National
Engineering
Policy Centre

Royal Academy
of Engineering

Prepared July 2024, Published April 2025

Low-carbon maritime fuelling

Executive summary

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The purpose of this study

The maritime industry contributes 2.8% of global greenhouse gas emissions and this is expected to rise, making it an important target for decarbonisation efforts.[1] This report explores the implications of meeting all the UK's maritime fuel demands from renewable sources. It looks at the production, transport and storage of these fuels (as well as wider factors such as safety and environmental concerns), drawing on original modelling as well as existing literature. It clarifies the implications of, but does not make recommendations among, the different fuels. It was scoped in collaboration with the Department for Transport, and a copy of the final report was submitted to the Department for consideration.[2]

The scope and approach of this study

This study considers four different renewable, low-carbon maritime fuels: hydrogen, ammonia, methanol and synthetic hydrocarbons. These are viewed in industry as the most likely and practical decarbonisation options.[3] The analysis involves modelling a production process for each of the fuels under a number of different scenarios. In the scenarios considered, the fuels are to be based on renewable electricity, water and nitrogen and carbon dioxide from the atmosphere, without any dependence on other materials (e.g. waste or biomass) to represent a scalable, carbon-free approach.

The analyses use quantitative measures to compare the fuel pathways, including: how much each unit of energy costs to produce (i.e. the levelised cost in £/GJ, reflecting the average net present cost of building and operating the infrastructure that generates that energy) and how efficient the supply chains are at turning energy into fuel (i.e. chain efficiency (energy in/energy out, %)).[4]

Key findings from the literature

Carbon neutrality

Each of the fuels considered can be produced in a way that leads to zero direct CO2 emissions, however this relies upon (a) the availability of renewable energy to power this production and (b) direct capture technology which is currently not in a fully mature state.[5] The costs of the different fuels are higher than those derived from fossil fuel today, but when factoring in the cost of carbon associated with the various approaches, the renewables represent a competitive option.

Energy density

Maritime fuels need to be highly energy dense, given the long distances and heavy loads they are used for. Hydrogen has the highest energy density of the four fuels, and synthetic hydrocarbons are also highly energy dense, making them a suitable replacement for energy dense fossil fuels. Methanol and ammonia, however, both have a lower energy density than conventional marine fuels, which would require more fuel and larger storage tanks.

Infrastructure

The fuels have different implications for existing infrastructure. Using hydrogen would require significant overhauls of existing fuel infrastructure and ship engine systems. Ammonia and methanol would have less significant implications– they are practical to store on a large scale, easy to transport and there is ready infrastructure for their transportation- however, converting the fleet to operate on ammonia or methanol would require additional costs. Finally, synthetic hydrocarbons would have minimal implications, as they could use existing infrastructure, vessels, and engines. The different fuel pathways are not mutually exclusive or 'once-and-for-all' options: it is expected that in the medium-term synthetic hydrocarbons will be used as a drop-in replacement for fossil fuels, and in the long-term there is a possibility of the emergence of more advanced fuels.

Energy input and cost

The production of low-carbon maritime fuels is generally more energy-intensive and costly than the production of traditional fossil fuels and requires a significant amount of renewable energy. Although the relative costliness of these fuels is mitigated once the wider costs of fossil fuels are factored in, and advances in renewable energy technologies and improvements in the e-marine fuel production processes may help to decrease costs and increase efficiency over time.

Sustainability of feedstocks

The production of ammonia, methanol and synthetic hydrocarbons rely heavily on the availability of renewable feedstocks, such as hydrogen and carbon dioxide. This has important implications for production and storage – for instance, green hydrogen can only be effectively produced in areas with high renewable electricity potential.

Key findings from the cost and regional modelling

Cost and supply chain efficiency

According to the modelling in the paper, hydrogen is both the cheapest and has the greatest chain efficiency relative to the other fuels. Synthetic hydrocarbons fare the worst on both metrics, with ammonia and methanol in the middle.

Fuel	2050 cost estimate	Chain efficiency	Downstream cost implications
Hydrogen	**16-32 £/GJ**	**48-69%**	**Relatively high**
Ammonia	**22-43 £/GJ**	**40-57%**	**Average**
Methanol	**21-45 £/GJ**	**39-64%**	**Average**
Synthetic hydrocarbons	**36-88 £/GJ**	**31-50%**	**None/negligible**

Trade off: production v retrofit costs

In general, the cheaper the fuel, the less convenient it is for downstream handling (e.g. logistics, storage and end use). There is a trade-off between the production cost of fuel and the cost of retrofit/conversion needed downstream. For instance, synthetic hydrocarbon is the most expensive of the fuels to produce, but would require no changes to downstream infrastructure to use it. Methanol and ammonia may be a promising compromise between these competing considerations but more analysis is required.

Implications for electricity supply and other regional dynamics

Electricity demands of between 7 and 11 GW will need to be met by 2050 for complete de-fossilisation of this sector. Identifying potential locations for alternative fuel production in the UK requires careful consideration of the relationship between regions with renewable electricity potential and their proximity to regions of high demand. For example, there are significant demands for maritime fuel in the South and South-East of England but wind resources are further North, meaning that there may need to be significant investments in transport or electricity transmission infrastructure if hydrogen is to be used in these regions.

A mixed approach

Although this analysis focuses on the assessment of individual fuel types in isolation, it is recommended that future work includes a consideration of various combinations of fuels together as part of a portfolio approach, as this may be the most effective way to meet demand.

Cost implications

	Hydrogen	Ammonia	Methanol	Synthetic hydrocarbons
Advantages	Cheapest to produce	Middling cost to produce compared to the other fuels	Middling cost to produce compared to the other fuels The Ammonia synthesis process (Haber-Bosch) is well-understood, established, and efficient	Lowest cost downstream cost implications
Disadvantages	Most expensive downstream cost implications	Middling cost to adjust infrastructure	Middling cost to adjust infrastructure	High cost to produce

Carbon neutrality

	Hydrogen	Ammonia	Methanol	Synthetic hydrocarbons
Advantages	Produces no CO2 upon combustion	No carbon or sulphur emissions upon combustion (in ICEs or ECs) Combustion characteristics of ammonia, such as flame velocity and heat release, do not prohibit its use as a fuel Green ammonia production, using solely renewable energy, leads to zero carbon emissions. Furthermore, nitrogen oxides' emissions during ammonia's combustion can be eliminated by selective catalytic reduction (SCR) systems	Produces CO2 upon combustion, but this CO2 can be considered as recycled as it is derived from DAC	Same chemical properties as conventional petrol and diesel Cleaner-burning compared to the fossil fuel alternative
Disadvantages	Hydrogen is an indirect greenhouse gas, as it interferes with atmospheric methane removal and produces ozone and water vapour when it reacts with OH radicals in the atmosphere. Thus any emissions of hydrogen (from equipment leaks or venting) would be counterproductive to the GHG reductions from fuel switching	Nitrogen oxides emissions; SCR systems are required	Produces CO2 upon combustion	Produces CO2 upon combustion

Energy density

	Hydrogen	Ammonia	Methanol	Synthetic hydrocarbons
Advantages				High energy density
Disadvantages		Lower energy density than marine fuels – which has implications for storage on ships	Lower energy density than traditional marine fuels	

Infrastructure

	Hydrogen	Ammonia	Methanol	Synthetic hydrocarbons
Advantages	Hydrogen can be stored in numerous forms (compressed, liquefied, as liquid organic hydrogen carries, in metal hydrides) which will also impact fuel storage.	No requirement for cryogenic storage Existing global supply chain infrastructure Ammonia is already carried in vessels Studies from several consortiums have demonstrated the similarity of ammonia engines to current internal combustion engines (ICE). Higher efficiencies can be achieved in the future exploiting fuel cell systems in ships which directly use ammonia.	Similar properties to conventional marine fuels Easy to transport Limited infrastructure adjustments needed Not geographically restricted but would be advantageous to locate close to source of hydrogen and carbon dioxide	Drop-in replacement Storage and transportation using existing infrastructure Not geographically restricted
Disadvantages	Would require new ships and ports infrastructure Expensive to store and transport Highly flammable Small molecule which can cause embrittlement of transport and containing materials Due to the cost of transport, it would be more convenient to co-locate production with demand, which introduces an additional constraint when selecting locations	Storage investments in ships and ports will be needed; Ammonia's on-board storage may require 2.75 times more space than HFO Required changes in ships combustion systems	Cost would be incurred to convert fuel infrastructure and ships to methanol	

Energy input and cost

	Hydrogen	Ammonia	Methanol	Synthetic hydrocarbons
Advantages				
Disadvantages				Requires significantly higher amounts of renewable electricity than other three fuels

Sustainability of feedstocks

	Hydrogen	Ammonia	Methanol	Synthetic hydrocarbons
Advantages	Fuels needed are wholly renewable (water (hydrogen), air and electricity)	Fuels needed are wholly renewable (water (hydrogen), air and electricity)	Fuels needed are wholly renewable (water (hydrogen), air and electricity)	Feedstocks are wholly renewable (from air and water only) Fuels needed are wholly renewable (water (hydrogen), air and electricity) Water consumption decreases significantly if water produced in the Fischer Tropsch and reverse water gas shift reactions is utilised
Disadvantages	Challenges regarding access to and availability of secure and steady electricity and water	Challenges regarding access to and availability of secure and steady electricity and water	Challenges regarding access to and availability of secure and steady electricity and water	Challenges regarding access to and availability of secure and steady electricity and water

Safety and environmental risks

	Hydrogen	Ammonia	Methanol	Synthetic hydrocarbons
	Highly flammable	Environmental and human health risks as ammonia is toxic	Additional fire risks in comparison to traditional marine fuels Additional human health risks in comparison to traditional marine fuels	Same risks as conventional maritime fuels

Taking a systems approach to achieving net zero by 2050

Policymakers are tackling increasingly complex challenges for example, upgrading the country's critical infrastructure, working to mitigate and adapt to the impacts of climate change, and building resilience against future crises such as future pandemics. Engineers are well placed to bring practical solutions and a *systems approach* to help policymakers address such challenges.

The National Engineering Policy Centre (NEPC) policy work promotes systems approaches, including on the path to net zero. Decarbonising maritime fuelling is a complex challenge that demands a systems approach, because solutions targeting one aspect of the system in isolation may impact others, resulting in negative unintended consequences. It is important to understand the interconnections between different parts of the system and how they might interact to achieve the desired goal. For example, while alternative fuelling options may mitigate greenhouse gas emissions, they come with other trade-offs including environmental considerations, infrastructure requirements in terms of power generation, production, transport, storage, and safety, and financial cost. All these need to be considered from a whole systems perspective to ensure that interventions are effective.

As set out in the NEPC report *Net Zero: A systems perspective on the climate challenge*, systems approaches can help policymakers to:

- Identify points of greatest leverage, where intervention will make most difference,
- Reveal important synergies, interdependencies, and trade-offs between different strategies,
- Identify incentives in the system that are working against the overall goal,
- Help account for social, cultural, and behavioural factors that can act as both barriers to and levers for change,
- Reduce the risk of unintended consequences.

For more information on the NEPC's Net Zero work, please visit: **nepc.raeng.org.uk/net-zero**

Notes

1 See Faber, J. et al. (2021), Fourth IMO GHG Study 2020, International Maritime Organization (IMO), Baldi et al. 2014 and Baldi et al 2016.

2 Although the Department for Transport (DfT) helped scope this research, the findings and recommendations are those of the authors and do not necessarily represent the views or opinions of the DfT. The information or guidance in this document (including third party information, products and services) is provided by DfT on an 'as is' basis, without any representation or endorsement made and without warranty of any kind whether express or implied. Any errors are the fault of the authors. To the fullest extent permitted by law, DfT shall not be liable or responsible for any error or omission in this document.

3 The study excludes options involving the re-use of fossil carbon (as this is not a truly renewable approach), waste or bio-derived fuels (which require too much land and potentially conflict with other supply lines), electric drive approaches (which, while likely to have some application, will not be relevant for the bulk of the fleet), and other decarbonisation strategies such as use of blue hydrogen or onboard carbon capture.

4 This work makes the simplifying assumption that the fuels are all equally effective at turning units of energy into motion, however this should be investigated further in the future.

5 This lack of maturity introduces additional uncertainties around costing and scaling.

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Registered charity number 293074