Conference Proceedings. 3rd International Conference on Technologies, Operations, Logistics and Modelling in Low Carbon Shipping,
University College London, 9-10 September 2013.

Cost-effective choices of marine fuels under stringent carbon dioxide targets

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Abstract

In order to investigate cost-effective choices of future marine fuels in a carbon constrained world, the linear optimisation model of the global energy system, GET-RC 6.1, has been modified to GET-RC 6.2, including a more detailed representation of the shipping sector. In this study the GET-RC 6.2 model was used to assess what fuel/fuels and propulsion technology options for shipping are cost-effective to switch to when achieving global stabilisation of atmospheric CO_2 concentrations at 400 ppm. The aim is to investigate (i) when is it cost-effective to start to phase out the oil from the shipping sector and what determines the speed of the phase out, (ii) under what circumstances are LNG or methanol cost-effective replacers and (iii) the role of bioenergy as a marine fuel. In our base analysis we analyse results from assuming that CCS will be large-scale available in future as well as if it will not. In the sensitivity analysis different parameters have been varied in order to investigate which impact for example different supply of primary energy sources and different costs for different transportation technologies will have on the choice of fuels in the shipping sector. Three main conclusions are presented (i) it seems to be cost-effective to start to phase out the oil from the shipping sector nearest decades, (ii) natural gas based fuels, i.e. fossil methanol and LNG are the two most probable replacers, of which methanol has been shown to dominate in the case with CCS (methanol or LNG depends on the availability of natural gas, on the methane slip and on infrastructure costs) and (iii) limited supply and competition for bioenergy among other end use sectors makes the contribution of bioenergy small, in the shipping sector.

Keywords: shipping; energy system modelling; marine fuels, LNG; methanol; cost effective; CO_2 emissions; carbon capture and storage.

1. Introduction

Global climate change, caused by increasing levels of greenhouse gases in the Earth's atmosphere resulting from human activities (IPCC, 2007) is a major issue of current concern. Carbon dioxide (CO_2) released, during fossil fuel combustion and deforestation, is the largest contributor to radioactive forcing of the climate system (IPCC, 2007). The United Nations Framework Convention on Climate Change (UNFCCC) has been ratified by 192 countries and calls for stabilization of greenhouse gas (GHG) concentrations in the atmosphere at a level that would ”prevent dangerous anthropogenic interference with the climate system” (UNFCCC, 1994). There is no consensus on a precise level of CO_2 in the atmosphere that would prevent such interference, but the 2007 Bali Climate Declaration, states that the primary goal must be to limit global warming to no more than 2°C above the pre-industrial temperature (Allan R et al., 2007). This limit has been formally adopted by the European Union (European Council, 2005), and later worldwide in the Copenhagen Accord (UNFCCC, 2009) and the Cancún Agreements (UNFCCC, 2010).

Rogelj et al. (2011) show that the 2-degree target can be met with at least fifty-fifty chance if the CO_2-eq emissions is halved by 2050 and reduced by 75% by 2100 compared to year 2000. Wigley et al. (1996) present a CO_2 reduction curve towards 450 ppm that has a similar relative reduction in CO_2 emissions as the CO_2-eq emissions presented by Rogelj et al. (2011), indicating that the 2 degree target can be met if the atmospheric CO_2 concentration is below 450 ppm in the end of this century.

Efforts to stabilize atmospheric CO_2 levels are complicated by many considerations, not least of which being the fact that CO_2 emissions are spread across different geographic regions and economic sectors (e.g., industrial, residential, agriculture, transportation). The development of a transport system that addresses its impact on climate change is challenging because of the multitude of different fuel and vehicle technology that can be

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combined, the uncertainties in the future costs of advanced vehicle technologies, and the competition for primary energy sources between the different energy sectors.

Shipping is an important part of the transport system, transporting more than 80% of the world's trade, (UNCTAD, 2011) but also a growing contributor to global CO_2 emissions. In 2007 global shipping was responsible for 3.3% of the global CO_2 emissions, of which international shipping accounted for 2.7% (Buhaug et al., 2009). During the past two decades, the shipping sector has grown faster than the global GDP (Eyring et al., 2005). Projections of future emissions from shipping thus indicate that shipping in future will account for significantly higher share of world anthropogenic CO_2 emissions. In 2050 the CO_2 emissions from shipping are estimated to 1.1–2.9 $GtCO_{2,}$ indicating an increase of up to 280 % (Buhaug et al., 2009, Eyring et al., 2005, Vergara et al., 2012).

Greenhouse gas emissions from international shipping were not included in the Kyoto protocol, but passed on to the International Maritime Organization (IMO), as countries could not agree on how to allocate emissions to individual countries (Oberthur and Ott, 1999). While progress has been criticised as being too slow(Oberthur, 2003), international regulation affecting all ships above a certain size is now in place. In July 2011, two measures related to the CO_2 emissions from ships were adopted by IMO: the Energy Efficiency Design Index (EEDI), for new ships, and the Ship Energy Efficiency Management Plan (SEEMP), for all ships (IMO, 2013). A recent study have however shown that these measures will not be able to reduce CO_2 emissions from ships in absolute terms as the projected growth in world trade outweighs the emission reduction (Bazari and Longva, 2011). Moreover, the effectiveness of these policy measures have been questioned, perhaps especially the SEEMP (Johnson et al., 2013).

The shipping industry mainly uses heavy fuel oil (HFO), which is a cheap oil fraction that is well suited for current marine engines but with high concentration of contaminants like sulphur (Buhaug et al., 2009). The shipping industry will, however, be forced to change fuels and/or implement abatement technologies in the near future as more strict exhaust emissions regulations are being implemented (IMO, 2013). For example, more strict requirements on sulphur content in fuels have already driven an increased interest in liquefied natural gas (LNG) (Verbeek et al., 2011, Germanischer Lloyd, 2012, Eide et al., 2012) and methanol (Fagerlund and Ramne, Port of Gothenburg, 2013) as a ship fuel. A number of studies have analysed the possibility to mitigate CO_2 emissions from shipping by operational and technical measures, mostly through increased energy efficiency (Buhaug et al., 2009; Eide et al., 2011). Recently, alternative fuels have also been addressed. Eide et al. (2012) suggests that LNG and biofuels can reduce CO_2 emissions to 50% below baseline growth in 2050. They also point at nuclear or biofuels as the solution if the shipping sector should be required to radically reduce their emissions (Eide et al., 2012). Vergara et al. (2012) suggests the use of synthetic fuels produced from carbon dioxide and hydrogen. Lin (2013) promotes biodiesel use in marine vessels and Bengtsson et al. (2012) assessed a transition towards use of biofuels in shipping.

Increased pressure on the shipping industry to abate CO_2 emissions, together with rising oil prices, makes it central to investigate which fuels that are cost-effective to implement in a carbon-constrained world where the competition for limited primary energy resources from other energy sectors are taken into account.

To facilitate discussions of strategies to reduce CO_2 emissions from shipping, the Global Energy Transition (GET) model (Grahn et al., 2009b, Wallington et al., 2010, Azar et al., 2003), was modified to include a more detailed description of the shipping sector (GET-RC 6.2). The GET-RC 6.2 model is used to assess which fuels that are most cost-effective to use in shipping in a carbon-constrained world. More specifically it is used to analyse under which conditions different fuels are cost-effective, for example depending on costs and availability of future technology options and actions in other energy sectors.

The aim with this study is to investigate (i) when is it cost-effective to start to phase out the oil from the shipping sector and what determines the speed of the phase out, (ii) under what circumstances are LNG or methanol cost-effective replacers and (iii) the role of bioenergy as a marine fuel. We would also like to analyse the effect on cost-effective fuel choices from assuming that CCS will be large-scale available technology option or not.

2. Materials and method

The GET model is a linear optimisation model, originally constructed by Azar and Lindgren and further developed by their co-workers (Azar et al., 2003, Grahn et al., 2009a, Grahn et al., 2009b, Wallington et al., 2010, Hedenus et al., 2010). The model is designed to analyse a transition of the global energy system while stabilizing at a specific atmospheric CO_2 concentration at the lowest total system cost for a modelling period of hundred years, where results for the time period 2020-2050 are analysed in this study. The energy and transportation demand is exogenously given and the model will allocate the available primary resources according to most cost-effective use in the end use sectors.

2.1 Model structure

The GET-model works with the concept of primary energy sources (coal, oil, natural gas, nuclear, wind, hydro, solar energy and biomass) that is converted into secondary energy carriers (heat, electricity, synthetic fuels (gas-to-liquid, coal-to-liquid and bio-to-liquid), hydrogen, natural gas, liquefied natural gas, gasoline, diesel, and kerosene) meeting the energy demand in the heat, electricity and transportation sector, respectively. In the model synthetic fuels is an umbrella term for methanol, DME, biodiesel, ethanol and Fischer-Tropsch fuels with costs and conversion efficiencies represented by data for methanol. Technology costs and performances are assumed at a mature level, which means the cost for the technology when it is commercialised and produced in large scale. As such, all costs are constant in the model. Assumptions of total primary energy supply potentials for oil and natural gas, are set to 12 000 and 10 000 EJ, respectively. For coal and bioenergy the estimated potential supply in the world is 260 000 EJ (Rogner, 1997) and 200 EJ/yr (OECD, 2007, Hoogwijk, 2004, Johansson et al., 1993), respectively. A total cost for using a specific fuel is calculated from the primary energy price[1], investment cost, conversion efficiency, capacity factor, operation and maintenance cost and distribution cost (see Appendix C). The use of nuclear power is kept constant over time. Primary energy sources as well as new energy technologies have expansion constraints to capture the real world inertia in how fast new technologies enter the market. Maximum use of intermittency energy (e.g. solar, wind and wave power), without energy storage, in the energy system is set to 30% of the total energy production (Giebel, 2007) Carbon capture and storage (CCS) is an option for the combustion of fossil fuels and biomass, and can be used in the production of heat, electricity and hydrogen, but not as an option in the transportation sector, and a maximum carbon storage capacity of 600 GtC is assumed (IPCC, 2005). In the model is also an optional low cost, low-emitting technology (LCLET) for electricity generation included that represents solar power and other future low cost, low-emitting electricity production technologies like advanced nuclear, geothermal or wave power.

In the model, the world is treated as ten distinct regions with unimpeded movements of energy sources between regions (with the exception of electricity), with costs ascribed to such movement. We aggregate regional solutions to supply global results and constrain global CO_2 emissions to be consistent with stabilization of atmospheric CO_2 concentration at 400 ppm in the base case. A carbon cycle module is used to calculate the atmospheric CO_2 concentration based on the use of fossil fuels. The model does not consider other greenhouse gases than CO_2. A cap limits the CO_2 emissions for each time step (10 years), which is taken from the global emission curves developed by Wigley and co-workers (Wigley et al., 1996).

The model is a simplification of the real energy system in at least the following important aspects:

- a limited number of technologies is included,
- an assumption of price inelastic demand is made,
- selections of fuels and technologies are made only on the basis of cost
- each sector acts rationally based on what is the cost-effective for the whole society
- “perfect foresight” with no uncertainty about future costs, climate targets and energy demand.

Energy system models are, however, not developed to predict the future; instead they are designed to give insights and deeper understandings of the mechanisms involved.

2.2 Energy demand

The regional energy demand in the model is obtained by combining data on global population, estimations of the per capita income and economic development from the ecologically energy driven demand scenario “C1”

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[1] In reality prices will increase, with a so called scarcity rent, when demand is higher than the supply. In the model demand is typically higher than the supply for oil, natural gas and biomass. The scarcity rent will increase with time, on oil and natural gas along with that oil and natural gas become more scarce and on biomass the more stringent the CO_2 restriction is since biomass is a cost-effective substitute for all fossil fuel use. In the model, as an approximation for the real world scarcity rent, we use the marginal values (shadow prices) on the supply constraint.

derived by IIASA/WEC (IIASA/WEC, 1995), assumptions regarding activity demand and energy intensity for a given activity. The World Energy Council assumes that future technical improvements will lead to an overall energy efficient improvement in the whole energy system of 0.7 % per year (IIASA/WEC, 1995). The GDP growth is assumed to stabilize at 1.8 % increase per year in the middle of the century and there is decoupling between economic growth and energy consumption. The population is assumed to grow to 10 billion people in 2050 and level off to 11.7 billion in 2100, which corresponds to a growth rate of 1–2 % per year (IIASA/WEC, 1995). The energy demand is divided into electricity, transportation and all other energy use apart from electricity and transportation, in this study called “heat”.

The present energy demand for shipping, 2007, is in this study taken from the IMO Second GHG study (Buhaug et al., 2009) where it is calculated from number of ships, ton-km, days at sea, mechanical output and fuel consumption for the period 1990–2007 (i.e. an activity-based approach, which is deemed to be more reliable than bunker sales statistics). Three alternative growth scenarios have been developed for the future energy demand in the shipping sector until 2100 based on the historical correlation between GDP and world seaborne trade. In the first alternative, the shipping industry is assumed to grow with 0.8 % faster than GDP, which is equal to growth of the shipping sector last 20 years. In the second and third alternative other growth scenarios are assumed, i.e., a high growth scenario, with 1.2 % faster than the GDP growth, and a low growth scenario, equal to the GDP growth. In 2011, the number of vessels was 103,000 (UNCTAD, 2011) and will in our estimations increase to 0.8–1.6 million vessels year 2100, depending on assumed growth scenario. 0.8–1.6 million vessels corresponds to an energy consumption of 45–135 EJ per year.

The shipping sector is also expected to improve in energy efficiency. The potential seems to be substantial; Eide et al. (2011) conclude that reductions of up to 30% compared to business as usual are possible at zero marginal cost by 2030. If measures are implemented so that savings from cost-effective measures contribute to the implementation of more expensive measures, more than 50% reduction has been argued to be possible in the same time span, at zero net cost (Hoffmann et al., 2012). In a report to the IMO, Bazari and Longvara (2011) assessed that the current regulatory regime (EEDI and SEEMP) can lead to a reduction of CO_2 with 35–40% in 2050 compared to business as usual. The yearly increase in energy efficiency is set to 0.7 % per year in the model, corresponding roughly to a 50% decrease by 2100.

2.3 Representation of the shipping sector

In this study the GET-model includes a more elaborately described shipping sector than previous GET-models, with three types of ships; short sea, deep sea and container ships (see Table 1). The selection of three vessel categories is a compromise between a detailed and a very rough representation. Although this is a rather rough division of ships, it still captures two important aspects: (i) the number of container vessels has historically increased considerably faster than other vessel categories and (ii) the relation between the tank capacity and size of the engine is different for different types of ships.

Table 1. Generic vessel types for maritime transport in the model

	Vessel types		
	Short sea	**Deep sea**	**Container**
Description	Ships used in short sea shipping; mostly passenger vessels, ferries and offshore vessels, <15000 dwt	Larger ships suitable for intercontinental trade, > 15000 dwt	All types of container vessels
Engine power (kW)	2400[a]	11000[a]	23000[a]
Voyage range full speed (days)	7[b]	30[c]	15[c]
Tank capacity (m^3 MGO)	90	1830	1920
Tank capacity (GJ[a])	3500[d]	71300[d]	74600[d]
Life time	30	30	30

[a] Average engine power for each ship category in 2007 (Buhaug et al., 2009).

[b] Based on the time it takes to travel from Marseille to Rotterdam (Stopford and Ebooks Corporation., 2009) assuming a speed of 20 knots times 1.5 (to account for backup tank capacity).

[c] Based on the time it takes to travel from Long Beach to Shanghai at 13.6 and 23 knots, respectively, for the ocean and container vessel (Stopford and Ebooks Corporation., 2009) times 1.5 (to account for backup tank capacity).

[d] Based on higher heating value (HHV).

Six marine fuel options are included in the model: marine gas oil, (MGO), liquefied natural gas (LNG), synthetic fuels (i.e. liquid fuels from coal (CTL), liquid fuels from gas (GTL), liquid fuels from biomass (BTL)) and liquefied hydrogen (H_2). Heavy fuel oil (HFO) is the most used shipping fuel today (Buhaug et al., 2009). However, with the coming global sulphur cap of maximum 0.5% sulphur in 2020 (or 2025 depending on the outcome of an availability assessment, see, for example, Svensson (2011)) (IMO, 2006), the use of HFO needs to be combined with exhaust gas treatment, e.g. scrubbers, or produced with very low sulphur content (Bengtsson et al., 2011). MGO is a distillate fuel with sulphur content usually below 0.5% and is therefore chosen to represent the oil-based fuels in shipping in the model. Powertrain technologies for vessels in the model are internal combustion engines (ICE) and fuel cells (FC). Nuclear-fuelled ships are not included since their contribution is currently negligible and may not find public acceptance in the nearest decades. Hybrids and "electric ships" are not an option in the model. In total 12 different combinations of fuel and vessel technologies are considered for each ship category. Hydrogen is forbidden in some alternative runs since there are many uncertainties with hydrogen as a marine fuel. The model does not consider the eventual consequence of reduced cargo capacity as an effect of larger space requirement and additional weight for fuels and other equipment when changing to new types of fuels and technologies.

Table 2 provides efficiency and cost data for the different combinations of fuel and propulsion technologies included in the model. The data are derived from published sources (Germanischer Lloyd, 2012, Nielsen and Schack, 2012, Ludvigsen and Ovrum, 2012, JJMA and BAH, 2002) and in discussions with stakeholders.

A typical marine diesel engine has an efficiency of 40–50 % depending on the load factor, size and age of the engine. The ICE is assumed in the model to have an efficiency of 40 % for all fuels and represent the "average" ship in the fleet. The engine efficiency is kept constant over time, although the energy demand increases faster than the number of ships, which leads to a total energy efficiency of 0.7 % per year. Fuel cell technology has a higher efficiency potential, ranging from 45–60 % depending of high temperature fuel cell technology, such as molten carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC), or low temperature fuel cell, such as proton exchange membrane fuel cells (PEMFC) and if heat recovery is included. In the base-case an efficiency of 45 % is used. The GET-model uses higher heating values (HHV) and the efficiency numbers therefore need to be transformed into higher heating values, and this is done by multiplying with the LHV/HHV ratio for each fuel, see Table 2 and Appendix A.

The cost of vessels is determined mainly by the construction cost, depending on the cost of engines, fuel tanks and other extra costs such as gas alarm system, pipelines or fuel processors. In the model runs, the cost for LNG-tank storage, H_2-tank storage and fuel cell cost have been varied between 70–330 USD/GJ, 110–600 USD/GJ and 2000–6700 USD/kW respectively. The first two corresponding figures in USD/tonne are 3,850–18,150 USD/tonne, and 15,620–85,200 USD/tonne. Ships running on synthetic fuels will have slightly higher engine cost per kW due to extra cost for fuel processing, which is assumed to be 20 USD/kW; further details are available in Appendix B.

Table 2. Propulsion system efficiency and vessel costs (for the base case analysis) for maritime transport in the model.

Propulsion system[a]	**Energy efficiency ratio (HHV)**	**Short sea vessel cost (kUSD)**		**Ocean vessel cost (kUSD)**		**Container vessel cost (kUSD) 2000-2100**[b]	
		Base	Incremental	Base	Incremental	Base	Incremental
MGO ICE	1	18,000[d]	0	87,000[d]	0	137,000[d]	0
MeOH ICE	0.94		100		1,500		1,800
LNG ICE	0.96		1,100		7,400		9,800
H_2 ICEV	0.90		1,600		15,100		18,600
MGO FC	1.13-1.25		7,900		37,300		80,400
MeOH FC	1.06-1.18		8,000		38,500		81,700
LNG FC	1.08-1.20		8,200		41,400		84,700
H_2 FC	1.01-1.13		8,800		50,100		93,800

[a] MGO ICE, MeOH ICE, LNG ICE, H_2 ICE are internal combustion engines powered by marine gas oil, synthetic fuels (biofuels, coal-to-liquid and gas-to-liquefied) represented as methanol, liquefied natural gas and liquefied hydrogen. MGO FC, MeOH FC, LNG FC, H_2 FC are fuel cell vessels powered by oil, synthetic fuels (biofuels, coal-to-liquid and gas-to-liquefied) represented as methanol, liquefied natural gas and liquefied hydrogen.

[c] Energy efficiency of the engine and other measurements are included since the demand increases faster than the number of ships in the model. The efficiency for internal combustion engine is 40 % and the efficiency for fuel cells range from 45 to 50%, see Appendix A for more details.

[d] Base cost (kUSD) for a short sea, ocean and container vessel, the cost for combustion engine is assumed to 500-700 USD/kW and the cost for storage tank is 25-30 USD/GJ see Appendix B.

The model only considers CO_2 emissions among greenhouse gases, as mentioned above, and the calculation is based on the carbon content in the raw materials used. One exception is however made in order to be able to include the 'methane slip' from marine gas engines. The methane slip, unburned methane emitted from gas and dual-fuel engines, is important to consider, when using LNG as a fuel, since methane is about 25 times more effective greenhouse gas compared to carbon dioxide (IPCC, 2007) and has a great impact on global warming (Bengtsson et al., 2011). It is therefore included in the model in terms of CO_2 equivalents. Very few measurements of slip from gas and dual fuel engines in operation are available. The size of the slip is reported in the range of 0-8 wt.% for different engine concepts (Nielsen and Stenersen, 2010, MAN Diesel & Turbo, 2012). Furthermore, it may be possible to reduce the methane slip with oxidation catalysts (Järvi, 2010). The methane slip has been varied between 0-4 wt.% in this study.

3. Results

In this study the GET-RC 6.2 model was used to investigate the development over time of the different cost-effective fuel and propulsion technology options for shipping when achieving stringent carbon dioxide targets.

Many of today's advanced technologies, like CCS, are in an early R&D phase. A lot of technical and practical uncertainties have to be solved before commercialisation and large-scale production can be reality. In this study we analyse results from assuming that CCS will be large-scale available in future as well as if it will not. The impact of a number of chosen parameters have been investigated in alternative runs, e.g. the atmospheric CO_2 concentration target, assumptions that LCLET will be large-scale available or not, different assumptions regarding the supply of limited primary energy sources as well as different assumptions on future costs and efficiencies (see Appendix D for details). Also the discount rate is uncertain and will affect both the fuel choices and the phase out of oil. Therefore, except from our base analysis, several alternative cases were analysed. The results are calculated for the three ship categories separately and then added together. Only the overall results for the shipping sector are presented (only small differences were seen between the different ship categories). In the below subsections, a base case is presented, followed by subsections discussing i) when is it cost-effective to start to phase out the oil from the shipping sector and what determines the speed of the phase out, (ii) under what circumstances are LNG or methanol cost-effective replacers and (iii) the role of bioenergy as a marine fuel.

3.1 Base analysis

The base case is modelled to meet a CO_2 concentration of 400 ppm, assuming that LCLET will be large-scale available, an LNG tank storage cost 110 USD/GJ, a hydrogen storage tank cost 250 USD/GJ, a fuel cell system cost 4000 USD/kW and that the fuel cell efficiency is 45 %. The base analysis is run assuming that either CCS will be large-scale available (Figure 1a) or not (Figure 1b).

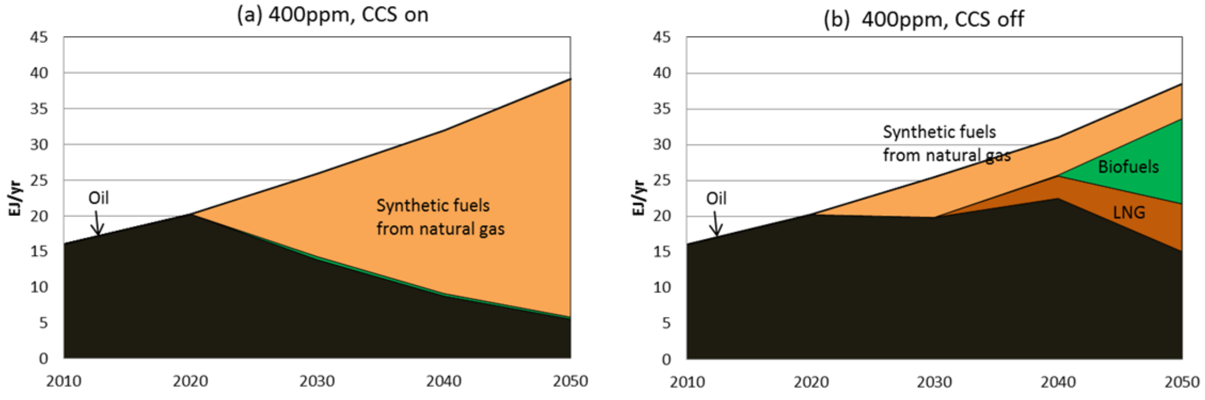

Figure 1. Global secondary energy consumption for shipping meeting a CO_2 concentration of 400 ppm (a) with CCS or (b) without CCS as a large-scale available technology option for CO_2 reduction.

In our base case run assuming CCS available (Figure 1a), the oil is phased out rapidly and replaced by synthetic fuels from natural gas. But as mention earlier CCS is in a very early stage and a scenario without, or with only a small-scale use of, CCS could be as likely scenarios. As seen in Figure 1, the large-scale use of CCS is of great importance for the cost-effective fuel choices in the shipping sector. The effect, that changes in one sector (assuming CCS available or not) affects results in another sector, is called an energy system effect and shows the importance of analysing future fuels for transport where also other sectors competing for the same primary energy sources are taken into account.

The results shown in Figure 1, that oil-based fuels remain longer in the scenario where CCS is not assumed large-scale available, is rather counter-intuitive and almost the opposite to the effect seen in the road transport sector when analysing fuel choices whether or not CCS is available. When CCS is assumed a large-scale available technology, CO_2 can be reduced at relatively low cost in the stationary energy sector. When assuming an upper cap for the emissions, from the entire energy system, slightly more CO_2 can be emitted from the transportation sector as a whole when more CO_2 are reduced in the stationary energy sector. For the road sector, the inclusion of CCS reduces the incentives to shift to more advanced vehicle technologies and will instead prolong the era of conventional fuels. For the shipping industry we see the opposite. When assuming that CCS is deployed on a large scale, the conventional oil based fuels are phased out more rapidly compared to when CCS is assumed to be not available. This is again an energy system effect where the results in the road transport sector affect results for the shipping sector. Without CCS, the stationary energy sector can no longer use coal as the main fuel and will use more natural gas as it is one of the most cost-effective alternatives. The increased competition for primary energy sources used in the transportation sector will increase the price of fuels for transport. Higher fuel prices will lead to increased energy-efficiency and the introduction of hybrids and plug-in hybrids where possible. Since these energy-efficient vehicle technologies are available in the road transport sector (and not in the shipping sector) minimisation of the overall energy system cost will lead to more CO_2 reductions occurring in the road transport sector than in other transport sectors, where such technologies are not available. That is, since the model finds it more cost-effective to reduce emissions in the road transportation sector, compared to in other transport sectors, the shipping sector may, in the case of no CCS, increase their emissions and prolong the era of conventional oil-based fuels.

Similar for both the road and the shipping sector is that the inclusion of CCS technology increase the use of coal leading to that the limited amount of natural gas (otherwise used in the stationary energy sector) will be available to use in the transportation sector.

3.2 End of oil in shipping

According to the model runs close to all available oil is cost-effective to use during the modelling period. The model runs also show that the majority of all oil and more than half of the natural gas are used in the transportation sector. Bioenergy and coal (with CCS) are more cost-effectively used in the stationary energy sector.

The aggregated use of oil during 2020–2050 is only 50–60 % of the energy demand and the share depends mainly on the total energy demand, cost of natural gas and other alternative fuels, discount rate and the assumption on whether or not hydrogen fuelled ships will be available. The share of the energy demand met by oil increases up to approximately 80 % if CCS is not becoming large-scale available. This is due to the fact that without CCS the heating sector will use an increased amount of natural gas. Then, the natural gas in the shipping sector is to some extent replaced by oil. If the oil and/or the natural gas resources are considerably larger than expected (roughly doubled), the oil will remain cost-effective for a longer time period (about 50 years), in all transport sectors. It turns out that the different demand assumptions do not significantly impact the phasing out of oil or the final fuel choices.

It is, according to almost all our runs, cost-effective already next decade to start the phase out of oil-based fuels from the shipping sector. In the case with a doubling of the oil resources, oil is phased out a couple of decades later. Within the transportation sector it seems that in most runs oil is out phased later in air and road-transport, compared to shipping. Oil-based fuels are replaced faster in the shipping sector mainly due to cheaper alternatives in this sector. In road transportation, the longer era of oil is probably due to the availability of more fuel-efficient hybrid technologies.

The results on cost-effective fuel choices for shipping from the two base analysis and 17 different alternative runs (aggregated over the time period 2020–2050) are presented in Figure 2. The results are sorted by the amount of oil-based fuels, where the lowest and highest belong to model runs assuming halved and lower demand growth, respectively. The majority of the alternative runs show similar levels of oil use as in our base analysis with CCS. Increased use of oil-based fuels are connected to cases where CCS are not available, low natural gas supply potential, high methane slip in marine engines or high oil supply potential.

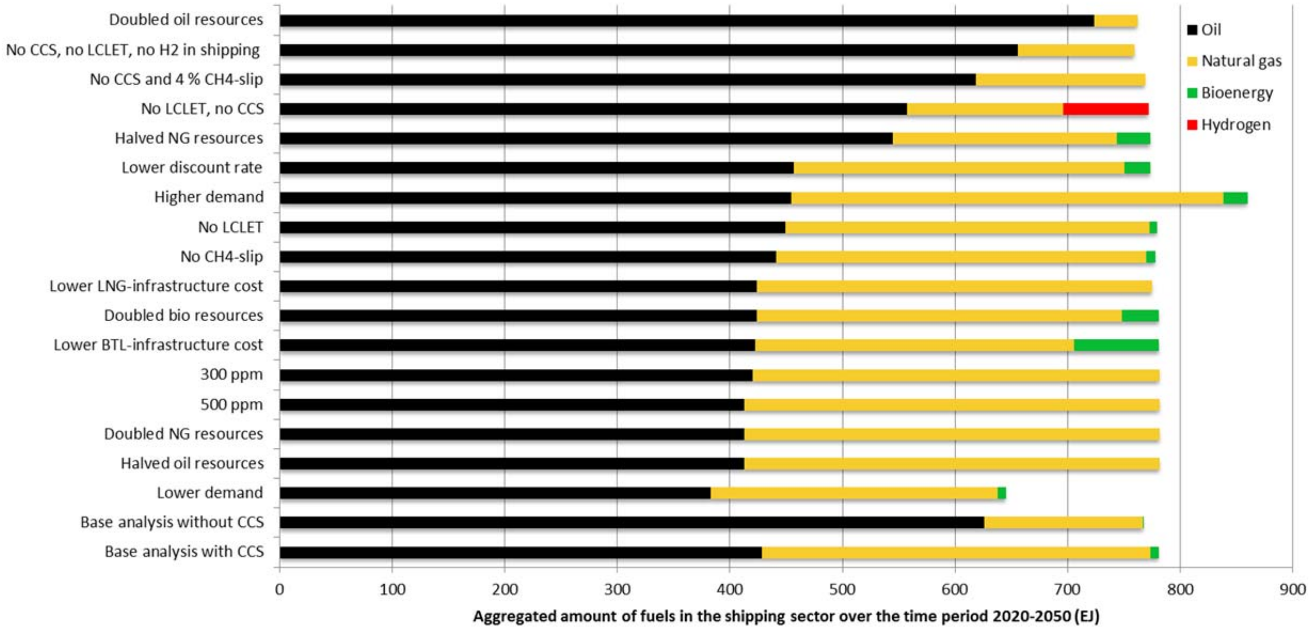

Figure 2. Amount of fuels in the shipping sector during the period 2020–2050 (details about the alternative runs are presented in Table D.1 in Appendix D). Note that “natural gas” includes both LNG and synthetic fuels produced from NG. Acronyms used are: H2=hydrogen, BTL=bio-to-liquid, NG=natural gas, bio=biomass, LNG=liquefied natural gas, CH4=methane, LCLET= low cost, low-emitting technology for electricity generation.

3.3 Liquefied natural gas or methanol in the shipping sector

Methanol is shown to be a cost-effective fuel choice in the shipping sector for all three ship categories in most cases, satisfying between 40–50% of the aggregated fuel demand in shipping sector during 2020–2050. A transition towards methanol as a marine fuel could be, as mentioned previously, cost-effective already next decades, reaching its peak some decades later.

However, in some of the cases we see LNG, instead of methanol, replacing oil. A number of factors affect the amount of LNG that is cost-effective to use in shipping. The most important are methane slip from engines, LNG cost, the availability of CCS and the discount rate. It is shown that LNG can be a cost-effective fuel in the shipping sector, when there is negligible methane slip from the marine gas engines. Approximately half of the aggregated energy demand in shipping during 2020–2050 is LNG if the costs in the base case are used and if there is no methane slip from the marine engines. This number can be compared with less than 10% of the aggregated demand for the period 2020–2050 with a 3% methane slip.

The infrastructure cost for LNG is assumed to be 1600 USD/kW in the base case and this represents a significant share of the fuel cost for LNG. Reducing the infrastructure cost increases the share of LNG in shipping. The share of LNG and methanol in shipping during 2020–2050 is equal if the LNG infrastructure cost is reduced with approximately 15%. Other factors that affect the cost for investing in LNG ships is the LNG-plant investment cost and the LNG tank cost, a reduction of these costs will also increase the share of LNG in shipping.

When CCS is allowed, coal can be used to produce relatively inexpensive low-CO_2 heat, which prolongs the use of more CO_2 emitting but relatively cheaper technologies in transportation. If CCS will not become a large-scale commercial technology, this will increase the share of LNG that is cost-effective to use in the shipping industry as LNG will reduce the CO_2 emissions from shipping slightly more than methanol produced from natural gas and much more than methanol produced from coal, even with a methane slip of 3%. However, with a 4% slip, LNG will be associated with larger CO_2-eq than methanol from natural gas and consequently not a cost-effective option for CO_2 emission reductions.

Decreasing the discount rate to 3% instead of 5% makes LNG less costly than methanol produced from natural gas (GTL). This is mainly caused by that the high investment cost for the LNG infrastructure has reduced impact on the total costs for LNG. The overall investment cost, including both production plant and infrastructure, is much higher for LNG than for GTL (as can be seen in Appendix C).

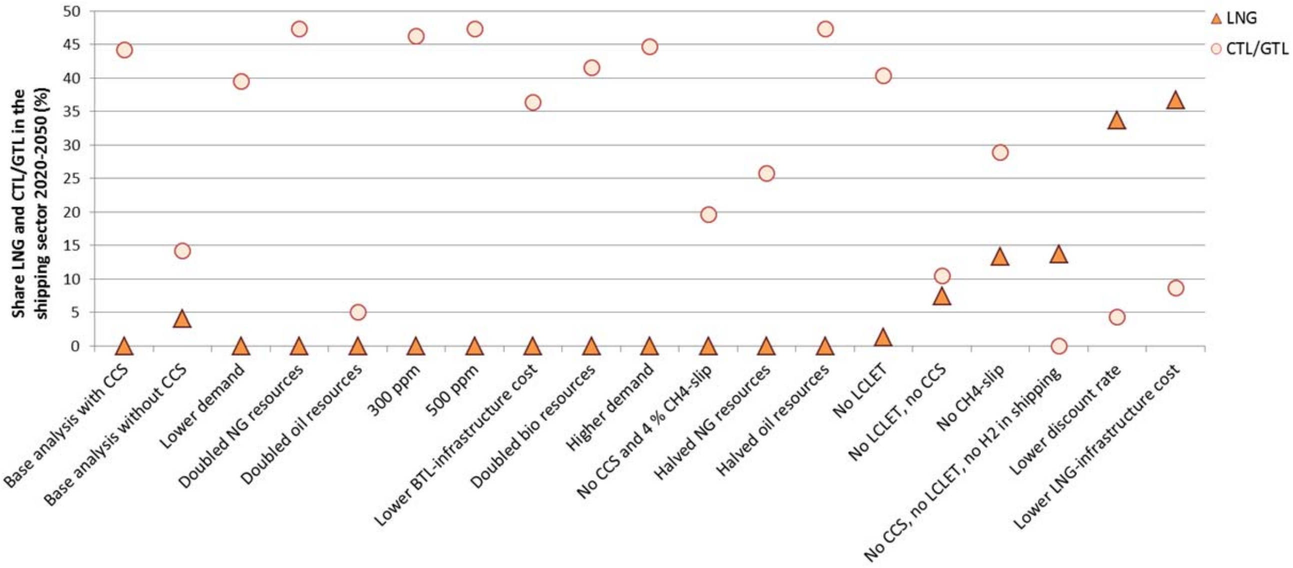

Figure 3. Share liquefied natural gas (LNG) and fossil-based methanol (CTL/GTL) in the shipping sector during the period 2020–2050, (details about the alternative runs are presented in Table D.1 in Appendix D). Acronyms used are: H2=hydrogen, BTL=bio-to-liquid, NG=natural gas, bio=biomass, CH4=methane, LCLET= low cost, low-emitting technology for electricity generation.

3.4 The role of bioenergy

As oil is phased out in the shipping sector natural gas and other alternative fuels enter the market. In the shipping sector these fuels are mainly produced from natural gas and not bioenergy. This is mainly due to the competition for the limited fuels.

In the base analysis, bioenergy is limited globally to 200 EJ per year and the potential is different for different regions. According to our model runs, bioenergy is rarely used and plays a minor role in reducing CO_2-emissions in the shipping sector. Not even a doubling of the biomass supply potential will lead to a significant use of bioenergy used in the shipping sector, see Figure 2. Instead, most of the biofuels used for transport is allocated to air and road transportation (the majority of bioenergy is used in the stationary energy sector). The infrastructure cost for methanol produced from bioenergy (BTL; bio-to-liquid) in shipping is set to 600 USD/GJ. This number is very uncertain and we have estimated the cost to be in the range of 200-600 USD/GJ. However, even if the infrastructure cost is reduced to the same level as for fossil methanol (200 USD/GJ) bioenergy is not seen in the model results as a dominant fuel in shipping. CCS will also have a small impact on the amount of bioenergy in the shipping sector. The share of biofuels in shipping is slightly increased if CCS is not a viable technology (see Figures 1 and 2).

4. Discussion and conclusion

The aim of the study was to investigate which fuel/fuels are cost-effective to use in the shipping sector in a future energy system with a cap on CO_2 emissions. Three main topics were scrutinised i) when is it cost-effective to start to phase out the oil from the shipping sector and what determines the speed of the phase out, ii) under what circumstances are LNG and methanol cost-effective replacers and iii) the role of bioenergy as a marine fuel.

Results from the model runs shows that it seems to be cost-effective to start to phase out the oil from the shipping sector nearest decades. Prolonged eras of oil-based fuels are connected to cases where CCS is not available, a low natural gas supply potential, a high methane slip in marine engines or a high oil supply potential.

A robust result is that several fuels are used simultaneously, even if some fuels are more dominating than others depending on the selected parameters. Today oil-based fuels dominate the shipping sector and results show that it is most cost-effective to replace oil in the shipping sector by natural gas based fuels: methanol produced from natural gas and LNG. However, the most cost-effective choices of methanol or LNG will depend on the relative cost difference between them and their emissions of carbon dioxide equivalents (since we also analyse the effect of changing the size of the methane slip from marine engines).

Previous studies have promoted the use of biofuels in the shipping sector (Bengtsson et al., 2012, Lin, 2013, Eide et al., 2012). Bioenergy plays only a minor role in the shipping sector in our study since it is a limited resource that is more cost-effective used in order to reduce CO_2 emissions in other sectors.

As mentioned in the introduction, the model is a simplification of the real energy system and gives insights and not forecasts of the future energy system. It is assumed that all sectors are behaving in a rational and cost-effective way when reducing CO_2 emissions on a global level with a global cap over all sectors. Our study shows that an early switch from oil to alternative fuels is cost-effective assuming that these are mature technologies. This does not mean there is no need for policies or regulations – apart from a price on carbon – in order to bring forward these technologies. Some of the alternative fuels and technologies are indeed today much more expensive and far behind in technical development and much more expensive compared to their assumed mature level. It is also essential to keep in mind that it can take time, sometimes decades, to develop, test, implement and build new infrastructure and propulsion technologies, so that new technology can become commercial, especially in the shipping sector where the lifetime of a ship is assumed to be 20-30 years. Sandén and Azar (2005) argues, for example, for the necessity of incentives that support the process of bringing new technologies to the market in order to meet longer term climate targets. The time aspect also implies that model results where a fuel is shown cost-effective in a certain decade, in reality to be able to fulfil such scenario the fuel must be ready for the market many years earlier. Another aspect is that in our model, the energy efficiency has been assumed to increase by 0.7 % per year. Energy efficiency measures have comparatively short pay-back times in previous literature, but this very same cost-effective potential indicates the presence of transaction costs (or barriers, depending on research framework, see e.g. Johnson (2013, pp. 29-39)) associated with the measures. Further policy support could be needed in order also to achieve increased energy efficiency.

LNG is today promoted as a future shipping fuel by many actors. However, we show in this study that the methane slip from marine engines greatly impacts whether or not LNG is a cost-effective shipping fuel. The gas and dual fuel engines used today in Norway are reported to have more than 3% methane slip. In our study, LNG is shown to have a minor role in the shipping sector for most cases with a 3% methane slip or more. It is possible to reduce the methane slip significantly with an oxidation catalyst, but the methane slip from marine engines is currently not regulated and this would therefore only happen on voluntary basis.

It is a challenging task to express firm opinions of which fuels and technologies that should be used in the shipping sector. Results from this study should be seen as a first attempt to get more knowledge about the mechanisms within a global energy system, where the energy transition in the shipping sector will act simultaneously as many other current fossil fuel users wanting to reduce their emissions. Future fuels for shipping will therefore compete for the same primary energy sources as many other energy sectors. Which sector that in the end will use attractive limited energy sources depend on a sector's willingness to pay as well as on what policies (e.g. subsidies or penalty fees) that may steer towards a specific group of users.

The study also points at the need of more research in the field of future marine fuels. The cost and performance of future vessel technologies are very uncertain during the time span investigated and further analyses will be needed. The model could also be used to further evaluate which role shipping should take to reduce emissions of greenhouse gases globally. The model could in the future be expanded to include also other fuels such as nuclear and synthetic fuels produced from carbon dioxide and water using e.g. solar or geothermal energy. These have been suggested as possible fuels in other studies.

This work is a first step towards a more detailed understanding of which fuels that are cost-effective to use in the shipping sector while reducing CO_2 emissions globally. This work also shows that it is important to take into account interactions with other energy sectors when analysing fuel choices in shipping as these may have a profound impact on which fuels that are cost-effective to use in the shipping sector.

In summary, three main conclusions can be drawn from this study (i) it seems to be cost-effective to start to phase out the oil from the shipping sector during the nearest decades, (ii) natural gas based fuels, i.e. fossil methanol and LNG are the two most probable replacers, of which methanol has been shown to dominate in the case with CCS (methanol or LNG depends on the availability of natural gas, on the methane slip and on infrastructure costs) and (iii) limited supply and competition for bioenergy among other end use sectors makes the contribution of bioenergy small, in the shipping sector.

Acknowledgements

We would like to thank Niclas Mattsson and Fredrik Hedenus (Physical Resource Theory, Chalmers University of Technology), Lennart Haraldsson (Wärtsilä), and Pierre Sames (Germanischer Lloyds) for valuable input and fruitful discussions, and region Västra Götaland, Sweden for financial support.

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Appendix A. Efficiency values for the vessel propulsion system used in the model

The diesel engine has today an efficiency of 40–50 % depending on the load factor, size and age of the engines. The ICE is assumed in the model to have an efficiency of 40 % for all fuels and represent the "average" ship in the fleet. The engine efficiency is kept constant over time, although the energy demand increases faster than the number of ships, which leads to a total energy efficiency of 0.7 % per year.

Typical values for specific fuel oil consumption are presented in the IMO Second Greenhouse Gas Study report. Their figures indicate that the specific fuel oil consumption varies depending on age and size of the vessel. Average values for engines for different ship categories from 2001–2007 are presented in Table A.1. This could be used to differentiate the engine efficiency between the three vessel categories (container vessel engine efficiency =48%, deep sea vessel engine efficiency=45% and short sea vessel engine efficiency=43%). This would make fuel cells less advantageous for deep sea and container vessels as the fuel cell efficiency is assumed to be independent of size.

Table A.1. Engine efficiency dependent on size for marine engines produced between 2001 and 2007 (Buhaug et al., 2009)

	Engine efficiency dependent on size		
	>15000 kW	**15000-5000 kW**	**5000 kW**
Specific fuel oil consumption (g/kWh)	175	185	195
Efficiency (assumed low heating value (LHV) (43.2 GJ/tonne)	48%	45%	43%

There is not much data available of the efficiencies of marine engines running on different fuels. Some data suggests that gas and duel fuel engines will have a higher efficiency compared to conventional technology. A position paper from Det Norske Veritas presents 12% higher efficiency for the 4-stroke gas engine compared to a 4-stroke diesel engine (Ludvigsen and Ovrum, 2012). However, another study report present almost the same engine efficiency when using heavy fuel oil, marine gas oil, liquefied natural gas and methanol in a marine 4-stroke engine (Haraldsson, 2013). In an article assessing the use of solar cells to generate hydrogen on-board they estimate an increase in engine efficiency with 11% with 30% hydrogen enrichment of the fuel (Glykas et al.). However, the uses of alternative fuels in internal combustion engines are more studied for automotive industry. Energy consumption for different powertrains for automotive vehicles is evaluated in the Joint Research Centre-EUCAR-CONCAWE collaboration (Edwards et al., 2011). They reported used similar figures for the hydrogen and diesel engine (167.5 MJ/100 km and 161.1 MJ/100 km respectively). From the limited information available we consider it reasonable to assume the same engine efficiency for all fuels.

Fuel cell technology has a higher efficiency potential, ranging from 45–60 % depending of high temperature fuel cell technology, such as molten carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC), or low temperature fuel cell, such as proton exchange membrane fuel cells (PEMFC) and if heat recovery is included. The PEMFC operates on high quality hydrogen in order not to damage the membranes. PEMFC have been tested on submarine yachts, ferries and recreational boats (Ludvigsen and Ovrum, 2012). MCFC and SOFC are high temperature fuel cells that are flexible regarding choice of fuels and can for example use methanol, natural gas and hydrogen. MCFC and SOFC fuel cells have been tested in marine application and then had an efficiency of 45–50% (Ludvigsen and Ovrum, 2012). In the base-case an efficiency of 45 % is used, but efficiencies of 48 % and 50 % in combination with different cost for fuel cell systems have been analysed as well.

The GET-model uses higher heating values (HHV) and the efficiency numbers therefore need to be transformed into higher heating values, and this is done by multiplying with the LHV/HHV ratio for each fuel, see Table A.2.

Table A.2. Efficiencies for marine engines and fuel cells used in the model

Propulsion system[a]	**MGO ICE**	**MeOH ICE**	**BTL ICE**	**LNG ICE**	**H_2 ICE**	**MGO FC**	**MeOH FC**	**BTL FC**	**LNG FC**	**H_2 FC**
Base case:										
Efficiency LHV[b]	40%	40%	40%	40%	40%	45%	45%	45%	45%	45%
Efficiency HHV[b]	37%	37%	37%	35%	35%	36%	34%	42%	48%	40%
Efficiency ratio LHV/HHV	1.00	1.00	1.00	0.94	0.94	0.96	0.90	1.12	1.28	1.06
With a 48% fuel cell efficiency:										
Efficiency LHV	40%	40%	40%	40%	40%	48%	48%	48%	48%	48%
Efficiency HHV	37%	37%	37%	35%	35%	45%	42%	42%	43%	41%
Efficiency ratio LHV/HHV	1.00	1.00	1.00	0.94	0.94	1.20	1.13	1.13	1.15	1.08
With a 50% fuel cell efficiency:										
Efficiency LHV	40%	40%	40%	40%	40%	50%	50%	50%	50%	50%
Efficiency HHV	37%	37%	37%	35%	35%	47%	44%	44%	45%	42%
Efficiency ratio LHV/HHV	1.00	1.00	1.00	0.94	0.94	1.25	1.18	1.18	1.20	1.13

[a] MGO ICE, MeOH ICE, LNG ICE, H_2 ICE is internal combustion engines powered by marine gas oil, synthetic fuels (biofuels, coal-to-liquid and gas-to-liquefied) represented as methanol, liquefied natural gas and liquefied hydrogen. MGO FC, MeOH FC, LNG FC, H_2 FC is fuel cell vessels powered by oil, synthetic fuels (biofuels, coal-to-liquid and gas-to-liquefied) represented as methanol, liquefied natural gas and liquefied hydrogen.

[b] lower heating value (LHV) and higher heating value (HHV)

Appendix B. Costs vessel technologies used in the model

All costs in the model, such as cost for conversion plant, transport modes, infrastructure and fuels are based on "mature level" and are constant with time. Since some of the technologies, e.g. fuel cells, carbon capture and storage technology or hydrogen production technology are not widely used today or even in some cases not present on the market, an estimation of the mature costs have been made on the technology potential and in relation to already commercial technology. The cost of vessels is determined mainly by the construction cost. The differences in vessel cost between different fuels and driveline technologies are depending on the cost of engines, fuel tanks and other extra costs such as gas alarm system, pipelines or fuel processors. Costs were calculated separately for the three vessel categories and are based on literature and discussion with the industry. A summary of all cost per kW installed capacity can be found in Table B.1. The cost for fuel cells in the base case is 4000 USD/kW assuming a cost of 1500 USD/kW for fuel cell installation and a cost for replacing the fuel cells stack every 5–6th year of 33% of the fuel cell cost.

In order to capture the uncertainty in the vessel cost for different fuels and driveline technologies a sensitivity analyses of the results have been made, where a range of costs assumptions has been investigated. Table B.1 presents data used for the base case and the range within brackets represents the spread found in literature.

Table B.1. Detailed cost for different fuels and vessel types divided on engine and storage system cost

Propulsion system[a1]	**Short sea vessel cost**		**Deep sea vessel cost (kUSD)**		**Container vessel cost (kUSD)**	
	ICE/FC (USD/kW)	**Storage tank (USD/GJ)**	**ICE/FC (USD/kW)**	**Storage tank[b] (USD/GJ)**	**ICE/FC (USD/kW)**	**Storage tank[a] (USD/GJ)**
MGO ICE	700	30	600	25	500	25
MeOH ICE	720[c]	50	620[c]	40	520[c]	40

LNG ICE	1015[d]	110 (110–460)	870[d]	80 (80–350)	725[d]	80 (80–350)
H_2 ICE	1015[e]	230 (155–600)	870[e]	170 (115–450)	725[e]	170 (115–450)
MGO FC	2000 (1500–6700)	30	2000 (1500–6700)	25	2000 (1500–6700)	25
MeOH FC	1500–6700 (2000)	50	2000 (1500–6700)	40	2000 (1500–6700)	40
NG FC	1500–6700 (2000)	110 (110–460)	2000 (1500–6700)	80 (80–350)	2000 (1500–6700)	80 (80–350)
H_2 FC	1500–6700 (2000)	230 (155–600)	2000 (1500–6700)	170 (115–450)	2000 (1500–6700)	170 (115–450)

[a] MGO ICE, MeOH ICE, LNG ICE, H_2 ICE are internal combustion engines powered by marine gas oil, synthetic fuels (biofuels, coal-to-liquid and gas-to-liquefied) represented as methanol (biofuels, coal-to-liquid and gas-to-liquefied), liquefied natural gas and liquefied hydrogen. MGO FC, MeOH FC, LNG FC, H_2 FC are fuel cell vessels powered by oil, synthetic fuels (biofuels, coal-to-liquid and gas-to-liquefied) represented as methanol, liquefied natural gas and liquefied hydrogen.

[b] A factor of 0.75 has been used for ocean-going and container ships storage tank since they have larger storage tanks compared to short sea ships, which gives a scaling effect due to less material per energy unit.

[c] An extra cost for fuel processor has been added, which is assumed to be 20 USD/kW

[d] The LNG engine is assumed to cost 40-45 % more than the diesel engine.

[e] The H_2- engine is assumed to cost equal to the LNG engine.

Appendix C. Cost and CO_2 data for shipping fuel options

A total cost for all fuels have been calculated from the primary energy price, investment cost, conversion efficiency, capacity factor, operation and maintenance cost and distribution cost (see Table C.1). The cost for MGO, except for distribution cost, is assumed to be the same as for gasoline and diesel. The distribution cost for MGO is assumed to be 10 Euro per tonne (Danish Maritime Authority, 2012). The distribution cost for LNG is estimated to 4.7 USD/GJ and based on the estimation of the distributions cost in the North European LNG Infrastructure Project. The investment cost for LNG production is assumed to be 200 USD/kW. The liquefaction costs for LNG was between 150–400 USD/kW in the literature (Engelen and Dullaert, 2010, Jensen, 2004, Cornot-Gandolphe et al., 2003) and the liquefaction efficiency is assumed to be 93% (Edwards et al., 2011) (Danish Maritime Authority, 2012). The distribution costs for methanol from coal and natural gas is assumed to be twice as high as for oil due to the two times lower energy density. However, since methanol from biomass have to be distributed larger distances on roads as biomass sources are usually produced in smaller scales and located far from ports it is assumed that methanol from biomass have a distribution cost of 1.80 USD/GJ, compare to 0.6 USD/GJ for methanol produced from natural gas. The fuel cost for hydrogen is based on transport of hydrogen in pipelines, which is assumed to be similar to liquefaction and distribution in liquid form. In this study all cost for transport fuels is separated for road-based transport modes and shipping. Shipping has a lower infrastructure cost than road transportation. For a more detailed description of the cost for fuels for road-based transportation modes, see Grahn et al. (2009b).

Table C.1. Fuel cost and CO_2 data for maritime transport in the model

Primary energy sources	**Secon-dary energy**	**Invest-ment cost USD/ kW$_{\text{fuel}}$**	**Con-versi-on effici-ency**	**Life time**	**Capa-city factor**	**Annul-ized inv. cost.[d] USD/ GJ$_{\text{fuel}}$**	**O&M cost USD/GJ$_{\text{fuel}}$**	**Distri-bution cost USD/GJ$_{\text{fuel}}$**	**Prim-ary energy price[a] USD/ GJ**	**CO_2-emis-sions[b] kgC/ GJ$_{\text{fuel}}$**	**Total fuel cost[c] USD/ GJ$_{\text{fuel}}$**
Oil	MGO	900	0.9	25	0.8	2.74	1.66	0.29	3.00	22.78	8.03
NG	NG	-	1	-	-	-	-	4.69	2.50	15.40	7.19
NG	LNG	200	0.93	25	0.8	0.61	0.37	4.69	2.50	20.07	8.36
Bio	BTL	1000	0.6	25	0.8	3.05	1.84	1.76	2.00	0.00	9.98
NG	GTL	600	0.7	25	0.8	1.83	1.11	0.59	2.50	22.00	7.09
Coal	CTL	1000	0.6	25	0.8	3.05	1.84	0.59	1.00	41.17	7.14
Bio	H_2	800	0.6	25	0.6	3.25	1.47	6.16	2.00	0.00	14.21
NG	H_2	300	0.8	25	0.6	1.22	0.55	6.16	2.50	19.25	11.05
Coal	H_2	700	0.65	25	0.6	2.84	1.29	6.16	1.00	38.00	11.83
Oil	H_2	400	0.75	25	0.6	1.62	0.74	6.16	3.00	27.33	12.52
Solar	H_2	2000	1	25	0.25	19.49	3.69	6.16	0.00	0.00	29.34
Bio-CCS	H_2	1000	0.55	25	0.6	4.06	1.84	6.66[g]	2.00	-52.36	20.02[e]
NG-CCS	H_2	500	0.75	25	0.6	2.03	0.92	6.16	2.50	2.05	12.52[e]
Coal-CCS	H_2	900	0.6	25	0.6	3.66	1.66	6.16	1.00	4.12	13.29[e]
Oil-CCS	H_2	600	0.7	25	0.6	2.44	1.11	6.16	3.00	2.93	14.10[e]
infra[f]	MGO	100	1	50	0.7						
infra	CTL_ GTL	200	1	50	0.7						
infra	BTL	600	1	50	0.7						
infra[f]	LNG	1600	1	50	0.7						
infra	H_2	2100	1	50	0.7						

[a] The primary energy cost does neither include the scarcity rent or carbon taxes. The primary energy cost increases over time due to limited supply and high demand.

[b] The CO_2-emission factor is: coal 24.7, oil 20.5, natural gas 15.4 and biomass 32 kgC/GJ. An additional emission factor for the methane slip from LNG used in marine engines is included in some cases calculated as a CO_2 equivalent (1% methane slip =1.17 kgC/GJ, 2% methane slip=2.34 kgC/GJ,3% methane slip =3.51 kgC/GJ).

[c] The total fuel cost has been calculated from primary energy/conversion efficiency + annual investment costs + O&M cost + distribution cost + CO_2 storage cost.

[d] The annual investment cost of energy conversion plants, A, is calculated as

$$A = \frac{(1+r)^5 I}{10\alpha C_f}\left(1-\frac{(1-1/T)^{10}}{(1+r)^{10}}\right)$$

where I is the investment cost, r is the discount rate (0.05/yr), T is the life time and C_f is the capacity factor. The constant α= 31Ms/yr is included to account for the conversion into GJ (remember 10 years per time step). The factor $(1+r)^5$ reflects that the investment is made between two time steps.

[e] An CO_2 storage cost: bio-ccs 3.82, NG-ccs 0.68, coal-ccs 1.37 and oil-ccs 0.98 \$/GJ$_{\text{fuel}}$ has been added. The total cost for CO_2 storage is 10\$/tCO_2 from fossil fuels and 20\$/tCO_2 from biomass. It is assumed that 90% of the carbon can be captured.

[f] Investments cost for infrastructure is assumed to be 10 Euro per tonne HFO and between 1500-1600USD/kW for LNG based on estimates of cost for bunker vessels and terminals, se the North European LNG Infrastructure Project *(Danish Maritime Authority, 2012)* for more information.

[g] Longer transportation distances for biomass to BioEnergy CCS plant add \$0.5/GJ to the distribution cost, since larger plants are desirable in order to capture economies of scale.

Appendix D. Sensitivity analysis

In order to test the robustness of the results a large number of the parameters have been varied. See Table D.1 for a description of the varied parameters shown in Figures 2 and 3.

Table D.1 Parameter values for sensitivity analysis. All other parameters are identical as in our base case assuming that CCS will be large-scale available.

Sensitivity test	**Description**
300 ppm	A global stabilisation of the atmospheric CO_2 concentrations at 300 ppm instead of 400ppm
500 ppm	A global stabilisation of the atmospheric CO_2 concentrations at 500 ppm instead of 400ppm.
Doubled bio resources	In the base run we assume 200 EJ/year. In this run we double the bioenergy supply potential.
Doubled NG resource	In the base run we assumed 10 000 EJ. In this run we doubled the amount of natural gas.
Doubled oil resource	In the base run we assumed 12 000 EJ. In this run we doubled the amount of oil.
Halved NG resource	In the base run we assumed 10 000 EJ. In this run we halved the amount of natural gas.
Halved oil resource	In the base run we assumed 12 000 EJ. In this run we halved the amount of oil.

Higher demand	In this run the energy demand grow with 1.2 % faster than the GDP growth instead of 0.8 % faster as in base case.
Lower BTL-infra cost	Here the infrastructure cost for BTL is 200 USD/GJ (the same as for GTL/CTL) instead of 600 USD/GJ as in the base analysis.
Lower demand	Here the growth in energy demand for shipping is equal to the GDP growth.
Lower LNG-infra cost	Here the infrastructure cost for LNG is 1200 USD/GJ instead of 1600 USD/GJ.
Lower discount rate	Here we assume a discount rate of 3 % instead of 5 %.
No CCS & 4% CH_4 slip	We simply assume that CCS never will be large-scale available and that the average methane slip from marine engines are 4%
No CH_4 slip	In the base run the methane slip from the combustion of LNG in ships is 3 %. In this run we assume that there is no slip.
No LCLET	We hereassume that there will not be any large-scale available low cost, low-emitting technology for electricity generation.
No LCLET, no CCS	Here we assume that neither CCS nor LCLET will be large-scale available.
No LCLET, no CCS, no H_2 in shipping	Here we assume that neither CCS nor LCLET will be large-scale available at the same time as hydrogen will not make it as a fuel for marine engines.