

[K] Smith, T.W.P. O'Keeffe, E. Haji, S. GloTraM method, UCL, London

[L] Smith T.W.P. O'Keeffe, E. Aldous, L, Agnolucci P. Assessment of shipping's efficiency using Satellite AIS data. UCL Energy Institute. London. 2013.

[M] Smith T.W.P. Sabio, N. Raucci, C. Argyros, D. Alternative fuels for international shipping

[N] IEA (2011). Technology roadmap. Biofuels for Transport, OECD/IEA, Paris. Available from: http://www.iea.org/publications/freepublications/publication/biofuels_roadmap.pdf [Accessed August 2013].

[O] Slade, R, Saunders, R, Gross, R and Bauen, A (2011) Energy from biomass: the size of the global resource, An assessment of the evidence that biomass can make a major contribution to future global energy supply, A report produced by the Imperial College Centre for Energy Policy and Technology for the Technology and Policy Assessment Function of the UK Energy Research Centre

[P] DECC (2011) DECC fossil fuel price projections: summary. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/65698/6658-decc-fossil-fuel-price-projections.pdf. [Accessed August 2013].