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Alternative Fuels and Technologies for Short Sea Shipping

Abstract

Awareness of the consequences of excessive greenhouse gas emissions in maritime transport has prompted research on the use of alternative fuels and technology, towards environmentally neutral ship propulsion, which has resulted in a number of possibilities. This review provides a systematic overview of the current state of use of ship propulsion and alternative options from the aspect of costs, infrastructure, regulations, availability, environmental protection, technology and the perspective of complete decarbonisation by 2050.

Keywords: alternative fuels, LNG, ammonia, hydrogen, fuel cells

1. Introduction

From the first estimates of limited fossil fuel supplies on Earth in the 1950s, scientists and engineers began serious research and search for alternative energy sources, especially in the field of transport, of which maritime transport was the most interesting. At one point in history, in 1959, when NS Savannah went into operation, many then relevant sources celebrated the beginning of a new era of marine propellants. The next moment came in the early 1960s with the outbreak of the First Oil Crisis (1973-1974) and only six years later (1978-1980) the Second Oil Crisis, which was a clear signal that the future could not rely on just one energy source. A period of intensive exploration of new oil and gas deposits followed, as well as alternative energy sources, in order to avoid the OPEC monopoly and gain energy independence. But it was only after the Environment and Development Conference (Rio de Janeiro 1992) that serious reflections began on the need to reduce greenhouse gas emissions and the need for decarbonisation was accepted by most countries at the 2015 Paris conference due to obvious climate changes.

The maritime merchant fleet is exposed to pressures to change the energy source for propulsion machines as one of the major polluters and emitters of CO2. Ship owners, as socially responsible stakeholders in maritime transport, express their readiness to use “clean” energy sources hen the technology of propulsion machines is available and the logistics of fuel supply on waterways are ready to supply ships.

In general, research aimed at replacing heavy diesel fuel for marine engines has developed in recent history in three different directions depending on the availability of energy, the development of technology and the required maritime properties and purpose of the ship. In any event, it was necessary to build new ships or adapt existing ones. The selection of a new energy source was to meet the economic requirements of the ship’s operation, except in cases of prototypes or trial use when the financing of construction and operation was agreed as an incentive or subsidy from the state.

Scandinavian countries have taken the lead in finding new solutions in liner coastal shipping using available energy sources such as natural gas and electricity. The first choice was certainly natural gas due to the relatively simple conversion of existing machines from diesel to natural gas, which created certain losses in power, but also achieved a significant reduction in CO2 in the exhaust gases. In addition, liquefied natural gas is easily stored on board, which allows a sufficient radius of movement in coastal navigation.

The other direction was made up of storage batteries that proved to be more environmentally friendly and recharging was available throughout coastal ports. The third direction leads to hydrogen as a clean energy source of high efficiency. All of the above options appear in multiple hybrid combinations and are in operation with more or less success. Serious announcements about the decarbonisation of the European Union focus on coastal liner shipping companies in the EU that need to be transformed into environmentally neutral carriers in the next three decades. This has activated a whole range of energy-neutral fuel manufacturers, the shipbuilding industry, the production of marine generators, logistics as well as a number of stakeholders, professional lobbyists, NGO innovators and protected patents. Consequently, unification that would distort competition is not to be expected, rather it is more likely that ship owners will make their choice based on their expert economic and safety assessments. This paper provides an overview of previous research, theoretical and practical applications and points out possible problems in terms of maritime transport, safety requirements and the advantages and disadvantages of current models of ship propulsion.

2. Transition period from 2020 to 2050

The transition period until 2050, for the transition to environmentally neutral propellants, is a necessity arising from insufficiently researched technology of supply of ecologically neutral energy sources and thus the choice of ship propulsion. In addition, it should be taken into account that between the decision of the ship owner which installation and which energy source to use and the beginning of operation, it is necessary to consider the free capacities of the shipyard, the capacity of making propulsion machines and the fuel supply schedule to each port of Short sea Shipping – SSS [1].

SSS vessels typically operate in limited geographical areas, on relatively short routes with frequent port calls. Due to their relatively low energy demand, these vessels are often ideal candidates for testing new fuels characterised by high energy or fuel storage costs. The Norwegian ferry sector is in the process of being electrified, with about 50 battery-electric ferries to be phased in during the upcoming period. The use of hydrogen is also technically feasible, and the Norwegian national road authorities, supported by DNV GL, are working on the development of hydrogen applications and intend to put a new hydrogen-powered ferry into service by 2021. [2]

The SSS fleet in the EU, with the exception of inland waterway vessels, makes up a respectable number of vessels that should be replaced or refurbished over a thirty-year period in accordance with the requirements of environmental neutrality of energy.

2.1. Framework for the transformation

The framework for the transformation of marine propulsion systems of the SSS fleet to be powered by environmentally friendly fuels is presented systematically by decision-making levels - the development of technology for supply, transport and application of environmentally friendly fuels of marine propulsion engines with the set goal - zero emissions by 2050.

I. Framework - European Green Plan

The European Green Plan is a strategy for achieving sustainability of the EU economy. This is intended to translate climate and environmental challenges into opportunities in all policy areas and to ensure a fair and inclusive transition. The European Green Plan includes an action plan for:

- Improving the efficient use of resources by moving to a clean circular economy,
- Restoration of biodiversity and reduction of pollution.

An efficient combination of renewable gas (biomethane) and electricity, together with existing gas networks, makes the optimal way to decarbonise the EU energy system, making its constitution fully renewable.

There is great potential for the production of low-carbon renewables and hydrogen in large quantities within the European Union. The Climate Gas study "Gas decarbonisation pathways 2020 to 2050" [3] describes how a large amount of 1,700 TWh of hydrogen could be produced in the EU by 2050. In the transition to a clean EU zero-emission energy system, hydrogen and biomethane will play a major role in the efficient combination with renewable electricity. The European Commission has a clear ambition to boost hydrogen growth as early as 2030, as highlighted in its Hydrogen Strategy [4] and Energy Integration Strategy [5], both published on 8 July 2020.

II. Framework - transition

1. Preparing for transition - Strategic, technical and policy planning to enable renewable and low carbon gases to play a significant role alongside renewable electricity in the transition to zero emissions. Long-term infrastructure strategy for the conversion of existing pipelines (pipelines) to hydrogen. Amendments to laws and regulations in favor of conversion and readiness for H_2.
2. Possible directions of transition - Increase biomethane production (in plants near the gas network). Start the first hydrogen projects. Improve energy efficiency in all sectors to enable electrification and the input of renewable and low-carbon gases.
3. Launch of the supply chain - Launch of a hydrogen production project integrated with supply, use and storage near large consumers and with a basic load, probably from industry. Developing a hydrogen production plant according to regional needs. Continuous increase in biomethane supply.
4. Expanding demand - Hydrogen use is expanding to commercial and residential consumers around the first hydrogen projects. Combining (up to 20%) rapidly increases initial demand, paving the way for hydrogen clusters (100%).
5. Creation of a regional, national biomethane and hydrogen transport network and connection to the European gas pipeline system.
6. 100% renewable and low carbon gases. Renewable and low-carbon gases fully integrated into the EU energy system All gas end-users are supplied with hydrogen and / or biomethane, the main type of which varies by region. Natural gas is no longer used except for the production of blue hydrogen. Achieved zero emission energy system by 2050.

III. Framework - Transition of SSS fleet persecution systems

Possible scenarios for the transition period - 2021 to 2050:

1. Development of internal combustion propulsion systems:
   a. development of dual fuel system - diesel fuel and LNG
   b. development of LNG-powered systems
   c. development of hydrogen-powered systems.
2. Development of electric propulsion systems:
   a. development of hybrid systems - diesel and electric power
   b. development of electrical systems - batteries
   c. electrical system development - batteries + hydrogen cells

The choice of possible scenarios depends on the technology of development of marine propulsion machines and infrastructural solutions for the supply of motor fuels.

Scenarios 1a and 2a under the condition of green hydrogen production reach the target zero emission of harmful gases.

There are two possible uses of hydrogen as a propellant for marine propulsion systems:

- indirect - use of hydrogen fuel cells to start electric motors and
- direct - the use of hydrogen as a gas in internal combustion engines.

Both methods are in the phase of testing, prototyping and calculation of economic viability.

Ship's hydrogen propulsion systems will prevail as soon as the issue of infrastructure (filling stations) is resolved, *i.e.* mass production and distribution of hydrogen. The SSS must therefore follow national and European trends in this area and be prepared for them.

The transition phase to the complete elimination of harmful gas emissions by 2050 means reducing emissions to the lowest possible level by using available technological solutions.

Limitations that cannot be overcome at the moment relate to the climatic and geographical conditions of the environment in which the fleet operates, which include the length of the lines served and the strength of the sea and wind to which the navigation is exposed.

It is proposed that in the transitional phase, the renewal of the fleet takes place according to the changes related to:

- Fossil fuels are used exclusively to drive the main machine in navigation and maneuvering,
- All other energy needed to maintain the ship's systems is obtained from renewable sources on board - photovoltaic cells, wind farms, stored energy in batteries - hybrid propulsion, batteries and onshore power sources.

This would achieve a reduction in emissions of harmful gases per vessel, which would confirm the savings on fuel.

This approach should guide the ordering of new construction as well as the reconstruction / adaptation of existing vessels wherever technically and technologically feasible.

Technology - electric ferry, in order to work properly, an electric ferry requires large batteries that provide reliability for a long time. Examples of electric projects:

1. Stena Jutlandica - 50.000kWh

The Stena Line shipping company plans to add a 1,000 kW battery system to the Stena Jutlandica ferry, which sails between Gothenburg in Sweden and Frederikshavn in Denmark. The project started in 2018 and consists of three phases, of which the first phase is the installation of batteries, the second phase includes the installation of 20,000 kWh batteries, which will allow navigation of ten kilometres electrically powered, while the third phase will focus on increasing battery capacity to 50,000 kWh. The amount of energy will allow the ferry to cross the entire distance between the two cities using electrical power.

2. AIDAperla - 10,000kWh

Corvus Energy has equipped the German passenger ship AIDA Cruises with a 10,000 kW lithium-ion battery system, as the largest battery ever delivered for such a purpose. This year, the battery was installed on the cruise ship AIDAperla, which can carry more than 4,000 passengers and crew. It is also the largest ordered battery for this type of ship. Due to the Covid-19 pandemic, the AIDAperla cruise ship was stopped in Barbados for a month. It returned to Europe in late April, and in July the company announced that AIDAperla would be one of the first cruisers to resume operations, departing from Hamburg on 5 August.

3. Ellen - 4,300 kWh

After taking five years to build, the Ellen electric ferry project completed its ten-month trial in June. The ferry, which will sail in the Danish part of the Baltic Sea, is part of the E-Ferry project and was partly funded by Horizon 2020, the largest EU-funded research and innovation program. With a 4,300 kWh battery system and a charging speed of 4 MW, the Ellen will reduce emissions by 2,000 tons of CO_2, as well as 41.5 tons of NOx and 1.35 tons of SO_2.

4. Project e5 - 4,000 kWh

A Japanese shipping company, Asahi Tanker, has been working on two electrically powered projects, which will sail as refuelling ships in Tokyo Bay. The tankers will use the e5 model designed by the e5 Lab, in collaboration with Asahi Tanker and Mitsubishi. The e5 project was conceived as a solution to the problems facing the Japanese shipping industry, including the reduction of greenhouse gas emissions and labour shortages. The name e5 denotes the principles of the project, which include electrification, environment, evolution, economy and efficiency.

Technology – hydrogen - In the long run, hydrogen may become an option to decarbonise industry and the maritime sector. However, this ship propulsion technology is still in the experimental phase. The strategy and the first projects as well as the hydrogen supply are planned between 2025 - 2030.

As intermediate phases or transition to environmentally neutral fuels, hybrid solutions are being developed in various combinations. However, the most common are 1) hybrids diesel - natural gas better known as dual fuel, 2) diesel - battery, 3) natural gas - battery, 4) diesel - hydrogen, 5) natural gas - hydrogen, 6) battery - hydrogen cells.

2.2. Dual fuel

The transition period, in which the best way to propel a vessel in coastal navigation is sought, is one in which preference is given to proven ship propulsion systems with less impact on the environment.

The use of natural gas as a fuel for marine diesel engines began in the mid-1980s. Due to low cetane number and high temperature self-ignition, natural gas cannot be used as fuel for conventional use in a diesel engine since such engines would have to have huge compression ratios and some kind of external heat supply to the cylinder. However, with certain modifications, the use of natural gas as a fuel is possible with diesel engines. Today, these problems are solved by using diesel engines with low-pressure (7-13 bar) or high-pressure (about 200 bar) injection of natural gas [6].

Basic principles of double fuel engine operation

Gas injection into the diesel engine is solved by sucking a mixture of gas and air into the engine cylinder as in a gasoline engine, and shortly before GMT a small amount of diesel (pilot) fuel is injected which ignites and starts combustion of the entire mixture inside the cylinder. This type of engine requires a slightly lower compression ratio and the addition of an injector to the engine's intake manifold. Wartsila has developed its series of modern 32 and 50 DF (Dual Fuel) engines, in which the time period and amount of injected pilot diesel fuel are controlled electronically. The engine always starts with pilot diesel fuel (100% share), and switches to natural gas operation only after the combustion inside the cylinder stabilizes.

The lower compression ratio and optimized injection time during the combustion of the lean gas and air mixture (Lean Burn) allow to increase the efficiency.

A poor mixture is a condition for avoiding knocking caused by self-ignition of a mixture of gaseous fuel and air. The cylinder is filled with gas during the suction stroke. Instead of an electric spark, the ignition of a lean fuel mixture is done by injecting a small amount of diesel fuel (pilot fuel) into the combustion chamber.

The declared emissions at full load for the 50DF engine are 1.4g / kWh of NOx and 430 g / kWh of CO_2. In order to achieve low NOx emissions, it is essential that the amount of injected pilot fuel is very small. Wartsila DF engines therefore use so-called "micro-pilot" injection with less than 1% of the injected pilot fuel at rated engine load.

In this way, in gas mode, NOx emissions are reduced to approximately 1/10 of the emissions in diesel engine mode.

During engine operation in gas mode, the ratio of gas / air mixture must be strictly controlled to avoid detonation combustion in the cylinder or the inability to ignite the sucked gas and air mixture. This is achieved by electronic control of both the amount of gas and the amount of injected pilot fuel. The electronic Wartsila (WECS) system of the DF engine controls combustion in each cylinder and optimizes performance and NOx emissions in all operating modes and allows each cylinder to operate within the operating range without detonation combustion or no fuel ignition due to a too poor a mixture.

Wartsila DF engines can run in gas mode and in diesel mode from MGO to heavy residual fuels. In diesel mode, the engine runs like a conventional diesel engine using a high-pressure fuel injection system into the working cylinder. The addition of gas fuel is deactivated in this case, and the pilot fuel branch remains active, which ensures reliable ignition of the fuel mixture of gas and air at the moment of switching the engine operation to gas mode. The gas pressure at the engine inlet is around 4 bar at full engine load. Gas injection control is realised via a robust, electronically controlled solenoid valve located on the head of each cylinder.

Gas-diesel engines

Wartsila gas-diesel (GD) technology differs from the DF concept in that instead of a low-pressure system, the DF engine uses a high-pressure gas injection system directly into the engine cylinder and 3% pilot diesel fuel to ignite the injected gas fuel into the engine cylinder.

Gas-diesel engines were developed in the late 1980s and were mainly used as propulsion engines in the offshore industry. High-pressure direct injection of gaseous fuel into the engine cylinder supported the diesel process by making the concept insensitive to the methane content in natural gas as a fuel for these engines. This fact has made the application of GD engines particularly suitable for mobile offshore systems where the composition of natural gas can vary from site to site and from production process to production process. Medium-speed GD engines can normally operate in light or heavy diesel mode and in gas fuel mode.

Changing the engine operating mode from diesel to gas fuel and vice versa is done automatically without stopping the engine. At the beginning of the development of these engines, the injection of gas into the cylinder was controlled by a mechanical-hydraulic system and a high-pressure pump controlled by a camshaft. Although reliable, this system did not offer the required flexibility in engine operation and was later replaced by an electro-hydraulic system based on the common rail principle and control of gas injection by solenoid valves.

Rolls-Royce, as a subsidiary of the Norwegian diesel engine company Bergen Diesel, has started the development of GD medium-capacity GD series K-series cylinders with a diameter of 250 mm with the combustion of lean mixture. GD engines from the same manufacturer of the KV-G4 series with variable turbocharger geometry and individual dosing control of air and gas fuel for each cylinder individually achieved a thermal efficiency of 44% at an average effective pressure of 16-18 bar with very low emissions of nitrogen oxides (NOx) from 1.1 g / kWh. The projected engine power was 3600 kW. The Bergen B32 medium-range GD series engine: 40 320 mm cylinder diameters is designed for an output of around 6000 kW.

The world's leading manufacturer of marine diesel engines MAN B&W Diesel has offered the market a four-stroke medium-speed GI (English Injection) engine 16V28 / 32-GI manufactured at the Holeby factory, and a 6L35MC two-stroke model.

Use of volatile organic compounds for marine fuels

Volatile Organic Compounds (VOCs) are a mixture of hydrocarbons (HC), predominantly methane, propane, butane, and several other gases produced by the evaporation of crude oil and its derivatives. VOCs are usually divided into non-methane (NMVOC) and methane (CH_4). These gaseous hydrocarbons are emitted into the atmosphere from oil rigs, tankers, terminals and refineries. During the loading or unloading of crude oil tankers or petroleum products, VOCs can be collected and liquefied at special terminals and used as fuel.

The primary goal of marine gas engine manufacturers is to use them for propulsion of liquefied natural gas (LNG) tankers, which use vaporized gas from tanker tanks as fuel. However, a modified high-pressure gas version of the MAN B&W MC engine in particular is designed to use volatile organic compounds that are mainly formed during the loading and unloading of crude oil tankers. Crude oil vapours or VOCs are volatile components of oil, i.e. mainly methane CH_4, which, in addition to developing during tanker loading and unloading operations, also develops during travel in cargo tanks.

3. Advantages and disadvantages of alternative fuels and technologies

All alternative fuel options are accompanied by benefits and challenges. Below is an overview of selected alternative ship fuels – LNG, LPG, methanol, biofuel and hydrogen – as well as emerging technologies such as batteries and fuel cell systems. To assess all fuels or technologies in a comparable manner, the data is categorized as follows [7]: 1) ***Price***: Accounts for production process, raw materials, market price and the reasoning behind it, current/foreseeable (five years) price/expected price (beyond five years); 2) ***Infrastructure***: Current/future distribution network, bunkering, availability; 3) ***Regulation***: Existing/expected regulations, consequences; 4) ***Availability***: Current / possible future production as related to the requirements in shipping; 5) ***Environmental impact***: CO2, NOX, SOX, particulate matter (PM) and others; 6) ***Technology***: Availability of current/future technology, foreseeable changes.

- ***LNG -*** The main component of liquefied natural gas (LNG) is methane (CH_4), the hydrocarbon fuel with the lowest carbon content and therefore with the highest potential to reduce CO_2 emissions (maximum reduction: roughly 26 % compared to HFO).
  - ◊ ***Price -*** Natural gas hub prices worldwide (except in certain parts of East Asia) have been below the price of crude oil and HFO for the last ten years. The delivered price of LNG fuel to ships must also account for the liquefaction or break bulk cost, distribution cost and applicable profit margins. Compared to other alternative fuels, LNG seems to have reached the most competitive feedstock price level historically among all alternatives fuels.
  - ◊ ***Infrastructure*** - While still limited, the dedicated LNG bunkering infrastructure for ships is improving quite rapidly. A large share of LNG bunkering as well as LNG distribution to bunkering locations is still taking place by road. Several LNG bunker vessels where delivered for operation in key locations such as the Amsterdam, Rotterdam, Antwerp (ARA) region, the North Sea, the Baltic Sea and at the coast of Florida.
  - ◊ ***Regulations -*** The IMO IGF Code for LNG and CNG came into force on 1 January 2017, establishing an international regulatory basis for the design and construction of LNG-fuelled ships.
  - ◊ ***Availability -*** For the foreseeable future, there are no principal limitations to production capacities that could limit the availability of LNG as ship fuel.
  - ◊ ***Environmental impact:*** Natural gas from LNG is the cleanest fossil fuel available today. There are no SO_X emissions related to it, particle emissions are very low, the NOX emissions are lower than those of MGO or HFO, and other emissions such as HC, CO or formaldehyde from gas engines are low and can be mitigated by exhaust gas after-treatment if necessary.
  - ◊ ***Technology -*** Gas engines, gas turbines and LNG storage and processing systems have been available for land installations for decades. LNG sea transport by LNG carriers also has a history going back to the middle of the last century. The technology required for using LNG as ship fuel is readily available. Piston engines and gas turbines, several LNG storage tank types as well as process equipment are also commercially available.
- **LPG -** Liquefied petroleum gas (LPG) is by definition any mixture of propane and butane in liquid form**.**
  - ◊ ***Price -*** Since 2011, prices have decoupled due to increased LPG production as a by-product of shale oil and shale gas.
  - ◊ ***Infrastructure*** - It is relatively easy to develop bunkering infrastructure at existing LPG storage locations or terminals by simply adding distribution installations. Distribution to ships can occur either from dedicated facilities or from special bunker vessels.
  - ◊ ***Regulations -*** The IMO IGF Code is mandatory for all gas and other low-flashpoint-fuel ships. LPG is currently not included and is not on the agenda for

the near future. The main safety concern that must be covered is related to the density of LPG vapours, which are heavier than air. Therefore, leak detectors and special ventilation systems should be used.

- ◊ ***Availability -*** According to the World LPG Association, global LPG production is about 284 million tonnes per year. Only 9 % of LPG is used for transportation. Other uses of LPG include homes (cooking and heating), chemical and other industries, and refineries.
- ◊ ***Environmental impact*** - LPG combustion results in CO_2 emissions that are approximately 16 % lower than those of HFO. When accounting for the complete life cycle, including fuel production, the CO_2 savings amount to roughly 17%.
- ◊ ***Technology -*** There are three main options for using LPG as ship fuel: in a two-stroke diesel-cycle engine; in a four-stroke, lean-burn Otto-cycle engine; or in a gas turbine. An alternative technology offered by Wärtsilä consists in the installation of a gas reformer to turn LPG and steam into methane by mixing them with CO_2 and hydrogen. This mixture can then be used in a regular gas or dual-fuel engine without derating.

➢ **Hydrogen** (H_2) is a colourless, odourless and non-toxic gas. For use on ships, it can either be stored as a cryogenic liquid, as compressed gas, or chemically bound.

- ◊ ***Price -*** The cost of H_2 depends to a large extent on the price of electricity (in the case of electrolysis) or gas (in the case of reformation), as well as on the scale of the production plant.
- ◊ ***Infrastructure -*** Today, most hydrogen is produced from natural gas using a related, mainly industrial, land-based infrastructure. Since there is currently no demand for H_2 fuel, there is no distribution or bunkering infrastructure for ships. Liquefied hydrogen (LH) could be distributed in a similar manner as LNG.
- ◊ ***Regulations -*** Hydrogen is a low-flashpoint fuel subject to the International Code for Safety of Ships using Gases or Other Low-flashpoint Fuels (IGF Code). The current edition of the IGF Code does not cover hydrogen storage.
- ◊ ***Availability -*** More than 50 million tonnes of H_2 are produced per year globally. This is about equal to the energy content of 150 million tonnes of ship fuel. Nearly all hydrogen is produced from natural gas. As hydrogen can be produced from water using electrolysis, there are no principal limitations to production capacity that could restrict the amount of available H_2 to the shipping industry.
- ◊ ***Environmental impact -*** There are energy losses associated with H_2 production and possible compression or liquefaction. When H_2 is generated from renewable or nuclear power using an efficient supply chain, it can be a low-emission alternative fuel for shipping. Current development initiatives explore hydrogen production from natural gas while safely capturing and storing the resulting CO_2 (CCS). Hydrogen used in fuel cells as energy converters does not produce any CO_2 emissions and could eliminate NO_X, SO_X and particulate matter (PM) emissions from ships. Hydrogen-fuelled internal combustion engines for

marine applications could also minimize greenhouse gas (GHG) emissions, while NO_X emissions cannot be avoided when using combustion engines.

- ◊ ***Technology -*** Power generation systems based on H_2 may eventually be an alternative to today's fossil-fuel-based systems. While fuel cells are considered the key technology for hydrogen, other applications are also under consideration, including gas turbines or internal combustion engines in stand-alone operation or in arrangements incorporating fuel cells.

➢ ***Methanol -*** (CH_3OH) is the simplest alcohol with the lowest carbon content and highest hydrogen content of any liquid fuel. Methanol is a liquid between -93°C to +65°C at atmospheric pressure.

- ◊ ***Price -*** Since methanol is typically produced from natural gas, its price per mass unit is usually coupled to natural gas prices and is higher in relation to energy content. Producing methanol from coal may bring the price down, but it increases GHG emissions drastically. Methanol is easy to produce from hydrogen and CO2. Therefore, the production of methanol from renewable energy makes it a green ship fuel. The costs are currently higher than the costs of methanol synthesis from methane.
- ◊ ***Infrastructure -*** Distribution to ships can be accomplished either by truck or by bunker vessel. In the port of Gothenburg, Stena Line has created a dedicated area for bunkering the vessel Stena Germanica, which includes a few simple safety barriers to avoid problems in case of a leak. In Germany, the first methanol infrastructure chain, from production using renewable energy to trucking and ship bunkering through to consumption in a fuel cell system on board the inland passenger vessel MS Innogy, was launched in August 2017.
- ◊ ***Regulations -*** For shipping, the main applicable guideline is the IGF Code, which is compulsory for all gas and other low-flashpoint-fuel ships. The rules for methanol are still under development.
- ◊ ***Availability -*** The global methanol demand was approximately 80 million tonnes. The production capacity is more than 110 million tonnes. The energy content of these 110 million tonnes is equal to approximately 55 million tonnes of oil. It is expected that the current production can safely cover the demand for shipping until 2030, assuming that the demand for methanol as ship fuel will grow slowly initially and remain at a moderate level.
- ◊ ***Environmental impact -*** Methanol combustion in an internal combustion engine reduces CO_2 emissions by approximately 10 % compared to oil.
- ◊ ***Technology -*** There are two main options for using methanol as fuel in conventional ship engines: in a two-stroke diesel-cycle engine or in a four-stroke, lean-burn Otto-cycle engine. Methanol is a liquid fuel and can be stored in standard fuel tanks for liquid fuels, with certain modifications to accommodate its low-flashpoint properties and the requirements currently under development for the IGF Code at the IMO. Fuel tanks should be equipped with a facility for safe inert gas purging and gas freeing.

- **Biofuels –** are derived from primary biomass or biomass residues that are converted into liquid or gaseous fuels. The production of biofuel is commonly categorized based on the carbon source:
  - ◊ First-generation biofuels: sources include sugar, starch or lipid directly extracted from plants;
  - ◊ Second-generation biofuels: derived from woody crops, purpose-grown non-food feedstock, and wastes/residues;
  - ◊ Third-generation biofuels: derived from aquatic autotrophic organisms (*e.g.* algae).

The conventional biofuels typically have lower energy content and lower greenhouse gas (GHG) emissions than conventional marine fuels. NOX emissions may be higher. The most promising biofuels for ships are biodiesel (*e.g.* hydrotreated vegetable oil [HVO], biomassto- liquids [BTL], fatty acid methyl ester [FAME]) and liquefied biogas (LBG). Biodiesel is most suitable for replacing MDO/MGO, LBG is the best replacement for fossil LNG, and straight vegetable oil (SVO) can substitute HFO.

Renewable HVO biodiesel is a high-quality fuel in which the oxygen has been removed using hydrogen, which results in long-term stability. It is compatible with existing infrastructure and can be used in existing engines, subject to approval by the manufacturer. The GHG emissions and particulate matter (PM) emissions are likewise lower. There are no sulphur emissions. Third-generation algae-based biofuels are still at the research and development stage but were tested in 2011 on the container ship Maersk Kalmar.

- ◊ ***Price*** In most cases, advanced biofuels will be more expensive than fossil fuels. The potential for reducing production costs is expected to be higher for second-generation biofuels compared to the first generation, where a major portion of the potential is already being realized. Prices and production volumes are the main barriers to widespread use in shipping.
- ◊ ***Infrastructure -*** There is a lack of global infrastructure and bunkering facilities. Biodiesel could potentially be used as a drop-in fuel. If biofuel is available, it can be distributed using the existing distribution systems for MGO and HFO.
- ◊ ***Regulations -*** Annex A of the ISO 8217:2017 fuel standard addresses bio-derived products, EN 14214 and ASTM D6751 provide biodiesel standards, while the EN 590 diesel standard is relevant for high-quality diesel for automotive use. The International Council on Combustion Engines (CIMAC) provides a guideline for ship owners and operators on managing marine distillate fuels containing up to 7 % v/v of FAME (biodiesel). The Global Bioenergy Partnership (GBEP) defines sustainability indicators for bioenergy, specifying three pillars: environmental, social and economic. Overall, there is a lack of globally accepted, maritime-specific standards for biofuels.
- ◊ ***Availability -*** Global production data indicates that 32 million tonnes of biodiesel and 170 million tonnes of straight vegetable oil (SVO) are produced per year.

◊ ***Environmental impact -*** The emission reduction potential of biofuels varies widely, depending on the specific feedstock, the biofuel generation, the engine type/model, and the supply chain. CO_2 reductions of up to 80 to 90 % for certain types of biofuels are possible, based on life-cycle assessments. The highest reduction potential is reported for advanced biofuels.

◊ ***Technology -*** Biofuels are used as drop-in fuels substituting conventional fossil fuels and are compatible with existing infrastructure and engine systems. In some cases, they require the modification of infrastructure and engine systems. Liquefied biogas (LBG) consists mainly of methane and can utilize the same technology as conventional LNG.

3.1. Electric drive

The electric motor uses electric current obtained from a) generators, b) rechargeable batteries and c) hydrogen cells to start propulsion on SSS ships.

The electricity produced by the electric generator, which originates from diesel engines or DF motors for starting electric motors, is not the subject of analysis due to the high presence of GHG.

Batteries

Batteries and hybrid power plants represent a transformation in the way energy is used and distributed on board vessels. Electric power systems using batteries are more controllable, and easier to optimize in terms of performance, safety and fuel efficiency. As ship power systems become increasingly electrified, and as battery technology improves and becomes more affordable, new opportunities emerge.

Fully electric ships represent a leap forward in power system design, but at present they are only feasible in limited applications such as ferries and short sea shipping. The feasibility of all-electric operation for other vessels is typically limited either by the size of the required battery system or its cost. Unsurprisingly, the same limitations apply to many other uses of battery systems as well. Further research and development is needed urgently to achieve significant improvements to this technology.

Commercially available battery chemicals on the market today utilize largely similar elements. Anodes have historically been carbon or graphite based, while electrolytes predominantly consist of organic carbonates such as ethylene carbonate, dimethyl carbonate, diethyl carbonate and ethyl methyl carbonate. Some of the most promising developments for lithium-ion battery safety, energy density, and longevity may come from advancements in these areas. Component quality and manufacturing process will have a substantial effect on performance, longevity, consistency, and safety. Other key factors are the anode chemistry and material properties, the electrode active material coating thickness and porosity, the electrolyte, the separator, the current collectors and the cell construction. However, the chemical composition of the positive electrode (cathode) is one of the most defining aspects of a given battery's performance characteristics. This is the name that is commonly referred to in describing different battery technologies (LiFePO, NCM). This material composition is important for such factors as power and energy characteristics, lifetime, safety thresholds, voltage as well as cost. A few of the most common cathode chemicals are listed below. Cell compositions also utilize a mixture of these different chemicals on the cathode more and more now.

- Lithium cobalt oxide, $LiCoO_2$ (LCO) - The main advantage of $LiCoO_2$ is its relatively high energy density. However, it typically displays lower power (rate) capabilities and shorter life cycle. Impedance increase over time is also a significant concern with $LiCoO_2$ based cells. Cobalt oxide suffers from safety concerns due to the exothermic release of oxygen at elevated temperatures – producing a self-heating fire resulting in thermal runaway concerns. LCO type cells are very common in consumer electronics rechargeable batteries where a three-year life span of a few hundred cycles to 80% of its original capacity is often sufficient.
- Lithium manganese oxide spinel, $LiMn_2O_4$ (LMO) - LMO is a somewhat unique cathode chemical, being a spinel structure, which provides a significant benefit in terms of power capabilities. The compound has additional safety benefits due to high thermal stability. However, it has significantly lower energy capacity compared to cobalt based compounds, and is known to have a shorter life cycle characteristics, especially at higher temperatures. Several material modification possibilities exist in order to improve the life cycle of LMO compounds.
- Nickel manganese cobalt oxide, LiNi1-x-yMnxCoyO_2 (NCM or NMC) - NCM is one of the most recent cathode developments and is the present market leader for large format applications. NCM is starting to replace LCO as the dominant chemical for consumer electronics. Its strength is the combination of attributes of its constituents - nickel (with a high specific energy), cobalt (high specific energy) and manganese (doped in the layered structure to stabilize it). The relative composition can be tweaked to produce different properties with regard to power density, energy density cost and safety, as well as to customize the cells to certain applications or groups of applications. NCM can also be mechanically mixed with LCO or LMO in the cathode in order to produce yet another customization of properties.
- Lithium iron phosphate. $LiFePO_4$ (LFP) - Like LMO, LFP differs significantly from most other cathode chemicals in terms of its structure, which is phosphorous-olivine rather than a layered metal oxide. A dominant benefit of this is the lack of an oxygen source at the cathode, thus posing a potentially reduced risk magnitude during thermal runaway. These cells are additionally more resilient to temperature fluctuations. The specific energy of $LiFePO_4$ is relatively low, and the electrochemical potential (voltage) is lower, reducing the cell's driving force. Power capabilities of a $LiFePO_4$ based battery cell are

inherently low; however, doping the $LiFePO_4$ material with small amounts of other materials, conductive coatings and nanostructured active material particles have enabled typically high power battery cells using $LiFePO_4$.

Another important characteristic of the different chemicals is the voltage level at which they operate. With some chemicals, it is possible to obtain a higher voltage when fully charged, but with a rapidly decreasing profile as the SOC reduces.

Batteries present many opportunities for benefits and increased system performance. However, the risks inherent to battery systems with regard to safety are different than those of traditional power system components, and thus require particular attention. These risks are manageable and it is feasible to ensure a safe battery system, but the risks and challenges need to be identified and appropriately taken into account with respect to battery system selection and integration. The main goal is to have the safety and reliability of a vessel with a large lithium battery installation at least at the same level as with a conventional vessel.

The technology of electric propulsion systems using batteries is possible in the operation of ships on short lines with the possibility of charging the batteries at both points. The problem that is not technologically solvable is the time required for battery recovery, which would cause longer waits on high-frequency lines during the tourist season. The use of hydrogen fuel cells would create the conditions for unlimited use of the vessel.

Fuel cells

Fuel cells offer high electrical efficiencies of up to 60 %, as well as lower noise and vibration emissions than conventional engines. The main components of a fuel cell power system are the fuel cells, which convert the chemical energy stored in the fuel directly into electrical and thermal energy by electrochemical oxidation. This direct conversion enables electrical efficiencies of up to 60 %, depending on the fuel cell type and the fuel used. There are several different fuel cell technologies, including alkaline fuel cells (AFC), proton exchange membrane fuel cells (PEMFC), high-temperature PEMFCs (HT-PEMFC), direct methanol fuel cells (DMFC), phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC). The three most promising fuel cell technologies for maritime use are SOFC, PEMFC and HT-PEMFC.

- ***Price -*** Mass production, which is expected to occur in 2022, should allow production costs to reach a competitive level. Development projects are underway, and the most promising project for maritime fuel cells, e4ships, is aiming for a market launch in 2022. With increased production, the impact of material costs will become a dominant factor in fuel cell prices.
- ***Infrastructure -*** Currently, relevant services are provided by the fuel cell manufacturers. With the exception of fuel cell systems for military submarines, all present fuel cell systems in shipping are non-commercial prototype installations. The most advanced projects regarding future commercial

application are those of the e4ships lighthouse project. Commercialization will include a guarantee and lifetime technical support. A service network similar to that for diesel engines has yet to be established.

- ***Regulations -*** The international rule base for the design and construction of maritime fuel cell applications is currently under development at the IMO as part of the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code). Existing class rules form the basis of special permits. The current international regulatory framework is geared towards combustion engines. Apart from some class rules, there is no binding international regulatory framework for maritime fuel cell applications.
- ***Availability -*** Fuel cell systems are currently available in small quantities from several manufacturers.
- ***Environmental impact -*** The fuels typically used in fuel cells reduce NO_X, SO_X and particulate matter (PM) emissions nearly to zero. Due to the high efficiency of fuel cells, a reduction of CO_2 emissions by 30 % is possible.
- ***Technology -*** Only small maritime fuel cell applications with an electrical power output of up to 100 kW are currently in operation. Current research and development aims to make maritime fuel cell systems marketable and scalable from 2022. It should be noted that the life span of fuel cell systems and reformer units has not yet shown satisfactory results. Since 2016, a methanol fuel cell system has been in operation on board the passenger ferry MS Mariella, operated by Viking Line between Helsinki and Stockholm. Another methanol fuel cell system is installed on board MS Innogy, an inland passenger vessel operated by the White Fleet Baldeneysee and Innogy. Proton exchange membrane (PEM) technology in particular has reached a development level comparable with the dimension of automotive engines and capable of handling ship load changes well.

The fuel cell projects vary from assessments of potential for fuel cell use, regulatory development and feasibility studies and concept design, to testing of fuel cells in various vessels [8] .

3.2. Hybrid propulsions

Electrified vessels do not have to be exclusively powered by batteries, but there are different levels of hybrid drives, from standard plug-in (parallel) hybrids, in which the engine provides mechanical propulsion, to extended-range hybrids (series), in which the propulsion is exclusively electric - it only produces electricity, to hybrid fuel cells. All of these types of hybrid vessels use some type of fuel that burns in internal combustion engines, with the exception of fuel cell hybrids. The latter vessels use hydrogen (or some other hydrogen-rich fuel, such as alcohol or ammonia) that does not burn, but goes through another process that usually involves catalysis through a proton alternating membrane (PEM) that produces electricity, water or water and CO_2, when the fuel molecule also contains carbon atoms [9]. Although hybrid systems tend to duplicate systems, which could be a disadvantage in terms of cost and maintenance needs, this could provide a positive change in the short and medium term as it allows minimizing the main current constraints of electric mobility: energy storage cost, density, reliability and charging time. Although some of these limitations are no longer critical for small ships on short lines, they are still critical for some driving modes (strong winds, sea currents) as well as for long voyages, which would require huge, expensive energy storage systems that need long charging or very high power fast charging stations that also have their challenges.

The type of power to propel a vessel varies greatly between the types of ships and the purpose and area of navigation. When the propulsion system is based on an electrical architecture, power systems can be combined to meet the overall power requirement (*e.g.* hybrid architectures of accumulators and combustion engines, or batteries and fuel cells, or combustion engines with fuel cell and battery, etc.). As shown in the following table, the power requirements range from approximately 150 kW to almost 100 MW - a scale factor greater than 500.

Table 1 – Power Requirement [9]

Vessel Category / Application	**Power Requirement, Approximate, MW**
Ferries	
Small Ferries	0.24 – 1.0
Large Ferries, Inland Waters	2 - 12
Large Ferries, Open Seas & High Speed	20 -44
Freight Vessels	
Inland Freight Vessels, USA, Towed & Pushed Barges	0.13 – 1.0
Inland / River Vessels, Europe, Class 1 – Vb (Self-Propelled) & Push-Tow Barges	0.2 – 4.5
River Cruise Vessel, Class Vlb	< 2
Tugs, Europe, Class 1	10
Inland Container Vessel, Mississippi River (proposed, 235m, up to 2960 TEU)	11.5
Cold Ironing (ports)	
Container Ships (5-13k TEU)	0.2 – 0.9
Cold Ironing; Tankers	Up to 3MW

Cruise Ships	
Cruise Ship, Hotel Load	3 - 10
Cruise Ship, Manoeuvring in Port	20
Cruise Ship, Emergency Power	2 - 4
Cruise Ship, Propulsion	25 - 97

4. Which fuels are the alternatives?

According to DNV-GL forecasts [10], decarbonisation pathways will depend on the level of growth of maritime trade. They use a scenario-based framework with three unknowns: regulatory policy measures, fuel prices and maritime trade. The Greenhouse Gas (GHG) model is used to develop a scenario that describes the path leading to the quantification of future fleet composition, CO2 emissions, energy consumption, fuel measurement and costs.

The first scenario (scenario 1) follows the IMO ambitions pathway with design and operational requirements, low renewable electricity prices, and high seaborne-trade growth. During the decade to 2030, we see growing LNG use in newbuilds, and some retrofit to scrubbers. In the 2030s, there is significant growth in LNG, but still only on newbuilds. Regulations start to have effect with some retrofits from DF LNG ICE to DF ammonia ICE. After 2040, we see most newbuilds being built with an ammonia-fuelled propulsion system.

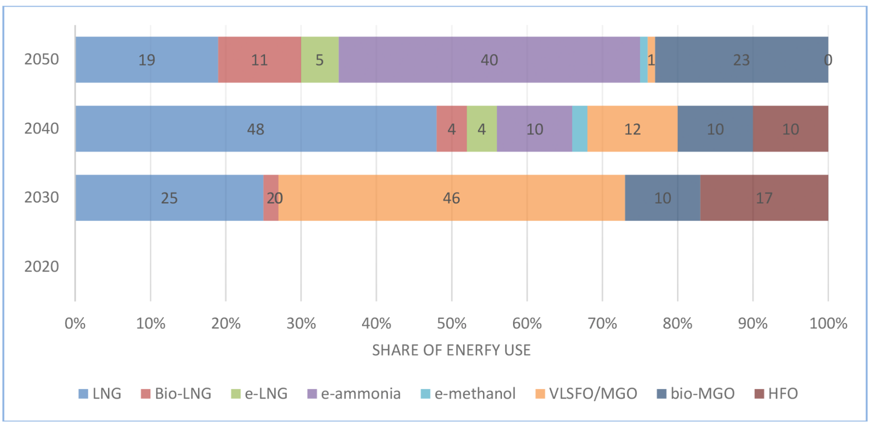

Figure 1 – Scenario 1. [10]

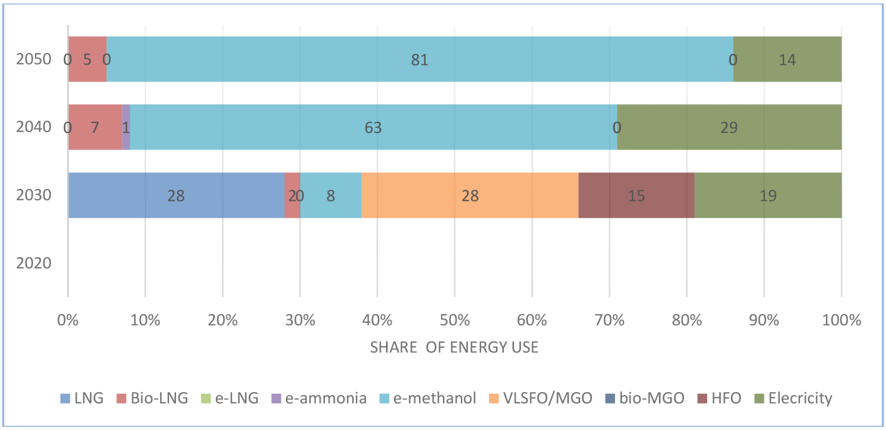

Figure 2 – Scenario 2. [10]

The second scenario (scenario 2) follows the Decarbonisation by 2040 pathway using design and operational requirements, low biomass prices, and low growth; and we see an entirely different technology path. The development between 2020 and 2030 is very similar to scenario 1, with retrofitting of scrubbers and growth in the use of LNG on newbuilds. After 2030, with new regulations coming into place, and with use of biofuels being the most economically feasible way to decarbonize, we see a quick transition to bio-methanol in 2040, including a high share of retrofits from LNG. LNG as a fuel is almost phased out, while we see some use of bio-MGO in part of the fleet in 2050.

Regulatory policies and primary energy prices are key drivers for uptake of carbon-neutral fuels and the future fuel mix. Fossil VLSFO/MGO and LNG are in rapid decline by mid-century, or even phased out in the most ambitious decarbonisation models. The uptake of carbon-neutral fuel picks up in the late 2030s or mid-2040s, reaching between 60% and 100% of the fuel mix in 2050.

◊ It is hard to identify clear winners among the many different fuel options across all scenarios, but e-ammonia, blue ammonia and bio-methanol are the most promising carbon-neutral fuels in the long run in the path to decarbonisation.
◊ Fossil LNG gains a significant share until regulations tighten in 2030 or 2040 depending on the decarbonisation pathway, when we see bio-MGO, e-MGO, bio-LNG and e-LNG used as drop-in fuels for existing ships, and bio-methanol, blue ammonia or e-ammonia for newbuilds and some retrofits.
◊ Although ammonia and methanol dominate the fuel mix in 2050, we also see that bio-LNG, e-LNG, bio-MGO and e-MGO have a limited but stable share for newbuilds, indicating that these fuels are not only transitional fuels, but a viable alternative for some ships.

4.1. Other possible fuels

Ammonia (NH_3) is primarily used in fertilizer production and there are over 150 million tons produced annually. Its production is very energy intensive (it uses about 2% of the total energy consumed in the world) and produces approximately 1% of CO_2 emissions in the world. In general, the production of one molecule of NH_3 results in the emission of a molecule of CO2. In nature, ammonia is produced in the process of decomposition (rot) of plant and animal waste by bacteria. It can also be obtained during the pyrolysis of coal, as a by-product of the production of coke and coal gas. In these cases, ammonia appears as ammonium hydroxide, a liquid commonly used as a cleaning agent commonly known as "ammonia." Ammonia is also used in absorption cycle refrigeration systems. Anhydrous ammonia (without added water) can be a substitute for petrol in petrol or diesel engines, and the main interest is to use it as an "energy carrier", to replace electricity (or hydrogen) as a means of transporting energy from the place where it is produced (wind farm or nuclear power plant) to the place where it will be used, for example for ship propulsion. As there is no carbon in its molecule, it does not produce CO_2, CO or HC. Comparing it to hydrogen (another energy carrier), one litre of liquid ammonia (at 10 bar and 25 C) has 30% more hydrogen than 1 L of liquid hydrogen (-253 ^{0}C). Therefore, it makes much more sense to use ammonia as an energy carrier than hydrogen.

It can burn in engines when mixed with diesel, but it would be useful to mix it with biodiesel or Dimethyl ether because these fuels have a higher cetane number. Ammonia in small quantities causes irritation, and in higher concentrations, it can be lethal. However, its distinctive and strong odour and the fact that it is lighter than air reduces the risks. Ammonia has special devices and processes for production, storage and delivery, so it has been extensively tested worldwide. Also, unlike gasoline, it is not carcinogenic, its combustion does not produce smoke and is much less prone to explosions. Currently, ammonia is produced from natural gas (70%) and from coal (30%) by the Haber-Bosch process where hydrogen and nitrogen react ($3H_2$ + N2 → $2NH_3$) in an iron oxide catalyst at temperatures ranging from 380 to 500 ^{0}C. When ammonia burns in the engine it reaches an efficiency of 40% which shows that the production and use of ammonia is not yet energetically or economically viable and will require the development of more efficient processes. However, the use of ammonia in fuel cells that generally need pure hydrogen is interesting.

Until recently, ***glycerol*** ($C_3H_8O_3$) was used as a substrate in the cosmetics industry (glycerine), in order to generate significant amounts of glycerol, which is not of interest, during intensive biodiesel production. Namely, for each part of the generated biodiesel, 10% glycerol is obtained by the transesterification process. Glycerol can burn in the atmosphere, but at temperatures below 300 ^{0}C it can form toxic compounds such as aldehyde acrolein. Acrolein is produced by the dehydration of glycerol and it is a black and sticky substance that forms during exposure to vegetable oils at high temperatures, such as deposits on pans and is responsible for their pungent odour. It is also carcinogenic and should be avoided [11].

As a fuel, glycerol burns heavily in the engine. It solidifies at 18 ^{0}C, so it has a high viscosity and must be injected hot (~ 100 ^{0}C) to allow sufficient spraying. Its auto-ignition temperature is 390 ^{0}C, so it is too high for direct use in compression-ignition engines. When mixed with diesel up to 20% then the intake air should be heated to 100 ^{0}C to maintain stable combustion. Power is slightly reduced and efficiency is slightly increased, while NOx and PM production is reduced, mostly at high power. One of the observed problems is the difficulty in producing and maintaining stable mixtures of hydrocarbons and glycerol. Nevertheless, experimental glycerol engines continue to be developed that use heated intake air (200 ^{0}C) as well as fuel (100 ^{0}C) so that glycerol burns cleanly and efficiently [12].

Aquafuel (Aquafuel 2020) has developed a generator for charging car batteries in Formula E races that use electric cars whose batteries must be charged in the pits. These generators are modified diesel engines (Cummins KTA50, 50 L, V16, turbocharger, power over 1 MW) that run on glycerol, because it is a pure biofuel. Each generator can produce 850 kWe, enough to charge 40 car batteries in 50 minutes. These generators are also used by biodiesel manufacturers, which allows them to use the by-product glycerol to produce electricity in their plants.

4.2. Hydrogen as the main fuel for marine engines - solution or utopia

The technology that is being developed with the aim of using hydrogen as the main fuel in transport (road and sea) is based on: 1) hydrogen fuel cells (HFCs) and 2) combustion of hydrogen in engines (H_2ICE). The advantages of hydrogen FCVs are high efficiency, lack of harmful emissions (water vapour is the only emission that is harmless compared to emissions created by burning fossil fuels such as nitrous oxide, nitrogen dioxide, carbon dioxide and sulphur dioxide), they work quietly and are modular [13] . FCVs use electrochemical reactions to produce electricity from hydrogen and oxygen. Alternatively, the benefits of H2ICE rely on a mature industry with a number of manufacturing infrastructures, capable of using "flexible fuel" in transition that could help deploy hydrogen infrastructures, lower hydrogen requirements compared to HFCs, ultra-low emissions, elevated peak and part of the load efficiency compared to conventional fuel and, most importantly, ICE does not depend on rare materials. Namely, FCV and battery vehicles (BEV) use rare materials which could limit the spread of these devices. FC require platinum, which is expensive anyway and will become more expensive as demand increases. BEVs use rare z elements that will be difficult to produce in large quantities.

Compared to ICE based on fossil fuels, the use of H_2 ICE achieves 20-25% efficiency. FC motors can achieve efficiencies of up to 60%, while the rest is lost as heat. The main challenge in promoting the use of hydrogen is on-board storage and the inaccessibility of refuelling stations. Significant progress must be made to adequately address the storage problem. Both infrastructure and financial resources must be allocated to the development of the hydrogen economy, which will require strong political support.

5. Conclusion

The transition to alternative fuels is a necessity that goes beyond the economic logic of maritime business. Awareness of the need for decarbonisation caused by maritime transport has prompted almost all European maritime states to find solutions, primarily in their own territory and for their own needs and then for commercial use. The models that will be applied are left to the market, which in turn expects an optimal solution from science, technology and logistics in order to start the production or modification of propulsion machines and ships.

The shipping industry is under increasing pressure to act upon the Paris Agreement and reduce greenhouse gas (GHG) emissions. The substantial emission reductions which must be achieved over the next decades are expected to drive technology development and, in particular, the introduction of low-carbon fuels. Marine fuel currently contributes approximately 3 % to global man-made CO_2 emissions. Most seagoing ships are still using heavy fuel oil (HFO) or marine gas oil (MGO), with a maximum sulphur limit of 3.5 % (mass) in force for HFO and 0.1 % (mass) for low-sulphur MGO. Looking at the future with the IMO 2020 [14] low-sulphur standards and upcoming CO_2 emission regulation regime in mind, the share of conventional oil-based ship fuels will drop and the share of alternative fuels will grow.

It is assumed that a hybrid energy system architecture consisting of fuel cells and batteries will be adopted for ferries and other vessels. The ratio between fuel cell and battery power will depend on the vessel, route and schedule. Hybrid systems can be designed so that the fuel cells operate in a steady state and the batteries are dimensioned for temporary power needs. The fuel cell can recharge batteries over time on low-power ships, for example while a ferry is loading or unloading vehicles and passengers at the dock. Maximum power can be delivered by batteries and fuel cells working together, and power in navigation can be delivered by fuel cells.

A ship's power system must have the ability to deliver maximum rated power, but ships rarely operate at maximum power. The power supply system should be optimized for efficiency at a typical or average operating speed. Redundant energy systems are required for propulsion. These points are important when considering possible zero-emission energy systems. The power needs for ferries and cruise ships vary greatly depending on whether the ship is moored or sailing. Regardless, the power supply system should be selected to operate efficiently over a wide power range.

Using very strict design requirements for newbuilds without corresponding operational requirements for all ships could severely disadvantage new ships, as they are forced to use a much more expensive fuel. This could again lead to older and less-efficient ships being kept in operation longer.

The speed of transition to carbon-neutral fuels will have major implications for the shipbuilding value chain and the land-based fuel supply chain. In practical terms, we need to start developing supply of carbon-neutral fuels in major ports, as well as developing the on-board solutions and corresponding regulations.

Starting with the current decade, it will be necessary to develop new-generation, carbon-neutral ships. This will require accelerated technology development for short sea shipping vessels, and safety standards development. These are needed to overcome key barriers including technical maturity, cost of the required machinery and fuel-storage systems on vessels, fuel price, fuel availability and widespread/global bunkering infrastructure. Safety is also a primary concern for some fuels. To further encourage development, use of fuel-flexible or fuel-ready solutions on board could help reduce the ship owners' investment risk.

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