Mutiny on the High Seas: exploring step-change technological mitigation in the shipping sector

Dr Paul Gilbert[1]*, Dr Alice Bows[2], Dr Conor Walsh[1], Dr Sarah Mander[1] and Michael Traut[1]

[1] Tyndall Centre for Climate Change Research, School of Mechanical, Aerospace and Civil Engineering, University of Manchester, M13 9PL
Email: p.j.gilbert@manchester.ac.uk; sarah.mander@manchester.ac.uk; michael.traut@postgrad.manchester.ac.uk

[2] Sustainable Consumption Institute, School of Mechanical, Aerospace and Civil Engineering, University of Manchester, M13 9PL
Email: alice.bows@manchester.ac.uk; conor.walsh@manchester.ac.uk

* *corresponding author*

Abstract

Due to the complexity of the shipping system, any significant and meaningful decarbonisation pathway is likely to require a range of global/EU policies and local/organisational policies to drive technical, operational and demand measures. However, concerning technical measures, current global policy is weak and existing technology is not being exploited to its full extent, both in terms of fuel efficiency and alternative modes of propulsion. This paper reviews technology measures from both within the shipping sector and elsewhere to scope those that, either on their own or in combination, could provide step-change emission reductions (>10%). These technologies are evaluated with regard to fleet penetration; flexibility and compatibility with other technologies and; level of demonstration to date. Distinctions are made between global, fleet wide technology measures and more specific market/fleet technology measures, highlighting the need for a range of policy channels to incentivise both. Conclusions are drawn with regard to the timeframe, scale and rate that these technologies are needed, to ensure that the sector reduces its absolute CO_2 emissions.

Keywords: climate change; shipping; technology; step-change; decarbonisation; policy

1. Introduction

To avoid experiencing high levels of climate change, as outlined by the Intergovernmental Panel on Climate Change (IPCC 2007), requires atmospheric concentrations of greenhouse gases to stabilise between 400 and 500ppmv. Nations that are signatories to the Copenhagen Accord are committed to this and have pledged to "hold the increase in global temperature below 2 degrees Celsius, and take action to meet this objective consistent with science and on the basis of equity" (UNFCCC 2009). This commitment will require all sectors to decarbonise to a very high degree in the coming decades – and the shipping sector is no exception (Anderson, Gilbert et al. 2012; Gilbert and Bows 2012). However, up until recently, climate change has not been a major environmental concern in the sector; historical efforts aiming to mitigate the impact of shipping on the environment have primarily focused on the control and reduction of local pollutants, namely SO_x and NO_x (MEPC 2008). Coupled with this, shipping's exclusion from national inventories under the Kyoto Protocol, its role in globalisation and the fact that it is the most energy-efficient mode of freight transport has also arguably left its increase in CO_2 emissions unchecked.

As the shipping sector is a complex system, consisting of interdependent and interrelated markets, services and actors, any significant decarbonisation pathway to tackle the sector as a whole is likely to require a combination of high level global measures coupled with sub-global, local, and organisational policies (Gilbert and Bows 2012). Such policy leverage could seek to implement technological, operational and behavioural measures and, at a wider systems level, there could be demand reductions for shipping services. To start addressing technological mitigation, the MARPOL ANNEX VI was revised to include the Energy Efficiency Design Index (EEDI), which when entering into force in January 2013 will set minimum energy efficiency for new builds (Lloyd's Register 2011). In addition, the Ship Energy Efficiency Management Plan (SEEMP) was also adopted to improve the efficiency of ship operations of all vessels. Lloyds Register in conjunction with DNV have produced a report assessing the impact of the EEDI and SEEMP on CO_2 emission reductions (Lloyds Register and DNV 2011). It demonstrates that the introduction of the EEDI and the SEEMP (under the averaged A1B-4 and B-2) could result in emission levels in 2050 being 1,602 Mt compared to business as usual 2050 emissions levels of 2,615 Mt. This assumes a substantial uptake of technological and operational measures. However, as there is currently no global agreement to control shipping emissions across the sector and with shipping increasing at a rate of 4.1% per annum (in tonne-miles) (IMO 2009), this is still a 84% increase from emissions levels in 2010 (870 Mt). Therefore urgent action is required in the short-term to ensure significant, meaningful policy is implemented to control absolute emissions across the sector as a whole in line with avoiding the 2°C temperature threshold.

Given the urgency and the scale of reductions required, it is desirable to focus on measures that will provide a radical step change in emissions reduction. Whilst recognising the importance of treating shipping as a system, and as such addressing technical, operational and demand side measures in unison, the purpose of this paper is to focus in on the potential technologies that could offer a step change in levels of mitigation, particularly if coupled within a supportive operational framework (Smith 2012). As such the paper declares mutiny on orthodox and incremental technology-led approaches for reducing the emissions from ships, arguing they risk relative stagnation and unintended technological lock-ins (Broderick. J., Anderson et al. 2011). With no global agreement to cap shipping emissions, analysing the potential for a step-change in technologies may catalyse opportunities for the sector to demonstrate a lead in early and meaningful reductions in emissions.

The broad aim of this paper is to critically review radical step-change technologies that could contribute towards complete decarbonisation of the sector over the coming decades, and to identify opportunities and barriers for progressing such change. However, to narrow down the scope of study, the paper concentrates on fuel substitution as a step-change opportunity, with a timely focus on a switch to liquefied natural gas (LNG). The paper examines the benefits and implications of pursuing a switch to LNG by exploring:

- The role of LNG in step-change decarbonisation
- Co-benefits and trade-offs with local pollutant control
- LNG longevity and technology lock-in
- Beyond LNG – ensuring further decarbonisation of the sector

2. The role of LNG in step-change decarbonisation

Technology measures that are considered radical and provide a step-change to emissions reductions are defined here as those as providing a reported CO_2 saving (or fuel efficiency) of > 10%. Figure 1, which is by no means to scale in terms of reduction size or rate, is a schematic to illustrate the process by which technology could provide absolute CO_2 reductions in the shipping sector, and in particular the role of LNG. The categories progress from the vessel-specific to being applicable to the global fleet.

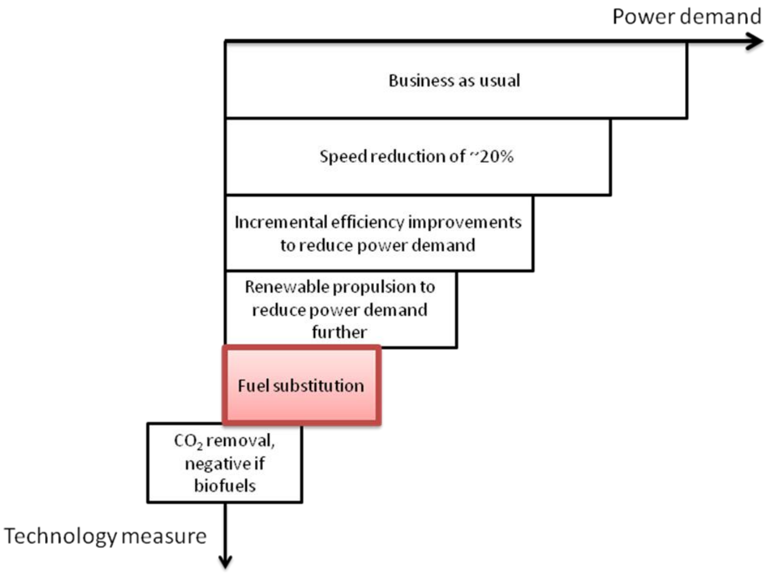

Figure 1: Categories for technology measures and associated reduction to power demand

If the sector is to move towards LNG it mainly involves a switch from heavy fuel oil and subsequent modification of the main diesel engine (if retrofitted) to run dual-fuel or solely LNG, or to use gas turbines. There is considerable experience of using 'boil off' gas on LNG carriers; nonetheless, LNG has the potential to be used on all vessel types. The reported CO_2 savings range between 15-25% (AEA Technology 2007; Fathom 2011; OCIMF 2011; SNAME 2011); the lower estimate attempts to account for the fugitive release of methane. In terms of a move towards LNG within the sector, the following summarises the situation well. *"The world's marine fleet of some 90,000 vessels burned 370 million tonnes of diesel last year (2010), roughly double the amount of energy traded as LNG. Thus, prospects for marine fleets fuelled by LNG have major implications for world LNG demand. During a recent Zeus seminar, a panel of specialists from DNV, Wärtsilä, and GE described how fuel savings coupled [with] clean emissions are driving demand for LNG fuel. DNV for one predicts LNG will be the fuel of choice eventually. DNV's CEO Henrik Madsen predicts the majority of owners will order ships that can operate on LNG by 2020"* (Zeus Intelligence Services and 2011).

3. Co-benefits and trade-offs with local pollutant control

Natural gas is currently being declared by some, as a low carbon alternative to coal in the UK for energy generation (Harvey 2012)and imports of LNG are increasing accordingly (Mander, Walsh et al. 2012). However, within the shipping sector, a potential switch to LNG powered ships is not being driven by climate change (Djønne 2011) – this is arguably more of a potentially convenient afterthought. The main driver is legislation to control the release of local pollutants – in particular SO_x. From 2015 onwards, the limit for fuel sulphur in Emission Control Areas will be 1,000 ppm and at a global level, the limit for fuel sulphur is 35,000 ppm in 2012, reducing to 5,000 ppm in 2020. The other options to meet this legislation are exhaust gas scrubbers and low-sulphur distillates and there is debate as to which is the most preferred option. While it would appear to be a convenient co-benefit that the Emission Control Areas may drive a move away from heavy fuel oil, which has a particularly high CO_2 emission factor, the fact that it is not directly in response to a climate-focused policy could be problematic both currently and in the longer-term. Firstly, there is an absence of incentives to alter current technology in response to such a measure, given those who operate the ships and pay for the fuel are not necessarily the same people who own the ships and fund technology developments. As a result, in the near term, operational measures to simply avoid using HFO in certain areas may be employed in preference to any widespread fuel switch. Secondly, only a full life-cycle analysis of the potential carbon savings of different fuels, taking into account the production of new facilities for the supply of the newer fuels, and any additional energy required to refine the fuel, will give a true picture of any carbon savings. Furthermore, the emissions associated with refining and even transportation will alter depending on how far in the future the assessment is considering. So, whilst existing legislation aimed at improving the environmental impact of shipping may appear to bring some benefits in terms of reducing greenhouse gas emissions, the absence of strong drivers aimed primarily at reducing CO_2 will more likely than not result in only incremental improvements, or in some instances deteriorations, in carbon intensity, when a radical shift is what is required to remain commensurate with the 2°C target (Anderson, Gilbert et al. 2012).

4. LNG longevity and technology lock-in

Looking ahead, the anticipated sectoral shift towards LNG to satisfy MARPOL Annex VI raises concerns from a climate change perspective in terms of technology lock-in and absolute CO_2 reductions. Granted when considering combustion alone, LNG provides a step change emission reduction when compared to using HFO. However, with a growth rate of 4.1% across the sector, unless there is a more coherent, strategic plan, emission reductions through fuel substitution to LNG will inevitably become obsolete within only a few years. Figure 2 illustrates this through a simple example. Assume that as of 2010 (using IMO based estimation of 870 Mt CO_2 (Lloyds Register and DNV 2011)), all vessels were to switch to LNG, providing an absolute emission saving of 20%. With the current growth rate of the sector, emissions will surpass 870 Mt in 5.5 years (assuming no other mitigation measures are implemented).

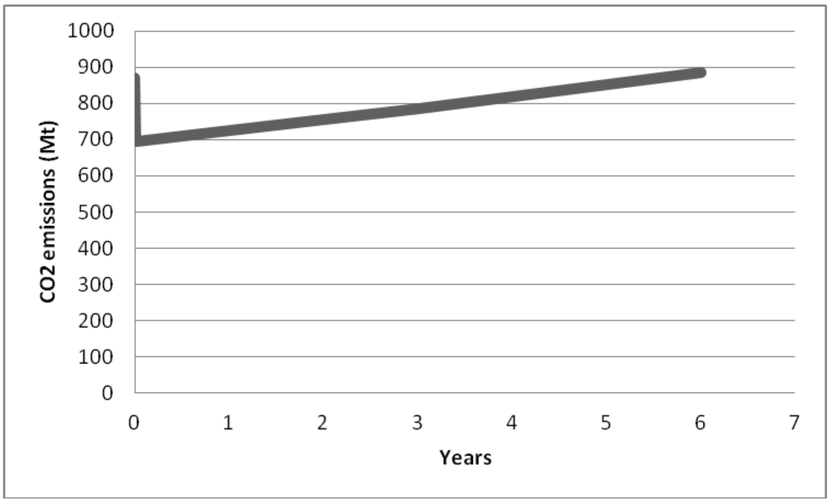

Figure 2: The implications of continued growth in the shipping sector when considering a full switch to LNG

There are already challenges related with a switch to LNG. These are associated with changes to infrastructure in ports and storage on ships, cryogenic effects and the current stability of LNG prices when compared to HFO (Djønne 2011; SNAME 2011). What Figure 2 draws attention to is very much in line with the discussions that are happening with regard to the decarbonisation of the energy sector on land – natural gas is at best, a transition fuel to a fully decarbonised economy (DECC 2012)[1]. Therefore, the sector needs to think beyond LNG if it is really serious about addressing the climate change challenge.

There is potential to decarbonise LNG fuel substitution further via several pathways – each of which are briefly explored in the remainder of this paper. It should be noted that as these technologies are not yet developed at any reasonable scale, nor are some of them technologically sound, there is still a role for LNG in the short-term.

[1] Even with carbon capture and storage, emissions from the production of electricity would not be reduced to zero.

5. Beyond LNG

The following low carbon step-change technologies could be considered in the medium- to long-term.

5.1 Hydrogen

Although burning hydrogen on a ship does not release direct carbon emissions, there are indirect emissions associated with its production and storage. It is important that these are accounted for over the full life-cycle and that hydrogen is not labelled 'carbon neutral'. If hydrogen is to be considered as a step-change technology measure, then the energy and carbon intensive processes to manufacture it – i.e. methane steam reforming or water electrolysis – need to be decarbonised. One of the most readily available approaches to achieve this could be biomass gasification, maximising the hydrogen stream (Gilbert and Thornley 2010) or to exploit a renewable supply of electricity – either directly on site from wind, tidal, bioenergy or solar, or indirectly by a wider electrical grid, under the assumption that it is decarbonised. Renewable hydrogen use is applicable to all vessel types, whereby the propulsive system could be a diesel engine – as with LNG, gas turbine / combined gas and steam (COGAS) or fuel cell. CO_2 savings of up to 90% could be achieved (compared to HFO use) if renewable hydrogen is sourced (AEA Technology 2007). The effectiveness of each propulsion approach is explored as a discussion point in Section 6.1 and the wider system implications of hydrogen use in vessels is discussed in Section 6.2.

5.2 Liquid biofuels

Liquid biofuels can be combusted in a diesel engine and are potentially applicable to all vessel types, with only small modifications of the main engine required (SNAME 2011). There are three generations of biofuels: 1st generation (e.g. bio-diesel and bio-ethanol); 2nd generation (e.g. biomethanol, synthetic natural gas and Fischer-Tropsch diesel); and 3rd generation, such as algae-based fuels produced in reactors and closed systems. In terms of CO_2 reduction potential, savings over the full life-cycle are very sensitive to a range of parameters including feedstock type / growing conditions, land-use change and the refining process. The Fuel Quality Directive (European Pariliament 2009) set out sustainability criteria, including minimum life-cycle greenhouse gas savings. The minimum savings are 36-63% for biodiesel, 32-71% for bioethanol, 91-94% for biomethanol and 95% for Fischer-Tropsch diesel. Although this Directive is automotive specific, these aspirations for savings could also be adopted by the shipping sector. Algae fuel is perhaps the most promising biofuel for shipping, as it could be produced in close proximity to ports and coastal areas. A further benefit when compared to algae development for the aviation or automotive sectors is that less refining would be required, as current diesel engines are well adapted to burning lower grade residual fuel. However, there are currently limitations associated with high costs for production and scale required to meet shipping demand. The wider sustainability implications of a switch from LNG to biofuels are explored in Section 6.3.

5.3 Synthetic natural gas (SNG)

Assessing the potential for continued use of LNG infrastructure and no further modification to main engines could incentivise the use of SNG from biomass gasification. Methanation (the main process step following gasification) is an established technology and although gasification is considered mature, there are still technical issues associated with biomass feedstock streams, and alignment of gas clean-up and end-use. SNG has been explored as an alternative fuel to LNG (Zwart, Boerrigter et al. 2006; Gassner and Maréchal 2009; Juraščík, Sues et al. 2010) and in particular for the shipping industry (Bengtsson, Fridell et al. 2012) and the automotive industry (Felder and Dones 2007). Greenhouse gas savings are achievable over the system life-cycle, but there are wider environmental impacts from fertiliser use, such as increases in acidification and eutrophication (Gilbert, Thornley et al. 2011; Bengtsson, Fridell et al. 2012) –this largely depends on the biomass feedstock.

5.4 CO_2 scrubbing and carbon capture and storage technology (CCS)

There are two options to be considered – carbon capture onboard ships and carbon capture on land. The first option could implement CO_2 scrubbing, whereby exhaust gases are scrubbed to capture and discharge CO_2 to water; in addition to local pollutants such as SO_x and NO_x (EcoSpec 2010; Fathom 2011). This process would allow for the continued use of LNG in diesel engines onboard ships. EcoSpec's CSNOX has reported savings of 77% with a gas removal efficiency of 33 ton/hr (result quoted in imperial units) and a reported saving of 46% with a gas removal efficiency of 70 ton/hr (EcoSpec 2010).

A variation on CO_2 scrubbing would be to sequester CO_2 from the exhaust gases via chemical or physical membranes and store it on the vessel, before transferring it to land. The CO_2 could then be transported offshore by pipeline to depleted oil and gas reservoirs or deep saline aquifers (Department of Energy and Climate Change 2012). The technology is currently being developed for land based CO_2 emitting sectors – in particular coal-fired power stations. CCS could be coupled with biofuels use – to potentially provide negative CO_2 emissions (bio-CCS).

The second option is to consider LNG use at an energy systems level. The CCS could be coupled with hydrogen production on land so that hydrogen production could be sustained using natural gas steam reforming (IFA 2009).

5.5Nuclear

Nuclear powered vessels would operate on the same principles as a steam vessel, but the heat source is a small nuclear reactor. The technology measure is only applicable to new-builds, yet this includes all vessel types. As a result, the continued use of the diesel engine as the main engine would not be an option. The advantage of nuclear power is that it enables the vessel to run for long periods of time without the need to refuel and furthermore, there is a reduced level of local pollutants compared to HFO (Makarov, Pologikh et al. 2000). The CO_2 emissions associated with operating the reactor are also nominal; however, there are upstream and downstream emissions (Dedes, Turnock et al. 2011). The wider sustainability implications for nuclear power are discussed in Section 6.3.

5.6 Diesel-electric, hybrid diesel-electric and battery-electric

A range of options exist here – but would require further modification of the main engine. Diesel-electric is applicable as a retro-fit option and is best suited for vessels that have frequent load changes and operational profiles (Crist 2009). It is therefore applicable as a retro-fit option for ferries, offshore supply vessels (OSV), RoRo and cruise vessels. They are considered a mature technology measure and reported savings range between 5-30% (ABB Marine 2007; Crist 2009; Fathom 2011). Hybrid diesel-electric captures the efficiency of diesel-electric drives at part loads, and reduced transmission losses using mechanical propulsion at high/full loads (Fathom 2011). The effectiveness is very much vessel/market specific and is best judged by examining the operational profile of the vessel. Finally, battery-electric could harness renewable electricity (either supplied from land via cold ironing or onboard the vessel via solar/wind power) to power the vessel. However, the relative savings would depend on the carbon intensity of the energy source that charges the batteries.

6. Implications for a move beyond LNG

6.1 Vessel and market specific measures and policy

If the sector is to move beyond LNG towards lower carbon fuels, it is clear that *'one fuel fits all'* is inappropriate. As a result, the current orthodoxy surrounding *'one global policy fits all'* will also not be appropriate. Policy needs to ensure the most fitting technology step-change measures are targeted at specific vessels and/or markets, within appropriate timeframes and scales. This is a consideration that could be applied to the whole sector, whether it is to incentivise incremental or step change technologies. A global policy for CO_2 reductions needs to be more than a top-down agreement. It needs to ensure the correct technology roadmaps are in place to advise ship builders, operators etc of the appropriate mitigation options for specific vessel types and/or markets to meaningfully decarbonise. This point is best illustrated using hydrogen and electric drives as examples.

As outlined, hydrogen could be liquefied and burnt in a diesel engine and as with LNG, be used with COGAS, or to generate electricity in a fuel cell. Electric vessels could operate using diesel generators, hybrids, batteries and again fuel cells. Hydrogen used in a diesel engine is a credible option to progress the fleet without major modifications to the main engine. With the high efficiencies of diesel engines at full loads, this could sustain benefits to larger vessels – in particular tankers, bulkers etc. In addition, liquefied hydrogen could function as a supplementary fuel in the short- to medium-term. However, as discussed, when considering vessels that have frequent load changes and operational profiles such as ferries, OSV, RoRo and cruise vessels, higher savings are achievable by moving towards electric drives. With this in mind, it is arguably more sensible to consider fuel cells or battery-electric drives for these vessels/markets in the medium- to long-term and to develop policies that incentivise accordingly. This is notwithstanding the development of hybrid drives that could benefit a wider range of vessels (ABB Marine 2007). However, there are technical barriers to the uptake of said measures: for fuel cells, the limited development at the MW scale, service life due to corrosion, high weight-to-power ratio and slow response rate to change in power output; and for batteries, storage capacity commensurate with high power demand.

Finally, hydrogen could be burnt in a gas turbine COGAS arrangement. In a shipping world where speed is likely to be constrained as an operational means to decarbonise, gas turbines are unlikely to feature highly. Nonetheless, there is a market for gas turbines in the Navy and in some cruise vessels benefitting from a high power-to-weight ratio. It therefore seems sensible to incentivise a move from natural gas fired gas turbines to hydrogen fired as a way to decarbonise these services in the medium- to long-term.

6.2 Wider system level implications

At a systems level, the barriers for hydrogen use in the shipping sector very much mirror what is happening with hydrogen use on land. The limiting factor is producing hydrogen in a cost-effective manner, and setting up appropriate infrastructure to facilitate such a change. The costs are more elevated for fuel cells, as they require expensive catalysts, membranes and electrodes. In addition, there are issues associated with decarbonising hydrogen production, storage and handling on board ships and regulations by the IMO regarding flammable materials onboard vessels (other than tankers). Nonetheless, the issue of infrastructure and storage could be readily addressed if hydrogen were to progress from the infrastructure deployed by more widespread uptake of LNG. It should be noted that infrastructure will also be required for biofuel- and nuclear-powered ships. One of the key challenges for nuclear vessels is port retrofitting/rebuilding to be able to refuel nuclear ships (Brown 1963; Dedes, Turnock et al. 2011). Nonetheless, nuclear does have the advantage that refuelling would be much less frequent.

A second systems level implication to consider is the competing end-uses for the fuels – in particular biofuels. Biofuels and biomass on the whole, are in demand in the electricity, heat, automotive, chemical and aviation sectors. As yet, there is very limited communication across these sectors and consequently, there is no clear strategy for the most appropriate use of our limited biomass resource. However, thinking strategically from a systems perspective, strong arguments can be made as to where biomass could be utilised. Electricity demand could be met by other forms of renewable technologies for example, wind, solar and tidal. Heat demand can be met by more informed building design and retrofit programmes in addition to behavioural change and a shift to a decarbonised grid. Automotive demand could be met through a shift to a decarbonised grid. However, there are outstanding issues surrounding credible low carbon aviation fuel – the most obvious and effective step-change decarbonisation option for aviation is demand reduction (Bows 2010). There are also issues around finding a suitable renewable fixed carbon sources in the chemical industry (Gilbert and Thornley 2010). Yet, there are a range of fuel substitution options beyond biofuels. As a result, further research is required in this area to demonstrate that pursuing biofuels in the sector is an appropriate end use of biomass.

Finally – the implications of putting more demand on to the grid needs to be highlighted. Although there are additional examples, the main technology measures in this paper are battery-electric drives and renewable electrolysis for hydrogen production. It is well documented that the UK's low-carbon energy transition will require electricity for heat and for land-based transportation, in addition to meeting conventional electricity needs (Mander, Bows et al. 2008). The implications of increasing demands being placed on the grid include a rise in capacity in order to significantly increase the size of the grid, and a smarter use of electricity through demand-side management. If the shipping sector is to add further load, then this must be considered alongside the existing challenges to decarbonising a grid serving a greater range of end-users in future.

6.3 Wider sustainability implications

The pursuit of biofuels in any sector raises concerns regarding the wider sustainability implications. Although 2nd and 3rd generation biofuels were/are being developed due to technological advancements, such as bio-refineries, they also attempt to alleviate some of the sustainability concerns associated with 1st generation biofuels. These are not limited to food, land and water security but also include socio-economic imbalance between suppliers and end-users and carbon savings over the life-cycle after land-use change is accounted for. There are also currently considerable cost implications for many of the biofuel technologies outlined in this paper – for instance although algal fuels are a credible option for the sector, unless they become economically attractive and issues associated with growing space is resolved, there is limited scope for them as a step-change technology measure.

Concerning nuclear power, one of the key sustainability aspects to consider is public acceptability and perception (AEA Technology 2007). Yet, there is also concern within the industry regarding responsibility for insurance and liability. Governments and society need to be convinced that nuclear operators can provide sufficient compensation for victims and any damage caused in the event of disasters. However, issues with insurance could be overcome via technical solutions, in the form of triple redundancy systems, emergency procedures, shielding and multiple years of testing. Finally, sources of nuclear power are finite, despite being relatively abundant at present. There is thus an inevitable need to consider alternatives much further into the future.

7. Conclusions

Due to the complexity of the shipping system, any significant and meaningful decarbonisation pathway which tackles emissions as a whole, is likely to require a range of global/EU policies and local/organisational policies to drive technical, operational and demand measures. With the urgency and scale of reductions required, this paper outlines an argument to examine radical step-change technological measures that could play an important role in delivering large emission reductions across the sector. In particular it focuses on fuel substitution to LNG in the short-term and the implications for a transition to hydrogen, biofuels, nuclear and diesel electric drives in the medium- to long-term. With the current growth rate of the sector, if LNG is to be combusted in all vessels providing a net saving of 20%, this study illustrates that emissions will surpass present day emissions in five and a half years. This outlines a case for looking beyond LNG if the sector is committed to *"hold the increase in global temperature below 2 degrees Celsius…"*. There are challenges associated with this. The current orthodoxy is to pursue a global agreement to control CO_2 emissions. Yet different fuel substitution technologies are applicable to certain vessel types and markets. Therefore, policy needs to ensure the most fitting technology step-change measures are targeted accordingly – within appropriate timeframes and scales. Examining the transition to lower carbon fuels in the medium-term suggests also that shipping's interaction with the wider energy system needs to be examined. Most notably: the infrastructure and storage implications of hydrogen and nuclear fuels; the wider demand for biomass in the heat, power and transport sectors and; the implications of placing more demand on to the grid if battery technology and renewable electrolysis (for hydrogen production) is to prosper. Finally, as with all sectors, the sustainability implications for biofuels need to be addressed to ensure society selects the least unsustainable process routes – by doing this it should be acknowledged that this may lead to biofuels not being used in the shipping sector.

8. Acknowledgements

This research was facilitated through funding from the EPSRC Energy Programme (through the High Seas Project) and the Sustainable Consumption Institute.

References

ABB Marine (2007). A new era in ship propulsion: The first large size (154K) LNG carrier with electric propulsion is now in operation., ABB Marine.

AEA Technology (2007). Low carbon commercial shipping: Report for the Department for Transport. Didcot, AEA Technology

Anderson, K., P. Gilbert, et al. (2012). "Executing a Scharnow turn: why, when and how the Shipping sector can be reconciled with international commitments on climate change." Carbon Management **forthcoming**.

Bengtsson, S., E. Fridell, et al. (2012). "Environmental assessment of two pathways towards the use of biofuels in shipping." Energy Policy **44**(0): 451-463.

Bows, A. (2010). "Aviation and climate change: confronting the challenge." The Aeronautical Journal **114**(1158): 459-468.

Broderick. J., K. L. Anderson, et al. (2011). Shale gas: an updated assessment of environmental and climate change impacts. A report commissioned by The Co-operative and undertaken by researchers at the Tyndall Centre, University of Manchester. Manchester, Tyndall Centre.

Brown, J. M. (1963) Nuclear Ship Savannah and the Law. University of Florida Law Review **15**, 299-325

Crist, P. (2009). Greenhouse gas emissions reduction potential from international shipping. Discussion Paper No. 2009-11, Joint Transport Research Centre of the OECD and the International Transport Forum.

DECC (2012). Emissions performance standards. Energy and Climate Change Select Committee.

Dedes, E. K., S. R. Turnock, et al. (2011). Possible Power Train Concepts for Nuclear Powered Merchant Ships. International Conference on Technologies, Operations, Logistics and Modelling for Low Carbon Shipping. O. Turan and A. Incecik. Glasgow, Scotland, UK: 261-271.

Department of Energy and Climate Change (2012). "Carbon Capture and Storage (CCS)." from http://www.decc.gov.uk/en/content/cms/emissions/ccs/ccs.aspx.

Djønne, K. (2011). Alternative fuels: LNG – a short or a medium term solution?, DNV.

EcoSpec (2010). CSNOx - e-brochure. Singapore, EcoSpec.

European Pariliament (2009). Directive 2009/30/EC of the European Parilament and of the Council, Official Journal of the European Union.

Fathom (2011). Ship efficiency: The guide. Berkshire, Fathom.

Felder, R. and R. Dones (2007). "Evaluation of ecological impacts of synthetic natural gas from wood used in current heating and car systems." Biomass and Bioenergy **31**(6): 403-415.

Gassner, M. and F. Maréchal (2009). "Thermo-economic process model for thermochemical production of Synthetic Natural Gas (SNG) from lignocellulosic biomass." Biomass and Bioenergy **33**(11): 1587-1604.

Gilbert, P. and A. Bows (2012). "Exploring the scope for complementary sub-global policy to mitigate CO2 from shipping." Energy Policy **in press**.

Gilbert, P. and P. Thornley (2010). Energy and carbon balance of ammonia production from biomass gasification. Bio-Ten. Birmingham.

Gilbert, P., P. Thornley, et al. (2011). "The influence of organic and inorganic fertiliser application rates on UK biomass crop sustainability." Biomass and Bioenergy.

Harvey, F. (2012). Gas rebranded as green energy by EU. The Guardian London.

IFA (2009). Fertilizers, climate change and enhancing agricultural productivity sustainably. Paris, IFA.

IMO (2009). Prevention of air pollution from ships. Second IMO GHG Study 2009 Update of the 2000 IMO GHG Study - Final report covering Phase 1 and Phase 2, International Maritime Organisation. **MEPC 59/INF.10**.

IPCC (2007). Working Group II Report "Impacts, Adaptation and Vulnerability". Fourth Assessment Report. IPCC.

Juraščík, M., A. Sues, et al. (2010). "Exergy analysis of synthetic natural gas production method from biomass." Energy **35**(2): 880-888.

Lloyd's Register (2011). LR MEPC 62 Executive Summary, Lloyd's Register.

Lloyds Register and DNV (2011). Assessment of IMO mandated energy efficienct measures for international shipping. Estimated CO2 emissions reduduction from introduction of mandatory technical and operational energy efficienct measures for ships. Report submitted to MEPC 63/INF.2., Lloyds Register and DNV.

Makarov, V. I., B. G. Pologikh, et al. (2000) Experience in Building and Operating Reactor Systems for Civilian Ships. Atomic Energy **89**, 691-700

Mander, S., C. Walsh, et al. (2012). "Decarbonising the UK energy system and the implications for UK shipping." Carbon Management **forthcoming**.

Mander, S. L., A. Bows, et al. (2008). "The Tyndall decarbonisation scenarios--Part I: Development of a backcasting methodology with stakeholder participation." Energy Policy **36**(10): 3754-3763.

MEPC (2008). Amendmants to the Annex of the Protocol of 1997 to amend the international convention for the prevention of pollution from ships, 1973, as modified by the protocol of 1978 relating thereto. (Revised MARPOL Annex VI), IMO.

OCIMF (2011). GHG emission-mitigating measures for oil tankers. Report submitted to MEPC 62 INF 7., Oil Companies International Marine Forum.

Smith, T. (2012). "Technical energy efficiency, its interaction with optimal operating speeds adn teh implications for the management of shipping's carbon emissions." Carbon Management **in press**.

SNAME (2011). Marginal abatement costs and cost effectiveness of energy-efficiency measures. Report submitted to MEPC 62 INF 7., The Society of Naval Architects and Marine Engineers (SNAME).

UNFCCC (2009). Copenhagen Accord. FCCC/CP/2009/L.7. Copenhagen, United Nations Climate Change Conference 2009.

Zeus Intelligence Services and (2011). LNG fuel application: Drilling sites and marine vessels. Austin.

Zwart, R. W. E., H. Boerrigter, et al. (2006). Production of Synthetic Natural Gas (SNG) from Biomass. Development and operation of an integrated bio-SNG system. ECN-E--06-018., Energy research Centre of the Netherlands (ECN).