Exploring the sectoral level impacts and absolute emission changes of using alternative fuels in international shipping

Haji, S.[1] Walsh, C[2]. Dray, L.[1] Gilbert, P.[2] Smith, T.[1] Kesieme, U[3].

[1] The Energy Institute, University College London
[2] Tyndall Centre for Climate Change Research, University of Manchester, Manchester
[3] University of Newcastle

ABSTRACT

The shipping sector is required to reduce fuel sulphur content to 0.1% in Emission Control Areas by 2015 and to 0.5% globally by 2020. At the same time there is regulation and a need to address NOx and PM emissions at a localised level and increasing pressure to address the sector's rising CO_2 emissions, which is a major contributor to global climate change. A measure to address these challenges is to switch from the use of heavy fuel oil to alternative fuels that are able to address local pollutants and carbon emissions in parallel. This paper aims to explore the wider impacts of decisions on the choice of fuel undertaken at ship level. This is achieved by incorporating into shipping tool deployed in this study (GloTraM) the upstream and operational emissions for a range of alternative fuels, and test running them with a series of future scenarios. Key research questions include: (1) what are the total CO_2 emissions when GloTraM is run with upstream emission factors added?; (2) what impact do these emissions have on the amount/type of fuels used in the sector?; (3) What are the non-GHG emissions and how significant are they compared to CO_2 emissions? A life cycle approach is used to generate the upstream, i.e. well-to-tank emissions, accounting for the emissions associated with the processes used to grow and/or manufacture, distribute and dispose of an alternative fuel. The functional unit is tonne of CO_2 per tonne of fuel delivered (to the vessel). These emissions are then incorporated alongside the operational emissions, which have been taken from the IMO's 3rd GHG study. The results of the study provide a better understanding of the magnitude of total emissions from international shipping and the wider system level implications of fuel switching decisions.

1. INTRODUCTION

Climate change is a global issue and the greenhouse gas emissions that exasperate its impacts are continuing to rise (Le Quéré, Moriarty et al. 2014). 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). The fuel mix in 2007 was approximately 257 million tonnes of residual fuel and 76 million tonnes of distillate fuel (Bauhaug et al. (2009)). Addressing climate change will require the proportion of fossil fuels used in shipping to reduce and alternative, lower carbon fuels to be used instead. At a global level, there is a need to ensure that these alternative fuels deliver such savings yet also minimize wider environmental impacts and have minimal impacts on the wider shipping system and society as a whole.

When considering the overall impact of a given fuel on the environment, it is important to take into account not only the direct emissions from using the fuel, but also emissions related to the production and transport pathway of that fuel. In addition, in the case of some fuels such as biofuels land and water usage becomes an important factor. Performing a life cycle assessment (LCA) study helps to collect quantitative information for these impacts and compare different pathways along the energy value chain from production to distribution to vessel operations.

The aims of the study are to:

- Assess a selection of alternative fuels through a whole systems analysis and to provide a series of initial recommendations for policy makers and future academic research of the overall feasibility of these fuels
- Study specifically the period 2010-2050 and how fuel mix is going to evolve given a set of input assumptions
- Review and select fuels that have potential to be used in the sector in the study period

2. ALTERNATIVE FUELS

The shipping sector is required to reduce fuel Sulphur content to 0.1% in Emission Control Areas by 2015 and to 0.5% globally by 2020. At the same time there is regulation and a need to address NO_x and PM emissions at a localised level and increasing pressure to address the sector's rising CO_2 emissions, which are a major contributor to global climate change. A measure to address this challenge is to switch the use of heavy fuel oil (HFO) to alternative fuels that are able to address local pollutants and carbon emissions in parallel. The former is important not just from the perspective of global emission constraints, but also as many regions such as the European Union (Ölçer and Ballini 2015) place additional controls for ships at Berth. Furthermore, given the likelihood that the demand for shipping will continue to increase in continuation of recent trends, the drastic emissions reductions envisioned necessary within Bauhaug et al. (2009) and IMO (2014a) will be difficult to achieve without some degree of fuel switching. This is particularly relevant in scenarios which project significant increases in demand, effectively requiring the fleet to achieve near total de-carbonisation by 2050.

In addition to any potential future regulation of GHG (e.g. MBM), there is existing regulation of air pollutants, which are expected to impinge significantly on the technology and economics of energy efficiency. IMO's MARPOL convention Annex VI contains regulation of both SOx and NOx, as shown in Figure 1 and Figure 2 respectively.

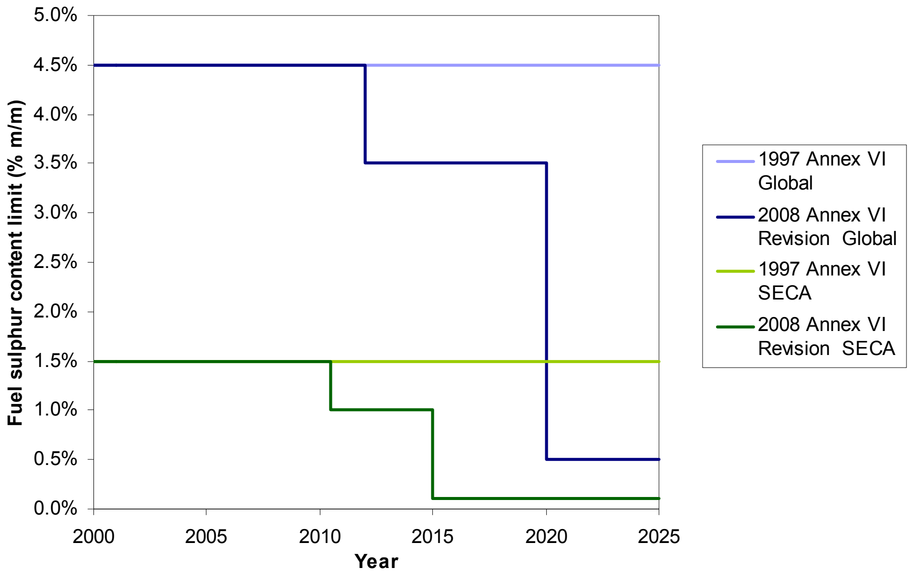


Figure 1: Regulation requirement SOx limit for new and existing ships

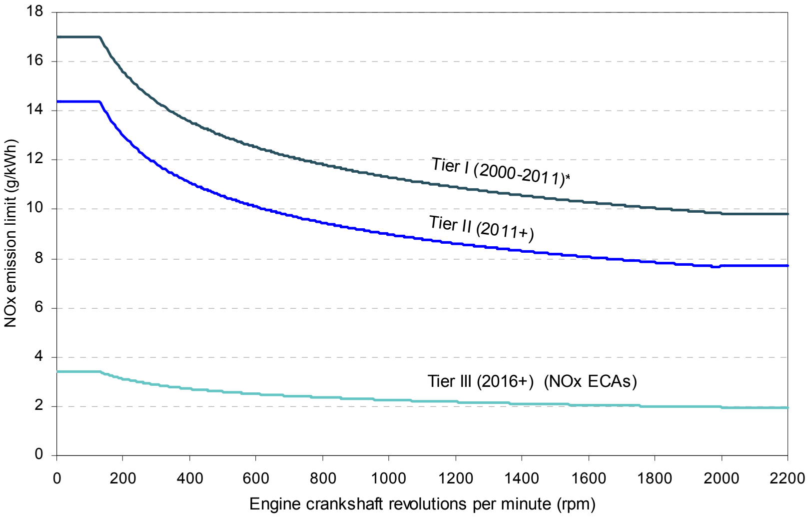


Figure 2: Regulation requirement NOx limit for new ships

Considering the life-cycle impacts of these fuels is an essential step to ensure that any alternative fuel is able to deliver meaningful savings for the sector as a whole. Furthermore, the alternative fuels might incur the release of such emissions at a different stage of the life-cycle, for example during refining or transportation, and/or may be derived from biomass feed stocks, which have life-cycle impacts associated with growth, land-use change and agricultural inputs. As a result, life cycle assessment tools are to be used in conjunction with primary and secondary data sources to assess the environmental impacts at a fuel-cycle level. The inclusion of lifecycle elements is particularly pertinent within the context of de-carbonisation. Specifically, in order to achieve the drastic direct emissions reductions deemed necessary, certain options such as liquid hydrogen or bio-fuels become quite attractive. However as mentioned, such fuels will have an embodied fossil emission which, when taken into account, may mean that required de-carbonisation levels are not achieved.

Conventional lifecycle assessment is sometimes referred to as attributional lifecycle assessment (ACLA). Within ALCA a boundary is placed around the system, which determines the supply chain stages involved. The choice of boundary will determine the functional unit, that being the goods or service to which the emissions are allocated. The gathering of data is termed the inventory stage of an ALCA and requires the resource and emissions associated with the provision of the functional unit to be expressed in terms of the functional unit (Heijungs and Wiloso 2014). Upon completion, the inventory stage can derive subsequent environmental impacts, for CO_2 equivalent (CO_2, CH_4 and N_2O) to assess Global Warming Potential; SO_x and NO_x to assess Acidification and Eutrophication Potential; and PM emissions.

Within this study what we are interested is one tonne of fuel delivered to the vessel, also known as well to tank. This accounts for the upstream, and where applicable, downstream life-cycle emissions associated with delivering the fuel to the vessel. For example, the CO_2 emissions associated with the manufacturing of a fuel will be provided as kg CO_2/tonne of fuel delivered.

3. AVAILABILITY OF BIO-DERIVED FUELS

In this work, global (and shipping) potential availability of bio-derived fuel is estimated using a number of international sources (e.g. IEA) and reviews mainly carried out by Sharmina and Gilbert (2015). A review by Offermann et al. (2011) of 19 studies finds that estimates of global bioenergy potential range from near-zero to 1,550 EJ per year (Figure 3). For comparison, the global primary energy supply in 2009 was just under 500 EJ, with biomass use accounting for a tenth of that (including traditional[1] biomass). There is a large spread in the assessments of global bioenergy potential. A significant number of reviewed studies argue that the bioenergy potential in 2050 exceeds current primary energy demand; at the same time, many assessments place it below current primary energy demand. A recent study by Searle and Malins (2014) warns that in 2050 the maximum sustainable bioenergy potential (including energy crops, residues, forestry and waste) is 60–120 EJ per year.

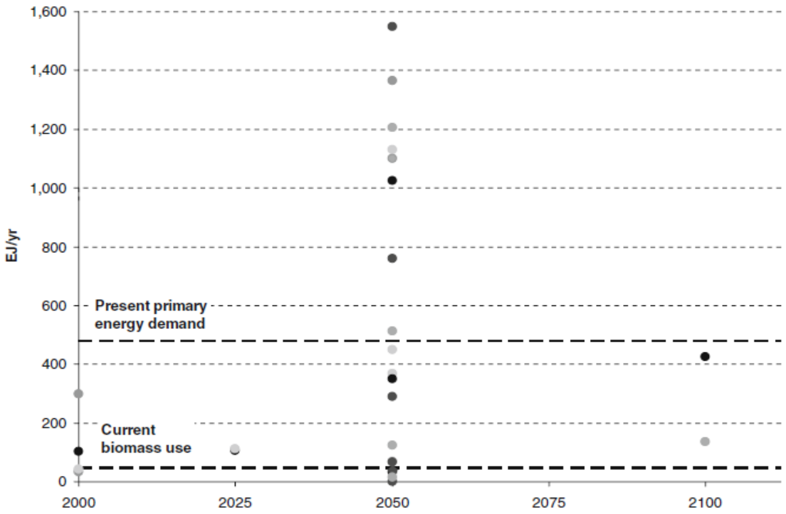


Figure 3: Global bioenergy potential as reported in 19 studies reviewed within (Offermann et al., 2011)

Assuming that the final share of international shipping is expected to be 2.42% of global bioenergy potential in 2050 (IEA, 2011), three levels of bio-derived fuel availability can be estimated. These are shown below. We further assume that the growth from base year 2010 out to 2050 is linear.

1. Lower bound 1EJ in 2050 (38EJ Global level)
2. Mid-range 4EJ in 2050 (172EJ Global level)
3. Upper bound 11EJ in 2050 (460EJ Global level)

4. SCOPE OF THE STUDY

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, hydrogen and biomass derived products equivalent or substitutes for the options mentioned. Table 1 shows the fuels considered in the study and their technology specification.

Table 1 – Conventional and bio-derived fuel options modelled in GloTraM

Fuel name	Fuel type	Feedstock	Production technology
MDO	Marine distillate including marine diesel and gas oil	Oil	Refinery
HFO	Marine residual oil	Oil	Refinery
LSHFO	Low Sulphur fuel oil	Oil	Refinery

---

[1] Traditional' biomass typically "recycles agricultural byproducts (animal dung and crop residues, especially) to useful energy for the household" (Victor and Victor, 2002). In addition to agricultural residues, traditional biomass can include fuelwood and charcoal.

LNG	Liquefied natural gas	Natural gas	Extraction and liquefaction
H2	Hydrogen	Methane	Steam methane reforming
Bio_MDO	Biodiesel	Biomass eg rape seed oil	Transerification
Bio_HFO	Biodiesel	Biomass eg rape seed oil	Mechanical extraction
Bio_LSHFO	Low sulphur biodiesel	Biomass eg rape seed oil	Mechanical extraction
Bio_LNG	Liquefied bio-methane	Food waste	Anaerobic digestion
Bio_H2	Hydrogen	Renewable energy (wind)	Wind / electrolysis

Meeting the SO_x and NO_x requirement for more conventional fuels, such as Heavy Fuel Oil (HFO) and Marine Diesel Oil (MDO), is technically feasible but can be very costly. Therefore, fuels that have the potential to reduce SOx and NOx emissions below the required levels can play a significant role in the future as substitutes. In addition, the requirement for reduced sulphur content in the fuel will also increase the cost of the fuel. Introducing new, Sulphur-free fuels can be a viable solution for this problem, provided that the substitute fuels and the necessary technologies are offered at competitive price levels. However, as a caveat it may be the case the development of fuels with reduced level of local pollutants (such as Sulphur) may displace emissions from the operational to the fuel production stage.

4.1 Method and assumptions

The model used to analyse the role of and demand for different fuels is GloTraM, a bottom-up model for estimating the CO_2 emissions trajectories of the shipping industry (Smith *et al*, . 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.

The model applies time-domain bottom-up simulation to calculate evolution over time of the global fleet. It produces a holistic analysis of the global shipping system in order to investigate how shipping might change in response to developments in fuel prices and environmental regulation (on emissions of SOx, NOx, PM, CO_2). Areas of particular interest are the possible trajectories of the CO_2 emissions from the shipping industry, where these emissions might be apportioned and to whom (ship types and stakeholders), and what the costs and impacts of substantial emission reduction of the shipping industry might be.

The period covered by the modelling is 2010-2050 and its scope includes three major contributor vessel types (i.e. container, dry bulk and oil tanker) and trade flows. The approach taken to develop this tool is multi-disciplinary in that it mixes engineering, economics and logistics algorithms and data. However, a quantitative modelling approach can only describe those parts of the shipping system, which are numerical in nature. As a result, much of the supporting work underpinning the assumptions used in the modelling are standalone and in-depth qualitative analyses (e.g. into market barriers, full cost accounting, end to end supply chains, regulatory and policy frameworks, operation and maintenance procedures etc).

4.2 Inclusion of emission factors

Previous versions of GloTraM have included only operational CO_2 emissions factors. For this study, a much wider range of emissions factors was incorporated into the model, including greenhouse gases CH_4 and N_2O, and other pollutants (SOx, NOx and PM). For reporting output CO_2e from non-CO_2 emissions, a 100-year GWP from IPCC (2013) is used, which includes climate-carbon feedbacks.

Upstream emissions factors are derived from the LCA analysis discussed in section 2 and are specified by year and fuel type. Operational emissions factors are more complex to add to the model. Non-CO_2 emissions factors are typically also a function of engine type and load (IMO, 2014a). This means that, for example, reducing vessel speed in response to increased costs will act to increase CH_4 emissions factors. Emissions factors may also be affected by applicable regulations from the engine manufacture year. These relationships are modelled by interpolating between the bottom-up emissions factors used in the IMO's 3rd GHG study (IMO, 2014a).

A further factor in the comparison between traditional and alternative fuel emissions is the use of exhaust after-treatment. Although these technologies can allow ships to operate using traditional fuels and still comply with Sulphur and NOx regulations, the consumables used in after-treatment also have associated lifecycle emissions – for example, urea for Selective Catalytic Reduction (SCR) to reduce NOx emissions (Anderson & Winnes 2011). As discussed by IMO (2014b), including after-treatment consumable emissions can add several percent to the total lifecycle emissions. We include emissions by type of after-treatment based on IMO (2014b) and Anderson & Winnes (2011). It is difficult to predict the uptake of different types of Sulphur and NOx after-treatment; for this study, we assume Sulphur treatment uses open loop seawater scrubbers, and NOx treatment uses SCR. In all cases, emissions after-treatment is assumed to reduce exhaust emissions down to the regulated limit. Where regulations are applied only in ECAs, it is assumed that after-treatment is only applied in ECAs too.

5. SENSITIVITY ANALYSIS

Five scenarios are considered in the study, which assume different levels of bioenergy available for shipping (Table 2). The main objective is to estimate total CO_2 emissions as well as SO_x and NO_x and taking into account upstream emissions. The first scenario is BAU (business as usual) and assumes no bio- derived fuel availability and zero carbon price. The following parameters referred to as external factors are exogenous and defined by the user. This forms the base of BAU scenario – S0 in Table 2.

- Regulation scenario
  - EEDI reduction
  - SOx and NOx (global and ECA)
- Fuel and carbon price scenario
  - Fossil fuels price (consistent with 2°C climate target)
  - Carbon price taken from TIAM-UCL (consistent with 2°C climate target)
- Trade scenario
  - Base year 2010 is taken from NEA where growth rates are applied according to IMO 3rd GHG study (Smith *et* al, 2014)
- Investment parameters
  - Barrier to market - the extent to which savings are passed on to the ship owner
  - Discount rate - the interest rate used to discount future profits
  - Return period - the time horizon over which the profitability of an intervention is assessed
- Engine technology options
  - 2-stroke engine
  - 4-stroke engine

    - Diesel electric
    - Internal combustion (LNG)
    - Internal combustion (Methanol)
    - FC (Hydrogen)
    - FC (Methanol)
    - FC (LNG)
- Fuel options
    - HFO
    - MDO
    - LNG
    - Hydrogen
    - Methanol
- Technology options
    - LCS technologies

Table 2 – Key characteristics of sensitivity runs

Scenario ID	Fuel cost scenario	Return period (years)	Barrier to market	Discount rate	Out-sector offsets	Carbon price	MBM start year	Bio availability
S0	2C	3	0.5	10%	0%	none	-	none
S1	2C	3	0.5	10%	0%	yes	2020	Central
S2	2C	3	0.5	10%	0%	yes	2020	High
S3	2C	3	0.5	10%	0%	yes	2020	Low
S4	2C	3	0.5	10%	20%	yes	2020	Central

S1 – S4 are variations of BAU where input assumptions are altered and the impacts of these variations are examined. Fuel and carbon prices used in GloTraM are derived from commodity price information taken form TIAM-UCL, an energy systems model developed at the Energy Institute - UCL. The objective function of TIAM-UCL is to satisfy all energy-service demands[2] in a cost-optimal manner. In TIAM-UCL commodity prices are therefore generated within each year within each region[3] on the basis of matching the regional demand for that commodity with the available supply options. Fuel prices are in line with 2°C climate target.

Scenario 6 assumes carbon rebate mechanism where a proportion of revenue raised from carbon pricing in spent in green fund and/or buy off-sets from from outside the shipping industry (up to 20% of the revenue) and these will count towards the emissions targets of the shipping industry. For more information and background on scenarios refer to Haji *et al* (2015). Results of the study are presented in the next section.

6. RESULTS AND DISCUSSION

In this section, outputs from GloTraM are displayed and discussed. We are specifically interested in monitoring emissions of SO_x and NO_x and the resulting combination of fuel choice between scenarios.

The main drivers for the choice of fuel between different scenarios are:

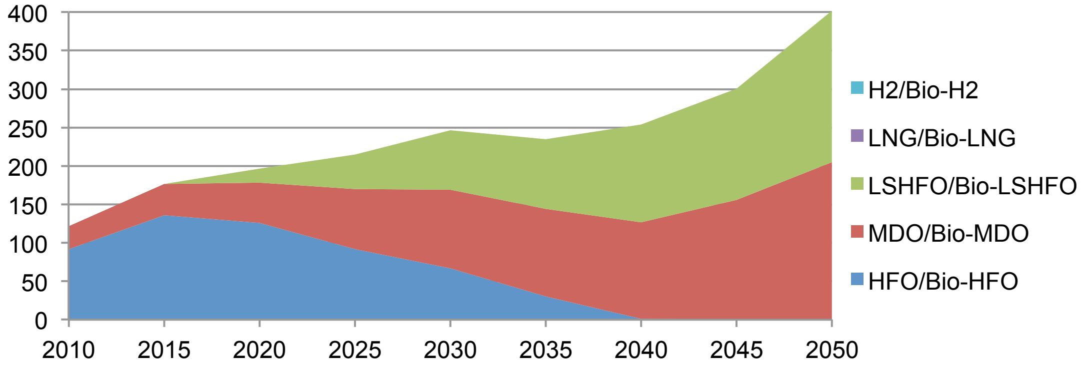
- Regulations (e.g. carbon pricing)
- Fuel price and price differential
- Availability of bioenergy

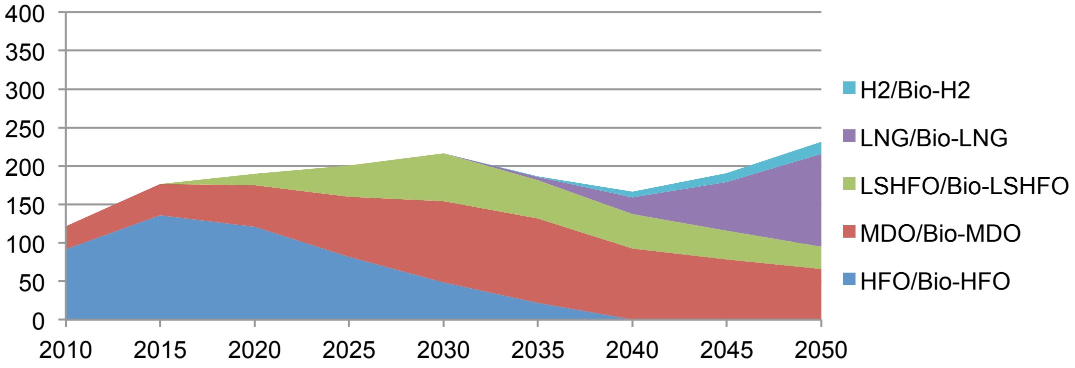
---

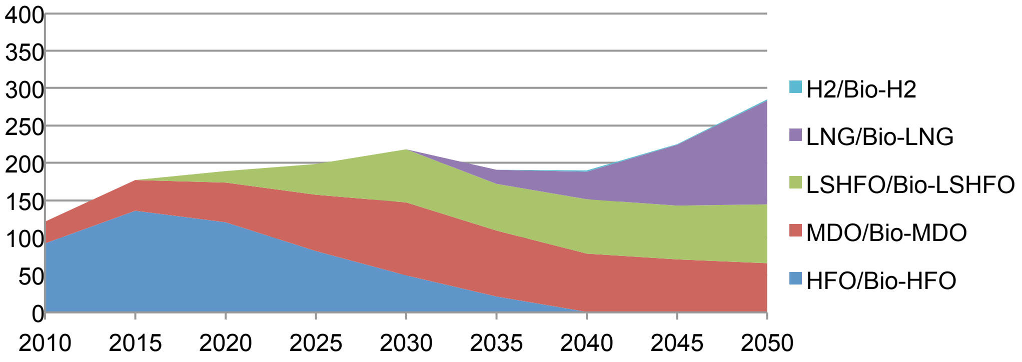
[2] Examples of energy service demands are vehicle kilometers, heat required in homes, steel production etc.

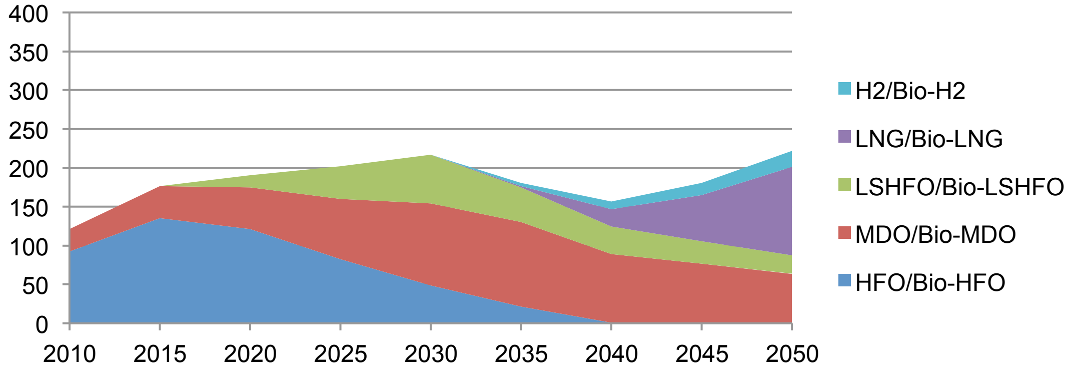
[3] There are 16 regions within TIAM-UCL

Figure 4 outlines the annual fuel consumption by each fuel type. It also outlines the switch between fuels through the years to 2050. HFO is the fuel of choice only until 2040 in all scenarios and there is no LNG in BAU.









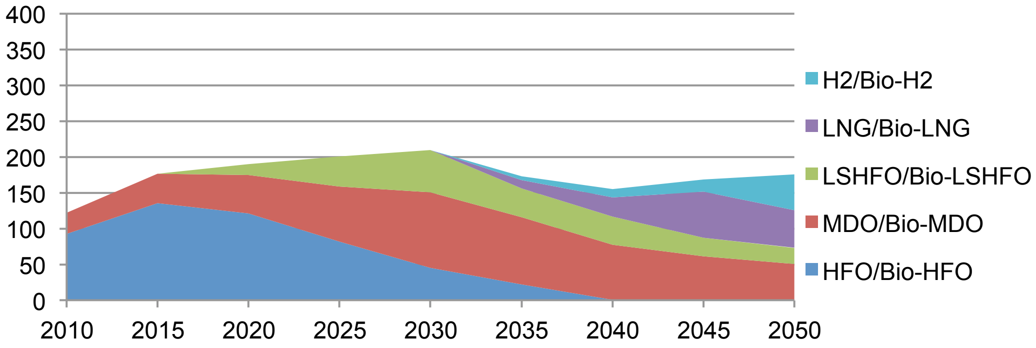


Figure 4: Fuel mix for BAU and scenarios 1, 2, 3 and 4 (all ship types)

The switch to LNG which occurs after 2030 (2035 in case of scenario 3) is consistent between all three scenarios. There are clear environmental benefits for using LNG as fuel: elimination of SO_x emissions, significant reduction of NO_x and PM, and reduction of GHG emissions. Hydrogen comes in scenarios 1 and 3 where there is medium to low availability of bio-derived fuels.

By including the upstream emission factors, we can estimate upstream emissions as well as operational. This enables us to gain an understanding of the magnitude of upstream emissions in relation to operational emissions. Figure 5 shows the operational CO_2 emissions (dotted line) and total emissions (solid line), which is the sum of operational and upstream CO_2 emissions. Therefore the difference between two lines indicates the magnitude of upstream emissions associated with each scenario.

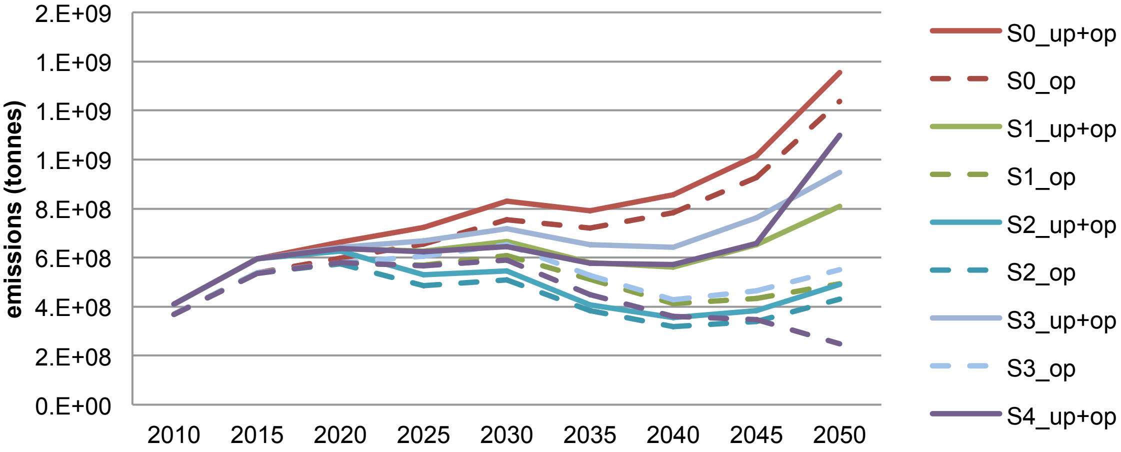


Figure 5: CO_2 emissions – operational versus total (tonnes)

Scenario 4 has the largest difference between operational and total emissions in 2050. This high amount of upstream emissions is due to the high take-up of hydrogen in 2050. There is similar pattern for scenarios 1 and 3 where hydrogen is fuel of choice. This is due to the significant emissions associated with fossil derived gaseous hydrogen as well as the liquefaction process. This highlights the value in adopting a full lifecycle perspective and not merely direct emissions. However, if the production route to decarbonize H2 improves out to 2050, then the upstream emissions will reduce accordingly.

Figure 6 indicates the magnitude of upstream emissions. The significance of taking into account the upstream emissions can be seen in scenario 4, which after the base scenario has the highest level of upstream emissions.

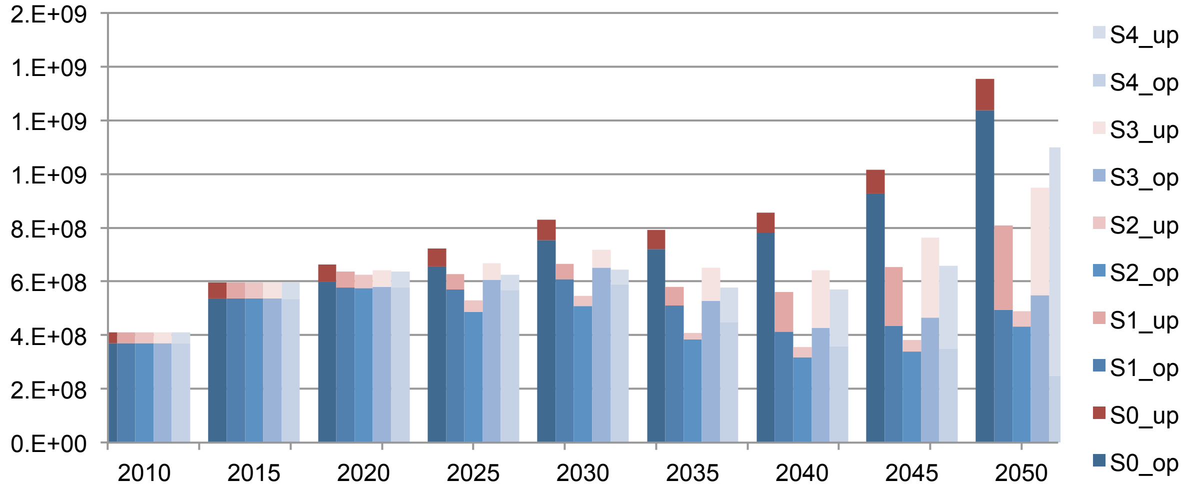


Figure 6: CO_2 emissions – operational versus total (tonnes)

CO_2e values can also be estimated. This term refers to all the gases that make up the GHG family. These include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). It is usually stated with a 'global warming potential' (GWP) figure which describes the amount of warming a gas causes over a given period of time. The life cycle assessment in this study is limited to Global Warming Potential of 100 years (GWP100). The CO_2e conversion factors are derived from IPCC 5th assessment report, using GWP100 including climate carbon feedback. These values are 36 for CH_4 and 298 for N_2O. Figure 7 outlines the CO_2e emissions compared to only CO_2 for all scenarios.

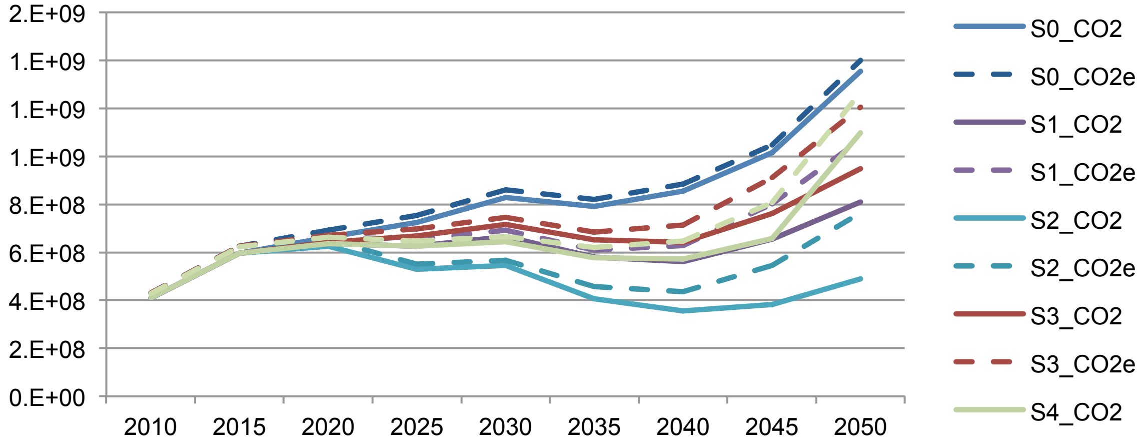


Figure 7: CO_2 emissions vs CO2e emissions (tonnes)

The difference between CO_2 and CO_2e is evident in Figure 7. Largest difference can be seen for scenario 2, which is due to the CH4 emissions resulting from LNG use.

6.1 Non-GHG emissions

We also explore non-GHG emissions including SOx, NOx and PM. Figure 8 outlines level of Sox and NOx emissions for base and S1-S4 scenarios.

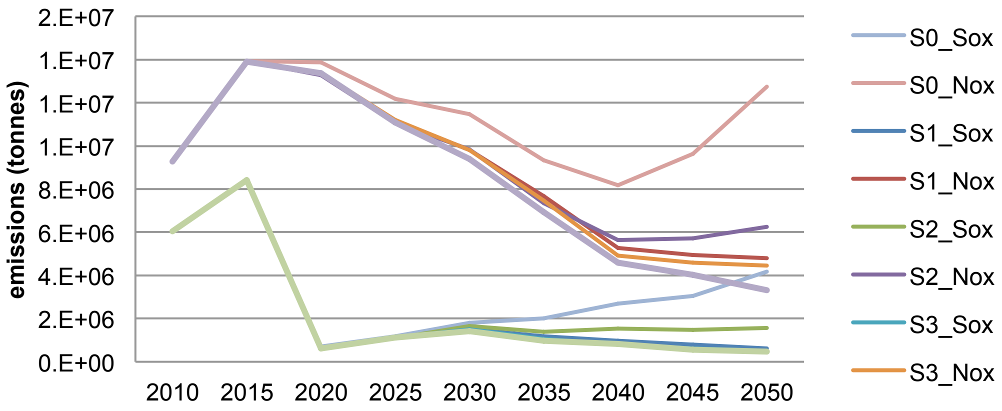


Figure 8: SOx and NOx (all ship types)

There is no carbon pricing and no bio-derived fuell availability in scenario 0 (BAU), therefore we can see high levels of SOx and NO_x associated with that scenario. Scenario 2 has the highest SO_x and NO_x level compared to the other two. There is significant improvement in SO_x and NO_x levels from BAU for all three scenarios considered here. This is down to NO_x regulations being applicable to new ships whereas SO_x regulation applies to all ships. Therefore, NO_x trajectories reflect fleet turnover whereas SO_x doesn't.

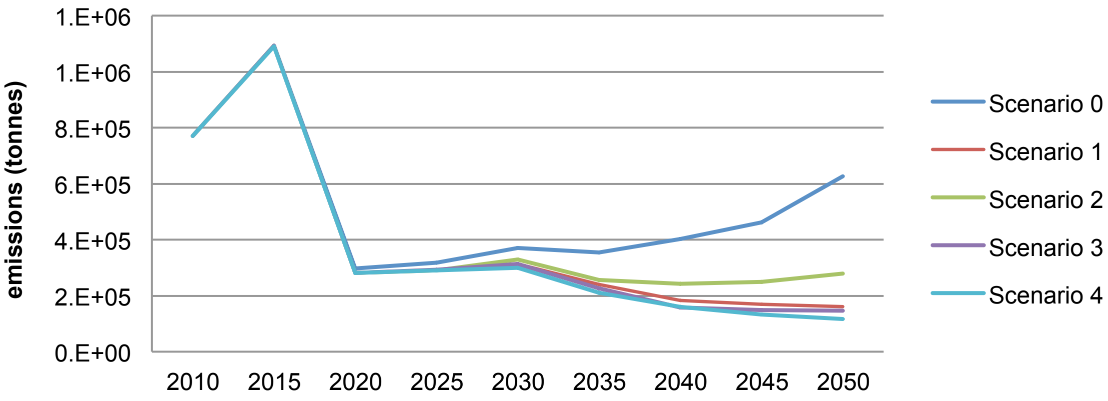


Figure 9: PM levels (all ship types)

7. CONCLUSIONS

In this paper, we explored a number of scenarios where we altered the level of bio-derived fuel availability and explored the influence of that on fuel mix and overall emissions. We also explored the influence of MBM (i.e. carbon pricing) coming into effect in 2020 following a 2ºC climate target. We have calculated upstream as well as operational CO_2 emissions to gain insight into the magnitude of upstream emissions. Key finings so far are that:

1. Upstream emissions contribute significantly to overall emissions levels and are worth considering when estimating CO_2 emissions.
2. One interesting outcome of the study is surprisingly high upstream emissions associated with future fuels such as H2. This may influence which future fuel trajectories should be targeted for lowering emissions.
3. Existence of carbon pricing scheme influences the fuel mix. Where there is a carbon price there's swich to LNG and H2 in some cases.
4. When carbon price is estimated by the model (Scenario 4) a carbon price can reach as high as $646.9/tonne

8. REFRENCES

Andersson, K. and Winnes, H. (2011) Environmental trade-offs in nitrogen oxide removal from ship engine exhausts. Journal of Engineering for the Maritime Environment, 225, 33-42

Heijungs, R. and E. I. Wiloso (2014). "4 Life Cycle Assessment" Sustainable Bioenergy Production: 99

Haji, S, Smith, T, Walsh, C, Traut, M and Raucci, C (2015) Policy implications of meeting the 2°C climate target, SCC conference, Strathclyde university, Glasgow

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].

IMO (2014a) Reduction of GHG Emissions from Ships: Third IMO GHG Study 2014 – Final Report

IMO (2014b) Well-to-Wake GHG impact study on LNG as marine fuel. MEPC 67/INF. 15

IPCC (2013) Climate Change 2013: The Physical Science Basis.

Le Quéré, C., R. Moriarty, et al. (2014). "Global carbon budget 2014." Earth Syst. Sci. Data Discuss. 7(2): pp. 521-610

Offermann, D., Hoffmann, P., Knieling, P., Koppmann, R., Oberheide, J., Riggin, D.M., Tunbridge, V.M. and Steinbrecht, W. (2011)**.** Quasi 2 day waves in the summer mesosphere: Triple structure of amplitudes and long-term development. *Journal of Geophysical Research 116: doi: 10*

Ölçer, A. and F. Ballini (2015). "The development of a decision making framework for evaluating the trade-off solutions of cleaner seaborne transportation." Transportation Research Part D: Transport and Environment 37: pp. 150-170

Sharmina, M., and Gilbert, P (2015) A review of bioenergy conversion processes, current bioenergy trade and future bioenergy availability. A technical report for the EPSRC Shipping in Changing Climates project, Version 02/20/2015