Batteries on board ocean-going vessels

MAN Energy Solutions
Future in the making

Investigation of the potential for battery propulsion and hybridisation by the application of batteries on board

Future in the making

Contents

The International Maritime Organization has adopted a strategy to reduce the emission of greenhouse gasses from global shipping by at least 50% by 2050. Considering the long lifetime of a vessel, fulfilling this requires radical changes to vessels being delivered in the near future.

Current technology must be combined in new ways, new inventions, and alternative fuels must be brought to the global scene. In the light of these needs, this paper will focus on one of the potential ways to reduce emissions, namely the application of batteries on large ocean-going vessels.

Introduction

Developments within battery technology have been vast within recent years. As depicted in Table 1, the modern application of batteries is not only limited to consumer electronics or road traffic, but also appears within the maritime industry: The first battery-electric short-sea ferry headed out in 2015.

The scope of this paper is to exemplify the energy consumption and power needs of large ocean-going merchant vessels and to discuss the potential applications of batteries within this field of the maritime industry. A field traditionally dominated by the low-speed two-stroke engine.

The potential for pure battery-electric propulsion and batteries in combination with a two-stroke main engine in a hybrid system will be evaluated.
The technology behind batteries and then potential maritime applications hereof, are uncovered through four chapters:

In “Battery technology“, the technology is explained, including the auxiliary systems required to support the batteries. Considerations on the weight, volume, and cost of a maritime battery system of today and tomorrow are included.

The energy consumption for various operations and routes of large ocean-going vessels is considered in “Energy demands for battery-electric propulsion“, along with the potential for covering the electric hotel load by batteries while the vessel is at quay.

Based on this, short-sea ro-ro shipping, if supported by a significant speed reduction, is established as a potential field for battery-electric propulsion within the domain of large ocean-going vessels. A thorough case study of battery-electric propulsion of a large ro-ro vessel operating between mainland Europe and the United Kingdom is performed.

In “Hybrid propulsion with a two-stroke main engine”, it is evaluated if and how batteries can support propulsion of the vessel by a traditional two-stroke main engine in a hybrid solution. The possibilities for peak load shaving of the two-stroke main engine are evaluated. The capabilities of batteries to boost acceleration through the barred speed range and assist during adverse weather conditions are also evaluated along with the technical possibilities for leaving port powered by batteries alone.

“Benefits of battery hybrid systems in the electric grid“ evaluates the possibilities for peak load shaving of the electric load for example during crane operations or for power backup during critical operations. The potential for replacing an auxiliary engine by a battery is considered as well.

For further information on the application of batteries in connection with four-stroke diesel/hybrid-electric propulsion of smaller vessels, please refer to the separate paper “Hybrid propulsion”, which can be found on our webpage → Marine → Four Stroke → Downloads.

Battery capacities of various products and vessels

	Year	Battery capacity	Character	Project costs, approx.
Mobile phone	2019	15 Wh	High-energy, short life	50 USD
Nissan Leaf	2018	40 kWh	High-energy, medium life	20,000 USD
Battery peak shaving, Grieg Star 50,000 dwt	2015	67 kWh	High-power, long life	200,000 USD (1.5 m. NOK)
Tesla Model S100d	2013	100 kWh	High-energy, medium life	100,000 USD
MAN Lion‘s City E (MAN Truck & Bus)	2019	480-640 kWh	High energy, long life	
***Ampere* – first modern electric car ferry**	2015	1,000 kWh	Medium-power, long life	
***Aurora* and *Tycho Brahe* – world’s largest electric vessels**	2018	4,100 kWh	Medium-power, long life	35 m. USD (300 m. SEK)

Table 1

Fig. 1: *Aurora*, one out of two of the world’s largest battery-electric ferries as of 2019, operating on the 2.5 nautical mile route between Elsinore, Denmark, and Helsingborg, Sweden. Courtesy of ForSea

Executive summary

Propulsion of large ocean-going vessels is traditionally the domain of the low-speed two-stroke engine. This paper uncovers the vast energy requirements for crossing the oceans, and evaluates the feasibility of battery-electric propulsion of such trans-oceanic vessels.

Throughout the paper, three cost scenarios of 1,000, 500 and 250 USD/kWh for battery systems have been considered. These prices respectively represent the price of current retrofits, an expected price for large-scale new builds, and a possible price of the future.

Four sizes of bulk carriers, three sizes of container carriers, and one large ro-ro trailer carrier and their energy consumption on typical trades have been evaluated. The evaluation unveils that only short-sea ro-ro shipping seems a practically feasible area for battery-electric propulsion.

A thorough case study of such a vessel and trade is undertaken: At the present level of technology, a battery installation for this 5,000 lane metres ro-ro vessel on a 120 nautical mile route is feasible volume- and weight-wise. Though, even at the lowest cost scenario and aided by a significant speed reduction, the initial cost of battery-electric propulsion more than doubles compared to a traditional two-stroke solution. An expected exchange of the battery pack and related power electronics halfway through the vessel's lifetime must be added on top of this.

Based on this, other alternatives such as carbon-neutral synthetic natural gas, produced from renewable energy, bio or synthetic methanol oxidised in a traditional two-stroke main engine, seem to be more attractive in ensuring sustainable propulsion of large ocean-going vessels. Even carbon-free fuels, such as ammonia can be an option. For routes longer than short-sea ro-ro shipping, battery volume and weight will pose a significant reduction of the vessel's cargo carrying capacity. Pure battery-electric propulsion therefore seems mostly feasible for short-sea operations.

The present conclusions on battery-electric propulsion of large ocean-going vessels do not exclude the application of batteries on such vessels for other purposes than pure propulsion. Through a power take-in on the main engine a battery pack can, for example, aid the acceleration of the shafting through the barred speed range.

The integration of batteries into the electric grid on board a large ocean-going vessel seems to be the area where batteries and hybridisation can bring the largest benefits.

Peak shaving of the electric loads experienced by the auxiliary engines can reduce the overall energy consumption, especially for very dynamic loads, such as during crane or thruster operations.
Even larger benefits can be achieved if a battery replaces an auxiliary engine idling as spinning reserve during critical operations.

Future carbon neutral fuels are expected to be more expensive than the current residual fuels applied for the two-stroke engine.
Battery-hybrid systems are, as such, complementary to carbon neutral fuels, and the savings attained by hybrid systems will help to ease the transition towards such fuels and a carbon neutral shipping industry.

Battery technology

Battery technology has matured significantly during the past two decades as not only the world but also energy has become increasingly mobile. Today the field of batteries is dominated by lithium-ion batteries.

The utilisation of and requirements for the different battery applications illustrated in Table 1 are very different, as well as the expected lifetime. The chemical composition of the battery will greatly influence the characteristics of the battery and so will the charging rates and levels amongst other things as outlined on the following pages.

Lithium-ion batteries

The designation of lithium-ion labels the chemical composition of the cathode (the positive electrode). As the cathode is one of the elements of a battery most descriptive for its behaviour and performance, the chemical composition of the cathode is often applied to label various battery technologies. Today the most common types of lithium-ion batteries are:

- Lithium cobalt oxide ($LiCoO_2$) – first application of lithium-ion technology, most commonly applied in older consumer electronics due to its high energy density, but not seen in the maritime industry due to its short life cycle and limited power rates.
- Lithium iron phosphate ($LiFePO_4$) – the main benefit of this composition is that the cathode is more stable, which reduces the risk of a thermal runaway. $LiFePO_4$ has lower energy density but longer life and better charging rates than $LiCoCO_2$.
- Lithium nickel manganese cobalt oxide ($LiNiMnCoO_2$) – preferred for electric vehicles and within the maritime industry as its life cycle is long while the energy density is satisfying.
- Lithium manganese oxide ($LiMn_2O_4$) – offers high charging rates and thermal stability, at the cost of lower energy capacity compared to $LiCoO_2$, and a reduced lifetime why it is not of interest to the maritime industry.

Various mixing of the cathode materials are also seen for specific applications. Hereby, the capabilities listed above can be somewhat altered to suit specific needs.

While unloaded every cell type delivers a specific voltage, the so called open circuit voltage (OCV), which varies with the state of charge (SOC). The correlation between OCV and SOC is characteristic for each cell type and an important parameter for cell characterisation and the calculation of the SOC during operation.

Depending on type, lithium-ion cells typically have an OCV of 3.2 to 3.9 V, which must be connected in series to achieve the desired voltage of the system. In comparison, a lead acid battery cell has an OCV of 2.1 V, leading to the known connection of six cells to attain approx. 12 V in a car battery.

Lifetime

The degradation of a lithium-ion battery is governed primarily by two factors: Temperature, and the nature of the cyclic loading of the battery.

The temperature at which the battery is kept influences the degradation with time, sometimes referred to as the calendar effect. The optimal cell temperature is by [1] stated to be in the range of approx. 15 to 30°C. Temperature also influences the degradation due to the battery being cycled. If the battery is charged at too low temperatures, lithium plating can occur in the battery, resulting in a reduced lifetime.

Large changes in the SOC, i.e. charging to a very high level or discharging to a very low level will increase the rate of battery ageing. Operational limits (X% to Y% state of charge) are typically set, for large-scale batteries requiring a long lifetime, to prevent the battery from being fully charged or discharged (100% to 0% state of charge).

High charging or discharging rates promotes battery ageing as well, and the lifetime of the battery will benefit from over-capacity as the charging rates will be reduced. The mean SOC of the battery in operation will in addition influence the lifetime. However, the effects of these phenomena towards battery lifetime varies greatly with the specific cell type and application.

The operational limits set will influence the price per kWh available to the operator: A large "margin" i.e. conservative operational limits, will increase the actual capacity of the battery and hereby the price. When comparing price quotations it must be considered if operational margins are included.

It seems that an expected lifetime of the batteries of 10 years currently is the marine industry standard, varying somewhat with type and charging profile. This implies that a midlife exchange of the battery pack must be expected if the vessel lifetime is 20 to 25 years. When evaluating offers from battery suppliers, care must be taken if the capacity stated is the initial capacity achievable at the time of installation, or the "end-of-life capacity" after 10 years or a specified number of charging/discharging cycles.

Previously, traditional lead-acid batteries have seen application within the maritime industry, primarily for uninterruptible power supply (UPS) systems. Lead-acid batteries are cheap and can sustain large charging and discharging/power rates, but at a very low energy density. Therefore, lead-acid batteries are too heavy to take over the propulsion of many vehicles or vessels.

Battery systems and auxiliaries

When batteries are applied on a larger scale, power electronics and auxiliary systems are required. Power electronics control the battery charge and discharge, whereas a battery management system (BMS) provides the power limits for charging and discharging to the power electronics.

Typically, the capabilities and complexity of the auxiliary systems required increase with the capacity of the battery pack. Contrary to mobile phones that are often powered by one single battery cell, several battery cells must be connected to attain sufficient voltage and storage capacity for applications within road vehicles or vessels.

A module is the smallest unit of a battery system that can be independently electronically isolated from the rest of the system. A module may consist of connected single cells or of blocks of cells which are connected.

Several modules must be connected in series to form a pack and to achieve the desired voltage for an electric vehicle or a marine system. Packs are further connected in parallel to form a string, strings may additionally be connected in parallel in order to reach the desired capacity for a marine system.

A battery junction box (BJB) is utilised to connect and disconnect the pack from the string, and includes safety devices like contactors, fuses, and current sensors, see Fig. 2.

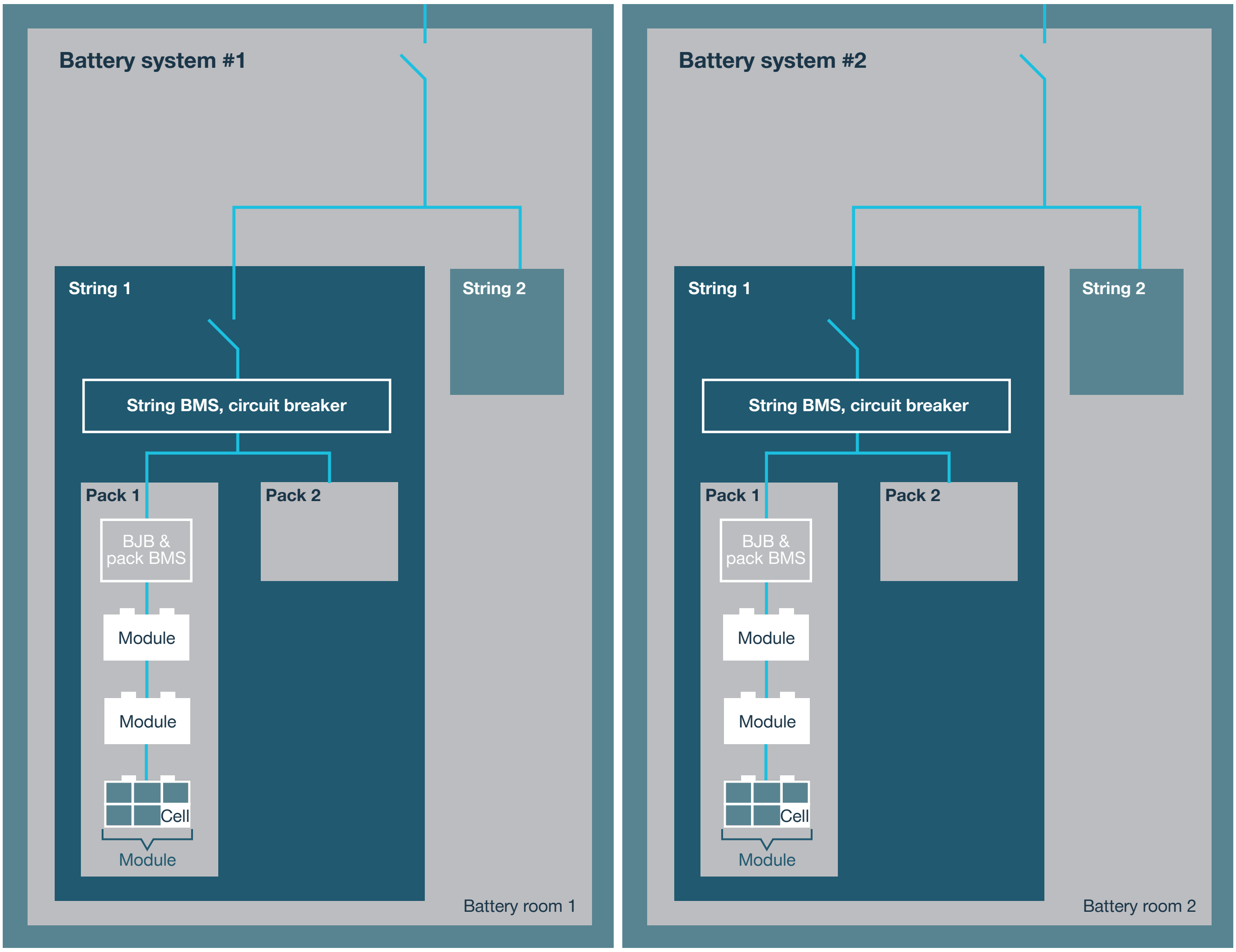


Fig. 2: Redundant battery systems

Battery Management System

One of the single most important components in a battery system is the battery management system. The BMS plays a vital role in the control of the charging and discharging of the individual cells, protects the battery against overloading, and monitors the state of charge, system voltage, etc. In order to perform these tasks, the BMS must be parametrised for the specific type of battery cells applied.

The BMS acts both on a system level and on cell level: On a system level, the BMS calculates the actual power limits for charging and discharging the battery in dependence of SOC and temperature. The BMS provides these limits to the onboard power management system (PMS) so that the power flowing in and out of the battery does not exceed the operational limits. The BMS furthermore determines the SOC and state of healt (SOH) on a pack level and provide this information to the operator.

On an individual cell level, the BMS monitors the voltage of the cell in order to protect the cell from under- and over-voltage as well as it monitors the temperature. Rules exist for the maximum temperature increase at any point that the BMS must be able to detect, see e.g. [2].

A high and consistent quality of the individual cells is required. It must be ensured that the nominal voltage and self-discharge rate of the cells are close to the same level. This is important for the BMS to ensure that as much as possible of the stored energy is available, at as low degradation rates as possible, and at the smallest possible risk of overloading individual cells.

Different self discharge rates and temperatures of the cells leads to differences in the SOC of individual cells over time. In order to level out the resulting variations in cell voltage, a balancing system is included in the BMS. From the cells with the highest SOC energy can passively be discharged through a resistor, or actively be transferred to the cells with a lower SOC.

Apart from ensuring safe operation of the battery, the BMS and its operation of the battery influences the battery lifetime, considering SOC, DOD, charging rates, etc.

If batteries are applied for pure battery-electric propulsion, redundant battery systems are typically required by the classification societies, e.g. [2]. In order to minimise the load on the individual battery systems and hereby extend the lifetime, the battery systems are typically interconnected during normal operations. The onboard PMS must be able to handle this and coordinate the supply from the batteries.

Cooling, thermal management system, and thermal runaway

The primary tasks of the thermal management system (TMS) are to ensure long battery lifetime and avoid a thermal runaway, the most severe risk affiliated with the operation of battery systems.

Cooling of the battery pack during normal operations is important, especially during charging and discharging. The TMS must ensure an equal temperature distribution throughout the system to ensure homogeneous ageing of the cells, and thereby prevent that variations arise in self-discharge rates and capacity between the individual cells. The optimum temperature during operation can be achieved by active cooling either through air ventilation or liquid forced-flow cooling.

Liquid cooling brings the advantage of a very compact system as there is no requirement for void spaces between the modules to ensure that air can access the components. In addition, it brings the advantage that ventilation of the battery room can be reduced, which minimises the exposure of the components to the salt-rich environment at sea. The water-cooled system is typically, via an additional heat exchanger, integrated with the regular cooling system of the vessel – at the cost of increased system complexity.

Air cooling is simple and can in particular be relevant for retrofit projects, as it does not require integration with other systems on board the vessel. Filters can be applied to reduce the exposure to salt in the air. The air-condition system only needs integration with the electric grid. The major advantage of an air-cooled system is the lower price of the components.

A heat loss power of 4-6 % while charging a 1 MWh battery at a C-rate of 3, see page 15, has been reported. The higher the C-rate, the higher will the heat loss be.

A thermal runaway is an exothermal reaction of the battery cell materials, occurring due to internal failures, where the temperature of a battery cell increases rapidly as the energy in the cell is rapidly released. This may lead to evaporation of gasses which may, depending on the composition of the cell, be flammable, why a requirement for gas channels that can safely lead away such gasses exist for marine battery systems.

As a first line of defence, the BMS must be able to detect a faulty cell at the risk of overheating. The BMS must be able to isolate the whole pack, or if this is insufficient, the string with the module containing the faulty cell.

If a thermal runaway within one cell cannot be avoided by disconnecting the cell, the main concern is that it may spread to other cells, creating a cascade effect. It is therefore important that cells are well insulated and that heat is lead away from the faulty cell to prevent a worsening of the situation. Means of ensuring this varies between applications. The requirements for insulation are one of the main reasons for the increased weight and complexity of marine battery systems compared to battery systems for road vehicles.

Marine applications

A system for battery-electric propulsion of a vessel is illustrated in Fig. 3, whereas the traditional mechanical system for propulsion of a large merchant vessel by a two-stroke engine is illustrated in Fig. 4. Various combinations and degrees of hybridisation are illustrated in Figs. 5 to 7 on the following pages.

Accurate knowledge of the SOC of the battery is important: For pure electric vessels, the SOC is important for the range.

For a hybrid solution accurate knowledge of the SOC will allow for optimum utilisation of the potential offered by the hybrid system. The BMS will determine the SOC by algorithms based on the measured current and voltage of the cells.

Battery-electric

In the battery-electric system in Fig. 3, the propellers are connected to electric motors, which are driven by the energy stored in a battery system that is typically charged from shore.
In some battery-electric systems, a smaller diesel generator is sometimes included to ensure operation if the batteries fail to charge or to enable longer voyages, i.e. when the vessel has to dock.

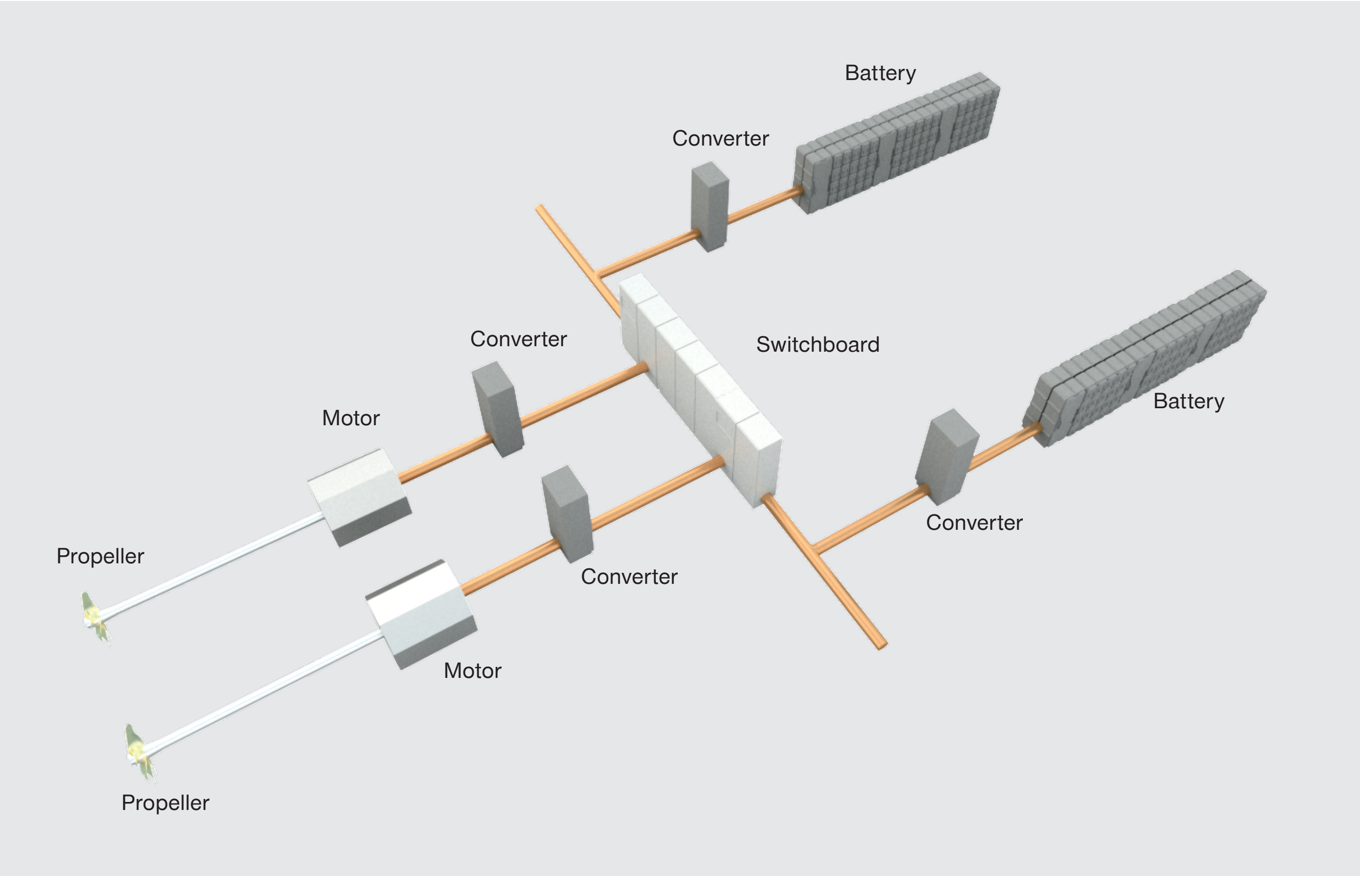


Fig. 3: Pure battery-electric propulsion

Diesel-mechanic

In Fig. 4 the two-stroke main engine undertakes the propulsion, and the hotel load is covered by the auxiliary engines/sensets installed on board the vessel. This represents the most typical installation on large ocean-going vessels.
An increasingly popular variant of this traditional system is the inclusion of a shaft generator/power take-off (PTO) on the propeller shaft. A PTO-solution is illustrated in Fig. 6.

Semi-hybrid diesel-mechanic

Various degrees of hybridisation through the application of batteries exist in between the battery-electric systems illustrated in Fig. 3 and the traditional system in Fig. 4:

In Fig. 5, a battery is included in a traditional system where the electric grid is separated from the propulsion of the vessel. Such a system could be relevant for e.g. peak load shaving for systems with fluctuating load requirements, see “Benefits of battery hybrid systems in the electric grid”.

Full-hybrid diesel-mechanic

In Fig. 6, a battery is included in combination with a PTO/PTI. This allows for the battery and auxiliary engines to support the propulsion of the vessel and for the main engine to charge the battery while at sea. Charging batteries with a PTO while at sea may for vessels with short port stays allow for emission-free port stays, something further investigated in the later section “Energy demands for battery electric propulsion”.

Full-hybrid diesel-electric

A major difference between the battery-electric propulsion systems in operation now, e.g. the fjord-ferry Ampere, and the traditional diesel-mechanic propulsion of large ocean-going vessels, Fig. 4, exists: The newbuild fjord-ferry Ampere would, if not propelled battery-electric, typically be powered diesel-electric, with power delivered by an auxiliary engine, as illustrated in Fig. 7
Being diesel-electric already, the *Aurora* and the *Tycho Brahe*, the world’s largest electric vessels as of 2019, see Table 1 and Fig. 1, were retrofitted to battery-electric propulsion

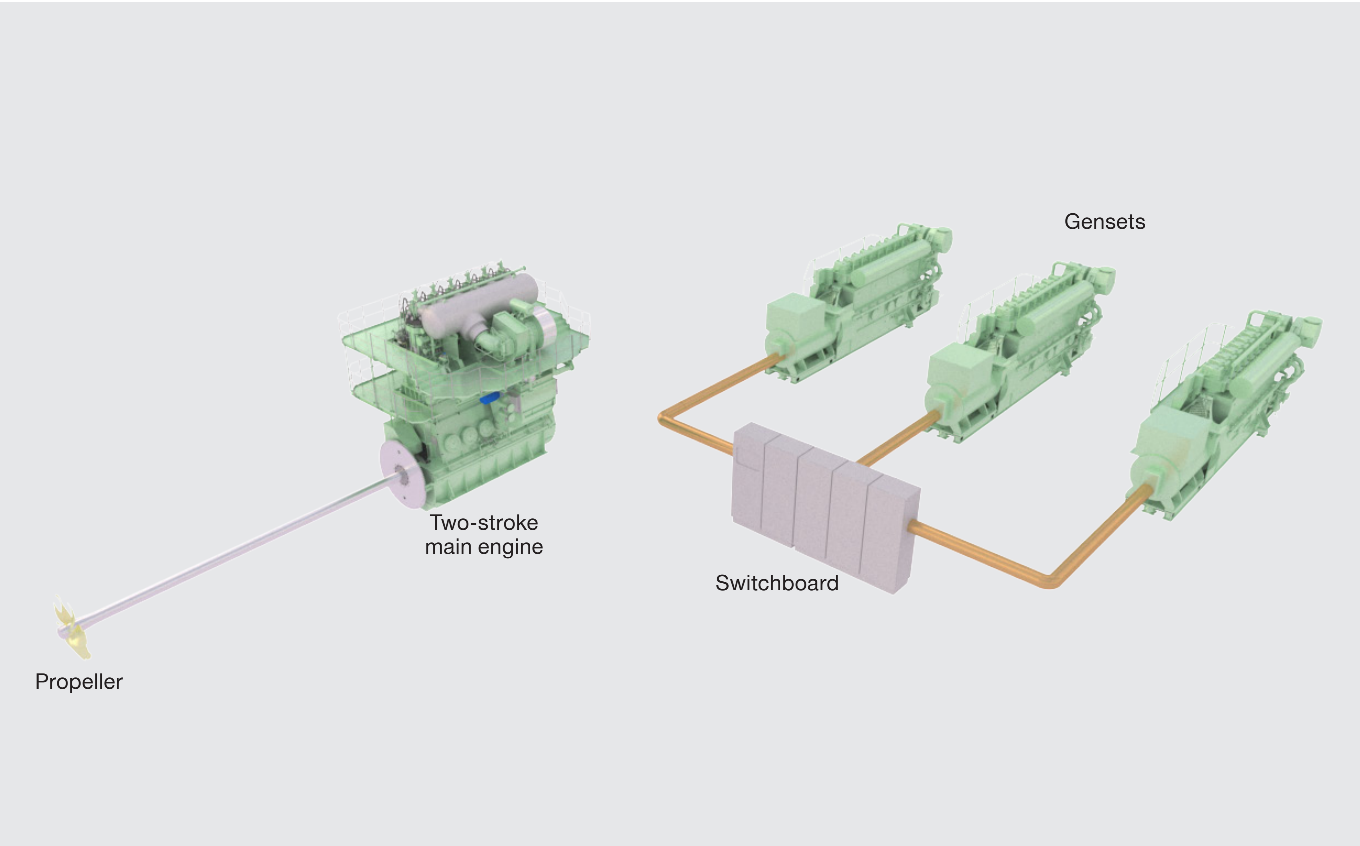


Fig. 4: Traditional diesel-mechanic propulsion of a large merchant vessel

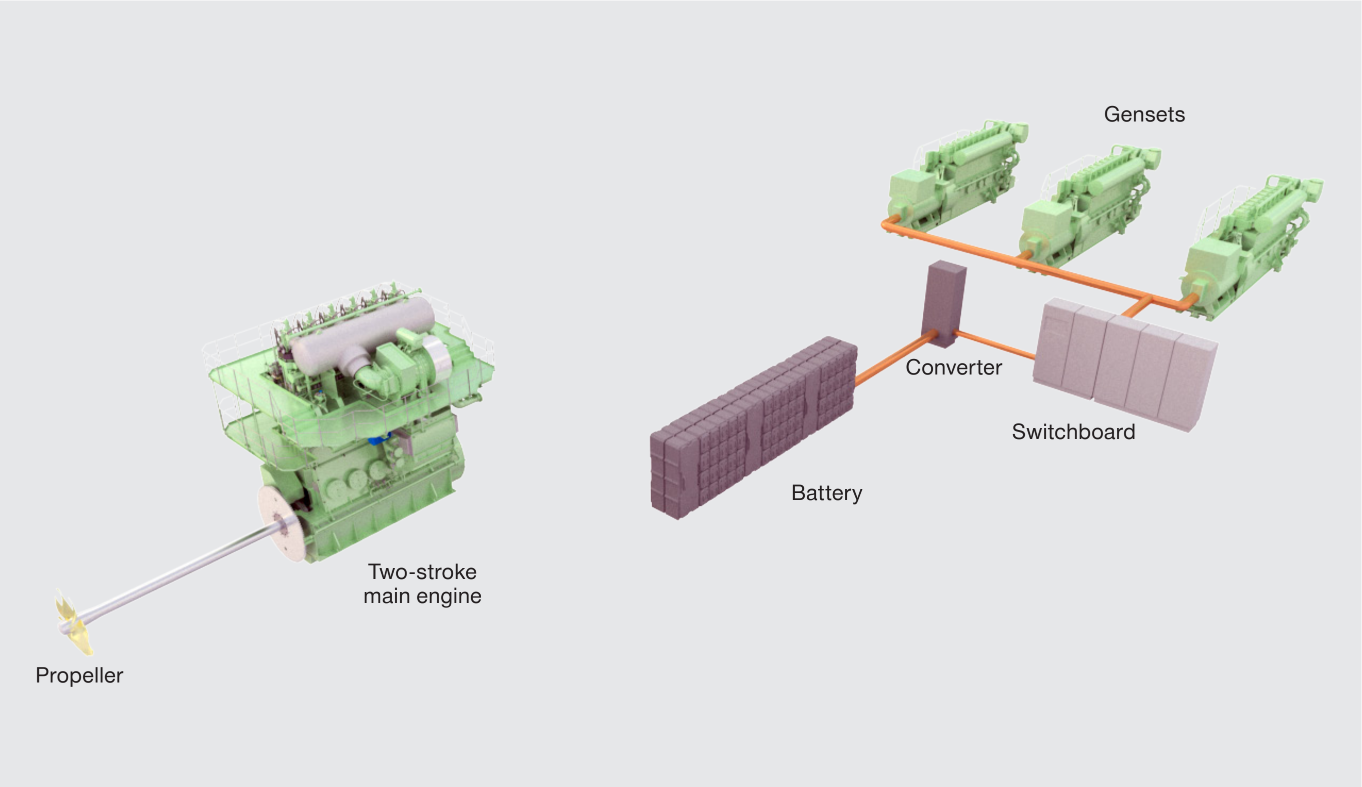


Fig. 5: Semi-hybrid diesel-mechanic propulsion of a large merchant vessel with hybrid electric grid

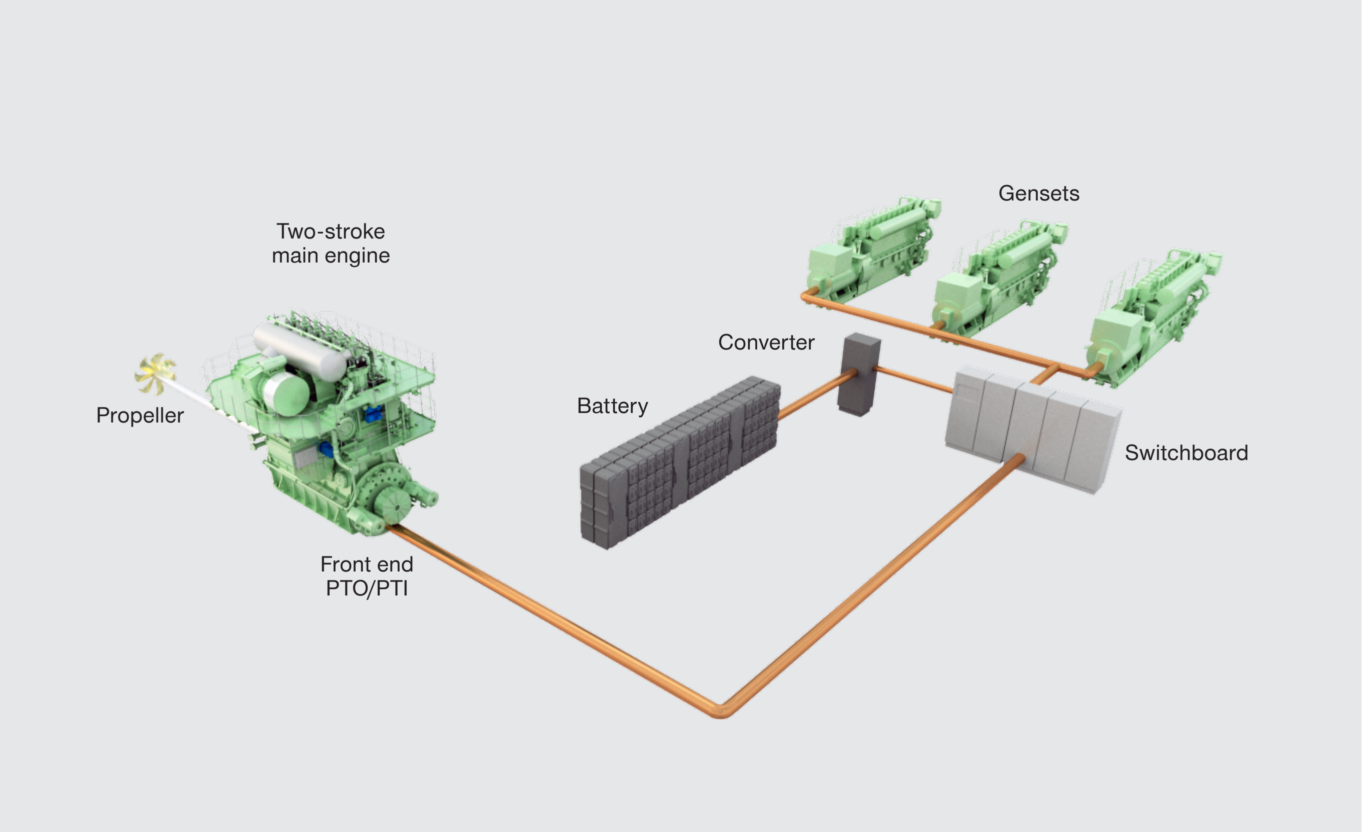


Fig. 6: Full-hybrid diesel-mechanic propulsion of a large merchant vessel with front end PTO/PTI from RENK

in 2018. The system for electric propulsion was already installed and only the power source had to be replaced. Retrofits from diesel-mechanic to battery-electric have not yet been seen, as it would require more than just a replacement of the power source.

Ocean-going vessel application

Traditionally, large ocean-going vessels utilise diesel-mechanic propulsion with the main engine directly coupled to the propeller shaft, see Figs. 4-6. Diesel-mechanic systems provide a higher system efficiency at and close to the optimisation point than diesel-electric systems, which makes it ideal for crossing oceans at constant load. Diesel-electric propulsion offers a higher system efficiency at low and dynamic loads why it is ideal for ferries, offshore supply vessels, etc.

The introduction of battery-electric propulsion for large ocean-going vessels will therefore require larger changes to vessel designs than when introducing battery-electric propulsion on diesel-electric vessels.

For example the DNV-GL battery (power) rules [2] requires redundancy for pure battery-electric vessels, and the two battery systems must be located in separate spaces. The capacity of one of the single battery systems must be sufficient for the planned operation, and an audible alarm must be raised if the minimum level required to finish the operation is reached.
The requirement for redundancy is also reflected in the fact that a significant battery over-capacity compared to the actual energy demand for a crossing is seen on present battery-electric vessels.

For the electric ferry *Tycho Brahe*, see Table 1, 4.1 MWh of battery power is installed, even if the consumption for one crossing according to the operator is approx. 1 MWh.

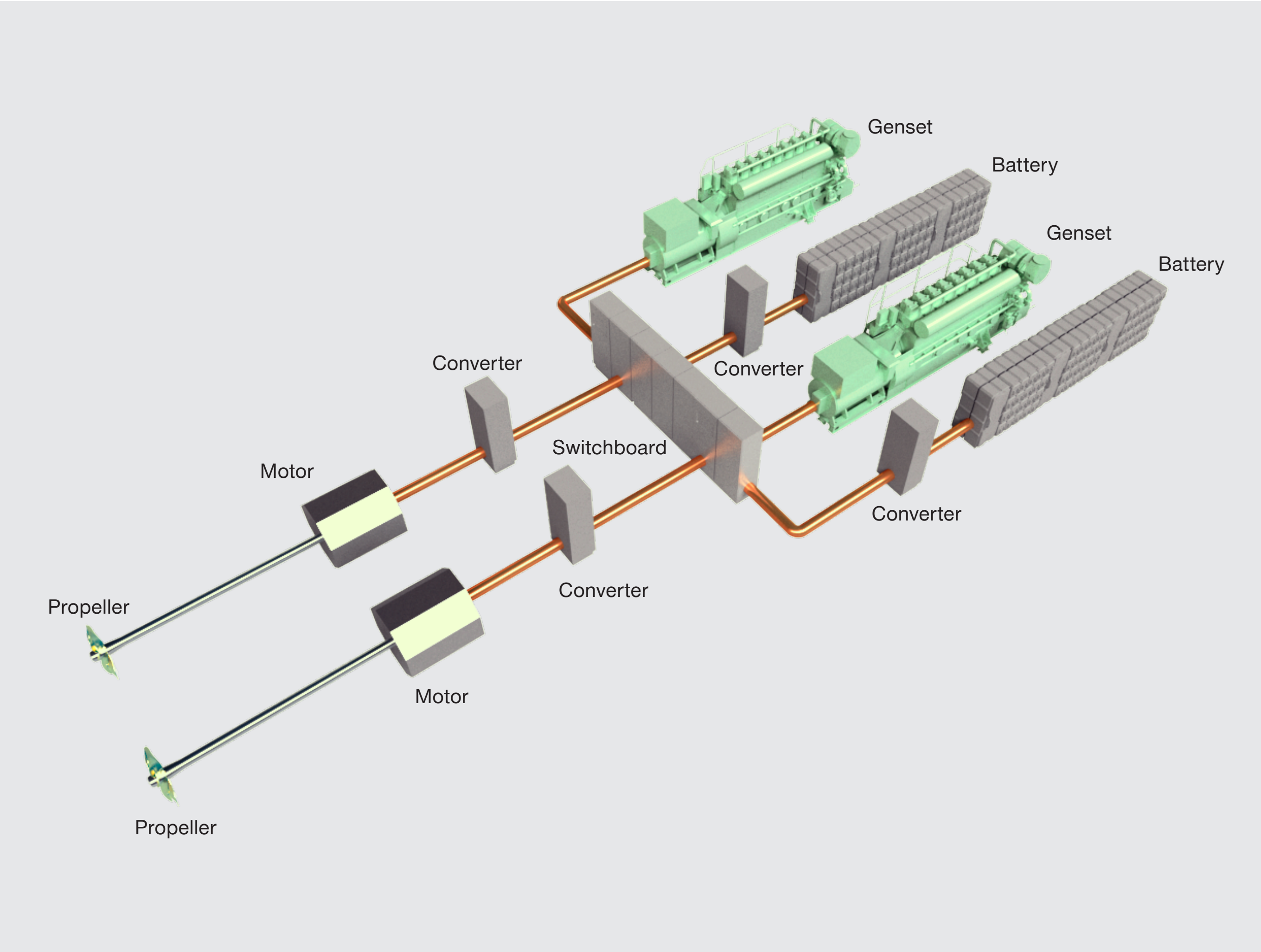


Fig. 7: Full-hybrid diesel-electric propulsion with batteries in a hybrid system

Battery dimensioning

Two main parameters are important when battery systems are dimensioned: The energy storage capacity and the power rate, at which energy can be transferred in and out of the battery.

The charge/discharge current that a battery can sustain is expressed as the C-rate. This expresses the rate at which the battery is discharged relative to the maximum capacity. The C-rate can be applied to compare batteries of different sizes and types. A C-rate of 1 corresponds to completely discharging the battery from 100% SOC to 0% SOC in one hour.

The possible charging rates vary with the SOC of the battery. If the battery is charged to a high level, the rate of charge must be reduced as 100% SOC is approached. This situation is well known for electric cars where it is typically stated that 80% of the full battery capacity may be charged within e.g. 1.5 hours. 100% capacity is not stated as charging the battery the final 20% may take as long as the first 80% – depending on battery type.

The smaller the percentage of the total capacity that is charged and discharged in one cycle (i.e. the smaller the DOD) the longer the battery will live, and the more expensive it will be. Two examples of different requirements are given in the following:

High-power for thruster operation
An example of a high-power, low-capacity battery system is the energy supply for thruster operation during manoeuvres. Thruster operation requires large amounts of power, but only for short durations. By the application of a battery, starting an additional auxiliary engine during manoeuvring can be avoided. The increased fuel consumption and maintenance associated with low-load running of gensets when the thrusters are not running are saved as well.

For a large vessel equipped with 2x750 kW bow thrusters, the battery must be capable of supplying 1,500 kW in the case that the running auxiliary engine fails. Assuming that the thrusters will operate for approximately 10 minutes during manoeuvring in a narrow harbour, the minimum battery capacity can be calculated, which will correspond to a C-rate of 6:

$$1500\ [kW] \times \frac{10}{60}[h] = 250\ kWh$$

$$\frac{Power}{Capacity} = \frac{1500}{250} = 6$$

This C-rate is on the very limit of what can be sustained by a long-life marine battery. If the capacity of the battery is increased and the C-rate reduced, the lifetime will be prolonged. A maximum C-rate of 3 is often stated for high-power batteries, which in this case will correspond to a battery capacity of 500 kWh, see page 32 for a case evaluation.

High-energy for harbour ferry
A harbour ferry is an example of a high -energy application of battery propulsion. The ferry is charged during the night and operates during the day with no intermediate charging. The power consumption of the harbour ferry is estimated at 100 kW, and if it operates for 10 hours a day, the required capacity is 1000 kWh. This corresponds to a C-rate of 100/1000 = 0.1. As such it is only required to take the effect of aging and degradation into account when the total battery capacity of the harbour ferry is dimensioned, i.e. adding approx. 20% to the capacity.

Battery weight and volume

Despite the fact that modern lithium-ion batteries are significantly lighter than traditional lead-acid batteries, the weight of the battery cells and the auxiliary equipment required is still a significant factor. In addition, the volume of the battery system can be critical for some applications.

The weight and volume of a battery system can be stated for many different levels, from solely taking the weight of the cells into account, and to include the weight of cooling, racks, etc., on a system level.

In Table 2, data on heavy-duty lithium-ion marine battery systems are given. The data varies largely depending both on the specific cell technology and system setup. Normally, specific capacities of batteries are given in units of energy/weight or energy/volume as in Table 3. In Table 2, alternative units for specific capacities, weight/energy and volume/energy, are applied to ease direct multiplication with the energy demand established in the later chapter "Energy demands for battery-electric propulsion". The system level values provided does not include the required transformers and converters.

The weight and volume of the battery on a system level are (apart from the cell weight) influenced by many factors, for example: type of insulation between the cells and modules, cooling systems (air/water-cooled), integration with other onboard systems, etc. Especially the method applied for thermally isolating the cells and modules, to mitigate the risk of a thermal runaway, influences the weight and volume of the modules. This is reflected in the significant increase from specific weight at cell level to module level.

As a rule of thumb, an air-cooled system will, at pack level, more

Specific weight, volume, and price of a large, >1 MWh, heavy-duty marine lithium ion battery as of 2019

	System level	Pack level	Module level	Cell level
Specific weight [kg/kWh]	11-30	7-28	6-24	6-8
Specific volume [l/kWh]	12-38	10-12	7-10	1.5-2.5
Specific price [USD/kWh]	500	-	-	200-250

Table 2

voluminous than a water-cooled system, as void spaces for ventilation must be included. On the other hand, the specific weight is lower, as the amount of piping is reduced.

In general, battery systems for marine applications are heavier than systems for automotive usage. For the Tesla car, the specific system weight of the battery (corresponding to pack level for a marine system) was approximately 9 kg/kWh in 2017. The lower weight of an electric-car battery is primarily a result of two things:

- Larger operational margins, i.e. the SOC allowed for a car is less limited than for a marine system. This reduces the specific weight but also the battery lifetime.
- Less (fire) insulation between the modules with no automated support system to cool and extinguish a fire caused by a thermal runaway. Like any other car, a electric car is not equipped with its own firefighting systems, and is left for the fire department to deal with if it catches fire.

Retrofits as an indicator of volume

Some retrofits have been seen where the battery systems are installed on board the vessel in standard containers. Installation of 4x1 MWh water-cooled battery capacity within 4x20-foot standard containers without transformers, converters, chillers, nor other support systems has been seen. Switchboards, chillers, and transformers for a capacity of 10 MW take up further four 20-foot containers. One MWh capacity of air-cooled batteries including support equipment and transformers has been seen in a 40-foot high cube container with an air condition plant on top. The air condition plant adds an extra 1-1.5 metres to the height of the container. As such, the air-cooled system takes up approx. 30% more space than the water-cooled, provided that the water cooling is undertaken by systems below deck, not included in the volume considered here.

Comparison to other alternative energy sources

Batteries are only one alternative source of energy considered for propulsion of large ocean-going vessels. A comparison to HFO and other fuels for specific energy, energy density, and required tank/system volume is found in Table 3.

The volumes are given relative to a 1000-m^3 tank for HFO. Additional space for insulation is not accounted for.

For the Tesla cell, only the cell and not the battery system is considered, and energy for cooling/safety nor classification is not considered.

Cost scenarios

Table 2 lists the current approximate prices of lithium-ion batteries. For marine applications, the system level price is of the greatest interest and it will here be considered at three different levels:

- 1000 USD/kWh
- 500 USD/kWh
- 250 USD/KWh

The cost of integration with the rest of the electrical grid of the vessel, i.e. converters, transformers, etc. must be added to the price of the battery system itself, and will vary on a case-by-case basis.

The past decade has seen a development within the cost of battery packs for electric vehicles where prices have dropped from 1000 USD/kWh in 2010 to 210 USD/kWh at the end of 2017 [3]. The cell price for electric vehicle batteries is stated to be approx. 25% lower than the price of the pack, corresponding to approx. 160 USD/kWh at end-2017.

Today, the difference in total price for a battery pack for an electric car (~210 USD/kWh) and a heavy-duty marine battery system (~500 USD/kWh) hereby constitutes almost 300 USD/kWh, see Fig. 8.

Comparison of alternative energy sources to HFO

Energy storage type	Specific energy MJ/kg	Energy density MJ/L	Corresponding tank vol. m^3	Supply pressure [bar]	Injection pressure [bar]	Emission reduction compared to HFO Tier II		
						SO_X	NO_X	CO_2
HFO	40.5	35	1,000	7-8	950			
Liquefied natural gas (LNG -162 °C)	50	22	1,590	300/Methane 380/Ethane	300/Methane 380/Ethane	90-99% 90-97%	20-30% 30-50%	24% 15%
LPG (including propane/butane)	42	26	1,350	50	600-700	90-100%	10-15%	13-18%
Methanol	18	15	2,330	10	500	90-97%	30-50%	5%
Ethanol	26	21	1,750	10	500			
Ammonia (liquid -33 °C)	18.6	12.5	2,800	50	600-700			
Hydrogen (liquid -253 °C)	142	10	3,500					
High-energy marine battery system	0.50	0.54	64,800					
Tesla model 3 battery cell 2170	0.8	2.5	14,000					

Table 3

The cell price for the electric vehicle battery pack is somewhat lower than the cell price for marine applications, as larger volumes are utilised by the automotive industry. However, the difference in cell price only explains a minor part of the difference in system price.

The majority of the difference is related to the insulation requirements, also imposed on a modular level, to the cooling equipment, fire detection and fire fighting equipment.

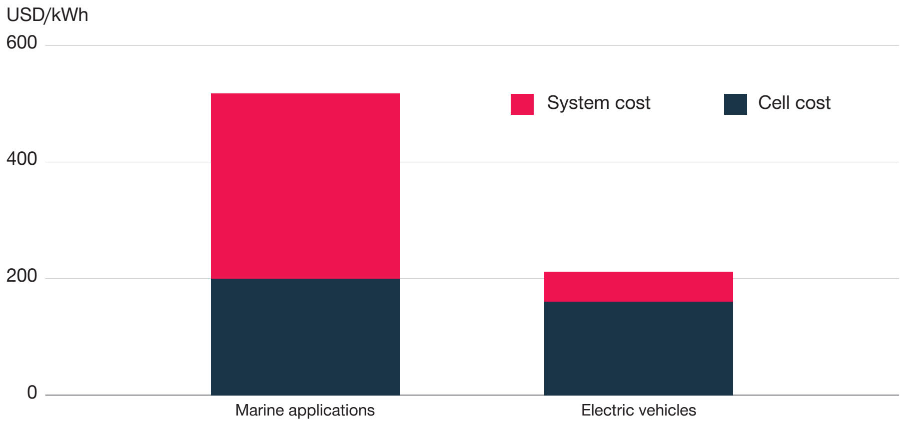


Fig. 8: The cell cost share of the total system cost shown for marine application and electric vehicles as of 2019

Cost development

Predicting the future price of batteries is challenging. It is sometimes stated that the price of battery cells is expected to drop at the same rate as the price of storage and processor capacity has dropped for computers.

This view is challenged by others as the cost of the rare earth metals required for the production constitutes a major part of the total cost of a battery cell. Rare earth metals are not expected to drop in price as the demand for batteries increases.

The price of battery packs for electric vehicles is predicted [3] to be 70 USD/kWh in 2030 (approx. 50 USD/kWh on cell level). Even if cell prices for marine applications drop with the same rate, the system cost for a marine battery system is not expected to drop as significantly.

Today, the cost of the cells constitutes roughly 40% of the total cost of the battery system, see Table 2. Even if the cell price is reduced by 75% compared to the current level, this will only correspond to a 30% reduction of the current total system cost.

The cost of power electronics, battery modules, and racks can be expected to drop with increased production volumes. On the other hand, the cost of the copper required to connect the modules and the steel for the racks is not expected to decrease in the future.

A system price of 500 USD/kWh, without operational margins, for a system to be implemented in a newbuilding is considered to be the minimum level as of 2019. The price of 250 USD/kWh is included to illustrate if and how a significant drop in price would affect possible areas for marine battery applications.

Energy demands for battery-electric propulsion

To evaluate the capability of batteries in the context of large ocean-going merchant vessels, the energy consumption for typical operations in and out of port as well as on typical routes has been investigated. The vessels considered are listed in Table 4. No tankers have been included, as propulsion-wise these are comparable to bulk carriers.

Energy consumption

The energy consumption for four typical situations is considered:

- Energy required when at quay
- Energy required for sailing 5 nm out of port
- Energy required for leaving the 12 nm territorial limit
- Energy required for leaving exclusive economic zones or emission control areas, 200 nm

When manoeuvring out of port, a vessel speed of 5 knots is assumed, 10 knots is assumed outside of port but within the territorial limit, whereas the design speed of the vessel is applied outside of territorial waters.

The design speeds of the vessels have been set to the lower side of typical values for the vessels considered. The resistance of the vessels at the speed of interests have been calculated by the method of Guldhammer & Harvald [4], through the DESMO tool [5]. The values have been reduced by 5% as the method is known to be conservative.

No margins have been included to account for weather conditions or fouling of the hull. A combined propulsive efficiency is assumed to be 0.75, accounting for the hull, open water, rotative and shaft efficiency. For further information on vessel resistance, see Chapter 1 of the paper "Basic principles of ship propulsion".

Energy at quay

The energy for a typical port stay is evaluated in Table 5. Charging the batteries while at sea using a PTO on the main engine to cover the hotel load at quay can ensure emission-free port stays.

For bulk carriers, the hotel load is low during port stays as the cargo unloading (except for smaller bulk carriers with cranes) is handled by equipment on the quay. Therefore, the hotel load is only for lighting, heating, and other commodities.

For container vessels, the electric load is high even at quay as these typically carry large amounts of reefer containers. For the calculations performed here, 1/10 of the total container capacity is assumed to be utilised for reefer containers with an average energy consumption of 4 kW/teu, depending on weather conditions. The duration of a harbour stay has been estimated, as it is assumed that 1/4 of the total capacity is exchanged, i.e. for the 2,500 teu feeder vessel, 750 containers are unloaded and 750 containers are loaded.

For the ro-ro vessel the hotel consumption while at quay covers both the average load of reefer units and the electric consumption for ventilating the decks during cargo handling operations.

Energy consumption of vessel types and sizes within the domain of the two-stroke main engine

Vessel type	Bulk	Bulk	Bulk	Bulk	Container	Container	Container	Ro-ro
Deadweight [dwt]	50,000	82,000	200,000	320,000	30,000	135,000	160,000	14,000
Characteristic size					2,500 teu	14,000 teu	20,000 teu	5,000 lm
Service speed [knots]	13.5	14	14,5	15	18	20	22	20
Resistance at 5 knots [kN]	78	89	142	195	61	143	170	59
Resistance at intermediate speed [kN]	299	334	528	731	265	533	631	223
Resistance at design speed [kN]	580	698	1,085	1,608	884	2,421	3,534	1,025
Resistance at half design speed [kN]	132	169	287	442	199	533	748	223

Table 4

Energy consumption during port stay

Vessel type	Bulk	Bulk	Bulk	Bulk	Container	Container	Container	Ro-ro
Size	50k dwt	82k dwt	200k dwt	320k dwt	2,500 teu	14,000 teu	20,000 teu	5,000 lm
Duration [hours]	36	48	60	72	18	24	32	5
Power [kW]	230	280	340	400	1,200	5,600	8,000	1,300
Energy consumption [MWh]	8.2	13.4	20.4	28.8	21.6	134	256	6.5

Table 5

The energy consumption during loading and unloading of tankers has not been considered as the energy requirements for pumping cargo ashore are vast, be it with steam- or electrically-driven pumps. For tankers, shore power seems to be a more attractive solution than installing a battery pack on board.

Considering the large electric consumption of container vessels while at quay, shore power will also be a more feasible solution than to charge batteries with a PTO while at sea. Shore power is especially relevant for container vessels as they typically operate in a liner schedule with fixed ports of call.

For the oncoming evaluations of energy requirements for propulsion, the hotel load is kept constant at the level required at quay, in order to reflect operation without a running main engine.

Energy for leaving port

The energy required for sailing 5 nm out of port is evaluated in Table 6. The total energy required for accelerating the vessel and sailing out of port is limited. For container vessels, the major energy consumption while leaving port stems from the electric load, and not the actual propulsion. In the calculations presented, no considerations on the energy consumption of the thrusters have been included. It must be noted that the energy consumption for manoeuvring can increase significantly in heavy winds.

Energy for leaving territorial waters

The energy required for sailing 12 nm away from the quay is given in Table 7. A speed of 10 knots is assumed. Depending on the layout of the port and coast line, the distance required to leave territorial waters may be longer than 12 nm. Still, the energy consumption for actually propelling the vessel is limited, and as such the total energy consumption is low for vessels with a low hotel load.

Energy for leaving 200 nm zone

Battery propulsion can be an option to ensure compliance with regulations within the 200 nm limit, as it is shown in Table 8.
Here it is assumed that the vessel accelerates to its service speed when outside of territorial waters (12 nm). The energy required to cover 200 nm is in this case dominated by the energy required for propulsion of the vessel and not by the load of electric consumers on board.

Energy consumption while leaving port, 5 nm

Vessel type	Bulk	Bulk	Bulk	Bulk	Container	Container	Container	Ro-ro
Size	50k dwt	82k dwt	200k dwt	320k dwt	2,500 teu	14,000 teu	20,000 teu	5,000 lm
Propulsion, quay → out of port [kWh]	314	428	873	1,324	212	655	777	198
Hotel, quay → out of port [kWh]	230	280	340	400	1,200	5,600	8,000	1,300
Total, energy, quay → out of port [MWh]	0.5	0.7	1.2	1.7	1.4	6.3	8.8	1.5

Table 6

Energy consumption while leaving territorial waters, 12 nm

Vessel type	Bulk	Bulk	Bulk	Bulk	Container	Container	Container	Ro-ro
Size	50k dwt	82k dwt	200k dwt	320k dwt	2,500 teu	14,000 teu	20,000 teu	5,000 lm
Propulsion, quay → territorial [MWh]	2.2	2.7	5.1	7.5	1.7	4.2	5.0	1.5
Hotel, quay → territorial [MWh]	0.4	0.5	0.6	0.7	2.0	9.5	13.6	2.2
Total, energy, quay → territorial [MWh]	2.6	3.2	5.7	8.2	3.7	13.7	18.6	3.7

Table 7

Energy consumption while leaving economic zone/200 nm zone

Vessel type	Bulk	Bulk	Bulk	Bulk	Container	Container	Container	Ro-ro
Size	50k dwt	82k dwt	200k dwt	320k dwt	2,500 teu	14,000 teu	20,000 teu	5,000 lm
Propulsion, quay → eco. zone [MWh]	77	94	147	219	116	320	467	134
Hotel, quay → eco. zone [MWh]	3.6	4.2	5.0	5.7	14.6	62.1	82.0	14.4
Total, energy, quay → eco. zone [MWh]	81	98	152	225	131	383	549	149

Table 8

Energy consumption for typical trades

Besides the energy required for leaving the various zones of interest evaluated on the previous pages, the energy consumption on a typical route of the same vessels has been investigated as well.

The routes, cargos and distances are listed in Table 9 and shown on Fig. 9.

Typical routes for the vessels considered

Route	Cargo	Distance [nm]
Saint Petersburg – Gdansk	Timber	532
Ponta da Madeira – Shanghai	Soya beans	11,100
Newcastle (AUS) – Osaka	Coal	4,280
Ponta da Madeira – Rotterdam	Iron ore	4,100
Hamburg – Gothenburg	Containers	326
Busan – Houston	Containers	9,800
Singapore – Piraeus	Containers	5,610
Rotterdam – Harwich	Lorry trailers	118

Table 9

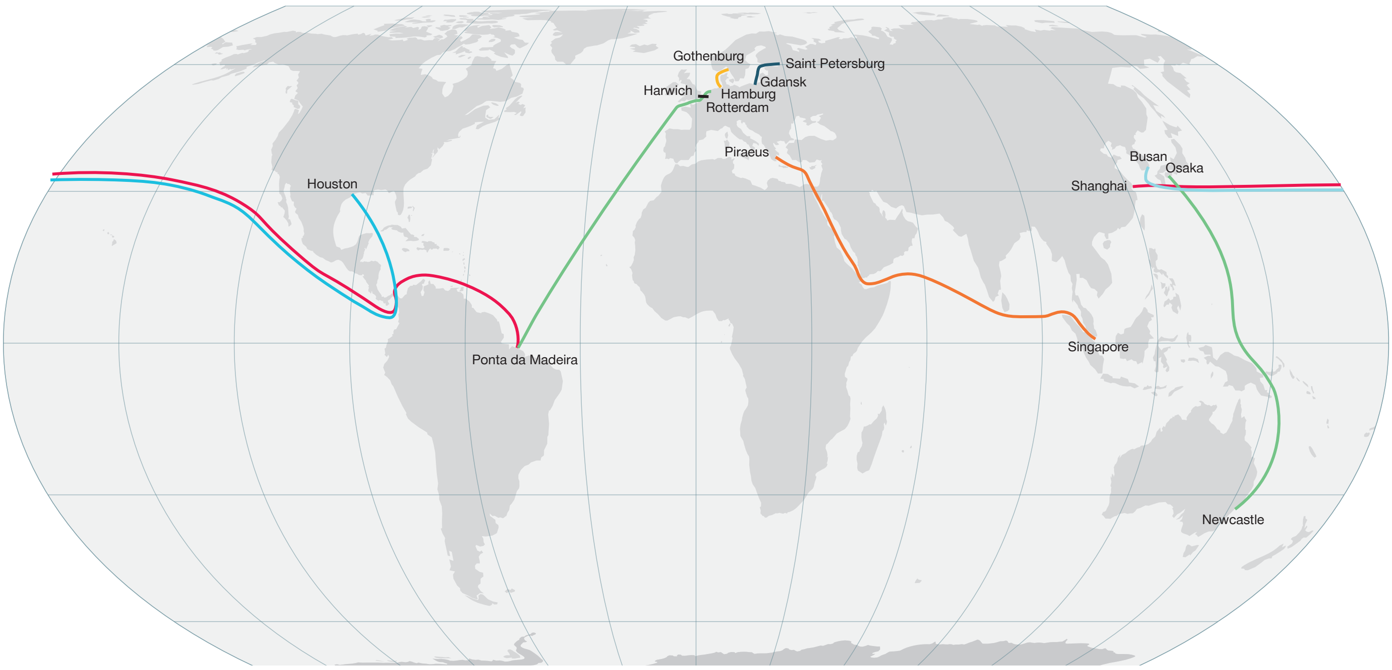


Fig. 9: Routes considered

The energy required to perform these passages is initially considered for the vessels travelling at their service speed, Table 10, and secondly at half of the service speed, Table 11. This is done to evaluate the influence of a drastic speed reduction. When the service speed is halved, two vessels are required to maintain the same cargo transport rate, see Table 12 for the combined consumption of two vessels.

No considerations on the effect of the reduced service speed towards the challenge of minimum propulsion are given in this evaluation, see Chapter 4 of the separate paper "Basic principles of ship propulsion". No margins are included to account for added resistance from fouling, wind or waves. In both Tables 10 and 11, the hotel load is maintained at the harbour level, excluding energy for operating the main engine. For an overview of the cost of the battery packs, see Fig. 10.

Table 12 shows that a reduction of the service speed has the largest influence on vessels that have a low electric load i.e. carry non-refrigerated cargo. The price scenarios applied in Fig. 10 are described in the previous chapter "Battery technology", whereas the volume and weight are calculated on the basis of the minimum specific values given in Table 2, no additional capacity to account for battery ageing are included in the values stated.

It is remarkable that for the normal service speed the weight of the battery will in some cases exceed the cargo carrying capacity of the vessel:

The system required to propel the 14,000 teu New-Panamax container carrier on its route will weigh 209,200 tonnes. This must be compared to a

Energy consumption and battery dimensions for typical routes at service speed

Vessel type	Bulk	Bulk	Bulk	Bulk	Container	Container	Container	Ro-ro
Size	50k dwt	82k dwt	200k dwt	320k dwt	2,500 teu	14,000 teu	20,000 teu	5,000 lm
Service speed [knots]	13.5	14	14.5	15	18	20	22	20
Travelling at service speed [MWh]	212	5,314	3,185	4,522	198	16,274	13,599	83
Time [h]	39	793	295	273	18	490	255	6
Hotel [MWh]	9	222	100	109	22	2,744	2,040	8
Total consumption, service speed [MWh]	221	5,536	3,286	4,632	219	19,018	15,639	91
Minimum weight of battery [tonnes]	2,430	60,900	36,150	50,950	2,410	209,200	172,030	1,000
Minimum volume of battery [m3]	2,650	66,400	39,450	55,580	2,630	228,220	187,670	1,090

Table 10

Energy consumption and battery dimensions for typical routes at half of the regular service speed

Vessel type	Bulk	Bulk	Bulk	Bulk	Container	Container	Container	Ro-ro
Size	50k dwt	82k dwt	200k dwt	320k dwt	2,500 teu	14,000 teu	20,000 teu	5,000 lm
Half speed [knots]	6.75	7	7.25	7.5	9	10	11	10
Travelling at half speed [MWh]	48	1,287	843	1,243	44	3,583	2,878	18
Time [h]	79	1,586	590	547	36	980	510	12
Hotel [MWh]	18	444	201	219	43	5,488	4,048	15
Total consumption, half speed [MWh]	66	1,731	1,043	1,462	88	9,071	6,958	33
Minimum weight of battery [tonnes]	730	19,040	11,470	16,080	970	99,780	76,540	360
Minimum volume of battery [m3]	790	20,770	12,520	17,540	1,060	108,850	83,500	400

Table 11

Energy consumption for typical routes at half service speed and twice the number of ships

Vessel type	Bulk	Bulk	Bulk	Bulk	Container	Container	Container	Ro-ro
Size	50k dwt	82k dwt	200k dwt	320k dwt	2,500 teu	14,000 teu	20,000 teu	5,000 lm
Total consumption, service speed [MWh]	221	5,536	3,286	4,632	219	19,018	15,639	91
Total consumption, equivalent cargo rate [MWh]	133	3,461	2,087	2,923	176	18,142	13,917	67
Reduction [%]	40	37.5	36.5	37	20	4.6	11	26

Table 12

scantling deadweight tonnage of approx. 150,000 dwt for such a vessel. Even at half of the present service speed, the weight of the battery system will constitute approx. 1/4 of the capacity of the 82,000 deadweight tonnage bulk carrier.

For the typical routes of the large ocean-going vessels considered, it seems that the 5,000 lm ro-ro vessel for short-sea shipping between mainland Europe and the UK is one of the only routes where battery-electric propulsion could be feasible. This route will therefore be analysed in detail in the coming section on the next pages.

For some of the other typical routes considered here, stops along the route would be possible, even if not performed today. Such stops would allow for charging or exchange of the battery pack. Two things must be borne in mind when evaluating this option:

- Firstly, many of the shipping routes of today travel along parts of the world where the electricity production capabilities along with infrastructure for distributing it are limited.
- Secondly, many of the vessels must be able to cross open seas, at least the Atlantic. The shortest crossing spans approx. 1,700 nm between Fortaleza in Brazil and Dakar in Senegal.

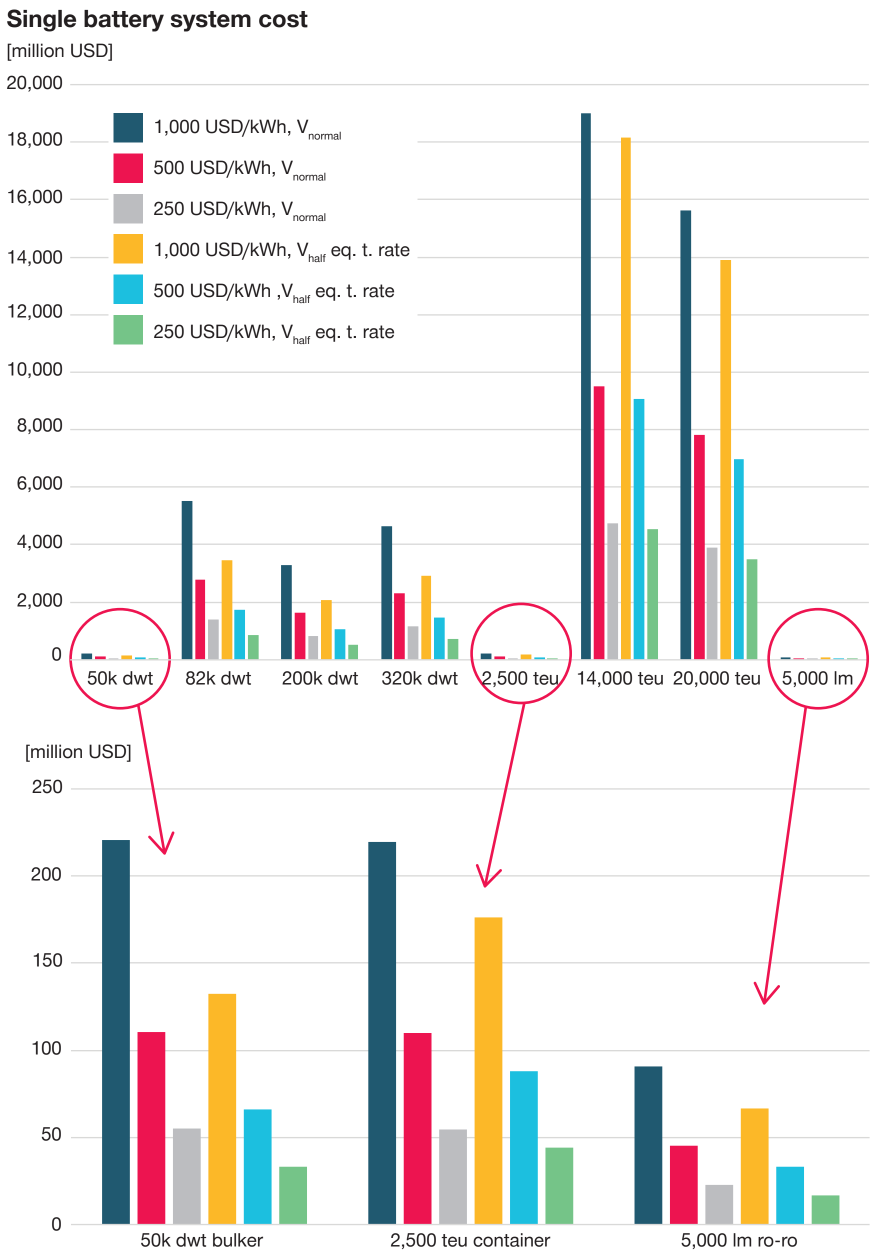


Fig. 10: Cost of battery installation for normal service speed and half of the service speed at an equivalent cargo transport rate, no margins or redundancy are considered. For clarity, the smaller installations are enlarged in the lower part of the figure

Case study, energy consumption of ro-ro short-sea shipping

A thorough investigation of the crossing between the UK and mainland Europe is undertaken. The crossing is popular and many routes exist. In this case the route between Harwich and Rotterdam is considered. Numerous operators carry lorry trailers across the English Channel here, see Fig. 11.

A 5,000 lm ro-ro vessel is considered. The route of the vessel has been determined considering the location of waterways, traffic separation schemes, etc., providing a total distance of 118 nm. The approximate water depth along the route has been plotted in Fig. 12, which is applied for calculating the energy consumption including shallow water effects.

Fig. 11: Route between Harwich and Rotterdam, Northern Europe

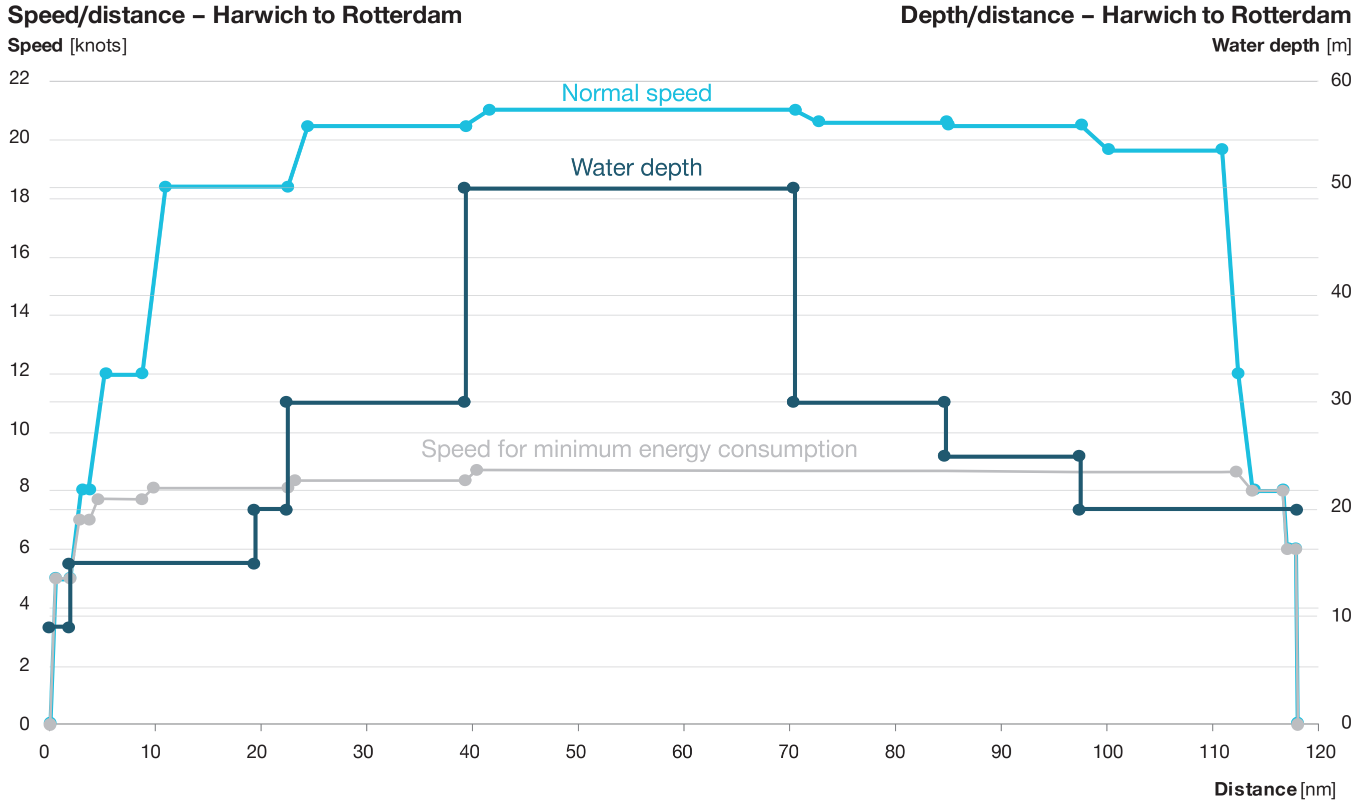


Fig. 12: Water depth and speed along the route

Two cases are considered:

First a traditional operation, where port is left at a speed of 5 knots, 12 knots are applied in the channel out of Harwich, and the speed in open waters adjusted so that the duration of the crossing is approx. 7 hours and 15 minutes. This duration will allow sufficient time to exchange cargo at the quayside and perform one journey within a total duration of 12 hours.

A service speed reduction to 8.7 knots is included as the second case. The duration of the crossing will almost double to 14 hours and 20 minutes. Further speed reductions below 8.7 knots will increase the energy consumption to cover the hotel load to an extent larger than the reduction in energy required for the propulsion of the vessel.

Energy consumption
The energy consumptions for the crossing at the two different speeds are illustrated in Fig. 13. It is remarkable that the electric energy consumption during the crossing at the reduced speed constitutes more than half of the combined consumption. At the normal service speed, the electric consumption is only approx. 10% of the combined consumption, as the crossing time is shorter and the consumption for propulsion is higher.

When adding the 4 hours and 45 minutes for turning the vessel around in port, the total duration of a crossing at the reduced speed will be approx. 19 hours. This is equivalent to a cargo transport rate reduction of 60%.

If this is included in the combined consumption for the reduced service speed, a total energy consumption for an equivalent cargo transport rate of 62.8 MWh is achieved. To keep an equivalent transport rate, three vessels at the reduced speed must replace two vessels at the normal service speed. This reduced-speed solution is analysed further in the following and compared to a traditional solution.

No margins to account for wind and added wave resistance in harsh weather have been included in the calculations. The absolute magnitude of the added resistance from wind and waves is not reduced significantly when the service speed is reduced.

A battery pack with a capacity of more than double the combined energy consumption of 37 MWh must be installed. This is to ensure that the vessel can reach port also in windy weather, and to have redundancy as required by the class rules. Accordingly, a 90 MWh battery is selected, to include some margin.

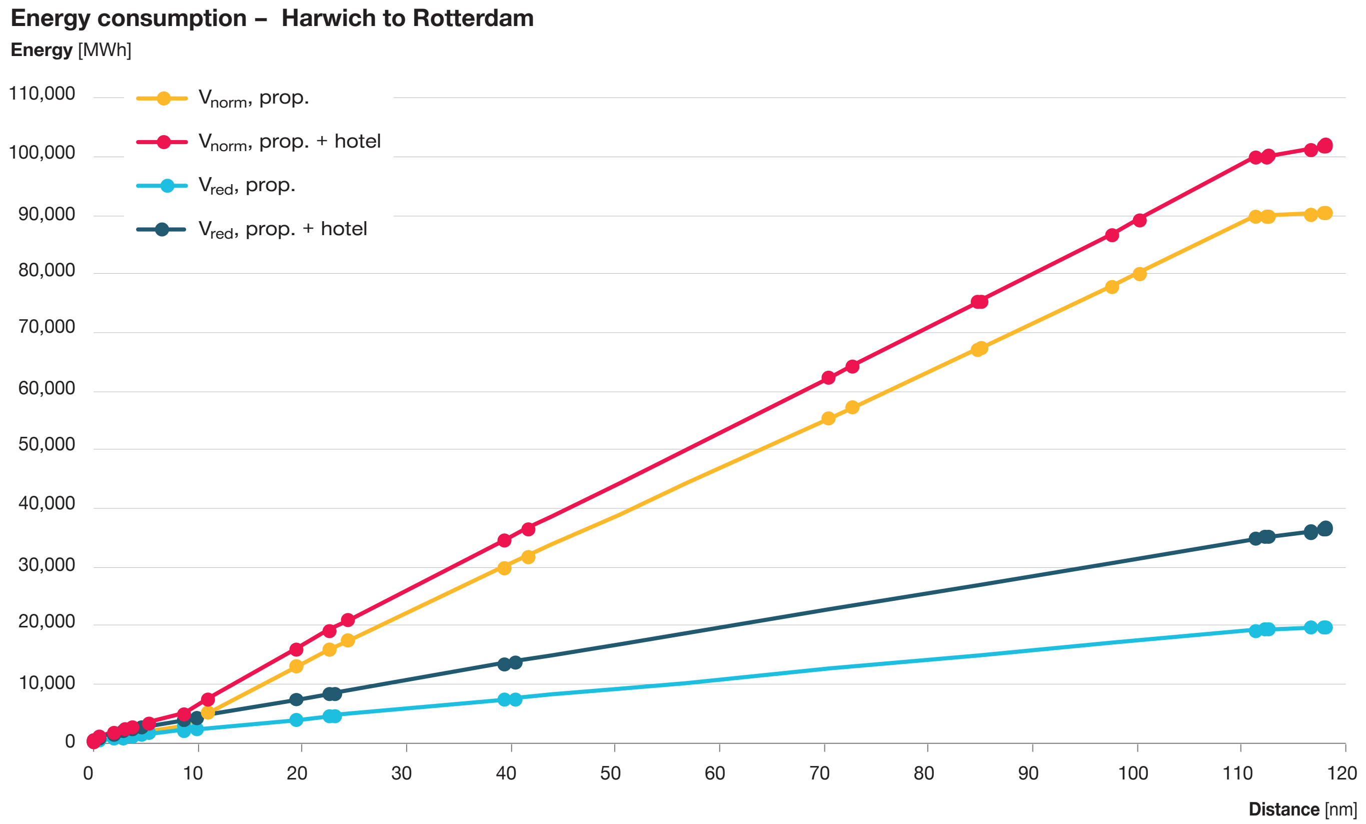


Fig. 13: Energy consumption at normal and reduced speeds. Neither wind nor added wave resistance is included

Weight, volume and cost of battery installation

Based on the absolute minimum of the specific volume and weights of the batteries given in Table 2, the actual minimum volume and weight of the 90 MWh battery can be determined, see Table 13.

For a 5,000 lm vessel a typical two-stroke mechanical propulsion plant will weigh around 500 tonnes. This can be subtracted from the total 990 tonnes of the battery system if it is assumed that the weight of the electric motor driving the propeller is equivalent to the weight of the shafting from the two-stroke engine to the propeller.

Furthermore, it is not necessary to carry any fuel on board, on average it is estimated that 300 tonnes of fuel would be in the tanks on this trade.

The added weight of the battery system will, after correction for the above factors, be approx. 200 tonnes compared to a traditional solution. This is equivalent to 7 lorry trailers of 28 tonnes – a number that must be compared to the total capacity of approx. 350 trailers on a 5,000-lm vessel.

The draught or fullness of the vessel can be increased to carry the added weight while maintaining the full trailer capacity. An additional weight of 200 tonnes corresponds approx. to a 0.6% increase of displacement in scantling condition. This corresponds only to a slight increase of the wetted surface area and, hereby, of the frictional resistance of the vessel. The volume of the battery is not assessed to be a challenge, as it can be accommodated in the otherwise empty engine room.

An issue not related to the onboard installation of the battery is the charging capacity required to turn the vessel around within the normal duration of a port stay, here 4 hours and 45 minutes. To cover the minimum consumption for the crossing of 37 MWh, a charging power of 8.8 MW is required in port. This is similar to the power requirement of a cruise vessel receiving shore power, and it is therefore considered possible – provided that the electrical grid in the port can support it.

Compared to an approx. price of 50 to 80 million USD for a vessel of this type and dimensions (depending on outfitting, deck load capacity, current steel price, market, etc.) , the battery pack constitutes a significant increase in capital costs. In the calculation it is assumed that the price of the power electronics and electric motor to drive the propeller is roughly the same as the price of the two-stroke main engine

In addition, three vessels must operate the route at the reduced service speed compared to two vessels at the present service speed, further increasing the cost of the battery-electric propulsion. The capital cost for two traditional vessels will constitute 100 to 160 million USD. The capital cost for the battery-electric transport solution with an equivalent cargo transport rate will be three times 75 to 170 million USD, i.e. 225 to 510 million USD. Considering an expected lifetime of 10 years for the batteries, and a vessel lifetime of 20-25 years, a change of the battery pack must be considered at least at midlife of the vessel, which is not included.

Prices of battery systems for 5,000 lm ro-ro cargo vessel on a 120 nm route

Cost of battery installation			
90 MWh battery	250 USD/kWh	500 USD/kWh	1,000 USD/kWh
Specific volume, m^3	90x12 = 1,080	90x12 = 1,080	90x12 = 1,080
Specific weight, tonnes	90x11 = 990	90x11 = 990	90x11 = 990
Cost, million USD	22.5	45	90

Table 13

Alternatives to battery-electric propulsion of large ocean-going vessels

The energy consumption on the short-sea ro-ro route analysed, and hereby required battery storage capacity is amongst the lowest in the traditional domain of the two-stroke engine. Considering the more than doubling of the first costs for battery-propulsion, alternative or GHG-emission-neutral fuels for use in a two-stroke main engine seem to be a more attractive solution than battery-electric propulsion.

For example ammonia can be produced from hydrogen and nitrogen by the Haber-Bosch process. If the electricity required for this is supplied from renewable sources, it will provide carbon-free propulsion.

On large ocean-going vessels, benefits can still be achieved by combining a traditional two-stroke main engine with batteries in a hybrid system. These benefits will be uncovered in the oncoming chapters “Hybrid propulsion with a two-stroke main engine” and “Benefits of battery hybrid systems in the electric grid”. Through a reduced energy consumption, a hybrid solution will reduce the required amounts of carbon-neutral or carbon-free fuels and ease the transition towards carbon neutral shipping.

Hybrid propulsion with a two-stroke main engine

First, the technical possibilities for leaving port on battery power and later engaging the two-stroke main engine are considered. Secondly, it is considered if a battery can provide benefits by peak shaving the load of the two-stroke main engine, and thirdly if and how batteries can assist acceleration of the vessel through the barred speed range of the shafting or during adverse weather conditions.

Operation of main engine for emission-free port departure

An often-discussed hybrid solution for propulsion of a large ocean-going vessel is to leave port on battery power (with the energy consumptions determined in “Energy demands for battery-electric propulsion”) and hereafter engage the main engine. For a typical two-stroke engine directly coupled to the propeller, two possibilities exist:

- The main engine can be turned/motored along with the propeller shaft, without compression and fuel injection
- the main engine can be decoupled from the propeller shaft.

Turning/motoring main engine

The torque required to overcome the friction of a main engine directly coupled to the propeller shaft can be assessed by a simplified consideration: At the selected maximum continuous rating (SMCR) of the engine, the frictional mean effective pressure (mep) constitutes approx. 1 bar, equivalent to 5% of SMCR power as the SMCR-mep is around 20 bar. If the engine is to be turned/motored along with the propeller shaft by an electric motor, it will be beneficial to leave the exhaust valves open. By this, the peaks in torque required from turning past the top dead centre (where the air is compressed the most) can be avoided. Pumping air in and out of the cylinder will induce relative pumping losses larger than usual. The increased pumping losses are considered to be cancelled out by the fact that the motoring is performed at speeds lower than SMCR-rpm, where the frictional losses are lower than at SMCR-rpm. 5% of SMCR-power is therefore assumed to be a sensible estimate for the power required for motoring at low rpm.

The torque required to overcome the static friction to initiate the turning can be supplied by the starting air system. The lubricating oil system of the engine must be active while the engine is turned.

For a 10,000 kW engine, as can be found, e.g., on the 82,000 dwt old Panamax bulk carrier previously described, the frictional power for turning the engine along with the propeller shaft constitutes approx. 500 kW. In comparison, 1,300 kW is required to propel the 82,000 dwt bulk carrier at 5 knots in calm waters. Turning the engine with the propeller shaft will increase the energy consumption by 40%.

Clutches

The alternative to turning/motoring the main engine is to disengage it from the propeller shaft. The clutches capable of this can be separated into two groups; one group requires the shaft to be at standstill when the main engine is engaged, whereas the second, and more advanced type, allows engaging the engine when the shaft is already spinning.

The clutches requiring engagement at standstill have primarily been developed with power-take-home (PTH) solutions in mind. Here, the main engine is not running as the PTH is a backup for failures on the main engine.

Clutches that can engage the engine while the shaft is spinning are more complicated and have higher first costs. More information is available, e.g., at the marine gear and clutch manufacturer RENK.

For ocean-going vessels, stopping the vessel to engage the main engine after leaving port may be acceptable, whereas for short-sea shipping, with daily port calls, it seems unattractive. The significant capital costs of clutches can make other solutions to reduce the energy consumption more attractive on large vessels. An evaluation of the optimum solution must be performed at an individual case-by-case basis.

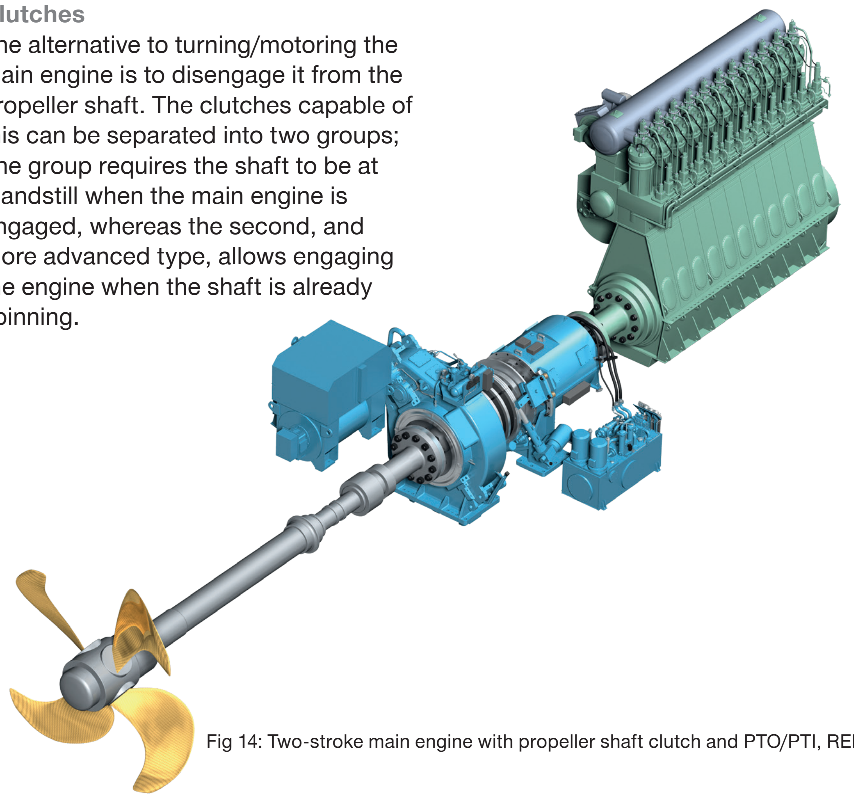


Fig 14: Two-stroke main engine with propeller shaft clutch and PTO/PTI, RENK

Batteries for peak shaving of two-stroke main engines

Peak shaving is the process of keeping the engine load constant while peaks in the required power is supplied by a battery. A main engine equipped with a PTO/PTI and a battery, as illustrated in Fig. 6 is considered. The PTO/PTI and battery could be used to shave main engine peak loads, thus keeping the power fixed, i.e. maintain a steady load. It has been proposed that performing peak shaving, on the two-stroke main engine would lead to a reduction in fuel consumption.

During operation in waves, the main engine load varies cyclically due to increase and decrease of the ship resistance felt by the propeller, due to the waves.

Electric losses exist in the generator, motor, inverter, rectifier, battery, and on the electric power-lines required as part of the system to perform the peak shaving. Such losses are not present with the propeller directly coupled to the engine where the engine absorbs the fluctuation of the load.

MAN Energy Solutions has compared operation at a steady engine load of 75% and operations with extreme cyclic variations of torque, keeping the mean load at 75% with peak-to-peak amplitude slightly greater than 20% of the SMCR and a period of 20 seconds.

The study has been performed including simulation of the cycle process (scavenging, combustion, heat loss, mechanical loss, etc.), engine control system (speed governor, exhaust gas valve, injection actuator controls, etc.) and turbocharging system. The simulations were carried out for a 6G70ME-C9.5 engine with N SMCR of 15,570 kW at 72 rpm.

The mean SFOC was calculated by integrating the total injected fuel mass and the energy delivered by the crankshaft, shown in Fig. 15. The integration was performed in an SFOC evaluation window of 100 seconds. This time window corresponds to 5 complete cycles of the load variation. In the simulation with cyclic load variations, the SFOC evaluation does not start before the 'cycle response' has converged.

The mean engine power was 11,678 kW (i.e. 75% of SMCR). The load deviation from the mean was 1,167 kW in average, see the results listed in Table 14. The mean SFOC for the simulation without peak shaving is 168.8 g/kWh. The simulation for the steady load with peak shaving resulted in an SFOC of 168.1 g/kWh, a saving of 0.7 g/kWh or approx. 0.4% of the mean load.

The losses in the electric generator, motor, etc. are in the order of 5% each, combined 10%, which when multiplied to the load deviation from mean, i.e. 1,167 kW, implies an absolute loss of approx. 117 kW. This corresponds to 1% of the mean load, or approx. 1.7 g/kWh increase in SFOC.

As the losses are greater than the savings, peak shaving the two-stroke main engine is not considered to be feasible. However, peak shaving can, due to different SFOC characteristics, be beneficial for auxiliary engines, see the later chapter "Benefits of battery hybrid systems in the electric grid".

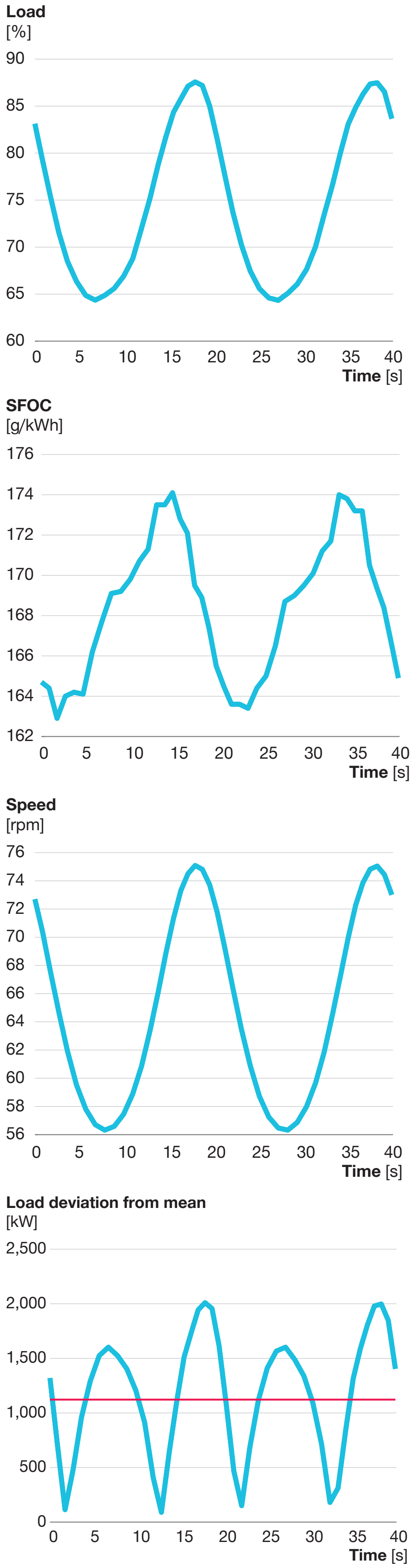


Fig. 15: Variation of load and rpm, as a result of changing propeller load with change in SFOC

Minimum and maximum values obtained during simulation of cyclic load

Property		Minimum	Maximum
Engine load	%SMCR	65	87
SFOC	g/kWh	163	174
Speed	rpm	56	75
Scavenge air pressure	bara	2.74	2.88
Turbine inlet temperature	C	300	435
Turbine outlet temperature	C	195	305
Mean indicated pressure (MIP)	bar	14.6	15.6

Table 14

Batteries for boosting passage of the barred speed range

A barred speed range imposed by vibrations in the shafting must be passed sufficiently quickly, in order not to damage the shafting due to vibrations resulting in excessive stresses.

As the installed power on board tankers and bulk carriers is reduced to meet EEDI requirements, less power will also be available to accelerate the shafting and the vessel. Hereby, considerations on a sufficiently quick passage of the barred speed range have become increasingly important.

In general, the barred speed range must be passed within seconds, not minutes. Furthermore, the definition of "sufficiently quick" depends on how often the barred speed range will be passed during the expected lifetime of the ship and of the strength of the shaft compared to the stress levels the shafting experiences during barred speed range passages.

For vessels equipped with a PTO/PTI, as illustrated in Fig. 6, a battery pack or an auxiliary engine can be applied to boost the acceleration of the shafting. The battery pack can be charged from a shore connection while in port or from a PTO while at sea, etc.

Example

Consider an 82,000 dwt bulk carrier with an SMCR of 10,000 kW at 78 rpm, a light running margin of 5%, a bollard pull curve running 17.5% heavy, and a barred speed range extending up to 48 rpm, i.e. 62% of the SMCR-rpm. For this vessel the barred speed range power margin, BSR_{PM}, as illustrated in Fig. 16, is only 8%:

$$BSR_{PM} = \frac{P_L + P_{boost} - P_P}{P_P} \times 100$$

$$= \frac{3900 + 0 - 3600}{3600} \times 100 = 8\%$$

In the BSR_{PM} equation, P_L represents the engine power limit at the upper range of the barred speed range, and P_P the power required by the bollard pull propeller curve at the same point. The power, P_{boost}, to be delivered by the battery system via the PTI to attain a 20% margin may then be determined to $P_{boost} = 500$ kW.

With this BSR_{PM}, the barred speed range is assumed to be passed within 30 seconds, and the required capacity of the battery can be determined.

$$Capacity = P_{boost} \times duration$$

$$= 500 \times \frac{30}{60 \times 60} = 4.25\ kWh$$

This corresponds to a C-rate of $C = 500/4.25 = 120$, which cannot be sustained by a battery. If a high-power battery with an extreme C-rate of e.g. 6 is applied the capacity must be 85 kWh.

$$Capacity = \frac{Power}{C_{rate}} = \frac{500}{6} = 85\ kWh$$

If an energy battery with a maximum C-rate of 1 is desired, in combination with other usages on board, 500 kWh capacity is required.

$$Capacity = \frac{Power}{C_{rate}} = \frac{500}{1} = 500\ kWh$$

The relatively short duration of the acceleration makes it suitable for battery assistance, as the required capacity of the battery is limited. However, installation of a battery pack of the capacity established above, does not provide a solution to keep the operational point of the main engine above the barred speed range in adverse weather conditions, as such conditions can last for days, see the evaluation in the coming section.

For more information on the barred speed range, see Chapter 2 of "Basic principles of ship propulsion".

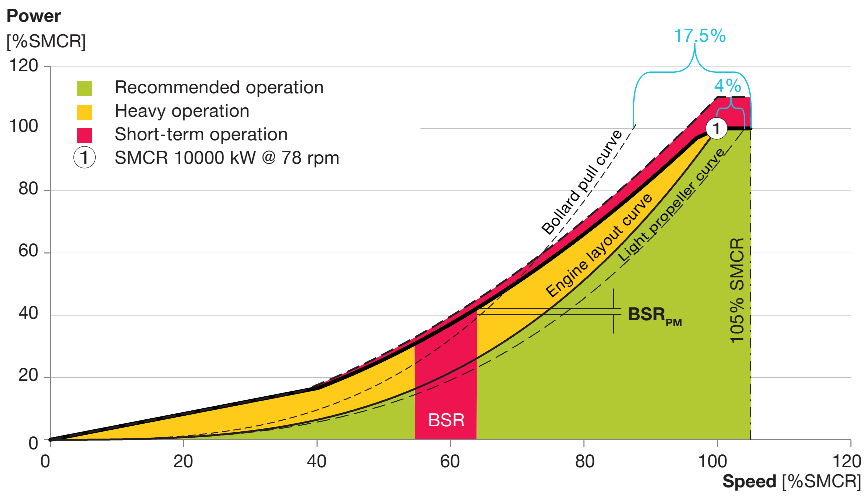


Fig. 16: Engine load diagram with barred speed range

Batteries for boosting torque in adverse weather

Batteries in combination with a PTI (see Fig. 6) have also been proposed as a possible solution to ensure sufficient power for navigation during adverse weather conditions.

It is typically assumed that a storm lasts approx. 48-72 hours, depending on the vessel's position and possibilities of avoiding or escaping the situation. A case of a typical 50,000 dwt bulk carrier (introduced in "Energy demands for battery-electric propulsion" and with principal dimensions as given in Table 15) is considered for the evaluation of batteries for boosting torque in adverse weather.

Vessel particulars for a typical MR tanker

Scantling draught	m	12.2
Design draught	m	11.0
Length overall	m	183
Length between perpendiculars	m	174
Breadth	m	32.2
Wind resistance coefficient	-	1
Frontal area	m^2	350

Table 15

The IMO guidelines on minimum propulsion power [6] require the performance of the MR tanker to be evaluated for a significant wave height of H_S = 4.0 m at a mean wind speed of V_{wind} = 15.7 m/s. If a minimum propulsion speed of 4 knots is considered, the wind resistance from headwind is estimated by the following equation, [7]. Here V_S is the speed of the ship in m/s, C_w the wind resistance coefficient, and A_F the frontal area.

$$R_{AWind} = 0.5 \times \rho \times C_W \times A_F \times V_{wind}^2 - 0.5 \times \rho \times C_W \times A_F \times V_S^2 = 52\ kN$$

And the added wave resistance is determined by [8]:

$$R_{AWaves} = 1366(5.3 + V_S) \left(\frac{B \times T}{L_{pp}}\right)^{0.75} H_S^2 = 285\ kN$$

During adverse conditions, the propeller loading increases, and the propeller efficiency decreases. At the speed of 4 knots, a total power requirement of 2,100 kW is attained for a heavy propeller efficiency of 0.33.

If a battery is to supply 20% of this power via a PTI it corresponds to 2,100 [kW] x 20 [%]/100 x 48 [h] = 20.2 MWh for a storm of 48 hours. Depending on the cost scenario considered, i.e. 250, 500 or 1000 USD/kWh, the cost of this installation will be 5, 10 or 20 million USD. At an MR tanker price of approx. 40 million USD, the best case corresponds to an eighth of the price of the vessel, or in the worst case, half the price.

Contrary to the short duration of the passage of the barred speed range, operation in adverse weather conditions extends over long periods, and as such requires a large battery capacity. An alternative option during adverse weather conditions is to utilise energy from the auxiliary engines to provide additional torque to the shaft via a PTI.

Benefits of battery hybrid systems in the electric grid

Batteries can be integrated into the electric grid on board the vessel. Implementing batteries here does not involve changes to the propulsion principle, see Figs. 4-6.

For the electric grid on board, three operating modes stand out among hybridisation potentials: spinning reserve, peak shaving and dynamic load transition ramps. The term spinning reserve refers to the use of batteries in replacement of an auxiliary engine idling in stand-by mode, ready to take on load if one of the running engines fails or if a generator trips. The principle of peak shaving is outlined in the previous section "Batteries for peak shaving of two-stroke main engines".

The purpose of dynamic load transition ramps is to soften the steepness of a load transition, see Fig. 17. Too steep load changes may result in high particle emission as well as knocking in low-pressure gas engines, which might be critical for the engine. Smoothening the load transition by supplying power from a battery can bring further benefits and reduce the fuel consumption. The dynamic behaviour of individual systems can vary greatly and as such, the shape of transition ramps will not be considered here.

In all cases, the battery must be dimensioned to withstand the charge-discharge rates resulting from the intended operation, see Chapter 2.

Battery as spinning reserve

Spinning reserve, also known as operating reserve, is the power generation (or, in the case of batteries, storage) capacity of the system that is connected to the grid but unloaded. It is the extra load capacity of the running engine, the whole capacity of an idling engine, or the available energy stored in a battery. The spinning reserve is available when a sudden increase in electric power demand occurs, i.e. as a result of a sudden start of a large crane or pump or even a trip of one of the generators.

A typical auxiliary system configuration is arranged with (at least) three auxiliary engines, see Fig. 18. Two engines are running at low loads (typically below 40%) with one engine in stand-by during critical operations as manoeuvring or cargo unloading of a tanker where blackouts must be avoided. This configuration allows for a sudden stop of one engine. During ocean crossings, one auxiliary engine can cover the load, the second be ready to start, and the third be under maintenance.

A battery has a great potential for savings every time two or more auxiliary engines run at constant low load for safety purposes. It can be used to buffer unforeseen events and sudden engine shutdown. Furthermore, it can optimise the fuel consumption of the auxiliary engines by increasing the load on the engine by running only one of them. This increases the efficiency, reduces operating costs and maintenance as illustrated in Fig. 19.

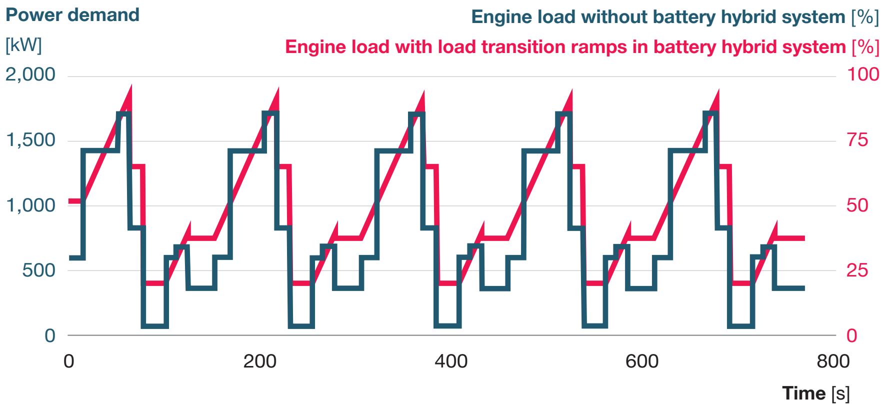


Fig. 17: Principle of dynamic load transition ramps

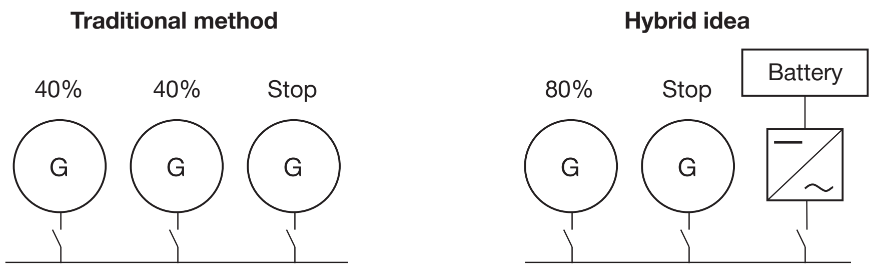


Fig. 18: Illustration of operating principle during critical operations with and without battery

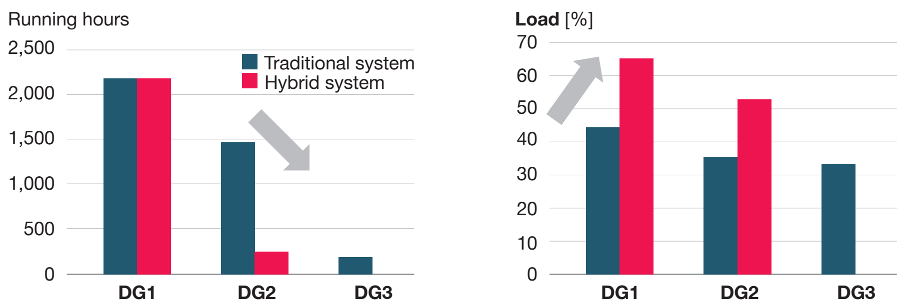


Fig. 19: Runtime and load percentage of auxiliary engines for a traditional and battery hybrid system

Batteries for peak shaving of the electric load

Peak shaving of auxiliary engines represents another potential for savings. A battery connected to the grid results in a steadier engine load while the battery is charged and discharged to shave the peak load demands. The principle of one particular recurring operation that generates a peak, while keeping the rest of the hotel load constant, i.e. a hoisting crane, is illustrated in Fig. 20.

Both curves represent the same amount of energy consumed, but the drastic peak of the blue curve tend to increase the fuel consumption. With a battery system, the engine can be kept at an average load, charging the battery while the blue curve is at its lowest, and discharging during peaks.

The difference in the power distribution for a case study of a bulker during crane operation is illustrated in Fig. 21. A battery installed for peak shaving leads to an operating cost reduction from acting as spinning reserve as well, as it will be possible to limit the time during which two auxiliary engines operate simultaneously.

By installation of a battery of sufficient capacity, installation of only two auxiliary engines along with a battery can suffice to operate the vessel. The benefits and costs of such a solution is, amongst other things, investigated in a case on the next page.

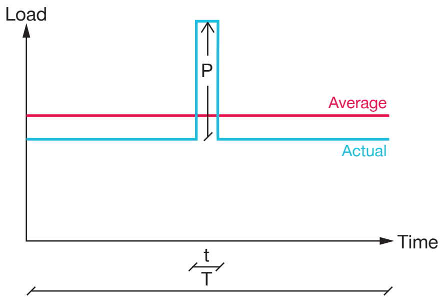
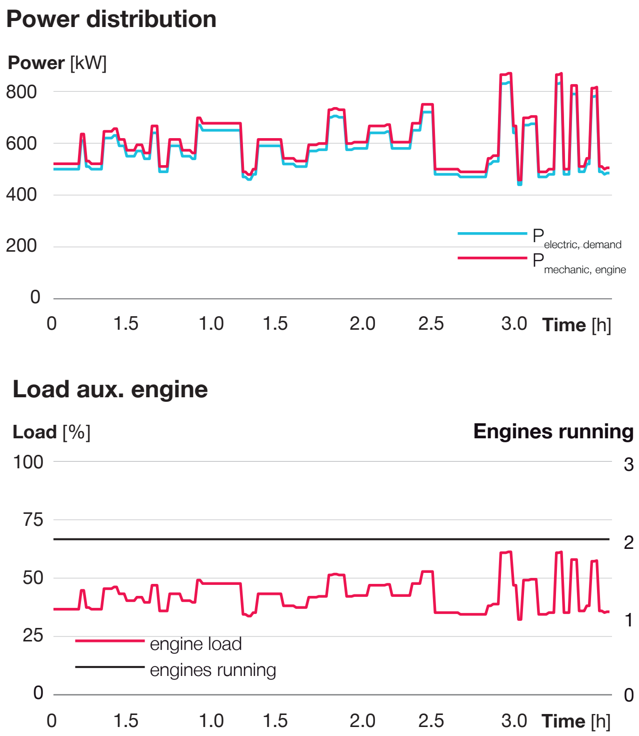


Fig. 20: Principle of peak load shaving



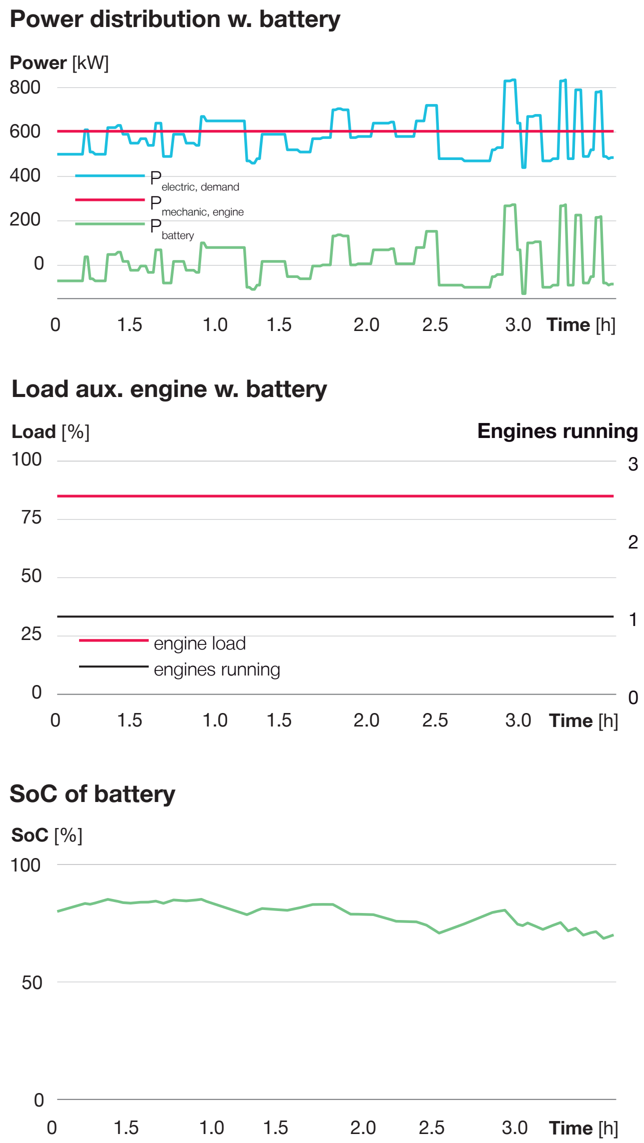


Fig. 21: Comparison of auxiliary engine load in a traditional (left) and a hybrid system (right)

CAPEX and OPEX of hybrid power supply for a 82,000 dwt bulk carrier

A traditional installation for a 82,000 dwt bulk carrier could be three MAN 5L23/30 auxiliary engines.

The battery has to be able to supply the base hotel load, assumed to be 280 kW in Chapter 2, for a certain period of time in open seas or at quay. To act as backup during critical situations, such as manoeuvring, the battery must be able to supply additional electric power. In this case 650 kW is assumed in total, requiring 682 kW from the auxiliary engine, when assuming 95% efficiency of the generator.

The time duration which the battery must cover depends on the expected, unplanned downtime of the auxiliary engine. According to experience, 15 minutes of battery operation will be enough to avoid blackouts and to restart a tripped auxiliary engine and reach full load. In this case, the battery system will not be considered a replacement for an auxiliary engine, but a supplementary system.

A solution considering six hours of battery operation, which is assumed to be sufficient to rectify an issue with an auxiliary engine, is also considered. In this case, only the hotel load of 280 kW is considered, as periods of manoeuvring are short, e.g. 10 minutes and not decisive for the capacity.

Applying the time requirement, two capacity requirements are obtained as shown in Table 16. The C-rate is allowable in both cases.

With the largest battery system it is an option to install only two auxiliary engines. This will reduce the capital cost of the battery hybrid solution, see Table 17.

Potential saving by hybridisation
It is considered that the ship, during critical operations, has two MAN 5L23/30 engines running at the same time for 1,000 hours per year, at approx. 40% load, including losses. In the conventional case, two engines are operated at low load in order to have sufficient spinning reserve for a generator trip. If a battery with sufficient capacity to take up the full load, with according C-rate, is installed, it would allow only one auxiliary engine to run at 80% load without compromising the redundancy of the system.

This reduces the SFOC from 207 g/kWh to 194 g/kWh. Besides, it means 1,000 operating hours less per year, reducing maintenance costs. This results in a yearly saving of roughly 15,700 USD on less fuel and maintenance, see the equations below.

Additionally, based on dynamic simulations, see e.g. Fig. 21, approx. 4,300 USD can be saved by applying the battery for peak load shaving.

Apart from the savings in fuel, CO_2-emissions and maintenance costs, the hybrid system will emit less particulate matter thanks to the constant load. Furthermore, other commercial benefits can be achieved. For example some ports have lower fees for hybrid vessels.

Applying a discount rate of 2.9% (nominal discount rate of 6.0% and inflation rate of 3.0%), the savings would pay off the investments outlined in Table 17 according to the results in Table 18.

Thereby, istalling three auxiliary engines in combination with a relatively small battery, as for spinning reserve and peak load shaving proves to be feasible – contrary to replacing one auxiliary engine by a large battery.

$$fuel = Power^{genset}_{mechanical} \times \Delta SFOC \times Price_{fuel} \times time_{Operation} =$$

$$682\ kW \times (207 - 194)\ g/kWh\ \times 10^{-6}\ ton/g\ \times 640\ USD/ton\ \times 1000\ h\ \approx 5{,}700\ USD$$

$$maintenance \approx 10\ \frac{USD}{Running\ Hours} \times 1\ Engine \times 1000\ h \approx 10{,}000\ USD$$

Battery type and capacity for the two different operating modes

	T = 0.25 h	T = 6 h
E (kWh)	217 kWh	1,866 kWh
C-rate	3	0.15 (0.35 during manoeuvring)
Battery type	High-power	High-energy

Table 16

Battery costs in to different price scenarios

Price	250 USD/kWh	500 USD/kWh	1,000 USD/kWh
T = 0.25 h	54,250 USD	108,500 USD	217,000 USD
T = 6 h	466,500 USD	933,000 USD	1,866,000 USD
T = 6 h - one aux. engine less	286,000 USD	753,000 USD	1,686,000 USD

Table 17

Years for return of investment for battery systems

Price	250 USD/kWh	500 USD/kWh	1,000 USD/kWh
T = 0.25 h	3 years	6 years	13 years
T = 6 h	20 years	33 years	49 years
T = 6 h – one aux. engine less	14 years	28 years	47 years

Table 18

Conclusion

This paper explains and evaluates battery technology and possible applications on board large ocean-going vessels. Both pure battery-electric propulsion along with hybrid-propulsion solutions, involving a two-stroke main engine, power take-off/take-in, and a battery pack have been evaluated.

Throughout the paper, three cost scenarios of 1000, 500 and 250 USD/kWh for battery systems have been considered. These represent the price of current retrofits, an expected price for large-scale new builds, and a possible price of the future, respectively.

In recent years, battery-electric propulsion has successfully been applied for short-sea ferries. Within the field of large ocean-going vessels, the traditional domain of the two-stroke main engine, short-sea ro-ro shipping seems to be the only area where battery-electric propulsion constitutes an alternative that is weight and volume wise practically feasible at the current stage of development of battery technology.

As illustrated in a case study considering a 5,000 lane metres short-sea ro-ro vessel on a 120 nautical mile route, the initial costs of a battery-electric solution for an equivalent cargo-transport rate are more than twice the cost of a traditional solution, even for the lowest cost scenario. The costs of exchanging the battery pack halfway through the vessel's lifetime must be added on top of this.

Due to the cost, weight and volume of batteries, a two-stroke engine operating on carbon-neutral fuels seems a more attractive solution for large ocean-going vessels to become carbon neutral. Such fuels could be bio-dimethyl ether, synthetic fuels like ammonia, synthetic natural gas or synthetic methanol.

The present conclusions on battery-electric propulsion of large ocean-going vessels do not exclude the application of batteries on such vessels for other applications.

A battery pack can, through a power take-in on the main engine, aid the acceleration of the shafting through the barred speed range. On the other hand, peak load shaving of the load on the two-stroke engine, does not bring any benefits. The losses in the electric system required for peak shaving the load of a two-stroke main engine are larger than the gains created.

The integration of batteries into the electric grid on board a large ocean-going vessel seems to be the area where batteries and hybridisation can bring the largest advantages. Peak shaving of the electric loads experienced by the auxiliary engines can reduce the overall energy consumption. Especially for very dynamic loads, such as during crane or thruster operations. Even larger benefits can be achieved if a battery pack replaces an auxiliary engine idling as spinning reserve during critical operations.

Charging batteries while at sea via a power take-off on the main engine, and using the energy in port will not only eliminate emissions during port stays, but also reduce the overall energy consumption. This is due to the higher efficiency of the two-stroke main engine compared to the auxiliary engines. Though, completely avoiding the use of auxiliary engines during port stays appears only feasible if the hotel load of the vessel is limited and the port stays are lasting only a few hours.

As illustrated in this paper, an important part of including batteries in any large ocean-going vessel, is a power take-off/take-in on the main engine. It is worth highlighting that, as of today, only a small percentage of vessels delivered are equipped with a power take-off/take-in. Significant reductions of the overall energy consumption and, thereby, emissions can be achieved just by letting the main engine cover the electric load of the vessel during the sea passage – reductions that in itself will ease the transition towards carbon neutral shipping.

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