

A framework to evaluate hydrogen as fuel in international shipping

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Abstract

The shipping industry is today challenged by tighter regulations on efficiency, air pollution and the need to reduce its greenhouse gas emissions. The decarbonisation of the global energy system could be achieved with the use of alternative energy and fuels, and so a widespread switch to the adoption of alternative fuel in shipping could be experienced within the coming decades. Lately, many scenarios of alternative fuels in shipping have been investigated. Among the options of alternative fuels with different propulsion technologies, hydrogen with marine fuel cells (FCs) represent an example of such an alternative fuel. This paper proposes a framework to examine a possible transition path for the use of hydrogen in shipping within the context of decarbonisation of the wider global energy system. The framework is based on a soft-linking the global integrated assessment model (TIAM-UCL) and the shipping model (GloTraM). Initial results from this work-in-progress describe the trajectories of hydrogen prices, the characteristic of the hydrogen fleet and the consequences for shipping CO₂ emissions, the hydrogen infrastructure requirements, the use of hydrogen in other sectors, and the consequences for global energy system CO₂ emissions.

Keywords: hydrogen, shipping model, energy system model, GloTraM, TIAM-UCL

1 Introduction and Context

During the last and current centuries, the energy required by international shipping has been provided mainly with the combustion of oil-fuels. Many analysts agree that the consumption of such fuels worldwide is not only an environmental issue but also has effects on the equilibrium of the global energy and economic systems. Lately, scenarios of alternative fuels in shipping have been investigated due to introduction of stringent environmental and energy efficiency regulations in shipping such as the MARPOL Annex VI regulations by the IMO. Such scenarios have indicated that there will be multiple implications for shipping, such as the required changes in both on-board and onshore technologies. These in turn depend on the type of alternative fuel that will be used. Liquefied Natural Gas (LNG) is the most-frequently proffered alternative fuel for shipping (DNV, 2012, Wartsila, 2012, Abadie et al, 2011, Adamchak and Adede, 2102, Tri-Zen, 2012, Aagesen, 2012), but hydrogen and marine fuel cells (FCs) represent another example that could see take up in the next few decades (McConnell and Vicki 2010, Sattler 2000, Ludvigsen and Ovrum 2012).

While it is still uncertain whether marine fuel cells will actually be used in shipping many research and demonstration projects have been undertaken aiming to explore its potential (Vogler, 2011, Ludvigsen and Ovrum, 2012). These have identified numerous technical, economic, and environmental criteria that could aid or hinder the deployment of hydrogen in international shipping. In this study, we aim to add to this growing literature by exploring further the uptake of hydrogen, using computer models, within the wider energy system.

The majority of previous studies have used shipping models to examine possible switches to alternative fuels in shipping by assuming scenarios with different fuel availability and prices, together with other exogenous assumptions for the global energy and economic systems that would drive international trade by ships (Smith et al 2012a, DNV, 2012). While these models can find an optimal mix of fuels for shipping, the results are very sensitive to the assumptions made for fuel prices. Moreover, they fail to take account of the fact that the fuel prices available to the shipping sector, such as for LNG and hydrogen, are affected by other energy service demands that are external to the shipping system yet internal to the dynamic of the

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global energy system.

Conversely, studies that have used energy system models to investigate alternative marine fuels (Taljegard 2012, EPA 2008) generally lack of a proper representation of the shipping system. Moreover these types of models do not capture the interaction between the technical and operational specifications of ships that would occur in the event of switching to an alternative fuel.

Although a number of findings and conclusions have been made using these approaches, the results are therefore highly dependent on the numerous exogenous assumptions that are required by both methods. Further, both appear to fail to take account of the supply and demand balance for alternative marine fuels. The conclusions reached are therefore not necessarily sufficiently robust, which suggests that a more rigorous approach is needed.

This study proposes a framework to examine possible transition paths for the use of hydrogen in shipping while taking into account the ‘bigger picture’. We use a scenario-based approach to model the shipping sector and global energy system in conjunction. This requires soft-linking the shipping model GloTraM with the integrated assessment model TIAM-UCL. By doing so, we avoid the need to make exogenous assumptions on fuel price and availability but have a rich representation of the dynamics of the shipping sector. The aim is to develop a framework that maintains the strengths of each modelling approach, allows the models to interact in a transparent manner, and is able to explore the on board and on shore implications of a variety of scenarios. Through the analysis and interpretation of the results, it will also be possible to test and re-assess some of the key assumptions within both models.

Although there are difficulties in reaching consistency between the two models, since they differ in terms of structure and methodology, we believe that the interaction between them will significantly improve the present decision-making process.

The remainder of this paper is organised as follows: section 2 provides a literature review to highlight the current state-of-the-art of existing studies. Section 3 defines the development of the framework in detail by describing the soft-linking methodology, the two models used, and how the information is transferred between each other. Section 4 presents and discusses initial results of the developed framework applied to one single climate scenario.

2 Literature review

In this section, we first take another brief look at existing approaches to modelling the deployment of new fuels in the shipping sector, we then discuss the literature that explores the use of hydrogen in the energy system, before providing an overview of literature on the soft-linking approach that we propose to use in this framework.

There are a number of models that attempt to illustrate the characteristics of the international shipping industry with the aim of predicting the take up of alternative fuels. The first set of studies are those that have use a Life Cycle Assessment (LCA) of marine fuels such the recent DNV GL (2014). These are used to compare the environmental burden of different fuel pathways, for example the ‘well to tank’, or ‘tank to propeller’ emissions of a certain fuel. While these studies provide useful insights, we will not explore them in detail here since they do not actually model the uptake of different fuels since they cannot take into account the dynamic characteristics of such processes.

Bottom-up shipping models that have investigated the possible take up of marine fuels have been used in Smith et al (2012a) and DNV (2020), Lloyd’s Register and UCL (2013), and Bauhaug et al (2009). As discussed above, the results from this type of model are highly dependent upon the exogenous assumptions required, such as fuel prices and their availability, carbon price and trade scenarios.

To date, marine fuels have only been studied with an energy system models by Taljegard (2012), which used the Global Energy Transitions (GET) model to explore cost-effective fuel choices in the shipping industry under stringent global CO₂ emissions constraints. This approach has a weak representation of the shipping system and is not able to capture the interaction between technical and operational specifications of the shipping sector.

The EPA (2008) developed a framework to examine the petroleum refining industry and marine fuel markets. In this approach, a model of shipping activity was used to estimate regional and worldwide projections of future marine fuels demand, with these consumption projections then providing a baseline for the WORLD model, a bottom-up model of the downstream oil sector. While this approach represents an improvement from considering the two sectors in isolation, it is not as powerful as a soft-linking method since the outputs from one model are used as input to the other, but no convergence is reached between them. Moreover the boundaries of the WORLD model included only the supply of oil and not alternative fuels (such as LNG and hydrogen).

There is a rich literature addressing the role of hydrogen as an energy vector. A history of the 'hydrogen economy' is described by Bockris, J. O. (2013), and a review of models, methods and approaches for the planning and design of the future hydrogen supply chain is described in Dagdougui, H. (2012). A detailed review of hydrogen delivery and production technologies for energy system models can be found in Dodds, P. and McDowall, W. (2012) (a and b), which highlighted the strengths and weaknesses of how hydrogen infrastructure is usually represented within energy system models.

In contrast to the rich literature of hydrogen, the literature of how to soft-linking models is relatively new. Nevertheless, there are many studies that have classified the various approaches that can be used to link two models and compared these to each other; they also define the soft-linking approach and describe the advantages conveyed and challenges posed in attempting to do so (Wene, 1996, Bauer et al., 2007, Böhringer and Rutherford, 2009, Kumbaroglu and Madlener, 2003, Riekkola et al. 2013).

3 Method and assumptions

3.1 Overview of the Method – Soft linking methodology

This section provides a description of the new method proposed in this paper for soft-linking the shipping model GloTraM to the global integrated assessment model TIAM-UCL. When the models are soft-linked, they operate together in an iterative process until convergence in central parameters are achieved, e.g. fuel price and quantity parameters. In this work, these parameters are the average of the regional fuel prices and the transport demand of energy commodities.

A soft-linking approach takes advantage of the strengths of both models. TIAM-UCL provides scenarios of the global equilibrium of the energy system, as well as hydrogen infrastructure requirements. GloTraM provides scenarios of the evolution of shipping fleet's composition and their technical and operational specifications, as well as the annual share and consumption of the marine fuels. TIAM-UCL is first used to provide marine fuels prices and the trade of energy commodities to GloTraM, with GloTraM then providing shipping energy service demands, and fuel mix shares back into TIAM-UCL. TIAM-UCL is then re-run and this process repeated until convergence.

Without this linking, shipping energy service demands and fuel mix shares are exogenous assumptions to TIAM, while fuel and carbon prices are exogenous assumptions to GloTraM. However, by permitting the iteration process, the attempt is to make all of these variables endogenous within the framework.

In the first iteration of TIAM-UCL, we make an initial assumption that there is an uptake of hydrogen and LNG in shipping. However, after the first iteration it is then left to the shipping model to decide which marine fuels are to be used and in what proportion.

In this work, we use a single scenario to demonstrate how the new proposed framework operates. In this, we make the following assumptions regarding emissions mitigation: from 2005 to 2015 (only) the model must follow a pathway that is on course to an average global surface temperature rise of 4°C by 2100, this therefore effectively assumes that no emission mitigation is required between these years - which follows the approximate trajectory of emissions actually observed. From 2015 onwards the emissions must be such as to keep the mean global surface temperature rise below 2°C in all years to 2200. This means that the model is constrained to keep the atmospheric concentrations of CO₂ to below 425 ppm in all years up to 2100.

Details of all exogenous variables for GloTraM can be found in Smith, T.W.P. et al (2013a). In this work, the conventional marine fossil fuels are modelled in GloTraM by one category representing marine

distillates (MDO/MGO) and one categories representing residual fuel (HFO). Residual fuel of different sulphur contents (LSHFO) is not taken in account since they are not modelled in TIAM-UCL, however they will be considered in future modelling. The alternative fuel choice implemented for this work includes LNG and Hydrogen. Biomass derived products are not taken in account assuming that they would be used in other transportation mode rather than shipping. In future modelling Bio-Diesel will be represented and the share of its use in the shipping mode will be determined by TIAM-UCL, and used as assumption in GloTraM .

The two models differ slightly in their regional definitions; for this study, regions in GloTraM were therefore changed to correspond with the regions in TIAM-UCL. The scenario generated in this study using TIAM-UCL uses a modelling period from 2005 to 2100, however since the results are used in GloTraM, which has a modelling period up to 2050, only results between 2010 and 2050 are shown.

The following sub-sections describe the two models and their main assumptions, and how information is transferred between the models after each iteration.

3.2 TIAM-UCL model

The 16-region TIAM-UCL global energy system model has been developed at UCL through the UK Energy Research Centre (UKERC). It is a modified version of ETSAP-TIAM model, which was developed under the IEA ETSAP implementing agreement. TIAM-UCL is a linear programming cost optimisation model, which minimises total discounted energy system cost in the standard version and maximises social welfare (consumer surplus + producer surplus) in the elastic demand version (which is the version used here) over the modelling period (Anandarajah et al., 2013).

TIAM-UCL models all primary energy sources (oil, gas coal, nuclear, biomass, and renewables) from production through to their conversion, infrastructure requirements, and finally to sectoral end use. Each region in the 16-region TIAM-UCL model has its own energy system and each region can trade fossil fuel resources, biomass or emission permits with other regions or a central market (McGlade C. and Ekins P. 2014). Figure 1 shows the regions in TIAM-UCL. Energy service demands are initially based upon energy balances in 2005 and are projected using drivers such as GDP, population, number of households, sector output, etc. (Anandarajah et al., 2013). The climate module of TIAM-UCL, which converts emissions to atmospheric concentrations to radiative forcing to temperature rises, is used in this study to constrain the model to an average global temperature rise of 2°C. A detailed description of input assumptions, approaches, and data sources for TIAM-UCL can be found in Anandarajah et al. (2011).

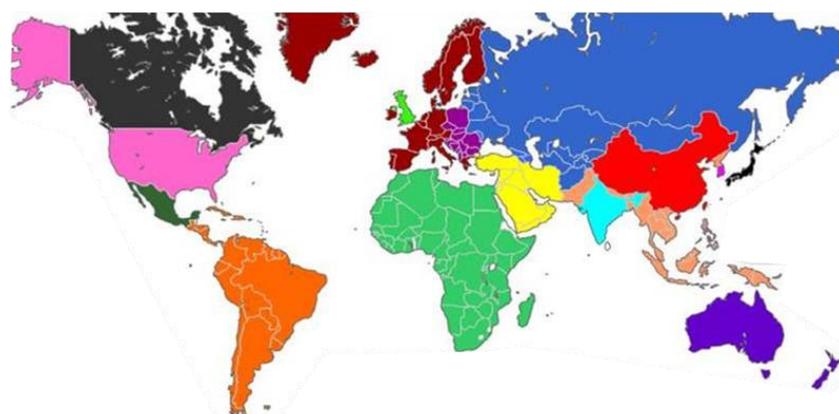


Figure 1 Map of TIAM-UCL regions

In TIAM-UCL the price of producing a commodity affects the demand for that commodity, while at the same time the demand affects the commodity's price. This work uses the elastic demand version of the model, which allows energy service demands to react to changes in commodity prices. When all markets are in equilibrium the total economic surplus is maximized (the sum of consumer and producer surplus) (McGlade, C., and Ekins, P. 2014, and Loulou, R., & Labriet, M. 2008.). TIAM-UCL endogenously produces a shadow price for all commodities; this is the price paid for an increment of additional production. 'Price' and 'shadow price' are not necessarily the same, however in this work we refer to price

as the shadow price calculated by TIAM-UCL. Therefore, shadow price is a simplification since it does not include some elements that are included in the real world. e.g. taxes.

The representation of hydrogen infrastructure in TIAM-UCL consists of different pathways in the supply side of the model, as shown in **Figure 2**. The production technologies are categorised into three classes: centralised large, centralised medium, and decentralised plants. The centralised large plants can be equipped with carbon capture and storage (CCS) although at additional cost and with an efficiency penalty. Large plants have additional cost for long distance transportation (either pipeline or tanker) as it is assumed that they are constructed near to the deposit of the feedstock from which the hydrogen is production. A distribution network is modelled for the hydrogen produced from the centralised large plants and medium plants with a transportation and distribution network modelled separately for gaseous (H₂-G, pipeline) and liquid (H₂-L, tanker) hydrogen. Only gaseous hydrogen is available for use in refuelling stations, however in this work liquid (H₂-L, tanker) hydrogen and liquid hydrogen from decentralised plants are available for shipping, since it is assumed that liquid hydrogen would be used on board ships. For this work, gaseous hydrogen was not taken into account for shipping, on the basis that the extra volume required to store gaseous hydrogen on board ships would affect the payload and therefore dramatically decrease the competitiveness of the fuel. There is no distribution cost for decentralised plants, but there is an additional cost mark-up compared with large scale plants to represent the loss of scale. Interregional hydrogen trade is not enabled in the current version, however this could be enabled in future modelling efforts. A range of end-use transportation technologies are modelled to meet different transport energy service demands, including cars, light trucks, heavy trucks and buses (Anandarajah et al. 2013). A discussion of the data and assumptions can be found in Anandarajah (2012).

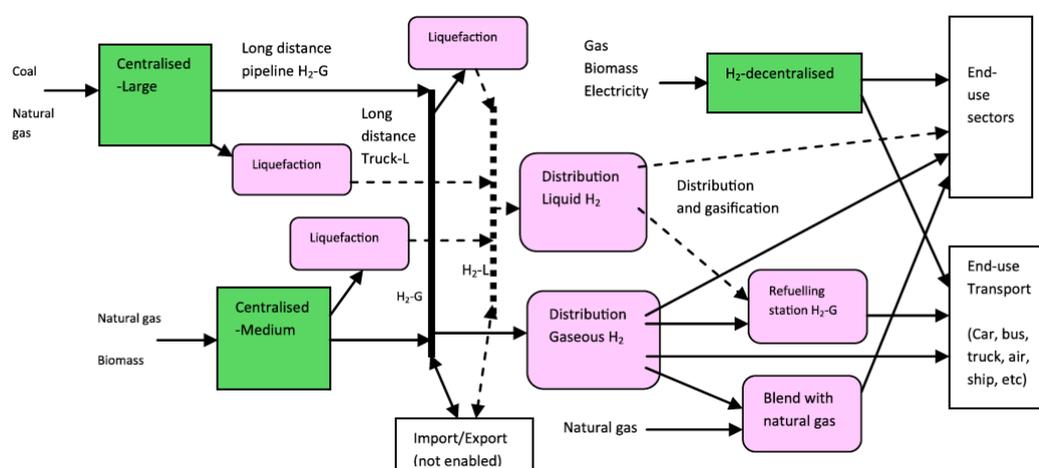


Figure 2 Representation of hydrogen infrastructure in TIAM-UCL. Source Ababdarajah et al., (2013)

The representation of LNG infrastructure involves three steps – liquefaction, transport and re-gasification. The construction costs of LNG liquefaction terminals are assumed to be identical in all regions and are equivalent to around \$0.7/m³ natural gas liquefied. During liquefaction 11% of the gas is assumed to be lost. Re-gasification facilities are assumed to be much less expensive, at around \$200mn per million tonnes of LNG capacity (around \$0.1/m³ natural gas processed), and to consume 1% of the gas received. Liquefaction and regasification plants that have been constructed, are in construction, or have been announced, were used to set the upper bound on the construction of new facilities up to 2018. The model can, however, choose not to invest in projects that have been announced but not yet constructed if they are not cost effective.

Although in future modelling the assumptions on actual LNG trade will be reassessed using outputs from GloTraM, for this work it is assumed that all LNG ships travel at a speed of 19 knots, have a 145,000m³ capacity (carrying around 65 kt LNG or 90 million m³ gas), have hire-rates of \$100 k/d, and have a boil off rate of 0.15% per day.

By choosing a particular configuration of the hydrogen and LNG infrastructure, the model endogenously generates hydrogen and LNG regional prices.

3.2.1 Shipping in TIAM-UCL

Two categories of shipping are included in TIAM-UCL, one that considers the trade of non-energy commodities, and another that considers the trade of energy commodities.

The trade of non-energy commodities consists of two energy service demands that must be satisfied, international shipping (called TWI) and domestic shipping (called TWD). Two generic “ship technologies” called TWI010 and TWD010 can satisfy these demands. These generic ships can use six types of marine fuel: heavy fuel oil (TRAHFO), diesel (TRADSL), gasoline (TRAGSL), coal (TRACOA), LNG (TRALNG), and liquid hydrogen (TRAHHS), however in this work only TRAHFO, TRAGLS, TRALNG, and TRAHHS are considered.

Usually in TIAM-UCL international and domestic shipping energy service demands in the model base year (2005) are based on the sum of the fuels that were consumed in that year in each region using IEA statistics. These energy service demands are projected forward using the regional growth in GDP. However, in this study, results from the shipping model are used to project these shipping energy service demands.

TIAM-UCL determines the trade of energy commodities endogenously based on the supply/demand balances between regions. To prevent the model from carrying out unrealistic trade patterns, and to prevent any unwanted ‘short-cuts’, trade of each of the commodities is only allowed between specific regions, and a number of other constraints are applied (Anandarajah et al., 2011). It is important to note that generally the trade of energy commodities does not consume any fuel itself in TIAM-UCL. However, we transfer this trade in the trade transport demand in GloTraM, and so the results include the fuel consumed by the trade of energy commodities.

The commodities that can be traded by ship in TIAM-UCL are shown in

Table 1.

Table 1 Energy commodities that can be traded by ship in TIAM-UCL

Commodity	Name in TIAM-UCL
Coal	COAHCO
Liquefied Natural Gas	GASLNG
Crude oil	OILCRD
Diesel	OILDST
Gasoline	OILGSL
Heavy fuel oil	OILHFO
Naptha	OILNAP
Natural gas liquids	OILNGL
Uranium	DMYNUC
Solid biomass	BIOSLD
Bio-crops	BIOCRP
Diesel from biomass	BIODST
Naphtha from biomass	BIONAP
Jet kerosene from biomass	BIOJTK
Kerosene from biomass	BIOKER

3.3 GloTraM model

The shipping model used to analyse the role and demand for hydrogen as fuel in international shipping, called GloTraM, is a bottom-up model for estimating the CO₂ emissions trajectories of the shipping industry. GloTraM is a model that was developed under the project ‘Low Carbon Shipping – a Systems Approach’. The model applies time-domain simulation to calculate the evolution of the global fleet over time (Smith et al., 2012b). The two main drivers of CO₂ emissions in the model are: transport demand (e.g. t.nm), and the transport carbon intensity (e.g. gCO₂/t.nm).

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, and 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 Smith et al., (2012a) is used in this work for this. 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 as defined in Smith et al., (2012a). The ship type is matched to the commodity type and there is not assumed to be any substitution outside of the market. In this study energy commodity trade is excluded from the transport demand scenario of GLOTRAM and they are taken from results obtained from the energy system model TIAM-UCL.

Transport carbon intensity is a function of the evolution of a fleet's composition (ships) and their technical and operational specifications. 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 (Smith et al., 2012b, Raucci et al., 2013).

From the allocation of ship types and sizes to specific trade flows and routes, national and regional statistics can be obtained for CO₂ emissions and fuels consumption. In this work, four type of ship are taken in account: unit container, dry, wet crude and wet chemical products. A more complete description of the method can be found in Smith et al., (2012b), and the derivation of the model's baseline input data can be found in Smith et al., (2012c). An overview of the assumptions and method details are explained in greater detail in Smith et al., (2012d), assumptions pertinent to hydrogen are provide below.

3.3.1 Hydrogen main machinery assumptions

As in Raucci et al., 2013, in this study numerous assumptions were made for the main machinery on board required to use hydrogen as propulsion. Alternative fuels such as LNG were matched with both fuel cell and 4 stroke spark ignition technologies, while hydrogen was considered only in combination with fuel cell technology. For input to GloTraM, the following performance and costs parameters for each fuel and main machinery combination were estimated:

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

A summary of the estimated variables for hydrogen is provided in **Table 2**, with details of their derivations and assumptions found in Smith et al., (2012d) and Raucci et al. (2013).

Table 2 Costs and performance parameters for Hydrogen and LNG concepts design

Concept design description	Costs		Performance	
	UPC (\$/MW)	TLC (\$/MW)	sfc (@75% MCR) (g/kWh)	dwt_loss (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
LNG +4 stroke spark ignition	1.65E+06	-	150	0.09

3.4 Transferring information from TIAM-UCL to GloTraM

As mentioned above, the information that is transferred from TIAM-UCL to GloTraM are the trade of energy commodities, fuel prices for shipping, and CO₂ prices.

TIAM-UCL calculates the trade of energy commodities in order to satisfy the energy demands in each region. Although in each iteration only the shipping energy service demands (i.e. the trade of non-energy commodities) are changed, it is possible that there would be a consequent change in the trade of energy commodities. Therefore, after each iteration, these changes are captured from TIAM and added to the

trade scenario input data required in GloTraM. This is an important feature since it allows the examination of the results for different global scenarios in future modelling. As TIAM-UCL calculates only the trade of energy commodities between different regions, two assumptions were made. First, the trade of energy commodities for a given region are equal to the reference trade scenario in GloTraM. Second, for the trade of energy commodities between different regions, a representative country was chosen for each region, since GloTraM calculates the fuel consumption based on the route distances between countries (not regions) that trade specific commodities.

TIAM-UCL also calculates the prices of all fuels that can be used by shipping (as given above in Section 3.2.1) within each region. By resolving its internal objective function, TIAM-UCL determines the production and delivery infrastructure require to meet the shipping energy service demands. By doing this, regional marginal prices for hydrogen in shipping and all other marine fuels are provided. These fuel prices are used as inputs to GloTraM. As GloTraM uses global prices, the average of all regional prices are transferred from TIAM-UCL to GloTraM. This approximation implies that in the long-term marine fuel prices are likely to be homogenous worldwide and regional price differences will not affect ship-owners' investment decisions.

Finally, TIAM-UCL endogenously generates a CO₂ price that is required in each years to meet the climate targets for the given emissions mitigation scenario. Similarly to fuel prices, this CO₂ price is transferred into GloTraM. We assume that these global CO₂ prices are applied to the shipping industry.

3.5 *From GloTraM to TIAM-UCL*

Regional marine fuels demands and fuels mix shares are transferred from GloTraM to TIAM-UCL. In order to calculate these, some modifications were applied to the current version of GloTraM. Disaggregated consumption of each fuel were calculated based on estimated ship movements for inbound, outbound and 'domestic' voyages in each region (where domestic flow is defined as trade to and from the same region). After each iteration, GloTraM is able to calculate the fuel consumption allocated to these discrete voyages. The number of discrete voyages that are required to satisfy the allocated transport supply were calculated assuming that the operational data are consistent for inbound, outbound and domestic voyages. The allocated transport supply to each region was then calculated by breaking down flow and haul to 'inbound', 'outbound' and 'domestic', retaining the allocation to specific categories of ship type and size. In order to consider the differences in fuel consumption between the loaded and ballast voyage, it is also assumed that the voyage is always loaded if it is a container ship, otherwise, it is assumed that every loaded voyage is followed by a ballast voyage.

The disaggregated consumption of each fuel that is calculated by GLOTRAM does not represent the regional marine fuel demand that needs to be input in TIAM-UCL. We therefore assume that the regional marine fuel demand in TIAM-UCL is a percentage of the disaggregated fuel consumption allocated to a specific region. For each region these percentages were estimated for the base year using IEA fuel oil sales data, and they are assumed to be constant for all type of fuels over the years. This is a starting assumption that needs further investigation. Future modelling will investigate the sensitivity of results to this assumption and whether other representations of where ships refuel can be considered, according to present day data/behaviour. However, we consider this will remain a reasonable approximation if we assume that ships refuel in specific regions mainly because of the constraints in routes rather than changes in fuel prices.

As the disaggregated consumption of each fuels is calculated for each fuel type, both the regional fuel demand and fuel shares were obtained for each fuel using the same fixed percentages, and they were transferred in TIAM-UCL after each iteration.

4 **Initial results**

This section displays a number of outputs generated by the framework described above. Although a wide range of results could be obtained from the models, we present a selection of the key variables, to demonstrate the assumptions and drivers for the use of hydrogen as fuel in international shipping.

The two models achieved convergence after four iterations. The trajectories of fuel prices and CO₂ prices obtained from TIAM-UCL are shown in Figure 2 and Figure 3. As mentioned above, the demand of these fuels affect their prices and vice versa. Hydrogen prices appear only from 2045 and show a consistent gap

from the rest of fuel prices. CO₂ price increases constantly over the time, reaching about 600 USD/tonnes in 2050.

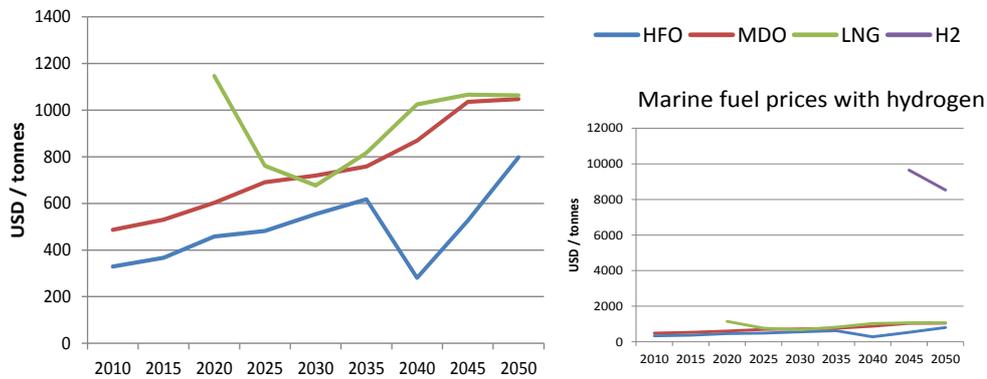


Figure 2 Marine fuel prices. Prices of HFO, MDO, and LNG (left), the comparison with hydrogen price (right)

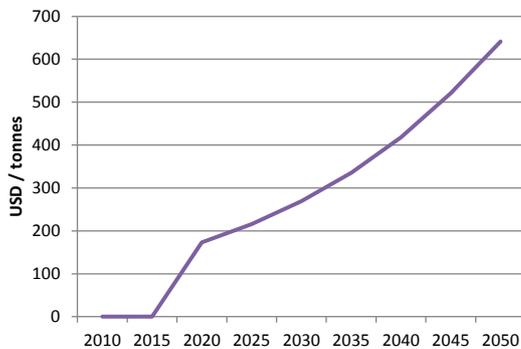


Figure 3 CO₂ price 2010-2050

Hydrogen is the fuel of choice for new ships from 2045 (Figure 4), despite its higher price. This suggests that further incentivisation from a high CO₂ price could increase the competitiveness of hydrogen relative to other fuels. Before 2045, LNG continually increases its share from 2015, with a particularly rapid rise between 2025 and 2040, by which time almost the entire global fleet is powered by LNG. This suggests that a switch to alternative fuels may be a more cost-effective way of meeting the emissions reduction requirements than speed or technology on its own.

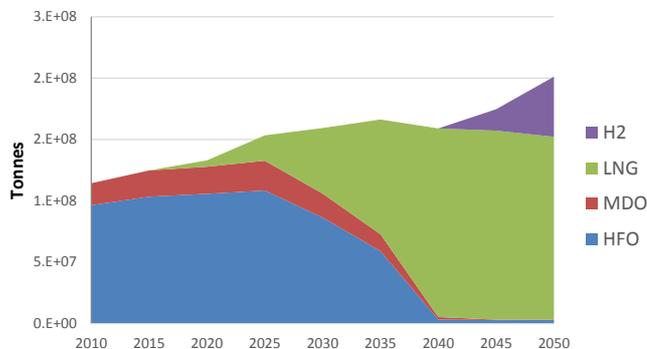


Figure 4 Mix of fuels used by shipping

An explanation of the dynamics of the fuel/machinery selection is described at the end of this section, but we first examine the use of hydrogen in the context of the decarbonisation of the wider global energy system. In particular, we can observe how in this scenario the decarbonisation path is achieved in the

transportation sector and the global energy system. Figure 5 shows the energy consumption by fuel in the whole transport sector, while Figure 6 displays global primary energy production and energy consumption by fuel. While oil remains the main fuel in transportation, gas and electricity from renewables grow significantly, taking an increasingly large share.

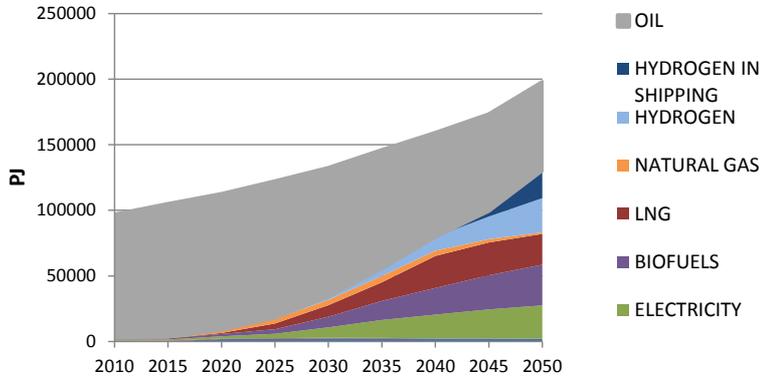


Figure 5 Transport Energy Consumption by fuel

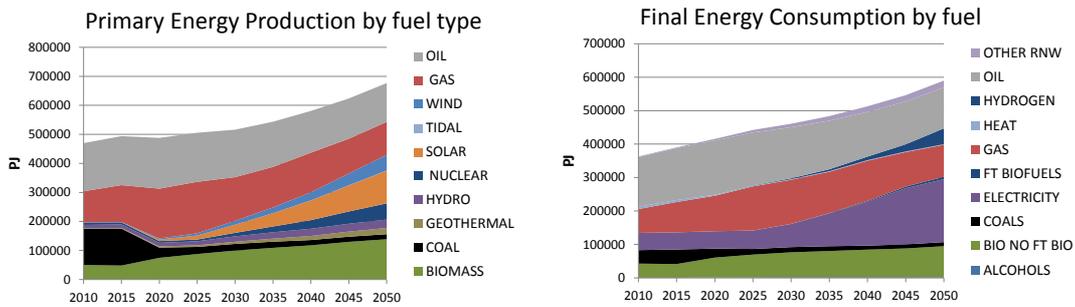


Figure 6 Primary Energy Production and Final Energy Consumption by fuel

TIAM-UCL provides a more detailed description of the upstream path of hydrogen (i.e. what feedstocks are used to produce hydrogen); this is given in Figure 7. In this scenario, we can see that electricity and biomass are mainly used rather than natural gas, and that decentralised small plants are preferred over centralised large plants. This suggests that natural gas is more cost-effective in other markets, with hydrogen finding its market in specific regions.

We can also examine the deployment of hydrogen as fuel for transportation in others vehicles; this is shown in Figure 7 Hydrogen production by fuel

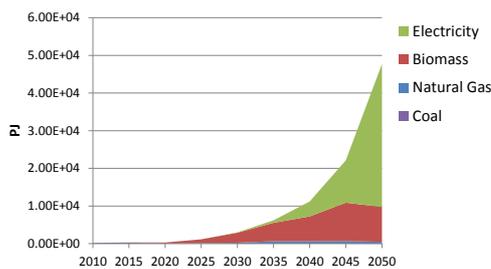


Figure 7 Hydrogen production by fuel

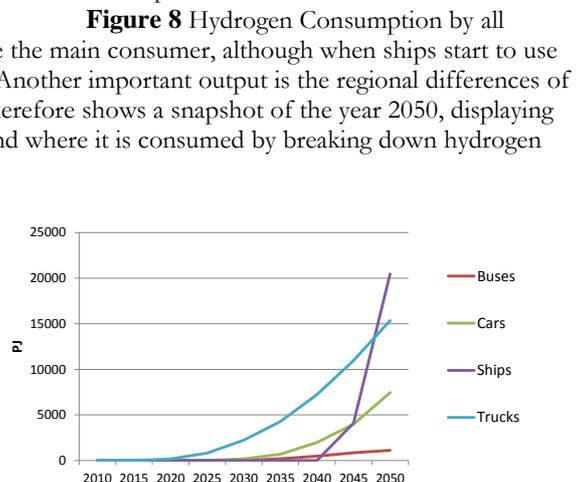


Figure 8 Hydrogen Consumption by all vehicle modes

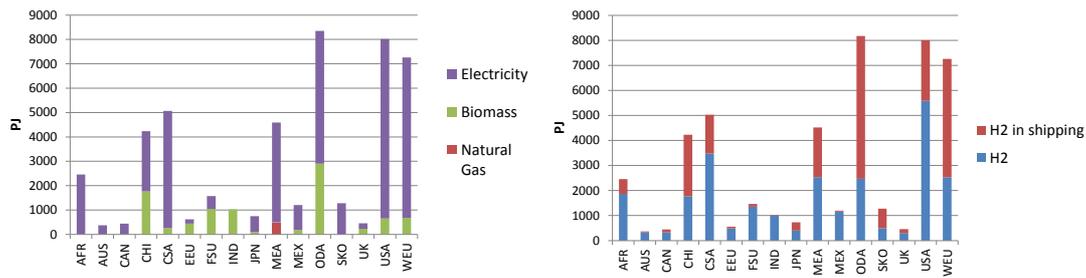


Figure 9 Regional Hydrogen Production (left) and Consumption (right) by fuel in 2050

The shipping fleet can be analysed in details by examining results from GloTraM. In particular, Figure 10 displays the results for shipping CO₂ emissions by ship type. Unit container CO₂ emissions increase significantly between 2010 and 2035 mainly due to the increased transport demand for this ship type category. A similar trend is seen for wet chemical product, but with a slightly lower increase. Conversely, CO₂ emissions for dry and wet crude seem to decrease over time.

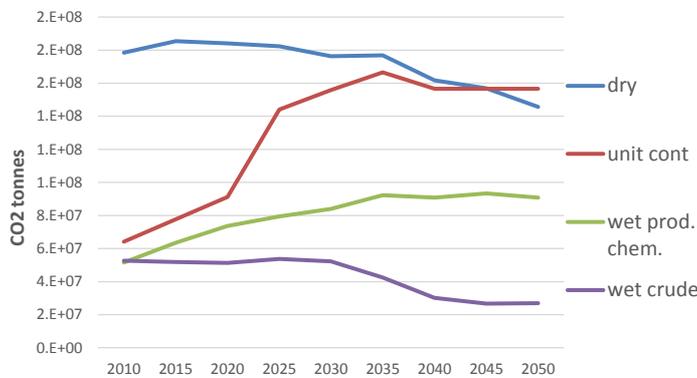


Figure 10 CO₂ Emissions by ship type

Figure 4 previously showed the mix of fuel that would be used in shipping until 2050 in this scenario. The fuel/machinery selection, however, depends from the global profit maximization and regulatory compliance of the option. To explain the selection process, we display in Figure 11 the 'fuel/machinery cost' of hydrogen and fuel cells compared with the range of other fuel and machinery choices. This parameter takes into account fuel prices, carbon prices and fuel/machinery efficiency. It is only intended to be indicative of the relative advantages of different fuel/machinery options, although in combination with other technical and operational abatement and energy efficiency interventions, it does allow the model to select the best global profit maximization option.

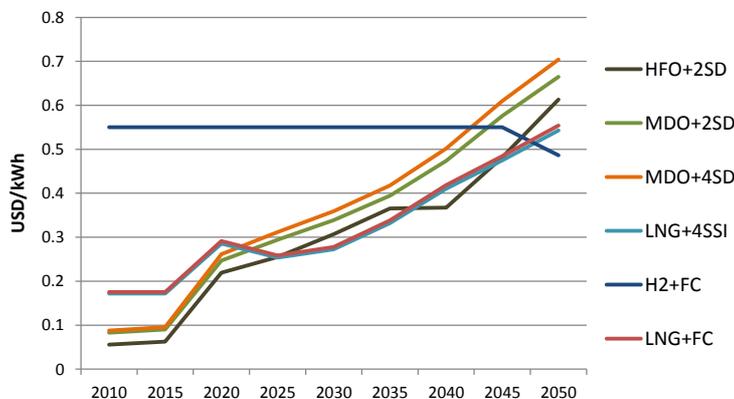


Figure 11 Trend of fuel/main machinery costs (2SD: 2stroke fuel engine, 4SD: 4stroke fuel engine, 4SSI: 4stroke pure gas spark ignition engine, FC: Fuel cells)

Figure 12 shows the hydrogen consumption by ship type in 2045 and 2050: it can be seen that hydrogen is used across all of shipping fleet, except for wet crude. Although not presented here, details of hydrogen take up in the shipping fleet can be analysed by specific ship type and size category. For example, one of the common outcomes is that the ship size is an important factor as the increased hydrogen storage volume required has different impact on the ship's payload capacity and therefore the revenue.

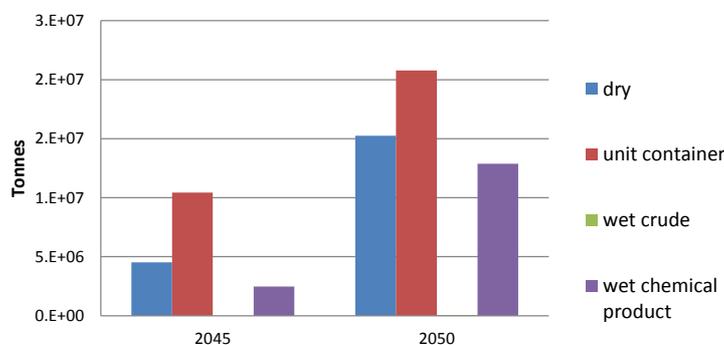


Figure 12 Hydrogen Consumption by ship type

Finally, it is important to show how this scenario affects the operational speed and EEDI of the global shipping fleet. Figure 13 displays the operational speed trend and the EEDI trend by size category for unit container ships. We can see that both parameters decrease over time.

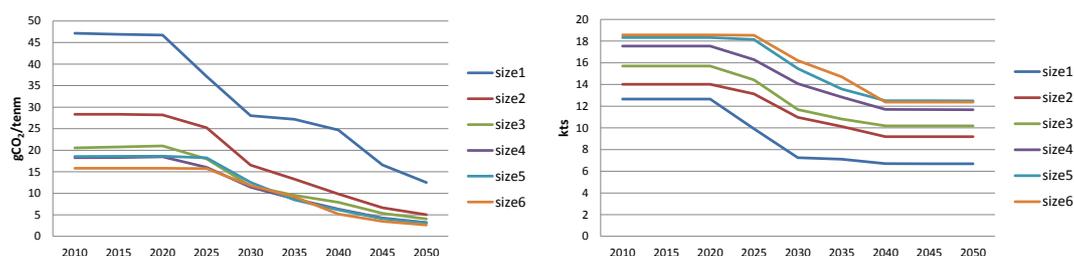


Figure 13 Trends of the operational speed (right) and EEDI (left) for unit container by size category

To conclude this methodology paper, we provided a description of the role of hydrogen in shipping in this particular scenario within the context of decarbonisation of the wider global energy system. We demonstrated that this framework is capable of providing results for a large number of interesting parameters that will help to analyse in detail several implications of the use of hydrogen in shipping. We have not presented a detailed discussion of results, as we preferred to focus on the novel framework that has been developed. We believe that this framework has the potential to analyse the underlying dynamics between shipping and the energy systems in the case of using hydrogen as fuel in international shipping. Moreover, the uncertainties associated with the obtained initial results can be enhanced in future modelling by a number of suggested modifications, the reassessment of the key assumptions for hydrogen, and running a wide variety of scenarios.

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