CIMAC CONGRESS 25
ZURICH, MAY 19 – 23, 2025

2025 | 158

Battery-electric propulsion for ocean-going cargo ships – design, operations and techno-economics

Electrification and Fuel Cells Development

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ABSTRACT

The Mærsk-McKinney-Møller Center for Zero Carbon Shipping has launched a pre-feasibility study to explore pathways for direct electrification of ocean-going cargo ships. The investigation encompasses vessel design, operational practices, and techno-economic considerations.

The shipping industry's journey toward decarbonization involves a dual focus: alternative fuels and technologies that reduce net fuel consumption. E-fuels are one promising avenue for reducing GHG emissions in the mid- to long term. These fuels are synthesized from renewable hydrogen and, where feasible, recycled carbon. However, the scale of renewable electricity required for hydrogen production via electrolysis remains a significant challenge.

While other industrial sectors are actively pursuing direct electrification, battery-electric vehicles (such as passenger cars, trucks, and freight locomotives) have gained substantial traction, particularly in developed economies. The inherent benefits of battery-electric propulsion lie in its high lifecycle energy efficiency. Yet, the energy density of batteries is low compared with fuels used today and in future scenarios. As a result, large-scale adoption of pure battery-electric propulsion for ocean-going ships has not materialized.

Based on an analysis of the global fleet in container ships, tanker vessel and dry-bulk vessel segments, study cases were derived for the investigation. The focus was put on 1,100 TEU container ships, Handysize product tankers (40k dwt) and Handysize dry-bulk vessels (35k dwt) and hypothetical voyages based on realistic assumptions were used to evaluate the potential of battery-electric propulsion in these study cases.

While pure battery-electric propulsion systems face technical and economic limitations, a hybrid power plant — combining battery-electric components with internal combustion engines — offers a promising solution. This hybrid approach, in which on average 80% of the required energy is supplied from batteries, ensures overall gains in lifecycle energy efficiency and operational flexibility for sea-going vessels.

Furthermore, this hybrid power plant philosophy allows to reduce the installed battery capacity, which in turn facilitates the integration of the batteries into the vessels and limits the loss of cargo capacity.

It was found that battery-powered container ships applying the hybrid power plant philosophy have a viable business case compared with equivalent vessels powered by methanol dual-fuel internal combustion engines. This assessment considers current prices of the baseline vessels as well as projections for battery system prices, electricity prices and methanol prices.

On a lifecycle perspective, the demand for renewable energy is reduced by more than 65% in our battery-powered case studies compared with the methanol dual-fuel internal combustion engine baseline. As a result, targeting smaller-sized merchant vessels on short voyages ultimately has the potential to address up to 17% of today’s carbon dioxide emissions in the respective vessel segments. Furthermore, by increasing the lifecycle energy efficiency in this way, an additional 1.8 exajoules of renewable energy can be freed up for e-fuel production. To make this happen, it will be necessary not only to design, build and employ the vessels, but also to ensure a widespread roll-out of shore-power and charging infrastructure in ports.

1 INTRODUCTION

Electrification offers higher efficiency in the energy conversion process and can potentially reduce greenhouse gas (GHG) emissions by increasing deployment of low-GHG energy sources. Thus, it is seen as a crucial pathway towards decarbonization across all sectors.[1]

The purpose of this pre-feasibility study is to identify whether battery-electric propulsion is a viable transition pathway for maritime transport at scale, which vessel segments and sizes are potential candidates from a technical perspective, and to what degree these segments represent solid business cases if electrified.

While battery-electric solutions are already state-of-the-art in road transport, heavy-duty off-road applications, such as mining trucks and locomotives, are gaining momentum.[2][3] Today, battery-powered ships are most commonly used for short ferry crossings or in hybrid installations with internal combustion engines (ICE). The main purpose of these installations is to enable load shedding, peak shaving and similar power balancing operations. Installed battery capacity is typically a few MWh, as seen with the Danish ferries Ellen, Tycho Brahe, and Aurora, which have just enough capacity for their operating sea passages. To charge during the very short turnaround in port, both vessel and port are equipped with custom-designed, dedicated charging interfaces that provide high charging power.[4][5] COSCO has launched a battery-electric container vessel with an installed battery capacity of 50 MWh, utilizing a battery-swapping concept with containerized batteries.[6]

However, the perception remains that batteries would occupy the entire cargo capacity of a large cargo vessel, making them seem impractical., Several studies have investigated battery-electric shipping from commercial and systemic perspectives with varying results. More detailed considerations of international trade or vessel integration have only been partially addressed.[7][8][9]

The study identifies technological and economic barriers to the uptake of battery-electric propulsion in merchant shipping and the developments required for marine batteries to overcome these barriers. First, it highlights the increased conversion efficiency through the direct use of renewable electricity compared with the use of e-fuels in ICE-powered vessels. This is followed by an analysis of the global fleet of container ships, tanker vessels, and dry bulk vessels, to identify suitable study cases for more detailed investigations into operations and vessel integration. The report concludes with a techno-economic analysis of the study cases, and statements about life-cycle emissions.

2 EFFICIENCY POTENTIAL OF BATTERY-POWERED VESSEL OPTIONS

On today's conventional vessels, propulsion and auxiliary power are provided by internal combustion engines (ICE) and boiler systems that convert chemically bound energy in fuels via thermo-chemical processes into final energy. The GHG intensity of these vessel operations can be reduced by using low-GHG fuels, such as biofuels and e-fuels.

Both the synthesis of e-fuels, such as e-methanol and e-ammonia, and the thermo-chemical conversion in the vessel's power system are subject to conversion losses. Thus, it is interesting to compare how much of the renewable energy harvested through photovoltaic modules or wind turbines remains available for final energy use between an e-fuel pathway (e.g., e-methanol) and a battery-powered vessel pathway.

To this end, a bottom-up calculation of the major conversion steps and their associated losses, using simplified assumptions based on state-of-the-art conversion efficiencies, was performed.[8][10] This analysis uses e-methanol produced with biogenic carbon dioxide (CO_2) derived from a point source as the reference fuel pathway. We chose to focus on comparison with e-methanol because methanol dual-fuel configurations are already available for many vessel sizes and segments today. A comparison of battery-powered vessels with other e-fuel pathways (e.g., e-methane or e-ammonia) might yield different, though similar results, due to varying efficiencies in the fuel synthesis process.

The bottom-up calculations assume a fixed energy demand for propulsion and auxiliary services, representing 100% in the Sankey diagrams in Figure 1. In the methanol dual-fuel (MeOH-DF) case, more than 4.5 times the final energy requirement is needed in terms of renewable electricity for methanol synthesis. In the battery case, only 1.2 times as much energy in terms of renewable electricity is needed to satisfy the energy requirements of propulsion and auxiliary services. Thus, the MeOH-DF case requires 3.7 times more renewable electricity than the battery-only case. Despite this clear advantage in energy conversion efficiency, battery-powered vessels face opposition in merchant shipping due to expected constraints in terms of vessel range and cargo capacity, as well as excessive battery cost.

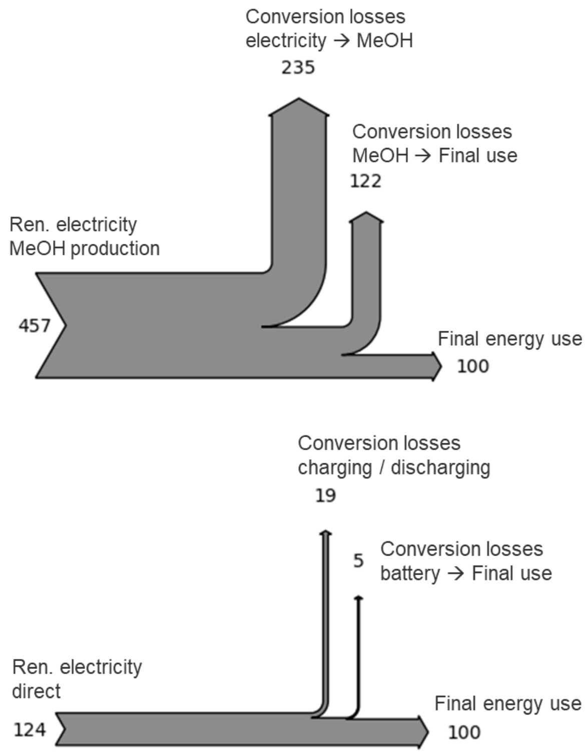

Figure 1. Comparison of life-cycle energy demand of an e-methanol pathway with dual-fuel ICE (top) and a battery-powered pathway (bottom) for a low-GHG-emissions vessel and associated energy conversion losses. Values are given in arbitrary units.

3 DEFINITION OF STUDY CASES

To understand which vessel size classes are most relevant for our study, the voyage legs of the globally operated fleet in the tanker, dry-bulk, and container segments were statistically analyzed. This, however, implies that no distinction between vessels that only operate on short voyages, or only on long voyages, or a mix of both has been made.

3.1 Analysis of the global fleet

Based on voyage data, the energy requirements for propulsion and auxiliary services during sea passage were calculated and classified into bins. In brief, we found that short voyage legs with energy requirements of up to 250 MWh account for 8% of the total CO_2 emissions from container vessels, 17% for tanker vessels, and 5% for dry bulk vessels. We estimate that, if the fleet operating on these short voyages switched completely to battery power, 1.8 EJ of renewable energy could be freed up for e-fuel production.

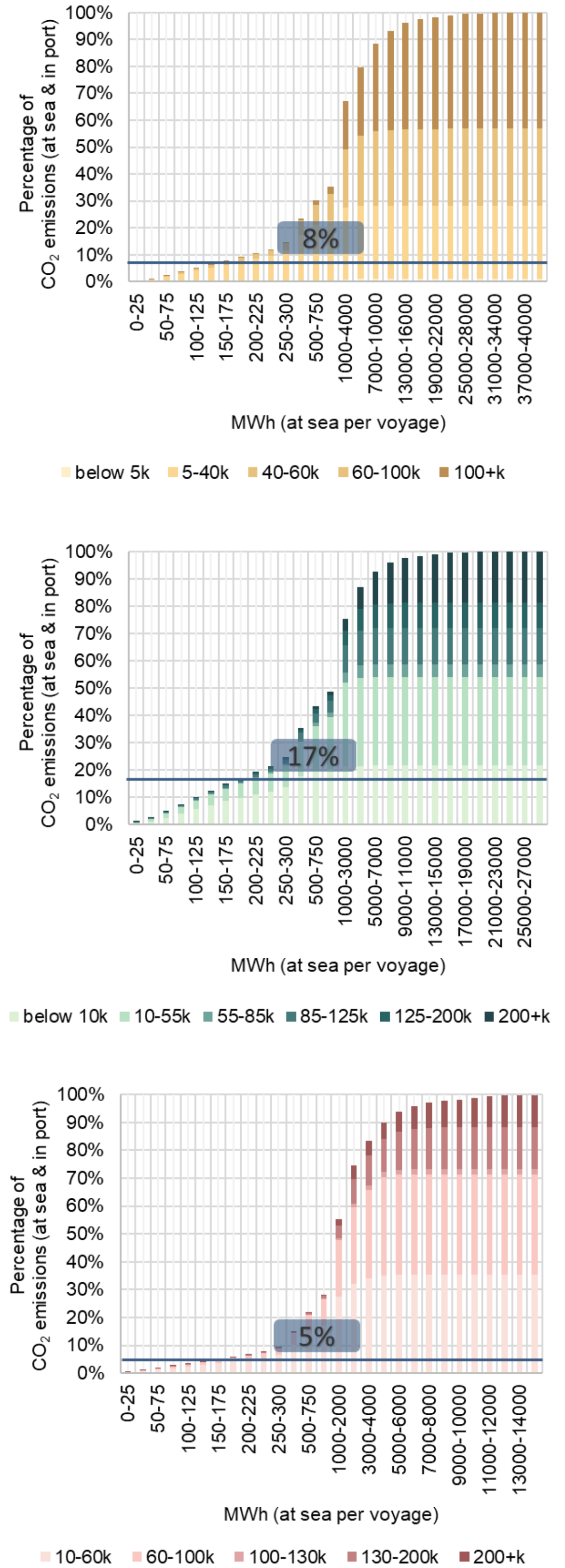

Figure 2. Analysis of energy requirements for propulsion and auxiliaries at sea of the globally

operated fleet in container (top), tanker (center), and dry bulk (bottom) segments. Color-legend: deadweight.

The results shown in Figure 2 indicate that smaller vessel sizes (up to 55k deadweight tonnage [DWT] for tankers, up to 60k DWT for dry bulk, and up to 40k DWT for container vessels) dominate shorter voyage legs with energy requirements of up to 250 MWh.

3.2 Detailed voyage selection

When examining the services and historic voyage data of the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) strategic partners involved in the study, similar trends were identified in the relationship between vessel sizes, segments, and voyage energy requirements to those seen in the global fleet data.

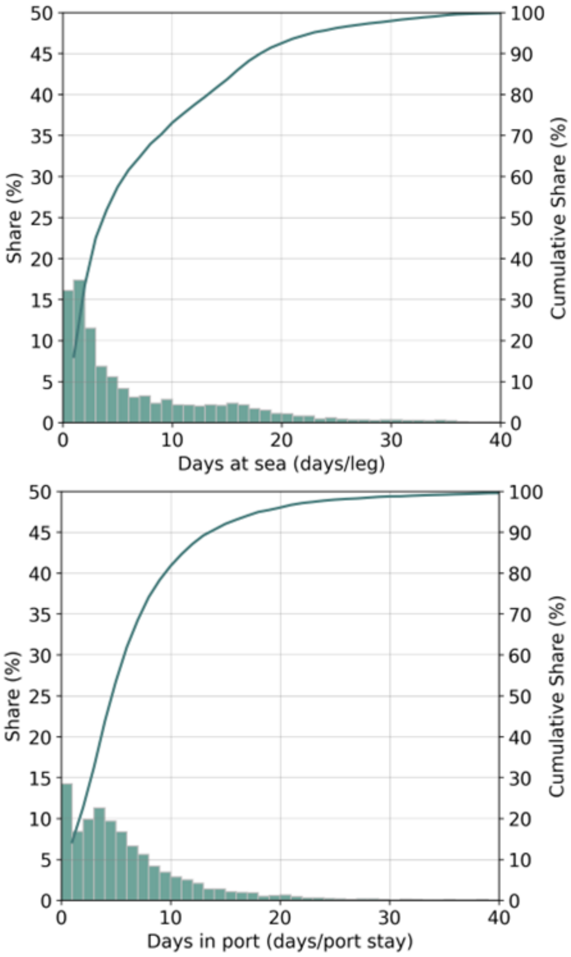

Figure 3. Analysis of NORDEN operated fleet in Handy-size dry bulk vessels. Days at sea per voyage leg (top). Days in port per voyage leg (bottom).

For example, over 4,000 voyage legs of Handy-size dry bulk vessels in NORDEN’s operated fleet from 2021 to 2023 were analyzed. It was clearly identified that most voyage legs encompass less than 10 days at sea, with around 35% of these voyages lasting only 1 to 2 days at sea. Similarly, port stays show that approximately 45% are up to 5 days, with 12% being 4 days in port (cf. Figure 3).

Both consumption at sea and consumption in port are almost normally distributed around 18 tonnes of low-sulfur fuel oil (LSFO) equivalent per day, and 4 tonnes of LSFO equivalent per day, respectively. The analysis further shows that, as a consequence, 40% of voyage legs have energy requirements for propulsion and auxiliaries at sea below 250 MWh (cf. Figure 4).

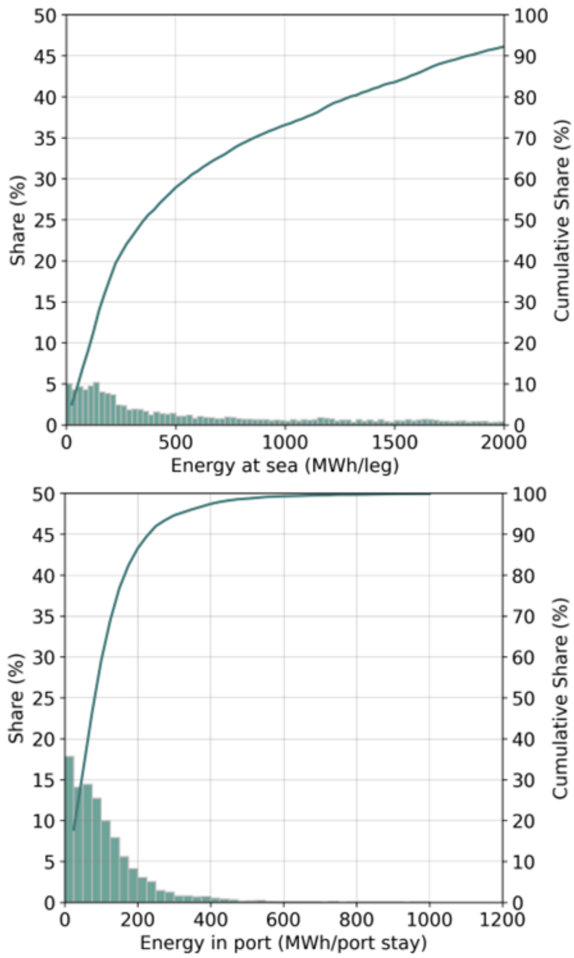

Figure 4. Analysis of NORDEN-operated fleet in Handy-size dry bulk vessels. Energy at sea per voyage leg (top). Energy in port per voyage leg (bottom).

Based on these findings, both the vessel sizes and routes for studying the viability of battery-electric propulsion for merchant vessels were derived. Voyage energy requirements up to around 250 MWh and smaller vessel segments are assumed to represent a relevant field for the current investigation. As previously shown, the selected range of energy requirements per voyage covers a significant share of merchant shipping operations. Therefore, both the most favorable short-sea legs that can be easily electrified (such as ferry crossings) and intercontinental trades that may lead to excessive battery sizing are avoided. At the same time, a target of 250 MWh represents a significant stretch compared with existing marine battery applications, which are around 50 MWh.

Table 1. Description of case study vessels and trades.

Segment	Vessel size	Region	Trade	Max. energy at sea per leg	Min. energy at sea per leg	Av. energy at sea per leg
Container	1,100 TEU	Western Mediterranean	Intra-regional service	320 MWh	42 MWh	112 MWh
Tanker	40k DWT	Baltic Sea	Clean petroleum products and SAF	230 MWh	162 MWh	196 MWh
Dry bulk	35k DWT	Gulf of Mexico	Agricultural products	210 MWh	138 MWh	174 MWh

4 OPERATIONAL CONSIDERATIONS AND OPTIMISATION

Before going into more detailed investigations on vessel design and machinery configuration, it should be noted that, already at the beginning of the study, several optimisation steps with regards to operation of the vessels were taken.

4.1 Adapting voyage schedule and port calls

Although only voyages and services with comparably short distances at sea have been selected for the present study, the possibilities of reducing the voyage legs even further to reduce the required energy at sea have been considered. For the dry bulk and tanker vessel cases, an additional port call could be foreseen for discharging or loading of cargo in the case of parcelling trades.

For the container ship, we decided to introduce an additional port of call. When this schedule was designed, there was no incentive to divide the voyage on the westbound journey, since it prolongs the total voyage distance and duration, and introduces another port fee. However, by accepting the compromise of introducing a port call on the eastbound journey, maximum energy demand can also be halved to around 190 MWh.

To maintain service frequency, the time lost with the extra port call must be recovered elsewhere in the schedule. In this case, since the original schedule included ample buffer time, it is assumed that the extra port time can be compensated by slightly increasing terminal productivity and adjusting berth windows to reduce idle time. This may not be feasible for all schedules, where other adjustments such as additional tonnage or slight increases in voyage speed might be necessary. Alternatively, new schedules could be planned with optimized battery use from the outset. Although hypothetical, this example illustrates the impact of adapting schedules for battery-electric operation, showing that the same cargo flow can often be maintained with acceptable compromises.

4.2 Hybrid power system philosophy

Based on the container ship schedule, there is clearly an uneven distribution of the energy demand of the individual legs. This non-uniformity results in an excessively high battery capacity design, if laid out for the highest energy demand (Battery X in Figure 5). Furthermore, the battery is not fully utilized on all other voyage legs. The battery is utilized on all voyage legs if laid out for the lowest energy demand leg (Battery Y in Figure 5). However, the potential to increase energy conversion efficiency is reduced.

In practice, an optimal compromise could be found for the specific operation. However, for simplicity, this study chose an arbitrary capacity design that, on average, meets 80% of the energy demand at sea. The remaining energy will be supplied via non-heated fuels, such as renewable methanol or biodiesel, combusted in a generator engine. It is further assumed that energy consumed in port will be supplied directly from shore. By accepting that 20% of the energy at sea is supplied by onboard generation, the required battery capacity in the container ship case is reduced from 190 MWh to 100 MWh (usable).

This hybridisation approach is, therefore, different to the state-of-the-art in maritime applications, where the comparably small battery capacity is used for peak shaving, load balancing and zero-emission port entries.

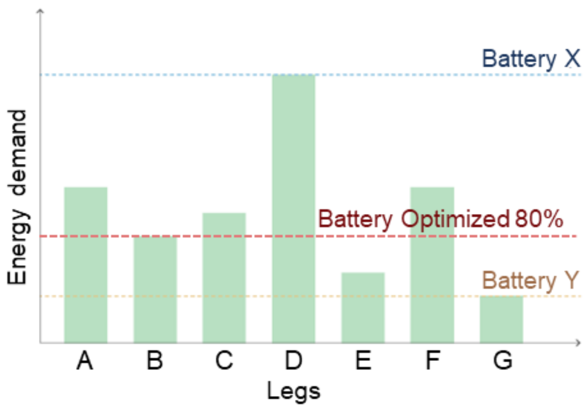

Figure 5. Principal approaches to battery capacity dimensioning when operating on a regular schedule. Battery X is dimensioned according to the leg with the highest energy demand, while Battery Y is dimensioned according to the leg with the lowest demand.

5 CONSIDERATIONS IN VESSEL AND MACHINERY LAYOUT

When designing a vessel and its machinery layout, several critical considerations must be addressed to ensure optimal performance and safety. Key aspects include the design of the battery system and battery room, the integration of batteries into the vessel, and the overall machinery layout. Each of these elements plays a vital role in achieving efficient energy management, maintaining operational flexibility, and ensuring the vessel's structural integrity. Proper planning and execution in these areas are essential for the successful implementation of battery-powered and hybrid vessels.

5.1 Battery system and battery room design

The design of battery rooms must ensure safe operation and serviceability, adhering to the requirements set by both battery system vendors and classification societies.[12][13] Current battery installations are primarily based on the principle of combining multiple cells to form a battery module, which is approximately the size of a suitcase. Several such modules are then connected to form a pack, similar in size to a wardrobe. These packs are combined in parallel to create a battery string, with several strings required to achieve the desired capacity. These strings are then placed in a separate battery room, providing ample space for accessing individual modules. The energy density of such a room is significantly reduced compared with that of a single pack.

The overall space required to accommodate the batteries on a vessel is further increased by the ancillary systems (e.g., ventilation, fire-fighting equipment) and the necessary access space to the comparatively densely packed battery racks. Additionally, current requirements from classification societies for ships powered solely by batteries mandate redundancy in the battery room arrangement, thereby duplicating ancillary systems and ‘empty’ spaces.[12]

Based on an analysis of both vendor and classification society requirements, the size of an example battery room arrangement for an installed battery capacity of around 50 MWh was outlined (see Figure 6). This arrangement can be multiplied to meet the installed capacity requirements of a given vessel. Due to the previously mentioned redundancy and accessibility requirements, the energy density of the battery room is only 29 kWh/m³.

Based on conversations with battery vendors, continuous development of battery technology, such as cell chemistry and package design, is expected. Following battery vendor estimates for a five-year period from 2023, a more compact battery room design with an energy density of 47 kWh/m³ was derived (see Figure 6). This compact design also entails a reduced battery weight. Consequently, stowage is reduced by 40% and battery weight is reduced by 45% compared with the initial design, based on requirements from vendors and classification societies.

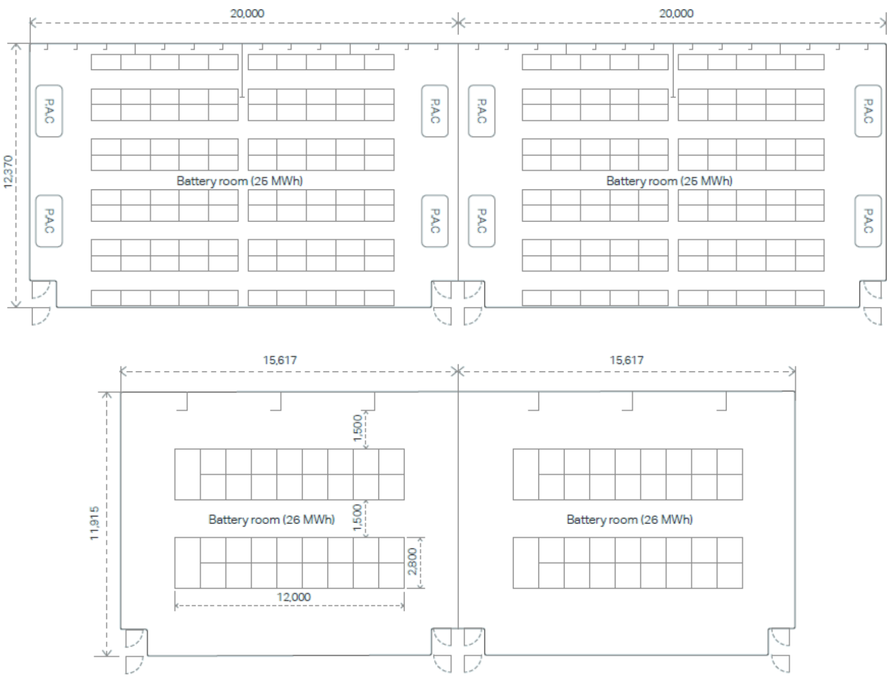

Figure 6. Sample marine battery room designs for high-capacity installations. Top: Non-optimized design based on current requirements from classification societies and vendors for a battery capacity of 50 MWh. Bottom: Compact design based on current systems for stationary utility-scale application or railroad with an outlook towards 2028 and a battery capacity of 52 MWh.

The results of the present study suggest, however, that the current principles and designs of battery rooms will not be applicable to the large-scale systems required for many ships using batteries as their main energy source. As economic incentives for larger capacities increase, battery room arrangements will be optimized with much larger battery unit sizes and more centralized power electronics, battery management systems, and so on. Even without improvements at the cell level, these changes would significantly increase the volumetric energy density of the complete battery storage system by drastically reducing the space currently needed for accessing the smaller modules. A standard twenty-foot equivalent unit (TEU) is likely to become the future battery unit size. Ongoing work, such as that of the Maritime Battery Forum, aims to develop and establish a standard for containerized battery systems.[14] Such units would also potentially enable the adaptation of the total energy capacity to the changing operation of a particular ship.

Therefore, such a containerized battery room design was also included in our study. For this investigation, it was assumed that such battery units can achieve energy density levels comparable to those of existing maritime lithium iron phosphate (LFP) battery systems at the rack level (physical stack of modules). This design still includes a significant degree of packaging and does not consider any improvements at the cell level. A separate space for power conversion, centralized cooling systems, and other auxiliary infrastructure to support and integrate such battery units would then be needed elsewhere. However, the energy density of the battery room increases to approximately 95 kWh/m^3.

5.2 Charging infrastructure

An essential aspect of this study is the technology and infrastructure for charging the vessel's battery during port stays. Ferries operating on pre-determined short-leg routes usually have access to a dedicated charging facility in one or both ports of call. The layout and design of existing port charging facilities allow for maximum charging power to supply enough energy during the relatively short port stay, but these facilities are usually customized to the specific application.[4][5] However, recent environmental regulations encourage the wider supply and use of shore power during port stays to reduce air pollution and global warming. Thus, the availability of shore power connections in ports is expected to increase in the coming years.[15][16]

Available standards for shore power connections can potentially support both vessel port operations and battery charging.[17] This is particularly important for the tanker segment, as the auxiliary power demand in port can be very high due to the requirement for vessels to self-discharge their cargo. The Oil Companies International Marine Forum (OCIMF) recommends a supply voltage of 6.6 kV AC and a frequency of 60 Hz for tanker terminals equipped with shore power connections. By employing a single standard cable connection, a power supply of up to 5.7 MVA is possible.[18] As a result, charging a battery with a capacity of 100 MWh takes more than 20 hours, depending on the required power demand for port operations. This performance can be sufficient in some cases (e.g., dry bulk vessels) or challenging in others (e.g., container vessels).

The charge rates required for the optimized container ship schedule range from 2 MW to 8 MW, depending mainly on port productivity. In some cases, the battery is not fully depleted upon arrival at the next port, allowing for a full charge in a shorter period or at a lower charge rate. The study determined that the charging requirements for this example case are achievable within the limits of a typical shore power connection. For cases where longer sea passages or larger ship sizes lead to a substantially larger total battery capacity, a regular shore power connection will no longer suffice, and alternative approaches need to be considered. These include using multiple connections in parallel, the deployment of dedicated high-power charging infrastructure in terminals, offshore charging (e.g., in connection with offshore wind farms), or swappable battery units that are charged on shore over longer durations.[14]

5.3 Minimum power requirements

The layout of the ship's machinery, following the hybrid power system philosophy, requires detailed consideration of the minimum power output of the generating sets that provide power to both auxiliary services and propulsion when battery capacity is low. The layout must respect the boundary conditions of the vessel's commercial operation, ensuring sufficient power reserve to accelerate the vessel if needed. Additionally, the vessel must remain maneuverable, even in adverse weather conditions. Table 2 presents both the boundary conditions of the calculations and the results to determine the minimum required power output of the generating sets on board hybrid battery-powered vessels.

The IMO's Guidelines for determining minimum propulsion power to maintain the manoeuvrability of ships in adverse weather conditions (MEPC.1-Circ.850-Rev.3)[19] were used to determine the minimum propulsion power necessary to maintain the maneuverability of ships in adverse weather conditions. The methodology, which is based on minimum power lines (Appendix 1 of the guidelines), results in minimum power requirements exceeding the MCR power of the engines installed on tankers and dry bulk vessels. However, the minimum power lines methodology is not valid for container ships, as there are no model parameters for these vessels in the guidelines. To allow a uniform approach for all three ship types, minimum propulsion power was consequently determined using the minimum power assessment methodology (Appendix 2 of [19]).

Table 2. Boundaries, assumptions and results of the minimum power requirement calculation.

	Container Ship	Tanker vessel	Dry bulk vessel
Deadweight (tonnes)	13,181	39,999	37,662
MCR power (kW)	5,521	7,211	5,920
Design speed (kn)	16	14	13.5
Propulsion power (kW)	4,907	5,433	5,715
Min. propulsion power[1] (kW)	4,380*	8,568	6,248
Min. propulsion power[2] (kW)	3,504**	4,013	4,392
Speed at design cond. (kn)	14	12.7	12.4
Hotel electrical load (kW)	500	570	435
Min. required A/E power battery-powered vessel	4,004	4,583	4,827

[1]…as per MEPC.1-Circ.850-Rev.3 Appendix 1
*…as per MEPC.1-Circ.850-Rev.3 Appendix 1 using coefficients for bulk carriers
[2]…as per MEPC.1-Circ.850-Rev.3 Appendix 2
**…derived using best engineering practices not directly following MEPC.1-Circ.850-Rev.3 Appendix 2

This methodology involves determining the calm water resistance and added resistance of the vessel due to headwind and head waves, resulting in the required propeller torque and rotational speed to overcome the combined vessel resistance. The hotel load of the vessel must be added to the propulsion power requirement to arrive at the rough dimensioning of the auxiliary engines on the battery-electric vessel. It is clear that the power output of the combined generating sets is lower than the maximum continuous power rating of the engine of the baseline vessel, but still in the megawatt range. However, the calculation results in Table 2 also show that vessel speeds acceptable in today's market can be achieved.

5.4 Integration of batteries into the vessel

The application of a currently typical existing battery room arrangement to the presented container ship case reveals that most of the ship's internal volume must be allocated to battery energy storage, as depicted at the center of Figure 7. Consequently, it can be concluded that such an arrangement is unlikely to be feasible or economically viable. However, by optimising the required energy capacity and adopting the alternative battery storage concept described above, the result changes significantly.

From a cargo intake perspective, the optimal location is as low as possible and as close to the midship region as feasible. This placement optimizes the ship's stability and minimizes the amount of ballast water required for trimming purposes.

A possible arrangement following this approach is illustrated in Figure 7. In this example, for simplicity, the lower two tiers in the central cargo holds are entirely allocated to battery storage, corresponding to 48 battery units. This arrangement allows space for auxiliary equipment or future expansion of energy capacity, in addition to accommodating the required 34 battery units.

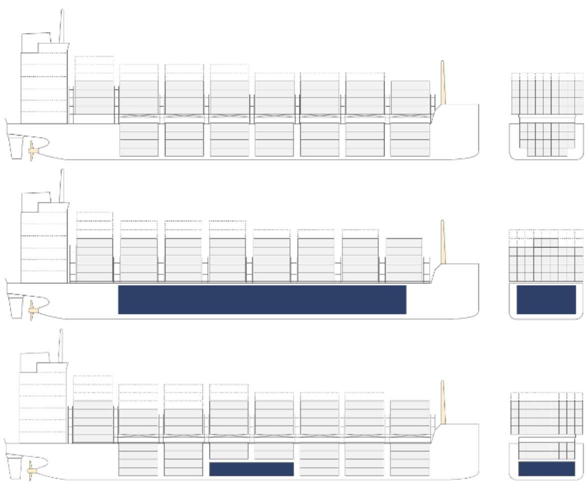

Figure 7. 1,100 TEU container ship general arrangement. Top: Baseline vessel (conventional-fueled, ICE-powered). Center: Battery-powered vessel with non-optimized battery system design. Bottom: Battery-electric vessel with optimized battery system design. Battery spaces are marked in dark blue.

At this stage, it is assumed that the engine room volume is identical for both the conventionally fueled, ICE-powered vessel and its battery-electric equivalent. A hybrid electric power plant limited to using non-heated fuel oil types will, in practice, lead to a certain reduction in auxiliary equipment and, of course, the volume taken up by the two-stroke engine is freed up. On the other hand, the hybrid electric concept will increase the size and number of electric components, such as switchboards and transformers, and introduce large electrical propulsion motors. In practice, we expect a certain reduction in engine room space required for the battery-electric vessel.

The hybrid electric power system of a ship is designed to integrate multiple power sources and components, enhancing both efficiency and environmental performance. This system comprises several critical elements.

First, two generator engines are utilized to generate electrical power. These engines are designed as methanol dual-fuel engines, as described in the previous section. They are connected to alternators that convert mechanical energy into electrical energy. This setup ensures a reliable source of power while the ship is at sea.

The switchboard acts as the central hub for distributing electrical power throughout the ship. It manages the power generated by the engines, stored in the batteries, and supplied via the shore power connection, ensuring consistent and effective delivery of electricity to all necessary systems and components on board.

Batteries play a crucial role in the hybrid system, providing a means to store electrical energy and supply power when needed.

The shore power connection allows the ship to connect to an onshore electrical grid while docked. This enables the vessel to draw power from the shore, significantly reducing the need to run generator engines. Consequently, this minimizes fuel consumption and emissions when the ship is in port, contributing to environmental sustainability.

Finally, the propulsion motors, which drive the main thruster/propeller, are powered by electricity supplied through the switchboard. These motors are essential for the ship's propulsion, receiving power from the generator engines, batteries, or both, depending on the operational context

Despite a reduction in machinery weight, the deadweight of the battery-electric vessel is reduced by approximately 800 tonnes, or 6%. However, the reduction in cargo intake capacity is lower than the reduction in deadweight (0.5%-2%) due to the improved stability resulting from the low center of gravity of the heavy batteries.

In conclusion, it can be observed that the cargo carrying capacity of the battery-electric hybrid container ship can be maintained in this example. It should be noted that, for very heavy cargo and a stratified loading scenario (i.e., heavier containers at the bottom, lighter at the top), the amount of ballast water required is reduced. At some point, the loss of cargo intake will approach the deadweight loss in the fully loaded condition.

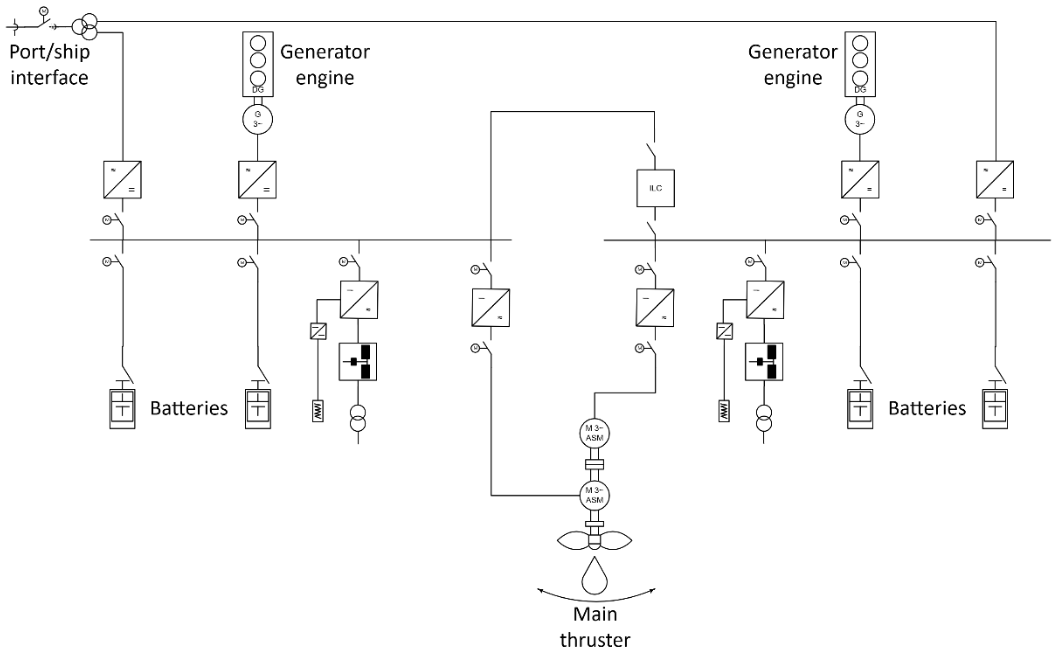

Figure 8. 1,100 TEU Container ship power system layout.

6 TECHNO-ECONOMIC ANALYSIS

6.1 Life-cycle energy demand and emissions

The lifecycle energy demand of the optimized battery-electric container ship was analyzed and compared with that of an equivalent ICE-powered container vessel fueled by e-methanol (baseline case). It was assumed that the ICE-powered vessel was already equipped with a shore power connection.

The detailed analysis of energy flows shows that direct electricity supplied via the shore power connection in the baseline case contributes only a minor portion of the total required renewable energy. In fact, most of the total required renewable energy for this design is used to produce the e-methanol. By applying the hybrid power plant philosophy, most of the energy supply during sea passage can be shifted from methanol to the battery. Consequently, the renewable electricity required for methanol production could be reduced to less than one-quarter of that in the baseline case. Direct electricity, comprising shore power connection and battery charging, contributes the same demand for renewable energy as electricity for e-fuel production. Overall, by comparing the baseline case with the battery-electric vessel, the lifecycle renewable electricity demand can be reduced by more than 60% (cf. Figure 9).

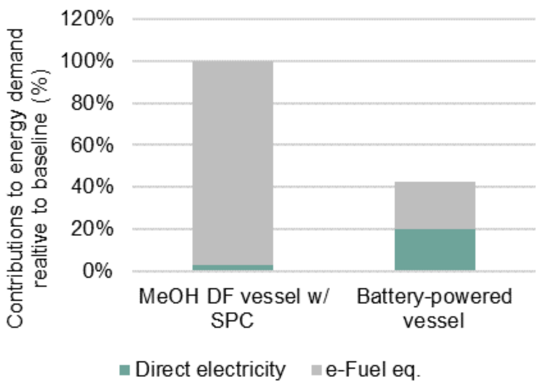

Figure 9. Analysis of renewable electricity required to power a hypothetical 1,100 TEU container ship using a methanol dual-fuel ICE (MeOH DF, baseline case) or a battery with methanol-fueled auxiliary power. Contributions to energy demand

relative to baseline. Left bar: Baseline DF vessel with SPC. Right bar: battery-powered vessel.

Based on the results of the detailed energy analysis, the emission intensity of the energy use on board the respective vessels was calculated. It was assumed that five percent of the fuel used on board the vessel (described as e-fuel equivalent in the energy analysis) is the pilot fuel for initiating the combustion of methanol in a diesel engine. Furthermore, this pilot fuel was assumed to be fossil marine gas oil, which has a well-to-wake (WtW) emission intensity of 90.7 g CO_{2e}/MJ as per Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC (FuelEU Maritime).[16] The e-methanol was considered at a level of 3.2 g CO_{2e}/MJ [10], and electricity was assumed to be zero, in line with FuelEU Maritime.

Although fossil marine gas oil (MGO) was assumed as the pilot fuel, a 92% reduction towards the FuelEU Maritime target intensity of 89.3 g CO_{2e}/MJ for the period of 2025 to 2029 was achieved by the ICE-powered container vessel fueled by e-methanol and equipped with a shore power connection, as shown in Figure 10.

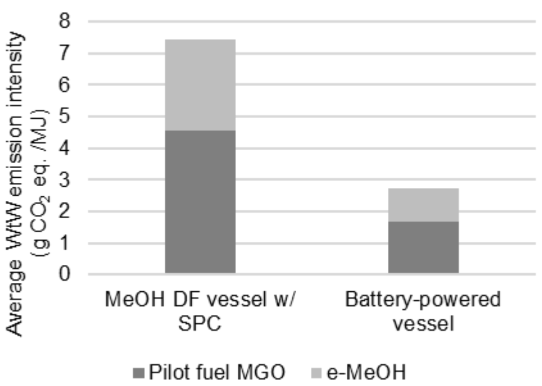

Figure 10. Average WtW emission intensity of the container ship using a methanol dual-fuel ICE (MeOH DF, baseline case) or a battery-powered vessel with methanol-fueled auxiliary power.

However, as fuel usage could be drastically reduced in the battery-powered vessel, the emission intensity was further reduced to below 3 g CO_{2e}/MJ, resulting in a 97% reduction against the FuelEU Maritime target intensity. Consequently, if such vessel is employed with a high exposure to EU port calls, the improved benefit in terms of compliance pooling can contribute to a positive business case. This potential, however, is impacted by the reduced energy consumption of the battery-powered vessel compared with the e-fuel powered benchmark, as the FuelEU Maritime compliance balance is calculated using the actual amount of energy used.

While the battery integration case has shown to provide substantial benefits for the onboard vessel efficiency and WtW emission intensity, comparable to the methanol dual-fuel ICE baseline case, the additional environmental impact of battery production also needs to be considered

Recent studies of electrical vehicles (EV) have demonstrated that LFP cells require the least energy for production among all battery types analyzed.[20] High-energy (HE) configurations are even more favorable compared with high-power (HP) configurations. Furthermore, the findings indicate that, in terms of global warming potential (GWP), LFP and nickel manganese cobalt cells (NMC900) are the most sustainable battery types, when focusing solely on battery cell production. Based on these findings and the use of LFP HE batteries, the study can utilize a Global Warming Potential of approximately 64 kg CO_{2e}/kWh_{cell}.

For the hypothetical 1,100 TEU container ship using a methanol dual-fuel ICE (MeOH DF, baseline case) in this study, and only accounting for the additional CO_{2e} for the batteries, it was found that battery production adds another 7,680 tonnes of CO_{2e} emissions to the vessel's life-cycle emissions.

As previously established, the MeOH-DF case requires 3.7 times as much renewable electricity as the battery-powered case. This ratio was used to evaluate the years required to compensate for the additional CO_{2e} emissions from battery production. Additionally, the average WtW emissions intensity results described above were utilized.

Using these numbers, an average of approximately six years is necessary before emissions from battery production have been compensated, which is well within the expected lifetime of the batteries. The actual compensation time will, however, be very sensitive to the carbon intensity of both the local grid used for charging the batteries and the electricity used to produce e-fuels and batteries.[21] If the battery powered vessel is operated in a region with limited renewable energy, compensation time is expected to significantly increase.

6.2 Total cost of ownership

Finally, the total cost of ownership (TCO) of these two vessel configurations was evaluated based on current market prices for the vessel in a methanol dual-fuel configuration (Figure 11). In the present calculation, the vessel's lifetime is 20 years, with its value depreciated linearly to its scrap value throughout this period. Debt financing is assumed to cover 60% of the total cost, with an interest rate of 5% applied to the debt. The cost of equity is set at 10%, and the weighted average cost of capital, used as the discount factor for present value calculations, is 7%. Energy costs are based on the NavigaTE TCO v1.511 model.[10] Operational expenditures (OpEx) are calculated as a lump sum per vessel day, identical for all vessel configurations within a segment, and are escalated at a rate of 2.5% per year. Battery cells are exchanged after 10 years of operation, representing 50% of the total battery system price. The resale price of battery cells is estimated to be 30% of their new price, with the price of new battery cells expected to decline by 20% over 10 years. The price for the battery system was based on input from battery system vendors, with a deployment date around 2028 in mind. This assumption matches the expected price level for stationary utility-scale battery systems, estimated at 300 USD/kWh.[22]

Around 50% of the TCO originates from fuel expenditure in the baseline vessel configuration (Figure 18). However, while energy expenditure is drastically reduced in the battery-powered vessel configuration due to increased lifecycle energy efficiency, the capital expenditure (CapEx) increases enough to almost fully compensate for the reduced energy expenditure. The increased CapEx is primarily driven by the initial cost of the entire battery system. Although the cost of replacing the battery modules over the vessel's lifetime is also a factor, it is assumed that this contribution will be relatively minor, based on expectations regarding battery resale value and declining battery prices over time. A break-even point between both configurations is observed when the battery system cost is around 350 USD/kWh.

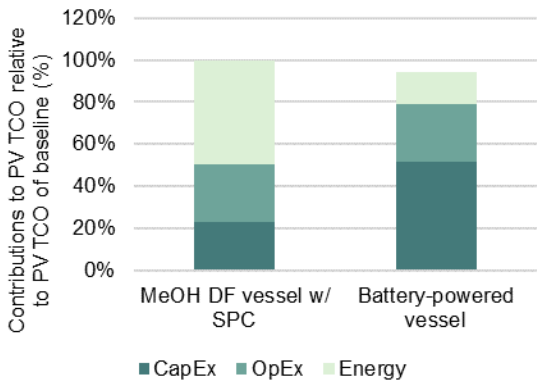

Figure 11. Financial analysis of container ship case study. Contributions of CapEx, OpEx, and energy cost to the present value (PV) TCO (relative to the baseline. Left bar: Baseline methanol dual-fuel (MeOH DF) vessel with shore power connection (SPC). Right bar: Battery-powered vessel applying the hybrid power plant philosophy.

7 CONCLUSIONS

This study investigated the role of battery-powered vessels in merchant shipping. It found that battery-powered vessels alone are not viable for most vessel sizes and segments today. Even for smaller merchant vessels on short voyages, this concept results in operational inflexibility, significant cargo capacity loss, and high CapEx.

Therefore, a hybrid power plant solution was identified as a reasonable pathway. In this solution, 80% of the vessel's energy requirement is covered by batteries, while the remaining 20% is covered by generating sets running on renewable fuel. This approach reduces renewable energy demand by up to 70% compared with a methanol dual-fuel vessel, while maintaining operational flexibility and ensuring safe navigation in adverse weather conditions. Additionally, the installed battery capacity can be substantially reduced compared with a first-order capacity design, depending on the vessel's operating profile, thereby reducing CapEx.

Compact packaging of modular battery systems is required to design primarily battery-powered small merchant vessels without significant cargo loss compared to today's baseline vessels. Discussions with battery suppliers indicate that the required battery system technology will be available by 2030 at competitive prices.

Electrifying smaller merchant vessels on short voyages has the potential to address between 5% and 17% of today's CO_2 emissions in these segments. Additionally, increasing the lifecycle energy efficiency of vessel operations could free up 1.8 EJ of renewable energy for e-fuel production. However, to fully exploit this potential, ports must be equipped with shore power connections or dedicated charging infrastructure with sufficiently high power supply.

8 DEFINITIONS, ACRONYMS, ABBREVIATIONS

AC: Alternating current

CapEx: Capital expenditure

CO_2: Carbon dioxide

CO_{2e}: Carbon dioxide equivalent

DF: Dual-fuel

DWT: Deadweight tonnes

EJ: Exa Joule

GHG: Greenhouse gas

ICE: Internal combustion engine

IMO: International Maritime Organization

kn: Knots, nautical miles per hour

kV: Kilo volt

kW: Kilo watt

LFP Lithium iron phosphate

LSFO: Low sulfur fuel oil

MeOH: Methanol

MGO: Marine gas oil

MVA: Mega Volt Ampere

MWh: Mega Watt-hour

NMC900: Nickel manganese cobalt

OpEx: Operating expenditure

PV: Present value

SPC: Shore power connection

TCO: Total cost of ownership

TEU: Twenty foot equivalent unit

USD: United States dollars

WtW: Well-to-wake

9 ACKNOWLEDGEMENTS

The project was a collaboration between the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping and NORDEN, Maersk, Siemens Energy, the American Bureau of Shipping, and Stolt Tankers, as well as Tsuneishi Group. Additional data for this project was provided by Sea. The authors would like to express their deepest gratitude to everyone who contributed to the project.

A extensive report on the project results can be found at the following link: https://www.zerocarbonshipping.com/publications/understanding-the-potential-of-battery-powered-vessels-for-deep-sea-shipping/

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