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Report

Alternative fuels and propulsion systems for fishing vessels

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ABSTRACT

The main objective of CoolFish is to increase energy efficiency of the utility systems (cooling, freezing and heating) onboard fishing vessels. To achieve a full potential of efficiency and environmental benefits the ship must be considered as an engineering system, i.e. also considering the propulsion system. Stricter environmental regulations and an increased awareness of energy use and emissions force the shipping sector to adapt new fuels and/or propulsion systems to replace the conventional mechanical diesel engines. This report provides an overview on such alternatives with focus on new-built and ordered Norwegian fishing vessels.

The review shows a development towards diesel-electric or hybrid propulsion systems, often with hybrid power supply (e.g. batteries). Hybrid propulsion and hybrid power supply enables several operating modes, to match speed and auxiliary requirements, enabling flexible and fuel-efficient operation. However, it also implies challenges in relation to waste heat availability and sizing of heating and cooling equipment.

Alternative fuels with high technical feasibility for the fishing sector include LNG/LBG and biodiesel for all fishing vessel types, and hydrogen fuel cells for coastal fishing ships. Battery implementations for partly electrified propulsion are considered highly feasible for the whole fishing sector.

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1 Introduction

This report provides an overview of propulsion systems and fuels, applied to replace conventional mechanical diesel engines, with focus on new-built or ordered Norwegian fishing vessels. Some examples from the international fishing fleet, as well as future scenarios for uptake of alternative fuels in the shipping sector, are also presented.

Stricter environmental regulations and an increased awareness of energy use and emissions force the shipping sector to adapt new fuels and/or propulsion systems. Even though CoolFish is not directly focused on the fishing vessels' propulsion system, this theme is closely related to the topics addressed in the project. The main objective of CoolFish is to increase energy efficiency of the utility systems (cooling, freezing and heating) onboard fishing vessels. To achieve its full potential of efficiency and environmental benefits, a ship must be considered as an engineering system, i.e. also considering the propulsion system, within its intended operational profile.

The change towards new propulsion systems and fuels requires and enables development of new efficient utility system concepts. One example is the possibility to use surplus cold from the fuel system, for ships driven with liquefied natural gas (LNG), to cover parts of the cooling demand for fish preservation. Another example relates to vessels with hybrid propulsion including batteries, which implies less quantity of surplus heat available compared to conventional propulsion. This could be addressed by, for example, implementing a heat pump for upgrading waste heat from the refrigeration system or other waste heat sources.

CoolFish also aims at evaluating and adopting methods for calculating the carbon footprint of fisheries and quantifying the potential for its reduction by using natural refrigerants and energy-efficient integrated utility systems. Today's methods (reviewed in a separate report) for estimating fuel consumption per landed fish are based on conventional diesel operation. The use of other fuels and/or hybrid propulsion including batteries, might have a significant impact on the carbon footprint. To enable proper evaluation of energy-saving measures it is important to disaggregate the fuel usage between different operations and modes, such as fishing, steaming to and from the fishing field, onboard processing, and refrigeration. Knowledge about alternative propulsion systems, and operation modes, will make such fuel disaggregation more accurate.

Chapter 2 gives a brief overview of the main international and national regulations on emissions related to fuel consumption of ships. In chapter 3, different types of propulsion systems are described, while chapter 4 addresses the operating modes available for hybrid ships. Chapter 5 provides examples of fishing vessels having installed the different propulsion systems. It also summarises a study comparing hybrid propulsion systems in relation to different operating modes. In chapter 6, a brief overview of alternative fuels and their relevance for use in fishing vessel are presented, together with scenarios related to usage of alternative marine fuels towards 2050.

2 Regulations

The main regulatory institution for the shipping sector is the International Maritime Organization (IMO). IMO's international convention MARPOL (International Convention for the Prevention of Pollution from Ships) aims at preventing pollution of the marine environment due to operational or accidental causes. Emissions to air are regulated in MARPOL Annex 6, which entered into force in 2005. Among others, Annex VI sets limits on sulphur and nitrogen oxide emissions from ships' exhausts, both globally and more stringently in designated emission control areas (ECAs). To reduce emissions of carbon dioxide, a new chapter was adopted in 2011, covering mandatory technical and operational energy efficiency measures [1].

2.1 Sulphur oxides (SO_x)

Figure 2-1 shows the development of the IMO regulation related to maximum allowed sulphur content in fuels used onboard ships. Until 2019, the limit for ships operating outside of designated ECAs was 3.5%. This year (2020) the limit was significantly reduced, down to 0.5%. For ships operating within ECAs it has been mandatory to use fuel with a sulphur content of 0.1% or less since 2015. The ECAs established for SO_x emissions (shown in Figure 2-2) are the Baltic Sea area, the North Sea area, as well as designated coastal areas of the United States and Canada, and designated areas in the US Caribbean Sea area. Examples of ECAs that are under discussion include the Mediterranean and the Norwegian west coast [2].

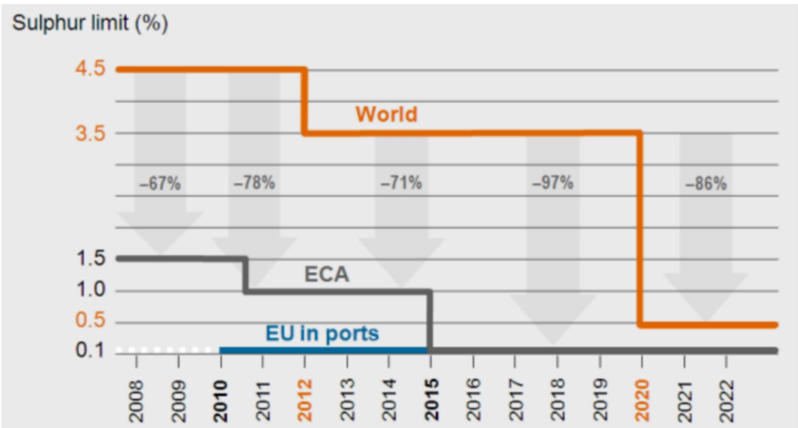


Figure 2-1: IMO sulphur limits timeline [3]

Figure 2-2: Existing and future ECAs for sulphur limit regulations [4]. Used with permission from DNV-GL

In Norway, fishing in distant waters is exempt from sulphur tax, while fishing in Norwegian coastal waters (i.e., within 250 nautical miles ashore) is subject to sulphur tax for fuels containing over 0.05 percent by weight of sulphur. For 2020, the rate is NOK 0.1355 for every 0.1 percent sulphur [5].

Today there are three major options that can be considered for conforming to this regulation [6]:

1. Switch to fuels with low or no sulphur content, such as low sulphur fuel oil (LSFO) and LNG
2. Install exhaust gas treatment system (scrubber) and continue to use conventional high sulphur fuel
3. Consume less fuel, for example by improved energy efficiency, and, consequently, emit less SOx.

There are challenges with all three measures, which is outside the scope of this report.

2.2 Nitrogen oxides (NO_x)

The IMO regulations regarding NO_x emissions have become steadily stricter over the last two decades, as shown in Figure 2-3. The strictest regulation, Tier III, entered into force in 2016, but only applies for designated ECAs. At present, there are only two effective NO_x ECAs: the North American and the US Caribbean Sea Areas, indicated in green in Figure 2-4. For Europe, the Tier III regulation will come into effect in the North Sea and Baltic Sea areas from 1 January 2021. This means that all vessels with an engine output greater than 130 kW, and with a keel-laying date after 2016 for the US waters and 2021 for North Sea and Baltic Sea waters, must comply with Tier III regulations when entering these areas [7, 8].

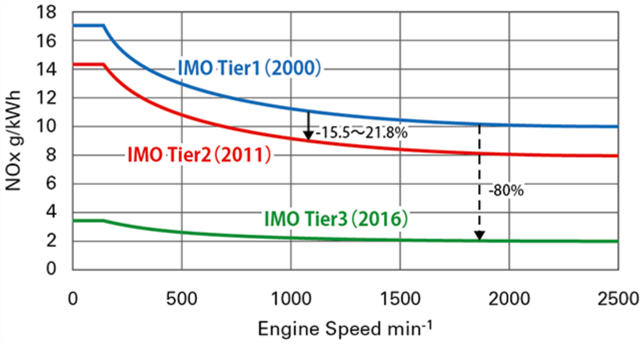


Figure 2-3: IMO NO_x Tier III emission standards in relation to IMO Tier II and IMO Tier I [9]

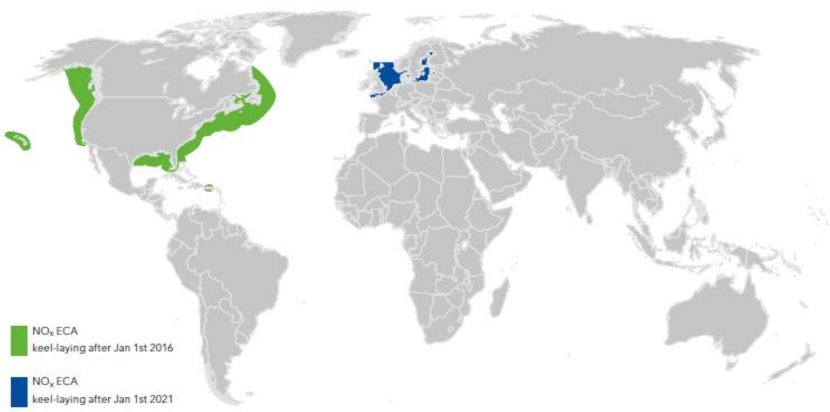


Figure 2-4: Emission control areas (ECAs) [4]. Used with permission from DNV-GL

In 2012, the Gothenburg Protocol was revised to set, among other factors, NOx ceilings for 2020. To comply, Norway introduced a NO_X tax in 2007 at 15 NOK / kg emitted NO_X. As a part of the Environmental Agreements on NO_X, 2018-2010 and 2011-2017, between the Norwegian state and business organizations, a NO_X fund was established. The Norwegian Fishermen's Association, the Norwegian Fishing Vessel Owners' Association, and the Norwegian Seafood Federation are among the cooperating organizations. Parties pay a smaller amount to the NO_X fund instead of tax when NO_X emission-reducing measures are implemented [10].

The "NO_X Agreement 2018-2025" is an extension of the "Environmental Agreement on NO_X" and constitutes the framework for the NO_X Fund. Electrification, LNG operation and NO_X cleaning with catalysts are examples of technologies with high volume triggered by the NO_X Fund's support. Further NO_X-reducing measures are still needed to ensure that the emission ceiling in the NO_X Agreement are met by 2025. In 2020 the NOx tax is 22.7 NOK/kg emitted NOx, while the NO_X funds payment rate is 16.5 NOK/kg for oil and gas operations on the shelf, and 10.50 NOK/kg for all other NO_X taxable activities, including shipping and fishing [11].

To go from complying with the current Tier II down to Tier III, the NO_x emissions must be reduced by approximately 75%. There are several technologies, or combinations of them, that can reduce emissions to Tier III levels, for example [7]:

- Dual fuel (DF) engines (operating on both diesel and LNG) or gas engines (operating only on LNG)
- Selective catalytic reduction (SCR)
- Exhaust gas recirculation (EGR)
- Hybrid propulsion with batteries/fuel cells in combination with NO_x reduction technologies

2.3 Carbon dioxide (CO_2)

MARPOL Annex VI was revised in 2011 to also control CO_2 emissions, by introducing the Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP). The EEDI is related to mandatory technical measures, while the SEEMP deals with operational measures. In 2018, IMO agreed on a strategy for reducing GHG emissions, with targets on CO_2 emissions [12].

2.3.1 Energy efficiency measures

Energy efficiency design index (EEDI). Since 2013, new ship designs need to meet a reference level of minimum energy efficiency per capacity mile (gram CO_2 per ship's capacity mile), for their ship type. The level is tightened every five years to stimulate continued innovation and technical development. However, the EEDI does not apply to fishing vessels [12].

Ship energy efficiency management plan (SEEMP). The SEEMP applies since 2013 and includes fishing vessels of 400 GT and above. It aims at establishing a mechanism to increase energy efficiency in a cost-effective way. In addition, it provides an approach for shipping companies to manage ship and fleet performance over time by, for example, using the Energy Efficiency Operational Index (EEOI) as a monitoring tool [12].

Energy efficiency operational index (EEOI). The voluntary use of EEOI enables operators to measure the fuel efficiency of a ship in operation and to gauge the effect of any operational changes or introduction of technical measures. There are studies on how the EEOI could be applied for fishing vessels, for example by using the formula below. It includes the specificity of operational activities of fishing vessels and applies the relation recommended by IMO [13].

$$EEOI_F = \frac{\sum_j FC_j C_{Fj}}{m_{fish} D} \quad [\,gCO_2/t_{fish}nm]$$

- *$EEOI_F$ is the energy efficiency operational index of a fishing vessel*
- *FC_j* is the mass (in grams) of consumed fuel (of type *j*) by main and auxiliary engines and oil-fired boilers during operational task performance,

- CF_j is the conversion factor expressed by the relation of CO_2 (in tonnes) generated from combusting one tonne of the *j* type fuel,
- m_{fish} is the weight of fish brought (in tonnes),
- *D* is the distance in nautical miles corresponding to the operational task performed.

This formula implies the value of $EEOI_F$ being strongly correlated with the distance travelled and the quantity of fish caught. The $EEOI_F$ value will be different in various operational states, for example between steaming and trawling. It is advisable to determine $EEOI_F$ for the entire voyage of the vessel with regards to the total distance travelled, the total mass of consumed fuel and the total weight of fish caught [13].

2.3.2 CO_2 reduction targets

During 2018, IMOs member states agreed upon the so called GHG initial strategy, envisaging, for the first time, a reduction target of total GHG emissions from global shipping. This was considered as a landmark for the shipping industry, which seeks to align with the Paris Agreement goals.

The green line in Figure 2-5 shows the initial target of reducing annual GHG emissions from ships by at least 50% by 2050, compared to 2008, meaning a reduction in carbon intensity by 85 . Further strengthening of the strategy, which will be revised in 2023, could result in a commitment of 100% reduction by 2050 (dotted green line) depending on evidence available during the five-year period. The red line represents a business as usual scenario, based on the IMO GHG study, indicating a rise in emissions of 150% by 2050 [14].

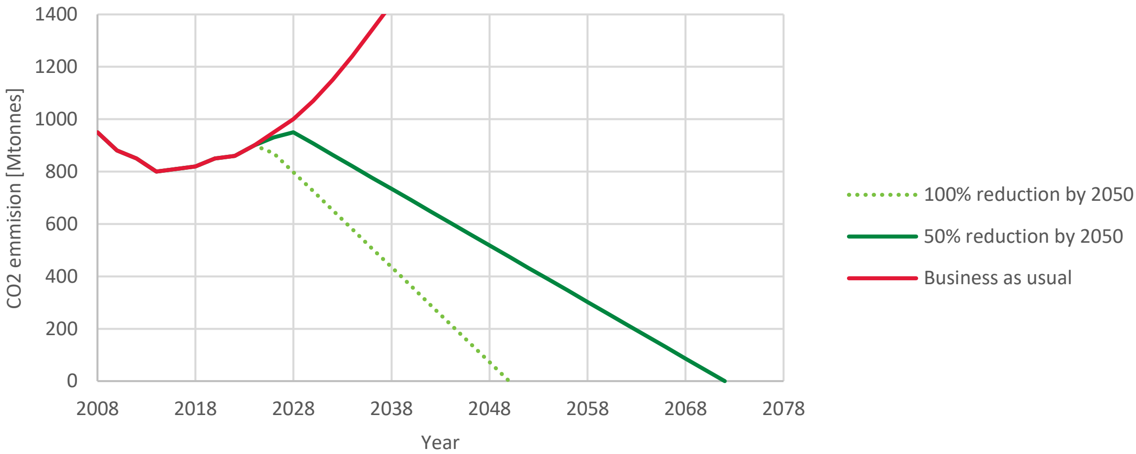


Figure 2-5: Pathways for international shipping's CO_2 emissions (adapted from [14])

Norway has committed itself to reduce its total GHG emissions with 40% by 2030 - a huge challenge to which the shipping sector must contribute. The organisation Fiskebåt[1] has set up a goal to reduce the CO_2 emission from its fishing fleet with 40% between 2005 and 2030 [15].

Several measures can be adopted to reduce CO_2 emissions, such as [16]

- Improving energy efficiency using technical and operational measures
- Switching to fuels with less emissions per unit of work done.
- Using renewable energy sources, such as wind and sun (either directly onboard or as shore power for charging batteries).

[1] fiskebat.no

3 Propulsion systems

The increasing demand for fuel efficiency and reduced emissions, together with the diverse operational pattern of different shipping segments, such as cargo vessels, cruise ships and fishing vessels, have led to the development of various propulsion system solutions. Moreover, within each shipping segment, there can be large variations in the operational profile, such as between coastal and deep-sea fishing vessels.

Propulsion solutions are often categorised in *mechanical, electrical* or *hybrid propulsion*. The ships' electrical power demand can be supplied by combustion engines (generators), fuel cells, energy storage (batteries) or a combination (hybrid power supply). In this chapter, diesel is assumed as fuel for the combustion engines and/or generators, but it could also be alternative fuels, such as LNG, which are addressed in section 6.2.3.

3.1 Diesel-mechanic propulsion

Figure 3-1 shows a principal sketch of a typical conventional diesel-mechanic propulsion system. The main diesel engine (1) drives the propeller (3), either directly or via a gearbox (2). Diesel generators (7) supply power to a separate alternate current (AC) network (6), distributing electric power to auxiliary loads (5) such as HVAC (heating, ventilation and air conditioning), refrigeration and diverse frequency-controlled equipment (4) [17]. A shaft generator, powered by the main engine, could also be used to supply electrical power to the ship´s grid (not shown in Figure 3-1).

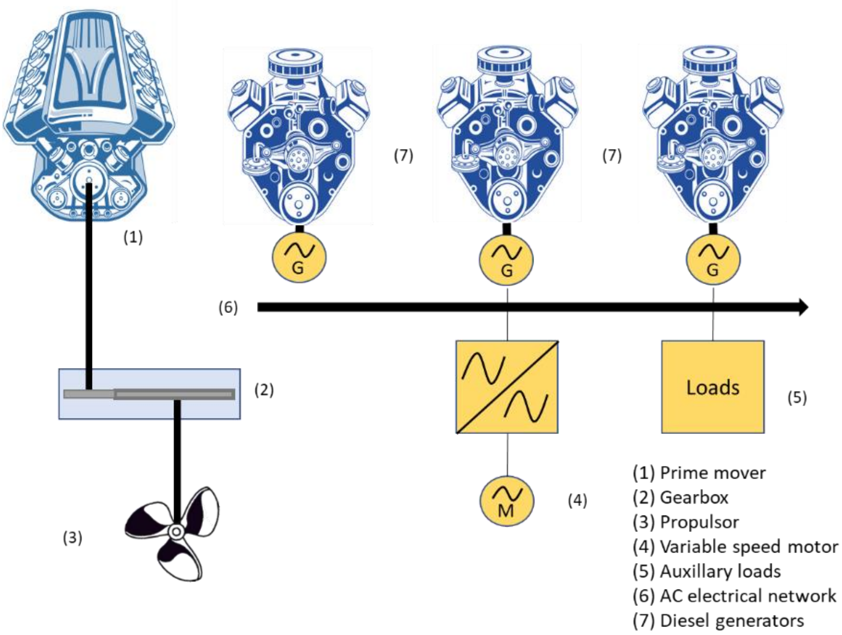


Figure 3-1: Example layout of a conventional mechanic propulsion (adapted from [17])

Mechanical propulsion is particularly efficient at design speed, which is normally between 80% - 100% of top speed. Therefore, for "transport ships" operating at a constant speed a mechanical propulsion system together with waste heat recovery (WHR) might be the preferred solution for reducing fuel consumption and emissions. However, for speeds below 70% of top speed the fuel efficiency is poor since fuel consumption is significantly increased below 50% of rated power. For many ship types, a mechanical propulsion system implies operation at low engine load during certain periods, resulting in high specific fuel oil consumptions (SFOC) and related emissions. For these ships, an electric or hybrid propulsion might instead be the most efficient solution [17].

For small ships, the conventional machinery is one small diesel engine supplying both the propulsion, with a direct propeller drive, and the electric power demand, via an alternator (Figure 3-2). The ship often has a large thermal energy surplus since the engine operates also when the ship is at zero or low speed [18].

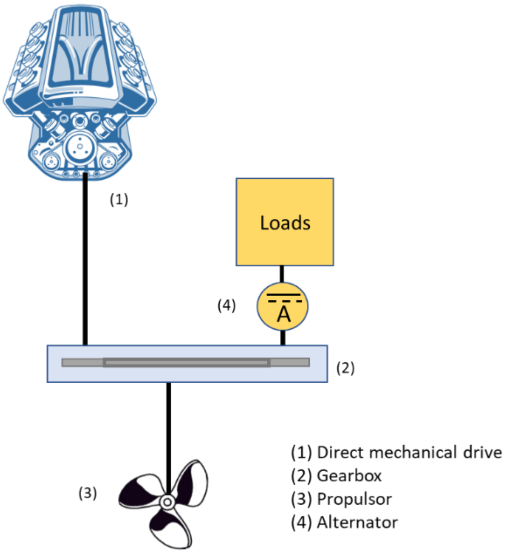


Figure 3-2: Typical layout of a diesel-mechanical system for small ships

3.2 Diesel-electric propulsion

Figure 3-3 shows a "typical" layout of a diesel-electric propulsion system. Multiple diesel generators (1) supply power to the AC electric network (2). From there, electric power is distributed, via transformers (3) and/or variable speed motors (4) to electric propulsion motors (5), and to auxiliary loads and motors (6) [17].

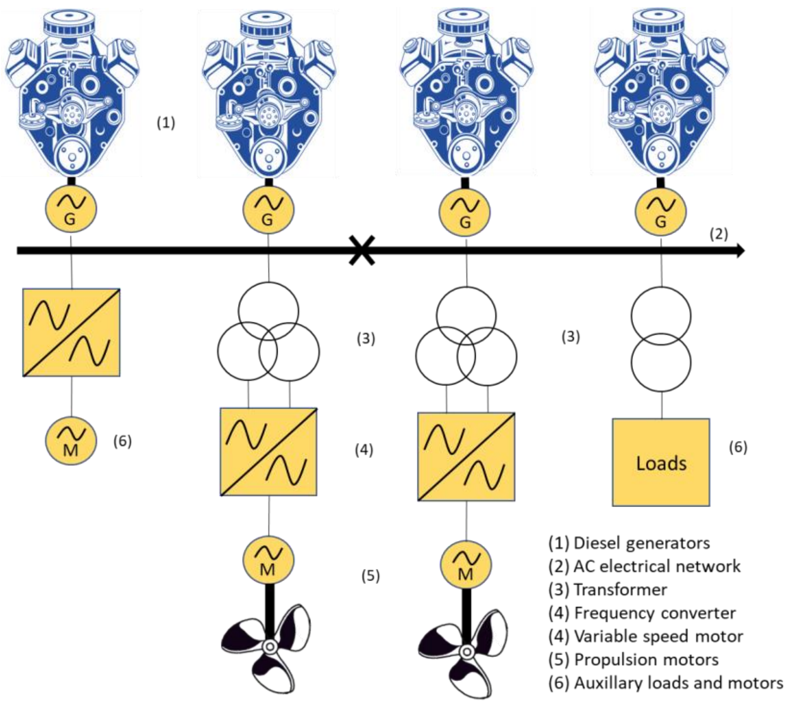


Figure 3-3: Example layout of an electrical propulsion system (adapted from [17])

Diesel-electric propulsion is especially fuel-efficient when the utility (auxiliary) load constitutes a significant fraction of the propulsion power demand (e.g. cruise ships) and for ships with a large variation in their operation profile. A power management system ensures the engines to not operate on part-load, but instead matches the number of engines in operation for covering the combined propulsion and auxiliary load. With such a concept, the diesel generators operate closer to their design point and at rated speed, leading to higher fuel efficiency and lower emissions (especially NO_x). A disadvantage is the higher conversion losses due to the additional conversion stages (between electrical and mechanical energy), implying a high specific fuel oil consumption (SFOC) especially near the top speed [17].

The implementation of diesel-electrical propulsion has been very successful in the cruise industry, due to factors such as fuel efficiency, robustness, redundancy, flexibility in location of machinery spaces, noise- and vibration reduction. Electric propulsion is also frequently applied on ferries, icebreakers, offshore and drilling vessels. [19]. In relation to fishing vessels, diesel-electric propulsion is increasingly considered for fishing ships having large load variations, while maintaining a constant load for a relatively long time, such as ocean-going bottom-trawling and long-line vessels [18].

There are many possible arrangements of a diesel-electric propulsion system. Examples of layouts used on large fishing vessels are a twin-screw propulsion including four electric motors of varying size, four generators and two main switchboards. The generators start and stop automatically as the electrical load varies (total demand of propulsion and auxiliary systems). The electric motors drive the propeller(s) providing highly reliable and efficient operation. The concept has been delivered to Norwegian purse seiners and around 30 fishing vessels in other parts of the world. Reported advantages from ship-owners include fuel savings, reduced noise levels and reliable operation [20].

3.3 Hybrid propulsion

A hybrid propulsion system enables the vessel to be propelled in two ways, namely electrical (diesel-electric and/or battery) and mechanical (direct diesel-drive). This section covers mechanical-electric propulsion, while the next section includes electric propulsion with hybrid power supply (e.g. diesel and batteries). Figure 3-4 shows a mechanical-electrical hybrid propulsion system.

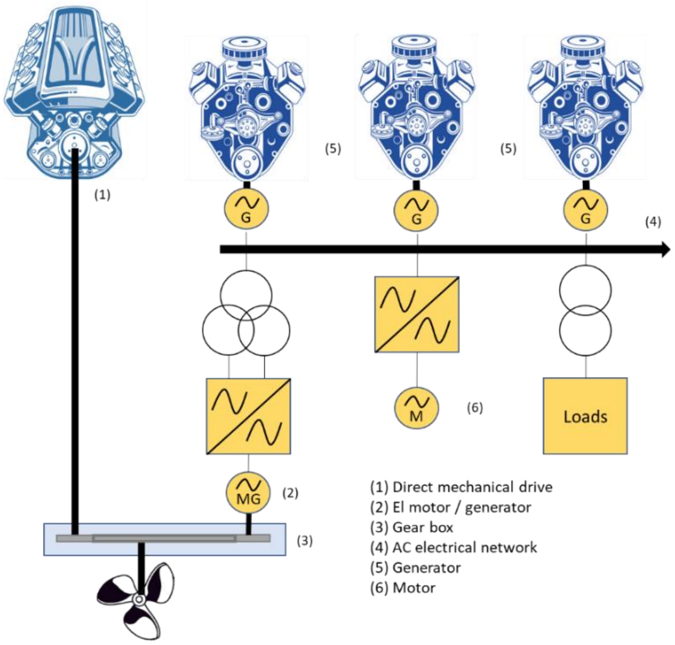


Figure 3-4: Example layout of a hybrid (mechanical-electrical) propulsion system (adapted from [17])

A mechanical diesel engine (1) provides direct propulsion for high speeds, with a high efficiency. An electric motor (2), which is coupled to the same shaft through a gearbox (3) or directly to the shaft driving the propeller, provides propulsion for low speeds. Thus, running the main engine inefficiently in part load is avoided. The electric motor could also be used as a generator, supplying power to the ship's auxiliary electrical network (4). When the mechanical main engine is running, the system allows generating power for ship's auxiliaries either from the main engine, via the electric generator (2), or from the generating sets (5). In other words, the control strategy allows transferring electrical power from the mechanical drive to the electric network and vice versa [17].

This concept exploits the benefits of electric propulsion at low power, and the benefits of direct mechanical propulsion at high power. The propulsion efficiency is optimised, and at the same time, the system responds quickly to a variable power demand. The inclusion of power electronics for controlling the hybrid shaft generator (HSG) leads to an extensive operating flexibility [21].

For certain ships, operating with varying speed conditions, a hybrid propulsion system enables a considerable reduction in fuel consumption and emissions. This is especially true for a ship where the auxiliary load is only a fraction of the required propulsive power. If such a ship would be equipped with a pure diesel-electric system, the losses associated with the electrical conversion would lead to increased fuel consumption. The extra electrical equipment also means increased weight, size, and cost. Therefore, ships that frequently operate at low speed can benefit from a mechanic-electric hybrid propulsion system [22].

For fishing vessels requiring high propulsion capacity, a hybrid solution could be favourable since a diesel-electric solution can be relatively expensive. Typical operation is diesel mechanical for steaming to and from fishing field, while a typical operation for the electrical propulsion is transit at lower speeds and fishing operations. In occasions with heavy steaming, a parallel operation can be applied. This enables optimised fuel economy for all operation modes. Generally, economic benefits are to be expected if the fishing vessel operates below 15% propulsion power, equivalent to 40% of top speed, for a significant amount of time [17].

3.4 Electric propulsion with hybrid power supply

With a hybrid power supply, a combination of two or more types of power sources provides the electrical power, for example diesel generators together with batteries and/or fuel cells. Since commercial applications of fuel cells in ships is limited, so far, a hybrid power supply here refers to diesel generators and battery banks. Figure 3-5 shows such a system with three diesel generators and an energy storage unit consisting of batteries. The battery banks (2) are connected to the main electrical grid but could be connected at various locations of the electrical system [17].

The battery capacity can be designed to enable switching off one or more diesel generators when they would be running inefficiently at part load. Recharging of batteries is made when the engine is running in an efficient operating point or when connected to shore supply. Implementing a battery package large enough to replace all diesel generators in certain operating modes enables temporarily zero-emission operation and increased comfort due to significantly reduced noise.

Another purpose of implementing a battery solution is for peak-shaving, i.e. the batteries add power during periods when a high power is required and are recharged when less power is required. With this operational strategy, the installed engine power can be reduced. Batteries handling power fluctuations also enable a more constant engine load and thereby maintaining a more efficient operating point.

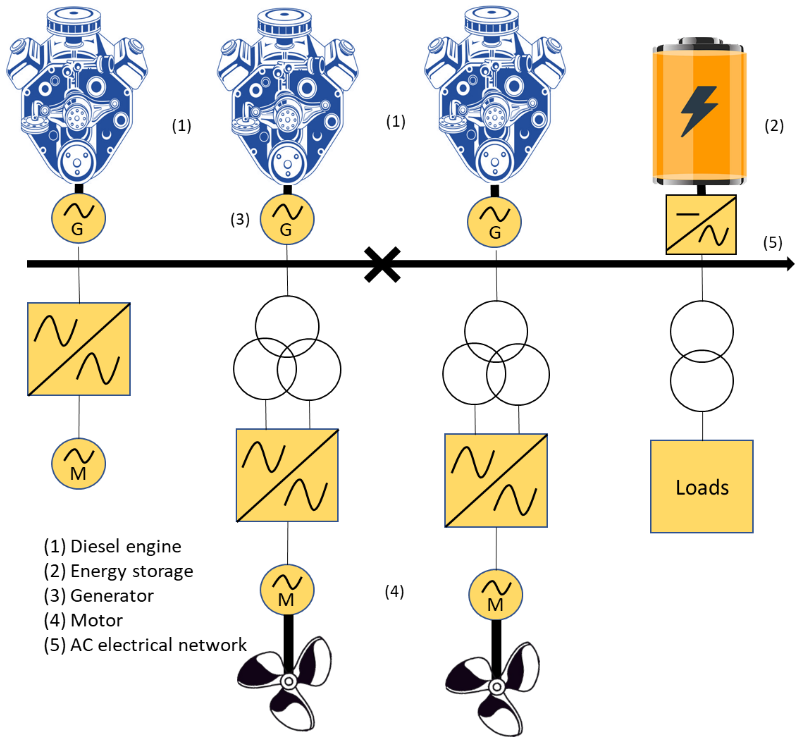


Figure 3-5: Typical layout of electric propulsion system with hybrid power supply (adapted from [17])

Fuel and emission reduction are estimated to 5% - 25% for installations where batteries support propulsion and optimise the main engine propulsion. The largest benefit is for ships with varying power demand, much low-load operations, and large share of operation with power redundancy requirement. A smaller reduction (below 10%) is expected for concepts where batteries are solely used for supporting auxiliary machinery [21].

Implementation of batteries onboard can be made without the possibility for shore power connection, even though this would represent additional potential for high energy efficiency and emission reduction. A "plug-in-hybrid ship" enables the battery bank to be recharged from the shore grid, reducing fuel consumption and local emissions. However, the emissions of power generation in the grid must be considered.

Battery solutions are also highly relevant for ships with a large power demand in port, where the battery package can replace (partly or fully) the use of auxiliary engines. This includes ships with much use of cranes, winches, pumps and power-demanding cooling and heating systems in connection to loading and un-loading operations, or other power-demanding cargo-handling onboard [23].

An additional benefit with an energy storage solution (batteries) is the facilitation of including intermittent renewable power production (e.g. solar, wind) on-board. The batteries can also be used for storing regenerated energy from, for example, heavy winches for fishing gears. In relation to safety, the battery bank can provide back-up power during a failure of combustion power supply (i.e. diesel generators).

Small fishing vessels, whose gears typically have low energy demand during fishing, could benefit from batteries. One example of a commercially available propulsion system for use on coastal fishing vessels includes one electric motor, one propeller, one auxiliary engine (generator), a battery package and shore connection. For larger vessels, such as auto-liners, the same system can be applied but with two electric motors, four auxiliary engines and two battery packages [24].

3.5 Hybrid propulsion with hybrid power supply

Figure 3-6 shows a hybrid propulsion system with hybrid power supply. At low propulsive power, the electric drive (2, 3, 4) enables ship propulsion with the main engine (1) switched off. In other operational modes, when the main engine is running, the electric motor (MG) can be used as a generator, i.e. delivering electric power from the main engine to the ship's utility power demand.

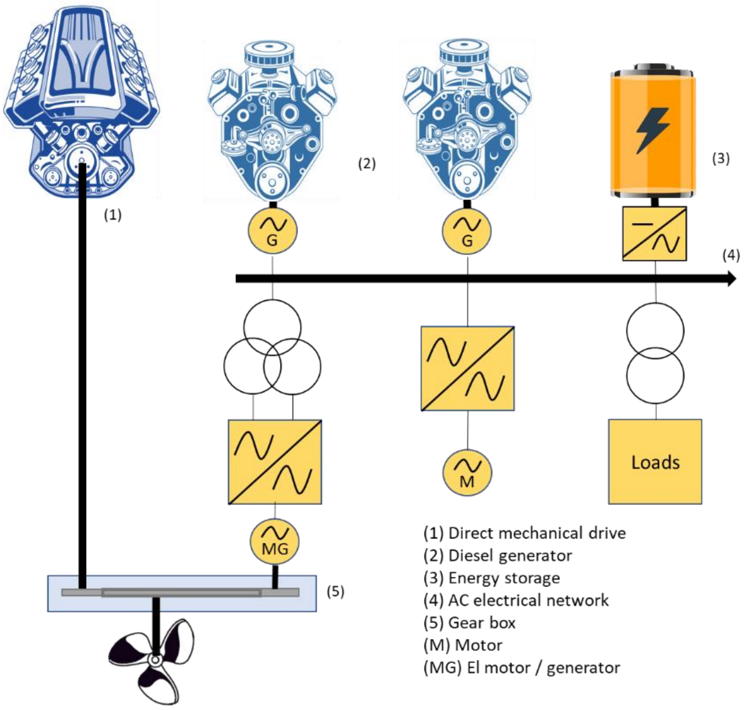


Figure 3-6: Typical hybrid propulsion with hybrid power supply (adapted from [17])

An example of a commercially available system developed for a trawler [25] consists of one main diesel/gas engine, one electric motor, one propeller, four diesel/gas auxiliary engines, battery package(s) and shore connection supply.

3.6 Pure electric propulsion

A pure electric propulsion refers to a ship operating solely on batteries, which are charged exclusively with shore power. In this case, the ship's onboard emissions are reduced to zero. To achieve "true" zero emission operation, the shore electricity must be produced from renewable sources, nuclear power or by using CCS (Carbon Capture & Storage) technology. The amount of electricity that can be transferred from shore to ship depends on the shore electrical grid capabilities, the battery charging facilities and the time spent at berth.

Short-sea shipping has naturally the highest potential for pure battery operations, specifically ships on short routes, with regular schedules and operating on long-term contracts. Deep-sea shipping can install batteries for energy optimisation during cruising, or as low-emission solution when operating in sensitive areas or near harbours. The main barriers are cost, infrastructure, and space requirements [26].

4 Operating modes for hybrid ships

This chapter describes some possible operating modes available for a ship with hybrid propulsion and hybrid power supply. In relation to the topics addressed in CoolFish, considering different operating modes is of high relevance due to the influence on parameters, such as waste heat availability, sizing of heating and cooling equipment, and the need for thermal storage. The example presented in this chapter is for a ship operating in highly variable speed and power modes [21].

4.1 Propulsion and electrical demand

The ship is equipped with a hybrid propulsion system consisting of a mechanical drive (3 MW main diesel engine), an electrical drive supplied by auxiliary diesel generators (2 x 1 MW), and/or a battery package with a power capacity of 2 MW. Five operating modes are defined, all having different demands for propulsion and auxiliary electrical power (see Figure 4-1). Each operating mode is described in the following sections.

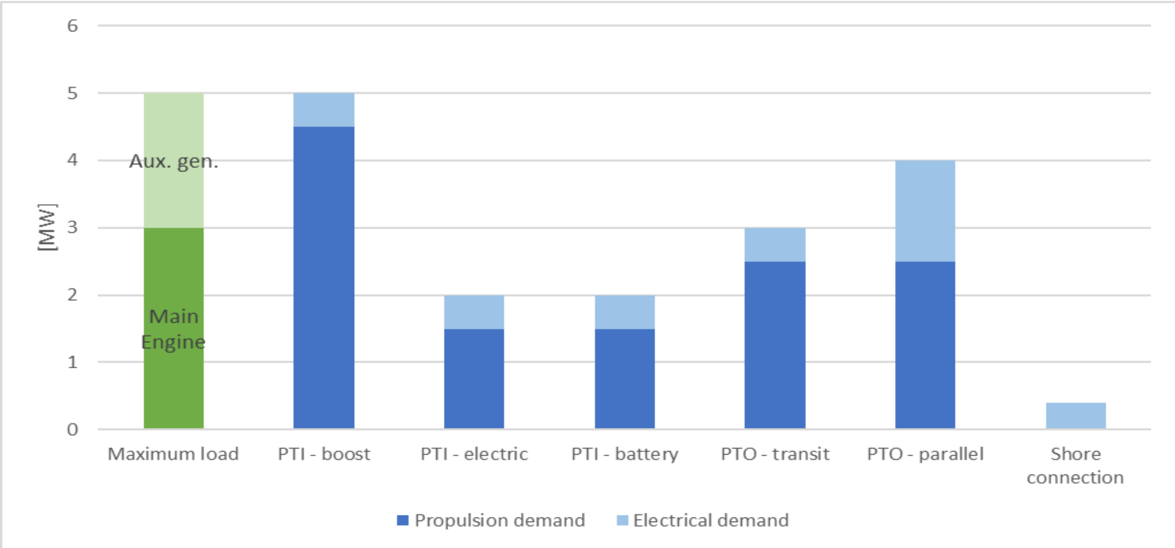


Figure 4-1: Maximum load of main engine and auxiliary generators (green), and the demand for propulsion and electrical power for five different operation modes. Figure created based on data in [21].

4.2 PTI booster mode

This operation mode, shown in Figure 4-2 (left), represents a high propulsion power (4.5 MW) for operating at maximum speed. The main engine is used for propulsion and the shaft generator functions as an auxiliary propulsion motor (P_2) working concurrently to the main diesel engine (P_1). Thus, it operates with power take-in (PTI) to boost the propulsion in periods when maximum speed is required. The gensets supply electrical power to both the propulsion motor (P_2) and to ship's consumers. In the event of a main engine failure, the PTI setup enables propulsion at reduced speed, so called Power Take Home (PTH) mode.

4.3 PTI electric mode

The operation mode PTI electric shown in Figure 4-2 (right) represents propulsion at such a low speed that the main diesel engine is not needed. Instead, the gensets supply both the ship's electrical load and the propulsion load (through the shaft generator functioning as a propulsion motor).

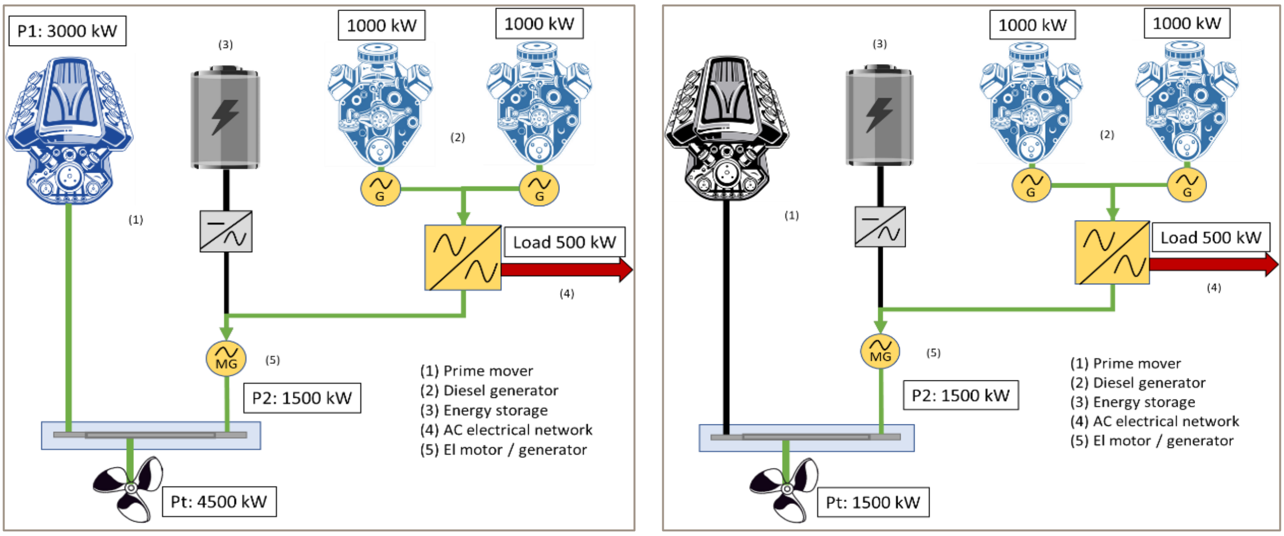


Figure 4-2: PTI booster mode - maximum speed (left) and PTI electric mode - low speed (right) (adapted from [21])

4.4 PTI battery mode

In the pure electrical mode (Figure 4-3, left), batteries supply the power needed for both propulsion and auxiliary power consumption. The main engine and gensets are switched off, eliminating emissions and noise. Operating on batteries also permits the PTH functionality.

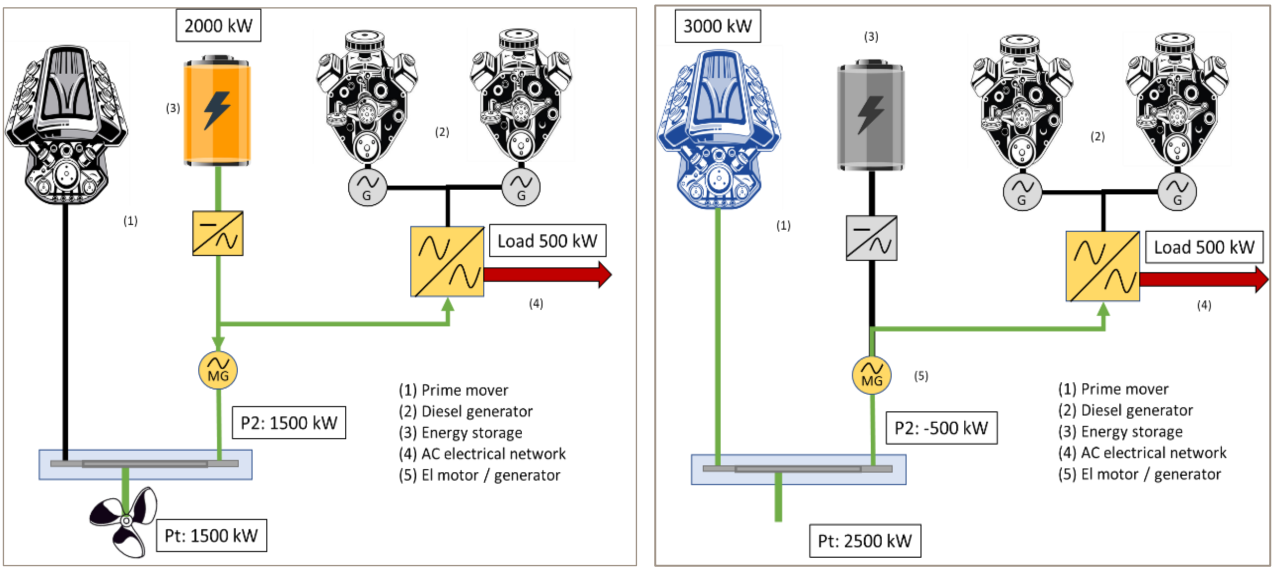


Figure 4-3: PTI battery mode (left) and PTO transit mode medium speed (right) (adapted from [21])

4.5 PTO transit mode

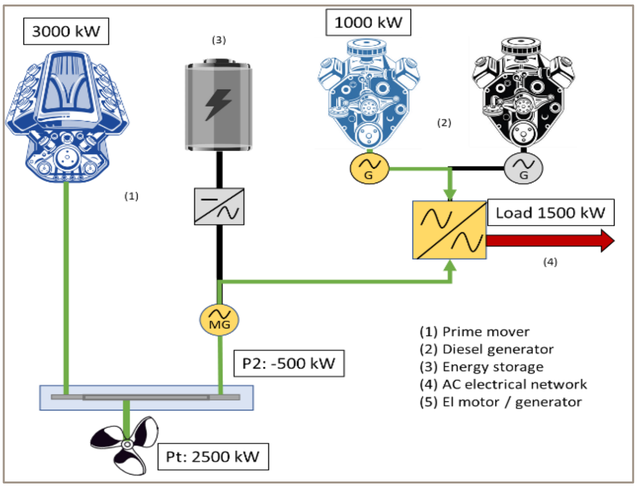
The transit operation mode, shown in Figure 4-3 (right), represents propulsion at medium/normal speed. The main engine supplies the power needed for propulsion as well as auxiliary power consumptions. It operates in a so-called power take off (PTO) mode, delivering auxiliary power from the main engine, enabling the generators to be switched off.

4.6 PTO parallel mode

This operation mode, shown in Figure 4-4 (left), is applied in periods when the power required for propulsion and auxiliaries is higher than the power that the gensets or main engine can provide by themselves. Thus, parallel operation is needed. The main engine can then be operated at a preferable (efficient) load to supply propulsion power and parts of the auxiliary load (through PTO) together with one of the generators.

4.7 Shore connection

In Figure 4-4 (right), the vessel is connected to port power supply. The battery provides the auxiliary load, meaning that the main engine and the gensets can both be switched off, with subsequent reduction in fuel consumptions and local emissions. Noise and vibrational levels are also reduced to a minimum.



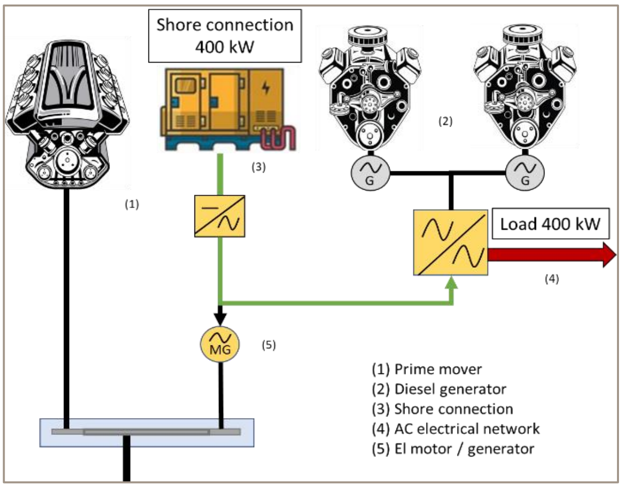


Figure 4-4: PTO parallel load (left) and shore connection (right) (adapted from [21])

4.8 Summary

Figure 4-5 provides an overview of the different operating modes presented in section 4.2- 4.7, showing how the propulsion and auxiliary power demands are covered for each of the operating modes. The magnitude of fuel savings enabled by these operating modes are not specified. However, section 5.7 summarises a study of different hybrid propulsion systems (i.e. enabling some of these operational modes) installed on fishing vessels, indicating potential savings in fuel consumption and engine operating hours.

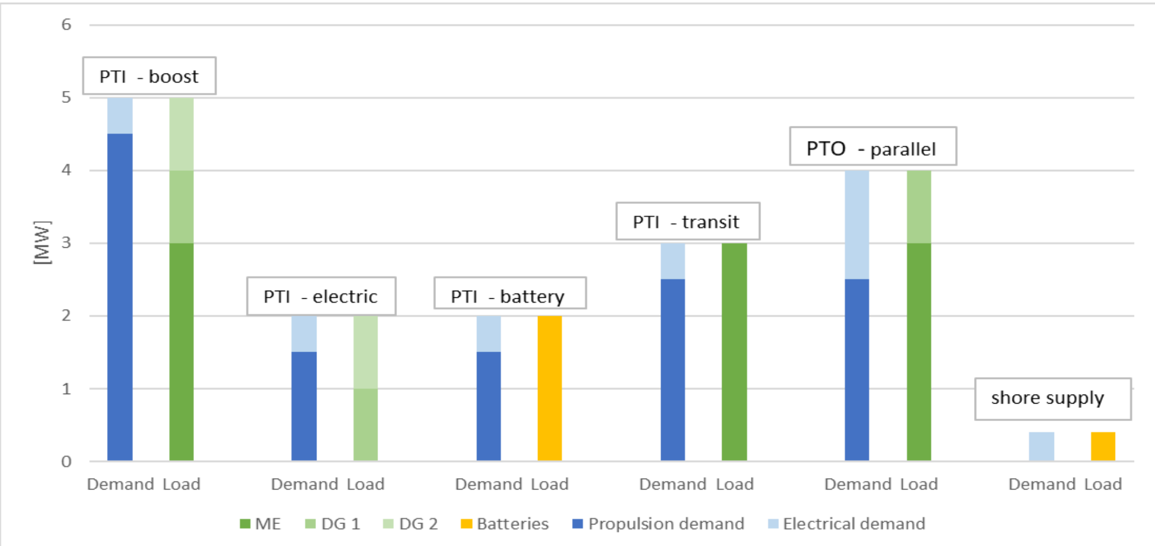


Figure 4-5: Load of main engine (ME) diesel generators (DG) and batteries, for supplying the propulsion and electrical power demand in the different operating modes. Created based on results in [21].

5 Examples of fishing vessel propulsion systems

This chapter provides examples of recently built or ordered fishing vessels that are equipped with the propulsion systems described in chapter 3. Most examples are from the Norwegian fishing fleet.

5.1 Diesel-electric propulsion

Figure 5-1: Purse seiner – Harto [27]

Already in 2009, the first diesel-electric coastal fishing vessel was delivered; a Norwegian 28 m **purse seiner** (Figure 5-1). It was equipped with four diesel generators and two electrical motors. When searching for fish, it can operate with a much lower noise level since only one generator is running instead of running the main mechanical engine. Improved redundancy and reduced fuel consumption were experienced, compared to conventional diesel engine operation. This delivery was followed by other similar ships from the same yard (e.g. Meløfjord and Voldnes) [27].

Most recently built/ordered fishing vessels with diesel-electric propulsion are, at least in Norway, equipped with hybrid power supply (i.e. batteries in addition to diesel gensets), as exemplified in the next section.

5.2 Electric propulsion with hybrid power supply

Figure 5-2: Netter - Angelsen Senior [28]

Figure 5-2 shows the 21 m **netter** Angelsen Senior, mainly fishing cod, haddock and saithe. The factory deck includes a 150 m^3 fish room fitted with an ice machine (5 tonnes/day). A hybrid electric propulsion system, consisting of two diesel gensets (650 kW) and a battery pack (270 kWh), was chosen to reduce noise and vibration, as well as emissions [28].

The intention is to operate solely on batteries when there is a low power requirement, such as when setting the gear or hauling. A switch to diesel-electric mode is made when shooting gear or when steaming up to ten knots, which also provides an opportunity to charge the battery packs. The battery solution, implying more efficient operation of the diesel generators, enables a reduction in fuel consumption by 25% and in generator running time by 75%, thereby cutting annual CO_2 emissions by 200 tonnes [28].

MS Geir, with a scheduled delivery in 2020, is a 63 m **long-liner** with an electric hybrid propulsion system including a battery capacity of 270 kWh [29]. Østervold, a Danish shipping company, has ordered a hybrid electric propulsion system for their 67 m **long-liner/seiner** to be delivered in 2021. It will operate on either diesel fuel or battery power depending on its operating conditions [30]. Both ships are shown in Figure 5-3.

Figure 5-3: Long-liner - MS Geir (left) [29] and a Danish long-liner /seiner (right) [30]

Figure 5-4 shows an 88 m **pelagic trawler** contracted by the Danish fishing company Gitte Henning. Its propulsion system is based on five diesel generators and a large battery package. When the trawl is set, electrical winches regenerate energy which can be used for propulsion, RSW (refrigerated sea water) cooling or battery charge [31].

Figure 5-4: Pelagic trawler - Gitte Henning [31]

Generally, the propulsion and electric power demand for a pelagic trawler fluctuates significantly with operational conditions, cooling requirements, varying weather, speed etc. The number and size of generators were chosen to optimise the energy power balance based on the specific operational profile, giving the engine optimum operating conditions and, thus, high efficiency. The large battery pack supports the generators when the load is high and recharges when the load is low. This peak shaving for avoiding large engine load variations gives a fuel reduction in the range of 10% [31].

The 64 m **auto-liner** Atlantic (Figure 5-5) will be delivered in 2020 with a diesel-battery propulsion system. There will be a factory onboard, with an installed freezing capacity of 60 tonne/day (incl. freezing of cuttings from filet production) and the ship is designed for being out fishing for a month. The energy that can be generated when the propeller is in motion will be used for lighting and heating onboard [32].

Figure 5-5: Auto-liner – Atlantic [32]

Figure 5-6: Flyshooter – SpesNova [33]

The fly-shooter/twin-rigger SpesNova (Figure 5-6) was delivered in 2019 to its Netherland operator. It is equipped with three identical diesel-electric generator sets, coupled to a power management system with a battery set-up and an energy regeneration system for the unspooling of winches when setting out nets. The ship is entirely emissions-free when stationary in the harbor, and also periodically underway at sea, due to the battery capacity on board of the vessel [33].

5.3 Hybrid propulsion (mechanic/electric)

Today, most Norwegian fishing vessels that are equipped with a mechanical-electrical propulsion system also have some battery capacity installed (i.e. hybrid power supply). Such ships are presented in section 5.4.

The Norwegian factory trawler Ramoen (Figure 5-7), with a cargo freezing hold of 1.200 m^3, was built in 2016 and are equipped with a diesel-electric propulsion system [34].

Figure 5-7: Factory trawler - Ramoen [34]

Figure 5-8 shows a 74 m Canadian **freezer trawler**, having an extensive electrical demand for its processing factory, but also for the accommodation block and navigation equipment.

Implementation of electric winches, instead of conventional hydraulic winches, enables utilising regenerative power from the winches when setting the trawl gear. This "produced" power is used for other major consumers onboard, such as the fish factory, freezing machines and hotel load. In the case of low auxiliary power demand, this free power will be put on the propeller through the shaft motor (operated in PTI mode). Expected delivery is during 2020 [35].

Figure 5-8: Canadian freezer trawler [35]

Tuna long-liner fishing is an important part of the pelagic fishery. The process of tuna fishing consists of two completely different working conditions: high-speed navigation and low-speed fishing operation. To meet the requirements of the two conditions, Shanghai Ocean Fishing Company has built five tuna long-liners, which are equipped with electric-mechanical hybrid system. According to real ship tests, fuel savings range between 8% and 25% for the hooking stage in the operation period, while fuel savings in the navigation period reached 14% [36].

Figure 5-9 shows a 78 m **offshore fishing** vessel equipped with a mechanical main engine (3.6 MW), three auxiliary gensets (2 x 900 kW, 1 x 600 kW) and a shaft motor with PTI, PTO and PTH operations. This enables four main operation modes [37]

1. *Diesel-mechanic*: the main engine provides propulsion power while gensets supply auxiliary power consumers.
2. *Diesel-mechanic with PTO*: The main engine supplies both propulsion power demand and auxiliary power demand, through the shaft motor in PTO operation. Thus, the gensets are switched off.
3. *Diesel-mechanic with boost*: Both the main engine and gensets are running. The shaft motor is operated as a PTI-motor, boosting the propeller.
4. *Diesel-electric*: The main engine is switched off since the gensets supply both the propulsion power, via the shaft machine operating in PTH mode, and electric power to consumers.

Figure 5-9: Off-shore fishing vessel [37]

5.4 Hybrid propulsion with hybrid power supply

The ships presented here can be operated either as diesel-electric or diesel-mechanic, or a combination of both, and they are also equipped with an energy storage system (batteries).

Figure 5-10 shows a 75 m **purse seiner/trawler**, ordered in 2018. It is equipped with an electric deck machinery (e.g. winches) and a comprehensive battery solution to fully benefit from the power regenerated by the winches. The batteries can be used for peak shaving to achieve the best possible operating conditions for the diesel engine, to enable reduced fuel consumption and emission, as well as wear and tear [38].

Figure 5-10: Purse seiner trawler - Hardhaus [38]

Figure 5-11 (left) shows a 77 m **trawler** from Prestfjord Seafood, with scheduled delivery in 2020. It is designed for operation in Arctic waters catching whitefish and shrimps. Onboard, there is a freezing room (1500 m^3) and a fish meal production plant. Battery packages are installed for regulating load changes [39].

Olympic Seafood har ordered a 70 m stern **trawler** for delivery in 2020 (Figure 5-11, right). Onboard there is a modern factory, which can handle and freeze both shrimps and whitefish [40].

Figure 5-11: The trawler Prestfjord (left) [39] and a trawler from Olympic Seafood (right) [40]

Nordic Wildfish plans to build a new **trawler** (Figure 5-12) with enhanced technology for bringing big loads of fish onboard live, then storing them in tanks before processing. In addition to the more sustainable fishing method, its hybrid propulsion system including batteries will be more fuel efficient and it complies with the DNV-GL SILENT ("low-noise") class notation [41].

Figure 5-12: Nordic Wildfish's trawler [41]

5.5 Small fishing vessels (< 15m)

According to the Food and Agricultural Organization of the United Nations (UN FOA), the number of small motorised fishing boats is estimated to 2.5 million globally, dominating inland fisheries [42]. With increased electrification across all sectors of society, the market for hybrid fishing boats is thus potentially massive.

Karoline (Figure 5-13) - "the world's first electric fishing vessel" - is a 11 m shark owned by Selfa Arctic. Its hybrid electric propulsion system consists of a diesel generator and a 195 kWh battery solution. The ship operates on diesel to and from the fishing ground, while switches to battery operation for fishing, loading and unloading. Pure battery operation is possible during 2-3 hours per day, provided a recharge overnight by plugging into the shore electrical grid. Except from fuel savings of around 70% and corresponding emission reductions, there is reduced noise and exhaust from the diesel engine, thus improved working conditions for the fisherman [43].

Figure 5-13: Shark – Karoline [43]

In 2019, Selfa Arctic started working on their second hybrid-electric fishing boat "Sundsbøen" (12 m), which will be operated by LofotFishing. The combination of diesel-electric engines and batteries (charged with onshore power supply) is expected to reduce the fossil fuel consumption by 50% and the number of engine operating hours with up to 80% [44].

5.6 Fish farm vessels

Even though this report focuses on fishing vessels, this section provides some examples of fish farm vessels. The Norwegian aquaculture industry has also joined the "green shipping wave" with several pioneering electric fleet initiatives [45]. Already in 2016, one of the world's largest well-boats (Figure 5-14, left) operating for Lerøy Seafood group, was equipped with a diesel-electric propulsion system [46].

Figure 5-14: Wellboat – Seihav (left) [46] and Salmars's hybrid wellboat - RoVision [47]

Figure 5-14 (right) shows RoVision, the world's first hybrid well-boat, delivered to the salmon farmer SalMar in 2020. A battery pack (600 kWh) has replaced one of the four 1300 kW diesel generators that would normally be onboard a diesel-electric vessel of its type. The battery package is used for peak-shaving and as back-up [47].

In 2015, the initiative "Green Coastal Shipping Program", led by DNV-GL, was launched. Together with 25 partners from Norwegian maritime industry and authorities, five pilot projects were defined, of which one targeted the aquaculture sector [48]. The objective was to develop a hybrid powered concept for a fish farm vessel, with focus on defining how to best use a battery package in combination with a combustion engine to achieve maximum energy efficiency. The concept is based on a 70-meter long vessel (Figure 5-15, left) that can be converted to fit either a LNG-battery powered propulsion system or a diesel-battery system [45].

Figure 5-15 Example of electric propulsion projects for fish farm support vessels [45] [49]

Figure 5-15, (right) shows a prototype of a zero-emission fish farm workboat (*GMV Zero)*, developed by the shipyard Grovfjord Mekanisk Verksted. The 14-metre vessel will start operating for the Norwegian salmon producers Northern Light Salmon and Sørrollnes Fisk. It is designed to service 12 cages up to five nautical miles from its base for a full day without recharging [50].

The idea for *GMV Zero* originally started several years ago to eliminate the exposure of the workers on board to diesel exhaust particle emissions. Since then, the prices of batteries have dropped dramatically and the number of fish farms along the Norwegian coast with electricity from the grid has increased to about 85% of all farm locations. Both factors have contributed to making 100% battery operation feasible [50].

5.7 Propulsion systems and operation modes for troll fishing vessels

This section summarises the main results from a study of fishing vessels operating in Alaska [51]. The study presents a comparison between a conventional and a hybrid propulsion system, considering the operational profile of trolling vessels, with and without freezing capacity onboard. Also included, but not presented here, was a comparison of freezers that are hydraulically driven (through a hydraulic pump connected to the main engine) with those that are electrically driven (through auxiliary generators).

The following different propulsion systems were evaluated:

- diesel mechanic propulsion – with and without auxiliary diesel generators for electrical power supply
- hybrid propulsion – diesel mechanic and battery electric
- hybrid propulsion – diesel mechanic and diesel electric
- hybrid propulsion (diesel mechanic and diesel electric) with hybrid electrical power supply (diesel generators and batteries).

5.7.1 Load profile

Figure 5-16 shows a simplified load profile for a typical fishing day of a troll vessel, equipped with blast freezers operating 24 h/day. As seen, a large power peak occurs during a short transit period at the beginning and end of the day, and there is a rather constant load during the fishing period.

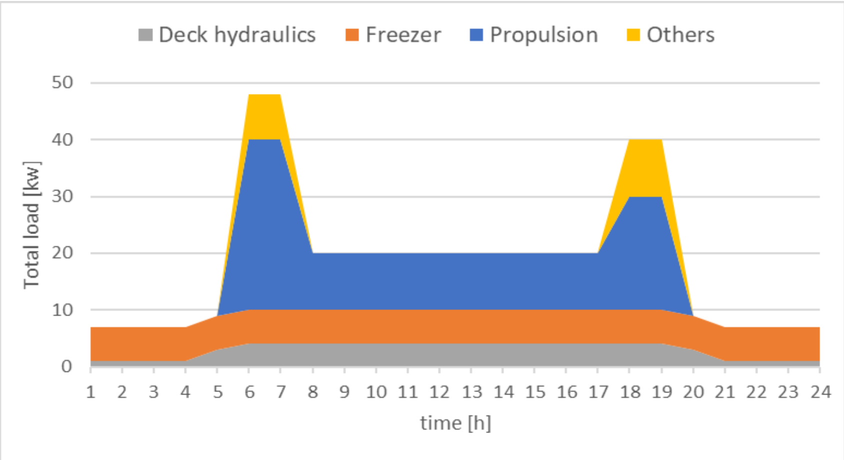


Figure 5-16: Load profile. Figure created based on [51]

A trolling vessel without a freezer system (instead carrying ice supplied from shore) would have a similar load profile, but with the freezer system load subtracted.

5.7.2 Propulsions systems and operation modes

Different propulsion systems and operating modes were compared to a conventional diesel-mechanical propulsion system. For the "ice troller" (no freezer installed onboard), only one hybrid propulsion system was evaluated, while for the freezer troller several systems are compared. The naming of the different propulsion systems / cases (in bold blue) below, is used for presenting the results in Figure 5-17**Error! Reference source not found.** and Figure 5-18.

Ice troller:

The reference case (**"Ice, base case"**) is a conventional mechanic propulsion with a single diesel engine supplying both propulsion and electric needs. This case is compared with a hybrid propulsion system (**"Ice battery hybrid"**), consisting of a ***diesel mechanic engine and batteries***, with the following operation modes:

- Diesel engine supplies all propulsion and electrical needs, as well as battery charge.
- Diesel engine is switched off. Batteries, with a capacity of 20 kWh, supply propulsion, through an electric propulsion motor, and all electrical needs. After two hours of pure battery operation, one hour of charge is required.

Freezer troller:
For the evaluation of hybrid propulsion systems for the freezer vessel, two base cases are defined - without and with an auxiliary engine supplying power to the refrigeration plant (blast freezer).

The base case without an auxiliary engine (**"Freezer, base case"**) consists of a single diesel mechanic engine operating 24 h / day, to supply propulsion, refrigeration, and other electric needs. This base case is compared to a hybrid propulsion (**"Freeze, battery hybrid"**), consisting of a ***diesel mechanic engine and batteries***, with the following operating modes:

- Diesel engine supplies propulsion, refrigeration and other electrical needs, as well as battery charge
- Diesel engine is switched off. Batteries (20 kWh) power a propulsion motor and provide refrigeration and other electrical needs. After one hour of battery operation, one hour of charge is required.

The second reference case for the freezer troller **(**"**Freeze, auxiliary, base case"**) includes a diesel mechanical main engine and an auxiliary diesel generator:

- The auxiliary generator powers the refrigeration systems and runs 24 h / day
- The main engine powers all propulsion and other electric needs
- While underway, the auxiliary generator and main engine operates simultaneously

This base case is compared with a mechanic-electric hybrid propulsion system, without and with batteries for hybrid power supply.

The ***diesel-mechanic, diesel-electric hybrid propulsion system*** without batteries (**"Freeze, auxiliary, hybrid"**) consists of a main mechanical engine and an auxiliary generator. The electric propulsion motor acts as a generator (PTO) when powered by the main engine. The system provides redundant refrigeration and propulsion and enables operation of only one engine at the time. The main operational modes are:

- Auxiliary generator (30 kW) powers the electric propulsion motor when fishing, in addition to supply refrigeration, other electric load and battery charge.
- Main engine is used for transit to and from fishing ground, and for peak electrical loads.

The ***mechanic-electric propulsion system including batteries*** for hybrid power supply (**"Freeze, auxiliary, battery hybrid"**) has the added advantages of being able to operate solely on batteries (20 kWh) during certain periods. The main operational modes include:

- Auxiliary generator (30 kW) powers electric propulsion motor when in fishing mode, in addition to refrigeration and other electric load, as well as battery charge.
- Main engine is used for meeting peak loads and for transit to and from fishing ground.
- Both main engine and auxiliary generators are switched off in fishing mode. Pure battery operation for approximately one hour (then recharge for one hour is required).

5.7.3 Fuel consumption and engine operating hours

In Figure 5-17 the results are presented in terms of annual (100 days of fishing) fuel consumption for the different propulsion systems described above, while in Figure 5-18 the corresponding operating time for the main and auxiliary engine are given.

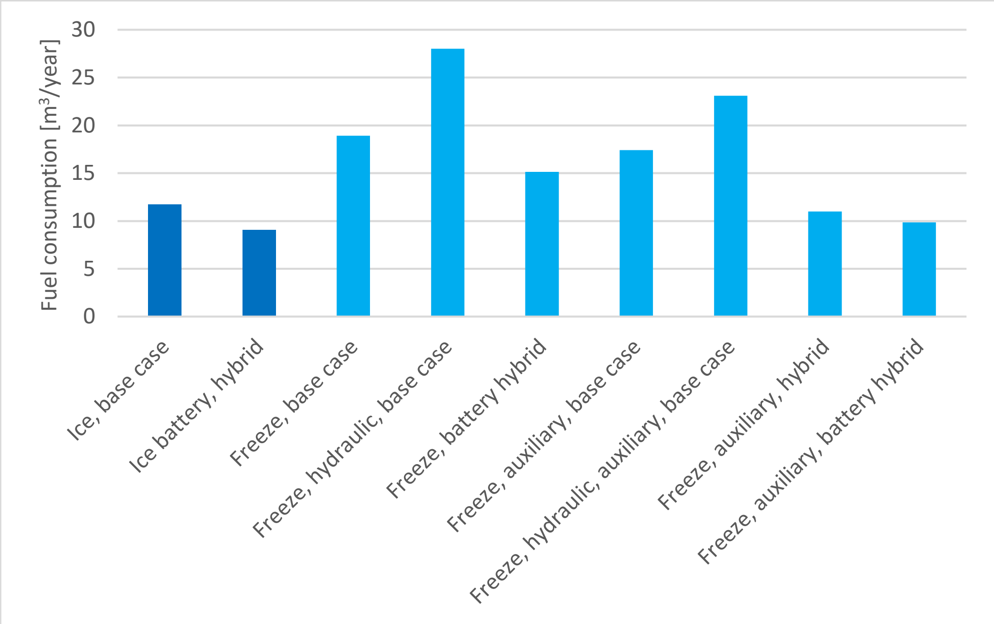


Figure 5-17: Comparison of fuel consumption (100 fishing days) for the different propulsion systems on the ice troller (dark blue) and freezer troller. Figure created based on results in [51].

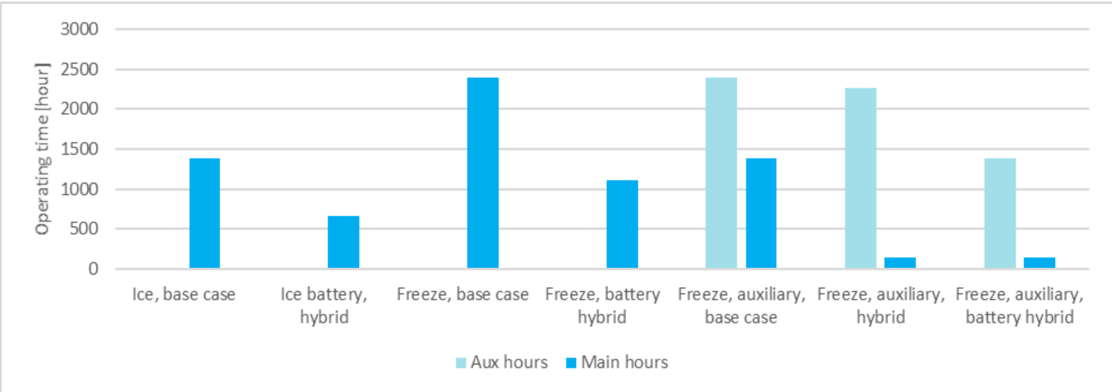


Figure 5-18: Comparison of operating hours of the main engine and auxiliary engine (100 fishing days) for the different propulsion systems. Figure created based on results in [51].

6 Fuels

Globally, fishing ships are typically operated with conventional diesel-mechanical engines. However, the new international regulation from 2020, limiting the sulfur content of marine fuels, as well as IMOs GHG reduction strategy, has and will push further exploration of alternative fuels. This chapter gives a brief overview, with focus on LNG, hydrogen and batteries. Batteries are generally classified as an alternative fuel when charged from shore electricity, differently from being charged onboard by fossil-fuelled engines/generators.

6.1 Carbon neutral fuels

Carbon neutral fuels refer to a variety of fuels that have no net GHG emissions, including [52]:

- Fuels with no carbon emissions at the stack, such as hydrogen (H_2) and ammonia (NH_3), provided that the energy used for producing them does not emit any GHGs. This is valid for energy produced from nuclear power and renewables, or by using CCS.
- Fuels with carbon emissions at the stack, such as biofuels, provided that the carbon contained in the fuel is sustainably sourced and part of the natural carbon cycle, meaning that fuel combustion of the fuel does not lead to added CO_2 in the atmosphere. In addition, energy used for producing the fuel must, itself, be without GHG emissions.

6.2 Liquefied Natural Gas (LNG)

The global use of LNG is assumed to increase significantly, especially in coastal shipping. Main drivers for such a development include regulations (e.g. MARPOL, Annex VI), potentially low gas prices compared to oil and diesel, as well as positive profit related to sustainability and more environmentally friendly operation. Using LNG as fuel enables compliance with all known future regulations for NO_x and SO_x emissions without the need for exhaust gas treatment. It will also contribute to reducing the carbon footprint from ships. The reduction in CO_2 emissions compared to diesel/gas oil is typically 20% but can be somewhat counteracted by methane slip from certain engines. In an LCA perspective, it is also important to include GHG emissions from LNG production and transport [53] [54].

Despite having many advantages, LNG is scarcely used in the fishing sector. There is scepticism relating to bunkering opportunities, safety issues, investment costs as well as space required for installation. Another possible disadvantage connected to LNG operation of fishing vessel is that a dual-fuel engine, operating on both LNG and diesel, has a longer response time than a diesel engine. This can be a challenge during fishing and maneuvering when fast load control is needed. However, a hybrid propulsion system including a battery package enables “boosting” via an electric motor, which eliminates the response time problem [55].

6.2.1 Uptake of LNG

Figure 6-1 shows the number of LNG-fuelled ships in operation (green) and on order (blue) for different ship types. As illustrated, only three fishing vessels is on order, and they are all Norwegian (see also section 6.2.3). Figure 6-1 also shows the geographical distribution of existing and ordered LNG-fuelled ships, clearly showing that Norway has been a pioneer, especially for passenger ferries [56]. As seen in Figure 6-2, most LNG-fuelled ships (almost 80%) are equipped with a dual-fuel (DF) engine, enabling operation on both LNG and diesel.

Figure 6-2 shows that the orders for LNG-fuelled ships have increased steadily since the first LNG-fuelled ship was taken in operation in 2002 and has accelerated more sharply since 2015, most probably explained by the SECA regulation.

A drastic increase is expected for the coming years[2], due to the global limit of sulphur content which entered into force in 2020.

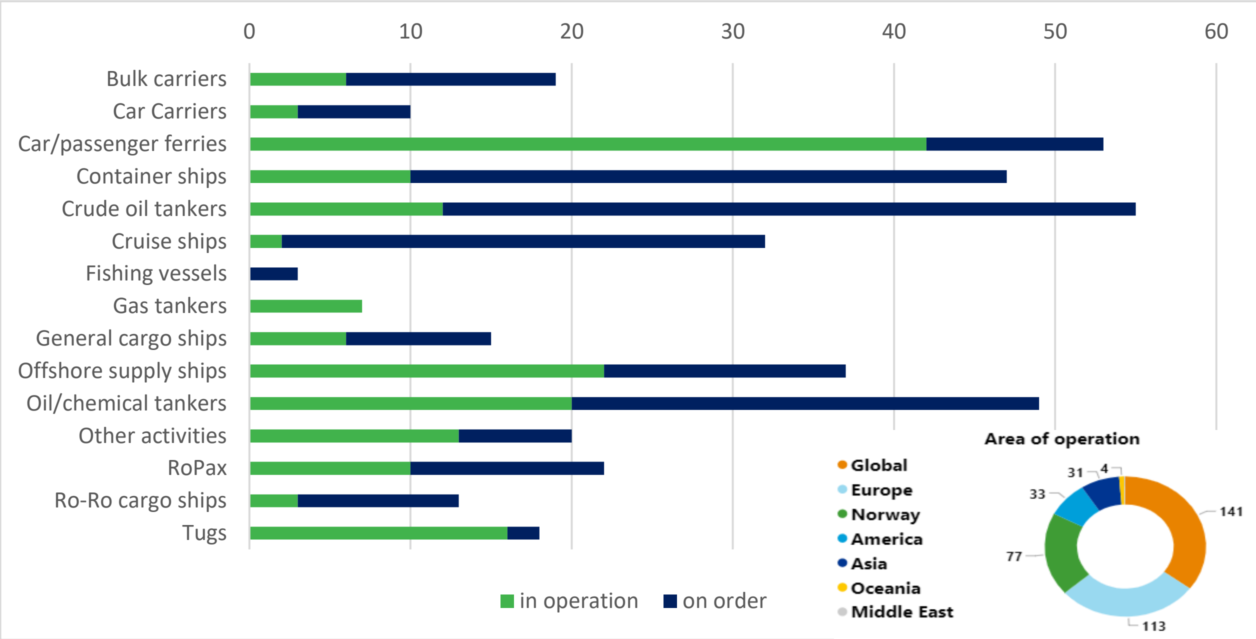


Figure 6-1: LNG uptake for different ship types and operational area [56]. Used with permission from DNV-GL.

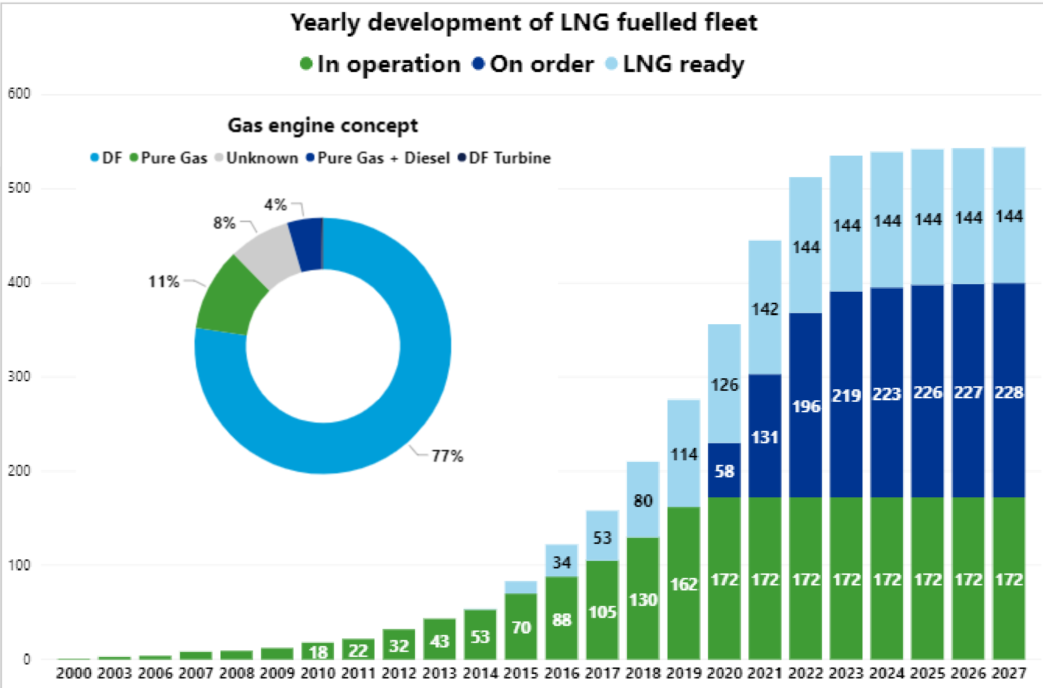


Figure 6-2: Yearly development of LNG uptake as marine fuel, and percentage distribution of engine types [56]. Used with permission from DNV-GL

[2] The reason for the limited increase in ordered ships from 2023 towards 2027, shown in Figure 6-2, is probably that data on confirmed orders are not official as far in advance

6.2.2 LNG bunkering

For fishing vessels, bunkering from trucks is considered the most relevant bunkering mode, due to the relatively small amounts of fuel required. It is also possible to establish marine bunker stations with tank systems supplied by trucks or small LNG bunker/tanker ship from nearby terminals.

Along the Norwegian coast, the availability of small-scale LNG bunkering is comparatively high, as indicated in Figure 6-3, showing a map of opportunities for LNG bunkering in Europe. Figure 6-4 shows the increase in number of LNG bunker vessels, which is almost doubled between 2019 and 2020. The bunker vessels' coverage in key locations is improving and loading facilities for bunker vessels are also developing [56].

Figure 6-3: LNG bunkering infrastructure [56] https://afi.dnvgl.com/Map. Used with permission from DNV-GL.

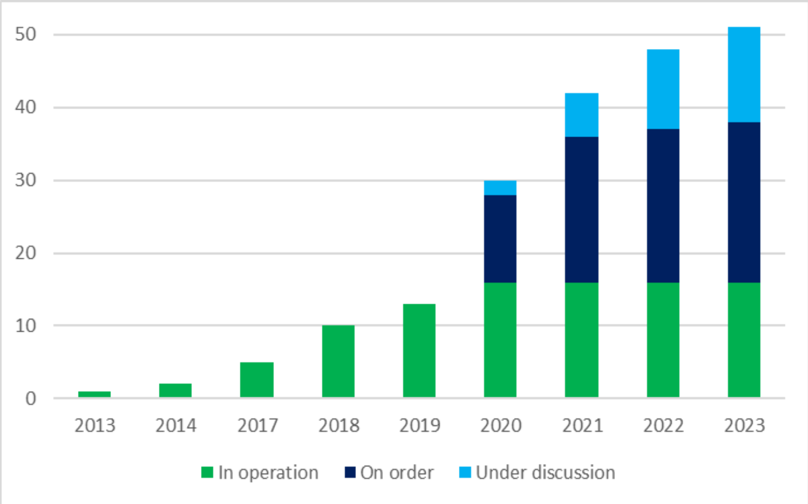


Figure 6-4: Development of LNG bunker vessels [56]. Used with permission from DNV-GL.

6.2.3 Example of LNG-fuelled fishing vessels

Figure 6-5 (left) shows the **trawler** Libas, owned by the pelagic fishing company Liegruppen Fishery. It will be delivered in 2020. Being equipped with a hybrid LNG-electric-battery propulsion system , it is the world's first LNG-fuelled fishing ship. The dual fuel main engine can operate on both LNG and diesel but will be 95% powered by LNG, supplied from a 350 m^3 cylindrical vacuum-insulated tank. An auxiliary engine, which also can switch between LNG and diesel, complements the main engine during some work tasks and in bad weather [57].

The battery system, with a storage capacity of 500 kWh, is designed for the ship's typical operating profile. It provides short response time and adequate leveling of short-term load variations (peak shaving), enabling reduced fuel consumption through more stable and optimal operation of the main engine. Compared to a conventional diesel-mechanic propulsion system, a 15% reduction in total fuel consumption is expected. In addition, the SO_x and particle (PM) emissions will be almost eliminated, the NO_x emissions will be reduced by around 80%, and the CO_2 emissions by 20% - 25% [58].

The battery pack, in combination with an LNG-fueled boiler, also provides the ability to remain docked for up to ten hours without the engines running or using land-based electricity. When the ship is connected to a shore power grid, the battery pack will support any electric power requirements such as crane operation or the like. Libas will also be equipped with electric winches and fish pumps, which for ships with hybrid power supply are more efficient than hydraulic solutions [58]. In addition, surplus energy from electrical winches, will be recovered (power regeneration) to supply electrical demand onboard or to charge the batteries [58].

Figure 6-5: LNG fuelled trawler Libas (left) [58] and LNG-fuelled trawler/purse seiner from Teige (right) 37].

Figure 6-5 (right) shows the 86 m **trawler/purse seiner** Sun-Lady, owned by the fishing ship company Teige. It will be equipped with a similar hybrid-electric propulsion system as the one installed on Libas. The dual-fuel main engine will operate mainly on LNG (350 m^3 tanks) and diesel will only be used as back-up. Batteries, with a storage capacity of around 1000 kWh, are used for peak shaving, for storing regenerated power during trawling, and to reduce noise and emission at berth. Even if the ship can be powered solely on batteries for very short periods, it is not designed for operation on battery alone [59].

Figure 6-6 shows one of the two **live-fish carriers** (well-boats) recently ordered by Nordlaks.

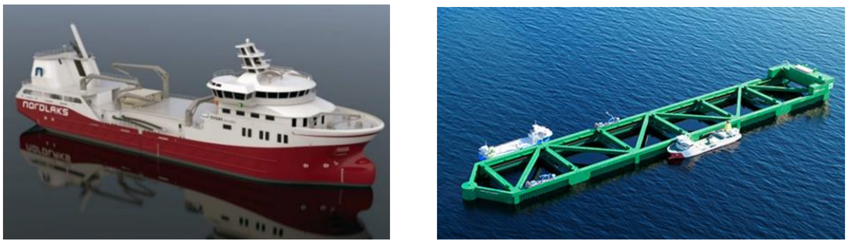


Figure 6-6: Nordlaks' new live fish carrier and off-shore salmon farm [60]

Both ships are equipped with an LNG-battery electric propulsion and will transport live salmon (600 tonnes) from off-shore fish farms to onshore processing facilities. Emission reductions of 30% CO_2 and 90% NO_x is expected [61].

Figure 6-7 shows "Catchy" - DNV-GLs concept fishing vessel for the future – primarily intended for purse seine and pelagic trawling. The fuel system design allows bunkering of LNG fuel for two weeks' operation.

Figure 6-7: DNV-GL concept vessel [62]

Estimated fuel efficiency improvements compared to a conventional ship is 16%, divided between the following implementations [62]:

- Hybrid (mechanic-electric) setup: 3%
- Waste heat recovery: 9%
- Waste cold recovery: 1%
- Hull design: 3%

As previously mentioned, the slow uptake of LNG in the fishing sector can partly be explained by the limited number of bunkering facilities, especially outside Norway. However, there are indications of an increased interest in LNG also in other countries. India is one example, where the Kochi LNG terminal is being under-utilized, due to lack of infrastructure connecting the terminal to the main gas demand areas within the region. One explored way to increase the terminal's utilization is to support the use of LNG as a marine fuel [63].

Figure 6-8: Indian fishing vessel included in a pilot project for LNG-fuelling [63]

As a consequence, an expression of interest has been issued for a pilot project to use LNG as fuel for a fishing boat (Figure 6-8), currently operating outside the city of Kochi. The aim is to retrofit the existing diesel engine system to enable operation on both LNG and diesel [64].

6.3 Liquefied Biogas (LBG)

Biogas is a renewable energy carrier that can be used as marine fuel after up-grading it (drying, purification, liquefaction). It can be produced from various types of organic waste, such as waste from fish and forest industry, food waste, and wastewater. For shipping companies that are already using LNG as fuel the transition to LBG does not require any extra investment in new vessels/equipment. Moreover, the same pipeline infrastructure can be utilized, meaning the same trucks, ships, tanks and filling stations can be used for supply of LNG and LBG [26, 52].

Using LBG in existing LNG engines will generate the same emissions of NO_x, SO_x and CO_2, but the CO_2 emissions from LBG combustion are not considered as GHG emissions. However, in an LCA perspective, the emissions related to production and transport should also be included, which might be larger for LBG compared to LNG [65] (see section 6.10).

The availability of biogas is today limited but is assumed to raise in a near future. A biogas plant in Skogn (Biokraft) has a production capacity of around 9000 tonnes/year and could be further increased. Several biogas plants are planned in Norway but the demand for biogas is limited. To accept LNG as a temporary solution in decarbonising the shipping sector, and in periods with limited LBG availability, would facilitate the introduction of LBG.

In 2018, the world's first LBG bunkering took place in Sweden; an LNG-fueled tanker ship received 40 m^3 of LBG directly from a road tanker [66]. In 2021, Hurtigruten will be the world's first cruise shipping company using biogas on a larger scale, when several of their ships will be fueled by a mixture of LBG and LNG [67].

6.4 Hydrogen

Hydrogen can be used as marine fuel, either transformed to electricity in fuel cells or in combustion engines. Fuel cells enable transformation of energy carriers (e.g. hydrogen, methanol, ammonia, natural gas, biogas) with a higher efficiency than traditional combustion engines. Water is the only emission generated from a hydrogen-driven fuel cell, which therefore is considered as a zero-emission technology [26] [52].

However, in an LCA perspective, there are GHG emissions linked to the production of hydrogen, the magnitude of which depends on how hydrogen is produced. Figure 6-9 shows the estimated GHG emissions related to three different production technologies; electrolysis using electricity generated from wind power, steam methane reforming (SMR), and SMR in combination with CCS [68].

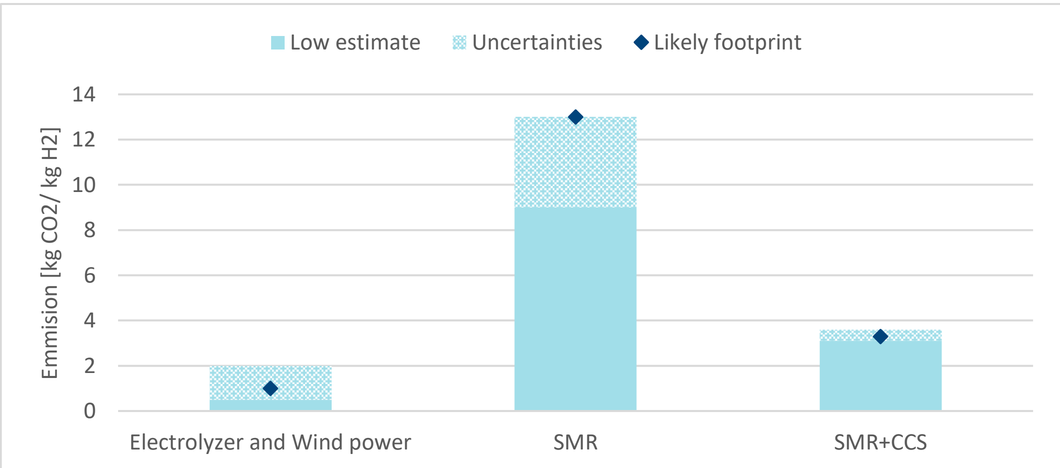


Figure 6-9: GHG emissions related to different hydrogen production technologies (adapted from [68])

A comparison of onboard generated emissions from hydrogen and diesel propulsion (using typical values of efficiencies) shows that 1 litre of diesel in a conventional engine is equivalent to around 0.2 kg hydrogen in a fuel cell with an electric motor. With an assumed emission factor for hydrogen fuel of 120 g CO_2/kWh ("average" production emission included), it implies a 75% reduction compared to a diesel engine [68].

There are several pilot projects on hydrogen fuel cell installations, both compressed hydrogen and liquid hydrogen (LH2). Norled is building Norway's first hydrogen-powered ferry, with a hybrid energy mix (50/50) of LH2 fuel cells and batteries [69]. Havila plans for the world's first LH2 fuel cell cruise ship to be in operating in 2023, combining a 3.2 MW fuel cell with battery storage [70]. Hydrogen-powered ferries do exist elsewhere in the world, but most are smaller vessels used for low-speed tours on lakes and rivers. Within a 2030 horizon, hydrogen is estimated to be best suited for small passenger ships [71], but there are studies showing the potential for zero-emission operation with fuel cells and batteries also in other ship segments [72].

Main challenges experienced include cost, space requirements and to get the installation approved from authorities. There is on-going development of IMO regulations related to hydrogen propulsion. The latest edition of the IGF code, originally developed for LNG-fuelled ships, also includes hydrogen (though not into force yet). DNV-GL has developed classification rules/regulations for marine fuel cell installations, but not yet seen as complete for covering all aspects with use of hydrogen on ships. Another challenge is that frequent bunkering is required since both fuel cells and hydrogen storage tanks are heavy. Hydrogen can be locally produced, by water electrolysis, nearby the bunkering facility or it can be delivered by transport [54].

Even though small passenger ferries are considered as most suitable for fuel cell applications, there are some projects related to Norwegian fishing vessels. For example, the electric fishing boat Karoline (section 5.5) was planned to be refit with a hydrogen fuel cell, including a storage tank of 20 kg hydrogen which was estimated to be enough for one day's consumption. Hydrogen could also be used as a fuel to produce electricity and oxygen for coastal fish farms. However, large barriers are connected with these projects since there is a need to build the whole value chain – a hydrogen station for production and storage as well as filling (bunkering) [73]. Recently, the Norwegian Seafood Research Fund (FHF) funded a project lead by SINTEF Ocean to investigate the use of hydrogen (and ammonia) onboard a coastal fishing vessel [74].

The Japan Fisheries and Education Agency collaborates with Toyota Motor to build a tuna farm fishing boat fuelled by hydrogen fuel cells. Sea tests are planned for 2022 [75]. The main reason behind this specific project is that a nearby island has built a wind farm power plant at sea but cannot use all the electricity by itself. It was also built a facility to produce hydrogen with the surplus electricity, but no significant user exists on the island. On a national level, Japan plans to increase the number of hydrogen supply facilities by 2030 and reduce the cost of hydrogen fuel by around one fifth of the current price by 2050 [76].

6.5 Ammonia

Ammonia can be used as fuel in both combustion engines and fuel cells. Compared to hydrogen, ammonia has a higher energy density and is easier to store, thus enables operating on longer distances. Since ammonia is widely used in the fertilizer industry, it is globally accessible. Main challenges with ammonia are toxicity and corrosiveness. The only emissions from an ammonia-driven fuel cell is water and pure nitrogen. Thus, if ammonia is renewably produced, it can be considered as a carbon-neutral fuel. There are feasibility studies on building up an ammonia producing infrastructure at sea, using ocean wind [26] [52].

Ship-owners of ammonia tankers are especially interested to utilise ammonia as fuel, but there is an increased interest also in other shipping segments. For example, the off-shore supply ship Viking Energy (Figure 6-10), which today is operated on LNG, is planned to be retrofitted with a large ammonia fuel cell. One part of the project is to develop a renewable (zero-emission) production of the ammonia, to make the ship truly emission-free [77]. As mentioned above, the use of ammonia (and hydrogen) for a coastal fishing vessel will also be investigated in a FHF-funded project [74].

Figure 6-10: Viking Energy [77]

6.6 Batteries

Hybrid propulsion and power supply including batteries was addressed in chapter 3. Batteries are generally classified as an alternative fuel when charged from shore power, differently from being charged onboard by fossil-fuelled generators. By using shore power there are no local emissions, but emissions related to shore power generation should be included. Even if Norwegian electricity production is considered as almost zero-emission, Norway is integrated in the Nordic electricity market which has an influence on the CO_2 emission factor. Nevertheless, the reduction in CO_2 emissions, compared to diesel is still above 90% [26] [52].

Naturally, pure battery operation is most feasible for relatively short distances with opportunities for frequent charging. The most common battery type applied today are Lithium-ion batteries, which have a relatively large power density. Still, the battery bank is heavy and it offers much shorter operational distance compared to a ship with a diesel tank of corresponding size [54]. Figure 6-11 shows the number of ships with batteries installed, divided on different ship types [56]. By August 2020, there were 7 fishing vessels equipped with batteries in operation, and 11 on order. As for LNG, a clear majority of the battery installations are on ships operating in Norway (as shown in Figure 6-11).

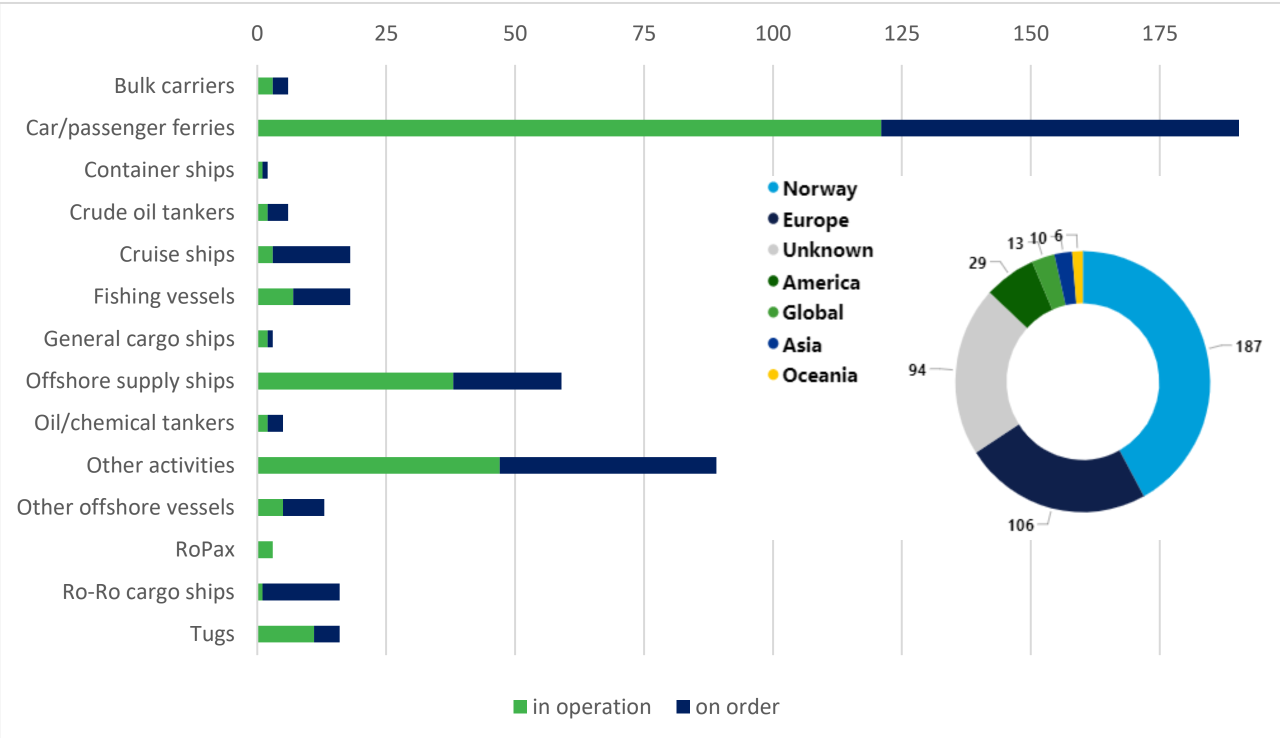


Figure 6-11: Battery installations - ship types and operation areas [56]. Used with permission from DNV-GL

Figure 6-12 shows the yearly development of battery installations[3], and the distribution of propulsion system applied [56]. As seen, more than 70% are equipped with a hybrid propulsion system, either with (20%) or without (52%) the "plug-in feature". Installations for pure battery operations represents 22%.

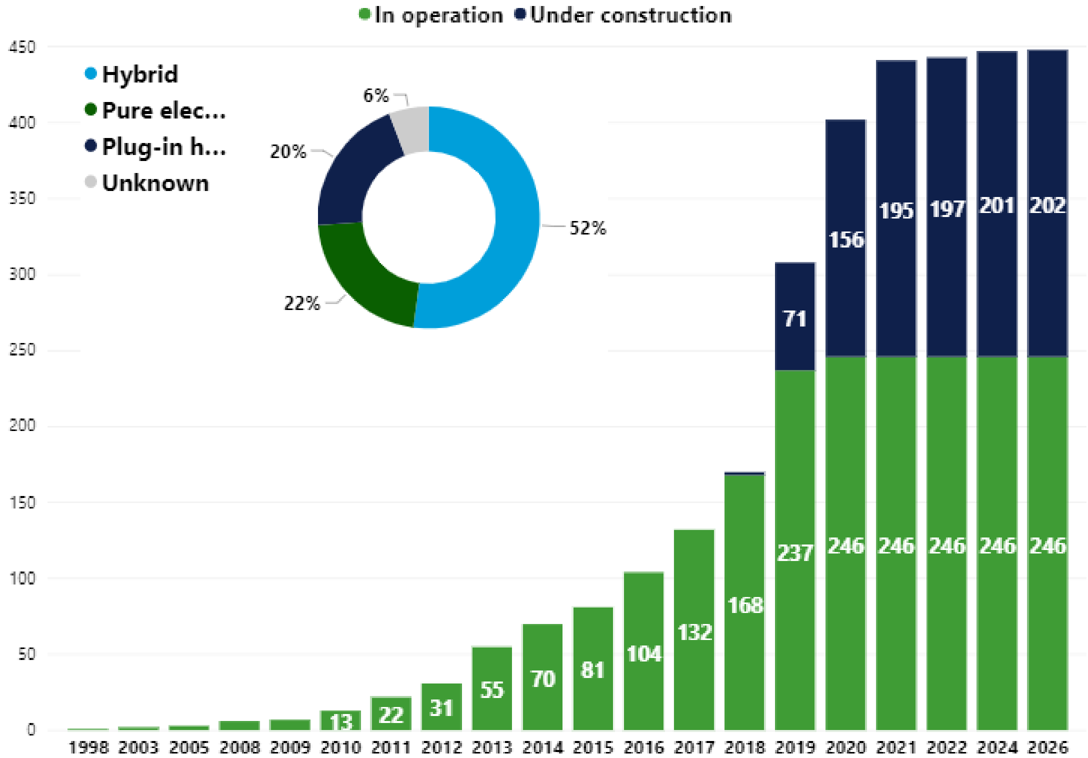


Figure 6-12: Development of battery installations onboard ships [56]. Used with permission from DNV-GL.

6.7 Liquefied Petrol Gas (LPG)

So far LPG is solely used as fuel on ships carrying LPG as cargo. In 2019, four LPG carriers were retrofitted to LPG-fuelling and seven such vessels were ordered. LPG combustion results in approximately 15% lower CO_2 emissions compared to diesel. In addition, the emissions of SO_x and PM emissions are significantly reduced, or even eliminated, while the level of NO_x reduction depends on engine technology [78].

There are two main sources of LPG, namely as by-product from oil and gas production or as by-product from oil refining. It is also possible to produce LPG from renewable sources, for example as a by-product from renewable diesel production. The LPG production generates relatively low GHG emissions. From an LCA perspective the reduction in GHG emissions, compared to diesel, is therefore often slightly larger than the 15% reduction related to fuel combustion [26] [52] (see Figure 6-13).

6.8 Methanol

In addition to seven existing and five ordered methanol tankers, there is one Swedish passenger ship equipped with a methanol engine. A methanol fuel tank requires twice as large volume as for diesel with the same energy content. Except from extra space requirements, the main challenge reported is fuel cost [78]. Using methanol virtually eliminates SO_x emissions. PM emissions are also significantly lower, compared to diesel, while the reduction in NO_x emissions depends on engine technology.

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[3] As for LNG, the reason for the limited increase in ordered ships from 2023 towards 2027 (Figure 6-12) is probably that data on confirmed orders are not official as far in advance

The reduction in CO_2 emissions is around 10%, considering only fuel combustion. If including the complete life cycle, there is a large variation depending on how the methanol is produced (see Figure 6-13). Methanol can be produced from several fossil resources, such as natural gas or coal, or from renewables, such as biomass and CO_2. If produced from natural gas, the CO_2 emissions are equivalent or even slightly higher than oil- based fuels, while if produced from biomass the emissions are significantly lower [26] [52].

6.9 Biodiesel

There are various biodiesel fuels available. One that can be applied for ships, with only minor modifications is HVO (hydrogenated vegetable oil). However, the availability (and demand) is still low. If including the CO_2 emissions from producing HVO, the reduction in CO_2 emissions is about 50% compared to diesel oil [26].

6.10 CO_2 emission factors

When comparing CO_2 emission factors for various fuels it is important to clarify whether they are based solely on CO_2 emissions generated onboard ("tank-to-propeller"), or if emissions related to fuel production are also considered ("well to tank"). Figure 6-13 shows the CO_2 emissions for most of the fuels discussed in this chapter, based on DNV-GLs report "Assessment of selected alternative fuels and technologies (2019)". Note that the emission in Figure 6-13 should not be taken as exact values, since, especially, the production-related emissions are connected to several assumptions. For further information, refer to the DNV-GL report [26].

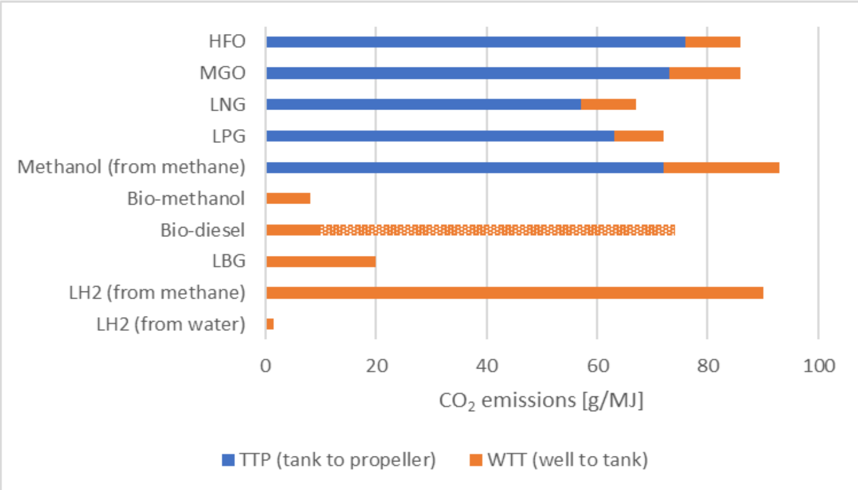

Figure 6-13: CO_2 emissions for various marine fuels. Figure created based on [26]

6.11 Current uptake of alternative fuels

Figure 6-14 shows the uptake of alternative fuels (methanol, LNG and battery) in 2018, as presented by DNV-GL. As seen, for ships in operation the alternative fuels represents only 0.3% of the global fuel use, while for ships in order the alternative fuel uptake is 6% [52].

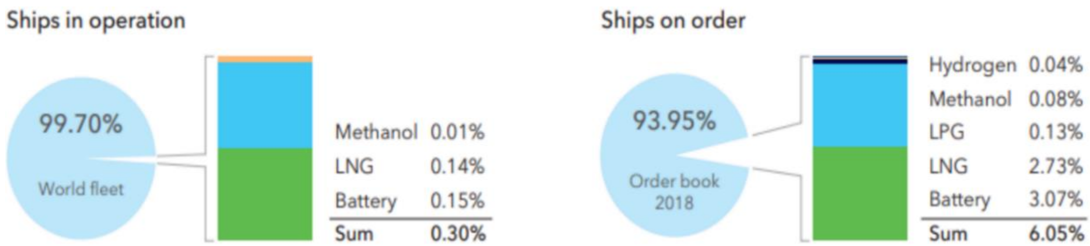

Figure 6-14: Alternative fuel uptake (2018); operating and ordered ships [56]. Used with permission from DNV-GL.

6.12 Future uptake of alternative fuels

Here, some scenarios of future fuel use in the global shipping sector, as predicted by DNV-GL, are presented.

6.12.1 Whole shipping sector

In relation to IMO's target on 50% reduced CO_2 emissions by 2050, DNV-GL has assessed three future scenarios, considering global fleet development (all ship types), uptake of technical measures, fuels, and policies like EEDI. Two of the pathways focus on ship design or operational requirements to achieve IMO's goals, including regulations for individual ships to incentivize the necessary emission reduction. The third pathway describes a scenario in which no further policies are introduced [79].

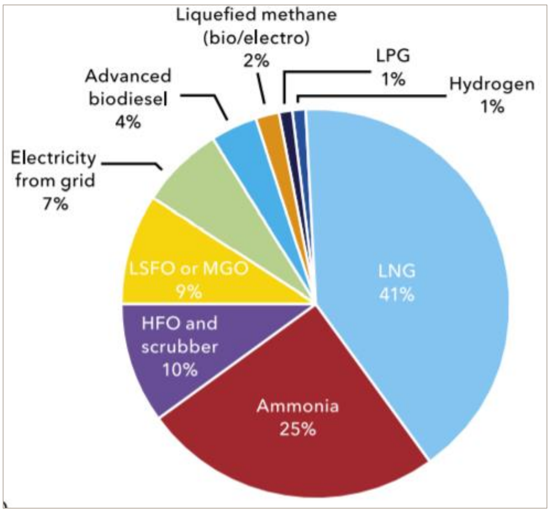

Figure 6-15: Fuel mix towards 2050 [52]. Used with permission from DNV-GL.

The results are presented in DNV GL's "Maritime Forecast to 2050". For all three pathways, LNG has a dominant share of 40% - 80% in 2050. The primary energy source for LNG varies between fossil, biomass and other renewables. Ammonia, primarily applied in combustion engines, is considered the most promising long-term carbon-neutral fuel for new-builds. Carbon-neutral fuels must supply 30% - 40% of the total energy for international shipping. Figure 6-15 shows the results for the scenario focusing on design requirements [52].

In the report "Charting a course for green coastal shipping" DNV-GL describes a scenario for uptake of alternative fuels in the coastal ship segment, which will enable large cuts in emissions to take place in a cost-efficient manner. It involves the use of biofuels on traditional cargo vessels and fishing vessels, LNG-fuelled offshore vessels and an electrically powered ferry fleet [80].

6.12.2 Fishing vessels

"The Green Coastal Program", lead by DNV-GL, includes a study on potential measures to reach Fiskebåt's goal of reducing CO_2 emissions with 40% in the period 2005-2030. The study considers both technical-operational measures and alternative fuels. In relation to fuels, the technical feasibility (high/medium/low), as well as emission reduction impact, are presented for four different types of fishing vessels: bottom trawler, pelagic trawler (and purse seiner), conventional deep sea fishing (auto liner) and coastal fishing. The following estimations were made [54]:

- LNG: medium feasibility and medium impact for all the fishing vessel types
- Batteries (fully or partly electrical propulsion): high feasibility and large impact
- Hydrogen (fuel cells): medium feasibility and large impact for coastal fishing vessel, while low (no) feasibility for the other vessel types.
- Biogas: medium feasibility and large impact for all vessel types
- Biodiesel: high feasibility and large impact for all vessel types

Note that these estimations are *only for fishing vessels and only towards 2030*. Therefore, they differ from the future fuel mix presented, for example in Figure 6-15, in which the whole shipping sector towards 2050 is considered, implying a larger uptake of long-term solutions like ammonia.

7 Conclusions and further work

From the review on fuels and propulsion systems for fishing vessels, these indicative conclusions were drawn:

- Today, most fishing vessels are equipped with a conventional diesel-fuelled mechanical propulsion system. However, for new-ordered ships there is, especially in Norway, a development towards diesel-electric or hybrid propulsion systems, often with hybrid power supply (e.g. batteries).

- Diesel-electric propulsion is especially fuel-efficient when the utility (auxiliary) load constitutes a significant fraction of the propulsion power and for ships with a large variation in operation profile.

- Hybrid (mechanical-electrical) propulsion enables increased fuel efficiency for ships operating with varying speed conditions, and where the auxiliary load is only a fraction of the required propulsive power. For fishing vessels requiring high propulsion capacity a hybrid solution could be favourable. Typical operation is diesel-mechanic propulsion for steaming to and from fishing field, and electric propulsion for transit at lower speeds and fishing operations.

- A hybrid or electric propulsion system enables hybrid power supply (e.g. diesel generators and batteries). The battery package can be designed to handle power fluctuations and peak-shaving or to enable switching off diesel generators and by that realising zero-emission operation and significant noise reduction. Hybrid power supply is most beneficial for ships with varying power demand, much low-load operations, and large electric power demands in port. Additional benefits with battery implementations include facilitation of integrating intermittent renewable power (solar, wind) production on-board and for storing regenerated energy from heavy winches for fishing gears.

- Hybrid or electric propulsion with hybrid power supply offers several possible operating modes, enabling flexible and fuel-efficient operation. However, it also implies challenges in relation to waste heat availability and sizing of heating and cooling equipment.

- The global uptake of alternative fuels in the shipping sector is expected to increase significantly due to stricter environmental regulations. By 2050 LNG/LBG is estimated to be the dominating marine fuel while ammonia is considered the most promising carbon-neutral fuel. For the fishing sector, alternative fuels with high technical feasibility include LNG/LBG and biodiesel for all fishing vessel types, and hydrogen fuel cells for coastal fishing ships. Battery implementations for partly electrified propulsion are considered highly feasible for the whole fishing sector.

Considering these indicative conclusions, the following topics for further work in CoolFish are suggested:

When developing integrated cooling and heating solutions for fishing vessels (WP1 & WP2) it is suggested to:
- Identify the waste heat characteristics for ships with hybrid propulsion and/or hybrid power supply, including diesel, LNG, (hydrogen) and batteries.
- Develop models to estimate waste heat characteristics for various propulsion systems and modes.

When adapting methods for estimating the carbon footprint of fishing vessels (WP3) it is suggested to:
- Identify changes in fuel consumption for some reference ships with alternative propulsion systems.
- Develop models for estimating the fuel consumption for different operational modes, disaggregated between propulsion and auxiliaries.

8 Acknowledgements

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9 References

[1] IMO, “Prevention of air pollution from ships,” 2019.

[2] IMO, “Sulphur oxides (SOx) and Particulate Matter (PM) - Regulation 14,” 2019.

[3] Wärtsilä, “wartsila.com,” 2010. [Online]. Available: http://www.annualreport2010.wartsila.com.

[4] DNV-GL, “DNV-GL Maritime,” [Online]. Available: https://www.dnvgl.com/maritime. [Accessed 2020].

[5] Norwegian Tax Administration, “Mineral Product Tax,” 2020.

[6] DNV-GL, “Global Sulphur Cap 2020,” 2019.

[7] DNV-GL, “IMO NOx Tier III requirements to take effect on January 1st 2016,” 2015.

[8] IMO, “Nitrogen Oxides (NOx) - Regulation 13,” 2019.

[9] Daihatsu, “Nitrogen Oxides (NOx) Regulations,” 2020.

[10] Jafarzadeh S., “Energy efficiency and emission abatement in the fishing fleet. PhD thesis,” Norwegian University of Science and Technology (NTNU), Trondheim, 2016.

[11] NOx-fondet, “The Nox fund,” 2020.

[12] IMO, “Energy Efficiency Measures,” 2019.

[13] Behrendt C., “Energy Efficiency Operational Indicator of the selected type of Polish fleet fishing cutter in dependence of the main engine type.,” *Journal of Physics: Conference Series,* no. 1172, 2019.

[14] Lloyds Register, “IMO GHG Strategy – What does it mean?,” 2018.

[15] Fiskebåt, “Fiskeflåten når sine miljømål,” 2018.

[16] IMO, “Third IMO GHG Study 2014,” London, 2014.

[17] Geertsma R.D., Negenborn R.R and Hopman J.J, “Design and control of hybrid power and propulsion systems for smart ships: A review of developments,” *Applied Energy,* vol. 194, pp. 30-54, 2017.

[18] Aarsæther K.G., “Energy Savings in Coastal Fisheries,” *IEEE Electrification Magazine,* no. Sept., pp. 74-79, 2017.

[19] WorldFishing&Aquaculture, “Electric propulsion gets relevant for fishing,” 2019.

[20] Stadt, “Simply the best solution for all fishing vesselss,” 2019.

[21] Ingeteam, “PTI/PTO Hybrid Electrical Drives,” 2019.

[22] Berger Maritime, “Hybrid or electric ship propulsion,” 2018.

[23] DEIF, “Marine Hybrid - Battery Applications,” 2019.

[24] Siemens, “BlueDrive PlusC Coastal Fishing Vessels,” 2019.

[25] Siemens, “BlueDrive PlusC Pelagic Purse Seiner trawler,” 2019.

[26] DNV-GL, “Assessment of selected alternative fuels and technologies,” 2019.

[27] Skipsrevvyen, “MS "Harto",” 2018.

[28] FiskerForum, “World's largest hybrid fishing boat reaches homes,” 2019.

[29] Marinelog, “Corvus battery solution picked for advanced hybrid fishing vessel,” 2018.

[30] FiskerForum, “New seiner/longliner for Østervold,” 2019.

[31] Salt Ship Design, “New Green Gitte Henning,” 2019.

[32] The Explorer, “What happens when traditional fishing methods meet green technology,” 2019.

[33] WorldFishing & Aquaculture, “SpesNova joins EcoFish fleet,” 2019.

[34] Ramoen AS, “F/T RAMOEN,” 2020.

[35] Haig-Brown A., “Hybrid electrical service for stern trawler,” 2019.

[36] Jingsong D.U, et al., “Analysis of fuel saving effect of tuna longliner electric-mechanical hybrid power system,” CNKI, 2016.

[37] Man Diesel & Turbo, “Hybrid Propulsion - Flexibility and maximum efficiency optimally combined”.

[38] Salt Ship Design, “New "Hardhaus" with battery hybrid propulsion,” 2018.

[39] TekFisk, “Prestfjord bygger ny supertråler hvert fjerde år,” 2018.

[40] Cemre Shipyard, “Cemre Signed New Trawler for Olympic Seafood AS,” 2018.

[41] UndercurrentNews, “Nordic Wildfish plans new trawler to bring ‘big loads’ of cod onboard live,” 2018.

[42] FAO, “The State of World Fisheries and Aquaculture 2018,” 2018.

[43] The Explorer, “The world’s first hybrid fishing boat,” 2017.

[44] NCE Maritime CleanTech, “Hybrid-electric fishing vessel,” 2019.

[45] Norway exports, “Fish Vessels go Electric,” 2018.

[46] Skipsrevyen, “M/S "Seihav",” 2018.

[47] Fishfarmingexpert, “World’s first hybrid wellboat charges into action,” 2020.

[48] DNV-GL, “Green Shipping Programme,” 2019.

[49] KystMagasinet, “GMV Zero,” 2015.

[50] ilaks, “Forste provetur for GMV Zero,” 2017.

[51] Chandler K., Gaffney M. and Falvey D., “Hybrid Propulsion Vessels in Alaska's Longline and Troll Fisheries,” 2017.

[52] DNV-GL, “Maritime Forecast to 2050 - Energy transition outlook 2018,” 2019.

[53] S. Jafarzadeh, N. Paltrinieri, I. Utne and H. Ellingen, “LNG-fuelled fishing vessels: A system engineering approach,” *Transportation Research Part D: Transport and Environment,* vol. 50, pp. 202-222, 2017.

[54] Fiskebåt, “Tiltak for reduksjon av klimagassutslipp fra fiskeflåten,” Grønt Kystfartsprogram, 2018.

[55] GoLNG, “LNG Powered Future Fishing Vessel,” 2018.

[56] DNV-GL, “Alternative Fuels Insight,” 2020.

[57] UndercurrentNews, “Award-winning designer: More fishing vessel owners will order LNG power systems,” 2018.

[58] NauticExpo, “World’s First LNG-Powered Fishing Vessel,” 2018.

[59] Baird Maritime, “Cemre to build hybrid LNG trawler for Norwegian owner,” 2019.

[60] Rolls-Royce, “Rolls-Royce to deliver technology for innovative ocean fish farm and live fish carrier,” 2018.

[61] LNG World News, “MAN Cryo tech ordered for Nordlaks' LNG fueled fish carrier,” 2019.

[62] Davies M., “DNV's Fishing Vessel for 2015,” 2012.

[63] NGV Journal, “India: Kerala announces pilot project to convert fishing boat to LNG,” 2019.

[64] Fish Information Services, “Kerala plans to test use of LNG to power fishing boats,” 2019.

[65] Norwegian Ministry of Climate and Environment, "The Government's action plan for Green Shipping," 2019.

[66] Port of Gothenburg, "First ever bunkering of liquefied biogas -in Sweden at the port of Gothenburg," 2018.

[67] Hurtigruten, "Hurtigruten to power cruise ships with dead fish," 2018.

[68] Endrava AS, "Smøla hydrogen value chain," 2019.

[69] Norled, "The appearance of the hydrogen ferry begins to take shape," 2019.

[70] RECHARGE, "World's first liquid hydrogen fuel cell cruise ship planned for Norway's fjords," 2020.

[71] DNV-GL, "Analyse for tiltak for reduksjon av klimagassutslipp fra inneriks skipstrafikk," 2018.

[72] Sandia National Laboratories, "SF-BREEZE San Francisco Bay Renewable Energy Electric vessel with Zero Emissions," 2020.

[73] TU, "Hydrogenfiskebåt," 2017.

[74] FHF, "Elektrifisering av kystfiskeflåten ved bruk av batterier og brenselceller," 2020.

[75] Safety4Sea, "Japan, Toyota to build fishing boat powered with hydrogen fuel cells," 2019.

[76] Gasworld, "FRA developing hydrogen-powered fishing boat," 2019.

[77] Baisotti V. and Sommerfeldt P.A., "Dette skipet blir verdens første utslippsfrie offshoreskip," NRK, Bergen, 2020.

[78] Wold M., "Alternative Fuels Online Conference - Session 1: Uptake of alternative fuels and technologies (DNV GL)," 2019. [Online].

[79] DNV-GL, "Forecasting the effects of world fleet decarbonization options," 2019.

[80] DNV-GL, "Chartering a course for green coastal shipping," Green Coastal Shipping, 2016.

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