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Submitted by:
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Biographies

- **Charles J McKinlay** is a PhD candidate researching future fuels for shipping with a particular focus on hydrogen. He is a member of the EPSRC Centre for Doctoral Training in Energy Storage and its Applications and his research is partially sponsored by Shell Shipping and Maritime.
- **Professor Stephen Turnock** FRINA is Head of Civil, Maritime and Environmental Engineering at the University of Southampton. He has long standing interests in decarbonisation of shipping and in particular analysis and modelling of alternative power trains including the use of hybrid battery systems. He is a member of IEA HIA Task 39 Hydrogen in Maritime.
- **Professor Dominic Hudson** is Shell Professor of Ship Safety and Efficiency at the University of Southampton. He has interests in hydrodynamics and ship design and operation for energy efficiency, in particular modelling energy requirements for ship propulsion. He is a Chartered Engineer and is a member of the 29^{th} ITTC Specialist Committee on Ships in Operation at Sea and the RINA IMO Committee.
- **Dr Yikun Wang** is a Senior Research Fellow in the Maritime Engineering Group at the University of Southampton and an Industrial Fellow within Lloyd's Register. She has research interests in material degradation and structural integrity in marine environments. She has recently been leading a number of research activities developing new experimental and numerical frameworks at the University to characterise shipboard metallic tank structures carrying liquid hydrogen.
- **Dr Richard G.A. Wills** is an Associate Professor in Energy Technologies Research Group at the University of Southampton. His research focusses on electrochemical energy storage and the integration of renewable energy technologies. Specific research areas include redox flow batteries, lead acid batteries, fuel cells and electrode materials.
- **Dr Wassim Dbouk** is a Marine and Maritime Policy Research Fellow at the University of Southampton. Following a PhD in Marine Environmental Law, and in combination with his diverse past work experience in the private, public, legal and research sectors, most notably with the Lebanese Parliament, Wassim brings a broad, flexible skillset and an astute understanding of the interaction between research, law and policy. Dr Dbouk oversees the University's relationship with the Maritime and Coastguard Agency to identify and fulfil evidence needs to ensure impactful knowledge exchange.
- **Professor Damon A.H. Teagle** is Director of the Southampton Marine and Maritime Institute (SMMI) that pulls together the University of Southampton's diverse and extensive expertise in the natural and societal challenges confronting the oceans, from climate change, pollution, the sustainability of resources, and the wellbeing of seafarers and coastal/port communities. A geologist by background, he held a Royal Society Wolfson Research Merit Award (2014-2018) and has been chief scientist on numerous oceanographic and terrestrial research expeditions. He has broad interests

in developing solutions, and the trajectories towards those solutions, to the challenges of decarbonisation and zero-pollution especially in the challenging maritime domain.

Recent relevant publications

- McKinlay, C. J., Turnock, S. R., & Hudson, D. A. (2020). A comparison of hydrogen and ammonia for future long distance shipping fuels. *LNG/LPG and Alternative Fuel Ships, Royal Institute of Naval Architects, HQ, 8-9 Northumberland Street, London WC2N 5DA, United Kingdom. 29 - 30 Jan 2020.* 13 pp. http://eprints.soton.ac.uk/id/eprint/437555
- McKinlay, C. J., Turnock, S. R., & Hudson, D. A. (2021). Route to zero emission shipping: hydrogen, ammonia or methanol? *In review – submitted to International Journal of Hydrogen Energy. (available on request)*
- McKinlay, C. J., Turnock, S. R., & Hudson, D. A. (2021). Fuel cells for shipping: to meet on-board auxiliary demand and reduce emissions. *In press - 5th Annual CDT Conference in Energy Storage and its Applications. (available on request)*
- Wang, Z., Wang Y., Afshan, S., Hjalmarsson, J. (2020). A review of metallic tanks for H_2 storage with a view to application in future green shipping. Dec 2020. *International Journal of Hydrogen Energy.* https://doi.org/10.1016/j.ijhydene.2020.11.168
- Bassam, A. M., Phillips, A. B., Turnock, S. R., & Wilson, P. A. (2017). Development of a multi-scheme energy management strategy for a hybrid fuel cell driven passenger ship. *International Journal of Hydrogen Energy*, *42*(1), 623–635. https://doi.org/10.1016/j.ijhydene.2016.08.209
- Bassam, A. M., Phillips, A. B., Turnock, S. R., & Wilson, P. A. (2016). An improved energy management strategy for a hybrid fuel cell/battery passenger vessel. *International Journal of Hydrogen Energy*, *41*(47), 22453-22464. https://doi.org/10.1016/j.ijhydene.2016.08.049

Executive Summary

1. HM Government's "Clean Maritime Plan" (2019) targets zero emission shipping to be "commonplace" by 2050 and that all new ship orders by 2025 should be capable of delivering zero emission propulsion.[1] For these goals to be achieved, significant investment in alternative fuels is required.
2. The long-life span of large ships requires an early start to both retrofit of existing vessels as well as preparing the ground for a transition to new build zero carbon ship from 2025 onwards.
3. Large scale shipping is a challenging sector to decarbonise, primarily due to large energy demands coupled with limited onboard storage capacity. Alternative fuels are imperative to eliminate both greenhouse gas emissions and harmful pollutants that damage the health of seafarers and port communities.
4. Hydrogen is a viable candidate to provide emission-free propulsion and is cleaner and easier to produce without emissions than other alternatives being considered (such as ammonia or methanol). All combustion technologies are relatively inefficient and even those using zero carbon fuels (*e.g.*, ammonia) lead to polluting emissions (*e.g.*, NOx). Consequently, immediate research and innovation into electro-chemical

[1] Department for Transport (2019) Clean Maritime Plan. *UK Government*

approaches for powering large ships and other heavy-duty industrial uses are essential.

5. Our main policy recommendations are:
    - Invest in the research and development of hydrogen production, storage and transfer technologies for ships, ports and large industrial users.
    - Develop and introduce evidence-based safety regulations and protocols specific to alternative fuels and in particular hydrogen.
    - Increase subsidies for zero emission/zero carbon hydrogen production (such as water electrolysis).
    - Further research into the development of fuel cells or fuel cell/battery hybrid systems for ships and other major industrial off-grid applications.

The suitability of the Government's announced plans for "Driving the Growth of Low Carbon Hydrogen"

6. Here we consider the challenges of decarbonising shipping that carries 90% of global trade. Presently shipping has a global carbon footprint about the size of Germany (2-3% of global CO_2 emissions) and is also the source of harmful atmospheric pollution (NOx, SOx, particulate materials). HM Government's "Ten Point Plan for a Green Industrial Revolution" aims for a 5 GW hydrogen production capacity by 2030[2] although recent proposals from the Climate Change Committee indicate that more ambitious targets (10 GW of electrolyser capacity by 2030)[3] are required to reach 2050 Net Zero goals and avert dangerous levels of global warming (<1.5°C). Using the example of a typical large liquefied natural gas (LNG) tanker, our calculations show the likely delivered energy consumption (for propulsion only) for such a vessel is 54.2 GWh per year. Based on an expected system efficiency of 60% for hydrogen fuel in a fuel cell, this would require an annual energy input of 90.2 GWh/year. Hence, 5 GW of hydrogen production would equate to 43.8 TWh/year, enough to power 485 ships of this scale. Given that the intended use of this hydrogen production includes other applications (heating, *etc.*) and that the global shipping fleet is around 50,000 ships and is expected to increase, then substantially increasing production levels of hydrogen would help to ease concerns over meeting supply.

The infrastructure that hydrogen as a Net Zero fuel will require in the short- and longer-term, and any associated risks and opportunities

7. For hydrogen (or any alternative fuel) to be deployed successfully as a shipping fuel, refuelling ("bunkering") infrastructure will be required. Consequently, HM Government investments in storage and refuelling equipment in UK ports would significantly accelerate the uptake of emission free shipping. This presents an opportunity for UK maritime engineering businesses to be at the forefront of developing this technology globally. Several countries, including the Netherlands, Norway, Denmark and Germany, have deployed or are planning to deploy hydrogen vessels (albeit for small scale applications at present).[4]

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[2] The Ten Point Plan for a Green Industrial Revolution (2020). *UK Government*
[3] Committee on Climate Change, The Sixth Carbon Budget, The UK's path to Net Zero, Dec 2020
[4] Zemships, "One Hundred Passengers and Zero Emissions: The First Ever Passenger Vessel to Sail Propelled by Fuel Cells," ed, 2013.

8. Additionally, other countries have been investing in hydrogen infrastructure. For example, it is estimated that Japan will be importing between £5.5bn and £11bn of hydrogen annually by 2030.[5] The movement of large amounts of hydrogen as a cargo could significantly increase the viability of using it as a maritime fuel itself, as has been demonstrated with LNG.
9. Hydrogen on board storage challenges may limit the range of hydrogen vessels. Therefore, port-side storage and transfer infrastructure will be required in many more ports than required for current use of heavy fuel oil (HFO).
10. Each port bunkering station would need to select between local hydrogen production, either with dedicated wind/solar resources or connection to electricity grid with a high proportion of zero carbon electricity, or supply of hydrogen via pipeline or by sea.
11. Integrating the use and distribution of hydrogen with the marine sector can be facilitated by co-location of renewable hydrogen production from seawater electrolysis.

The engineering and commercial challenges associated with using hydrogen as a fuel, including production, storage, distribution and metrology, and how the Government could best address these

12. The main challenge with hydrogen as a shipping fuel is storage. Storage options include: liquid storage (requiring temperatures of between -259.4°C and -240°C);[6] compressed gas storage (which has large volume requirements especially for long distance vessels); chemical absorption (*e.g.*, metal hydrides; chemically bonding of hydrogen to metal) and physical adsorption (*e.g.*, metal organic framework; hydrogen is physically adsorbed on to material surfaces). Technological advancements in the field of hydrogen storage could significantly improve feasibility, therefore further research into this area would be strongly recommended. Ammonia (NH_3) and methanol (CH_3OH) are both significantly easier to store, and therefore may be viewed either as transitionary technologies, or as hydrogen carriers.
13. The focus of the current studies on hydrogen storage techniques is predominantly for land-based vehicles and aviation applications, which typically have small storage capacities, ranging from 0.1 to 20 m^3. Research is required to investigate whether the small-scale testing/simulation results can be extrapolated to large-scale applications.
14. Cryogenic hydrogen storage has shown great potential for achieving Net Zero in a wide range of engineering sectors. However, quality data of vessel system design and materials/insulation failure characterisation is scarce. The rapid build-up of knowledge and material databases are needed to enable developing new test/approval requirements for safety and quality assurance of such systems.
15. Areas identified for further research into hydrogen storage include: materials; energy cost of cooling and liquefication; inert gases required for sweeping/purging and their supply (*e.g.*, helium). The public perception of the risks associated with hydrogen (*e.g.*, explosiveness) compared to other alternative fuels (such as the toxicity of ammonia) should be considered, especially for storage and transfer in ports.
16. A fuel cell is the most efficient system for extracting energy from hydrogen (as well as ammonia and methanol). However, to date the only fuel cells to be deployed at sea

[5] R. F. Service. (2018) Liquid Sunshine. Science. Available: https://science.sciencemag.org/content/sci/361/6398/120.full.pdf
[6] M. Hirscher, "Handbook of hydrogen storage," *Topics in applied physics,* vol. 12, 2010.

have been limited to small-scale or niche applications. Further research into whether fuel cells or internal combustion engines would be most appropriate for hydrogen ships is recommended. The combustion in air of even zero carbon fuels such as ammonia will still lead to atmospheric pollution especially harmful nitrogen-oxide compounds.

17. There is an urgent need to invest in the production of zero carbon hydrogen production through the hydrolysis of (sea-)water using renewable energy. Current methods of hydrogen production, such as steam reforming of methane (SRM) are energy intensive and produce large amounts of CO_2. Although this production may provide an essential hydrogen supply that will stimulate regional and potentially national hydrogen economies, industrial processes such as SRM urgently need to be coupled with effective carbon capture and storage deployments. A short-term goal for the UK should be the generation of significant “green hydrogen” from water hydrolysis by renewable energy. There are significant research and engineering challenges for the industrial scale deployment of these new green technologies, and it will require an excess of renewable energy beyond that required for the decarbonisation of the UK electrical grid. It may be sensible to use remote maritime renewable sites to directly generate hydrogen and then ship in liquified form to point of use.

The relative advantages and disadvantages of hydrogen compared to other low-carbon options (such as electrification or heat networks), the applications for which hydrogen should be prioritised and why, and how any uncertainty in the optimal technology should be managed.

18. HM Government’s “Clean Maritime Plan” targets zero emission shipping to be commonplace by 2050 and to achieve this, all vessels ordered after 2025 should be capable of delivering emission free propulsion. Energy saving technologies and techniques can only reduce emissions up to a maximum of 14%.[7] Therefore, a change in propulsion is necessary to achieve zero emission shipping, with three types of alternative fuels being the most realistic: hydrogen, methanol and ammonia. Of these options, hydrogen is the cleanest (ammonia can produce NOx emissions and methanol can produce CO_2 emissions) and the easiest to produce emission free (via electrolysis).
19. Hydrogen or hydrogen-based fuels (such as ammonia or methanol) appear to be the only feasible concept for the complete decarbonisation of certain sectors such as long-distance shipping.
20. Hydrogen is often dismissed for transport applications due to its low volumetric energy density. However, our study based on historical energy usage of a typical large, long distance vessel has shown that volume requirements (especially for liquid storage) are feasible with a by-voyage approach to bunkering (see McKinlay et al., 2020).
21. At current market price, hydrogen is relatively expensive compared to currently used fuels such as LNG and HFO. However, water electrolysis technology has developed considerably in recent years and projections suggest that producing hydrogen using this method (which can be emission free) will be cost competitive by 2025, at

[7] J. E. Buckingham, "Future Fuels for Commercial Shipping," presented at the LNG/LPG and alternative fuels, London, 2020.

between 50 £/MWh and 185 £/MWh depending on the electricity price.[8] Additionally, as electrolysis requires only water and electricity, this could be globally available and capitalise on the falling cost of solar photovoltaics (Solar PV) electricity.

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[8] E. Shafiei, B. Davidsdottir, J. Leaver, H. Stefansson, and E. I. Asgeirsson, "Energy, economic, and mitigation cost implications of transition toward a carbon-neutral transport sector: A simulation-based comparison between hydrogen and electricity," Journal of cleaner production, vol. 141, pp. 237-247, 2017.