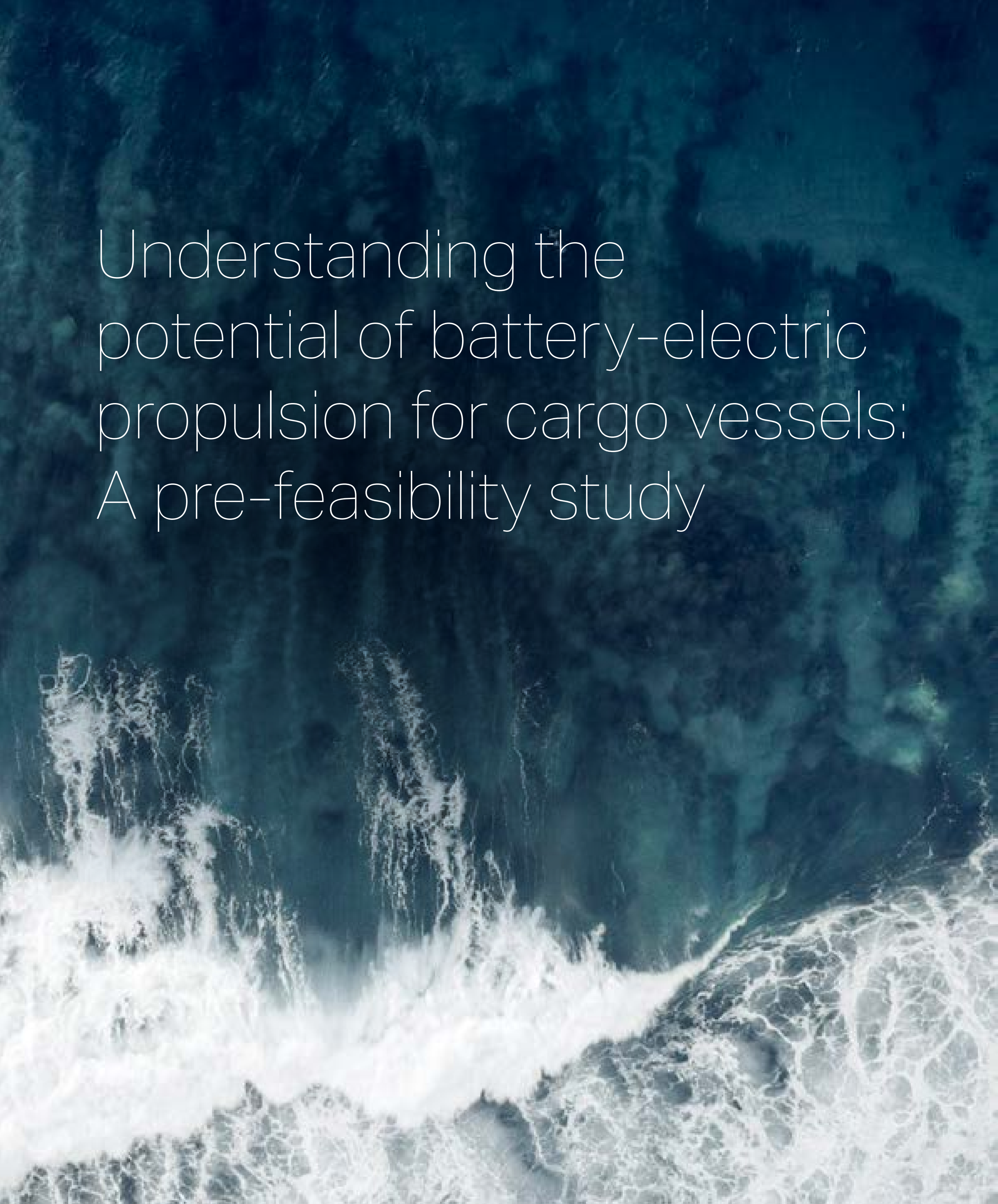
Understanding the potential of battery-electric propulsion for cargo vessels: A pre-feasibility study



Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

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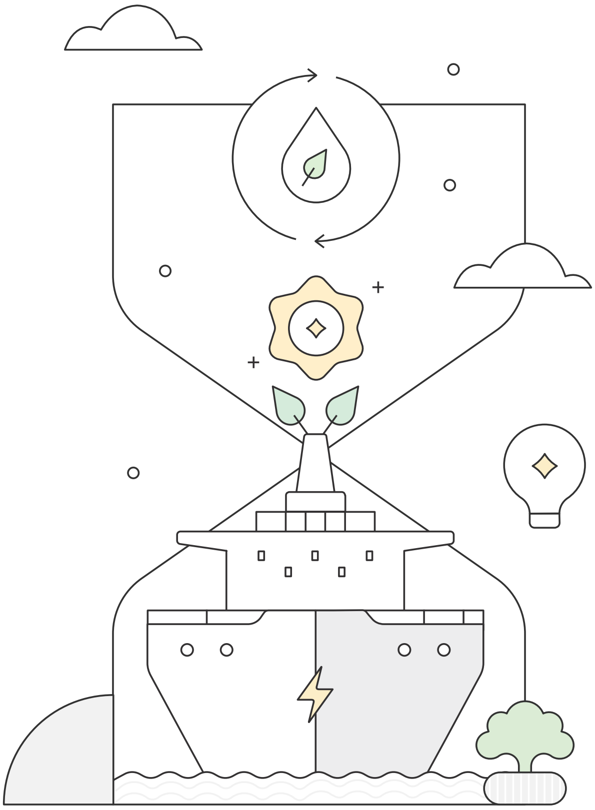
Executive summary

The shipping industry's journey toward decarbonization involves a dual focus on alternative fuels and technologies that reduce net fuel consumption. E-fuels are one promising avenue for reducing greenhouse gas emissions in the mid- to long term. These fuels are synthesized from renewable hydrogen. However, the scale of renewable electricity required for hydrogen production via electrolysis remains a significant challenge. As a consequence, methods to reduce demand for renewable electricity are needed to facilitate widespread decarbonization.

While other industrial sectors are actively pursuing direct electrification, battery-electric vehicles such as passenger cars and trucks have gained substantial traction, particularly in developed economies. The inherent benefits of battery-electric propulsion lie in its life-cycle energy efficiency. Yet, the energy density of batteries is low compared to chemical energy carriers (fuels). As a result, large-scale adoption of pure battery-electric propulsion for deep-sea vessels has not materialized.



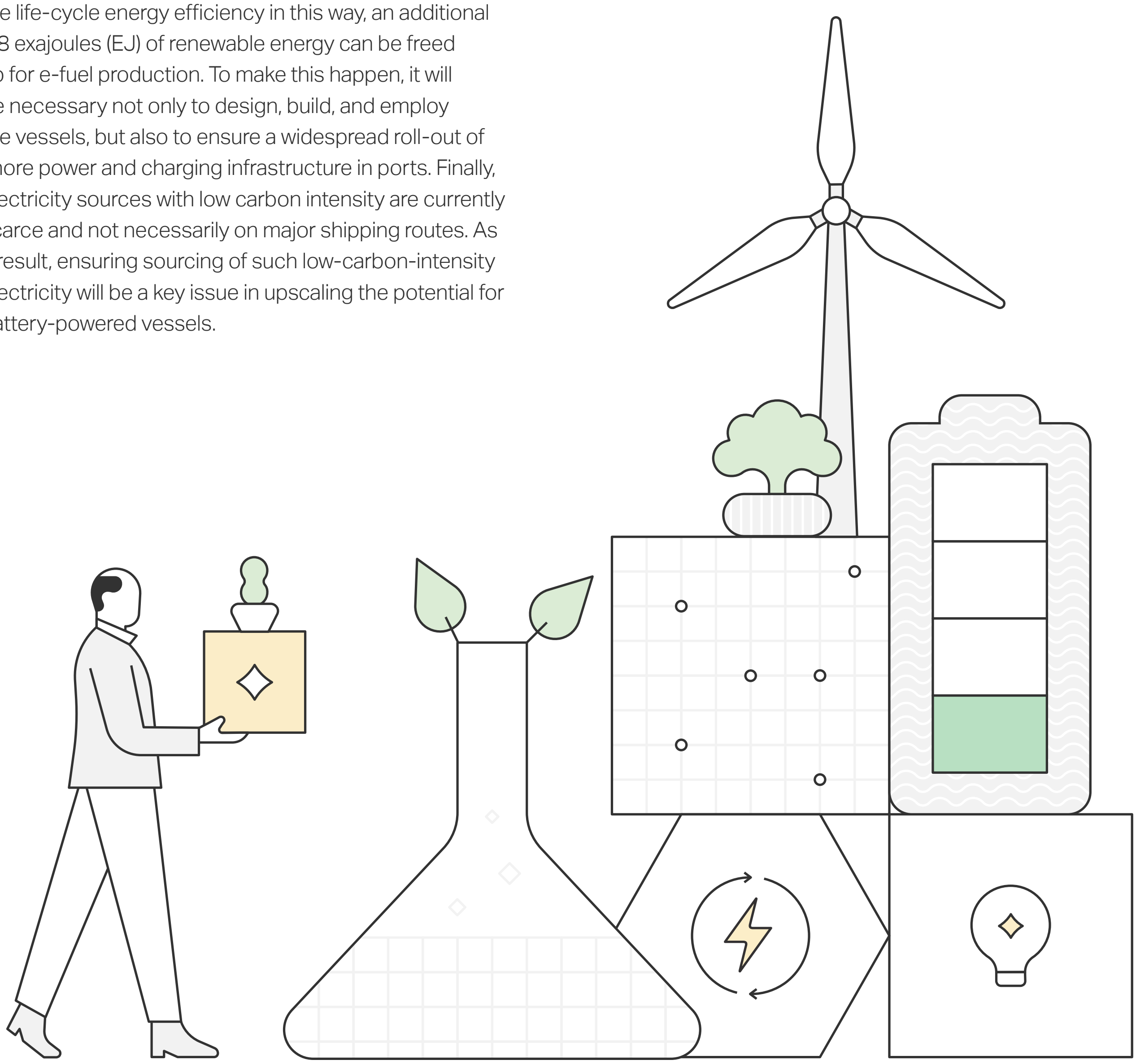
To explore direct electrification further, the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) has launched a pre-feasibility study to explore pathways for direct electrification of cargo vessels. The investigation encompasses vessel design, operational practices, and techno-economic considerations.

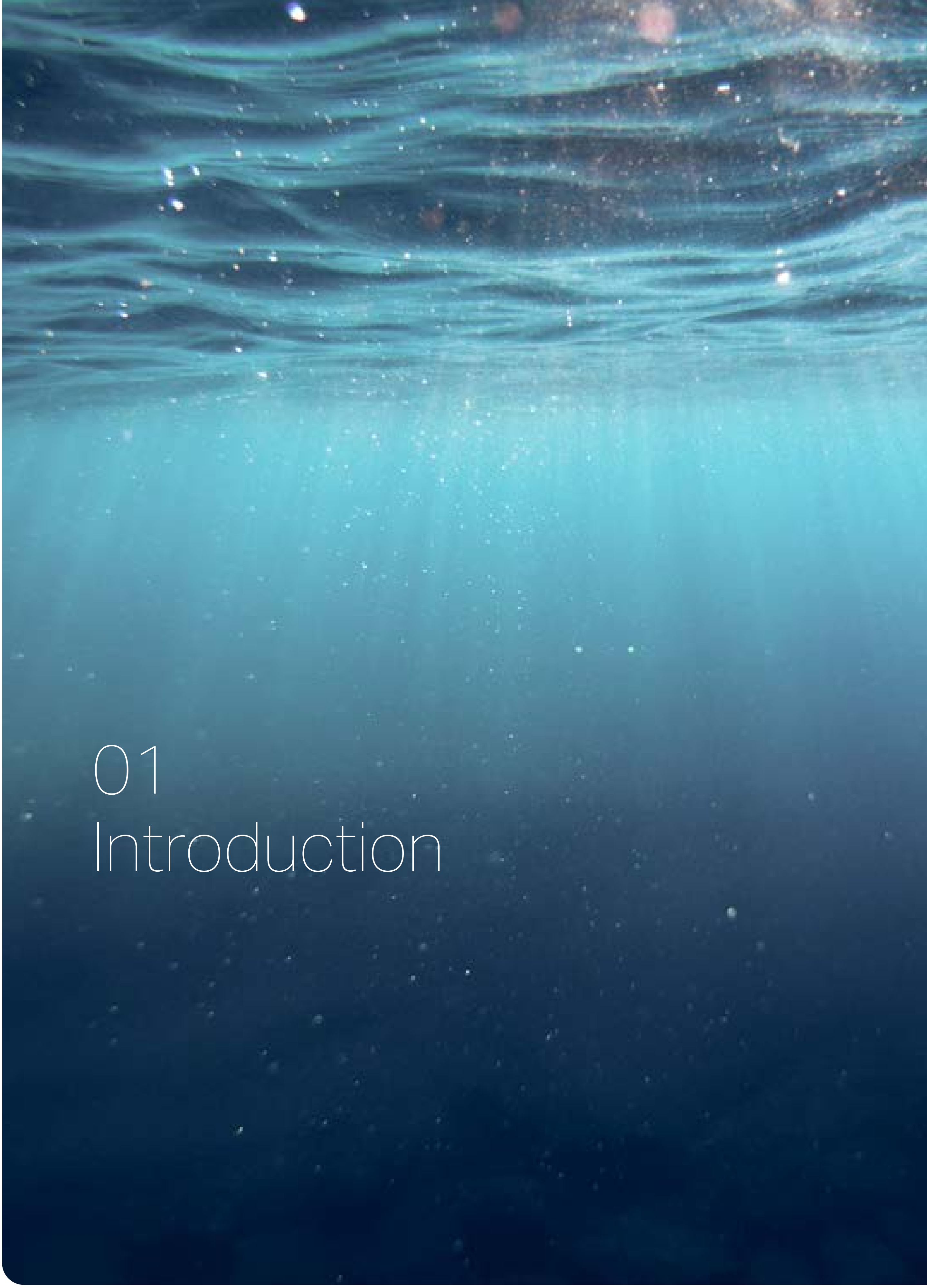
Based on an analysis of the global fleet in the container ship, tanker, and dry-bulk vessel segments, we derived study cases for the investigation. We chose to focus on 1,100 twenty-foot equivalent unit (TEU) container ships, Handysize product tankers (40k deadweight tons (DWT)) and Handysize dry-bulk vessels (35k DWT). For each vessel type, we used hypothetical voyages based on realistic assumptions to evaluate the potential of battery-electric propulsion in these study cases. We compared the results to vessels propelled by internal combustion engines running on e-methanol as a representative example of an alternative energy carrier.

While pure battery-electric propulsion systems face both technical and economic limitations, a 'hybrid power plant' approach—combining battery-electric components with internal combustion engines—offers a promising solution. This hybrid approach ensures overall gains in life-cycle energy efficiency and operational flexibility for seagoing vessels. Furthermore, this hybrid power plant philosophy reduces the installed battery capacity, which facilitates the integration of the batteries into the vessels and limits the loss of cargo capacity.

We find that battery-powered container ships applying the hybrid power plant philosophy have a viable business case compared to equivalent vessels powered by methanol dual-fuel internal combustion engines. This assessment considers current prices of the baseline vessels as well as projected prices for battery systems, electricity, and methanol.

From a life-cycle perspective, the demand for renewable energy is reduced by more than 65% in our battery-powered case studies compared to the methanol dual-fuel internal combustion engine baseline. As a result, targeting smaller-sized merchant vessels on short voyages for partial electrification ultimately has the potential to address up to 17% of today’s carbon dioxide (CO_2) emissions in the entire respective vessel segments. Furthermore, by increasing the life-cycle energy efficiency in this way, an additional 1.8 exajoules (EJ) 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. Finally, electricity sources with low carbon intensity are currently scarce and not necessarily on major shipping routes. As a result, ensuring sourcing of such low-carbon-intensity electricity will be a key issue in upscaling the potential for battery-powered vessels.





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Introduction

Electrification is seen as a crucial pathway towards decarbonization throughout all sectors, as it offers a higher efficiency of the energy conversion combined with a potential to reduce greenhouse gas (GHG) emissions through increased deployment of low-GHG energy sources.[1] Apart from battery-electric road transport (passenger cars and trucks), electrified solutions are also being developed in heavy-duty transportation. For example, heavy-duty freight locomotives with an installed battery capacity of up to 15 MWh were introduced to the market in 2023.[2,3]

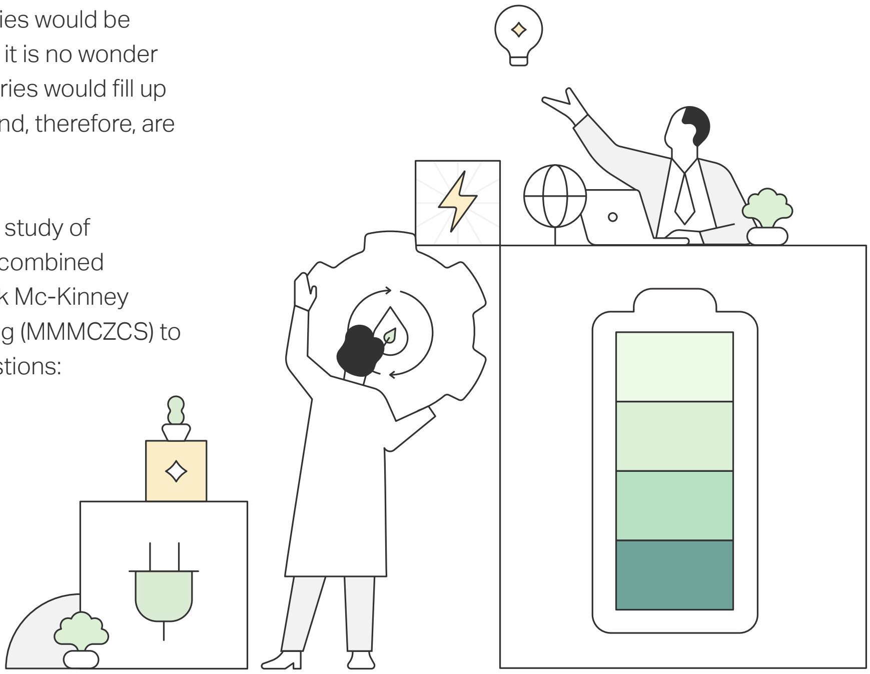
Battery-powered vessels have also entered the shipping segment in applications with short ferry crossings or in hybrid installations with internal combustion engines (ICE). Short-sea ships such as the ferries Ellen, Aurora, and Tycho Brahe have been in commercial operation for several years.[4,5] These ferries have an installed capacity of about 4 MWh, sufficient for the short sea passages the vessels are deployed on. In 2023, COSCO launched a battery-electric container vessel operating on the Yangtze River with an installed battery capacity of 50 MWh.[6] To allow a sufficiently short duration for energy replenishment, the vessel designers foresee a battery-swapping concept using containerized battery solutions. This concept is already used on inland waterway vessels operating on the Rhine, but at a smaller scale.[7]

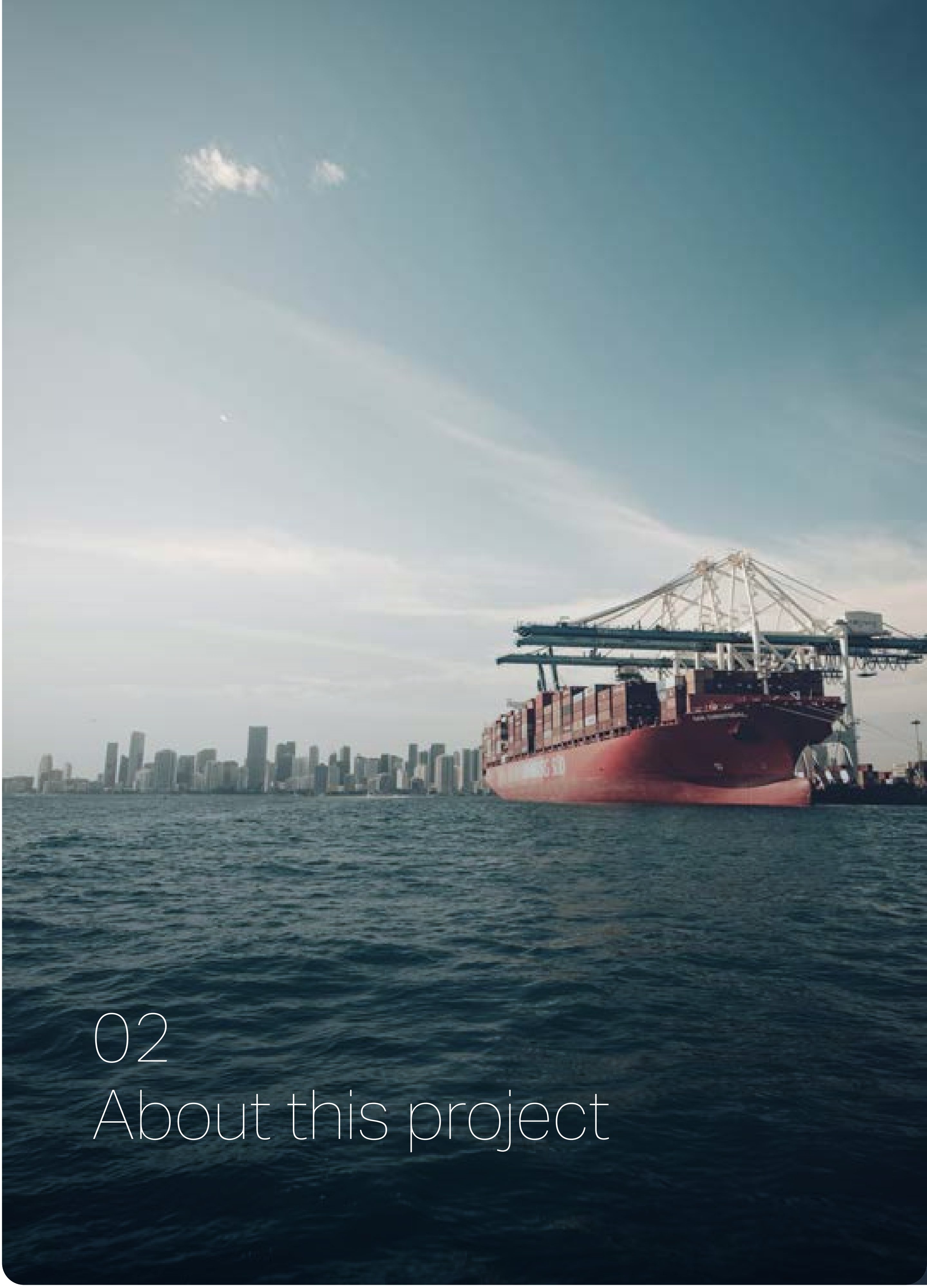
Several studies have previously investigated commercial and systemic aspects of battery-powered vessels for deep-sea shipping, with varying results.[8,9,10] However, these studies do not fully cover the practical aspects of ship operations in international trade, nor a detailed consideration of how batteries would be integrated with the vessels. Therefore, it is no wonder why the perception remains that batteries would fill up the entire cargo capacity of a vessel and, therefore, are not an option for deep-sea shipping.

Consequently, we decided to launch a study of battery-powered vessels, utilizing the combined knowledge and expertise at the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) to derive a position on the following questions:

- Is battery-electric propulsion a viable transition pathway and, if so, at what scale?
- In which vessel segments and sizes could battery-electric propulsion be a technically viable pathway?
- In which vessel segments and sizes can battery-electric propulsion represent a solid business case?
- How big is the potential of battery-electric propulsion to save renewable energy from a life-cycle perspective compared to usage of e-fuels?

In this report, we identify technological and economic barriers to the uptake of battery-electric propulsion in cargo vessels and the development required to help marine batteries overcome these barriers. Based on analyses of the global fleet in container, tanker, and dry-cargo segments, we derive case studies that enable us to explore the design and arrangement of battery rooms for each case and how operations can be optimized to accommodate for battery-electric propulsion. We also present the results of techno-economic assessments of battery-powered vessels and how they compare to ICE-powered vessels. We find that both operational practices and vessel segments and sizes have a big impact on the viability of a battery-electric propulsion pathway. Furthermore, we highlight the requirements for charging and shore power infrastructure development that are needed to facilitate this decarbonization strategy.





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About this project

The project was a collaboration between the MMMCZCS and our strategic partners DS NORDEN, Maersk, Siemens Energy, the American Bureau of Shipping (ABS), and Stolt Tankers, as well as our mission ambassador Tsuneishi. Additional data for this project was provided by our knowledge partner Sea.

Strategic Partners

MAERSK

NORDEN

SIEMENS energy

ABS

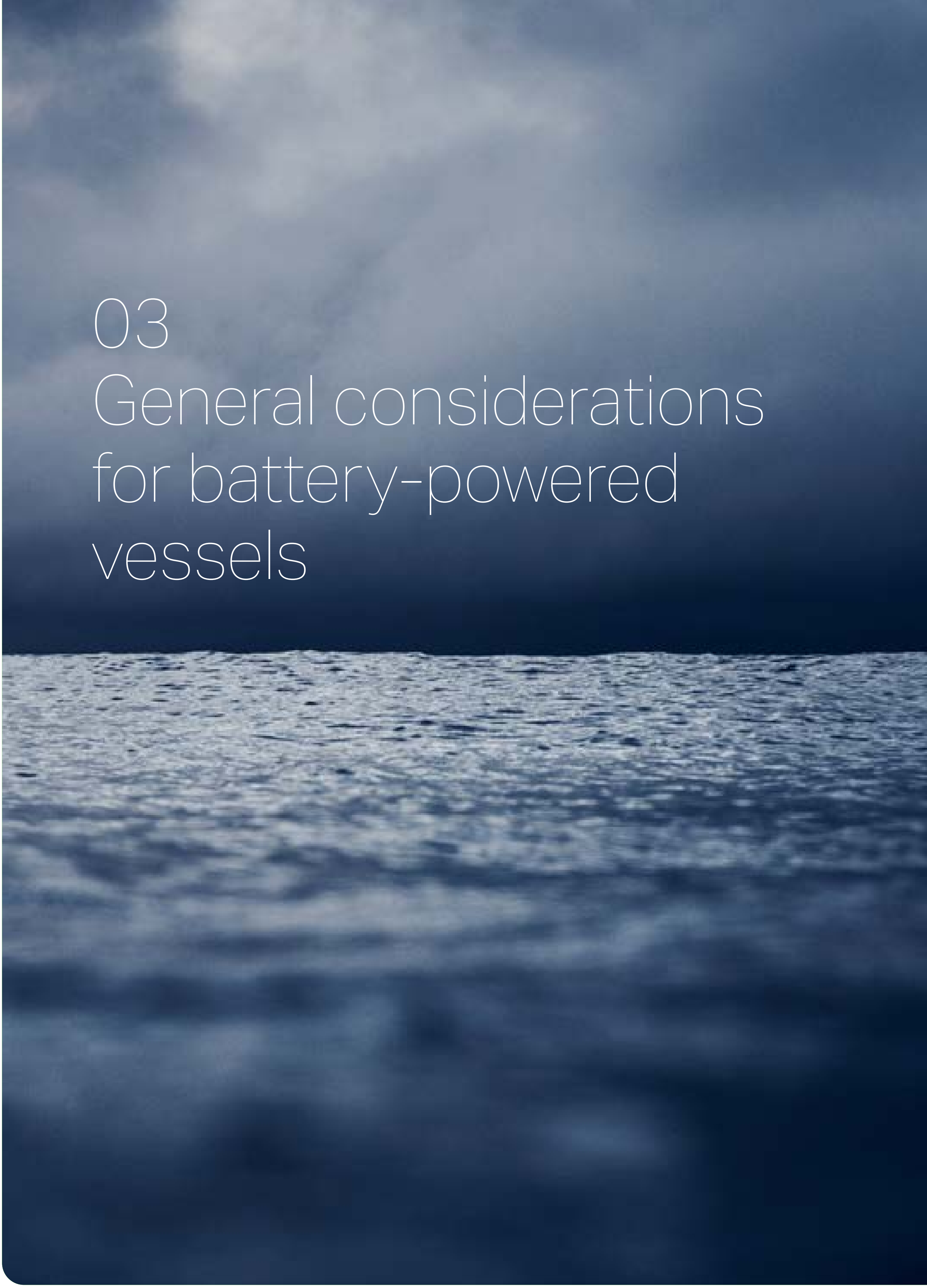
Stolt Tankers

Knowledge Partners

sea

Mission Ambassadors

TSUNEISHI
TSUNEISHI TECHNICAL SERVICES (PHILS.), INC.



03

General considerations for battery-powered vessels

3.1 Efficiency potential of battery-powered vessel options

On today's ocean-going vessels, propulsion and auxiliary power are provided by ICE and boilers–in other words, systems that convert chemically-bound energy (in fuels) via thermo-chemical processes into the 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 see how much of the renewable energy harvested through photovoltaic modules or wind turbines remains available for the final energy use comparing an e-fuel pathway (e.g., e-methanol) and a battery-powered vessel pathway.

To this end, we performed a bottom-up calculation of the major conversion steps and their associated losses using simplified assumptions based on state-of-the-art conversion efficiencies (Table 1). 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 lead to different results due to higher or lower efficiencies in the fuel synthesis process.

Table 1: Assumptions regarding life-cycle conversion efficiency to assess the potential of battery-powered vessels.[9,11]

Configuration	Conversion step	Conversion efficiency
MeOH-DF	1. Methanol synthesis	49%
	2. Methanol consumption in ICE (average of 2-stroke ICE, 4-stroke ICE and boilers)	45%
Battery	1. Charging/discharging	85%
	2. Electricity to consumers	95%

MeOH-DF = methanol dual-fuel

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 as much renewable electricity as the battery-only case. Despite this obvious advantage in energy conversion efficiency, battery-powered vessels experience opposition in merchant shipping due to expected constraints in terms of vessel range and cargo capacity. As the carbon intensity of electricity varies around the world, the geographical overlap between shipping routes and electricity sources with low carbon intensity is also an important consideration for the battery-electric propulsion pathway. However, it was outside the scope of this report to complete a quantitative evaluation of the availability of low-emissions electricity to support the implementation of this pathway.

Therefore, our calculations regarding life-cycle energy demand should be interpreted with the caveat that we assumed renewable electricity would be used directly for either e-fuel production or battery charging.* We have indicated our qualitative assumptions regarding the local availability of low-emissions electricity in the description for each case study (see Sections 4, 5, and 6).

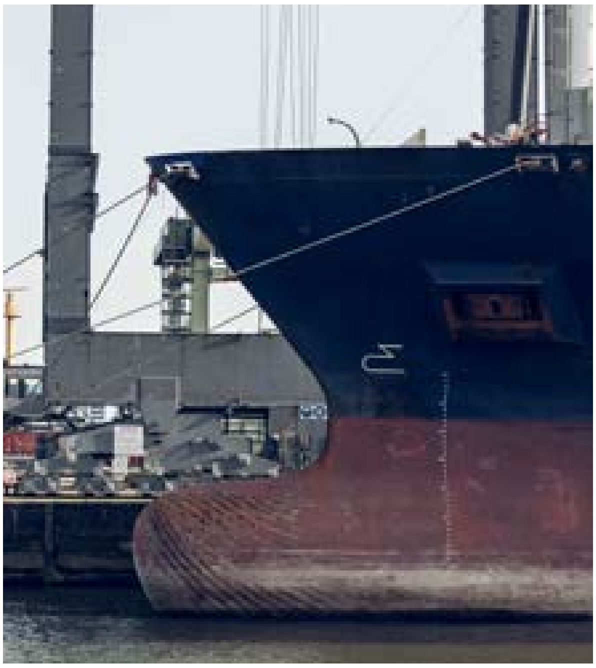
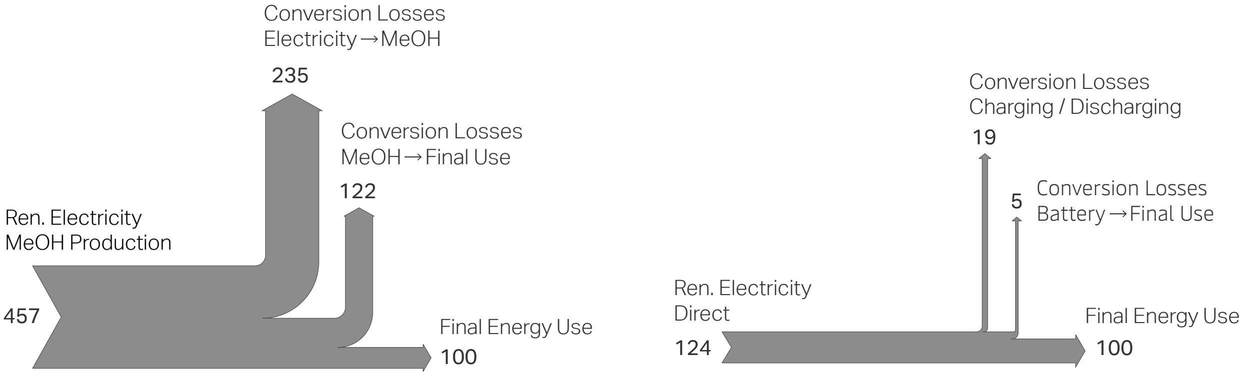


Figure 1: Comparison of life-cycle energy demand of an e-methanol pathway with dual-fuel ICE (left) and a battery-powered pathway (right) for a low-GHG-emissions vessel and associated energy conversion losses. Values are given in arbitrary units.



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* We did not consider, for example, a case of e-fuel being combusted in a power plant to supply electricity to charge a battery.

3.2 Identification of study cases

To understand which vessel size classes are most relevant for our study, we statistically analyzed the voyage legs of the globally operated fleet in the tanker, dry-bulk, and container segments. Based on voyage data provided by our knowledge partner Sea, we calculated the energy requirements for propulsion and auxiliary services during sea passage and classified the results into bins. Further details of this analysis are shown in the Appendix (Section A.1). 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.

When looking at the services and historic voyage data of strategic partners to the MMMCZCS involved in the study, we found similar trends in the relationship between vessel sizes, segments, and voyage energy requirements as in the global fleet data. Based on these findings, we derived both the vessel sizes and routes for studying the viability of battery-electric propulsion for merchant vessels (Table 2). More details on the selected case routes are shown in the dedicated sections of this report.

Based on our analysis, we believe that voyage energy requirements up to and around 250 MWh and smaller vessel segments represent a relevant field for our current investigation. The selected range of energy requirement per voyage covers a relevant share of merchant shipping operations. We therefore avoid both the most favorable short-sea legs that can be easily electrified (such as ferry crossings) as well as intercontinental trades that may lead to excessive battery sizing. At the same time, a target of 250 MWh represents an important stretch in comparison to existing marine battery applications, which are around 50 MWh.

Table 2: Description of case study vessels and trades.

Segment	Vessel size	Region	Trade
Container	1,100 TEU (Feeder)	Western Mediterranean	Intra-regional service
Tanker	40k DWT Product Tanker (Handysize T)	Baltic Sea	Shuttle service for clean petroleum products and renewable fuel
Dry-bulk	35k DWT (Handysize)	Gulf of Mexico	Agricultural products

3.3 Charging infrastructure and shore power connection

An essential puzzle piece in 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 either one or both ports of call.[4,5] The layout and design of existing port charging facilities allow for a maximum charging power to supply enough energy during the relatively short port stay, but these charging facilities are usually customized to the specific application. However, some recent environmental regulations encourage the wider supply and use of a shore power connection during port stays, in order to reduce air pollution and global warming.[12,13] Thus, the availability of shore power connections in ports is expected to increase in the coming years.

Figure 2 gives a non-exhaustive overview of the available and planned shore power connectivity worldwide, based on our own research. This overview map is accompanied by a detailed list in the Appendix (Section A.5), which also indicates which vessel segment the shore power connection is dedicated to and a reference to the source of information. We can see from Figure 2 that shore power availability is highly concentrated in Northern Europe, complemented by some availability along the North American Pacific coast and in East Asia.

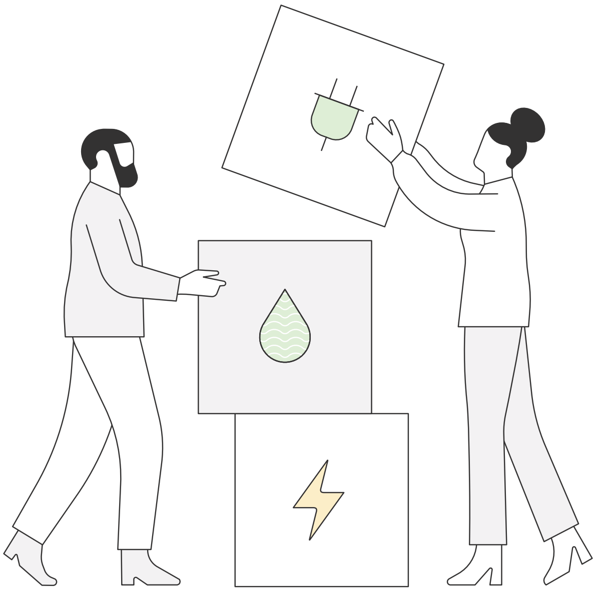


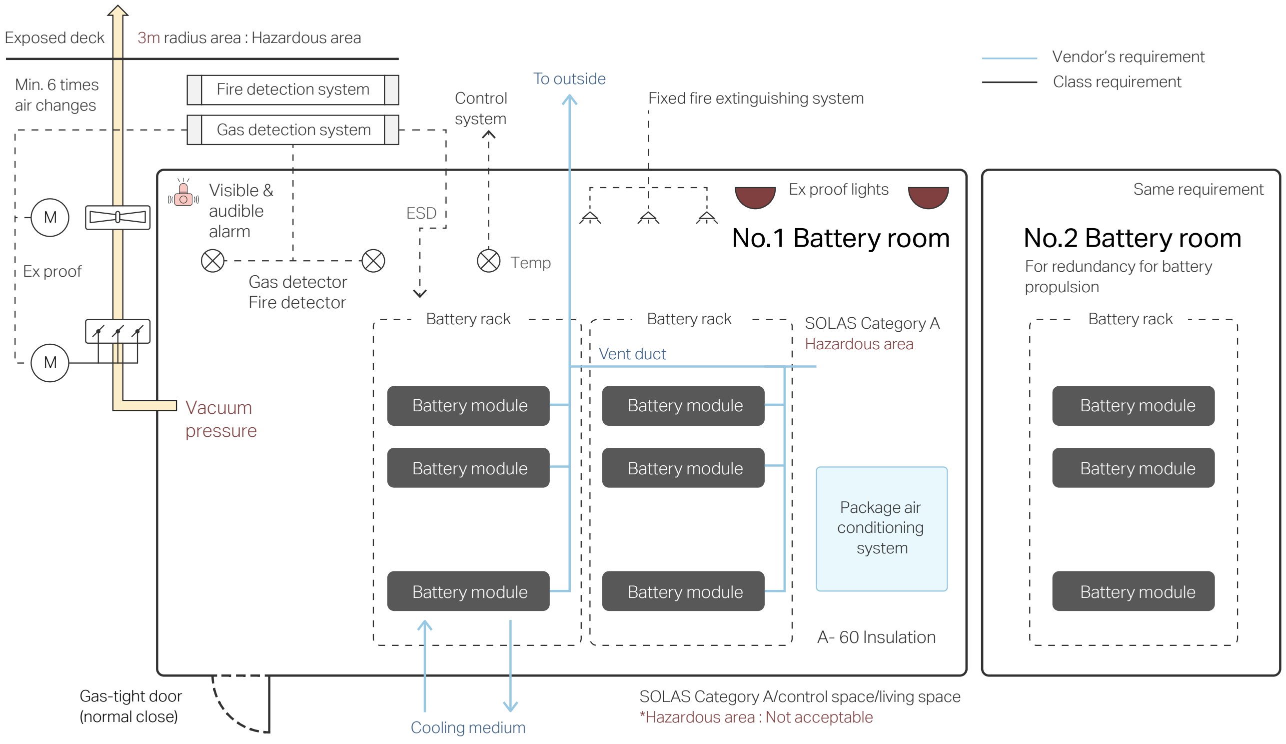
Figure 2: Overview of shore power availability (current and near-future). Ports with shore power availability are indicated by dark green dots. A list overview of these ports can be found in the Appendix (Section A.5).

We also investigated the available standard for shore power connection to find out if the power provided by these standard systems can be sufficient to simultaneously support vessel port operations and battery charging.[14,15] This is of particular importance for the tanker segment, because the auxiliary power demand in port can be very high as these vessels are required to self-discharge the cargo. The Oil Companies International Marine Forum (OCIMF) recommends a supply voltage of 6.6 kV AC and frequency of 60 Hz for tanker terminals equipped with shore power connection.[15] By employing a single standard cable connection, a power supply of up to 5.7 MVA is possible. 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).

3.4 Battery room design

Battery room design must allow for safe operation and serviceability and thus must follow the requirements of both battery system vendors and classification societies (graphically represented in Figure 3). Current installations are primarily based on the principle of multiple cells being combined to form a battery module, which can be around the size of a suitcase. Several such modules are then connected to form a pack, which could be similar in size to a wardrobe. Several packs would then be combined in parallel to form a battery string, of which several might be needed to attain the desired capacity. Such strings are then located in a separate battery room with ample space for accessing the individual modules. The energy density of such a room is significantly reduced compared to that on, for example, just a pack level.

Figure 3: Overview of necessary equipment and battery room design features based on requirements from vendors and classification societies.[16,17]

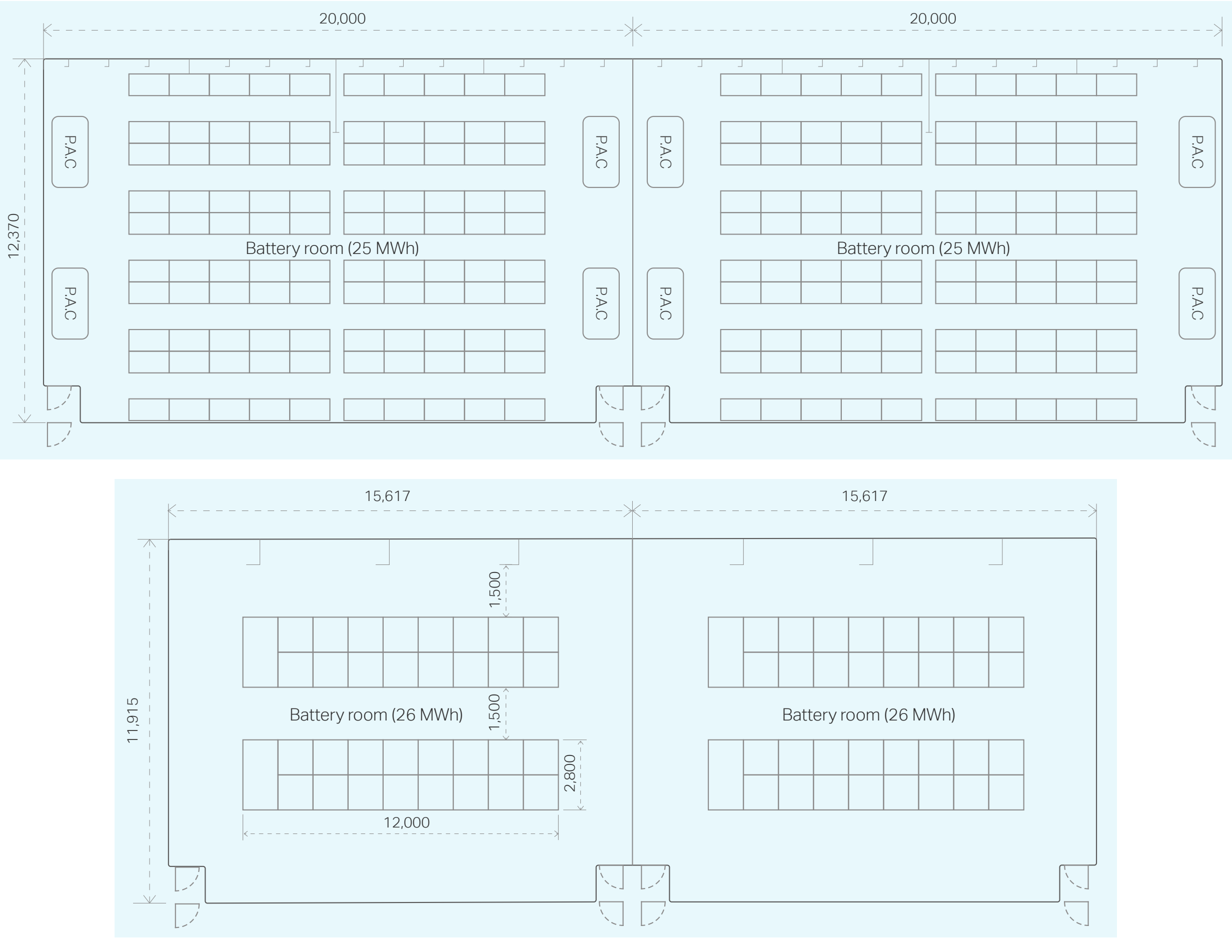


The ancillary systems (e.g., ventilation, fire-fighting equipment) and the necessary access space to the comparatively densely packed battery racks increase the overall space needed to accommodate the batteries on a vessel. In addition, current requirements from classification societies regarding ships powered solely by batteries ask for redundancy in the battery room arrangement, thereby duplicating ancillary systems and 'empty' spaces.[16]

Based on our analysis of both vendor and classification society requirements, we outlined the size of an example battery room arrangement for an installed battery capacity of around 50 MWh (see Figure 4). The arrangement could be multiplied to increase the installed capacity to the requirements of a given vessel. Due to the redundancy and accessibility requirements previously mentioned, the energy density of the battery room is only 29 kWh/m³.

Continuous development of battery technology, such as cell chemistry and package design, is expected based on conversations with battery vendors. Following the estimates given for a five-year period towards 2028, we derived a more compact battery room design with an energy density of 47 kWh/m³ (Figure 4 bottom). This compact design also entails a reduced battery weight (see Table 3). Thus, stowage is reduced by 40% and battery weight is reduced by 45% compared to the initial design based on requirements from vendors and classification societies (Figure 4 top).

Figure 4: 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.



PAC = Package air conditioning system

However, we believe 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 centralization of power electronics, battery management systems, and so on. Even without improvements on the cell level, these changes would significantly increase the volumetric energy density of the complete battery storage system through drastic reduction of the space currently needed for accessing the smaller modules. A standard twenty-foot equivalent unit (TEU) is a likely future battery unit size. Work is ongoing, for example by the Maritime Battery Forum, to develop and establish a standard for containerized battery systems.[18] Such units would also potentially enable adaptation of the total energy capacity to changing schedules or deployments of a particular ship. Therefore, we also included such a containerized battery room design in our study. For this investigation, we assumed that such battery units can achieve energy density levels comparable to those of existing maritime lithium iron phosphate (LFP) battery systems on a rack level (physical stack of modules). This design still includes a significant degree of packaging and does not consider any improvements on 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.

Table 3: Summary of battery room design specifications for non-optimized, compact, and containerized designs.

Parameter	Non-optimized design	Compact design	Containerized design
Battery capacity	50 MWh (=200 Racks at 250 kWh)	52 MWh (=8 battery strings)	58 MWh (=16 TEU)
Battery pack total footprint	198.5 m^2	134.4 m^2	N/A
Battery pack total weight	675 tonnes	465 tonnes	471 tonnes
Battery room area	494.8 m^2 (Height = 3.5 m)	372.2 m^2 (Height = 3.0 m)	238 m^2 (Height = 2.6 m)
Spec. battery room area	~10 m^2/MWh	~7.2 m^2/MWh	~4.1 m^2/MWh
Spec. battery room volume	~35 m^3/MWh	~21.5 m^3/MWh	~10.5 m^3/MWh
Battery room/battery footprint	~2.5 m^2/m^2	~2.8 m^2/m^2	~1 m^2/m^2

04

1,100 TEU container ship case study

The container shipping industry is based on liner services operating on fixed schedules with regular calls to the same ports. Several such services are integrated to form a regional or global network. The network comprises both inter-regional services with long ocean crossings and intra-regional services of shorter voyages. We assume that shorter intra-regional services will likely be the first to be electrified. Making this pathway interesting in the greater picture will require demonstrations that a certain scale of total transport work and emissions can be addressed by direct electrification.

As a case study, we selected a sub-network of four existing services centered around the Strait of Gibraltar and connecting North Africa with southern Europe. The four services differ in their number of port calls and individual leg lengths. Each service would have a dedicated vessel deployed, and it takes four vessels of about 1,100 TEU nominal capacity in total to maintain a weekly schedule. For the sake of simplicity, we combined all four schedules into one for our analysis, thereby generating a sort of average service. We did not consider in detail the availability of renewable electricity in these specific ports. Although the required natural resources are likely abundant, the local infrastructure for renewable electricity might not be mature. The overall case is thus hypothetical, but serves to illustrate the main drivers and considerations relevant to a battery-powered operation for this segment.

We derived the energy requirement for every individual leg of the service, which can be found in Table 4. Whereas most of the legs are comparatively short in distance (100 to 500 nautical miles, NM), there are several legs that span from the Strait of Gibraltar to Sfax, Tunisia–a distance of roughly 1,000 NM. Depending on the employed vessel speed, these longer legs will result in a total energy requirement at sea of up to 320 MWh.

Figure 5: Container vessel case study, consisting of a sub-network of four existing services around Strait of Gibraltar and connecting North Africa with southern Europe.

Table 4: Breakdown of the individual legs comprising the combined schedule used in the container ship case study. The values in each row are indicative of the voyage leg from the port of that row to the port of the following row. The last row ends at the port of the first row.

Port	Distance	Speed	Port time	Energy demand (MWh)				
	NM	kn	hrs	Propulsion	Aux at sea	Total at sea	Aux in port	Total
Port Tangier (Morocco)	612.8	14.7	16.0	151	30	181	7	188
Skikda (Algeria)	479.5	13.4	33.0	97	27	124	15	139
Sfax (Tunisia)	1,081.3	14.1	94.5	243	62	304	42	346
Algeciras (Spain)	239.0	7.8	16.0	23	42	64	7	71
Oran (Algeria)	243.9	7.8	178.0	22	35	57	79	136
Port Tangier (Morocco)	423.8	12.7	16.0	78	24	103	7	110
Algiers port (Algeria)	643.9	13.0	22.0	124	39	163	10	172
Sfax (Tunisia)	1,081.3	13.7	91.5	229	63	292	40	332
Port Tangier (Morocco)	526.5	11.8	15.0	85	34	119	7	126
Barcelona (Spain)	300.8	11.8	6.0	50	29	80	3	82
Béjaïa (Algeria)	103.2	12.3	37.0	19	23	42	16	58
Algiers port (Algeria)	429.9	12.3	72.0	76	31	106	32	138
Port Tangier (Morocco)	526.5	11.8	15.0	85	34	119	7	126
Barcelona (Spain)	300.8	11.8	6.0	50	29	80	3	82
Béjaïa (Algeria)	103.2	12.3	37.0	19	23	42	16	58
Algiers port (Algeria)	429.9	12.3	72.0	76	31	106	32	138
Port Tangier (Morocco)	526.5	11.8	15.0	85	34	119	7	126
Barcelona (Spain)	300.8	11.8	6.0	50	29	80	3	82
Béjaïa (Algeria)	103.2	12.3	37.0	19	23	42	16	58
Algiers port (Algeria)	429.9	12.3	72.0	76	31	106	32	138
Port Tangier (Morocco)	526.5	11.8	15.0	85	34	119	7	126
Barcelona (Spain)	300.8	11.8	6.0	50	29	80	3	82
Béjaïa (Algeria)	103.2	12.3	37.0	19	23	42	16	58
Algiers port (Algeria)	429.9	12.3	72.0	76	31	106	32	138

4.1 Direct application of existing battery room rules and guidelines and ‘simple’ capacity dimensioning

As a starting point, we took a ‘naïve’ approach to dimensioning the battery capacity. We assumed that 100% of the energy required according to the schedule should come directly from the batteries. This meant that the battery capacity was dimensioned according to needs on the longest leg in Table 4, which is about 320 MWh (useable*) when also accounting for electrical conversion losses from the battery to consumers. When applying a typical existing battery room arrangement as outlined in Figure 4, we find that the majority of the internal volume of the ship needs to be allocated to battery energy storage, as shown in Figure 6. We can conclude that such an arrangement is unlikely to be feasible or economically viable.

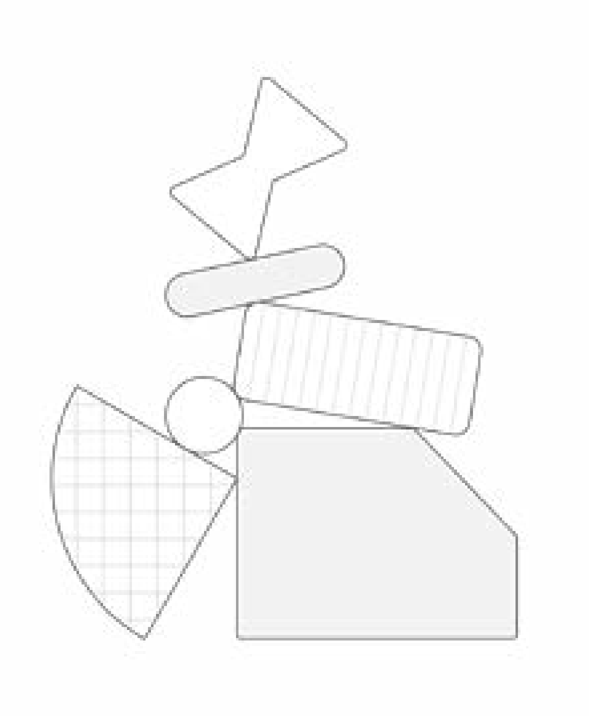


Figure 6: 1,100 TEU container ship general arrangement. Top: Baseline vessel (conventional-fueled, ICE-powered). Bottom: Battery-powered vessel with non-optimized battery system design. Battery spaces are marked in dark blue.

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* Assuming cycling between 10% and 90% charge level, which we consider reasonable considering the expected very low charging/discharging rates in this application.

4.2 Optimization of the battery-powered container vessel case

However, this ‘naïve’ approach does not account for the rapid development of battery technologies and potential impact of economically incentivized improvements and compromises. Therefore, we next identified three reasonable steps to significantly optimize this study case.

4.2.1 Adapt the service schedule

The initial battery capacity is dimensioned according to energy needs on the voyage from Sfax, Tunisia to Algeciras/Tangier, which is significantly longer than the other legs in the schedule. On the eastbound part of the schedule, this voyage is split up by a call to an Algerian port. 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 in the eastbound journey, we can almost halve the maximum energy demand to around 190 MWh.

Naturally, since we usually want to maintain the frequency of the service, the time ‘lost’ in this extra port call must be found somewhere else in the schedule. In our case, and since this schedule already includes a lot of buffer time, we assumed that the extra port time can be found by a slight increase in productivity of the various terminals and by adjustment of berth windows to reduce ‘dead’ buffer/idle time. This will not necessarily be possible for all schedules, where other adjustments such as additional tonnage or slight voyage speed increase might be required. On the other hand, new schedules could also be planned with optimized battery use in mind from the outset. While still hypothetical, we believe this example illustrates the impact of adapting schedules for battery-electric operation and that, in many cases, the same cargo flow can be maintained with acceptable compromises. The adapted schedule is detailed in Table 5.

Table 5: Breakdown of the individual legs comprising the combined schedule used in the container ship case study after adaptation to optimize for battery-electric operation.

Port	Distance	Speed	Port time	Energy demand (MWh)				
	NM	kn	hrs	Propulsion	Aux at sea	Total at sea	Aux in port	Total
Port Tangier (Morocco)	612.8	14.7	16.0	151	30	181	7	188
Skikda (Algeria)	479.5	13.4	33.0	97	27	124	15	139
Sfax (Tunisia)	481.0	14.3	71.0	113	32	145	31	176
Skikda (Algeria)	619.5	14.7	23.5	152	30	182	10	192
Algeciras (Spain)	239.0	7.8	16.0	23	42	64	7	71
Oran (Algeria)	243.9	7.8	178.0	22	35	57	79	136
Port Tangier (Morocco)	423.8	12.7	16.0	78	24	103	7	110
Algiers port (Algeria)	643.9	13.0	22.0	124	39	163	10	172
Sfax (Tunisia)	648.7	13.9	77.5	142	35	178	34	212
Algiers port (Algeria)	429.9	13.4	24.0	89	24	113	11	123
Port Tangier (Morocco)	526.5	11.8	15.0	85	34	119	7	126
Barcelona (Spain)	300.8	11.8	6.0	50	29	80	3	82
Béjaïa (Algeria)	103.2	12.3	37.0	19	23	42	16	58
Algiers port (Algeria)	429.9	12.3	72.0	76	31	106	32	138
Port Tangier (Morocco)	526.5	11.8	15.0	85	34	119	7	126
Barcelona (Spain)	300.8	11.8	6.0	50	29	80	3	82
Béjaïa (Algeria)	103.2	12.3	37.0	19	23	42	16	58
Algiers port (Algeria)	429.9	12.3	72.0	76	31	106	32	138
Port Tangier (Morocco)	526.5	11.8	15.0	85	34	119	7	126
Barcelona (Spain)	300.8	11.8	6.0	50	29	80	3	82
Béjaïa (Algeria)	103.2	12.3	37.0	19	23	42	16	58
Algiers port (Algeria)	429.9	12.3	72.0	76	31	106	32	138
Port Tangier (Morocco)	526.5	11.8	15.0	85	34	119	7	126
Barcelona (Spain)	300.8	11.8	6.0	50	29	80	3	82
Béjaïa (Algeria)	103.2	12.3	37.0	19	23	42	16	58
Algiers port (Algeria)	429.9	12.3	72.0	76	31	106	32	138

4.2.2 Introduce hybrid power plant approach

Even after splitting up the longest leg, variations in the energy demand of the individual legs remain. This non-uniformity means that, if the battery is dimensioned for the highest demand, it is not fully utilized on most of the legs (see Battery X in Figure 7). In contrast, if the battery capacity is dimensioned for the leg with the lowest demand, it is fully utilized on each voyage, but the total benefit of increased energy efficiency is also reduced (see Battery Y in Figure 7).

In practice, we expect an optimum compromise to exist. In our case study, we made the initial arbitrary choice of dimensioning the battery capacity such that 80% of the energy consumed while not in port comes from the battery. The remaining energy must then come from another onboard electricity generation source. We term this method the 'hybrid power plant' approach.

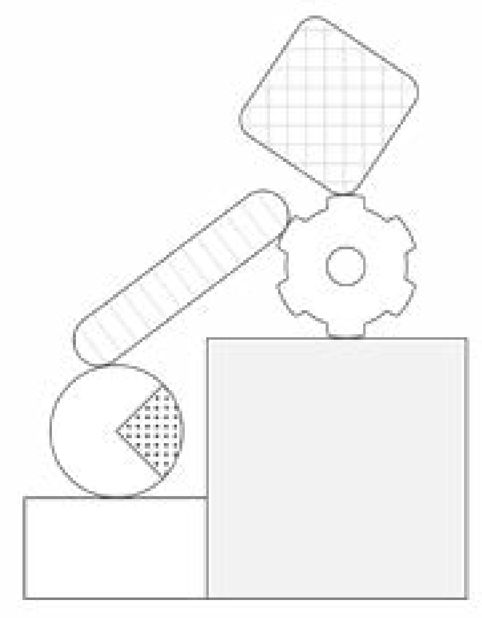
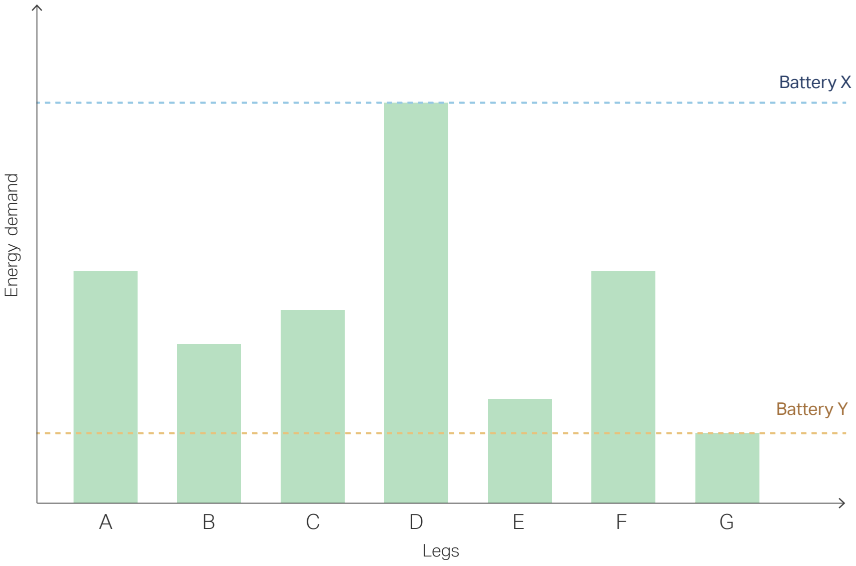


Figure 7: Principal approaches to battery capacity dimensioning when operating on a regular schedule. Battery X is dimensioned according to the leg with the highest energy demand, while Battery Y is dimensioned according to the leg with the lowest demand.



In our case study, we assume that the secondary electricity generation source will be conventional generator sets operated on a non-heated, low-GHG fuel, such as bio-diesel or renewable methanol. These generator sets must be sized to allow for safe navigation even in adverse weather conditions without battery assistance. We further assume that energy consumed while in port will be supplied directly from shore. By accepting that 20% of the energy (at sea) is supplied by onboard generation, we reduce the required battery capacity from 190 MWh to 100 MWh (useable). Figure 8 shows an overview of the energy demand per voyage leg as well as the chosen installed capacity.

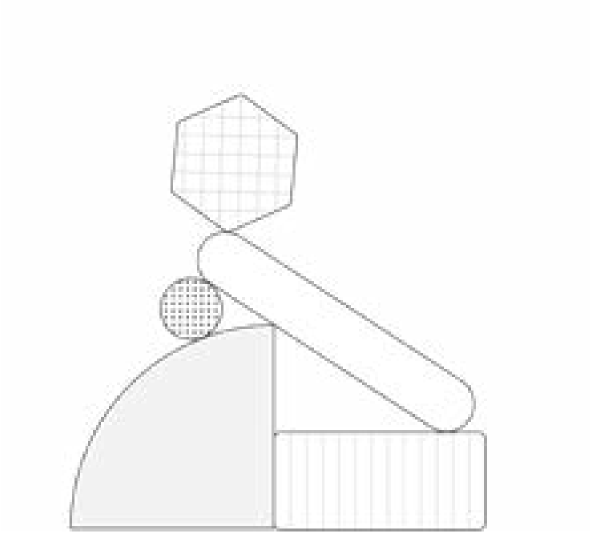
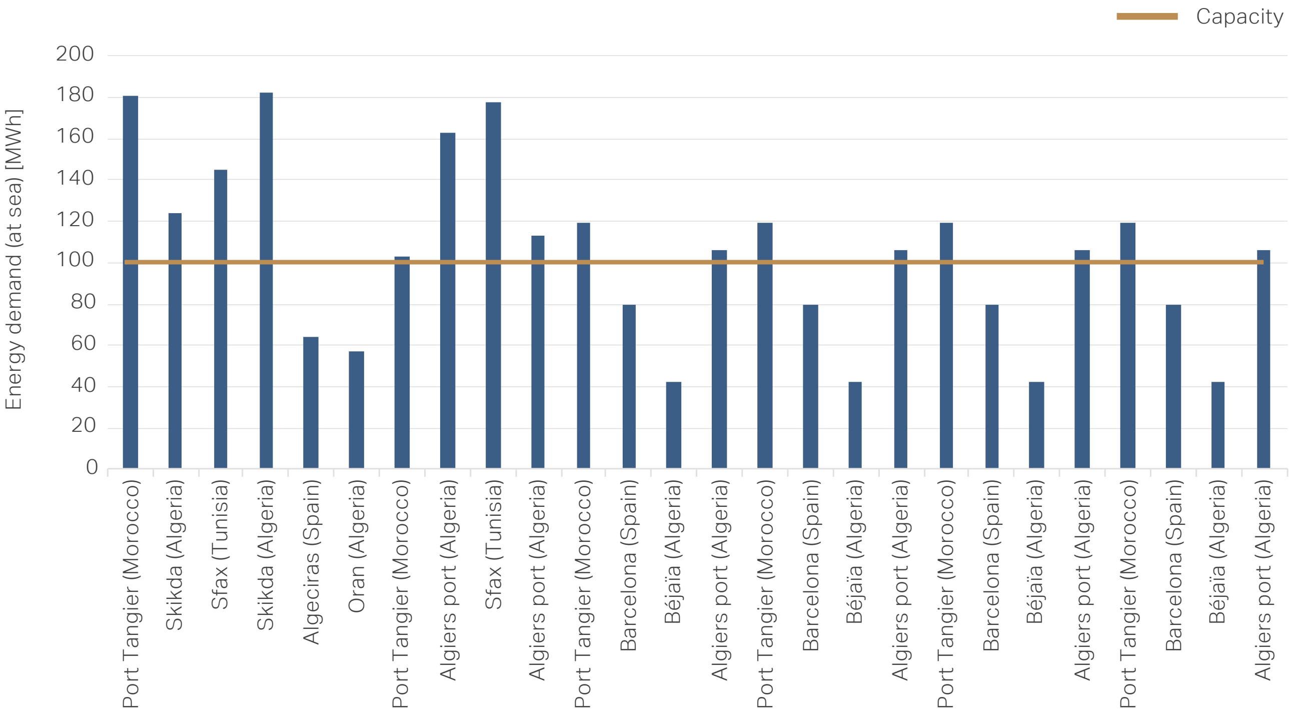


Figure 8: Overview of energy demand per voyage leg for the container ship case study schedule after adaptation to battery-electric operation. The horizontal line indicates the chosen installed battery capacity.



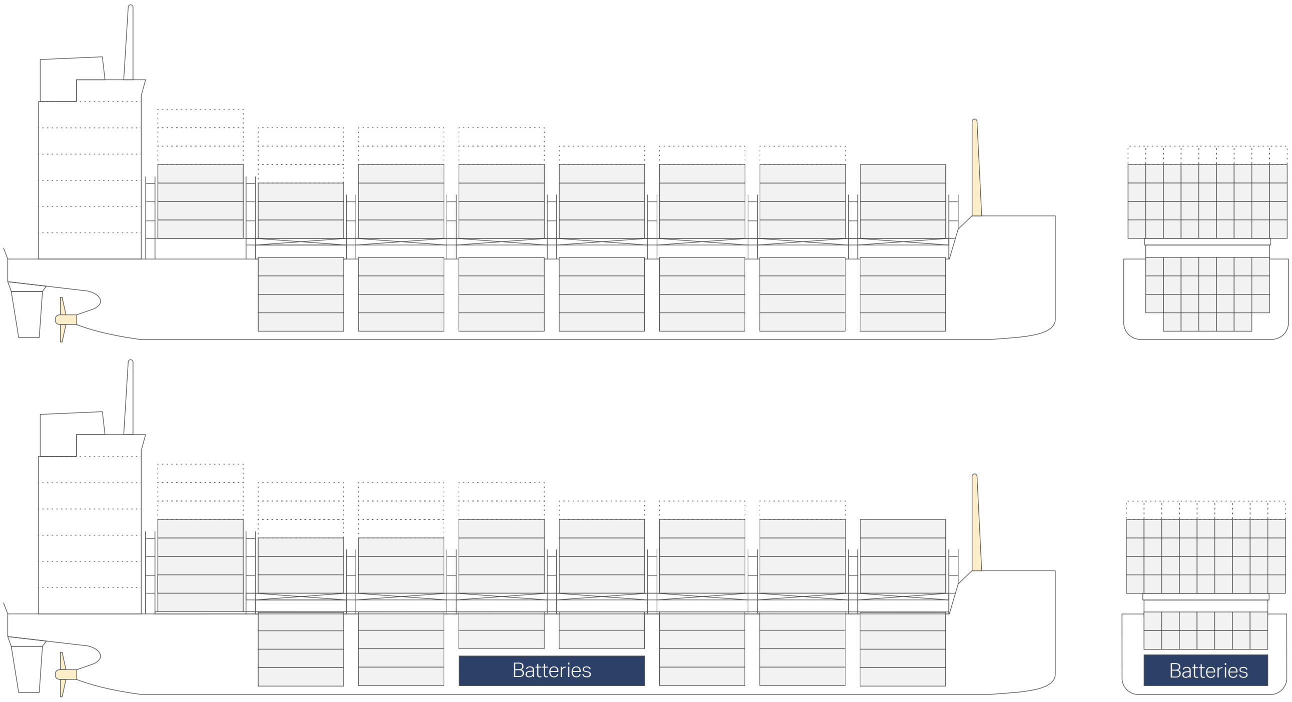
4.2.3 Adopt larger, containerized battery units

Lastly, we considered a case where, instead of a conventional battery room, a more flexible installation is adopted using large-capacity containerized battery units as outlined in Section 3.4. With the properties described in Table 3, approximately 34 units would be needed to achieve a total useable capacity of 100 MWh (120 MWh gross). From a cargo intake perspective, the best location is as low as possible and as close as possible to the midship region. This will optimize stability of the ship and minimize the amount of ballast water needed for trimming purposes.

Figure 9 shows a possible arrangement following this approach. In the example, for simplicity, the lower two tiers in the central cargo holds were completely allocated to battery storage, although this volume in fact corresponds to 48 battery units. This arrangement thus allows space for auxiliary equipment or later expansion of energy capacity, as well as for the required 34 battery units themselves.

At this stage, we assume that the engine room volume is identical for both the conventional-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 for the battery-electric vessel.

Figure 9: 1,100 TEU container ship general arrangement. Top: Baseline vessel (conventional-fueled, ICE-powered). Bottom: Battery-electric vessel with optimized battery system design. Battery spaces are marked in dark blue.



4.3 Optimized ship arrangement and performance

Table 6 shows a comparison of some key particulars and performance characteristics of the baseline vessel and the battery-electric vessel after the three optimization steps outlined above. Despite some reduction in machinery weight, the deadweight of the battery-electric vessel is reduced by about 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, we find that the cargo carrying capacity of the battery-electric hybrid container ship can be maintained in this example. We could note 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 and, at some point, the loss of cargo intake will approach the deadweight loss in the fully loaded condition.

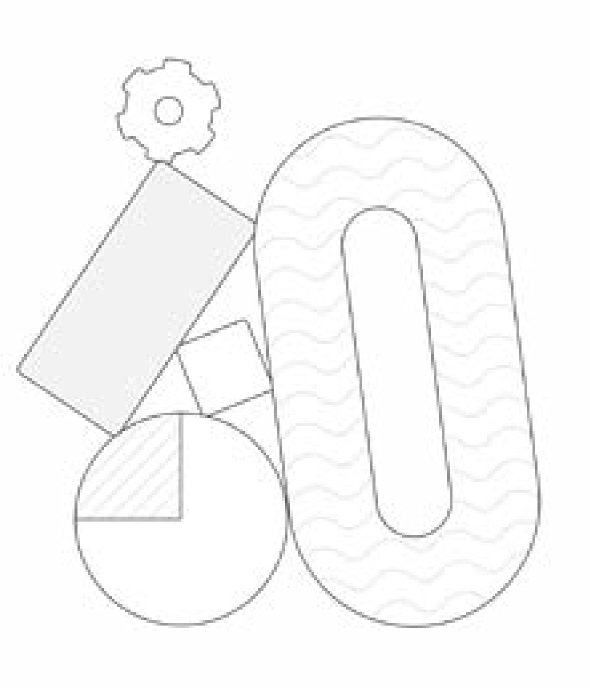


Table 6: Key particulars and cargo capacity for the baseline vessel (conventional-fueled) and the optimized hybrid battery-electric vessel (BEV).

Key vessel particulars and cargo capacity		Baseline	BEV	Diff.
Length	m	149	149	
Beam	m	23.3	23.3	
Depth	m	11.5	11.5	
Nominal TEU	TEU	1,056	1,070	14
Displacement	tonnes	19,883	19,883	
Deadweight	tonnes	14,381	13,577	-804
Homo. Intake @ 9t/TEU	TEU	902	896	-6
Homo. Intake @ 11t/TEU	TEU	808	800	-8
Homo. Intake @ 14t/TEU	TEU	718	704	-14

4.4 Charging rates and infrastructure considerations

The charge rates required for the optimized schedule are in the range of 2-8 MW, depending mainly on port productivity. In some cases, the battery is not fully depleted when arriving at the next port, and a full charge can be achieved in a shorter period or at a lower charge rate. We find that the charging requirements for this example case are achievable within the limits of a typical shore power connection. For cases where, for example, 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, such as:

- Dedicated high-power charging infrastructure in the terminals

  High-power charging concepts from 10 MW to 35 MW are already available and in operation or under construction.[5,19] However, the impact of this option on flexibility of berth allocation, local electricity availability, and the levelized contribution to the electricity cost needs further exploration.

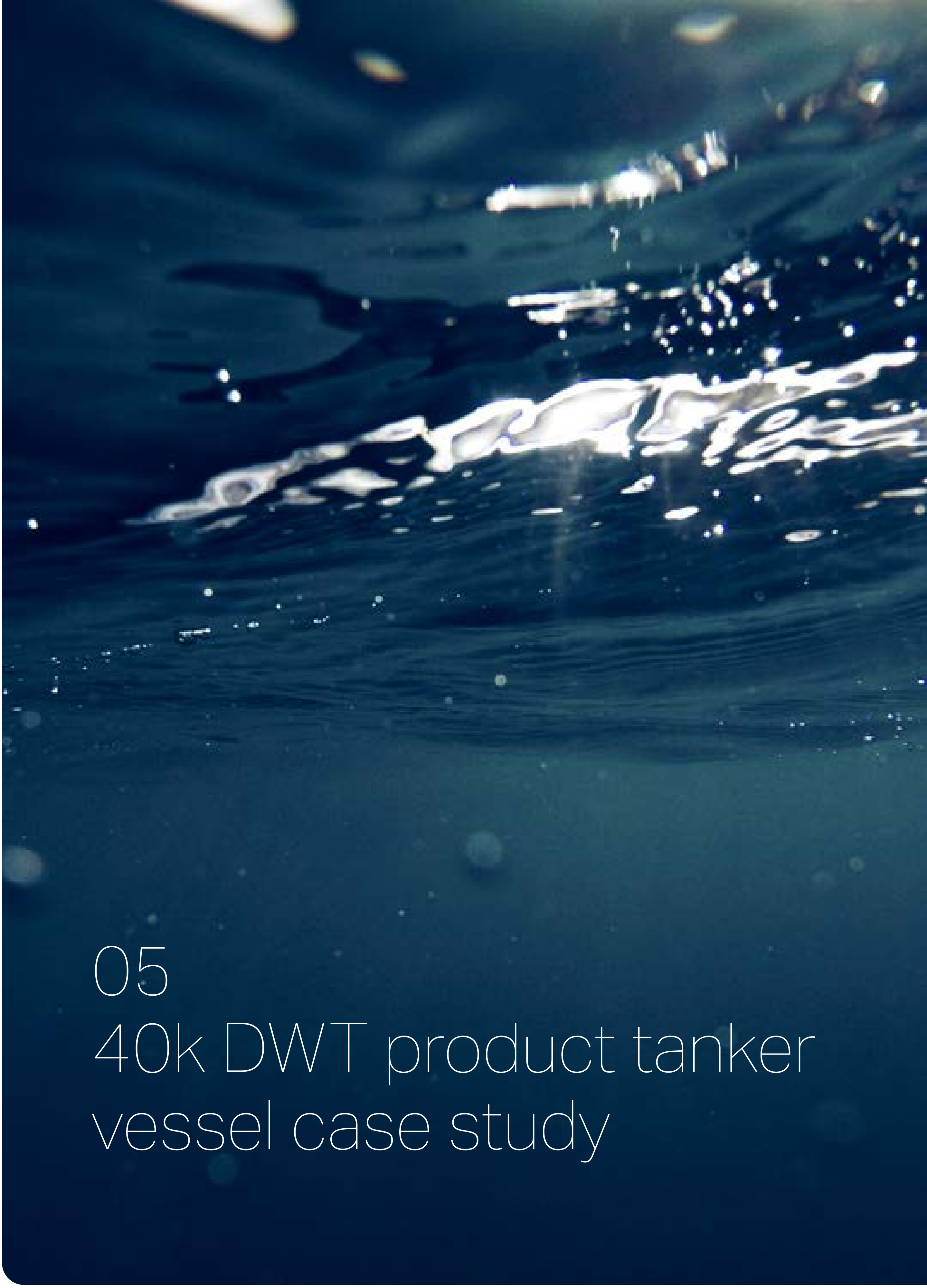
- Offshore charging (e.g., in connection with offshore renewable energy farms)

  As already shown in this case study, the necessary battery capacity can be reduced considerably by introducing additional charging stops. In addition to lowering the initial investment cost, this strategy could potentially lower the necessary charging rate.

  Offshore wind turbine farms are expected to account for a significant part of existing and future renewable energy production capacity.[1] These farms are typically located relatively close to the shore, based on consideration of water depth and transmission infrastructure cost. Such wind turbine farms could constitute a potential charging point where major investment in power generation, transformers, and electrical transmission infrastructure is already financed. If the wind turbines are operational, they can supply the charging power directly. If not, the power can be supplied from the shore grid using the existing cable and transformers.

- Swapping of battery units

  Swapping of discharged battery units with others charged onshore theoretically allows very high charging rates. This practice has the additional benefit of allowing the existing container cranes and vehicles to be used and avoiding issues with dedicated berth allocation. The charging of the battery units can become independent of the vessel's port call, thereby evening out grid load and potentially allowing cheaper electricity costs. The main drawback to this approach is that a larger total battery capacity is needed, since additional sets of battery units will have to be charging while the ship is sailing. This challenge can be somewhat mitigated by multiple ships sharing a fleet of battery modules.



05

40k DWT product tanker vessel case study

Tanker vessels transporting refinery products are traditionally operated in a so-called tramp shipping scheme, with global deployment of the vessels and irregular transits between regions depending on market conditions. Smaller vessels, however, are also used in more regional shuttle-like services, where the refinery products are distributed to multiple discharge ports or transported to a storage facility for further distribution.

Based on data provided by partners to the MMMCZCS, we derived a hypothetical shuttle service between a refinery for renewable road transport and aviation fuels and a central storage facility in Denmark or the south of Sweden. The vessel is assumed to transit from the load port in Porvoo, Finland loaded with cargo (laden condition) to the discharge port in Kalundborg, Denmark, and returns empty (ballast condition) to the refinery. We assume that, in both ports, renewable electricity is available and shore power connection will be established in the near future due to regulatory pressure.

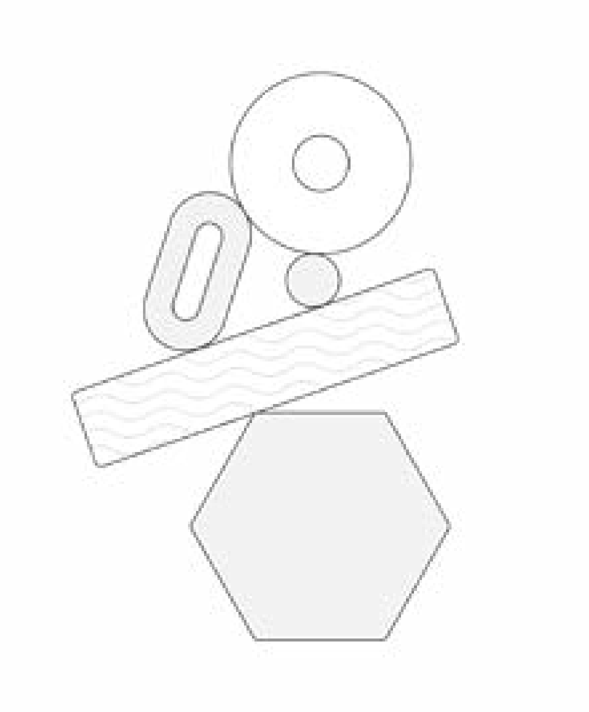


Figure 10: Product tanker case study. Shuttle service between refinery in eastern Baltics and Denmark.

We simulated the performance and fuel consumption of a conventional, fossil-fueled 40k DWT product tanker on this voyage, considering historic weather conditions, and derived an average energy demand. We did not assume that the baseline vessel would be equipped with a shore power connection.

We can see that, due to the relatively short length of the sea passages, the port operations contribute more than one-third of the vessel's total energy requirements (Table 7).

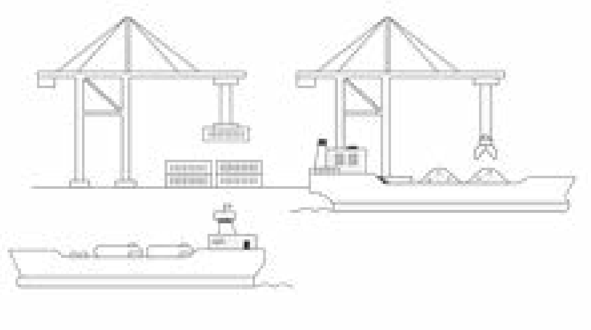


Table 7: Breakdown of 40k DWT product tanker vessel average performance for shuttle service between refinery in eastern Baltics and Denmark. Length of voyage leg 712 NM, vessel speed (laden/ballast) 12 knots. Port stay (load/discharge) three days.

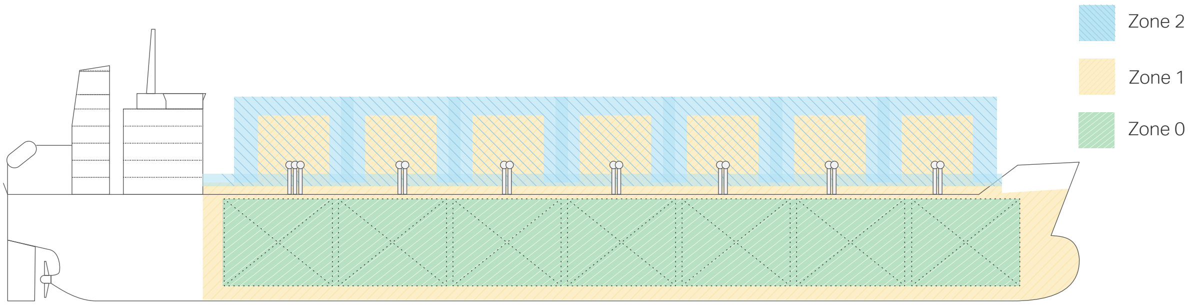
	Average ME power	MGO eq. consumption	Final energy demand
Load port		15 tonnes	71 MWh
Sea-passage laden	3,587 kW	42.1 tonnes	230.6 MWh
Discharge port		33 tonnes	157 MWh
Sea-passage ballast	2,531 kW	30.3 tonnes	162.2 MWh

ME = main engine, MGO = marine gas oil.

Applying the hybrid power plant philosophy (introduced in the container vessel case), we consider that, on average over a roundtrip from load port to load port, 80% of the final energy demand at sea should be supplied from the batteries, with the remaining energy supplied by generating sets fueled by methanol. Thus, an installed battery capacity of 250 MWh with a state-of-charge (SoC) range between 10% and 90% is sufficient. During port operations, the energy is supplied via a shore power connection. Looking at the expected energy consumption while in port, we see that a 5 MW shore power supply is sufficient, even for operations in the discharge port.

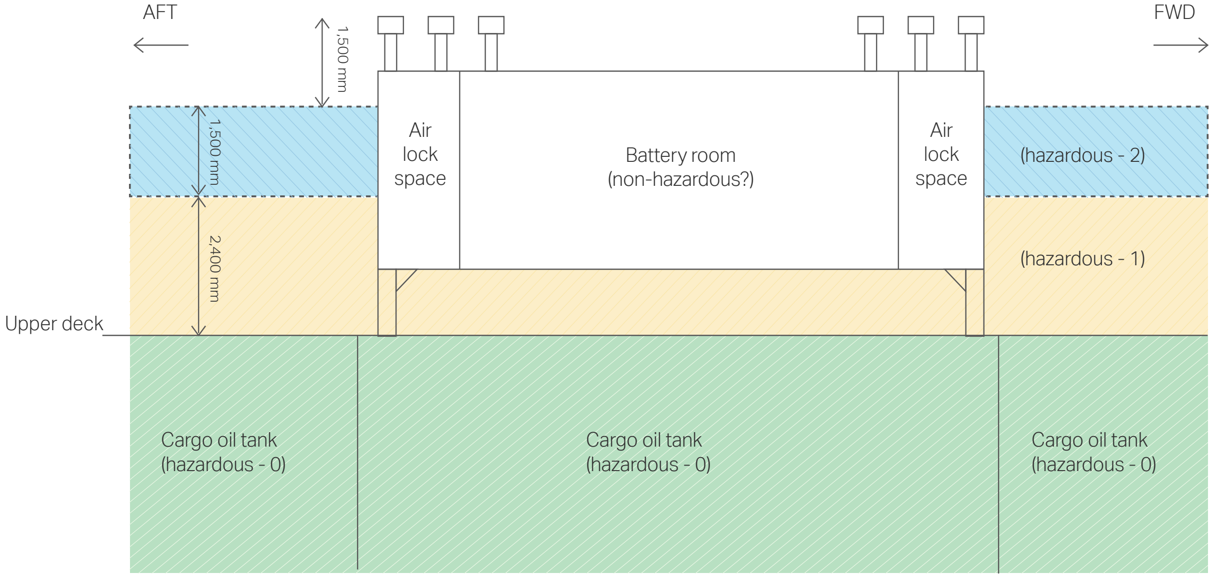
The integration of the battery rooms or spaces into the tanker vessel is not as straightforward as in the container ship case. This is because the majority of the space on board a tanker vessel carrying petroleum products is categorized as a hazardous zone.[20] For instance, the cargo tanks are hazardous zone 0, requiring the strictest safety measures, whereas the space above the cargo tanks on deck is either hazardous zone 0, 1, or 2, depending on the distance to the deck or any cargo tank ventilation ducts (see Figure 11).

Figure 11: Example hazardous zone plan of a product tanker vessel.



The battery room, as shown in Figure 12, can be categorized as a non-hazardous area under specific conditions, based on our interpretation of the classification society requirements.[16] For example, the bottom of the battery room must be detached from cargo tanks, the battery room must be fitted with air-lock spaces, and any ventilation inlets or outlets of the battery room must be arranged 1.5 meters above any hazardous area. In this case, a battery module without explosion-proof design can be arranged in this room. We acknowledge that this a disruptive design approach, and further investigations must be made in terms of risk assessment together with classification societies before such a battery integration could be approved based on an alternative design approach.

Figure 12: Battery arrangement on the 40k DWT product tanker vessel in relation to the hazardous zones present on a tanker vessel.



For our basic study, we decided to look at the integration of the most compact, containerized battery arrangement on the upper deck of the tanker. To accommodate the required installed battery capacity of 250 MWh, we will require 68 TEU batteries, located in four arrays, as shown in Figure 13. This compact packaging of the batteries also minimizes impact on the stability of the vessel, as only one tier of containers is required. A detailed calculation of the stability and longitudinal strength of the vessel could not be done at this stage, but must be performed during a detailed design of such battery integration to determine the feasibility of this concept.

The weight of the installed batteries is roughly 2,000 tonnes. We assume that the cargo capacity of the vessel will be reduced accordingly, although we do not reduce the volume of the cargo tanks.

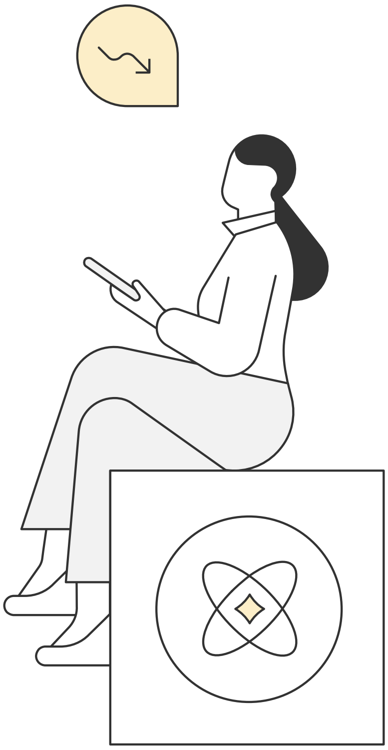
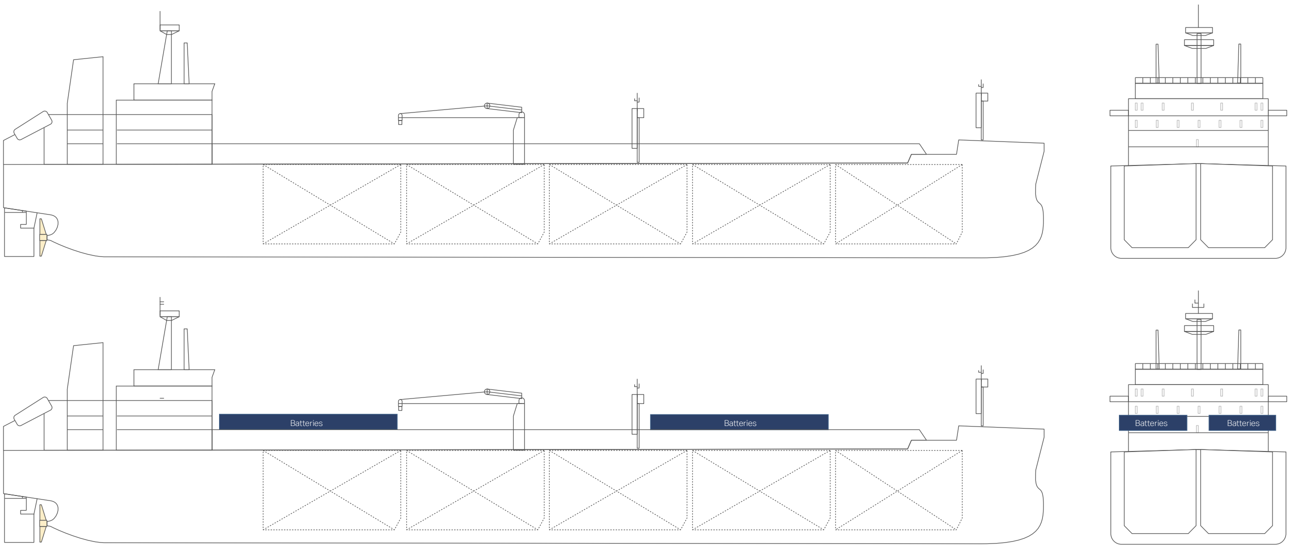


Figure 13: 40k DWT product tanker vessel general arrangement. Top: Baseline vessel (conventional-fueled, ICE-powered). Bottom: Battery-electric vessel with containerized battery system design. Battery spaces are marked in dark blue.



06

35k DWT dry-bulk vessel case study

Similarly to product tanker vessels, most dry-bulk vessels operate in a tramp shipping business model. Based on data provided by partners to the MMMCZCS, however, we found trades for small dry-bulk vessels with a strong regional focus. We selected a voyage in the Gulf of Mexico as part of a network of ports for the import and export of agricultural products. Here, the length of individual voyage legs is between 600 NM and 800 NM. We note that transporting agricultural products is a highly seasonal business, and there might also be trades with more of a regular shuttle-service character. Furthermore, based on our assessment, the availability of shore power connections is considered low to non-existent in that region. Conversely, the availability of renewable electricity is high, in particular on the US side of the Gulf. Consequently, this would be a suitable location to roll out shore power connections.

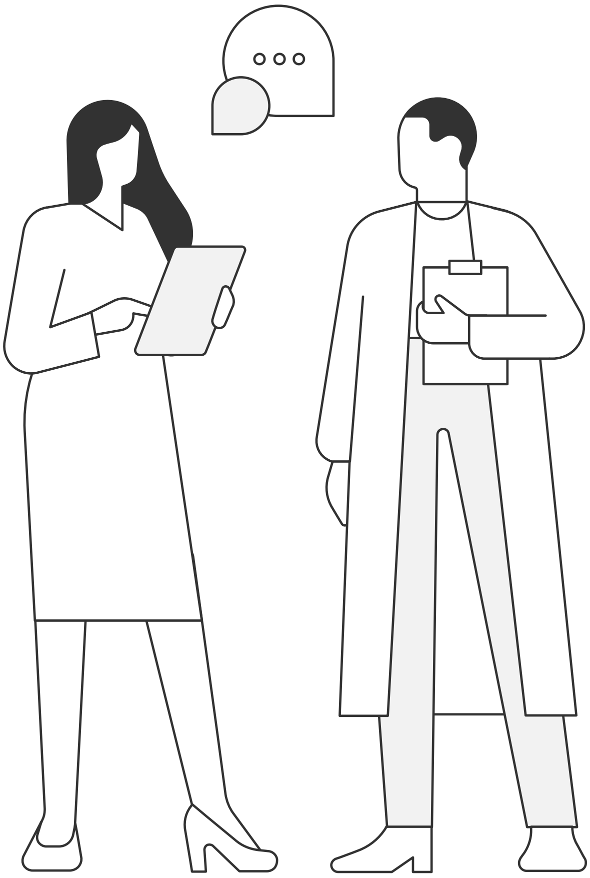


Figure 14: Dry-bulk vessel case study. Trade of agricultural products in the Gulf of Mexico.

We simulated the performance and fuel consumption of a conventional, fossil-fueled 35k DWT dry-bulk vessel on this voyage, considering historic weather conditions, and derived an average energy demand. We can see that, due to the relatively short length of the sea passages, the port operations contribute almost 40% of the total energy requirement (Table 8).

Similarly to the tanker vessel, we do not assume a shore power connection in the baseline case. In contrast to the operating profile of the tanker vessel, we do not expect much difference in terms of energy requirements between loading and discharging operations in port. However, we note that Handysize dry-bulk vessels are equipped with cranes for cargo handling. Therefore, we do consider an increased energy requirement during port stay in ports with insufficient cargo handling infrastructure.

Table 8: Breakdown of 35k DWT dry-bulk vessel average performance trading agricultural products in the Gulf of Mexico. Length of voyage leg 622 NM, vessel speed (laden/ballast) 12 knots. Port stay (load/discharge) five days.

	Average ME power	MGO eq. consumption	Final energy demand
Load port		22.5 tonnes	107 MWh
Sea-passage laden	4,245 kW	34.6 tonnes	210.6 MWh
Discharge port		22.5 tonnes	107 MWh
Sea-passage ballast	2,629 kW	23.3 tonnes	137.6 MWh

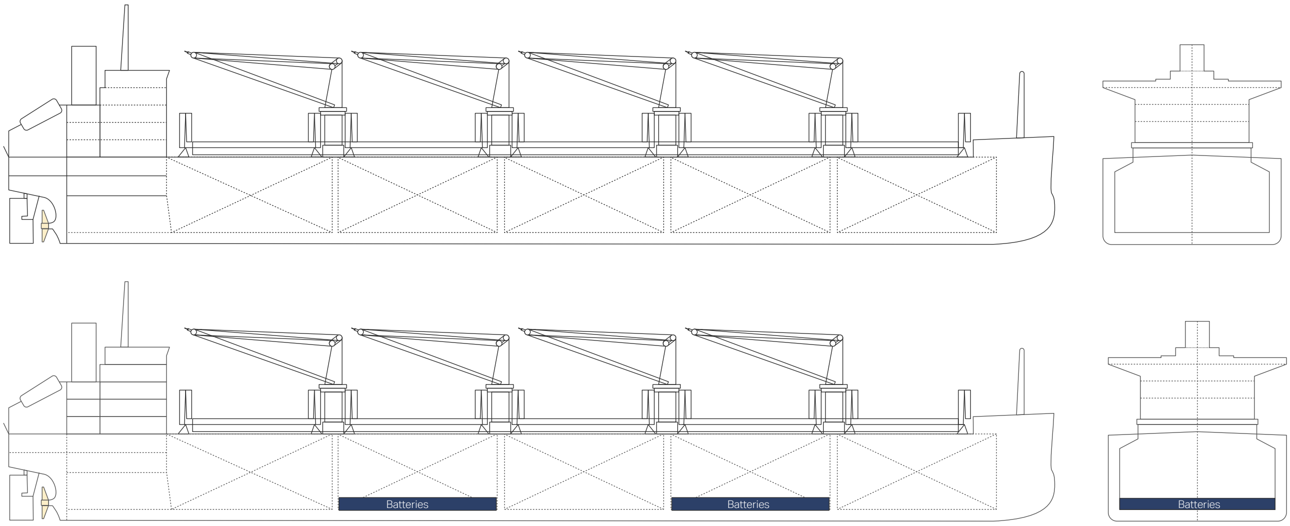
ME = main engine, MGO = marine gas oil

Applying the hybrid power plant philosophy (introduced in the container vessel case), we consider that, on average over a voyage from load port to load port, 80% of the final energy demand at sea should be supplied from the batteries, with the remaining energy demand supplied by generating sets fueled by methanol. Thus, an installed battery capacity of 220 MWh with a SoC range between 10% and 90% is sufficient. During port operations, energy is supplied via a shore power connection. A 5 MW shore power supply is sufficient, even considering the increased power demand due to cargo handling with ship-bound gear.

We studied the design implications of a 35k DWT dry-bulk vessel switching from a fuel oil-powered baseline vessel design to a battery-powered vessel design employing a non-optimized state-of-the-art battery arrangement. The accommodation of the non-optimized battery system requires a large amount of space, as shown in Figure 4. In addition to the battery system, the switchboard to connect consumers and energy input/storage also increases in size and weight. We decided to place the battery rooms in cargo holds No. 2 and No. 4 to avoid impact on alternate loading and give maximum flexibility for the placement of the switchboard, propulsion motors, and generating sets running on methanol in the engine room. To avoid exceeding limits on stability and longitudinal strength, however, the size of the fuel tanks had to be reduced from 1,450 m^3 to only 220 m^3.

Whereas the baseline vessel can operate for roughly 65 days on fuel oil, the battery-electric vessel can only operate for 4.5 days on methanol fuel alone, without considering the energy stored in the batteries. Considering that the latter vessel has a targeted range of 600-800 NM, the available amount of energy on board the vessel should be sufficient for either reaching the next safe harbor or even for relocating the vessel across the Atlantic Ocean at its smallest extension (between Fortaleza, Brazil and Kamsar, Guinea – 1,670 NM). The additional weight of the batteries and the volume placed in two out of five cargo holds reduces the cargo capacity from 45,600 m^3 (35,500 tonnes) to 39,300 m^3 (33,100 tonnes), representing a cargo loss of 13% (volume) or 7% (mass). This allows us to maintain the principal dimensions of the baseline design.

Figure 15: 35k DWT dry-bulk vessel general arrangement. Top: Baseline vessel (conventional-fueled, ICE-powered). Bottom: Battery-electric vessel with non-optimized battery system design. Battery spaces are situated in No. 2 and No. 4 cargo holds, marked in dark blue.



07

Techno-economic analysis

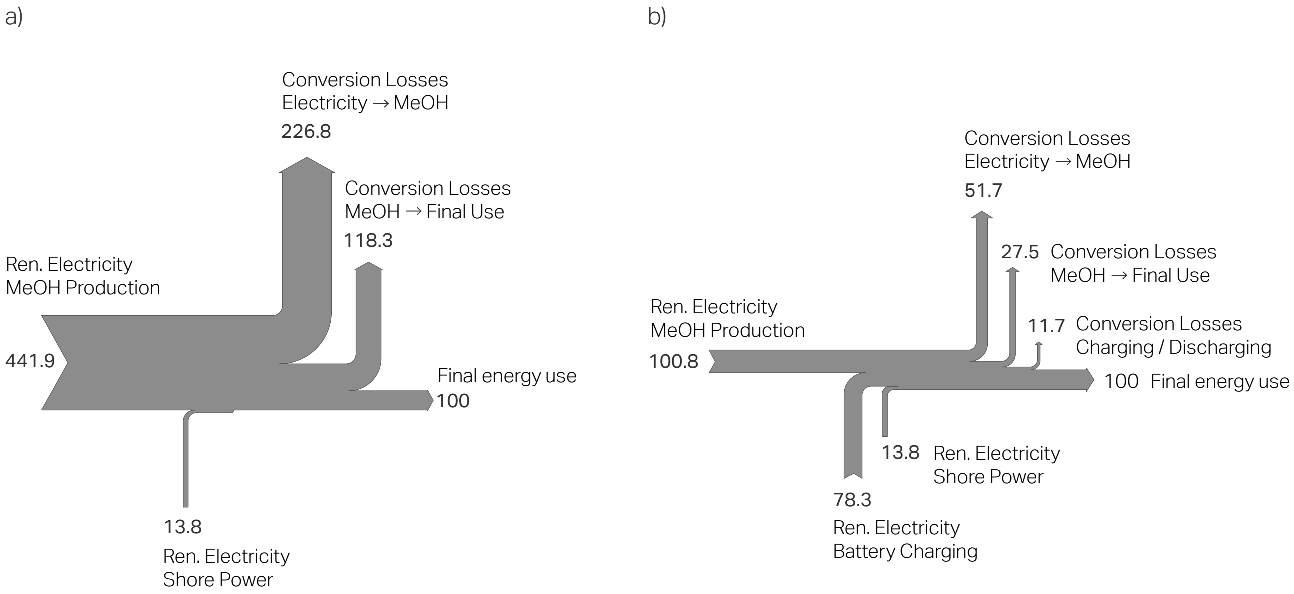
7.1 Life-cycle energy demand and total cost of ownership for battery-powered vessels

We analyzed the life-cycle energy demand of the optimized battery-electric container ship described in Section 4.3 and compared the results to an equivalent ICE-powered container vessel fueled by e-methanol (baseline case). We assume that the ICE-powered vessel is already equipped with a shore power connection.

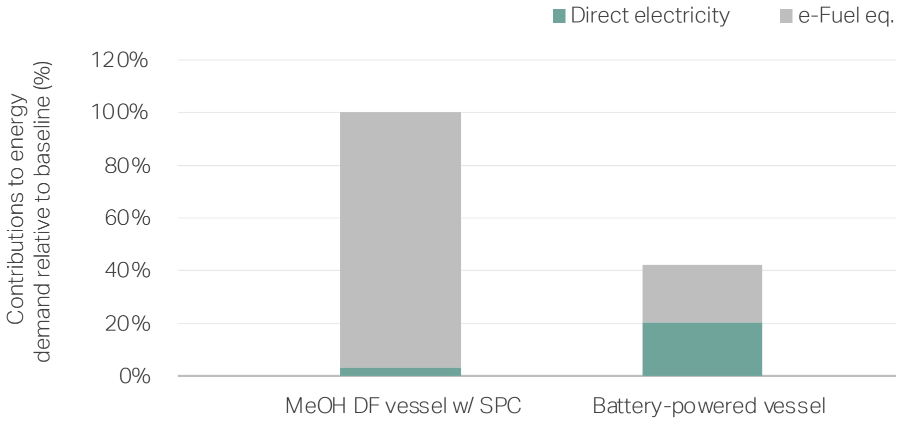
The Sankey diagram in Figure 16a shows that the direct electricity supplied via the shore power connection in the baseline case contributes only a minor amount of the total required renewable energy. In fact, most of the total required renewable energy for this design is used to produce the e-methanol. Applying the hybrid power plant philosophy, we can shift most of the energy supply during sea passage from methanol to the battery. Thus, the renewable electricity required for methanol production could be reduced to less than one-quarter of that in the baseline case (Figure 16b). Direct electricity, comprising shore power connection and battery charging, contributes the same demand for renewable energy as electricity for e-fuel production. Overall, comparing the baseline case with the battery-electric vessel, we can reduce the life-cycle renewable energy demand by more than 60% (Figure 16c).

Figure 16: 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.

a) and b): Energy flow and conversion losses (values in arbitrary units).
a) Baseline MeOH DF vessel with shore power connection (SPC).
b) Battery-powered vessel applying the hybrid power plant philosophy.
c) Contributions to energy demand relative to baseline. Left bar: Baseline MeOH DF vessel with SPC.
Right bar: Battery-powered vessel applying the hybrid power plant philosophy.



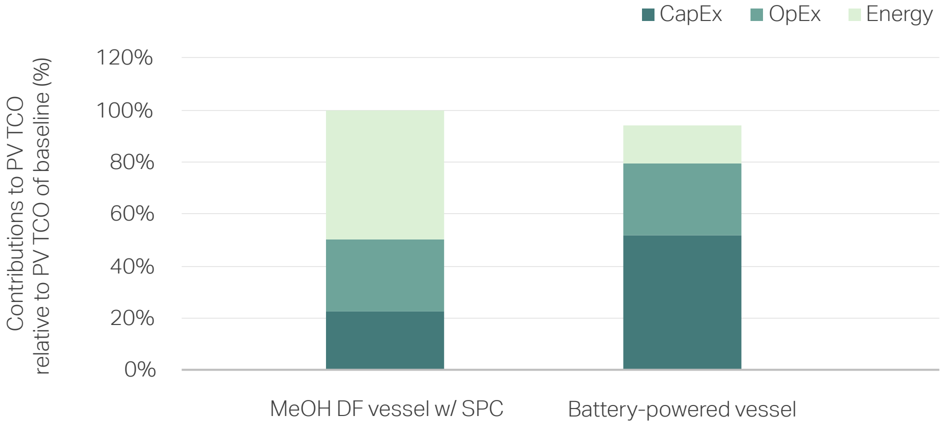
c)



Finally, we also evaluated the total cost of ownership (TCO) of these two vessel configurations based on current market prices for the vessel in a methanol dual-fuel configuration (Figure 17). A detailed description of the assumptions can be found in the Appendix (Section A.3). We derived pricing of e-methanol and electricity from MMMCZCS's techno-economic model, NavigaTE.[11] The price for the battery system was based on input from battery system vendors and with a deployment date of around 2028 in mind. Our assumption matches the expected price level for stationary utility-scale battery systems in the range of 300 USD/kWh.[21]

We see that around 50% of the TCO originates from fuel expenditure in the baseline vessel configuration (Figure 18). However, while the energy expenditure is drastically reduced in the battery-powered vessel configuration due to the increased life-cycle 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. The cost of replacing the battery modules over the vessel's lifetime is also a factor, but we assume that this contribution will be relatively minor based on our expectations regarding battery resale value and declining battery prices as time goes on. We see a break-even between both configurations when the battery system cost is around 350 USD/kWh. Our analysis of sensitivity to methanol price level, electricity price level, and battery price level is described in the Appendix (Section A.4).

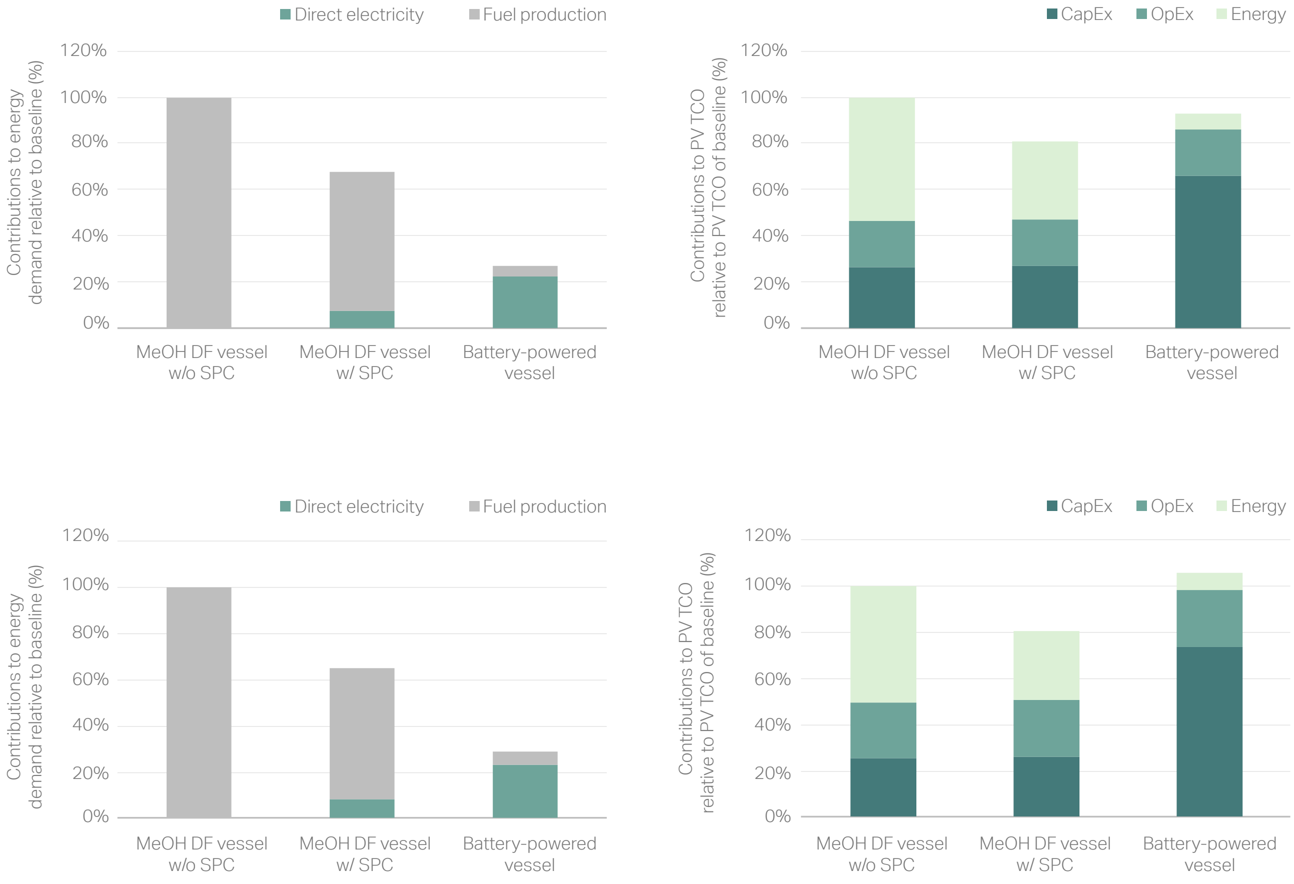
Figure 17: Financial analysis of container ship case study. Contributions of capital expenditure (CapEx), operating expenses (OpEx), and energy cost to the present value (PV) total cost of ownership (TCO) relative to the baseline. Left bar: Baseline methanol dual-fuel (MeOH DF) vessel with shore power connection (SPC). Right bar: Battery-powered vessel applying the hybrid power plant philosophy.



We also performed corresponding analyses of energy efficiency and TCO for both the tanker and the dry-bulk vessel cases. In these analyses, we assumed that the baseline vessel has no shore power connection. In this way, we could also investigate how shore power connection influences both life-cycle energy efficiency and TCO (Figure 18). We see that, in both cases, the shore power connection can already reduce the renewable energy demand by more than 30% compared to the baseline vessel configuration. The battery-electric vessel, however, can further reduce the energy demand by more than 70% compared to the baseline vessel.

Overall, the TCO results are similar for the battery-powered tanker vessel and container vessel. Conversely, the battery-powered dry-bulk vessel has a downside compared to the baseline vessel due to the stronger increase in CapEx for the battery system relative to the baseline vessel price. For both the tanker and dry-bulk cases, installation of a shore power connection reduces the TCO by roughly 20% (Figure 18).

Figure 18: Techno-economic analysis of the tanker vessel (top) and the dry-bulk vessel (bottom) cases. Left: Analysis of renewable electricity required to power case vessels using a methanol dual-fuel ICE (MeOH DF) or battery with methanol-fueled auxiliary power. Right: Financial analysis of the tanker and dry-bulk case studies. Contributions of capital expenditure (CapEx), operating expenses (OpEx), and energy cost to the present value (PV) total cost of ownership (TCO) relative to the baseline. Left bars: MeOH DF vessel without shore power connection (SPC). Center bars: MeOH DF vessel with SPC. Right bars: Battery-powered vessel applying the hybrid power plant philosophy.



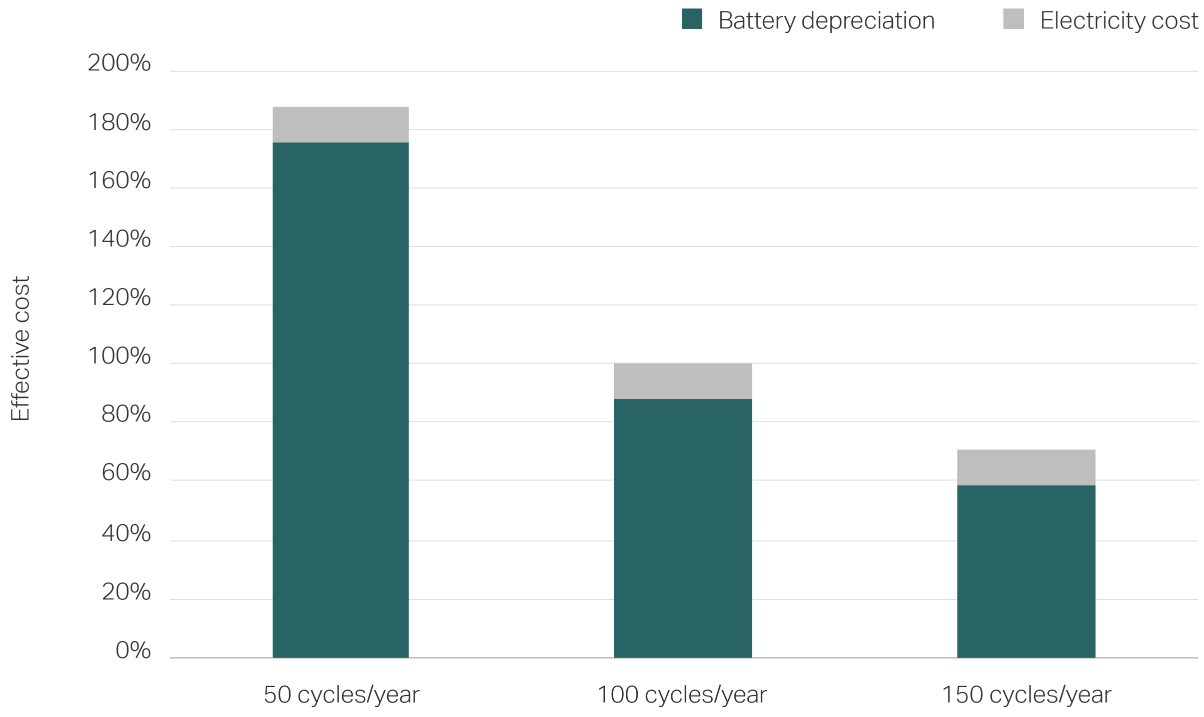
7.2 Drivers for effective battery energy cost

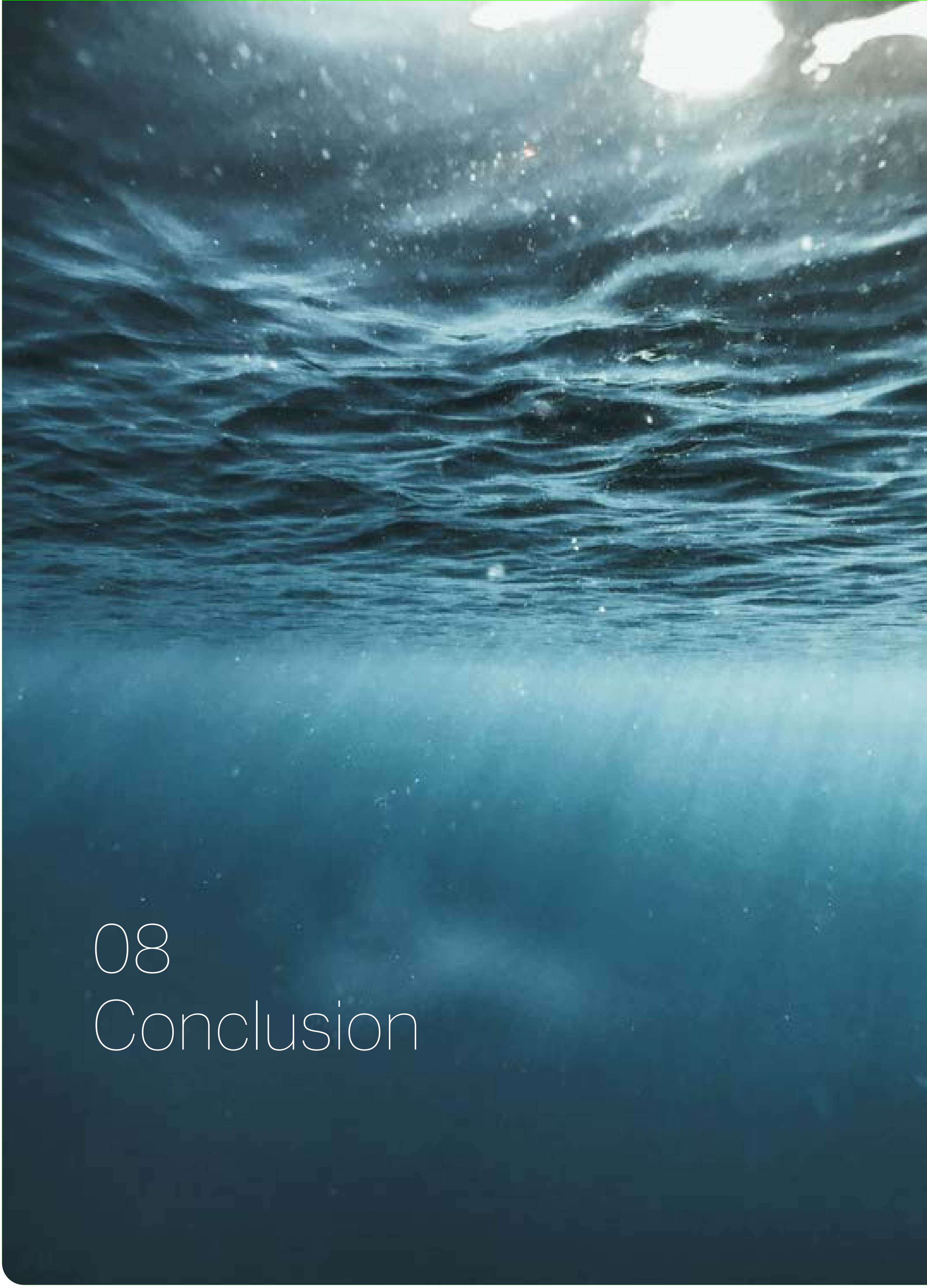
The attractiveness of using batteries for storing energy results from their high life-cycle efficiency considering the chain from production of electricity to consumption on board, e.g., propulsion. The cost of a unit of energy in the form of electricity is many times lower than what can be expected for e-fuels. However, the storage system (i.e., the battery) requires a high upfront investment.

Consequently, the effective cost of a unit of electrical energy is usually dominated by the cost contribution from the depreciation of the battery value. The application of batteries as large-scale energy storage on ships means quite low discharge rates and a small number of charging/discharging cycles in the lifetime of the battery. Consequently, the degradation of the battery is likely to be mostly in terms of calendar time, and the critical parameter for making batteries cost-competitive with alternatives is to ensure that as much electrical energy as possible is cycled through the battery.

Figure 19 illustrates how the number of yearly full battery cycles impacts the average effective cost of the electrical energy. The figure is just an example, and the ratio between direct electricity cost and battery depreciation is, of course, influenced by both battery-specific cost and the cost of electricity. Except for short-sea ferries, the depreciation is likely to remain the dominant contribution.

Figure 19: Illustrative example of the dependency of the effective cost of electricity in a battery on the number of yearly full charge/discharge cycles.





08
Conclusion

In this study, we have investigated whether and how battery-powered vessels may play a role in deep-sea shipping. We see that vessels powered by batteries alone are not a viable solution for every vessel size and segment today. Even for smaller merchant vessels on short voyages, this concept comes along with unreasonable operational inflexibility, a high loss of cargo capacity, and high CapEx.

Therefore, we identified a hybrid power plant solution as a very reasonable pathway going forward. In this solution, an average of 80% of the vessel's energy requirement is covered by batteries, while the remaining energy requirement is covered by generating sets run on renewable fuel. This approach enables a drastic reduction in renewable energy demand of up to 70% compared to a methanol dual-fuel vessel, while maintaining operational flexibility and ensuring safe navigation in adverse weather conditions. Furthermore, the installed battery capacity can also be reduced substantially compared to a first-order 'naïve' capacity design, depending on the operating profile of the vessel, thereby reducing the CapEx for the vessel.

However, we also see that compact packaging of modular battery systems is required to allow the design of primarily battery-powered small merchant vessels without detrimental cargo loss in comparison to today's baseline vessels. Based on discussions with battery suppliers, we expect that the required battery system technology will be available by 2030 at prices that allow for a competitive business case.

Targeting smaller-sized merchant vessels on short voyages for electrification ultimately has the potential to address up to 17% of today's CO_2 emissions in the respective vessel segments. Furthermore, by increasing the life-cycle energy efficiency of the vessels' operation, an additional 1.8 EJ of renewable energy would be freed up for e-fuel production. However, for this potential to be fully exploited, it is not only necessary to design, build, and employ the vessels, but also for ports to be equipped with shore power connection or dedicated charging infrastructure with sufficiently high-power supply. Stakeholders should additionally consider the availability of electricity sources with low carbon intensity and how these overlap with shipping routes.

We encourage shipowners to thoroughly investigate direct electrification of merchant vessels as a viable decarbonization strategy before considering alternative fuels. Our research demonstrates that hybrid solutions can effectively address the challenges associated with electric vessels.

Additionally, we call on regional and local governments to invest in infrastructure projects that facilitate shore power connections and charging infrastructure in ports. These initiatives not only support the growing demand for electrification but also alleviate pressure on grid connections, ultimately reducing the overall demand for renewable electricity required for e-fuel production.

09

The project team

This report was prepared by the Mærsk Mc Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) with assistance from our partners. Team members marked with an asterisk (*) were seconded to the MMMCZCS from their home organization.

Lead author: Jan Seidl-Zelenka (NORDEN)*, Lasse Normann de Boer (Maersk)*.

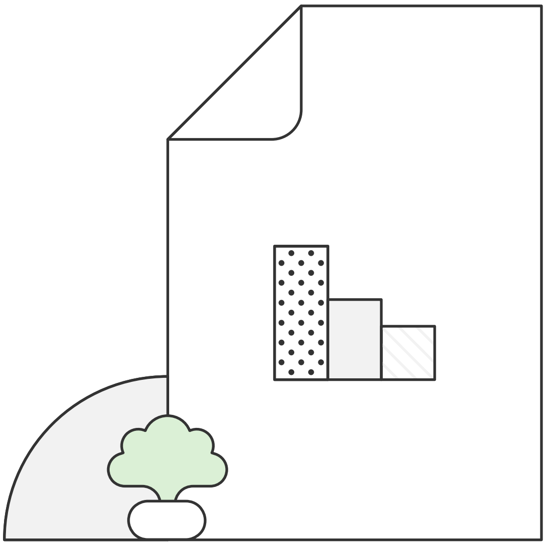
Contributing authors and project participants: Tadashi Inoue (Tsuneishi)*, Dafni Sofiadi (ABS)*, Sean Crowley (Stolt Tankers), Kay Tigges (Siemens Energy)*, Peter Lystrup Christensen (MMMCZCS).

Steering committee: Claus Winter Graugaard † (MMMCZCS), Estela Vázquez Esmerode (MMMCZCS), Octavi Sadó Garriga (MMMCZCS).

Reviewers: Claus Winter Graugaard † (MMMCZCS), Estela Vázquez Esmerode (MMMCZCS), Octavi Sadó Garriga (MMMCZCS).

Editor: Matilda Handsley-Davis (MMMCZCS).

Design: SPRING Production.



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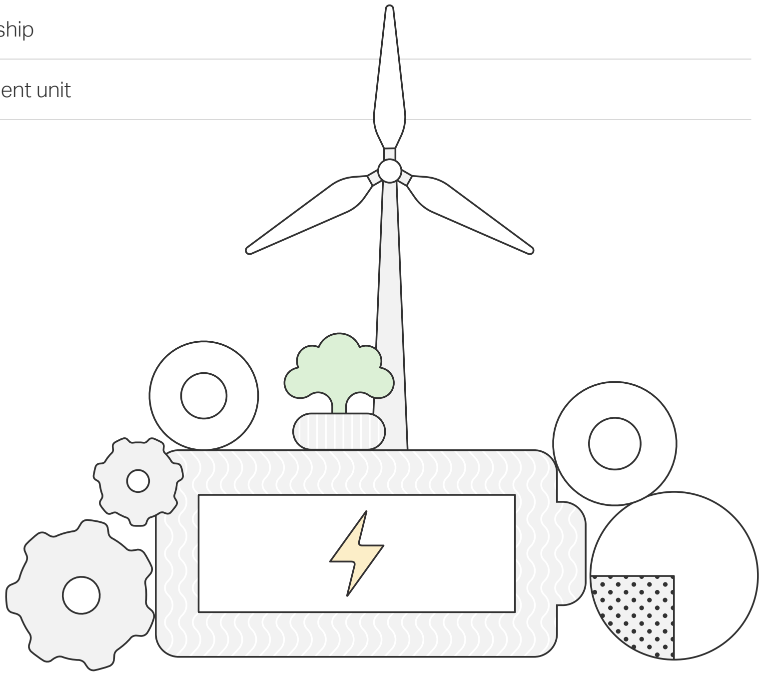
for Zero Carbon Shipping

10

Abbreviations

ABS	American Bureau of Shipping
CapEx	Capital expenditure
CO_2	Carbon dioxide
DWT	Deadweight tons
GHG	Greenhouse gas
ICE	Internal combustion engine
LFP	Lithium iron phosphate
MeOH-DF	Methanol dual-fuel
MMMCZCS	Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
NM	Nautical miles
OpEx	Operating expenses
SoC	State-of-charge
TCO	Total cost of ownership
TEU	Twenty-foot equivalent unit



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https://ww2.eagle.org/content/dam/eagle/rules-and-guides/current/other/275-requirements-for-use-of-lithium-ion-batteries-in-the-marine-and-offshore-industries-2024/275-lithium-ion-batteries-reqts-Apr24.pdf
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Appendix

A.1 Analysis of shipping energy requirements to define case study vessels

As briefly described in Section 3.2, we used voyage data supplied by partners to calculate energy requirements for propulsion and auxiliary services on different vessel types, and then sorted these requirements into bins. The results shown in Figure 20 indicate that the smaller vessel sizes (up to 55k DWT for tankers, up to 60k DTW for dry-bulk, and up to 40k DWT for container vessels) dominate the shorter voyage legs with energy requirements of up to 250 MWh. Furthermore, we can see that these voyages, on average over the different segments, already represent more than 5% of total CO_2 emissions of these segments (17% for tanker vessels, 5% for dry-bulk vessels and 8% for container vessels, respectively). Considering the increased life-cycle energy efficiency of battery-electric propulsion, a full switch of the fleet operating on these voyages (up to 250 MWh energy demand) would release 1.8 EJ of renewable energy for e-fuel production.

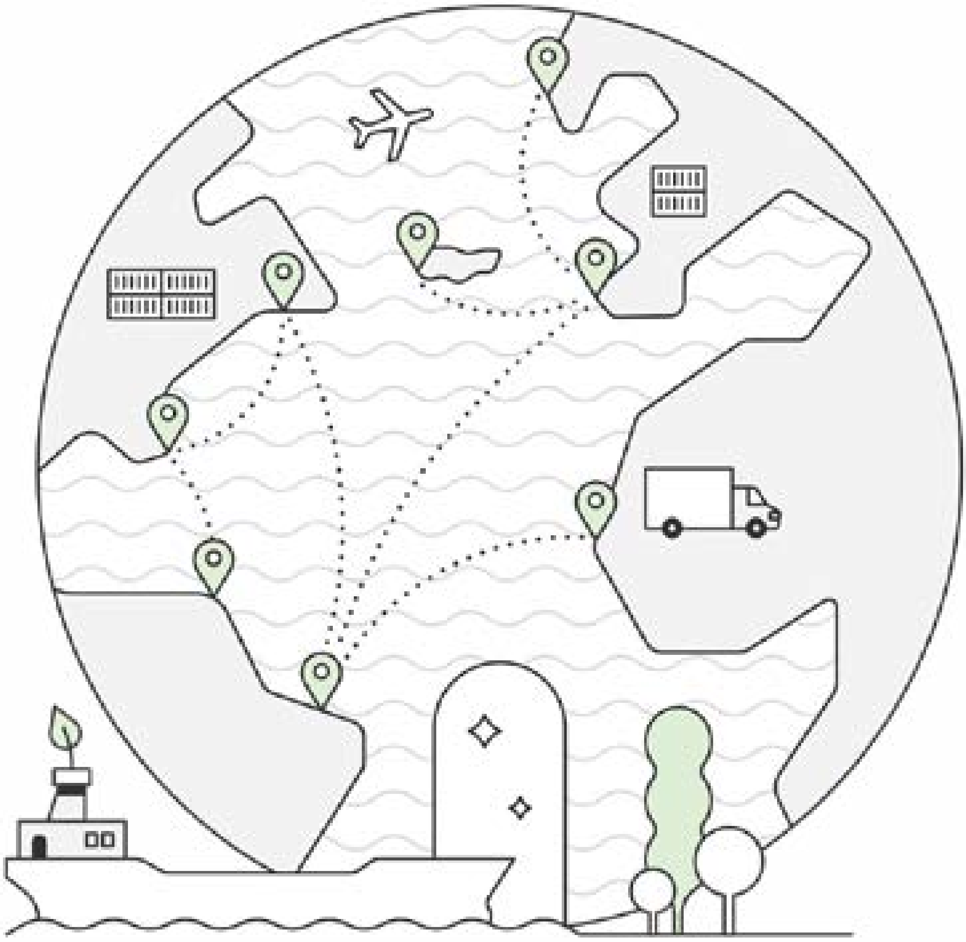
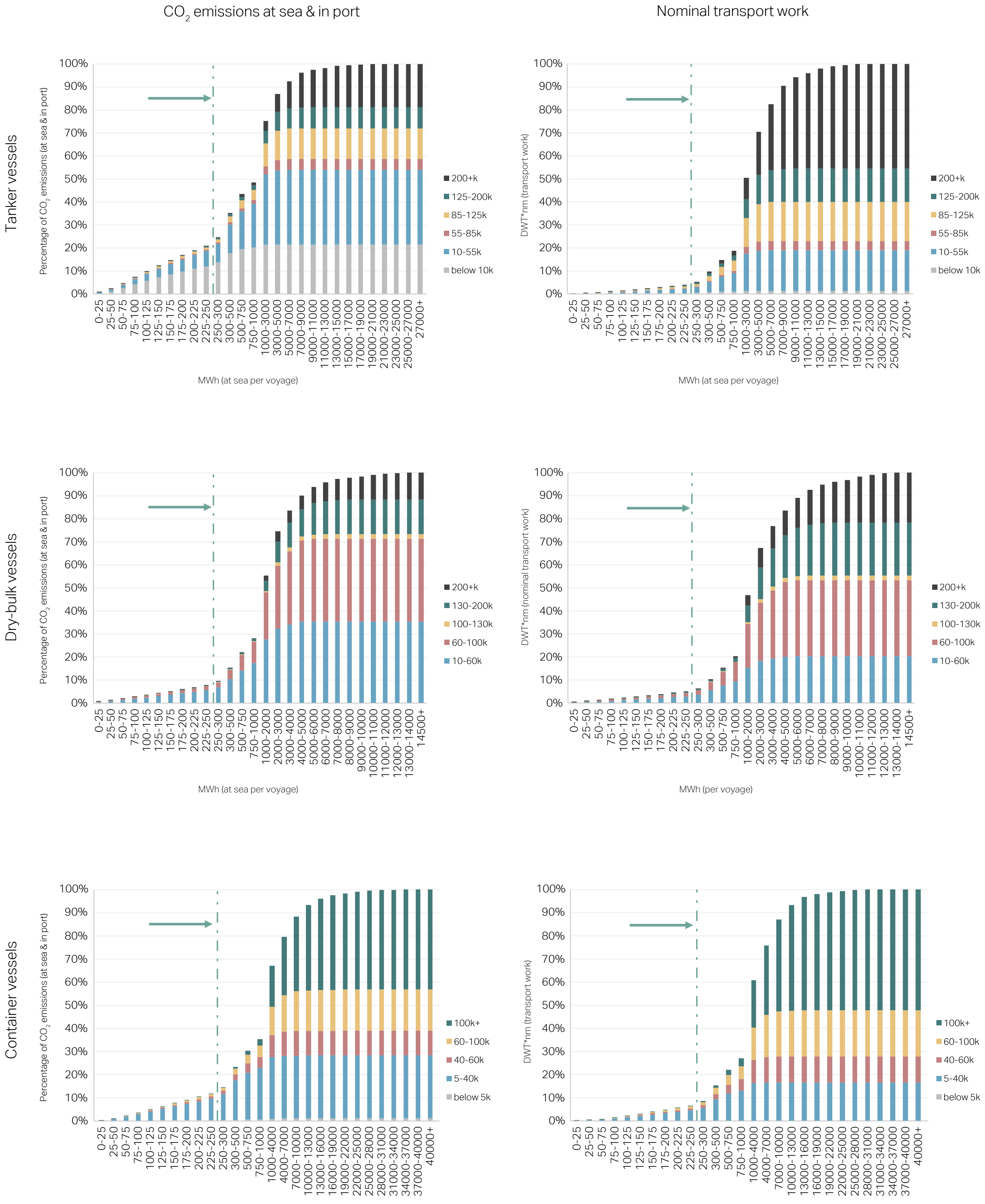


Figure 20: Analysis of energy requirements for propulsion and auxiliaries at sea of the globally operated fleet in tanker, dry-bulk, and container segments. Color-legend: deadweight, left: total CO_2 emissions of operations (at sea & in port); right: nominal transport work.



A.2 Life-cycle energy conversion analysis for tanker and dry-bulk cases

Figure 21: Analysis of tanker vessel case study energy flow and conversion losses (arbitrary units). a) Baseline MeOH-DF vessel without shore power connection. b) Baseline MeOH-DF vessel with shore power connection. c) Battery-powered vessel.

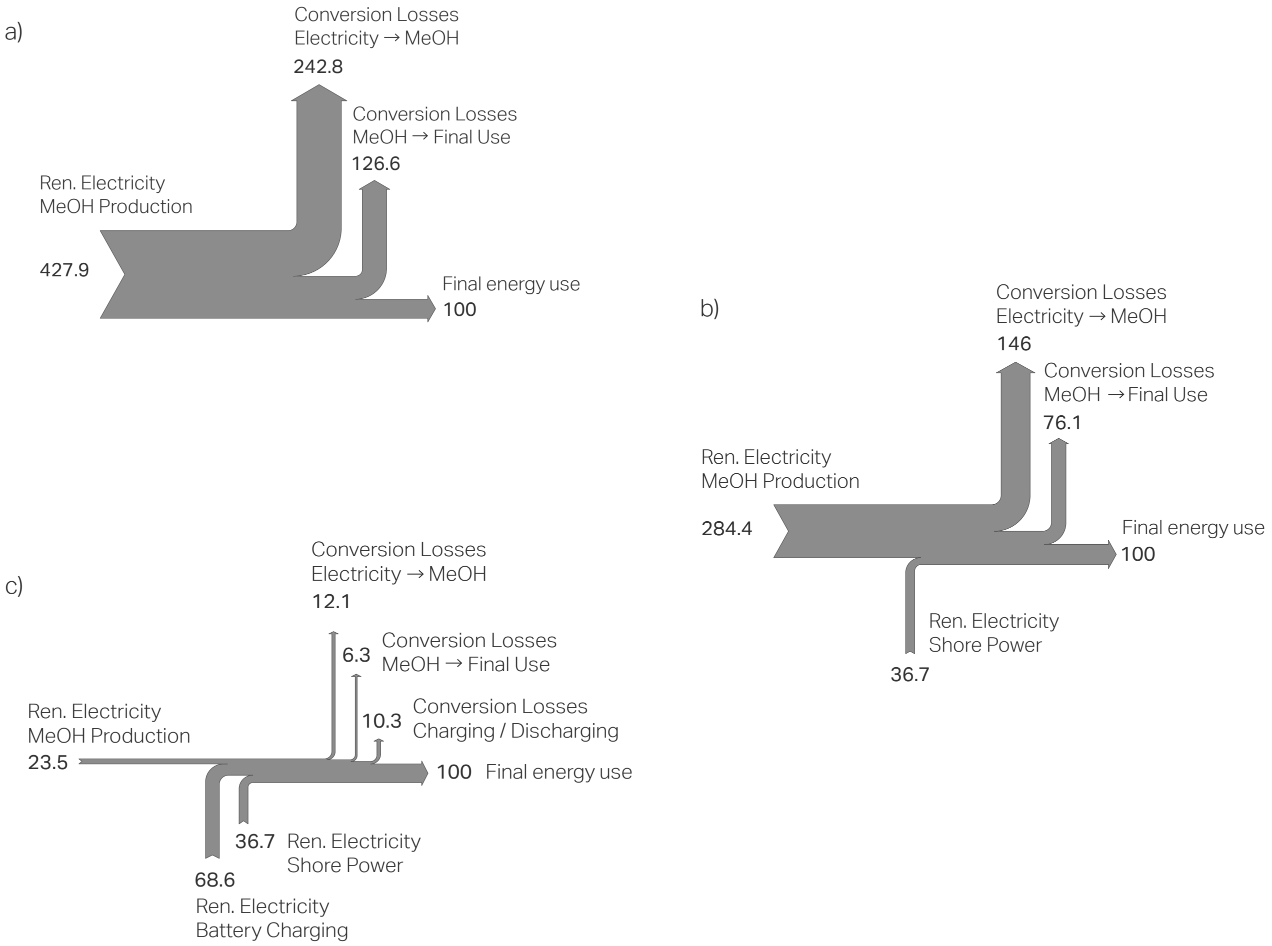
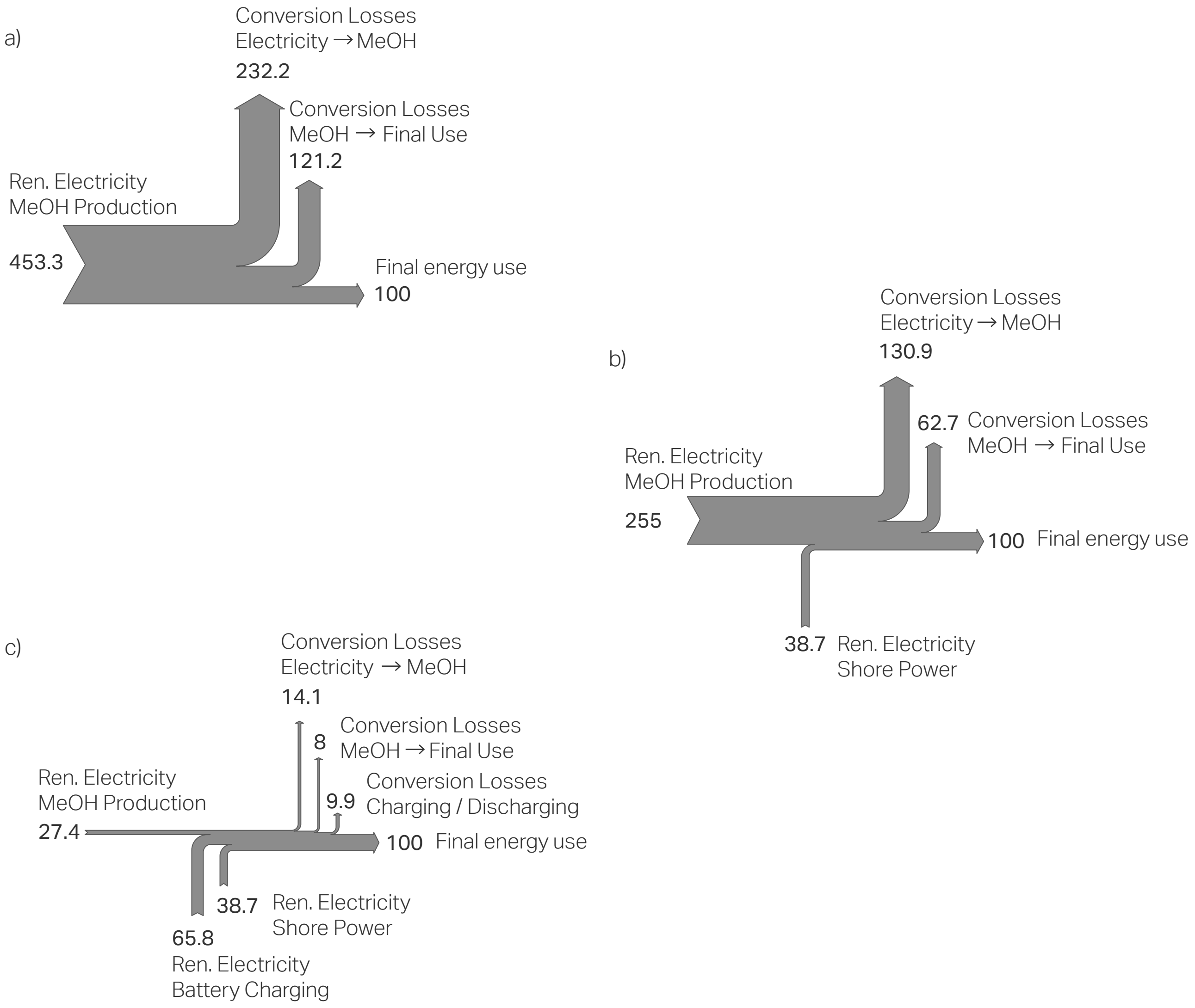


Figure 22: Analysis of dry-bulk vessel case study energy flow and conversion losses (arbitrary units). a) Baseline MeOH-DF vessel without shore power connection. b) Baseline MeOH-DF vessel with shore power connection. c) Battery-powered vessel.



A.3 Assumptions for economic evaluation of battery-powered vessels

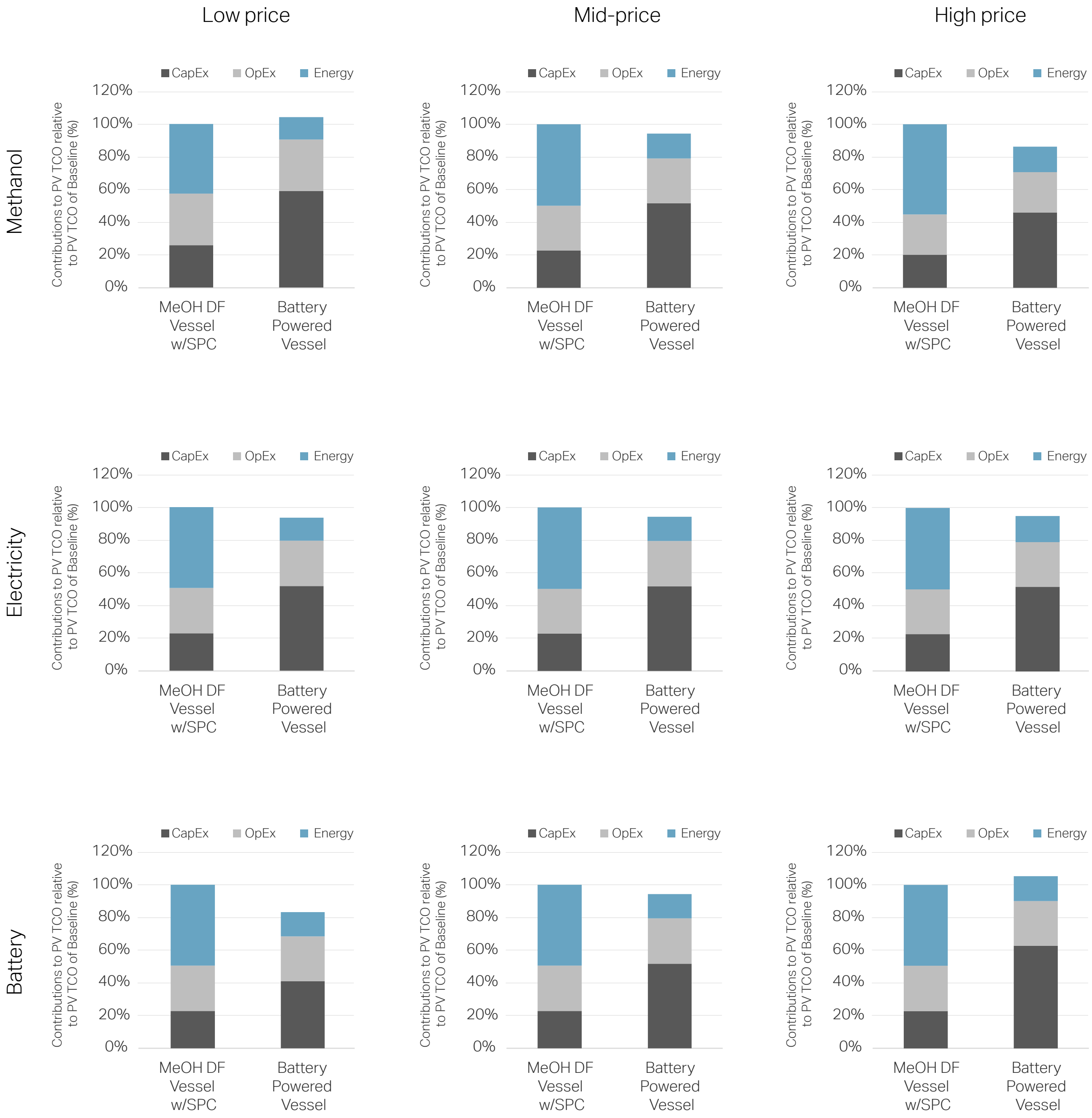
- Vessel lifetime: 20 years
- Linear depreciation of vessel value to scrap value throughout lifetime
- Debt financing rate: 60%
- Interest rate of debt: 5%
- Cost of equity: 10%
- Weighted average cost of capital used as discount factor for present value calculation: 7%
- Energy cost based on NavigaTE TCO v1.5[11]
- OpEx: Lump sum per vessel day, identical for all vessel configurations within a segment
- Escalation of OpEx: 2.5% per year
- Exchange of battery cells after 10 years of operation
  - Battery cells represent 50% of battery system price
  - Resale price of battery cells equals 30% of new price
  - Price decline of new battery cells equals 20% over 10 years

A.4 Sensitivity analysis

We investigated the sensitivity of the TCO calculation for the container vessel case to prices for methanol fuel, electricity for shore power and charging, and the battery system. We varied both methanol and electricity prices from 75% up to 125% of the base level (derived from the MMMCZCS's transition modeling tool, NavigaTE).[11] We also varied the price of the battery system from 200 USD/kWh up to 400 USD/kWh – in the range of forecasts up to 2030.[21]

We see that the battery-powered vessel configuration has slightly higher TCO than the ICE-powered baseline configuration if methanol prices are low, but a much lower TCO if methanol prices are high. In contrast, the electricity price only has a minor influence on the business case for the battery-powered vessel.

Figure 23: Sensitivity of financial analysis of container vessel case study to prices of methanol, electricity, and battery system. Contributions to the present value (PV) total cost of ownership (TCO) relative to the baseline. Methanol price: 0.75, 1.0 and 1.25 x NavigaTE price. Electricity: 0.75, 1.0, and 1.25 x NavigaTE price. Battery system: 200 USD/kWh, 300 USD/kWh and 400 USD/kWh.



A.5 List of ports with established or planned shore power connection

Table 9: List of shore power availability (non-exhaustive).

Port	Yes/No	Vessel types	Country	Source
Kiel Port	Yes	Ferries, cruise ships	Germany	https://maritime-executive.com/article/european-and-north-american-ports-preparing-for-cold-ironing
Hamburg Port	Yes (2028)	Cruise ships (Container ships)	Germany	https://www.hamburg-port-authority.de/en/themenseiten/lng-shoreside-power (https://www.portofantwerpbruges.com/en/our-port/climate-and-energy-transition/shore-power#Containerschepen)
Bremen	2028	Container ships	Germany	https://www.portofantwerpbruges.com/en/our-port/climate-and-energy-transition/shore-power#Containerschepen
Lübeck	Yes	RORO	Germany	https://transition-china.org/wp-content/uploads/2021/08/20200923_Tianjin_Studie_EN.pdf
Cuxhaven	Yes	RORO	Germany	https://ptr.inc/onshore-power-supply-gaining-popularity-in-european-ports/
Stockholm Ports, Baltic Sea ports of Copenhagen / Malmö, Aarhus	2023-2024	Ferries, cruise ships (connection ready for container ship in Stockholm)	Various	https://www.portsofstockholm.com/about-us/environmental-work/environmental-measures/onshore-power-connection/
Trelleborg Port	Yes	Ferries	Sweden	https://safety4sea.com/stena-line-port-of-trelleborg-inaugurate-shore-power-supply/
Visby	Yes	RO-Pax, ferries	Sweden	https://pub.nordicinnovation.org/On-Shore-Power-Supply-in-the-Nordic-Region/key-accomplishments-situation-analysis.html
Luleå	Yes	Icebreaking	Sweden	https://pub.nordicinnovation.org/On-Shore-Power-Supply-in-the-Nordic-Region/key-accomplishments-situation-analysis.html
Gothenburg Port	Yes	RORO, ferries, tankers	Sweden	https://www.portofgothenburg.com/services/onshore-power-supply/
Helsingborg	Yes	Ferry	Sweden	https://transition-china.org/wp-content/uploads/2021/08/20200923_Tianjin_Studie_EN.pdf
Piteå	Yes	RO-Pax	Sweden	
Karlskrona	Yes	RO-Pax	Sweden	
Ystad	Yes	RO-Pax	Sweden	

Port	Yes/No	Vessel types	Country	Source
Helsinki	Yes	RORO	Finland	https://transition-china.org/wp-content/uploads/2021/08/20200923_Tianjin_Studie_EN.pdf
Kemi	Yes	RORO and container ship	Finland	
Kotka	Yes	RORO	Finland	
Oulu	Yes	RORO	Finland	
Karmsund	Yes	Cruise ships	Norway	https://cruiseindustrynews.com/cruise-news/2021/12/zinus-develops-new-shore-power-solution-for-cruise-ships/
Port of Kristiansand	Yes	Cruise ships	Norway	https://sustainableworldports.org/project/port-of-kristiansand-shore-power-supply-for-cruise-ships/
Oslo	Yes	RO-Pax, cruise	Norway	https://transition-china.org/wp-content/uploads/2021/08/20200923_Tianjin_Studie_EN.pdf https://maritimecleantech.no/2022/01/24/the-nordics-should-accelerate-onshore-power-supply/
Bergen	Yes	Cruise and supply vessels	Norway	
Thirteen major Norwegian cruise ports	2030	Cruise	Norway	https://ptr.inc/onshore-power-supply-gaining-popularity-in-european-ports/
Valencia port	2030	Ferries, containers, cruise ships	Spain	https://www.valenciaport.com/en/the-new-electrical-substation-of-the-port-of-valencia-closer-to-completion/
Civitavecchia	Yes	Cruise ships	Italy	https://ptr.inc/onshore-power-supply-gaining-popularity-in-european-ports/
6 other major Italian ports	Yes	Information not found	Italy	https://ptr.inc/onshore-power-supply-gaining-popularity-in-european-ports/
Southampton	Yes	Information not found	UK	https://ptr.inc/onshore-power-supply-gaining-popularity-in-european-ports/
Haropa	2028	Container ships	France	https://www.portofantwerpbruges.com/en/our-port/climate-and-energy-transition/shore-power#Containerschepen
Marseille Port	Yes (2024)	Ferries (cruise ships)	France	https://sustainableworldports.org/project/port-of-marseille-provision-of-onshore-power-supply/
Toulon	Information not found	Information not found	France	https://ptr.inc/onshore-power-supply-gaining-popularity-in-european-ports/
Le Havre Port	Yes	Cruise ships	France	https://www.cruisemapper.com/news/8304-hlh-haropa-le-havre-launches-shore-power-strategy
Dunkerque port	2028	Container ships	France	https://www.sustainable-ships.org/stories/2023/overview-rules-regulations-ports/ http://www.dunkerque-port.fr/en/press/news/2020-07-08-dunkerque-port-is-even-more-dedicated-to-decarbonisation-en-65419.html

Port	Yes/No	Vessel types	Country	Source
Antwerp-Bruges Port	Yes (2028)	Barges, tugboats, (container ships)	Belgium	https://www.portofantwerpbruges.com/en/our-port/climate-and-energy-transition/shore-power
Piraeus port	2024	Cruise, ferries	Greece	https://www.ot.gr/2023/11/19/english-edition/port-of-piraeus-working-on-first-shore-power-connection-slots-for-2024/
Rotterdam Port	2030 (2028)	Info not available (Container ships)	Netherlands	https://www.portofrotterdam.com/en/port-future/energy-transition/ongoing-projects/shore-based-power-rotterdam https://www.portofantwerpbruges.com/en/our-port/climate-and-energy-transition/shore-power#Containerschepen
Amsterdam Port	2025	Cruise ships	Netherlands	https://www.portofamsterdam.com/en/news/sea-cruise-port-amsterdam-connected-ship-shore-power
Marsaxlokk port	Yes	Cruise ships	Malta	https://www.infrastructuremalta.com/project-categories/maritime
Barcelona port	2025	Ferries, cruise ships	Spain	https://www.cruiseandferry.net/articles/port-of-barcelona-calls-for-tenders-in-shore-power-project-1
Los Angeles Port	Yes	Container ships, cruise ships	USA	https://www.portoflosangeles.org/environment/air-quality/alternative-maritime-power-(amp)
Long Beach	Yes	Container, tanker, cruise	USA	https://transition-china.org/wp-content/uploads/2021/08/20200923_Tianjin_Studie_EN.pdf https://polb.com/environment/shore-power/#shore-power-program-details https://aapapowers.com/wp-content/uploads/2023/04/Shore-Power-Technology-Assessment-2022-Update.pdf
Oakland	Yes	Container	USA	
San Francisco	Yes	Container, cruise	USA	
San Diego	Yes	Container, cruise	USA	
Seattle	Yes	Cruise	USA	
Juneau	Yes	Cruise	USA	
Pittsburg	Yes		USA	
Montreal Port	Yes	Cruise ships, wintering ships	Canada	https://trends.nauticexpo.com/project-37840.html#:~:text=The%20Port%20of%20Montreal%20will,power%20system%20for%20wintering%20ships https://green-marine.org/stayinformed/news/shore-power-for-cruise-ships-at-the-port-of-montreal/
Greater Victoria Harbour	Yes	Cruise ships	Canada	https://gvha.ca/deep-water-terminal/shore-power-project/

Port	Yes/No	Vessel types	Country	Source
Halifax	Yes	Cruise ships	Canada	https://transition-china.org/wp-content/uploads/2021/08/20200923_Tianjin_Studie_EN.pdf
Vancouver	Yes	Container, cruise	Canada	
Prince Rupert	Yes	Cruise	Canada	
Port of New South Wales	2024	Cruise ships, bulk carriers	Australia	https://www.portauthoritynsw.com.au/sustainability/net-zero-energy/shore-power/#:~:text=Port%20Authority%20plans%20to%20provide,the%20White%20Bay%20Cruise%20Terminal
Singapore Port	2023	Passenger catamarans	Singapore	https://www.sustainable-ships.org/rules-regulations/port-singapore
Tianjin Port	Yes (to be converted)	Container ships (cruise ships, bulk carriers)	China	https://transition-china.org/wp-content/uploads/2021/08/20200923_Tianjin_Studie_EN.pdf
Shenzhen Shekou Port	Yes		China	https://www.sciencedirect.com/science/article/abs/pii/S1361920919305073
Shanghai Port	Yes	Cruise ships	China	https://www.sustainable-ships.org/rules-regulations/port-shanghai
Nansha Port (Guangzhou)	Yes	Container	China	https://sustainableworldports.org/project/port-of-guangzhou-onshore-power-supply-project/
Ningbo-Zhoushan Port	Yes	Passenger and other	China	https://www.swwlogistics.com/new/CMA-CGM-will-impose-an-overweight-surcharge-Ningbo-Zhoushan-Port-Terminal-can-use-shore-power-for-free.html#:~:text=On%20the%20basis%20of%20the,use%20shore%20power%20for%20free
Lianyungang	Yes	Passenger	China	https://transition-china.org/wp-content/uploads/2021/08/20200923_Tianjin_Studie_EN.pdf
Nanjing	Yes	Container	China	
Dalian	Yes	RORO, container ships	China	
Hanshin	2025	Container ships	Japan	https://splash247.com/initiative-launched-to-roll-out-shore-power-across-japanese-ports/
Keihin port	2025	Information not found	Japan	https://splash247.com/initiative-launched-to-roll-out-shore-power-across-japanese-ports/
V. O. Chidambaranar Port	Yes	Bulk	India	https://maritime-executive.com/editorials/first-for-shore-power-in-india

Port	Yes/No	Vessel types	Country	Source
Busan	Yes		Korea	https://transition-china.org/wp-content/uploads/2021/08/20200923_Tianjin_Studie_EN.pdf
Incheon	Yes	Passenger	Korea	
Ulsan	Yes	Information not found	Korea	
Yeosu	Yes	Information not found	Korea	
Pyeongtaek-Dangjin	Yes	Information not found	Korea	https://forourclimate.org/hubfs/Industry%20Trends%20Brief_Port%20Decarbonization%20Focusing%20on%20South%20Korean%20Five%20Major%20Ports.pdf
Taipei	Yes	Information not found	Taiwan	https://transition-china.org/wp-content/uploads/2021/08/20200923_Tianjin_Studie_EN.pdf https://kl.twport.com.tw/Upload/C/RelFile/CustomPage/3233/5a080a6f-694b-4087-a485-4ae383a5d49d.pdf

A.6 Life-cycle energy requirements

Table 10: Calculation of energy demand for 1,100 TEU container ship cases.

	MeOH DF with shore power	Battery-electric
Energy [MWh/RT]		
Propulsion	1,909	1,969
Aux. at sea	784	784
Port	441	441
Total	**3,134**	**3,194**
Fuel consumption [tonnes MeOH equ./RT]		
Main engine	1,242	0
Aux. at sea	0	283
Aux. in port	0	0
Total	**1,242**	**283**
Direct electricity [MWh/RT]		
Battery charging	0	2,500
Shore power	441	441
Total	**441**	**2,941**
Electricity (life-cycle) [MWh/RT]	**14,555**	**6,160**

MeOH = methanol, MeOH DF = methanol dual-fuel (internal combustion engine), RT = round trip

Table 11: Calculation of energy demand for 40k DWT product tanker cases.

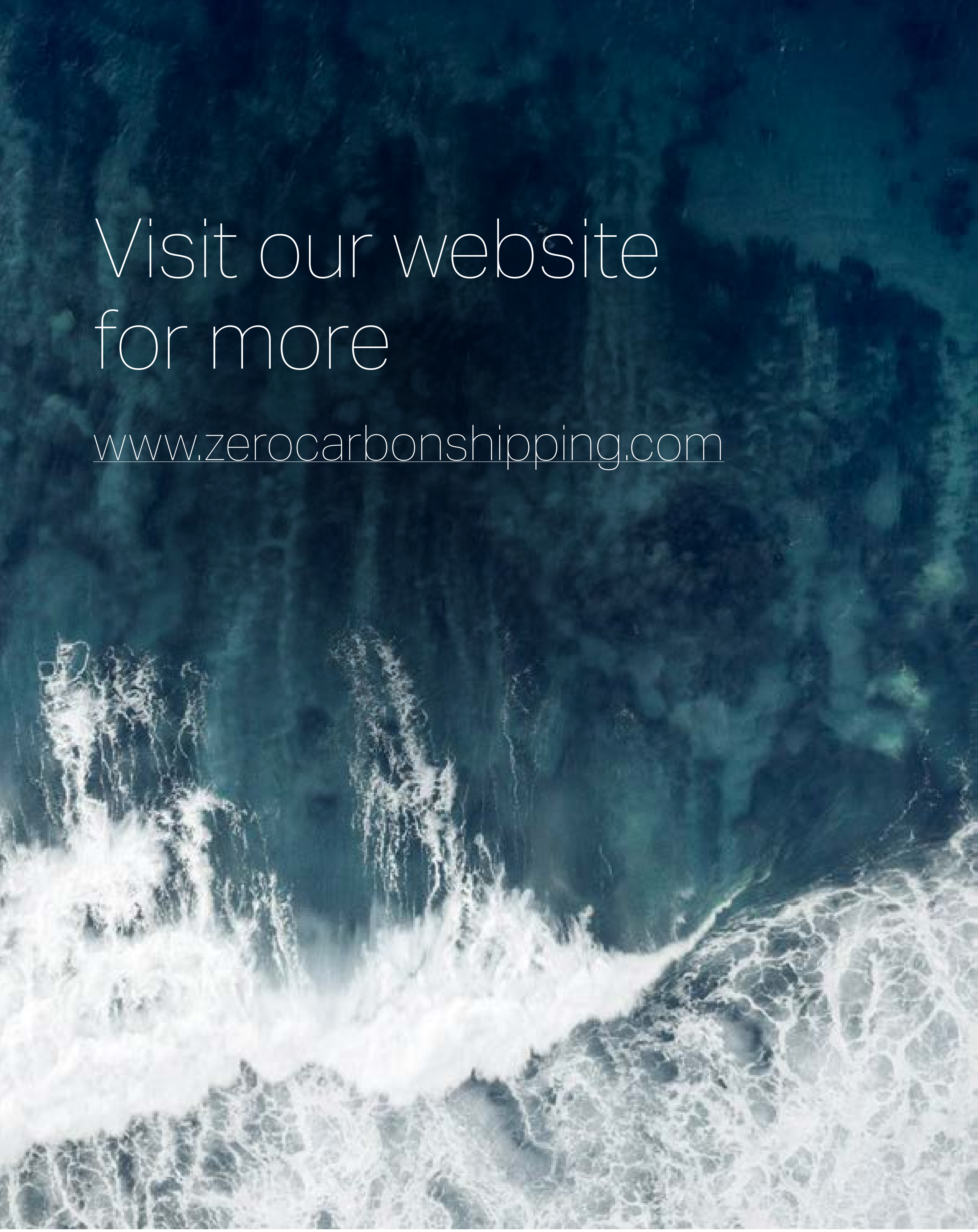
	MeOH DF without shore power	MeOH DF with shore power	Battery-electric
Energy [MWh/RT]			
Propulsion	323	323	323
Aux. at sea	70	70	70
Port	228	228	228
Total [MWh/RT]	621	621	621
Fuel consumption [tonnes MeOH equ./RT]			
Main engine	128	128	0
Aux. at sea	28	28	14
Aux. in port	103	0	0
Total	258	155	14
Direct electricity [MWh/RT]			
Battery charging	0	0	426
Shore power	0	228	228
Total	0	228	654
Electricity (life-cycle) [MWh/RT]	2,937	1,994	811

MeOH = methanol, MeOH DF = methanol dual-fuel (internal combustion engine), RT = round trip

Table 12: Calculation of energy demand for 35k DWT dry-bulk vessel cases.

	MeOH DF without shore power	MeOH DF with shore power	Battery-electric
Energy [MWh/RT]			
Propulsion	291	291	291
Aux. at sea	48	48	48
Port	214	214	214
Total	553	553	553
Fuel consumption [tonnes MeOH equ./RT]			
Main engine	104	104	0
Aux. at sea	20	20	16
Aux. in port	97	0	0
Total	221	124	16
Direct electricity [MWh/RT]			
Battery charging	0	0	368
Shore power	0	214	214
Total	0	214	581
Electricity (life-cycle) [MWh/RT]	2,507	1,623	764

MeOH = methanol, MeOH DF = methanol dual-fuel (internal combustion engine), RT = round trip



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