ENGINEERING
TOMORROW

Application paper

Decarbonizing shipping
How Norway is setting the pace for vessel electrification at scale

Abstract

At Danfoss Drives we work every day in marine decarbonization. We operate in many countries with diverse stakeholders: policy makers, shipbuilders, OEMs, system integrators and not least, vessel owners. We would like to spread awareness of the main factors influencing success and therefore this paper looks at three key issues in marine decarbonization, seen from the perspective of Danfoss Drives.

The first section examines vessel electrification in terms of Energy Storage Systems (ESS), mainly in the form of Battery Energy Storage Systems (BESS). We look at the strengths of BESS including primary economic and environmental benefits. In the second section, we investigate the Norwegian experience to understand the background for its achievements. Norway is widely recognized as by far the most successful nation in electrification of ships. We also look briefly at the experience of other countries. Lastly, we close with case studies from Danfoss' experience in vessel electrification projects. The third section deals with issues related to but beyond BESS. We review the three primary fuels hydrogen, methanol, and ammonia. Finally, we comment on the relation between fuel cells and batteries, and discuss shore power.

Contents

1. Introduction

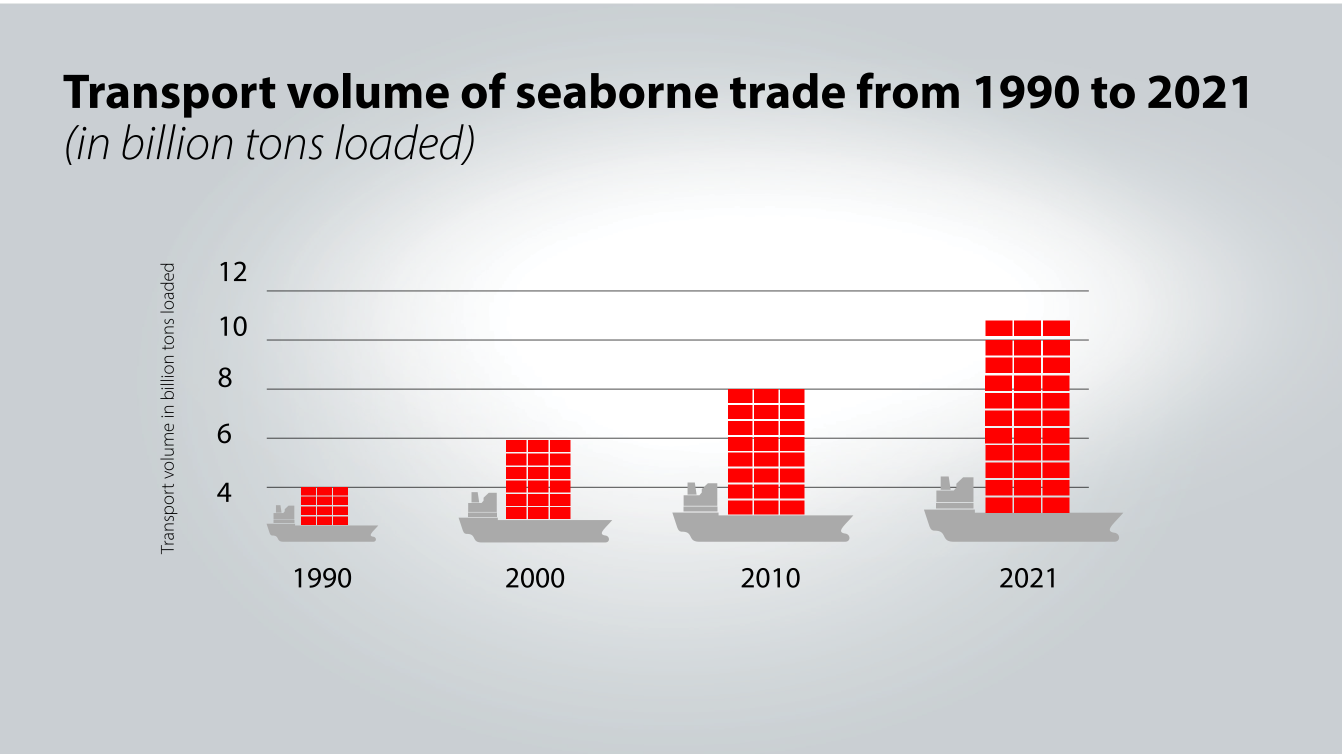
The volume of ocean shipping has grown 175% since 1990 [0] and now accounts for about 80% of goods transport, worldwide. Therefore, marine decarbonization has the greatest influence of all when reducing global emissions from freight.

The International Maritime Organization (IMO) wants to reduce GHG emissions from shipping by at least 50 percent by 2050 compared to 2008. However, the ambition of the European Parliament is much higher: at least 40% reduction in less than ten years (2030). And the Getting to Zero Coalition aims to have commercially viable zero-emission vessels (ZEVs) operating along deep-sea trade by 2030.

Shipping was the last industry to arrive at the climate change discussions - even later than aviation, another hard-to-abate sector. That is why the pressure to decarbonize seems so overwhelming. It is not only a demand by governments but also by some of the largest shippers such as IKEA, Nike, Nestle, and Tesla. Civil society groups are also demanding change, with the youth around the Fridays for the Future movement being the most vocal.

By developing state-of-the-art equipment for electrical applications, we at Danfoss are contributing to the massive energy transition away from fossil fuels. We are convinced that in the future, the only sources of electricity will be wind, solar, or other renewable sources. Nationwide grids will always exist, but they will become greener over time.

The shipping industry is now part of that gigantic transition process. Healthy competition between the green fuels of the future is already flourishing in full force. Hydrogen, methanol, and ammonia are among the top contenders. No matter the energy sources which prevail, it is undeniable that battery storage and electric power are already an indispensable part of the solution. Batteries are already integrated into fully electric vessels and form part of hybrid propulsion solutions.



Transport volume of seaborne trade, 1990-2021. Source: ***Statista***

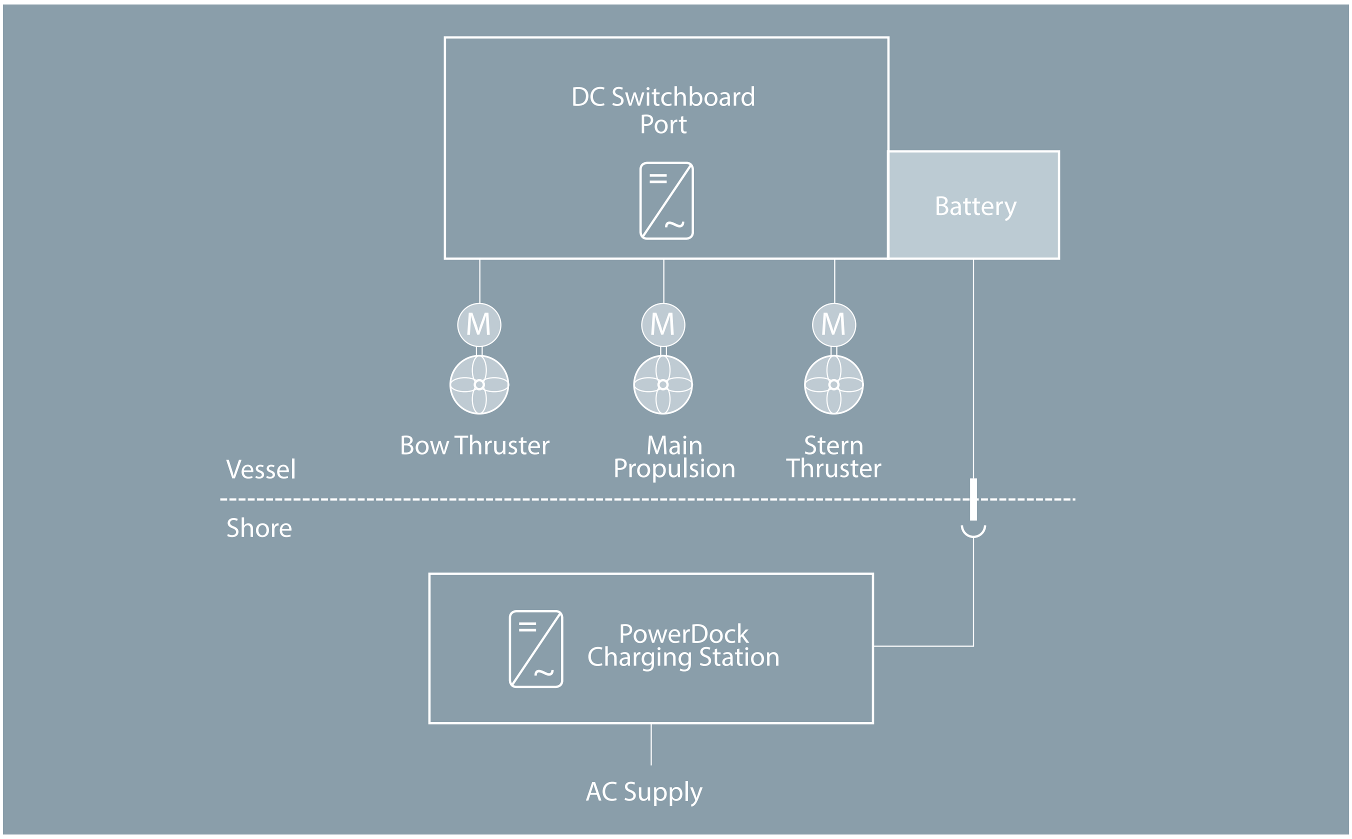
2. Why is energy storage taking off in marine?

The Maritime Battery Forum (MBF) keeps a detailed register of battery-powered ships, and identifies three recent periods in the expansion of battery power to vessels. These periods are the early years (1998–2013), the second generation of ships (2014–2018), and the current period (2019–2022) [1]. The salient features of the latter period are use of batteries in a wider range of vessel types and the increasing size of these battery systems. Installations are taking place in all types of vessels, from offshore supply vessels to cargo vessels such as container ships, bulk carriers, and tankers. And from fishing vessels and fish farm support vessels to cruise ships and ferries. The size of battery systems has increased to an average capacity of 1.2 MWh per ship over the last four years. The vessels with the largest battery systems are container ships, Ro-Ro, Ro-Pax, and cruise ships. And the largest system installed in mid-2022 has a capacity of 10 MWh.

Another trend is the predominance of hybrid vessels, including plug-in hybrids, over pure electric vessels. The expansion of shore power is reinforcing this trend. Regarding trends in battery types, the Maritime Battery Forum says that Lithium-nickel-manganese-cobalt oxide (NMC) has become the preferred Lithium-ion chemistry for ships. However, there could be a challenge to NMC from lithium-titanium-oxide (LTO) batteries coming up.

An energy storage system (ESS) stores energy to supply electrical energy later. Battery energy storage systems (BESS) are is the most common type of ESS, followed by flywheels (FESS) and supercapacitors (SESS), among other alternatives.

A current trend is to set up an ESS on board, in a 20-foot container (or other sizes if needed). The container accommodates all the required equipment, such as batteries, power converters, transformers, battery monitoring system, HVAC, fire detection, and firefighting system. An ESS has important economic and environmental benefits. In the next two sections, we look at these benefits.



Schematic diagram illustrating part of Future of The Fjords' electric propulsion with battery energy storage and charging system [2]

2.1 The environmental benefits of ESS

The main environmental benefits of an ESS are not only emission reduction, but also less vibration and noise. There is an ESS is at the heart of every hybrid propulsion system. Compared to traditional technologies, hybrid propulsion optimizes engine performance and cuts fuel consumption, resulting in lower emissions of all types (CO_2, NOx, SOx, VOC, PM, and more). This emission reduction contributes to climate change mitigation at the global level and brings down air pollution in ports and coastal areas. Using electric power for propulsion or hotel load when berthed reduces vibration and noise, making the life of seafarers more comfortable and ensuring lower impact on sea life.

These are the benefits of ESS in a nutshell. However, no explanation is better than a case study, and since Norway is a world leader in marine electrification, we illustrate the benefits of installing ESS on board ships with a Norwegian example: a vessel owned by Brodrene Aa that could not have a better name—"Future of The Fjords." [2] I would like to highlight the three main environmental benefits of such a ferry.

First, "electric propulsion is almost silent and is far quieter than any other technology available today." The fjords are popular tourist destinations and therefore also highly vulnerable destinations. Silence on board is good for the crew and passengers, who can appreciate and enjoy the view in peace. The noise reduction is also kinder and less disruptive to the natural environment. Towns around the fjords are also happier with the tourist traffic. Strict regulations are already enforced in Norway for sightseeing vessels, but the "Future of The Fjords" surpasses them all, as it is designed to fulfil the 2026 regulations.

Second, "the concept PowerDock was set in operation for the supply of energy" to the vessel. Since the local grid in Flam (the home port) cannot provide enough energy to recharge the vessel during its 20-minute stopover at the quay between trips, the world-first floating PowerDock was set in operation to supply energy to the vessel at each stop. The vessel receives energy from the dock via two charging cables, each delivering up to 1.2 MW. A reliable clean energy supply is no problem in the Norwegian fjords because the country already has an overcapacity of renewable energy.

Third, although energy for hotel load amounts only "to 30-35 kW, equivalent to about 3-4% of the energy consumption on board," the vessel optimizes energy consumption by using LED lighting and heat pumps/heat recovery and having insulated outer bulkheads to minimize heat loss. Another environmental advantage of the "Future of The Fjords" (not related to the ESS) is its low weight and efficient hull design, which "prevent wash induced shoreline erosion." This is important for protection of beaches along Naeroyfjord and the adjacent Flamsfjord. In recent decades, ferries and especially cruise ships with their large size, have caused coastal erosion when the waves they create have hit the beach.

2.2 The economic benefits of ESS

The main economic benefits of an ESS are the reductions it generates in CAPEX and OPEX. A BESS can replace generators powered by fuels, and sometimes, scrubbers or catalytic converters can be eliminated. In the long term. However, the greatest reduction is seen in operating costs because bunker fuel is the most substantial operating cost in a vessel. The operating cost reduction due to fuel replacement applies not only when the vessel is in transit but also when it is maneuvering, anchored, or berthed. Besides, the more environmentally friendly vessels increasingly have a competitive advantage: with shippers, for cargo vessels, and passengers, for cruise ships and ferries.

Since the quality of batteries improves every year while prices simultaneously decrease, we take a forward-looking view of total cost of ownership (TCO), rather than examining studies made in the past. A study that received coverage by one of the top scientific magazines, Nature, presented some astonishing numbers and information. The title already suggests the conclusion: "Rapid battery cost declines accelerate the prospects of all-electric interregional container shipping" [3]. The authors claim that "battery-electric ships powered by renewable electricity offer a near-term pathway to cut shipping emissions over intraregional and inland routes." They demonstrate that at battery prices of 100 USD per kWh, electric powered short-sea shipping of less than 1,500 km becomes economical. A land-based equivalent distance is the stretch from Algeciras in Spain to Genoa in Italy (1,572 km).

When environmental costs were taken into consideration (for example, carbon tax), the profitable range increases to about 5,000 km. This distance is further than the extent of the Mediterranean Sea, which reaches 3,547 km from Algeciras to Port Said.

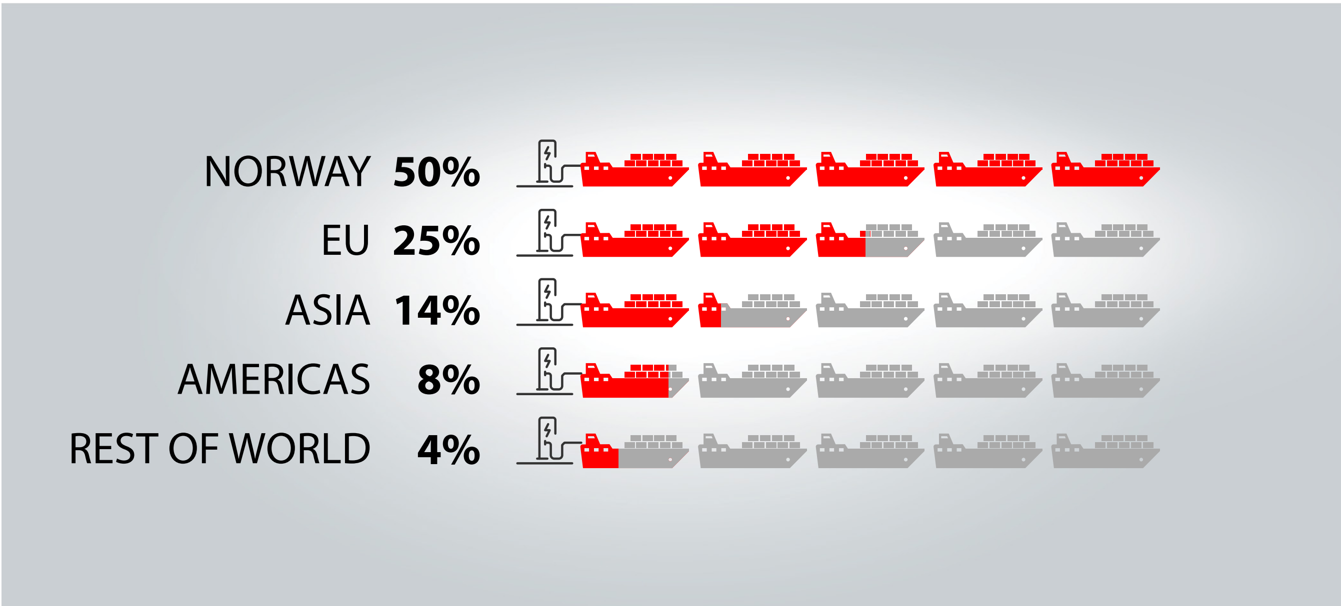
The authors, however, argue, as the title indicates, that battery costs are declining rapidly. They claim: "If batteries achieve a 50 USD per kWh price point, the economical range nearly doubles." That is why they boldly state that electrification can take place in "over 40% of global container ship traffic" already this decade.

3. The technology exists and it is mature enough to scale up

Although not many years have passed since BESS began to be installed on board ships and since hybrid propulsion has become one of buzzwords in the maritime industry due to its great benefits (more about this below), both technologies have matured and are scaling up. The trend is towards bigger BESS, achieveable due to the modularity of these devices, and the hybridization of vessels, either as new-build or retrofit.

And here is where one must look at the top leading country in the world: Norway. While in most fields the dominance is by large economies like the US, Germany or China, or there is no clear dominance with several countries disputing the leadership, in the field of ESS and hybrid propulsion, the first spot is unquestionable. According to the registries of the Maritime Battery Forum almost half of all the battery powered ships were in mid-2022 operating in Norway. That figure is almost double of the around 25% of ships operating in the rest of Europe. Asia has a share of 14%, and the Americas, mainly North America) barely have 8%. The rest (about 4%) operate globally[1].

What has been done in Norway that enables such a performance? Are those policies replicable to other countries of the word? What exactly do we mean by the second part of the equation, hybrid propulsion? And are there some case studies from our own experience at Danfoss?



Proportion of battery powered vessels operating worldwide, by country.
Source: "Current Status of Maritime Batteries and Future Outlook", Syb ten Cate Hoedemaker, Maritime Battery Forum, 2022

3.1 The Norwegian success

The Norwegian case has not been analysed thoroughly because it is a recent process. Surely in some years there will be different interpretations of how such a small country was able to overtake much bigger countries, particularly other European countries that are also following ambitious decarbonization strategies.

The best explanation one has at the moment is the one provided by Rostad Saether in his paper: "A green maritime shift: Lessons from the electrification of ferries in Norway" [4]. He argues that four critical factors explain the country's success: a national culture of innovation, an entrepreneurial behaviour of the state, lack of resistance from established interests, and the fall of oil prices in 2014. Let's look at each of them. Of course, we also add insights based on our own knowledge of the Norwegian ferry system.

First, competition between Norwegian ferry companies has not cancelled cooperation, information-sharing, and mutual trust amongst them. On the contrary, "the Norwegian ferry actors are close-knit and collaborative." They seemed to have behaved as a cluster, sharing knowledge and being transparent to each other. One would say that such a cooperation is feasible because ferries cover different destinations in the country, in other words, companies would not be competing directly among themselves. The truth is that they compete heavily each time a new tender is announced by the government of the Norwegian Public Road Administration (NPRA): "Operators bid on contracts that usually last 10 years."

Second, while the Norwegian government certainly channels support schemes as it is typical with public subsidies, it behaved entrepreneurially in helping market creation. The market creation in pursuit of zero or low emissions ferries started in 2011 when NPRA launched the first tender (the so-called Ampere tender after the name of the first vessel). Such a process was reinforced with the ambitious climate targets established by the government, guaranteeing that the private sector, in this case the ferry companies, would have a sizeable market. The author also sees Enova, the Norwegian climate and energy support agency, not as a bureaucratic institution but as "an integral part of the innovation systems [that] support and accelerate market creation and transformation." Concerning ferries, Enova offers generous support, which can reach up to a maximum of 40% of the cost.

Third, there was no resistance from vested interests. Although the maritime industry is quite conservative and opposes regulatory changes, the decarbonization of ferries in Norway did not result in the demise of any ferry companies "Instead, they were able and willing (and aided by the state) to pursue the necessary transition." The ferry sector saw the change towards lower emissions as a priority that could not be stopped or denied. Contrary to most cases, the ferry industry did not "influence policymakers to abandon or slow down electrification efforts."

Lobbying power, with the negative connotation that usually brings as resistance to change and defence of vested interests behave in a pro-active way supporting the government efforts to speed up the process of removing barriers for cleaner shipping. Such a positive environment, helped by access to renewable energy influenced the decision by Siemens and Corvus Energy to build maritime battery factories in Norway, a decision that reinforced an already virtuous circle.

Fourth, a crisis, the fall in oil prices in 2014, accelerated the electrification of ferries. The positive impact on the ferry industry was not a direct consequence of falling oil prices, because in that case ferries would have preferred to continue operating with a dirty but cheaper fuel.

The impact was indirect and shipyards formed intermediary links in the chain. The fall in oil prices severely impacted one of the most important shipping sectors in Norway: the offshore supply vessels (OSV), which represented most of the order book for Norwegian shipyards. Due to the oil crash, many orders were cancelled and therefore shipyards supported heavily the government policy for the construction of zero or low emissions ferries: "It was a stroke of good luck for the shipyards that there were ferries to be built." While new-builds of OSV have fallen in recent years, the orders for ferries increased from 562 during 2006-10 to 817 during 2016-20. Of course, the fall in oil prices also contributed to the 2015 parliamentary motion to increase the use of green technologies in the maritime industry in general.

One could certainly add more factors such as a state with such strong economic power that the climate change agency is able to support with not only 5-10% of the cost of a low emission ferry, but up to 40% of the cost.

Future research will certainly enrich the already excellent review made by the two Norwegian experts in their academic paper.

3.2 Key learning for speeding up to scale

3.2.1 Political commitment and government funds

The previous section highlights the Norwegian government's political commitment and financial support. Therefore, in this section, we refer to similar policies and subsidies in two other European countries with important shipping sectors: the UK and Germany. However, before leaving the Norwegian experience, we make some references to "The Government's action plan for green shipping," [5] which has consolidated the route map on the decarbonization of shipping. In particular, we want to highlight the following five issues:

First, the government is more ambitious than the IMO for all vessel categories: to reduce emissions by half by 2030 (IMO aims to cut emissions in half by 2050).

Second, because of the considerable difference between different segments of the Norwegian fleet, different measures may be required to decarbonize each segment.

Third, since OSVs account for about 23% of Norway's emissions from domestic shipping, the government may introduce zero- and low-emission solutions for new-builds. Similar action may be taken for aquaculture support vessels, given the increasing importance of the sector in Norway.

Fourth, the government will establish instruments such as carbon tax, lower electricity tax rates for commercial vessels, and differential port fees based on environmental grounds.

Fifth, Enova will continue to support installing shore power in Norwegian ports. It has already provided about 1 M NOK . The goal is to achieve totally emission-free ports by 2030.

The government of the UK, another important maritime country, launched its maritime strategy in 2019: "Maritime 2050: Navigating the Future," a long 338-page document [6]. After claiming that leading maritime nations need to adapt and plan and that the maritime strategy must take the country well into the second half of the 21st century, the document makes a series of commitments to create a competitive and sustainable maritime industry in Britain. Some of these commitments are:

First, the British government envisions a sustainable maritime sector by 2050, "reducing impacts to as close to zero as possible, while leading the way on green finance and setting international standards."

Second, it commits to lead: "[the country will move] faster than competitor countries and [will] be seen as a role model in the field."

Third, it is optimistic about environmental results: "the UK maritime sector will have negligible wider environmental impacts, with minimization integrated into the full ship life cycle from design and construction to operation."

Fourth, it offers an adaptation to climate change, mainly regarding the adaption by ports to the increased flooding from tidal surges. The strategy, despite its length, is not specific about policies, but it certainly has plenty of aspirations.

The German government launched a similar maritime strategy in 2017: "Maritime Agenda 2025: The future of Germany as a maritime industry hub"[7]. The document states at the beginning that its maritime industry can react faster than other countries to market changes because the maritime industry "is mainly operated by the private sector." Another important statement is that efficient ports and logistics and renowned research and training facilities are cornerstones in the success of the German maritime industry. Some of the announced policies are:

First, the federal government emphasizes its support to the maritime industry by developing long-term strategies with specific support programs and instruments.

Second, it also stresses the significance of a regular dialogue with the stakeholders of the maritime industry through the regular and well-established National Maritime Conferences.

Third, the maritime industry does not comprise the major ports in the North Sea and Baltic Sea but includes most of the country because of the extensive inland navigation network (the largest in Europe), mainly Baden-Wuerttemberg, Bavaria and North Rhine-Westphalia.

Fourth, the government plans to expand technological leadership in the maritime industry because it is one of the most research-intensive sectors in Germany.

Fifth, the government will bring together three maritime funding programs on research, development, and innovation under the headline of maritime technologies.

3.2.2 Hybrid propulsion is a mature technology

The installation of BESS on board a ship means, in most cases, that the vessel will be powered by hybrid propulsion unless the batteries are used only for hotel load. Hybrid propulsion is a buzzword in the shipping industry these days. In this section, we follow a paper published by us titled precisely "Hybrid propulsion" [8]. By providing two sources for power propulsion, the hybridization of vessels allows the optimization of energy sources depending on the task assigned to the vessel. Optimum energy power consumption results obviously in lower costs and less environmental emissions.

In hybrid propulsion with BESS, electrical power is used to power the motors connected to the propeller shafts. The chief advantage is that fuel-powered engines run closer to the design point, which optimizes fuel consumption. When additional energy is needed, the electrical motors can cover the additional demand; on the contrary, when less energy is needed, the excess can be stored in the batteries. Rather than sharp running curves, the "fuel-driven engines see smooth running curves." Hybrid propulsion helps improve vessel performance to approximate the levels defined by the stringent regulatory measures of the IMO.

Our paper from 2019 explains that "pure diesel and marine gas oil have a fairly fast dynamic performance (100 kW/second for a 2 MW generator). However, other fuels like LNG or biofuels are characterized by slower change response. They are not well-suited to abrupt changes in loading. Hence a need to have an even load on the engines arises." [8]

The traditional way to cope with peak loads has been to have several generators running as a spinning reserve. That scheme, however, wastes fuel, becoming inefficient, expensive, and polluting. Since fuel-powered engines "run best at a static load of around 65-80% of capacity depending on make," but power fluctuates all the time due to wind and waves or the switching on and off of onboard machinery, a stabilizing element is required: generators, or even better, BESS.

BESS operates on electronics, and "electronics are instantaneous, reacting in milli-seconds rather than seconds," making it possible for the batteries to deliver the excess supply of power needed at any moment. There is no more need for engine-based spinning capacity. And the batteries, which are bidirectional, "will take back" the power from the engines once the peak load has ended. The engines will work near the ideal static load. And, of course, the main engines can even be stopped when the vessel is idling, with the BESS and smaller diesel generators providing all the energy needed on board.

Besides lowering emissions, another significant benefit of BESS is a reduction in noise and vibration levels. This reduction is due to fewer running engines and generators on board.

Our paper from 2019 clearly summarizes the benefits: improved vessel performance, reduced emissions, lower operating costs due to lower fuel consumption, lower maintenance costs related to engines, reduced noise levels and vibrations on board - also reducing noise in the water, improved long-term efficiency of the power supply system, higher redundancy, and peak shaving - reduce the dynamic load on generators. [8]

3.3 Case studies

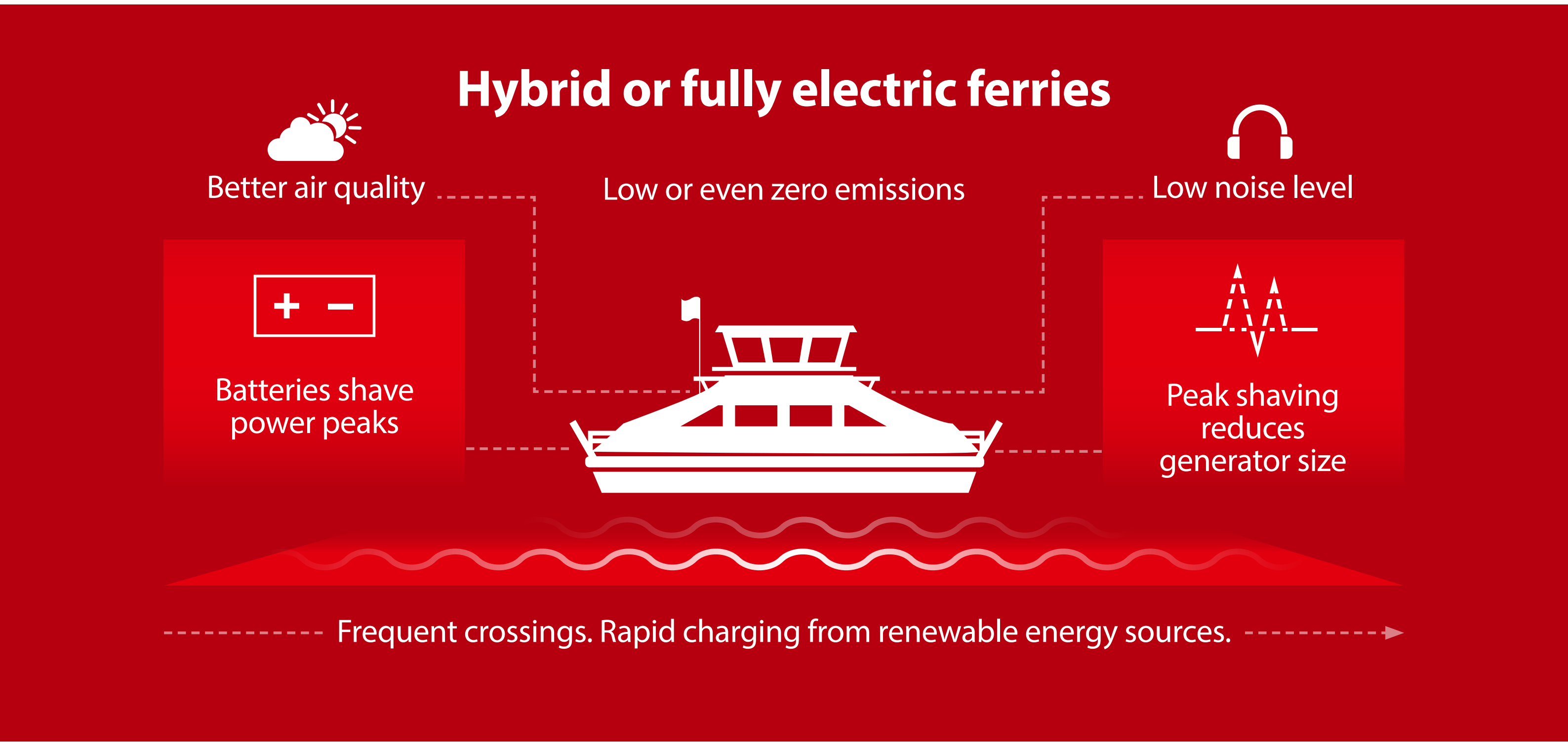
In this section we look at our own projects. On our website we have published more than 30 marine case studies during recent years. Here we highlight the most relevant facts about four of those projects; in some cases, the BESS has been used to convert a vessel to fully-electric and in other cases, hybrid propulsion has been possible thanks to the installation of BESS. In all cases, the system integrators have used our latest technologies. Before mentioning them, we would like to emphasize that one of the competitive advantages of Danfoss against its competitors is that we offer both entire systems (turn-key solutions) as installed in many of these vessels, and we can also support highly customizable solutions developed by system integrators, fine-tuning the applications according to the very specific needs of a client.

3.3.1 Political commitment and government funds (Norway)

The ferry operator on the Hareid-Sulesund crossing decided to replace diesel propulsion with pure electric. Although the crossing takes only 23 minutes, the transition from diesel to fully electric demanded not only the installation of BESS and electric motors on board the ferries but also the provision of all the needed shore power infrastructure for rapid charging and stable grid supply. The systems on board and on shore were designed as a single system by Norwegian Electric Systems (NES) using Danfoss technology[9].

The sister ferries Suloey, Hadaroey and Giskoey were retrofitted with batteries and the newest converter and power control technology in order to achieve an optimal electric-powered solution. The existing power grid was strengthened on both sides (also with BESS), allowing that with a single touch on the charging display, the ferry charges 350 kWh of power in only six minutes. The precise integration of both systems, on board and on shore, is one of the main features because by doing that the charging power transfers exactly the energy required.

When the ferries are approaching, the system receives information about the energy consumed on the trip that must be replaced. "By ensuring optimal charging power, the systems avoid unnecessary wear on batteries and power electronics, both on board and on shore." The annual reduction of CO_2 emissions achieved with the electrification of the ferries reaches about 7,000 tonnes, considering about 32,000 vessel charging sessions every year.



Hybrid or electric ferries with rapid charging facilities powered by renewable electricity offer a near-term pathway to cut vessel emissions on short-sea routes.

3.3.2 Solar-powered river tours at Krka National Park (Croatia)

Krka National Park commissioned two fully electric vessels, each with a capacity for 50 passengers. The vessels are equipped with solar PV panels and BESS. On sunny days, solar panels supply the power for the propulsion and for charging batteries. On cloudy days, the batteries provide the power required. Therefore, the ferries at Krka National Park always operate as zero-emission vessels. The vessels operate a cycle of eight hours on battery and twelve hours on solar panels.

The main technical challenge in this project was to perfectly synchronize the solar panels and the batteries in the driveline system, to deliver an optimal conversion from solar cells to batteries. Inmel, the system integrator of the project, installed all the necessary hardware and software from Danfoss[10].

The Croatian authorities chose the fully electric approach due to the particularly sensitive nature of Krka National Park, housing about 1,200 species of plants, more than 200 bird species, 17 species of bat, several species of amphibians, reptiles, and more. To protect the majority of the land-based animals which live in or near the Krka River, the authorities required the most environmentally friendly type of vessel available.

3.3.3 The shortest ferry route in the country to Veno island (Denmark)

The trip from the mainland to Veno island lasts barely two-three minutes, but it passes over a narrow 17-meter-deep sound with strong currents. The operator decided to convert the traditional vessel to hybrid because although the trip is short, and it runs every 30 minutes, it was consuming a large volume of diesel. Two diesel auxiliary generators ran for 19 hours each day, to power hotel load, bridge equipment, engine room pumps, and more, while the vessel was idle. The solution was to install BESS to power each crossing. This conversion has dramatically reduced fuel consumption, since now the generator runs only 20 minutes daily. From 19 hours to 20 minutes, that is a saving, indeed! [11].

Now the battery bank powers the energy for each crossing, and the ferry is recharged as soon as it arrives. Between the BESS and two identical Volvo Penta Marine diesel engines, the vessel has full redundancy.
Although the route was short, the task was complex: "Danfoss Drives thoroughly tested the system by using a test rig to simulate the generator. The actual battery and microgrid were employed in this test. The ship's load was simulated by a Danfoss drive with a load resistor and electrical motors." The project was a cooperation between Danfoss, EPTechnologies, Super B, Hvide Sande Shipyard, and contractor Vest-El.

3.3.4 Hybrid propulsion for the Scottish offshore islands (UK)

Caledonian Maritime Assets Limited (CMAL), the shipowner of the CalMac Ferries, is the company that provides most ferry services to Scotland's offshore islands. In 2011, CMAL started the process to install hybrid propulsion on its newest roll-on/roll-off (RORO) ferries to reduce fuel consumption and emissions. The solution chosen seems traditional in the sense that the "diesel engines drive generator sets to produce power for electric motors that drive the vessel's propulsion units." A critical difference, however, is that the propulsion motors can be powered also by high-capacity BESS. The batteries are charged overnight from shore supply, while the vessels are docked [12].

The first two vessels to be retrofitted were the sister ferries MV Hallaig and MV Lochinvar. Each accommodates 150 passengers and 23 cars or two large goods vehicles. The new drive systems installed provide a high level of redundancy. For instance, a ferry can continue to operate if one of its two drive systems fails: the battery power can run alone in the event that diesel fuel is not available. In fact, on certain short routes, such as the one between Raasay and Sconser, ferries are powered by battery alone, on some days. After the two initial vessel retrofits, a third vessel, MV Catriona, was also retrofitted.

4. But the future is not only electric

Batteries are being used on board ships more often and the trend will not stop, but probably grow exponentially in the coming years. Currently the only viable option is BESS. However, in the future flywheels (FESS) and supercapacitors (SESS) will also be used. As we have explained before, the electronics embedded in any of those ESS can provide instantaneous power. The main discussions about the decarbonization of the shipping industry, however, are not focused on batteries; these are considered essential for complementary power and essential for short- and medium-distance routes, but not realistic for deep-sea voyages.

The discussion around sustainable deep-sea shipping focuses on the so-called green fuels of the future, mainly hydrogen, methanol, and ammonia. Some experts also propose biofuels, and others, even nuclear energy. In this chapter we look at those three green fuels; at the combination of hydrogen and fuel cells, on one side, and batteries on the other; and at the supply of electricity from shore: so-called shore power or cold ironing.

4.1 The three leading contenders

Most of the sustainable fuel discussion in maritime conferences and webinars as well as in the shipping media has been about hydrogen, methanol, and ammonia. One can say that each of the fuels has committed defenders and detractors. Projects across the world are being supported by the European Union or national governments for all types of vessels and for those three different fuels. Most organizations and initiatives, however, are taking a pragmatical approach and avoiding compromising fully with any of them. The competition is certainly impressive because nothing like this had seen since the early 20th century, when the steamships were replaced by bunkers. We highlight here the main characteristics of each fuel.

4.1.1 Hydrogen

The most likely fuel for the future is green hydrogen (H_2), produced from renewable energy using electrolysis. Blue hydrogen, using natural gas, would be another option, but it would imply carbon capture and storage (CCS). Gray hydrogen (also using natural gas or methane) would be impossible because that does not involve CCS. "H_2 can be used in two forms, either in fuel cells or internal combustion engines" [13], with the first option as preferred. Hydrogen is already used in public transportation buses, but in the maritime sphere has been used only for the construction of small and prototype vessels.

One of the main criticisms against hydrogen is that its production requires considerable amounts of energy: "Consequently, even if the energy efficiency of H_2 converted to electrical energy in fuel cells may be high, the lifecycle energy efficiency is significantly lower due to the energy loss in H_2 production" [14]. Another criticism is its volumetric energy content, which is the lowest among the three.

Besides, as DNV points out, to power a vessel, H_2 will have to be stored at very high pressures (350-700 bar) as compressed gas or very low temperatures (-253 °C) as liquefied gas. However, the combination of fuel cells and H_2 would make the propulsion and hotel load completely zero-emission. Such a combination would also eliminate noise and vibrations. When using hydrogen with internal combustion engines, "the efficiency is lower than is possible to achieve by using fuel cells, and the combustion generates NOx" [14].

4.1.2 Methanol

Methanol is the simplest of all alcohols and has a high content of hydrogen as its formula indicate (CH_30H), it is four parts hydrogen, one carbon, and one oxygen. That is why green methanol can be produced with hydrogen, making methanol zero-emission if the feedstock is green hydrogen. Green methanol could also be produced from "lignocellulosic feedstocks such as agricultural waste, from biomass collected from sustainable managed forests to produce bio-methanol, or from gasification of municipal solid waste" [13] but in those cases, it would be only a low-emission fuel, not a zero-emission one.

Methanol can be used on board in internal combustion engines. It can be stored and transported using current infrastructure because at normal temperature and pressure it remains liquid (no need of cryogenic or pressurized tanks). It is considered one of the safest alternatives because is it has been used for many years for many energy purposes. The cost of conversion for existing vessels to run on methanol is lower than for any other green fuel, and it is already available for bunkering at many ports.

However, "methanol fuel tanks are typically twice the volume of oil tanks with the same energy content" [14], and furthermore, the combustion performance of methanol is not the best. This means more fuel volume is required in the combustion chamber of an internal combustion engine, and consequently the chamber must be larger than for other fuels.

4.1.3 Ammonia

In liquid form, ammonia NH_3 has a higher energy density than other green fuels. Ammonia may be liquefied by cooling it down to -33°C or by pressurizing it to about 10 bar [14]; therefore, it is easier to store and transport. Besides, the storage of ammonia in tanks is considered a mature and standard technology. And green ammonia could be produced from hydrogen made by electrolysis sourced by renewable energy.

There are several issues with ammonia as a shipping fuel. The first seems minor: it requires small amount of a pilot fuel to combust, which means that the pilot fuel needs to be also carbon zero for the ammonia to become zero-emission. The second is that the formula clearly indicates the presence of nitrogen; that means that when combusted it will produce water vapor, on one side, because of the combination of hydrogen with oxygen, but it will also produce NOx, which is a greenhouse gas.. In other words, although ammonia could become zero-carbon, will never really be zero-emission. The third problem is its high toxicity, which could represent serious risks for crew in case of an incident.

4.2 The future of ESS with hydrogen and other fuels

The future use of green fuels will allow many hybrid options. For instance, in a recent article published in the magazine Electric & Hybrid Marine Technology International, the case is made to use hydrogen with BESS, having methanol as the high-density hydrogen carrier feedstock [15]. Such a solution is interesting because of the difficulty of storing hydrogen, which, even in liquefied form, would occupy up to twice the volume of LNG. The use of methanol or ammonia would guarantee "a safe, constant flow of ready-to-use hydrogen on board." The reformer systems that create hydrogen from methanol as needed during the voyage are PEM fuel cells , which are just as modular and scalable as batteries, for convenient installation on board vessels. The author claims that such a combination of multiple cabinets would handle megawatt applications while ensuring high energy efficiency (>80%) and reducing the heavy footprint of pure hydrogen storage."[15]

We want to stress the convenience of fule cell modularity and scalability. Fuel cells come in all sizes, from a few kilowatts to several megawatts. They complement batteries almost perfectly. Fuel cells and batteries working together have great potential to improve performance and efficiency. During a voyage, batteries can power propulsion for shorter distances, while methanol-based fuel cells can power longer voyages. The match between both technologies increases the range of the ship. Since fuel cells can power propulsion but cannot store energy, any surplus power which is generated will not go to waste, but can be stored in the batteries. This is one potential solution for the shipping industry of the future.

And methanol is only one of the possible options. ABS [16] considers a similar process for ammonia, also concluding that: "Once cracked, the hydrogen from ammonia can be an abundant resource for fuel cells to generate electric power." They also tackled a typical dilemma: Why convert the ammonia to hydrogen when that implies energy losses and additional equipment and when certain types of fuel cells can run directly with ammonia? A similar case can be made for methanol. The answer to this question comes down to nitty-gritty technical details: ammonia can damage the fuel cells with acid electrolytes. This means use of ammonia requires the installation of an acid scrubber to remove any remnant of ammonia gas.

4.3 ESS is not only on board but also onshore

Cold ironing, also known as shore power or onshore power has one purpose: to bring power from the national grid (or a local grid) to berthed vessels, rendering diesel powered generators unnecessary. The evidence in favor of shore power is overwhelming. According to the US Environmental Protection Agency (EPA), "[in optimum conditions] when a vessel is connected to shore power, overall pollutant emissions can be reduced by up to 98% when utilizing power from the regional electricity grid." [17]

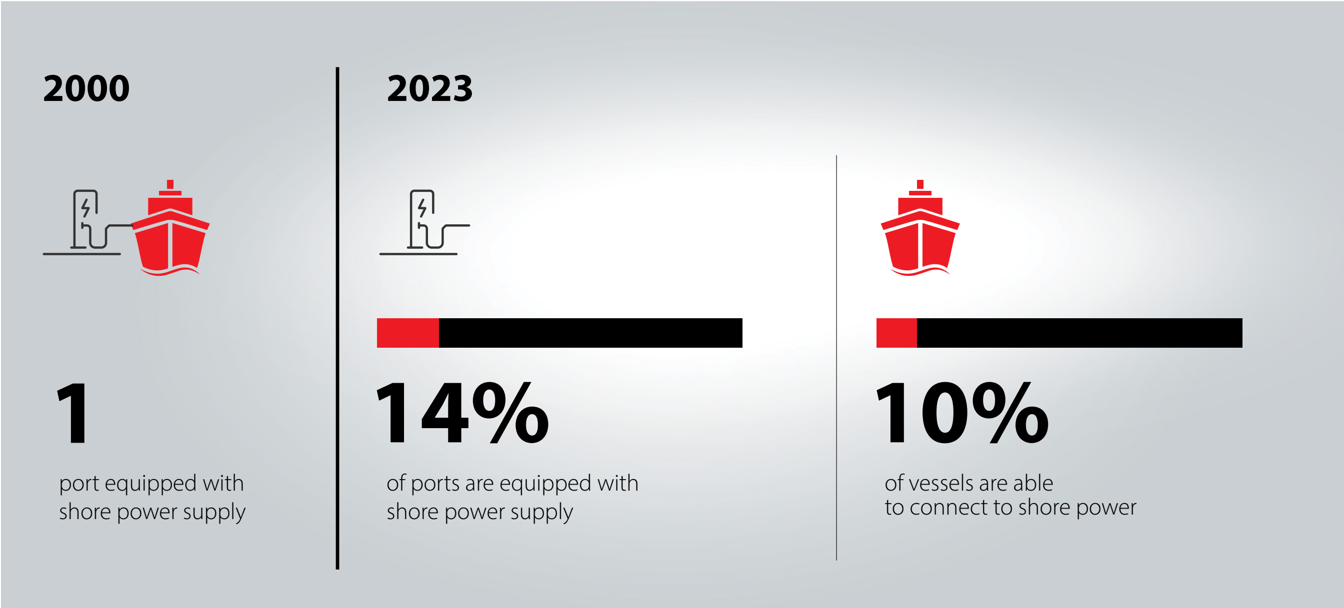
For ports, shore supply is not only about decarbonization, but also about elimination of air pollution (NOx, SOx, particulate matter) and noise while vessels are berthed. That is why public backing is high in Europe and other countries, and likewise there is active endorsement from national, regional, and local authorities. The following excerpts are clear enough:
The EU Green Deal states: "It [the Commission] will take action in relation to maritime transport, including to regulate access of the most polluting ships to EU ports and to oblige docked ships to use shore-side electricity."

The European Maritime Safety Agency and the European Environment Agency say: "Onshore power supply is a promising solution to improve air quality in ports and coastal areas. In place of using fuel, ships 'plug in' at ports. If electricity supply relies on clean and renewable energy sources, onshore power supply can reduce emissions at berth to zero and decrease noise levels. Close to 10% of ships calling at ports of the EU are equipped with it, with numbers steadily growing" [18]. Even the IMO says: "IMO is addressing the need for global standards for the process of providing shoreside electrical power to a ship at berth."

Despite its benefits, the expansion of shore power has not been easy. Although the first installation of HV shore power took place in 2000 in the Port of Gothenburg, and shore power has been expanded in Nordic countries, the coverage is limited. Even in Europe, which is the region with the highest installation density, barely 14% of ports and 10% of ships calling at its ports have shore power capability.

The consensus at the macro level faces plenty of difficulties when one gets down to the nitty-gritty of installing the equipment, beginning with the classical egg-and-chicken dilemma: Which party should make the first move to install shore power: the ports or the ships? The expenses for ports to supply shore power are certainly much higher than for ships to receive it. Port infrastructure involves not only the equipment to connect to the vessel but also, given the huge amounts of energy required by the largest vessels, the very expensive expansion of infrastructure to connect that equipment to the national grid. However, the tab for equipping vessels is not cheap for shipowners or operators either, because each on-board retrofit can easily cost 1 M EUR, if not more. Besides, there are many more ships than ports.

Another important difference between shore supply equipment for ports and ships is that the onshore equipment needs to adapt to the type of vessels calling at a particular berth: terminals for containers will need a different type of equipment than for bulk carrier terminals or passenger vessel terminals. Even the differences between cruise ships and ferries may result in different equipment requirements onshore. However, the equipment on board vessels can be installed relatively easily during a period in dry dock or even during commercial sailing. A new positive trend is that most new-builds are either designed and built with shore connection capability, or at least prepared for such a connection.



The shore power capability of ports - and ability of vessels to connect to it - has grown in the period 2000-2023. [18]
However, there is still plenty of scope for future growth.

4.3.1 Shore power supply installation paid back in less than five months (Denmark)

We close this section with a case study on shore power [19]. Because of the low oil price and challenges in the oil and gas industry, Maersk Supply Service had some of its anchor handling vessels and platform supply vessels in layup waiting for the next job in 2016. Up to 10 vessels are parked between jobs in the Port of Fredericia, Denmark, where the location and facilities are well-suited for longer-term storage.

To avoid damage to vital systems, these vessels are stored 'warm', which means that the diesel engines are preheated and the electrical control systems and ventilation systems are kept running. Initially, the vessels were powered by onboard harbor generators. This was not a satisfactory solution though, due to diesel exhaust pollution and constant noise.

The solution was shore power supply installed by Caverion: a container-based solution comprising switchboards and system integration, according to a topology designed by Danfoss.

Trefor, the electricity company, was also involved because they had to install a 10 kV to 450 V (max. 1800 A) transformer at the quay.
In the end, despite the civil engineering costs needed to install several hundred meters of 10 kV underground cables to the transformer, there was a reduction in costs and a significant environmental improvement. The business case proved to be even better than projected with a payback time of less than 5 months.

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5. Concluding remarks

The 21st century adventure in the quest for the decarbonization of shipping will have several passengers on board, such as hydrogen, methanol, or ammonia. At this stage, it is not clear which of them will sit on the bow of this zero-emission vessel. What is undeniable is that batteries will be part of the solution.

The time when batteries were suitable only for land-based applications are gone. New, more powerful and more resistant batteries are being designed for the maritime industry, and at some point, flywheels or supercapacitors will also play a role in ESS. Any ESS that supplies propulsion when needed and stores excess energy produced by the engines or fuel cells will improve performance and efficiency to enable genuinely carbon-free vessels of the future. Hybrid and e-vessels, therefore, are buzzwords all of us in the industry must get used to.

In particular, we have looked at the experience of Norway, the country leading the global electrification of shipping. Certainly, lessons from Norway can be extrapolated for adoption by other maritime countries. It is interesting to see how the combination of an entrepreneurial state with an environmentally conscious ferry industry has transformed the sector in Norway. With this approach, Norwegian short-sea shipping has delivered a clear example of success to other countries.

We complement such macro experience with our micro vision, which comes from installing batteries on board ships and retrofitting existing vessels, converting them to become hybrids. And we have closed this white paper with the case of shore power: an impressive trend bringing high voltage to berthed vessels. As a result, more docked ships will stop not only their main engines but also the auxiliary ones and run entirely on electricity provided by the national grid or local grids at the port. That is the perfect complement for an industry aiming to decarbonize in the second half of this century.

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