Evolution in the Engine Room: A Review of Technologies to Deliver Decarbonised, Sustainable Shipping

Technology options for the shipping sector to meet international ship emissions limits

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One of the more evocative cases of disruptive innovation is how steam powered vessels displaced sailing ships in the 19th century. Independent of wind and currents, shipping entered a new age. Faster shipping enabled more efficient trading and easier international travel. It fuelled economic growth and wealth creation. This transition was not rapid, taking half a century to evolve, a period in which hybrid vessels, those using sails and steam generated power were a common sight. The age of steam brought a period of change which affected many aspects of shipping, not only its appearance and practices but also its environmental impact. It facilitated further disruption and the emergence of what has become the industry standard for a ‘prime mover’: the diesel engine. Achieving the decarbonisation of the shipping fleet as soon as possible this century will be one of the most significant disruptions the shipping sector has had to manage. Meaningful change by 2050 requires strategic development and decisive action today, made all the more complicated by the immediate demands that the sector manages both the current and longer term impact that the COVID-19 pandemic will have on the shipping industry. This paper looks briefly at the transition from wind power to carbon based fuel power to gain insight into how the shipping sector manages disruptive change. It also reviews some technology options the shipping sector could adopt to reduce its environmental impact to meet a timetable of international requirements on ship emissions limits.

1. Introduction

International shipping is the lifeblood of the global economy, with over 90% of world trade carried by sea (Figure 1). It is the most efficient and economical (and in many cases the only practical) means of delivering goods across the world, but its sheer scale means that maritime transport is highly polluting. Powered by residual oil, shipping is responsible for a quarter of global nitrogen oxides (NOx) emissions (1, 2) and accounts for about 1 billion tonnes of combustion carbon dioxide emissions (3, 4) (greater than Germany’s and more than double those attributable to the UK).

Via the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI (6), the International Maritime Organization (IMO) has established rules that limit emissions of pollutants such as NOx and sulfur oxides (SOx) (7). In recent years these have required changes to engine room design and vessel operation. It has forced operators to consider carefully their fuel requirements and whether their vessels need emissions control equipment. More recently the IMO has set medium- and longer-term goals to reduce the carbon intensity of the shipping sector (8) and this looks set to revolutionise shipping. It has already stimulated a growing interest in alternative approaches to powering the world’s shipping fleet.
To achieve improved efficiency and better environmental performance the shipping sector has a range of options and strategies to pursue. These include optimised or alternatives to some shipping fundamentals such as propeller design, vessel design (9), assisted propulsion and the use of specialist hull coatings. Their effectiveness and cost will vary, a function of the technology, the vessel type and its charter.

Two of the most effective means of controlling emissions remain the choices of engine and fuel. To allow for non-conventional technologies that are in early stages of study or deployment we will use more general terms, energy conversion for the means of energy transformation (for example, combustion engine or fuel cell) that is used to propel the vessel and energy storage for the source of this energy (for example, fuel or battery).

Shipping has entered a transition state during which many technology options will be tested on board against key metrics such as safety, technical capability, economic performance and environmental impact. With the current regulation requirement incumbent technology and its analogues will be challenged to deliver improved performance with greater versatility. In the long term meeting the demands of very low emissions is likely to require quite different technology. This is expected to take a long time, acknowledging the typical lifetime of a vessel, the maturity of low emissions technology and the fact that the sector has not witnessed such a disrupting force for over a century, when on-board steam generated power challenged the long-established wind powered sailing fleet.

2. The Development of On-Board Power

Maritime trade has developed over many thousands of years. The earliest cargo vessels were single logs with attached shipment that floated downstream. About 5000 years ago some of the earliest trade routes had been established along the Arabian Sea. The Roman empire was (in part), established and maintained though development of its shipping fleet, for conquest, transport and trade. In the medieval period, the Arab Empire established efficient trade routes through Asia, Africa and Europe, helped by significant innovation in vessel development. During this period, remarkable designs emerged that set standards and influenced shipping for centuries. The caravel vessels that crossed the Atlantic to the New World in the 15th century could trace their lineage through incremental innovations on the medieval qarib. During the Age of Discovery from the 15th–19th centuries, there were advances in both ship building and navigation that opened up major global trade routes.

2.1 Steam Power

In 1818, the SS Savannah was built with a steam engine powering paddlewheels on each side of the vessel. As an insurance the Savannah also had sails and in 1819, it became the first steamship to cross the North Atlantic Ocean, a voyage that took about a month (10). Sails were used for most of the voyage. The Savannah was a successful pioneer but there were no rapid followers in the fleet. It took a further 20 years before steam ships
Innovation Case Study: The Carbon Age of Shipping

The sailing ships’ centuries of dominance were challenged by steam power in the early 19th century (Figure 2). Prone to breakdowns and occasional explosions, early steam vessels were deemed neither safe nor reliable enough for challenging, long distance travel such as transatlantic voyages. They found a niche application with river and lake transportation where their ability to travel independently of the wind conditions was a distinct advantage. With growing experience safety issues were addressed and reliability improved sufficiently to allow transatlantic service. Disruptive innovation (12) refers to situations where new technology is introduced to a market that offers similar capabilities to existing offerings, but with some disadvantages that make it less desirable, for example stage of development, reliability or cost; but with at least one distinctive advantage that allows it to find a niche, survive and grow. In this niche, the technology innovation can accelerate at a faster pace than the incumbent. In some cases, this eventually leads to the mass market adopting the new technology, sometimes via a hybrid phase where both new and incumbent technologies are on board.

As the safety and reliability of steam technology improved, early steam vessels began venturing further afield. On long haul charters they ran with sails partly as an insurance and partly as it was difficult to carry enough coal or water for these voyages. On 4th April 1838 the SS Sirus left Cork in Ireland and 18 days 4 hours and 22 minutes later reached New York, becoming (one of) the first vessels (13) powered by continuous steam to cross the Atlantic from Europe to North America, establishing the age of on-board combustion power (Figure 3).
made regular transatlantic crossings. Progress was slow but sure and no longer dependent on winds and ocean currents typical journey times fell significantly (by 50% or more).

Steam power evolved to use fuel oil and boilers to generate steam and finds niche application even to this day, for example in liquefied natural gas (LNG) carriers and navy vessels (using nuclear power). Early steam ships suffered their own significant problems. The coal bunkers took up precious cargo space. The operation of a furnace required significant manpower and combustible coal and coal dust meant the vessels were more vulnerable to catastrophic fires. These concerns over safety and efficiency set the challenge for further innovation and the emergence of an on-board solution that, in time, addressed many of the concerns: the diesel-fuelled internal combustion engine (ICE).

2.2 The Internal Combustion Engine

The ICE was introduced in the early 1900s, when British shipbuilding was at its peak. An early adopter of the technology was the Doxford Yard on the Wear in Sunderland. Doxford’s four-cylinder engine (11) combined efficiency with simplicity of operation and soon found wide adoption. This and similar engines offered the benefit of better revenue generation through more effective use of space (as the fuel did not require the same volume storage as coal) and cost savings, for example requiring less manpower to operate. They also offered a greater range between refuelling stops. The large two stroke (2T) engine became the standard for international shipping but innovation continued generally in response to specific sector needs.

2.3 Diesel Electric

Dielectric generators produce electricity that drives an electric motor unit that turns the propeller shaft or other propulsion devices. Diesel electric systems occupy less space than the two-stroke diesel engine equivalent and as it dispenses with the need for auxiliary power it also allows the weight in the hull to be more evenly distributed. Diesel electric technology also emerged in the early 1900s but for most of that century found niche application. Advances in alternating current drive technology have facilitated wider adoption of the central power station on board that efficiently manages both propulsion and other power requirements. It is particularly useful in applications where dynamic positioning is required and those where propulsion is one of many power demands, for example drilling vessels.

2.4 Co-Evolution of Engine with Fuel Oil

Critical to the development of on-board power was the symbiotic relationship between the diesel engine and fuel. As vessels changed and the engine room evolved, one of the critical factors in this was the way the shipping sector adapted to the availability of cheaper fuel, the heavy residual of the refinery. Ship engines were specifically designed and modified to be powered by heavy fuel oil (HFO). HFO has a tar-like rheology and contains high levels of sulfur (~3%) and other residual components such as heavy metals. Its physical chemistry means that HFO must be heated to allow it to flow and it is combusted at high temperatures that produce significant levels of NOx. The fuel borne sulfur is emitted as SOx. A typical fuel intake for a large two-stroke diesel engine and its indicative emissions are illustrated in Figure 4.

The diesel engine brought many benefits and became the workhorse of shipping, but success had a dark side: a rapidly growing and unsustainable environmental impact. By the 1990s there was growing pressure to address this and as shipping was a global industry it needed to be addressed at a global level.

3. Limiting Emissions from Shipping: Regulatory Approach

The IMO is the United Nations specialised agency with responsibility for the prevention of marine and atmospheric pollution by ships and prefers to govern by consensus, via a process of discussion and agreement. In this spirit it organises meetings to gather many of the interested parties including nation state representatives, industry groups and other non-governmental organisations (NGOs) to discuss and agree how to address environmental concerns. It seeks to balance the (economic) concerns of the industry with environmental concerns. This is not an easy task and in practice can result in a protracted process taking many years to reach an outcome.

The pressure for shipping to address its expanding environmental wake has seen some progressive
steps taken on emissions, especially those from new build vessels. New emission rules are signalled well in advance of enforcement dates to allow the sector to plan and adjust, minimising the economic cost of the change. This can lead to unintended consequences, exemplified in the IMO III rules for NOx. Agreed in 2008 and coming into force in 2016 for new build vessels operating in NOx Emission Control Areas (NECAs), the rules were expected to reduce the NOx emissions in these areas (15). In 2019 it was reported that very few port calls used Tier III compliant vessels. Since the new rules only applied to new build vessels it allowed operators to legitimately use older (more polluting) vessels to enter NECAs. This anomaly will correct itself in time, but it will take a decade or more, many decades from the initial discussions to lower NOx emissions.

It raises questions about a process that takes many decades to take effect when both environmental NGOs and progressive member states are looking for more rapid results from policy decisions. The aspiration of the consensus model of governance, even in complex multiparty problems, is to deliver a balanced outcome that all parties support. The outcome does not satisfy every party with some disagreement recorded over the timing, applicability and availability of technology (16, 17). It can also mean that there is little appetite and limited possibility to revisit, review and revise after a brief period of ‘real world’ experience and evaluation (18). After many years of discussing the sector approach to local pollutants and air pollution (chiefly NOx and SOx) the IMO focus has moved to another side effect of on-board power: greenhouse gas (GHG) and CO$_2$ emissions (19, 20).

### 3.2 Carbon Dioxide and Greenhouse Gases

In order to address emissions of CO$_2$ from the shipping sector the IMO developed the Energy Efficiency Design Index (EEDI) which is mandatory for new vessels and the Ship Energy Efficiency Management Plan (SEEMP) for all vessels (21). The EEDI is intended to stimulate accelerated innovation in the sector as it mandates the use of more energy efficient (less polluting) equipment to meet minimum energy efficiency standards on a per capacity distance basis (for example, tonne kilometre). In addition, it requires a progressive improvement on a five-year basis (10% in the first phase). It is a non-prescriptive, performance-based mechanism and uses a mathematical formula based on the technical design parameters for a given ship (Equation (i), (22)).
It leaves the choice of technologies in a specific ship design to the industry. The EEDI has been developed for the largest and most energy intensive segments of the merchant fleet and currently covers 72% of emissions from new ships including oil tankers, bulk carriers, gas carriers, general cargo, container ships, refrigerated cargo and combination carriers. For ship types not covered by the current formula, appropriate equations are being developed. The SEEMP establishes a mechanism to improve the energy efficiency of the existing fleet in a cost-effective manner. It allows shipping companies to manage ship and fleet efficiency over time by monitoring performance, using tools such as the Energy Efficiency Operational Indicator (EEOI). It is intended that SEEMP will incorporate best practice for fuel efficient ship operation, as well as guidelines for voluntary use of the EEOI for new and existing ships. In this way, at each stage, the ship owner or operator is encouraged to consider new technologies and practices as they optimise vessel performance.

In April 2018 the IMO took steps to clarify the intended outcome of its policy measures, announcing its GHG strategy with a vision to phase out GHG emissions as soon as possible this century. It outlined three ambitions:

a. Use the EEDI to reduce the carbon intensity of individual vessels
b. Reduce the CO₂ emissions per unit of transport work by at least 40% by 2030, targeting 70% reduction by 2050 (based on 2008 emissions)
c. Reduce annual GHG emissions by at least 50% by 2050 (2008 basis) on a pathway to CO₂ emissions reduction consistent with the Paris agreement.

This is a progressive agenda, especially given that trade and thus shipping is expected to grow significantly in the next few decades (creating a potential emissions gap) as illustrated in Figure 5.

The IMO recognises that delivery on this objective needs considerable support stating that: “technological innovation and the global introduction of alternative fuels and/or energy sources for international shipping will be integral to achieve the overall ambition”. In so doing the sector has recognised the key elements of technology strategy required to meet these targets. Meeting the three main options for reducing GHG emissions in shipping the sector will seek:

a. To improve vessel design
b. To use more efficient on-board powertrains
c. To substitute fossil fuels either directly with low-carbon biofuels or low or zero-carbon electricity, or indirectly by using low or zero-carbon electricity to produce hydrocarbon or carbon-free fuels (power-to-X, e-fuels).

![Fig. 5. Schematic summarising the IMO CO₂ and GHG strategy. Source: DNV GL](image-url)
4. Meeting Emission Requirements: Industry Options

To achieve the very low emissions required by 2040 and 2050 the engine or energy converter and the energy store (fuel type) will play an important role. Improvements can be tracked and monitored in several ways. One is to focus on the vessel as a system and point source and look at the impact it has on its environment i.e. a ‘tank-to-propeller’ analysis (23, 24). A more complete analysis also considers the supply chain, referred to as ‘well-to-wake’ analysis (25). Here the more holistic approach considers emissions associated (with land based activity) with aspects such as fuel manufacturing or production, storage and use, so that the wider aspects of emissions are measured, addressed and reduced. Some regulatory approaches allow for greater operator choice and versatility in approach by placing the emphasis on reducing emissions on a fleet (rather than a vessel) basis.

The well-to-wake analysis links the drive to decarbonise shipping with that of decarbonisation of power generation and transportation on land. Some in the shipping community argue that it would be more sensible and effective if efforts to decarbonise were focussed on other related sectors in energy and transportation where there might be a lower opportunity cost and higher return on effort, but a consensus has aligned around the message that shipping must play its part in a transition to a decarbonised world (26).

5. Propulsion in the Future

In order to meet significant reductions in GHG (CO₂, methane, nitrous oxide) it is the energy source and the energy conversion (and the interplay between them) that offer the greatest potential for impact. In the next sections we look at the main options that have emerged to help the shipping sector plot a course for decarbonisation.

6. The Energy Source

Figure 6 shows a number of energy source options available for shipping. This section will present the benefits and concerns for each.

6.1 Heavy Fuel Oil

Today, HFO and intermediate oils based on HFO (blended with distillate fuel) are the fuels of choice for international shipping. With well-developed supply chains and familiarity in operation, HFO has the benefit of incumbency and ready supply. It has advantages in cost as well as power density. The fact that it is a carbon based fossil fuel will lead to a phase out of HFO in the longer term (50–70 years) (28, 29) but more immediate concerns over its detrimental impact on the local environment (SOx emissions) may effect more rapid change. Operators face a restricting uncertainty with respect to these sulfur containing fuels. As recently as January 2020 70% of fuels sold in Singapore, the world’s largest bunkering hub, were...
low sulfur (30). The IMO and US Environmental Protection Agency (EPA) rules allow for vessels to use HFO so long as the emissions are treated (with an on-board SOx scrubber) to meet compliance; however a growing number of regions, for example port authorities, have banned the use of the most popular ‘open loop’ scrubbers (31). This has raised a significant question over future demand of higher sulfur fuels and may accelerate adoptions of cleaner alternatives, i.e. cleaner, lower sulfur fuel such as marine gas oil (MGO).

- **Benefits of HFO**: incumbency, experience, economics and energy density
- **Concerns of HFO**: in the short term, local pollution (NOx, particulate matter, SOx/SO₂⁻). Over the longer term GHG from hydrocarbon combustion (CO₂ emissions), availability (if demand falls).

### 6.2 Marine Gas Oil

MGO is a distillate fuel with lower sulfur content (1000 ppm). MGO is similar to diesel fuel but has a higher density. It has found application in medium to high speed engines. Unlike HFO, MGO does not have to be heated during storage. MGO and diesel fuels are cleaner with lower (though still significant) emissions of local pollutants compared to HFO. They are more expensive than the HFO based fuels and do not allow significant steps toward decarbonisation. Carbon based fuels such as biodiesels offer potential towards decarbonisation.

- **Benefits of MGO**: experience and energy density (cleaner than HFO)
- **Concerns of MGO**: short term significant local pollution (NOx, particulate matter, SOx/SO₂⁻). Longer term, GHG from hydrocarbon combustion (CO₂ emissions).

### 6.3 Biofuel

Biofuels such as biodiesel, bio-methane, bio-methanol and hydrogenated vegetable oil are derived from biological waste in sectors such as agriculture, forestry and farming, or from dedicated biofuel crops. Depending on the type of biofuel used, they can achieve CO₂ reductions of up to 90% (32). However in 2018, less than 1% of the fuel supply in shipping made use of biofuel (33), with the few initiatives operational mostly involving inland or short-sea shipping. A recent report suggests around 11% of fuels sold at one large port are blended with at least some biofuel (34). A major problem with biofuels for shipping remains their cost but concerns over their sustainability have underlined the requirement that those used for shipping must be advanced generation biofuel (35). Even with advanced generation biofuels, demand from other applications will restrict an already limited availability for the shipping sector.

- **Benefits of biofuel**: potential for lower GHG emissions (well-to-wake)
- **Concerns of biofuel**: high cost, availability, local pollution (NOx, particulate matter). Hydrocarbon fuel producing point source GHG CO₂ emissions (tank-to-propeller).

### 6.4 Liquefied Natural Gas

Other carbon-based fuels that allow a step towards lower carbon propulsion include natural gas. Over the last 20 years there has been a significant strategic effort in developing LNG as a marine fuel. Today hundreds of LNG powered vessels are in operation, representing 2100 engines with about 30 million hours operational experience (36). Some LNG powered vessels are mono-fuelled, but most are dual fuelled. This fleet is supported by a fuelling infrastructure that is established and expanding. LNG is available (or planned) in virtually all the major ports. The commercial viability of LNG vessels is supported by a growing order book across most vessel types. Most if not all vessels that are LNG powered are fully compliant with existing legislation for SOx and NOx emissions (providing the engines operate in their preferred lean burn mode). LNG engines have very low emissions of particulate matter and in lean burn mode can also claim higher CO₂ efficiencies. Supporters of the technology report CO₂ emission reductions of 7–21% on a well-to-wake basis, and up to 28% on a tank-to-propeller analysis (25). The wide range belies one of the most critical factors to continued confidence in LNG as a ship fuel: its true GHG emissions. Under lean burn conditions significant fuel slip can occur, where uncombusted fuel enters the atmosphere. In the case of LNG this is methane slip and since methane has a GHG factor of ~28 any gain in CO₂ efficiency can quite rapidly be lost in real (GHG) terms.

- **Benefits of LNG**: availability, lower emissions including NOx, SOx and GHG (tank-to-propeller) if significant methane emissions are controlled. Established and growing infrastructure and experience
- **Concerns of LNG**: Energy density (requiring cooling or compression for storage), hydrocarbon fuel remains a point source of
Innovation Case Study: Addressing the Issue of Methane Slip

Uncombusted fuel from natural gas engines is largely the GHG methane. Compared to more functional hydrocarbons, methane is difficult to oxidise as illustrated in Figure 7(a). This means conventional catalytic converters will not work. For methane oxidation catalyst systems higher temperatures are needed and for some engines this may require the system to be installed in a pre-turbo position. In addition to catalytic activity requiring higher temperatures, other performance related factors include resilience to hydrothermal ageing and susceptibility to sulfur poisoning. Improvements in the tolerance for hydrothermal ageing have been achieved via innovative catalyst development but the issue of sulfur is one that requires a more holistic system approach. Inhibition of catalyst activity occurs quite rapidly in the presence of sulfur species as indicated by the fall off in catalyst performance. Up to 50% of activity can be lost over a 24-hour period as indicated in Figure 7(b). This decay in performance is reversible. By heating the catalyst, for example by inducing an exotherm through fuel injection, the catalyst performance can be regenerated, as illustrated in Figure 7(c). Methane injection has little impact on regeneration but a pulse of a higher hydrocarbon such as propane proves very effective. The engine or oxidation catalyst system can be optimised to gain the lower carbon benefits of natural gas combustion with minimal methane slip.

There is a possibility to address the problem of methane slip, for example via deployment of catalytic aftertreatment to oxidise the methane (Figure 8). Another concern with natural gas is the fact that it has to be cooled and compressed or liquefied for storage. Converting natural gas or methane to methanol resolves this issue.

![Fig. 8. A methane slip reactor. Courtesy of Johnson Matthey](image-url)
GHG CO₂ emissions (tank-to-propeller) and significant methane emission.

6.5 Methanol

Methanol (37, 38) is a safe, cost-effective alternative marine fuel. It is the simplest alcohol with a low carbon to hydrogen ratio and is a basic building block for hundreds of essential chemical commodities. With an annual production capability of the order of 100 million tonnes per annum (39) it is one of the top five chemical commodities. It has an existing global infrastructure and many close connections to major ports. It is produced from natural gas, but there is potential for methanol as an outlet for ‘power-to-X’ electric fuels (40) when it is produced from renewable sources such as biomass and recycled CO₂. Methanol is a liquid under ambient conditions which means that relatively minor modifications to the existing bunkering infrastructure are required to handle it. Naturally low in sulfur it has gained interest as a fuel for operation in Sulphur Emission Control Areas (SECAs) (41) and with clean combustion methanol has relatively low emissions of NOx and particulate matter. The well-to-wake emissions of methanol (produced from natural gas) is a little higher than that of oil fuels but this is reduced considerably if a power-to-X pathway to production is used.

- **Benefits of methanol**: availability, liquid, lower emissions including NOx, SOx and GHG (tank-to-propeller). Potential for low well-to-wake emissions (if renewable energy sources are used in production)
- **Concerns of methanol**: Energy density, hydrocarbon fuel remains a point source of GHG (CO₂ emissions) (tank-to-propeller).

6.6 Liquefied Petroleum Gas

Liquefied petroleum gas (LPG) is any mixture of propane and butane in a liquid state. It is a byproduct of oil and gas production and oil refining, but it is also possible to produce LPG from renewable origins, for example bio-LPG can be separated as a by-product of the production of renewable diesel by hydrogenation of the triglycerides of vegetable oil or animal fat. Propane is a gas under ambient conditions, but it has a boiling point of −42°C and hence by applying a moderate pressure it can be handled as a liquid at room temperature. Butane’s isomers have higher boiling points and liquefy at lower pressure. The use of LPG as a shipping fuel is at a much earlier stage in technology development with a number of projects in the approval stage (by classification societies) (42). Early interest in LPG was driven by the fuel’s low sulfur content and thus applicability for operation in SECA regions. On a cost basis it is likely to be on a par with LNG (43). LPG also offers flexibility in terms of the combustion process used on board, capable of being applied to single fuel ICE, dual fuel engines, gas turbines and reformers linked to an ICE or fuel cell. LPG has fewer challenges related to temperature because in smaller tankers it is not kept at cryogenic temperatures, although larger tankers are cryogenic. However, it has challenges related to higher density as a gas and a lower ignition range. LPG combustion results in lower CO₂ emissions compared to oil-based fuels due to its lower carbon to hydrogen ratio. Considered in a lifecycle perspective, LPG production is associated with lower emissions than oil-based fuels or natural gas. The combination of low production and combustion emissions yields an overall greenhouse gas emissions reduction of 17% compared to HFO (44) on a well-to-wake basis. LPG combustion can also benefit from lower NOx emissions, but it does depend on the engine technology used. The development of bunkering infrastructure remains a barrier which is the case for the market adoption of any non-drop-in fuel, although such fuels could use LNG infrastructure.

- **Benefits of LPG**: liquid, lower emissions including NOx, SOx and GHG (tank-to-propeller). Potential for low well-to-wake emissions (if renewable energy sources used in production)
- **Concerns of LPG**: availability, ignition range, hydrocarbon fuel remains a point source of GHG (CO₂ emissions) (tank-to-propeller).

These fuels, including LNG, methanol, LPG and biodiesel, are still carbon based and though through use of renewable energy may have reduced GHG emissions on a well-to-wake analysis they will continue to make significant emissions at a tank-to-propeller basis. For low emissions on a tank-to-propeller basis, zero carbon fuels such as ammonia and hydrogen must be used.

6.7 Ammonia

As a fuel for shipping, ammonia (45) is at a very early stage of development, but as an energy carrier with no carbon it is very attractive on a tank-to-propeller basis and this can be extended to well-to-wake providing that a renewable energy source is used in a power-to-X channel of

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production. Ammonia is produced on an industrial scale by reacting hydrogen and nitrogen via the Haber-Bosch process. Hydrogen is supplied via steam reforming of natural gas, but this hydrogen could be produced via renewable energy, for example during times when there is surplus wind power. Though hydrogen is a fuel itself (see below) and can be compressed or liquefied, converting it to ammonia is attractive as it is then relatively easy to handle. Early stage adopters of ammonia as a fuel are still evaluating the options for on-board power generation. Ammonia can be used to fuel a conventional engine but the combustion system must be optimised to limit ammonia slip and emissions of N₂O (a GHG with an emission factor 298 times that of CO₂ (46)). In addition to the ICE, fuel cell technology is also attractive. Polymer electrolyte membrane (PEM) fuel cells require ammonia to be cracked to provide high-purity hydrogen whereas solid oxide fuel cells (SOFCs) can use ammonia fuel directly. The sector is particularly wary of this alternative fuel especially as it is caustic and hazardous and requires the development of new safety standards (47). It will require the development of infrastructure to support its bunkering. In the short term, it could be combined with LNG. What is very attractive however is its zero carbon emissions potential and it is for that reason that many see ammonia (and hydrogen) as being the long term winners in the race to fuel the global fleet (48).

- **Benefits of ammonia**: potential for low GHG emissions. Potential for use with different energy converters (engines), ICE and fuel cells
- **Concerns of ammonia**: availability and experience (safety). Risk of ammonia slip and N₂O emissions (significant GHG) during combustion.

### 6.8 Hydrogen

Hydrogen is expected to play an important role as an energy vector in a truly decarbonised economy. It has been described as the missing link in an integrated, sustainable and clean energy system (49). The product of its combustion in air is water which is also the starting material for its renewable production. Today hydrogen production via steam reforming is an industrial process that produces 70 million tonnes per annum (50), but it is as an outlet in a renewable power-to-hydrogen channel, for example via electrolysis of water, that excites most interest in terms of its future potential as a zero carbon energy vector.

Its major setback as a shipping fuel is linked to its relative energy density and storage (Figure 6). Hydrogen may be stored cryogenically in liquid form at -253°C but this may incur a parasitic loss of up to 18% in energy of cooling. It can be compressed but such pressurisation requires triple-layer carbon fibre reinforced tanks that are bulky and expensive. Alternatively, storage as a metal hydride or other molecular solid structure is possible but real-world success has been limited and metal hydrides and other containment solids are often difficult and dangerous materials to work with. An option for larger vessels would be to de-risk technology deployment by using a combination of technologies such as a hydrogen powered ICE or combined cycle turbine for propulsion and a fuel cell for auxiliary power.

- **Benefits of hydrogen**: Low GHG emissions tank-to-propeller and potential for low well-to-wake emissions (if renewable energy sources used in production). Potential for mixing with other fuels (natural gas), use with different energy converters (engines) ICE and fuel cells
- **Concerns of hydrogen**: Storage, power density, experience (safety).

### 7. Energy Conversion

#### 7.1 Combustion

The ICE has been the prime mover of international shipping for a century combusting hydrocarbon, mainly diesel fuels (HFO and ultra-low-sulfur diesel (ULSD)). Historically, improvements to engine design have focussed on maximising power and torque but more recently innovation has delivered more efficient, more environmentally friendly engines. Dual fuel engines that can switch between natural gas and diesel fuels smoothly during operation are now established (51). Their success underscores one of main strengths of the ICE: fuel flexibility. With an appreciation that a large range of fuels may be available in the future (as discussed above), with local variations in availability engine designers have targeted designs that need minor modifications to cope with different fuels.
7.2 Electric Drive: Fuel cells

A very different energy conversion process, from chemical to electrical energy is that used by fuel cells. Fuel cells (52) offer potential for low pollution with high (theoretical) efficiency. Here the chemical energy of the fuel is directly converted to electricity, thus fuel cells are not restricted by the Carnot efficiency limit (53) like combustion and heat engines. This high efficiency is available over a large power and temperature range making them suitable for dynamic load cycles especially at very low loads. Compared with conventional combustion engines, fuel cells’ application in shipping is at a much earlier stage of the development cycle. Significant progress has been made on making the technology more reliable and durable with considerable effort being devoted to achieving this at more acceptable cost (54–56). Over the last decade fuel cells have been the subject of early stage demonstration trials. Many types of fuel cell have been studied including molten carbonate, PEM and SOFCs. One of the problems holding back fuel cell applications in the shipping segment, as with many regulation driven markets, is the difficulty in displacing the entrenched incumbent technology (57). Few companies can continue to invest in product development for a period of many years in the hope that a market will eventually materialise.

There has been successful application of fuel cell technology in the shipping sector. PEM fuel cells using hydrogen are already established in the niche markets of submarines (58). Here the propulsion motor is electrical and the electric power to move the motor is produced by the diesel generator. When submerged, the energy to move the electric motor is obtained from an electrical source such as a battery or fuel cell. Capable of meeting high energy demand for short periods of time, hydrogen PEM fuel cells are particularly useful when the submarine needs maximum power.

7.3 Battery Technology

The use of large batteries in electric or hybrid ships is still at an early stage but already finding use in helping optimise power control and significantly reducing fuel costs, maintenance and emissions. Energy conversion and power generation units can be more compact compared to the current ICE systems and optimised for overall operation (average rather than peak load, and thereby reduce investment costs). Batteries can store energy harvested from several sources such as waste heat recovery and renewable energy. Additionally, they can improve propulsion systems based on LNG and other environmentally friendly fuels and improve the performance of emission abatement technologies. A study led by DNV GL (59) showed that the environmental impact of creating the battery system is small compared to the emissions savings and potential emission reductions can play an important role in reducing emissions from domestic and international shipping. Issues related to size, weight and range remain especially with application to long distance transportation.

The benefits of battery technology include zero emission at the point of use (tank-to-propeller). They can be complimentary to other energy converters (engines), ICE and fuel cells.

8. Discussion

The shipping sector is facing its greatest period of change since the transition of sail to steam. Today, the predominant market force effecting change is not economic but regulatory, driven by a societal demand for cleaner sustainable shipping and the growing interest in sustainable supply chains (60). Having defined its objectives, the sector will rely on market forces to determine the winning technologies and technology pathways to deliver zero emissions shipping by the end of this century. The 2050 target is a relative one, so could be impacted for example by a (COVID-19 caused) global recession and prolonged downturn in shipping (61, 62) (Figure 9). The exact nature of this and any future event that impacts the fleet will effectively make that goal a moving target. However, it is expected that post-recession there will be an economic recovery and that the shipping industry will return to growth (63).

8.1 Insight from the Transition to Steam Power

The transition from wind to onboard power generation in the 19th century and the eventual establishment of the diesel engine as prime mover in the 20th century was not a rapid one and faced many challenges (Figure 10). The first was the incumbent technology with all the associated benefits developed over many centuries, a firmly established practice with a well-trained workforce with specialised knowledge in navigation, an appreciation not only of the elements, but of
rigging and sailing in all its aspects, especially in how to sail close to the wind to achieve optimum performance at acceptable risk.

For significant technology transitions to be successful a skilled workforce is required. The supporting infrastructure must be developed, and the costs associated with the new technology must be acceptable (or offer promise of lower costs via a cost-down trajectory, engaging economies of scope, scale and the learning curve). The force of the transition is likely to be dominated by the superior characteristics or benefits (above the incumbent) brought by the new technology. In the case of the sail to steam transition it was driven by the overwhelming benefit of on-board power’s capability to operate independently of the hitherto effective but unreliable energy source: the wind (Figure 11). It suffered major drawbacks, in particular the safety issues, related to coal and coal dust related fires and costs associated with both storage (parasitic space) and cost of the energy source (coal). During a successful transition these issues are resolved or managed giving time for infrastructure development (for example, water and coal supply).

Critical to success is the identification of a niche market where the benefits are particularly valuable and the where some of the issues are more easily managed. For steam shipping this niche was inland waterways where the ability to move unassisted by external forces (for example, horse power) was valued, the need for an expensive supporting infrastructure less of an issue and the space requirements less of a concern. Crucially it allowed some of the critical concerns and barriers to adopting to be resolved. Issues of coal dust related fires became better understood, and risks mitigated. Operational experience led to a workforce trained and skilled in the new technology and its on board operation. As the issues of concern were resolved or managed, so the barriers to adoption were removed and the key benefit of continuous operation independent of the elements pulled the technology into the mainstream.

This approach offers a first order analysis of why significant change occurs but more in-depth
analyses look into the mechanism of how by establishing what other factors supported the evolution. Geels’ (64) approach is a more comprehensive study that uncovers the fine detail that facilitated and supported early steam powered vessels such as the deregulation of the British fleet and the impact of the Industrial Revolution and illustrates elegantly the importance of environmental or situational factors in how change evolves.

8.2 Towards Sustainable Shipping

In December 2019 at Marintec China, Martin Stopford of Clarkson Research (65) presented a model that would allow the shipping sector to meet its emission commitments. It is summarised in Figure 12.

The prime mover of a zero emission vessel is likely to have an electric drive based on a fuel cell using green hydrogen. Electric plants of this sort are not expected to be available for at least a decade so meeting the emission challenge will be a staged approach where each subsequent technology wave delivers decreased carbon intensity.

The first wave acknowledges two critical issues. That 2020 will see (the beginning of) a significant recession and recognises the current dominance of fossil fuels as an energy source and store (99% of cargo fleet) and the ICE as the energy conversion process (85% of cargo fleet) and that this will continue, due to the lack of any viable alternatives. Lower carbon and low polluting steps towards decarbonisation will focus on slow steaming and improved efficiency (66) through a more systems approach to vessel operation, using digital systems to communicate and optimise activity (67) and in so doing pave the way for a second wave. In this second wave or ‘transition state’, hybridisation of power technologies becomes the norm, placing greater emphasis on the role of the electric drive train and specifically on battery storage to reduce emissions on a tank-to-propeller basis. The third wave builds on this momentum to deliver designs for zero pollution, all-electric drive vessels and the emergence of new energy conversion mechanisms.

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Fig. 12. Likely scenarios for meeting emissions based on the three wave concept developed by Stopford (12)
for propulsion such as the fuel cell. To be zero (or very low) emission on a well-to-wake basis the energy source or fuel must also be decarbonised. Synthetic fuel, electro-fuels or green ammonia and hydrogen fuels offer this possibility but require an economically available and renewable source of energy. Recent reports (68) are positive, noting that the costs of renewable energy can fall below that of new fossil fuel power plants at US$0.05 kWh\(^{-1}\)–US$0.15 kWh\(^{-1}\). Hydroelectric power now has an average cost of US$0.05 kWh\(^{-1}\) and offshore wind generated power in places with good natural resources (with the right regulatory and institutional support) fall in the range US$0.03 kWh\(^{-1}\)–US$0.04 kWh\(^{-1}\). Solar energy in South America and in the Middle East have seen a levelised cost of electricity at US$0.03 kWh\(^{-1}\).

8.3 Delivering This Objective

In December 2019 (69) the global maritime transport industry proposed the formation of the world’s first collaborative shipping research and development (R&D) programme to help eliminate CO\(_2\) emissions from international shipping. It recognises that addressing the challenges will require the deployment of new zero-carbon technologies and propulsion systems, such as green hydrogen and ammonia, fuel cells, batteries and synthetic fuels produced from renewable energy sources and acknowledge that these do not yet exist in a form or scale that can be applied to large commercial ships, especially those engaged in transoceanic voyages which are currently dependent on fossil fuels. They envision a new non-governmental R&D organisation to pave the way for decarbonisation of shipping by encouraging the development of commercially viable zero-carbon emission ships by the early 2030s. Part of the proposal is the establishment of an International Maritime Research and Development Board (IMRB), that would be overseen by IMO member states and financed by shipping companies worldwide via a mandatory R&D contribution of US$2 per tonne of marine fuel purchased for consumption by shipping companies worldwide. This would generate about US$5 billion in core funding over a 10-year period. The proposal sets an ambition for the IMRB to be operational by 2023 and expects it to run for 10–15 years. Though universally welcomed, there is concern in some quarters (70) that it falls short of a strategy to cut emissions.

Decarbonisation of shipping is a complex problem, integrated with the wider ambition to decarbonise the power and (land based) transport sectors. On the face of it, the overall aim, for shipping to decarbonise as soon as possible this century, is challenging, but there is concern over how aspirational and how demanding it really is. Some have questioned the use of 2008 as a base line, since the economic downturn led to a reduction in CO\(_2\) emissions from shipping between 2008–2015 (71, 72), and how meaningful the interim challenges really are. A study by the International Council on Clean Transport (ICCT) (72) has shown that the IMO’s 2030 goal was actually already three-quarters met when it was approved in 2018, which has prompted calls for a rethink of the target. Without a forceful impetus driving innovation there is fear that a lack of meaningful action will lead to delay (73) especially as there are suspicions that the IMO process will not address the issue.

The frustration with the IMO process goes beyond disgruntled environmental NGOs. In December 2019 the European Commission announced its new Green Deal (74) indicating that shipping would be included in the EU Emissions Trading System (EU ETS) by 2023. This possibility had already been signalled by the European Parliament’s Environment Committee in 2016 warning (75) that (that to avoid inclusion in the EU ETS) the IMO needed to “deliver a further global measure to reduce GHG emissions for international shipping by 2021”. The IMO has warned that this could seriously undermine the global effort. If this leads to a further and significant development of the patchwork nature of shipping regulations the IMO will be deemed to have failed. If the IMO does not facilitate the meaningful reduction of emissions in the short term it will be deemed to have failed. Could another policy approach be more successful?

In his study of technology transitions, Geels (76) recognises three kinds of paradigms of innovation policy: how it can be supported at a governmental level. One of the models is based on setting a regulation with top down governance. A second uses market based incentives where the governance focuses on establishing the framework and the conditions. A third model that facilitates radical innovation involves network governance to help establish a vision and bring teams to work collaboratively to achieve a goal. Geels also recognises the attraction of cutting loose from a bureaucratic approach based on the desire to reach consensus but is cautious as for these problems there is no easy solution. New entrants tend to suffer from a lack of adequate skills, finance and scale-up capability and fail to
recognise the magnitude of the challenges they face. Incumbents may seem locked into the current regime with their ‘sunk investments’, their technical capabilities, operations, mindset, identity and practices but under certain circumstances incumbents can re-orient to radical innovation, collaborating with the disrupters, following a path outlined in Figure 13.

The first step is characterised by resistance and easy dismissal, for example on the grounds that it will not work or it is too expensive. In the second step the incumbent recognises some potential and invests in options and in the third targets early markets. In the fourth step the organisation has committed to scaling up. Regime transformation is not a deterministic process; though it may thrive given the right conditions, supportive policy, public attention and market demand, it may falter at any step if the impetus is not sustained.

The economic impact of COVID-19 is unprecedented but so too are governments’ responses to it: establishing stimulus packages to help economies recover. European State Aid rules have been suspended allowing nation states to act; for example, Germany’s Federal Government has committed €1.32 trillion (38% of its 2019 gross domestic product (GDP)) in liquidity and guarantee measures. The World Health Organization (WHO) suggests that “support to resuscitate the economy after the pandemic should promote health, equity and environmental protection” (77) i.e. these vast sums should support a green economy, furthering climate goals and preventing a return to business-as-usual which is not aligned with the goals of the Paris Agreement. The European Commission had indicated that recovery investments must be linked to green and digital transitions, and that “the Green Deal is not a luxury that we drop when we hit another crisis”. How much of this will impact shipping is unclear but any significant investment in the decarbonisation on land to accelerate technology development for both energy conversion and green energy storage (fuels) should benefit the decarbonisation effort in shipping.

9. Conclusions

Evolution is a scientific theory developed for the biological sciences and seeks to explain how change occurs in living systems, over long periods of time, how environmental factors, for example, create conditions where inheritable physical or behavioural traits bring a distinct advantage and thus improve the chances of survival and of passing on those traits to subsequent generations. The term evolution has found meaning to explain change in other complex systems, though the concept of inheritable traits is less tangible. Notwithstanding, studies on how and why innovation is successful suggest that there are common themes or ‘winner’s traits’: an innovative spirit, excellent network, access to high quality information or intelligence, an open attitude that embraces change, agility and timing of response.

Transitions in shipping take long periods, in part due the lifetime of the asset. Planning for 2040 and 2050 may seem like tomorrow’s concern, but they require decisions today and the wrong decision risks creating stranded assets. Even the best-informed decision makers face what Donald Sull (78) referred to as the “Fog of Uncertainty”. Those with resources can adopt a portfolio approach to distribute risk, others may be forced to take calculated risks. Some of the subtly important factors may only be comprehended in retrospect: seemingly trivial events that turn the tide. The decoupling of mail delivery from the rest of shipping in 1820 might not even be a footnote in history yet played a key role in the sail to steam transition. It isolated a growing need that was valued by the market so faster information transfer was incentivised and newer risky technologies, such as steam power, were developed, demonstrated and deployed.

So as the decision makers plot a course through the fog of uncertainty, they hope they have the most important of sea-faring traits. In some ways it is the sum of all the important traits outlined above. It is the trait that Napoleon (79, 80) reportedly demanded of his generals: “to be lucky”.

Fig. 13. A simple schematic of Geels’ theory of regime transformation (76)
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