NTRANS
Norwegian Centre for Energy Transition Strategies

Forskningssenter for miljøvennlig energi

Current status and future prospects of alternative fuels for ships

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Please note that this is a preprint of a chapter forthcoming in: De Gruyter Handbook of Ocean Governance and Maritime Affairs, edited by Espen Moe, Marco Grasso, Miranda Schreurs, Shaohua Yan & Thomas Michael Sattich

Working paper 02/24

ISBN 978-82-93863-32-8

Introduction

In the foreword to its most recent energy outlook report for the maritime sector, DNV (2023) states that "*Shipping's decarbonization is underway slowly like a supertanker coming about.*" This mirrors, as stated in the report, that there are currently very few vessels operating on lower-carbon fuel options, whereas orders for new ships able to do so are rising albeit slowly. The main source of ships' GHG emissions is exhaust gas from their internal combustion engines, estimated to be around 1 billion tonnes of carbon dioxide equivalents (CO_2e) annually, and over 1.25–1.5 billion tonnes of CO_2e when including the emissions from producing the fuels, thus accounting for around 3 percent of the 50 billion tons of anthropogenic GHG emitted annually (BP 2021; Lindstad et al. 2021).

This chapter presents and discusses the current status and future prospects of alternative fuels for ships, taking into account opportunities and challenges associated with developing new energy value chains that can supply the shipping sector with alternative low- or zero-carbon[1] (LoZeC) fuels. LoZeC fuels can be based on energy sources from fossil hydrocarbons, biomass, or electricity, which can all be converted into different types of fuels. While there is thus a broad range of alternative fuels available to shipping, none of these meet all desired criteria (e.g. costs, emissions, safety, availability) (Bilgili, 2023). Indeed, from the perspective of climate mitigation, alternative fuels dispel large variability in CO_2 reduction potential (Bouman et al., 2017), depending not only on primary energy source but also on overall energy efficiency including in processing, storage, conversion and final use (Lindstad, Lagemann, et al., 2021). What most novel fuels (e.g. e-fuels and biofuels) have in common is that production and distribution capacity largely remains to be developed for these fuels to make any significant impact on the carbon footprint of shipping, while market uptake requires newly built or retrofitted existing ships. It is furthermore important to note that in addition to a mix of new fuels and also end-of-pipe solutions such as onboard carbon capture and storage, shipping decarbonisation will rely extensively on energy efficiency measures that are both technical (i.e. more energy efficient hulls) and operational (i.e. slower speed). DNV (2023) expects that in the next decades, energy efficiency measures will be the biggest contributor to reducing emissions from ships by reducing energy demand. However, the role of carbon-neutral fuels will increase rapidly, and by 2050 contribute with two thirds of the decarbonization potential for shipping globally compared to current levels.

Shipping is considered a hard-to-abate sector, along with for instance aviation and the heavy process industries. What these have in common is that they are scale-, energy-, and capital-intensive, have long investment cycles and high entry barriers, and are characterised by high levels of technological heterogeneity (Bergek et al., 2023). The

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[1] Carbon here refers to fossil carbon.

longevity of ships means that previous technology choices have strong bearings on adaptation, while learning rates are slow compared to many other sectors (Malhotra & Schmidt, 2020). Bergek et al. (2023) argued that from an energy transition policy point of view, shipping is confronted with a complexity challenge that stems from its heterogeneity (i.e. substantial variation in types of ships, operation, traffic patterns, technological opportunities for decarbonization etc.) and interdependencies between technologies, value chains and user groups (Mäkitie, Hanson, et al., 2022). Our point of departure is that understanding the conditions for a transition to LoZeC fuels in shipping demands dual attention to transformation potential in shipping, and development and upscaling potential of novel fuels. This is mirrored in our main theoretical frame of reference - a multi-sector perspective on energy transitions (McMeekin et al., 2019) that acknowledges the need to understand transformation dynamics across different sectors and value chain segments. This chapter outlines how there are multiple paths towards decarbonisation of shipping globally, and that these can also be combined in different ways. Ultimately, their feasibility relies notably on changes in upstream parts of energy values, such as renewable energy production, and the establishment of necessary distribution and bunkering infrastructure for alternative fuels.

We briefly outline the theoretical perspective in the next section and illustrate key arguments with examples mainly from maritime transport. We then describe current technology and adoption status for alternative fuels that are relevant for deep sea shipping, and subsequently discuss future prospects. In the final section we summarize.

Energy transitions and multi-sector dynamics

As argued above, the decarbonisation of shipping is likely to rely on a mix of multiple alternative fuels as well as other measures. In the following we will mainly focus on alternative (low-carbon) fuels. This excludes battery-electric systems, which are a feasible decarbonisation solution for ships operating on shorter routes in coastal areas (see e.g. Bergek et al. (2021)), but not for the overwhelming bulk of ships and vessels globally that travel across vast ocean stretches. It should however be noted that hybrid battery-electric systems are relevant also for some segments within deep sea shipping. We must also stress the key importance of energy efficiency measures, which become even more important in the context of decarbonization due to the generally lower energy density and higher cost of alternative fuels. Finally, wind propulsion (together with engine propulsion) is showing signs of a ‘new dawn’ (Mander, 2017), yielding large energy and emission reduction potential at negative abatement costs (Lindstad et al., 2022), and is expected to become a normal feature on many ship types in years ahead.

The alternative fuels that are relevant to shipping differ in many ways. What they have in common is that to become viable alternatives to conventional fossil fuels, energy value chains (Figure 1) will need to develop and upscale, in many instances more or less from scratch (Mäkitie, Hanson, et al., 2022). These value chains transcend multiple sectors and often also geographies, implying that innovation and upscaling challenges may reside far from the ship so to speak, both from a value-chain perspective and geographically. To exemplify, the upscaling of biofuels will necessitate significant changes far upstream in biofuel value chains, i.e. in 'biomass producing' sectors such as agriculture, forestry, aquaculture and waste, as well in developing the necessary processing and distribution capacity. A general feature of the value chains for alternative fuels for shipping (and also other energy using sectors) is that they are encumbered by waiting games and chicken and egg problems (Mäkitie, Hanson, et al., 2022). It is furthermore important to note that shipping decarbonisation occurs in a context of inter-sectoral competition (and potentially collaboration) over what are essentially scarce material and capital resources.

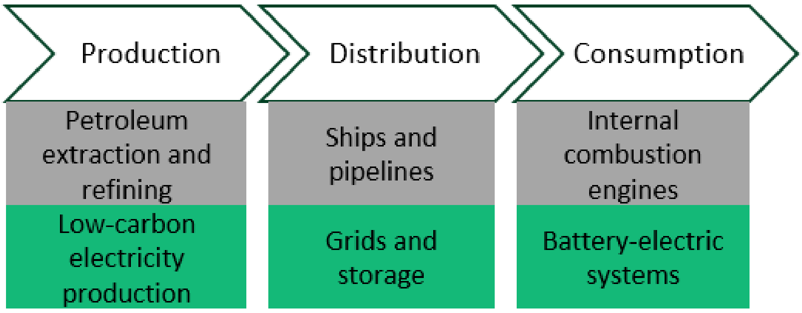

FIGURE 1 ENERGY VALUE CHAINS

Drawing on the seminal work of Henderson and Clark (1990), McMeekin et al. (2019), develop a framework to analyse 'whole system change'.[2] This refers to incorporating both production, distribution and consumption 'sub-systems' into analysis of transition processes to remedy the often compartmentalised foci found in most transition studies.

This framework basically distinguishes two main levels of innovation and change – modules and architectures – and assesses whether innovation leads to changes in couplings across sub-systems, and whether the overall outcome is system reinforcement or reconfiguration. This conceptualization results in a four-fold typology, which we use to organize our analysis (see Figure 5). *Modular incrementalism* refers to innovations that enhance efficiency of existing technologies/appliances but leaves the overall 'system' intact. *Modular substitution* similarly results in an overall unchanged system architecture, but where certain parts of a system are substituted. *Architectural stretching* implies that a system is expanded by adding new elements, i.e. by developing

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[2] As pointed out by McMeekin et al. (2019), the perspective of Henderson and Clark (1990) was developed to account for the reconfiguration of multi-component products, but argued to be useful also for understanding change and the level of systems.

new linkages to other (established or emerging) sub-systems. In the case of *architectural reshaping* there is a more profound reconfiguration whereby a product or service is ‘supplied’ by a system that is qualitatively different from the one that already exists.

To exemplify, the shipping sector is based on fossil fuels and internal combustion engines, whereas upstream sub-systems include petroleum extraction, fuel processing and refining, and fuel transport and bunkering. With a shift to for example biofuels, the degree of change in ships will be limited (i.e., modular incrementalism) because biofuels can be burned in conventional ship engines pending minor adaptation, whereas upstream changes in other sub-systems would be considerable. This would be indicative of architectural stretching. Conversely, a whole-sale shift to hydrogen produced from renewable energy via electrolysis would require changes across all sub-systems, amounting to modular substation and architectural reshaping.

The feasibility of upscaling and adoption of alternative fuels is likely to vary considerably, depending inter alia for degrees of modular and architectural change. Turnheim and Nykvist (2019) suggest that feasibility can be assessed along three key dimensions. First, alternative fuels differ with regards to maturity and expected developments moving forward. This includes the production of the fuels themselves as well as the necessary infrastructure and onboard energy conversion technology. Shipping companies are (naturally) risk-averse, and while early innovation adopters may be found in many shipping segments (Mäkitie, Steen, et al., 2022) the bulk of shipowners will be laggards. This also has to do with the longevity of ships which is typically at least 25-30 years. Second, new technology needs to be adapted to and integrated with not only ships but also in upstream infrastructure segments of energy value chains, as reflected in McMeekin et al.’s notion of architectural system change. Third, novel fuels and energy solutions often suffer from low legitimacy (for example related to safety concerns, performance, reliability), which may be cumbersome to overcome. Legitimacy is reflected in both political feasibility, given for instance the need for investment support, as well as social acceptance. The latter can for example be related to new energy storage infrastructure in harbour areas. Both political feasibility and social acceptance influence the development and upscaling potential of LoZeCs.

Sustainability transitions in shipping

Shipping has undergone shifts in main energy sources before. The first application of steam power occurred in the early 18th century, starting what would be a lengthy transition from sail to steam (and coal). Indeed, it would take a century before the arrival of the first ocean-going steamship. In the 1920s, shipping shifted from coal to diesel, and from diesel to heavy fuel oil (HFO) in the 1950s

(Balcombe et al., 2019). These previous technological shifts were driven by technological and/or competitive benefits, and were part-and-parcel of an increasing expansion and integration of the world economy. The difference this time around is of course that the 'green transition' is largely politically driven and part of a much broader agenda of dealing with the grand challenge of climate change. Not only will shipping need to reduce emissions – fossil fuel products such as crude oil and refined oil products and coal make up nearly 40% of global sea-borne trade, implying that decarbonization will have profound implications for the shipping sector. While fossil-based cargo will be reduced, other such as hydrogen, ammonia, biomass and (captured) carbon are likely to grow.

80% of all emissions from shipping stems from large ocean going cargo vessels, of which tank container and bulk add up to more than 60%. These are engaged mostly in international trade, and spend most of their time at sea. The vast majority of these ships are equiped with combustion engines running on fossil fuels, with power capacity installed over 5000 KW. These are the main target of international environmental and climate mitigation regulations.

Shipping is highly heterogeneous, segments differ with regards to their institutional and task environments, and whether or not different fuels/energy solutions are appropriate (Bergek et al., 2021). These are important factors explaining why shipowners vary considerably with regards to their susceptibility to adopt alternative fuels (Mäkitie, Steen, et al., 2022). Deep sea shipping, which is our main focus here, has commercial and operational characteristics as well as a governance system (Lister, 2015) that makes transition processes more complex than in sectors that are more locally embedded, such as in the energy sector or land-based transport. Alternative fuels must not only be available at reasonable price levels in different parts of the world, but also ensure safe voyages across vast stretches of ocean waters. The public procurement instruments that have been pivotal to enabling a transition to battery-powered ferries in Norway (Bjerkan et al., 2016) are not relevant for deep-sea shipping. Instead, the main governance instruments for decarbonizing deep sea shipping are found in supra-national institutions such as IMO, but also subject to firm-led environmental governance in global value chains (Poulsen et al. 2018). Increasing signs are evident of the latter, driven by large cargo owners seeking to lower the environmental footprint of their entire operation from upstream sourcing and production via logistics and distribution to downstream marketing and sales.

Taking into account the impact of increasing trade on shipping emissions, IMO is sharpening its requirements both for carbon intensity and operational efficiency. The latest update of IMO's Strategy on the Reduction of GHG emissions from ships (IMO, 2023), sets an even higher goal for 2050 than its previous version: 2050 emissions shall be net zero, and absolute GHG emissions shall be reduced by 70% compared with their 2008-level. In addition to existing policies on energy efficiency (design and operational index EEDI, EEXI, Cii) (IMO, 2022), new policy measures are expected to concretize in the next couple of years, such as a global fuel standard, for gradually reducing the carbon intensity of the fuels consumed by the international fleet and fostering the production and uptake of LoZeC fuels. Meanwhile, a significant step forward in terms of IMO GHG reduction policy is the switch of policy scope from CO_2 during combustion only (Tank-to-

Wake emissions, TTW) to a more comprehensive scope including emissions from fuel production (Well-to-Tank, WTT) and including other significant GHG, CH_4 and N_2O. This is formalised in the life-cycle analysis guidelines adopted by IMO in 2023.

At regional level, the EU has adopted very ambitious measures in the EU-fit-for-55 strategy, cutting 55% of emissions from international and domestic shipping by 2030. To support the transition towards LoZeC fuels, this package of measures include a.o. the emission trading scheme (EC, 2003) extended to the maritime sector, and a fuel standard to ensure a gradual reduction of shipping fuel GHG intensity of 80% by 2050.

Current status of alternative fuels

Since 2008, the carbon intensity of international shipping has decreased by 30% (Faber et al., 2021), mostly due to energy-saving technical measures (e.g. reducing frictional resistance) and operational measures (e.g. maximising utilisation, optimizing voyage and port calls). Absolute emissions, however, have continued to increase, mainly due to the increase in trade and shipping activity. In the near term, energy-efficiency types of measures are expected to dominate, and are highly relevant for the existing fleet. In the longer term, the potential for a maritime energy transition is real and alternative fuels and energy sources must play a key role if shipping is to contribute its share of GHG emission reductions. By and large, as we will outline in more detail in the following, alternative fuels are still under exploration. The world fleet is not ready for uptake of most of the available LoZeC fuels, partly due to engine incompatibility, and partly due to LoZeC value chains being far from realized and mature at the necessary scale.

The conversion of different main energy sources/feedstocks into fuels or energy carriers requires a number of intermediate process steps. These vary depending on both the energy source and the final fuel to be produced. Figure 2 displays the main production pathways for alternative fuels, illustrating variation in upstream energy sources (renewables, biomass, fossil energy), different process steps, and onboard energy conversion technologies. Variation along all these dimensions influence the total WTW emissions. The combustion of the same fuel in different energy converters generally results in different TTW emissions, depending on the thermal efficiency of the vessel engine and the load placed on the engine.

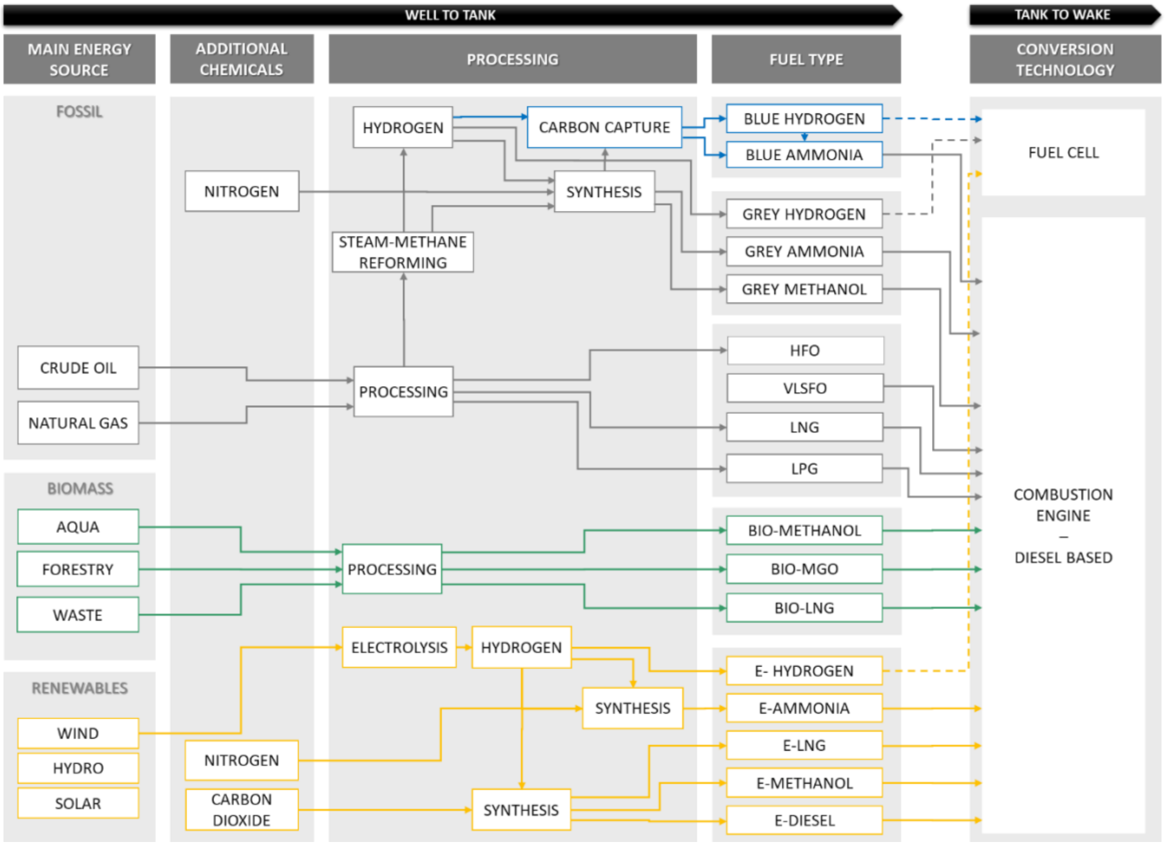

FIGURE 2 PATHWAYS TO ALTERNATIVE FUELS, BASED ON RIALLAND ET AL. (2023)

Fossil fuels

Compliant fossil-based fuels – meaning fuels complying with the IMO 2020's Global Sulphur Cap, prohibiting as of 2020 and on a global basis the utilization of fuel oil with sulphur content exceeding 0,50% (IMO, 2018) - include marine fuels HFO (Heavy Fuel Oil) in combination with scrubber (Exhaust Gas Cleaning System), VLSFO (Very Low Sulphur Fuel Oil), MGO (Marine Gas Oil), and lower-carbon alternatives LNG (Liquified Natural Gas) and LPG (Liquified Petroleum Gas). LNG/LPG offer a potential WTW GHG reduction around 17% compared to MGO at WTW-level, using the most efficient available engine technology: dual-fuel diesel engines. Fossil fuels are by definition not low-emission fuels. Given that global shipping almost exclusively runs on fossil fuels, these cannot however be ignored as they are likely to satisfy a significant share of the global shipping fleet's energy demand in years ahead. Decarbonization pathways based on fossil fuel include upscaling of alternative propulsion (wind-assisted propulsion) and onboard carbon capture systems. These technology combinations are being considered in carbon-intensity regulations in order to encourage and reward all relevant initiatives contributing to WTW GHG reduction from shipping. The expected continued relevance of fossil fuels has important implications for some alternative fuels, given that they are relevant as drop-in fuels.

Biofuels

Biofuels made from various waste streams and sewage including animal manure yield potential for reducing GHG emissions with 65% to 83% compared to MGO, and might even be climate negative. While production volumes are small, interest for biofuels and biogas is increasing rapidly, due to their high potential to reduce GHG emissions, but also given their compatibility with conventional combustion engines and possibility for blending with MGO and LNG. In other words, biofuels and biogas are highly relevant for the existing maritime fleet, with limited need for adaptation of ship engines and machinery. They also do not require any substantial alteration to existing infrastructure for fossil fuel transport and bunkering (Bach et al., 2021).

Biofuels are however by and large at piloting stage. Their low availability, limited scalability and the uncertainty and large variation in WTT emissions depending on their feedstock, makes it challenging to standardize biofuels globally. In a worse case, biofuels may raise WTW emissions due to farmland use and even deforestation compared to their fossil fuel counterparts. For conventional biofuels, rapeseed and palm oil for instance have 28% and 239% higher GHG emissions when land use is included.

E-fuels (electro fuels)

Electro fuels (or e-fuels) come in various types and have in common that electricity (from renewables) is used as the upstream energy source.

Hydrogen and ammonia

Hydrogen and ammonia are produced via electrolysis of water into hydrogen and oxygen, powered by renewable energy. For marine applications, these fuels must be liquefied at -253 °C for hydrogen and -33 °C for ammonia, a process that requires a substantial amount of energy. E-hydrogen is GHG emission free, meaning that no greenhouse gases are emitted when the power for propulsion is released in the fuel-cell or engine. E-ammonia has high energy density and no CO_2 emission when combusted, but higher N_2O emissions than conventional fossil fuels.

Common for both e-hydrogen and e-ammonia is that large amounts of renewable energy are needed in production (Lindstad, Lagemann, et al., 2021). Furthermore, liquid hydrogen and ammonia are more energy intensive to produce compared to conventional marine fuels, due to higher energy losses: approximately 30% loss during electrolysis, and an additional 20% loss for liquefaction (e-hydrogen) or 15% for processing to e-ammonia. In the context of shipping, e-hydrogen and e-ammonia are currently at a conceptual and piloting phase. An obvious challenge for both is that they require new vessels (or significant retrofitting) and supply infrastructures or conversions of existing ones, which makes these alternatives rather disruptive and slow to introduce into the global fleet.

On the other hand, hydrogen and ammonia are common commodities with a long history of production and distribution, albeit not for energy purposes. Indeed, the preferred production methods for decades (for economic reasons) has been to produce (liquid) hydrogen and ammonia from natural gas, so-called grey hydrogen and ammonia. Blue hydrogen (or ammonia) is based on fuels reformed from natural gas adding carbon capture and storage/utilization in the process. While not a renewable fuel if produced in this way, fuels derived from blue hydrogen can achieve significantly lower GHG emissions relative to crude oil-derived fuels currently used in international shipping. These are all candidate fuels because they are relatively energy dense, mean that they have similar or slightly lower energy density than the crude oil derived fuels currently used in shipping. Their storage would thus take up similar space on board. They also have the potential to be synthesised using renewable energy and industrial processes.

Synthetic e-fuels

Synthetic hydrocarbon fuels such as e-diesel, e-LNG and synthetic alcohols e-methanol are gaseous or liquid fuels produced from hydrogen and captured carbon (e.g. directly from air using renewable electricity). These fuels can have high emissions in the production phase unless they are produced with renewable electricity and electrolysis. They have high energy efficiency, are compatible with existing engine technology and existing infrastructure, and can be blended with conventional fuels (for example, e-diesel with MGO or e-LNG with LNG).

In addition to e-diesel and e-LNG, e-methanol (and also bio-methanol) has gained interest due to its technical and economic feasibility aspects. In theory, a vessel's diesel engine and fuel system can be modified to run on methanol. In practice however, methanol is likely to be mainly relevant for ships equipped with engines and fuels systems that are prepared for conversion to methanol. When it comes to TTW GHG emissions other than CO2, E-fuels are not free from challenges: as for conventional LNG, e-LNG faces the problem of un-combusted methane when combusted in a dual fuel Otto engine; in the case of ammonia, more N_2O is expected during the combustion than for all other fuels.

Synthetic fuels release CO_2 in the same amounts as conventional fuels when combusted, and therefore requires sustainably sourced carbon as inputs, as in biogenic carbon or carbon captured directly from the air, during their production process to be considered carbon neutral. Besides, and similar to electro fuels, their synthesis is heavily dependent on large amounts of renewable power.

Alternative fuels: emission reductions, energy use and life-cycle costs

As should be clear from the preceding summary of alternative fuels, they differ with regards to emission reductions, energy use and life-cycle costs. In the following we present an assessment of major alternative marine fuel options. The values and figures presented are from Lindstad et al. (2020); (Lindstad, Gamlem, et al., 2021; Lindstad, Lagemann, et al., 2021), following a life-cycle analysis WTW approach used to quantify (1) global warming potential, expressed in gram of WTW CO_2e emissions per kWh, (2) energy use expressed in amount of WTW energy needed to deliver one unit of brake power, and (3) life-cycle costs, expressed in total annual costs per kW of power installed on the ship, covering capital-, operational- and fuel costs. The relative figures displayed in the present assessment of alternative fuels are representative for large ocean carriers, and characteristic for a 55-65' dwt (deadweight tonnage) Supramax bulk carrier, which also can serve as a proxy for other bulk and tank vessels in the 35 – 80 000 dwt size range.

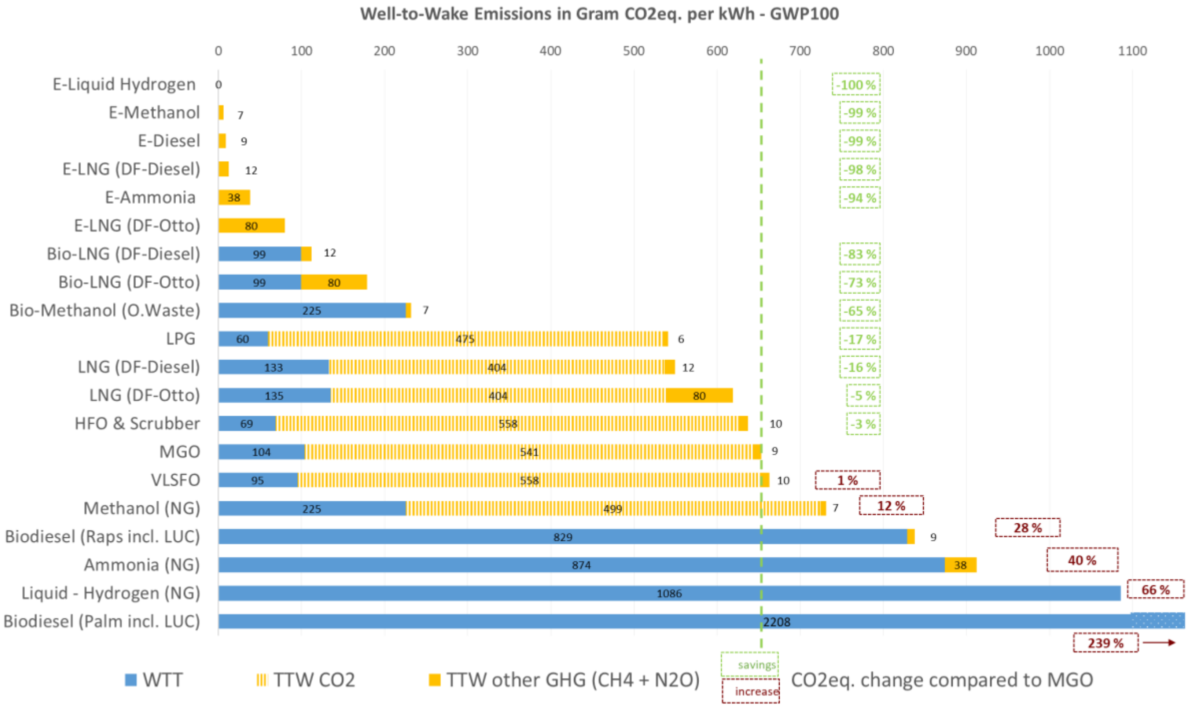

FIGURE 3 WELL-TO-WAKE EMISSIONS FROM SHIPPING FUELS. SOURCE: LINDSTAD, GAMLEM, ET AL. (2021)

One of the main decision drivers when considering alternative fuels, are lowest possible financial risk and disruption of operations. System flexibility in terms of fuel type and bunkering infrastructure is key, which is reflected in the strong interest for dual-fuel engines and conversion-ready solutions. The assessed fuels are therefore assuming 2-stroke engines installed, with average thermal efficiency of 50% assumed for all fuels & engine combinations assessed for simplification purposes and facilitating comparison.

Figure 3 displays each of the assessed fuels according to their WTW GHG emission per kWh, including a percentage variation compared to MGO as baseline.

With conventional fuels, combustion (illustrated in yellow colour) contributes to around 80% of the fuels WTW GHG emissions and energy usage, while their production, i.e. WTT (illustrated in blue colour), accounts for around 20% of their emissions and energy usage, whereas for non-conventional fuels, the production phase is energy intensive and emission reduction potential crucially dependent on renewable power.

Figure 4 displays a subset of the assessed fuel options according to their GHG emissions (as displayed in Figure 3), energy use and cost impact. The value of such juxtaposition is the visualisation of the contrast between fossil-based conventional fuels and renewable-based low emission fuels, not only in term of their GHG burden, but most importantly in terms of their energy intensity level and resulting impact on fuel costs. This highlights the energy burden of LoZeC fuels, an important aspect not to be overseen, even more significant than the cost impact of alternative fuels, which is affected by multiple factors, and can be counterbalanced by a CO_2 tax

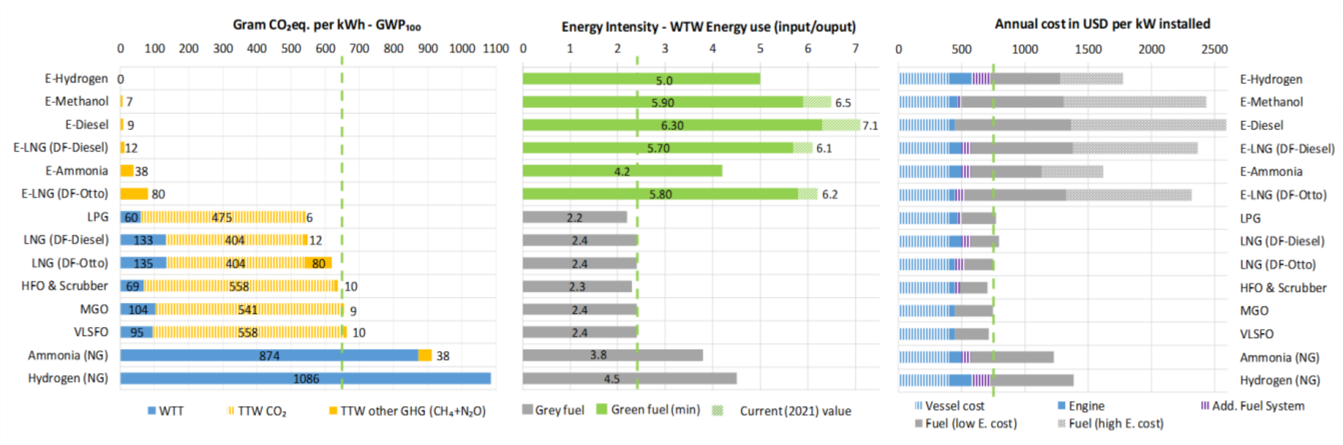

FIGURE 4 CO_2 EMISSIONS, ENERGY INTENSITY AND LIFE-CYCLE COSTS OF FUELS FOR SHIPPING. BASED ON LINDSTAD, GAMLEM, ET AL. (2021)

Alternative fuels and system change

Different fuel options imply larger or lesser need for adaptation and change both on ships (construction, design, machinery, operation) as well as in various upstream sectors. Following the framework adapted from McMeekin et al. (2019), the use of onboard CCS and drop-in biofuels (or other fuels that are compatible with internal combustion engines (ICE)) would surmount to modular incrementalism, i.e. very limited change from a broader system point of view. The same measures could also be important for modular substitution, including also hybrid propulsion. However, with more expansive use of biofuels or e-fuels, the use of captured carbon to produce those e-fuels, and the use of hydrogen or ammonia, the implications would be significant also for broader energy systems, amounting to architectural stretching or reshaping.

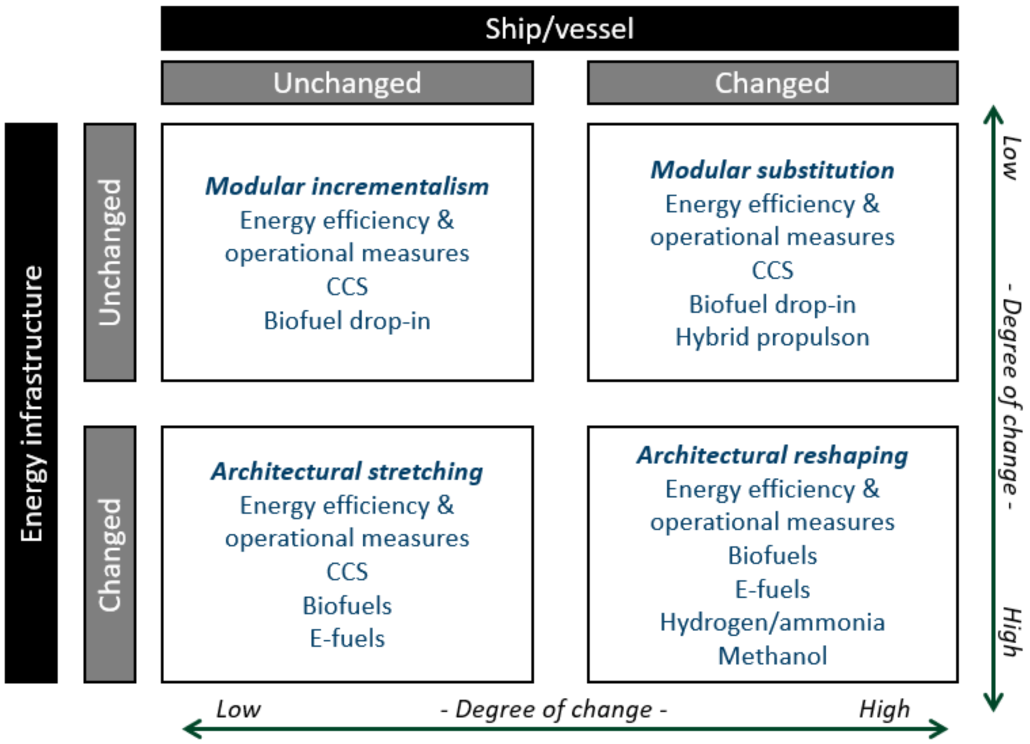

FIGURE 5 MODULAR AND ARCHITECTURAL CHANGE IN SHIPPING DECARBONISATION

Future prospects

Shipping faces a multi-pronged decarbonisation challenge. First, maritime transport forms the logistical backbone of the world economy and is expected to expand with global economic growth. Over the next decades at least, this is likely to impede overall emission reductions from the sector. Second, ships and port infrastructures are durable and have long lifetimes. Third, the heterogeneity of alternative fuels is both advantageous and a problem from an innovation point of view, in the sense that there is significant uncertainty with regards to which alternatives will ultimately mature and upscale to make a meaningful impact on shipping emission reductions.

Considering current orderbooks for major shipping segments, there is limited indication of ground-breaking investments in innovative designs or alternative energy systems other than combustion. Shipowners’ attention is instead mainly given to what can be controlled: alternative propulsion, energy saving devices and retrofits. Less investment is seen in alternative fuels, the main reason being lack of visibility in development and upscaling of production capacity and necessary for infrastructure globally. Indeed, Solakivi et al. (2022) estimate that emission reductions via alternative fuels will not be cost-effective “for a long time”, while Bouman et al. (2017) concluded that large sector-wide reductions could not be made with single measures, but rather that combinations of technological and operative measures are needed. This increases the importance of energy and operative efficiency to reduce overall energy consumption, as stressed also by DNV (2023). Pettit et al. (2018) argue that the technological solutions (i.e. LoZeC fuels) that are available to shipping, even when viewed optimistically, will not contribute sufficiently for maritime logistics to contribute to increased sustainability. Rather, shifts in the underlying systems of production and consumption (which are served by the maritime sector) need to be changed.

Going forward, various pathways are possible for shipping decarbonisation. Besides GHG abatement potential, alternative fuel strategies are influenced by fuel maturity, accessibility, compatibility and challenges associated with adoption and utilisation. We present some stylised examples of alternative technology paths and discuss their feasibility in the following.

Hydrogen fuel-cell path

As shown in Figure 3, e-hydrogen offers the highest GHG reduction potential and a real hope for full decarbonization of shipping. E-hydrogen is also cheaper and more energy efficient than hydrocarbon-based e-fuels. This path however implies a more or less complete substitution of the entire fleet, new operational standards, and massive build-out of renewable power, hydrogen production capacity and the relevant infrastructure in different corners of the world. Given this need for architectural reshaping, a pure hydrogen fuel-cell path currently appears to have limited feasibility.

Pure diesel path

Contrary to the fuel-cell path, a pure diesel path implies no disruption in technology or operation. It allows for maintaining the use of combustion engines and gradually reducing carbon factor by increasing the use of e-diesel as supply gradually picks up. Thus, a prerequisite for this path to lead towards decarbonisation would be a progressive increase in the share (drop-in) of e-fuel. However, given that full decarbonization is the ultimate target, this strategy is likely to be costly given expected future competition over/shortage of renewable electricity to produce e-diesel because of its high energy intensity. Considering biofuels as transition fuel from fossil to e-fuels, they do not necessarily play in favour of the diesel path given their low cost-competitiveness compared to bio-LNG or bio-methanol (LR&UMAS, 2020). The pure diesel path implies a more gradual system change, that starts with modular change and shifts towards architectural change as the share of e-fuels increases.

LNG dual-fuel path

A dual-fuel path with LNG enables a transition to zero emissions in several phases. First, LNG, even as a fossil-based alternative, enables around 15% GHG reduction compared to MGO and therefore several years of compliance in a fuel carbon-intensity reduction scheme. Secondly, e-LNG offers the largest GHG emission reduction when combusted in a dual-fuel Diesel engine. Replacing fossil-LNG with e-LNG in a dual-fuel LNG path thus offers a potential of up to 100% GHG reduction, achievable gradually depending on the pace of e-LNG introduction. The LNG path implies large additional capital expenditure (CAPEX) compared to the pure diesel path, and even with advantageous fuel price around 25% lower than MGO, LNG combined with dual fuel engine gives an abatement cost of up to 132 USD per ton of CO_2 reduction. In the case of e-fuels, high electricity prices gives a cost advantage to e-LNG over to e-diesel. However, in a full-decarbonization scenario and in the case of limited renewable electricity supply, e-LNG is disadvantaged by its higher WTW energy use compared to e-hydrogen or e-ammonia.

Methanol diesel dual-fuel path

Preparing for e-methanol requires lower initial investment than for ammonia or e-LNG. Even if switching to methanol gives no immediate WTW GHG emissions reduction as the LNG path does, bio-methanol can serve as a transition fuel towards e-methanol, provided that this alternative fuel becomes available. Should neither bio-methanol or e-methanol be available for a methanol-ready ship, the latter retains the possibility to run on VLSFO (very low sulphur oil) and MGO (marine gas oil).

Ammonia and methanol dual-fuel path

A dual-fuel path preparing for both e-ammonia and e-methanol is another alternative worth considering. This path can also include LPG (liquefied petroleum gas) as a transition fuel. This implies an engine and tank system able to accommodate both ammonia and methanol, plus LPG if selected as a transition fuel. A major drawback of this pathway relates to the lower energy density of the fuel, implying larger fuel tank volume (three times bigger than for MGO), and higher weight of the fuel (twice as high as MGO). In term of costs, getting methanol and ammonia ready yields a comparable CAPEX as the dual fuel LNG path. Enabling also for LPG as a transition fuel would require additional investments.

Summary

This chapter has outlined the current status and future prospects for decarbonizing shipping, focusing on the development and implementation of alternative fuels and energy carriers. We have argued that shipping is faced with significant challenges in its transition endeavours due in part to its sectoral characteristics, and in part due to challenges associated with developing and implementing novel energy solutions. Following McMeekin et al. (2019) we have furthermore suggested that the energy transition in shipping can transpire in different ways, involving both incremental and radical changes that pertain to both modules and architectures seen from a “systems” point of view.

It is fair to say that globally, the energy transition in shipping is at a very early stage. While there are numerous examples of innovation and technology substitution, for instance as witnessed in the shift to battery-electric systems in Norway’s ferry sector (Bugge et al., 2021), the shipping sector globally remains reliant on fossil fuels. Future prospects are highly uncertain, and appear to involve numerous solutions. Lindstad, Lagemann, et al. (2021) suggest «*that the most robust path for zero carbon fuels is through dual-fuel engines and systems to ensure flexibility in fuel selection, to prepare for growing supplies and lower risks*.” A general challenge with alternative fuels and energy carriers is that they tend to require large amounts of energy to be produced. Yet because so far the share of renewables in the global primary energy mix remains low, the GHG reduction potentials of for example (green) hydrogen or other e-fuels is dependent on the expansion of renewable energy supply to meet the renewable energy demands of both shipping fuel production and of wider energy system decarbonisation. Assessing the fuel alternatives that can allow shipping to decarbonize therefore demand attention to the implications on energy production globally, given that practically all sectors need to decarbonize while low- or zero-carbon energy production capacity struggles to meet this demand.

Acknowledgements

Elizabeth Lindstad passed away in May 2024. Elizabeth was an internationally leading researcher on the decarbonization of maritime transport and a fantastic colleague that will be dearly missed by all that knew her. This work was supported by the Research Council of Norway via grants #333118 (FME HYDROGENi), #296205 (FME NTRANS), and #295021 (INTRANSIT).

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We study the role of the energy system in the transition to the zero-emission society.