HYDROGEN ON BOARD SHIP: A FIRST ANALYSIS OF KEY PARAMETERS AND IMPLICATIONS

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ABSTRACT

Shipping Green House Gas (GHG) emissions could increase significantly in the future, and hydrogen fuel for ships could theoretically lower the operational carbon dioxide emissions of a ship to zero. In addition the hydrogen and fuel cell combination could have a higher efficiency compared to the current marine diesel engines. This paper examines the implications of using hydrogen as a fuel for ships. Two hydrogen storage methods, 350 bar compressed hydrogen gas tanks and cryogenic liquid hydrogen tanks, are evaluated in terms of cargo, volume and mass impact in comparison with a conventional HFO tank and a LNG tank. Moreover, the potential loss of cargo capacity for each of them are estimated in relation with the desired range and power. A Panamax container ship was used as a reference ship, in order to visually examine the impact of different fuel storage choices on cargo. A further method has been applied to estimate the relative loss of cargo capacity. It was found that Hydrogen storage systems have a high volume requirement which has implications for both stability and available deadweight. Liquid hydrogen has a lower impact on cargo capacity mainly due to its higher volumetric density than the compressed hydrogen tank. Such conclusions, however, are the result of this early work on the study of hydrogen fuelling as so many of other more detailed issues have yet to be addressed.

Keywords: Hydrogen, storage, container, cargo capacity

1. INTRODUCTION

The contribution of shipping's Green House Gas (GHG) emissions as a proportion of the world's total emissions could increase significantly according to Smith et al. [2014]. New ships are currently regulated by the Energy Efficiency Design Index (EEDI) and the European Commission in the European Union has regulation to monitor emissions from ships calling at EU ports from January 2018 [IMO 2012] [European Commission 2013]. Energy efficiency technologies and the introduction of alternative fuels can be very important to mitigate such emissions. Alternative fuels could be an option for a significant reduction in shipping emissions in the long term. The most attractive alternative fuels for shipping are: LNG, biofuels, methanol and hydrogen.

The most attractive uses of hydrogen within the context of a de-carbonization of the energy system are: a vector for storing renewable energy, for domestic heating, and as fuel for the transport sector. The drive behind the investigation of hydrogen fuel for ships is that it could theoretically lower the operational carbon dioxide emissions of the shipping fleet. Hydrogen and fuel cell combination could have a higher efficiency compared to current marine diesel engines [Ludvigsen and Ovrum 2012].

There are different perspectives from which hydrogen as a fuel for shipping can be studied. A wide scope could incorporate the entire shipping system and capture the interactions of hydrogen power ships with the rest of the system. Another possibility is to study the supply of hydrogen at refuelling port terminals and the infrastructure required. It depends how the regulation is applied, this paper examines the implications of using hydrogen on-board ships.

Assessing the use of hydrogen on board ships requires the study of the design and engineering of a hydrogen fuelled ship and the associated main propulsion system, and all implications associated with each of the technological components, the effect on the volume and weight of the ship due to the hydrogen storage system, capital and operational technology costs. Regardless of the specific hydrogen storage system chosen, special safety considerations have to be taken into account when hydrogen is stored on board ships, just as for any other fuel with low flammability limits. For example, new requirements would be needed for ventilation, alarm systems, and fire protection, as well as the introduction of other measures to limit the likelihood and consequences of hydrogen leakage [Ludvigsen and Ovrum 2012]. This paper represents the early work on a study of hydrogen fuelled ships that does not address some of these details.

Although there has been much work on the use of hydrogen in automotive applications, the literature for the use of hydrogen on-board ships is lacking and the implications that such storage systems would have on cargo carrying capacity is poorly understood. Moreover there are few studies that have compared different hydrogen storage systems, quantifying and visualising their possible impact, and comparing with conventional heavy fuel oil (HFO) tank or other alternative fuel storage systems, such LNG tanks. The purpose of this paper is to analyse the impacts of hydrogen storage systems on board ships in terms of quantifying and visualising their impacts on a specific ship and in terms of loss of cargo capacity that a ship might have due to the extra volume required in relation with other factors, such as range and power. This paper focuses on the comparison of four types of fuel storage systems: baseline HFO tank, LNG tank, 350 bar compressed hydrogen gas tanks, and a cryogenic liquid hydrogen tank.

2. THE HYDROGEN FUELLING OPTIONS

2.1 PROPULSION ENERGY SYSTEM CHARACTERISTICS

Fully evaluating the complete engineering impact of changing from HFO to an alternative fuel will require a consideration of the complete power and propulsion energy system; how energy is brought on board; how it is stored and transferred; converted to useful work; and how waste energy is recovered or leaves the ship. The initial studies described in this paper have focussed on the storage, and conversion to useful work, but in this section we will outline some wider considerations for future investigations into hydrogen fuelling of ships.

Energy Storage and Transfer: This study compares three possible fuels; conventional Heavy Fuel Oil (HFO), Liquefied Natural Gas (LNG) and Hydrogen. Hydrogen can be stored either as liquid (at cryogenic temperatures); as high pressure gas; or chemically bonded to various metals as hydrides. The hydrogen storage options are discussed in more detail in the next section, but there are some general considerations regardless of the choice. HFO can be pumped on board with simple single-walled piping and pumps, stored in unusually shaped tanks making use of void spaces, and is stable over a wide range of temperatures. The gas and liquid alternatives considered in this study will require higher quality piping, almost certainly double-walled as is currently the case with LNG fuelling. It is likely that fuel systems would be located in dedicated spaces and piping would pass through dedicated ducts. This would add to the volume required by the alternative fuel, and may present an arrangement challenge to reconcile a desire to reduce the piping lengths and maintain minimum distances are to be maintained between piping and connectors and manned spaces or sources of ignition. Additional support systems to maintain low temperatures or heat hydrides to release the hydrogen would also be required.

The high pressures or low temperatures required lead to prismatic tanks (typically cylinders) being used, which do not make such efficient use of internal space, and this is the focus of this paper. As with the piping, the use of gas fuel introduces additional safety considerations. LNG fuel tanks must be located in dedicated spaces a minimum distance from the side and bottom of the ship, with monitoring and ventilation systems in all spaces with gas piping. LNG and liquid hydrogen may have similar safety issues; leaks will expose structure to cryogenic temperatures and the phase change to gas will produce a large increase in volume. An overview of hydrogen safety (mainly from a land-based perspective) is provided by Barilo [2014].

Conversion to Useful Work: The main engine choices for a hydrogen fuelled ship are; fuel cells, reciprocating internal combustion engines and gas turbines. Fuel cells use hydrogen directly in electrochemical reactions, so would seem to be an ideal prime mover for hydrogen fuelling. A competed review on marine use of fuel cells can be found in McConnell (2010) and Han et al (2012).

LNG has been adopted as a fuel for diesel-engined ships operating in coastal water as it offers greatly reduced SOx and particulate emissions, whilst also having reduced CO2 emissions and potentially lower cost. Compressed natural gas (CNG) has a long history of application in internal combustion engines in small service vehicles such as forklifts and is also widely used as an automotive fuel in some nations. Hydrogen fuelling of ICE engines will introduce new issues such as NOx production but it may be attractive as it will capitalise on an existing engineering knowledge base, production infrastructure and ship design style.

Hydrogen has been of interest as an aerospace fuel for many years and the Pratt & Whitney model 304, a liquid hydrogen-fuelled gas turbine, featuring a sophisticated pre-heater/vaporiser for the fuel, was successfully ground tested in 1957 [Miller]. More recently, work has examined using hydrogen as a component in gas fuel mixtures for land-based power [Andersson et al, 2013]. For this initial study, however, the hydrogen engine choice was limited to fuel cells. Table 1 summarises the fuel and main engine combinations considered in this study, including the assumed efficiency of the main engine and the specific fuel consumption.

Table 1 Main engine characteristics

ID ME	MAIN ENGINE	EFFICIENCY (%)	FUEL TYPE	SFC
I	FC system + elec. motor	52.25	Hydrogen	57
2	4 stroke spark ignition	47	LNG	153
3	2 stroke diesel	52	HFO	171

Waste Energy Recovery: Cargo ships powered by diesel engines currently make use of the waste heat produced by these machines in a variety of ways. Cooling water may be used for distilling fresh water or providing domestic heating and heat from exhaust gases may be recovered to generate hot water and steam for domestic and cargo heating or electricity generation by turbines. All these contribute to the overall efficiency of the complete power and propulsion energy system, and may be affected by a change to alternative prime movers (such as fuel cells), or additional after-treatment for NOx that may be required in some hydrogen fuelled diesel options. In most cargo vessels, however, the energy recovered may will be much smaller than that used in propulsion, so for this initial study these holistic aspects were not addressed.

2.2 HYDROGEN FUEL STORAGE OPTIONS

Due to the low volumetric density of hydrogen it is of great importance to have storage systems that are able to reduce the volume requirement of hydrogen. The volumetric density can be increased by; extracting energy from the gas by cooling it below its critical point (i.e. below a temperature of 33K, at a pressure of 1.296 MPa); using energy to compress the gas; or by the chemical or physical interaction with other substances. Figure 1 shows the volumetric and gravimetric energy density of some of the main hydrogen storage options. There are at least three types of hydrogen storage system, including: high-pressure gas cylinders; liquid hydrogen storage; and metal hydrides. Gas storage cylinders are estimated to be around 4-7 times the volume of HFO tanks for the same energy content [Taljegard et al 2014, DNV GL. 2014, Vogler 2010] while liquid hydrogen stored in cryogenic storage has also been considered as it offers higher energy densities [Veldhuis 2007, Han et al 2012, and DNV GL. 2014]. The main concerns are the low temperatures, the large energy losses in compression or liquefaction, and the space required for very well insulated fuel tanks [DNV GL. 2014]. Moreover, liquid storage requires a refrigeration unit for keeping a cryogenic state, which adds extra cost and complexity [Han et al 2012]. Metal hydrides are in operational service in submarines, although this has a very low gravimetric density which may limit its application on board ships [Han et al 2012, Sattler 2000].

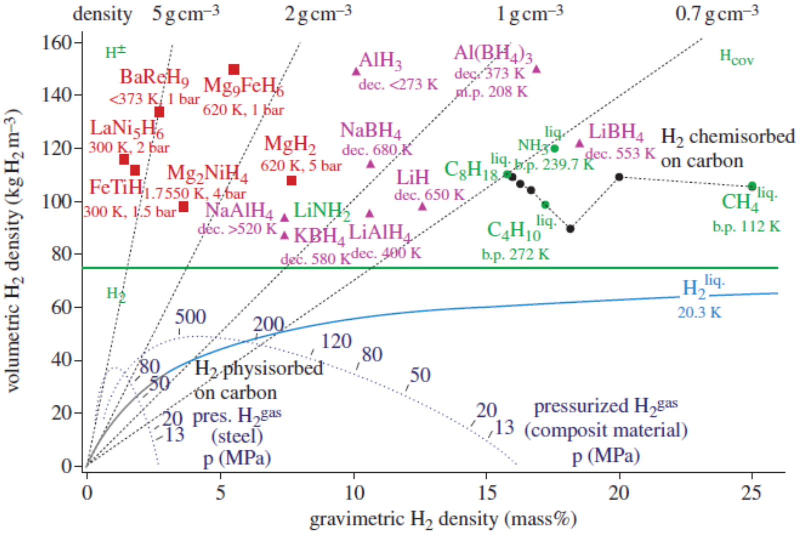

Figure 1 Volumetric and gravimetric hydrogen density of pressurized gas storage for steel and a hypothetical composite material, liquid hydrogen, and some selected hydrides. Source: Zuttel (2010).

A high-pressure gas cylinder based hydrogen storage system is used on board small inland passenger ships such as the *FCS Alsterwasser* and the *Hydrogenesis*. Tanks are usually made of aluminium alloys and austenitic steel since they are resistant to hydrogen interaction at the material surface but tend to be heavy [Klell 2010]. More advanced tanks are built from composite materials which can withstand higher pressures with similar volume but lighter construction.

Typical pressures for compressed hydrogen are 350 bar and 700 bar which give a density of 23.3 kg/m^3 and 39.3 kg/m^3 respectively. The greater the pressure, the more energy is required for compression, and a wider consideration of the viability of hydrogen fuelling should incorporate this aspect. However, this initial study will not consider this energetic cost. 350 bar storage systems are the most common option; they are typically packages of long, small diameter tanks, frequently in modules compatible with ISO container dimensions designed for road transport [FIBA Canning, 2008]. For the case of 700 bar or above the tanks tend to be smaller in volume in order to withstand the higher pressures. This means that a large amount of these tanks need to be used on board in order to cover the ship's fuel demand. Issues such as the cost of high pressure tanks are being improved over time due to interest from the automotive industry and future tanks may generally be of higher pressure [Hua et al, 2010], but this work will start with the conservative 350 bar tanks. The gravimetric energy density (i.e. the amount of energy in the fuel by mass of the storage system) fluctuates between 3.5% and 5.5% depending on the tank's pressure, construction and material used [Klell 2010]. In this work the gravimetric energy density is assumed to be 5% of the Lower Heating Value (LHV).

Liquid hydrogen storage systems can reach a volumetric density of about 75 kg/m^3 – approximately double that of high-pressure gas cylinders – and gravimetric density (kg H2/kg tank) of about 10%. In this work the volumetric density for liquid hydrogen is assumed to be 53 kg/m^3 which is the density used in some of the liquid hydrogen fuelled cars [Enke et al. 2007; Klell 2010]. Liquid hydrogen can be stored in cryogenic tanks at -253˚C, ambient pressure and in open systems. Rohde & Nikolajsen [2013] created a concept for a zero-emission ferry powered by liquid hydrogen. The hydrogen was stored in IMO type C tanks on deck capable of holding 140 m^3. The work in this paper will use also IMO type C tanks for liquid hydrogen.

Metal hydrides could be used to store hydrogen on board ships. They have been successfully used in the Type 212 submarines of the German Navy. Although they have a high volumetric density (150 kg/m^3 in Mg_2FeH_6 and $Al(BH_4)_3$ technologies), the metallic hydride systems working at ambient temperature and atmospheric pressure have a volumetric density of about 50 kg/m^3, and a low gravimetric hydrogen density limited to less than 2% of the total mass [Zuttel (2010).]. These solid-state storage systems also have additional requirements for heating systems to extract the hydrogen, and may not be compatible with fast-filling techniques. These aspects are beyond the scope of this paper, however. While this kind of hydrogen storage system is promising for specific applications in the future, it is insufficiently developed and so is not considered in this work. Table 2 summarises the storage options investigated for the gas fuelled options.

Table 2 Storage systems characteristics

ID FT	FUEL TYPE	FUEL STORAGE SYSTEM	VOLUMETRIC DENSITY (KG/M^3)
I	Hydrogen	350 bar tank	23[1]
2	Hydrogen	Liquid	53[2]
3	LNG	Tank	470

3. CARGO, VOLUME AND MASS IMPACT ON A PANAMAX CONTAINER SHIP

A Panamax container ship with a deadweight of 35032 tonnes (4584 containers) was used as a reference ship. In order to quickly and visually examine the impact of different fuel storage choices on cargo. Ship models were developed in Paramarine, a ship design and analysis toolset licensed by Qinetiq [QinetiQ GRC, 2015]. This allowed the majority of the design process and performance evaluation to be carried out using a ship design model previously developed at UCL for the Low Carbon Shipping Project [Calleya, J. et al., 2015]. This model allows the configurational and architectural aspects of the impact of new technologies to be evaluated, through the interactive 3D model of the vessel in Paramarine. These models are integrated with numerical architectural analyses such as resistance and powering, and stability. In the Low Carbon Shipping project the high-definition models of point ship designs were used to generate data for more flexible surrogate models, which reflect the impact of new low carbon technologies on typical ship designs over a wider range of deadweights.

The objective of this initial ship impact study was to assess the consequences of hydrogen fuelling on a typical current-day container vessel with a typical operating profile (incorporating the more flexible steaming practiced introduced after the 2008 financial crisis). The operating profile shown in Figure 2 is similar to that given for a container ship from a paper by Maersk [Cerup-Simonsen et al., 2009].

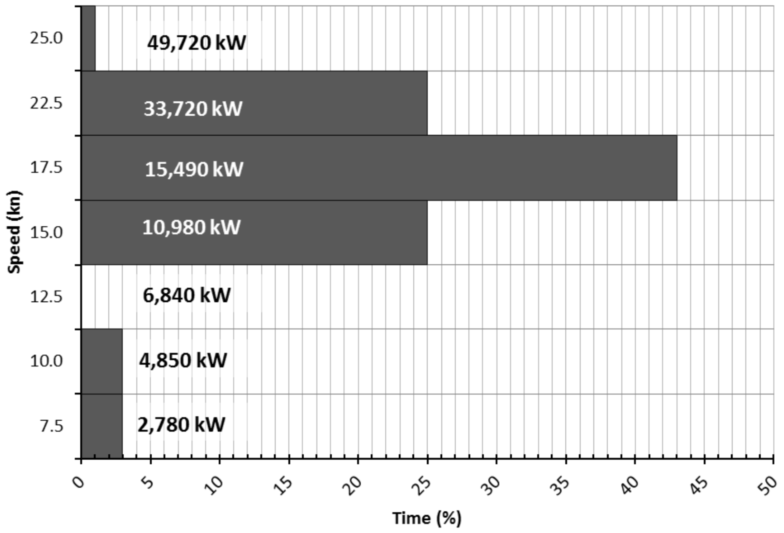

Figure 2 Operational profile for the container ship studied. The power required per speed is shown inside the bars.

Although a complete examination of the various practical aspects of hydrogen fuelling alluded to in Section 2 was not carried out in this initial study, some safety considerations were incorporated. It was decided that the hydrogen storage would be in the form of non-integral prismatic tanks, located in spaces displacing the lower cargo holds, immediately forward of the main machinery room. This arrangement reduces the length of the gas piping from the fuel tanks to the main engines, allows for side and bottom protection of the fuel tanks and keeps

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[1] Assuming a temperature of 25˚C.

[2] Assuming a temperature of -242°C and a pressure of 10 bar.

the heavy tanks low in the ship, so avoiding a significant increase in the height of the vertical centre of gravity (VCG) of the unladen vessel. The example vessel, using 350 bar hydrogen tanks, is shown in Figure 3.

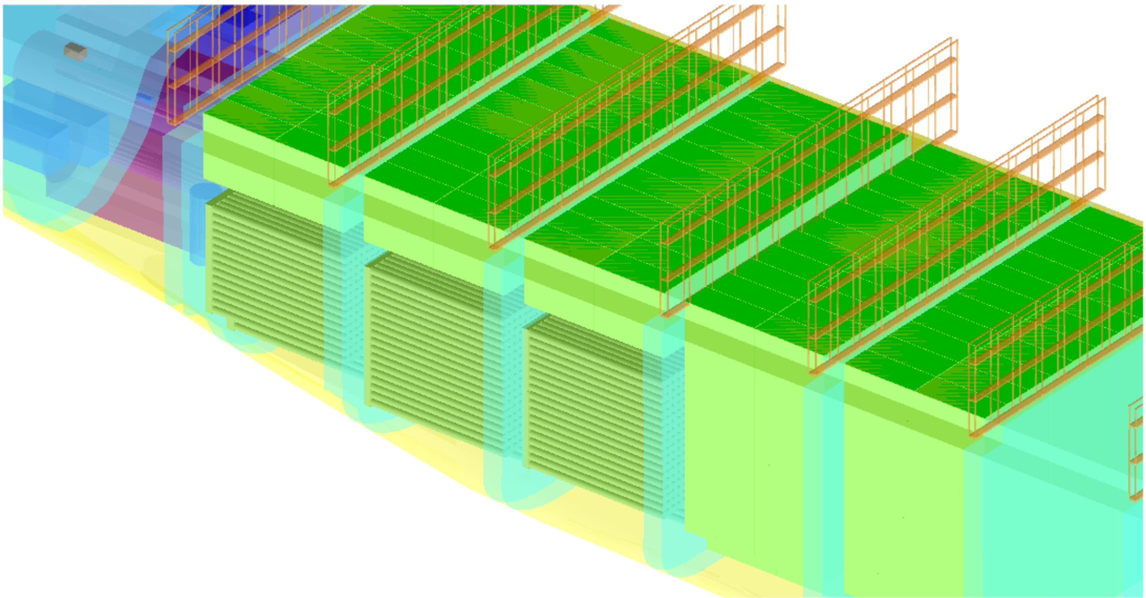

Figure 3 Compressed Hydrogen Tanks.

Although it was desired to reduce the impact on design and operation of the vessel to a minimum, providing sufficient compressed hydrogen for the very long range of large container ships would consume an excessively large amount of cargo space. A crucial design assumption was that ship operation in a notional hydrogen-fuelled future would feature more frequent refuelling, so reducing the required energy storage. The assumed endurance was 5.1 days assuming the operating profile shown in Figure 2. This reduced range was used for all variants. A comparison was made between the ship impact due to hydrogen storage and the storage of HFO and LNG. This comparison is shown in Table 3.

Table 3 Cargo volume and mass impacts

FUEL	**HEAVY FUEL OIL**	**LIQUID NATURAL GAS**	**COMPRESSED HYDROGEN (350 BAR)**	**LIQUID HYDROGEN**
DENSITY (KG/M3)	1010	470.0	23.3	53
DAILY FUEL USE (M3)	82.9	203.1	1185.5	521.8
RANGE (DAYS)	5.1	5.1	5.1	5.1
MASS OF FUEL FOR VOYAGE (TE)	421.1	485.08	140.35	140.35
VOLUME OF TANKS WITH FUEL	416.9	1195	12142	3120
MASS OF TANKS	0	450	8584	972
CONTAINERS DISPLACED	0	96	372	180
CONTAINERS (M3)	0	3701	14340	6939
CONTAINERS (TE)	0	1258	4878	3123

Figure 4 compares the aft cargo holds, where cargo was displaced to make way for fuel storage. The compressed gas tanks shown in Figure 4 are contained within modules the width and length of a FEU container, with half the height. 335 modules of 8 cylindrical tanks were used for the storage of compressed Hydrogen. It is not envisioned that the fuel tanks would be inside cargo holds, but the common module size may simplify installation and removal for maintenance. Wärtsilä “LNGPac” tanks, which are IMO type C tanks [Karlsson, S. and Sonzio, L., 2010] were used for the storage of the liquid fuels; LNG and LH_2. Although alternative tank configurations have been proposed [Sea NG, 2012], [Ramoo et al, 2011] these were not considered in this initial study. The difference between the liquefied gas tanks (consisting of 5 Wärtsilä “LNGPac” tanks) and the much larger compressed gas tanks are shown in Figure 4 for the same endurance of 5.1 days.

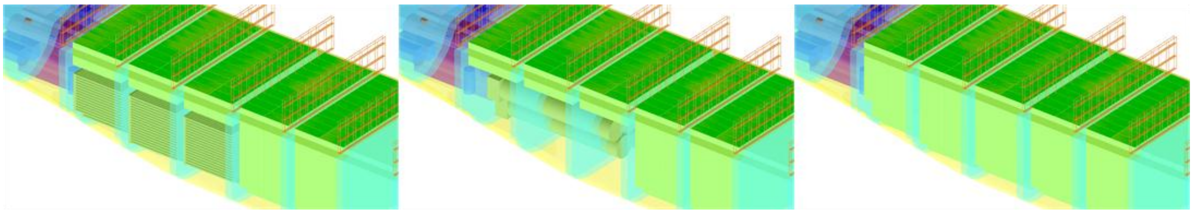

Figure 4 Comparison of Compressed Hydrogen Tanks, Liquefied Gas Tanks and the Displaced Cargo

Although the tank modules are compatible with ISO container dimensions, the considerations on tank installation noted in Section 2 require additional volume so increasing the impact on cargo. A further consideration is that the tanks are heavier than the containers they displace. This has implications for both stability and available deadweight. However, there is a significant degree of variation in the mass of containers, with the operational maximum capacity of a container ship being dependent on the number, mass and location of containers, rather than, simply, the volume. This initial design study has assumed that the container ship will reach a stability limit (VCG location) before a volume limit (number of container slots), and so locating the heavy tanks low down is desirable.

4. AN ANALYSIS OF THE LOSS OF CARGO CAPACITY

4.1 THE METHOD

In this section a more generic method to estimate the loss of cargo capacity due to the lower volumetric density of a different fuel storage system is provided. This method is based on [Raucci 2015]. The loss of cargo capacity (dwt_loss) is a parameter to estimate the effect of the fuel storage system on loss of cargo carrying capacity. The alternative fuel storage systems analysed in this study have a lower energy density than the conventional HFO tank, so in theory they require more space. This method only takes into account the extra space that might be required in comparison with a reference HFO tank on board a general container ship, and it analyses the theoretical loss of cargo capacity considering changes in range and power from the reference ship. This method is used to generalise the impact of using hydrogen on board on an entire fleet ship category, and so it estimates the parameter “dwt_loss” as being representative of the loss of cargo capacity for a specific ship category. The key assumptions are that the specific design and configuration of the fuel storage system don’t have any effects on the cargo capacity, and that the voyage conditions and operational profile during a full tank voyage are the same for the alternative fuel powered ship and the reference ship with HFO tank.

In order to evaluate the dwt loss, first the volume occupied by the alternative fuel storage systems is calculated, second the volume occupied by a baseline HFO storage tank is calculated as reference of comparison against which the extra volume is estimated. The extra volume required is then converted into tons of cargo per kWh, using a ship density ∂ in tons/m3, and dividing all for the energy stored on board in kWh (E_{st}). Equation [1] shows the formula used.

$$dwt\ loss = \frac{(V_f - V_{ref}) * \partial}{E_{st}} \qquad [1]$$

The parameter ship density ∂ is intended to represent the tons of cargo capacity per each m^3 on board ship, and it can vary by ship type. The ship density for container is assumed to be equal to a constant 0.34 tons/ m^3 considering 13 tonnes*TEU of mass, as this is the average container mass used in the container ship design in Sextion s.

The volume occupied by a fuel storage system can be expressed as a function of the amount of fuel required on board S_f and the volumetric density of the fuel storage system γ_f

There are a number of assumptions on the amount of fuel that would be stored on board, however it is possible to express S_f as in equation [2]:

$$S_f = E^{out} * sfc_{fmm} \qquad [2]$$

Where sfc_{fmm} is the specific fuel consumption which incorporates both the efficiency of the engine and the energy content of the fuel, and E^{out} is the energy produced on board.

It is possible to rewrite equation [1] as:

$$dwt\ loss = \left[\frac{E_f^{out} * sfc_{fmm} * \partial}{\gamma_f} - \frac{E_{ref}^{out} * sfc_{ref} * \partial}{\gamma_{ref}}\right] * \frac{\rho_{fmm}}{E_f^{out}} \qquad [3]$$

The energy produced on board can be estimated with the formula [4], taking in account the time T in % of range (R) in which the ship sails in each mode *i*, and the engine load L in % of the power P in which the engine is working in each mode *i*. This can be substitute in formula [3] and obtain formula [5].

$$E^{out} = \sum_{i=}^{n} (R * T_i * P * L_i) \qquad [4]$$

$$dwt\ loss = \left[\frac{\partial}{\beta_f * \gamma_f} - \frac{R_{ref} * P_{ref} * sfc_{ref} * \partial * \rho_{mm}}{R_f * P_f * \gamma_{ref}}\right] \qquad [5]$$

Using factors f_1, f_2 and f_3 as defined below it is possible to obtain the final formula [6].

$$dwt\ loss = \left[\frac{\partial}{\beta_f * \gamma_f} - \frac{sfc_{ref} * \partial * (\rho_{ref} + f_3)}{f_1 * f_2 * \gamma_{ref}}\right] \qquad [6]$$

Where:

β_f is the energy density of the fuel in kWh/kg

γ_f is the volumetric density of the energy storage system express in terms of kg of fuel per m^3 of the system.

sfc_{ref} is specific fuel consumption of the reference ship

ρ_{ref} is the efficiency of the main engine for the reference ship

γ_{ref} is the volumetric density of the reference HFO tank assumed to be 1010 kg/m3

∂ is the ship density parameter

f_1 is the ratio between the range of the alternative fuel powered ship and the range of the reference ship $\frac{R_f}{R_{ref}}$.

f_2 is the ratio between the power installed of the alternative fuel powered ship and the power installed of the reference ship $\frac{P_f}{P_{ref}}$

f_3 is the percentage of improvement of the efficiency from the efficiency of the reference ship.

Key parameters for the evaluation of the loss of cargo capacity are the volumetric density of the fuel storage systems, the efficiency and the new range and power.

4.2 LOSS OF CARGO CAPACITY

In this section results from the method provided above are described. Equation [6] was applied to the three type of fuel storage systems analysed in this study: LNG tank, 350 bar compressed hydrogen gas tanks, and cryogenic liquid hydrogen tank. The reference ship is assumed to have a conventional HFO tank.

Assumptions regarding the energy density, efficiency, and specific fuel consumptions are as described in the previous sections.

The surface plots in Figure 5 show the dwt_loss in ton/Kwh in relation with changes in range and power. On the left, the differences between the dwt_loss of the three type of fuel storage systems are shown. Not surprisingly, the 350 bar compressed hydrogen gas tanks have the highest impact. The upper surface represents how cargo loss changes with range and power for the compressed gas option, in comparison with the reference ship, which is represented by the grey surface. When range and power are assumed to be the same as the reference ship (f_1=1, and f_2=1), then dwt_loss is equal to 0.41 ton/kWh. The surface in the middle represents the dwt_loss of the liquid hydrogen tank option, its value with no changes in range and power is 0.15 ton/kWh. The lowest surface represents the dwt_loss of the LNG tank, which has the lowest impact in comparison with the hydrogen storage systems, at 0.025 ton/kWh.

The right side of the figure shows the differences between the deadweight lost of the liquid hydrogen tank varying with an increasing efficiency of the main engine. If the efficiency increases by 10 or 20 % compared to the reference ship, than it has an impact on the deadweight lost as less energy stored on board would be required. The deadweight lost, therefore, decreases with the increase of the efficiency, although the difference was be minimal.

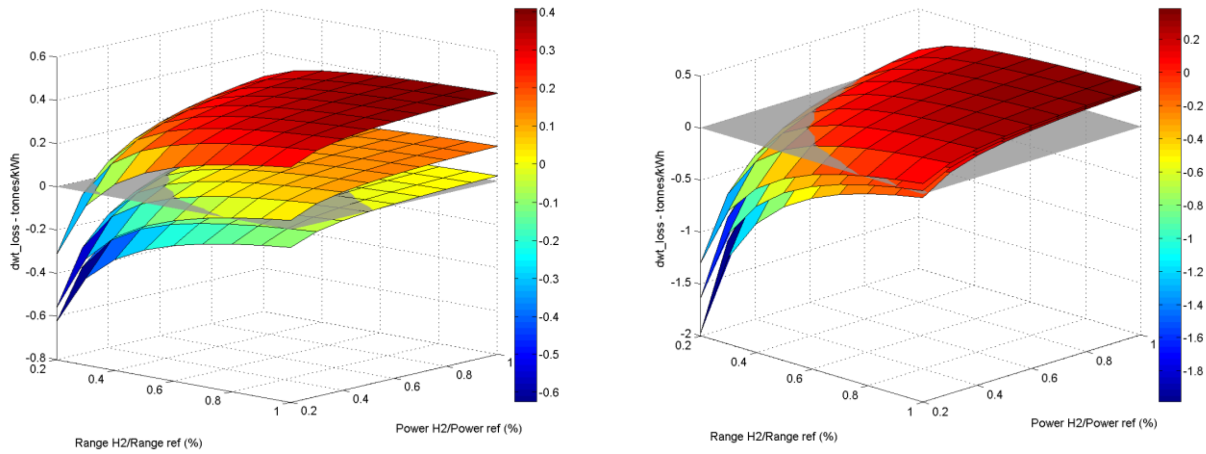

Figure 5 Variation in loss of cargo capacity in ton/Kwh with changes in range and power. On the left, differences between the deadweight lost of the three type of fuel storage systems analysed (350 bar compressed hydrogen gas tanks at the top, liquid hydrogen tank in the middle, LNG tank at the bottom). On the right, the different deadweight lost of the liquid hydrogen tank in relation with an increasing efficiency of the main engine. The grey surface represents the reference ship.

In conclusion, this initial analysis shows that the volumetric density of the fuel storage systems on board drives the potential impact on the cargo carrying capacity of a ship, however a reduction in range and power can minimize this impact, potentially to the point of no impact on the cargo capacity. Liquid hydrogen has a much lower impact on the loss of cargo than compressed hydrogen gas tank, so it might be preferable in maritime applications. Reducing the energy storage required by reducing range and power would reduce the impact of these alternative fuel storage systems on the cargo capacity of the ship.

5. CONCLUSIONS AND FUTURE WORK

In this paper hydrogen fuelling options were discussed in terms of propulsion energy system and hydrogen storage options. Two hydrogen storage systems have been considered: 350 bar compressed hydrogen gas tanks and cryogenic liquid hydrogen tanks, although other different hydrogen storage options exist that could be used in maritime applications.

A conventional Panamax container ship was used as a baseline reference ship, in order to examine the impact of such different fuel storage choices on cargo from a configurational perspective. Compressed gas and cryogenic liquid hydrogen tanks have fixed cylindrical shapes and so can only be accommodated in cuboid volumes, meaning that it is likely that they will have a significant impact on the volume available for cargo as they are competing for the space in the same areas of the vessel. As there is a significant degree of variation in the mass of containers, with the operational maximum capacity of a container ship being dependent on the number, mass and location of containers, rather than, simply, the volume, the exact impact on cargo would depend on a wide range of operational factors in addition to those open to consideration by the designer. The storage of compressed Hydrogen required 335 modules of 8 cylindrical tanks that provided an endurance of 5.1 days using an operating profile that incorporated a flexible steaming practice (with the majority of time spent at 17.5 knots). This is equivalent to a volume 4878 TEU. If liquid hydrogen is stored on board with the same assumptions then the volume occupied would be equivalent to 3123 TEU.

The potential loss of cargo capacity for each of hydrogen storage options were estimated in relation with a possible reduction in range and power in comparison with the reference ship. The method used takes into account only the extra space that it might be required in comparison with a reference HFO tank on board a container ship, and it analyses the theoretical loss of cargo capacity. Liquid hydrogen has a much lower impact on the loss of cargo than compressed hydrogen gas tank, so it might be preferable in maritime applications. The dwt_loss of the compressed and liquid hydrogen storage options with no changes in range and power are respectively 0.41 and 0.15 ton/kWh. The volumetric density of the fuel storage systems drives the potential impact on the cargo carrying capacity of a ship, however a reduction in range and power can potentially minimize or have no impact on the cargo capacity.

As has been noted at several points in this paper, this is an initial study and there are many other aspects of the hydrogen fuelling of ships that remain to be considered. These include the possibility of combustion-based prime movers as an alternative to fuel cells, more detailed considerations of safety aspects, and the interaction of operations and the variability of the cargo that will determine the typical (as opposed to theoretical) reductions in capacity that would be experienced in practice.

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