

Minimizing energy demand for a 15,000 TEU ammonia-fueled container vessel concept

Impact of energy efficiency technologies



Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

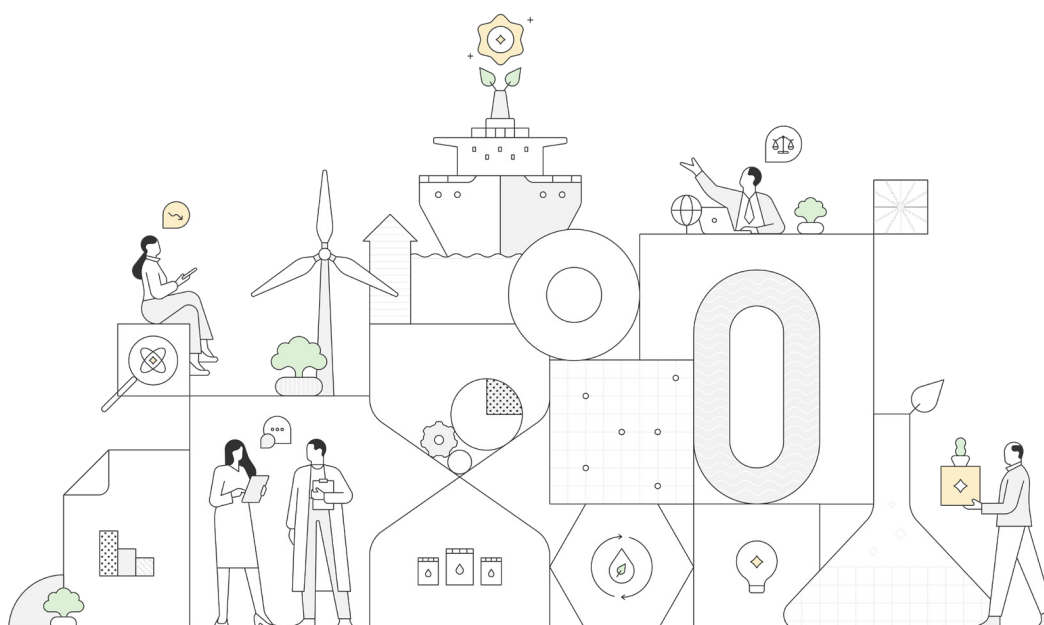
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Executive summary

Ammonia is a promising alternative fuel for low-emissions shipping. However, continuing the development of safe and efficient ammonia-fueled vessel designs remains an ongoing task for the industry. To support this aim, the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping and Seaspan have partnered on a project to develop a large ammonia-fueled container vessel design. The initial design from this project, published in 2023,¹ was granted approval in principle by the American Bureau of Shipping.²

As a next step in the project, we have sought to review the energy efficiency of this ammonia-fueled vessel design. An energy-efficient design can lower the vessel's operational costs, reduce greenhouse gas emissions, and manage the demand for low-emissions ammonia. To help optimize our design, we assessed the potential energy saving impacts of a large selection of energy efficiency technologies (EETs), assuming a given operational profile.

We found that, compared to our initial design, the selected EETs can collectively reduce the vessel's total energy consumption by approximately 260 TJ/year, or around 20%. Measures targeting the hull design and propulsion system offered the greatest potential energy savings, while other EET categories such as hotel load and waste heat recovery offered smaller but meaningful improvements.

We also undertook a high-level cost estimate for the selected hull and propulsion improvements. This estimate was limited in scope, and further vendor-specific analysis will be required in the future. With that said, our cost estimate suggests that the payback period for these improvements would be modest (under two years). As ammonia fuel is more expensive than conventional maritime fuel, the cost savings per kJ reduced mean that the estimated payback period depends on how much of each fuel is used.

Based on our experience, we offer the following key takeaways from this phase of the project:

- Understand which EETs have the highest potential for reducing annual energy consumption
- Explore additional onboard energy-saving measures to further optimize performance
- Maintain a holistic approach to vessel performance
- Plan for the long term

In this report, we share further details regarding the analyses summarized above. The report also includes a detailed appendix with descriptions of all selected EETs, their role in energy efficiency, and other relevant considerations. Readers can use this report to understand more about EET options that may be relevant to their business, and to gain insights into the benefits of EETs in the specific context of a large ammonia-fueled container vessel.



01 Introduction

Ammonia holds promise as a scalable low-emissions maritime fuel.³ However, the implementation of ammonia fuel poses several challenges for the maritime industry, including in ship design. To help address some of these challenges, the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) and our strategic partner Seaspan have collaborated on a multi-phase project to develop a design for a 15,000 twenty-foot equivalent (TEU) ammonia-fueled container vessel. In September 2023, we published the main output of the project's first phase: a report that introduced the vessel's concept design and outlined design opportunities and challenges, with a focus on safety and technical feasibility.¹

As part of the first project phase, we identified optimization of the vessel's energy efficiency as a key area for further development.¹ Improved energy efficiency can be seen as a 'win-win' that both reduces the vessel's operational costs and improves sustainability, helping companies meet environmental, social, and governance targets. In simple terms, energy efficiency results in reduced energy demand and thereby reduced fuel consumption. In the context of an ammonia-fueled vessel, these reductions bring several benefits:

- **Lower operational costs:** Reducing fuel consumption through increased energy efficiency translates to lower overall operational costs. This benefit is highly relevant for vessels operating on low-emissions ammonia, which is currently notably more expensive than conventional fossil-based maritime fuels.
- **Reducing greenhouse gas (GHG) emissions:** Although the ammonia molecule (NH_3) itself contains no carbon, even low-emissions e-ammonia is associated with some well-to-wake GHG emissions. For example, production and transportation of ammonia fuel generates some upstream GHG emissions.⁴

Ammonia combustion can also produce the GHG nitrous oxide (N_2O) – though available technologies can significantly reduce these emissions.^{5–7} Further, ammonia-fueled engines currently require some pilot fuel use for efficient ammonia combustion, creating a source of carbon dioxide (CO_2) emissions.^{8,9} In summary, reducing fuel demand through energy efficiency complements the use of low-emissions fuels by lowering the vessel's GHG emissions even further.

- **Managing the overall demand for limited resources:** Production of low-emissions ammonia will need to be scaled up considerably in the coming decades to meet the energy demand from international shipping¹⁰ – and other industries also generate demand for ammonia. Reducing individual vessels' consumption of ammonia means more to go around, especially while production is still scaling up. Furthermore, energy losses during e-fuel production mean that decreasing onboard energy demand can ultimately decrease the upstream demand for renewable electricity by a factor of four.¹¹

Energy efficiency can be improved through both technical and operational means. For this project phase, we chose to primarily focus on onboard energy efficiency technologies (EETs) as a subset of technical energy efficiency measures. Such measures are highly relevant when designing a newbuild vessel. We analyzed the impact of a range of EETs on our design for a 15,000 TEU ammonia-fueled container vessel, with the aim of understanding how to optimize the design's energy efficiency.

In this report, we share our estimates of expected energy savings from each EET individually, as well as the expected combined energy savings per year based on a defined operational profile. As systems on the vessel are partly interdependent, the combined energy savings are not simply the sum of energy savings from each EET. We also share the results of a high-level cost estimate focusing on hull and propulsion upgrades, as we found that this category of EET offered the greatest potential annual energy savings. Finally, we share some general takeaway messages with relevance for projects seeking to optimize the energy efficiency of a newbuild alternatively fueled vessel design.



Scope and target audience for this report

- Our project focused specifically on technology-driven energy efficiency improvements. Operational energy efficiency measures were outside of the project scope.
- Our analysis centers on a newbuild ammonia-fueled vessel. Trends from our analyses may have some relevance for retrofit projects, but specific calculations would be required for any given project.
- This report will not cover specific equipment suppliers. Our analysis focuses on general trends with respect to EETs.
- Considering the variability in costs for both technologies and fuels, we only consider cost trends in this report.
- The main target audience for this report is vessel owners and managers in the container segment. However, some of the findings may be adapted to other vessel segments.

1.1 About this project

This project was a collaboration between the MMMCZCS and our strategic partners Seaspam and Hapag-Lloyd.



02 Vessel design and operational profile

The baseline vessel design used in this project was presented in a previous MMMCZCS publication.¹ Figure 1 shows a rendering of the vessel design, while Table 1 outlines the design’s principal characteristics.

For modeling purposes, we assumed that the vessel’s operational profile was as follows:

- Average round trip distance:** 19,000 nautical miles (NM), with six annual trips
- Time for maneuvering:** 20 hours per trip
- Annual time in port:** 1,525 hours

Table 1: Principal characteristics of the 15,000 TEU ammonia-fueled container vessel concept design used in this study.

Capacity	15,000 TEU
LBP	c. 350 meters
Design draft	15.5 meters
Scantling draft	17 meters
Design speed	20 knots
Operating speed	15 knots
Operational profile at scantling draft	14-16 knots
Reefer slots	c. 1,500 (1,000 on deck and 500 in hold)
Main engine	Dual-fuel (ammonia and LSFO)
Auxiliary engines	Dual-fuel (ammonia and LSFO)
Vessel arrangement	Twin island design

Figure 1: Rendering of the 15,000 TEU ammonia-fueled container vessel design used in this study. Image used with Seaspan’s consent and shared for illustrative, non-commercial research purposes only.



TEU = twenty-foot equivalent unit, LBP = length between perpendiculars, LSFO = low-sulfur fuel oil



Table 2 summarizes our modeling assumptions with respect to the vessel's operational profile while at sea.

To capture the impact of changes in auxiliary energy requirements, we considered three different reefer load conditions:

- No reefers (zero slots used)
- Typical reefer operation (20% of slots used)
- Full reefer load (100% of slots used)

Table 3 shows the vessel's assumed fuel consumption per voyage across the different reefer load conditions. Unless otherwise specified, results presented in this report are based on the 'typical' condition.

Table 2: Vessel's assumed operational profile for a single average round-trip voyage.

Speed (knots)	<10	10-12	12-14	14-16	16-18	18-19	Total
Percentage of time	2%	7%	2%	28%	58%	3%	100%
Distance (NM)	380	1,330	380	5,320	11,020	570	19,000
Time (hours)	38	116	28	344	630	30	1,186

Table 3: Vessel's assumed fuel consumption per voyage based on reefer load condition.

Operational condition	Main engine fuel consumption (tonnes)		Auxiliary engine fuel consumption (tonnes)		Total fuel consumption (tonnes)	
	Ammonia	Pilot fuel	Ammonia	Pilot fuel	Ammonia	Pilot fuel
Transit, no reefers	47,200	1,300	11,500	500	58,800	1,900
Transit, typical reefer load (20%)	47,200	1,300	16,100	800	63,300	2,100
Transit, full reefer load (100%)	47,200	1,300	34,100	1,600	81,400	2,900

NM = nautical miles



03 Energy consumption and operational impact analysis

To understand options for reducing the vessel's energy consumption, we defined a selection of EETs for analysis. The selected EETs cover the following five categories: hull and propulsion, hotel load and air conditioning (AC), machinery, waste heat recovery, and other items. Please see the Appendix for more details on the selected EETs.

This selection was not intended to be comprehensive, but focused on common and well-documented technologies that were relevant to a container vessel and of interest to the project participants. Our approach was vendor-agnostic. Results represent general technology concepts and do not reflect or compare any specific supplier product.

We next estimated the energy saving from each selected EET in isolation. Depending on the individual EET, this estimate was based on either a comprehensive assessment customized to our vessel design, or previous experience in similar projects.

Each EET option contributes to overall energy savings – and thereby fuel savings – on a per-system basis. Table 4 summarizes the estimated annual savings, in terms of tonnes of ammonia fuel, for each EET considered in this analysis.

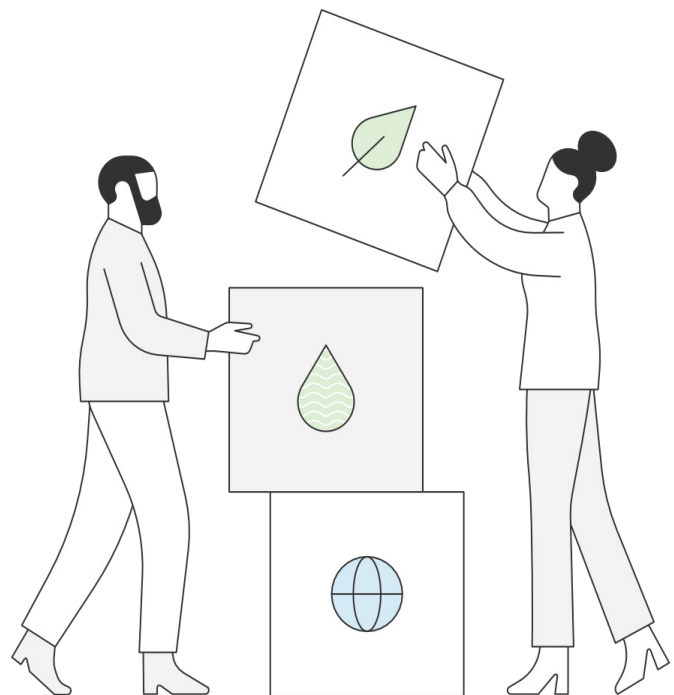


Table 4: Estimated annual ammonia savings for each energy efficiency technology. Values are rounded to the nearest ten.

		Annual ammonia saving from EET (tonnes)		
Energy efficiency technologies (EETs)		No reefers	20% reefers	100% reefers
Hull & propulsion	Hull form optimization	1,650	1,650	1,650
	Bow thruster grids & scallops	240	240	240
	Air lubrication	2,840	2,840	2,840
	Bow shield	470	470	470
	Weight optimization	50	50	50
	Stator fins & PIDs	2,360	2,360	2,360
Hotel load & AC	Optimized systems design	60	60	60
	Intelligent AC control	110	110	110
	Ammonia cold recovery	40	40	40
	Double-glazed & reflective windows	50	50	50
	Optimal thermal insulation	20	20	20
	Reefer container optimization	0	540	2,690
Machinery	Optimized cooling & ventilation	70	100	210
	Engine room ventilation	60	80	170
	Passive LO & FO treatment	10	20	30
	Regenerative LO heat exchangers	10	20	30
	Advanced wastewater treatment plant	0	0	0
	Occupancy & motion-controlled lighting	0	0	0
	Natural circulation EGB	10	10	10
	EGB for auxiliary engines	70	180	800
WHR	Sliding steam pressure	0	0	0
	HT WHR	230	320	680
	ORC unit	150	150	150
	Steam turbine generators	80	80	80
Other items	Freshwater production	0	0	0
	Auxiliary engine optimization	0	0	0
	Efficient electrical motors	170	240	510
	Extensive use of VFDs	670	940	1,990
	Fuel mass flow meters	0	0	0
	LED lighting	110	110	110
	PTI/PTO	170	240	510
	Energy management systems	230	230	230
	Fuel cells (auxiliary load and peak shaving)	190	190	190

EET = energy efficiency technology, PIDs = propulsion improvement devices, AC = air conditioning, LO = lubricating oil, FO = fuel oil, EGB = exhaust gas boiler, WHR = waste heat recovery, HT = high-temperature, ORC = organic Rankine cycle, VFDs = variable frequency drives, LED = light-emitting diode, PTI/PTO = power take-in/power take-out



Due to interdependencies between categories, the total energy saving is not simply the sum of the individual savings. Therefore, we conducted a careful category-level analysis to evaluate the effect of these EETs on energy usage and savings for the vessel overall. In other words, this analysis assesses the combined impact of all selected EETs on the vessel's energy consumption.

For this analysis, we estimated annual energy usage based on a detailed voyage profile. The profile represents a worldwide trade for a typical container vessel of this size (see also Tables 2 and 3). Figure 2 shows the vessel's baseline energy consumption, as well as the estimated potential energy savings from each category of EET. Overall, we estimate that the selected EETs may reduce the vessel's total energy consumption by approximately 260 TJ/year, or 20%, based on the assumed operating and reefer loading conditions.

Figure 2: Vessel's estimated baseline and improved annual energy consumption with typical reefer load conditions (20%).

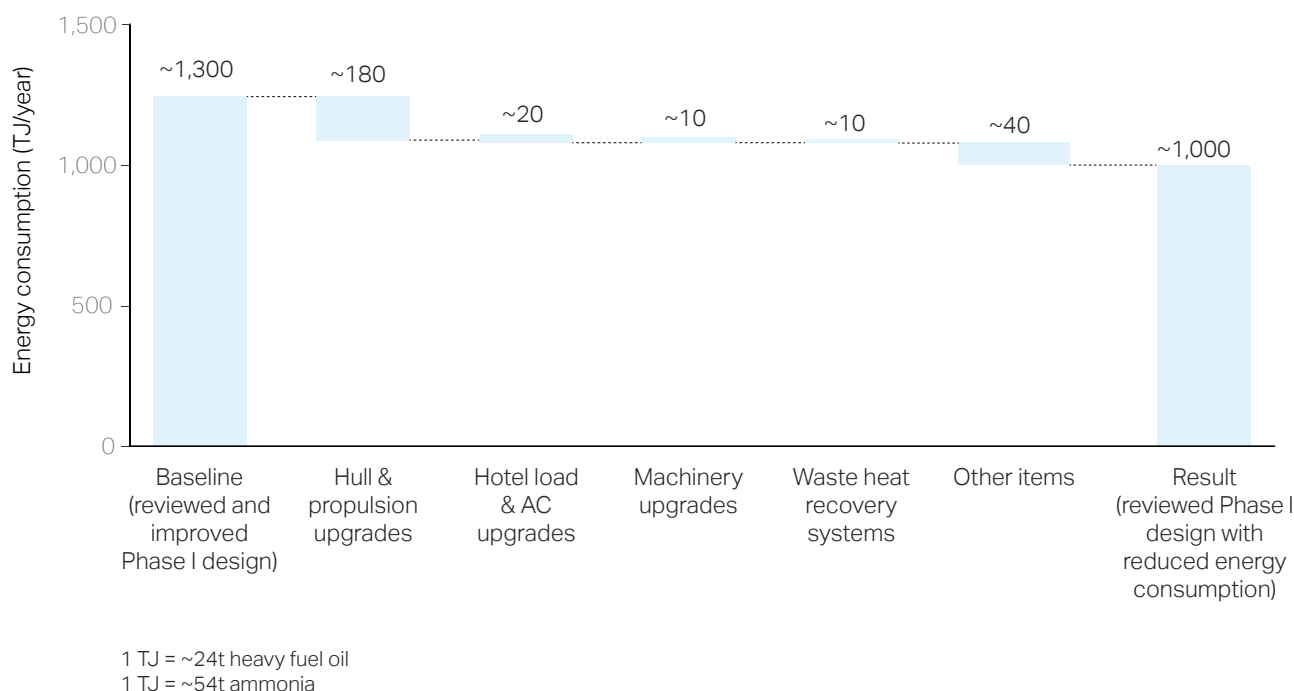


Figure 2 shows that the most substantial annual energy savings come from the hull and propulsion category. A more detailed overview of how these measures improve the vessel's energy efficiency can be found in the 'Hull and propulsion' section of the Appendix. As these hull and propulsion upgrades are tuned to the vessel's assumed operational profile, we expect that retrofits would be necessary in order to maintain the same energy efficiency if the vessel's operational profile changes.

Other EETs – including onboard systems, auxiliary equipment, and lighting – offer smaller but still potentially meaningful improvements (please see the Appendix for further details). For example, technologies such as power take-in/power-take-off (PTI/PTO) systems and high-efficiency fuel cells can reduce both fuel consumption and maintenance overheads by leveraging the efficiency of the two-stroke main engines. Waste heat recovery systems and regenerative heat exchangers maximize energy reuse, reducing the overall energy input needed.



Based on these results, we focused on high-impact hull and propulsion measures when optimizing the energy efficiency of this vessel design. We complemented these measures with additional technologies from the other EET categories to achieve cumulative efficiency gains.

Based on technical principles, we expect similar EET strategies to be relevant for other vessels with high operating speeds (e.g., cruise vessels, LNG carriers). Conversely, this approach may be less relevant for slow-steaming vessels (e.g., tankers and bulk carriers), which are optimized for high cargo intake.

While our primary focus here is on energy consumption and efficiency, we note that many of the measures considered can offer additional benefits for the vessel (see the Appendix for more information). These additional benefits include:

Improved performance

(e.g., increased cruising range)



Improved reliability

(e.g., reduced maintenance considering equipment operating under optimal load conditions)



Reduced emissions

(e.g., N_2O)



Safety improvements

(e.g., reducing the number of hazardous ammonia leak points by minimizing auxiliary engine runtime in key operational modes)



04 Cost considerations

As described in Section 3, we identified hull and propulsion upgrades as the EET category that offered the greatest potential for energy savings on an annual basis for this vessel design. To obtain order-of-magnitude insights into investment levels, we developed an illustrative high-level cost estimate for this specific category.

Table 5 shows the estimated net energy savings and additional capital expenditure (CapEx) for each of our selected hull and propulsion upgrades. Assuming that very low-sulfur fuel oil (VLSFO) costs 450 USD/tonne and ammonia fuel costs 1,200 USD/tonne,^{*} we estimate that the approximate payback period for these upgrades would range from six months for ammonia to

2.5 years with VLSFO. We did not include any financial gains from using ammonia fuel for overcompliance with the IMO Net-Zero Framework, as these would be covered in the business case for using ammonia.

The costs of many EETs can vary considerably, being highly dependent on supplier pricing and contractual details. As a result, we opted not to undertake a detailed, comprehensive cost review across all EET options. Such a detailed cost evaluation would require bespoke analysis and supplier engagement beyond the scope of this project phase. Before adopting a given EET, the shipowner and charterer would complete a detailed cost analysis in the form of separate, independently conducted supplier-specific feasibility assessments.

Table 5: Illustrative cost impact estimates for selected energy efficiency technologies in the hull and propulsion category (research modeling results).

Energy efficiency technology	Net energy saving	Additional CapEx [*]
Hull form optimization	2.60%	0.05%
Bow thruster design	0.40%	0.01%
Air lubrication	4.40%	0.71%
Bow shield	0.74%	0.08%
Weight optimization	0.07%	0.00%
Stator fins	3.70%	0.04%

CapEx = capital expenditure

^{*}Estimates based on an indicative cost for an ammonia dual-fuel vessel using assumptions from comparable alternative-fueled designs. These figures are provided for analytical illustration only and do not represent market prices or procurement guidance.



05 Conclusion

In this report, we have estimated the impact of selected EETs on the energy efficiency of a 15,000 TEU ammonia-fueled container vessel. While each EET contributes to energy savings, an estimate of the overall impact of these technologies must consider their independent integration.

We found that enhancements in the hull and propulsion systems offered the greatest potential annual energy savings. Other onboard systems (e.g., relating to lighting, auxiliary engines, waste heat recovery) provided meaningful incremental benefits. Optimized implementation of selected EETs can also create additional benefits for vessel performance, maintenance needs, and safety.

As the cost of EETs can vary widely, an in-depth cost analysis was outside the scope of this study. Nevertheless, our illustrative, research-based analysis suggests that the payback period for incorporating the hull optimization and propulsion EETs could be fairly

short – approximately 1-2 years under the assumed fuel-cost conditions. As the estimated fuel cost for ammonia is higher than that for conventional maritime fuels, the modeled EETs show greater cost-saving potential if we assume that the vessel operates primarily on ammonia. At the same time, carbon penalties may increase the future costs of operation on conventional fuels, further reinforcing the utility of onboard EETs.

For the purposes of this project, we considered that the EETs would be installed at the newbuilding stage. Careful assessment of EET options at the design and newbuilding stages can be beneficial – for example, by simplifying the implementation of large structural solutions such as optimized hull forms. Retrofitting EETs on existing vessels can also improve energy efficiency – however, the complexity of installation and the need to replace original equipment mean that our results cannot be directly extrapolated to a retrofitting context.

Based on our project findings to date, we offer the following general key takeaways on improving the energy efficiency of a newbuild 15,000 TEU ammonia-fueled container vessel design:

Understand which EETs have the highest potential for reducing annual energy consumption

In this study, we identified enhancements in hull design and propulsion efficiency as the area with the greatest potential impact for this specific vessel design and voyage profile.



Explore additional onboard energy-saving measures to further optimize performance

Examples of such measures include advanced energy management systems, variable frequency drives (VFDs), high-efficiency electrical motors, and LED lighting.



Maintain a holistic approach to vessel performance

Integration of energy efficiency improvements should not reduce the vessel's cargo capacity or affect operational safety and reliability.



Plan for the long term

Appropriate planning for long-term maintenance and eventual overhaul of systems (e.g., fuel cells) allows efficiency gains to be sustained throughout the vessel's operational life.



06 The project team

This report was prepared by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) with assistance from our partners. Contributors marked with an asterisk (*) were seconded to the MMCZCS from their home organization. All secondees and external contributors participated in a research capacity as part of the collaborative project and contributed technical input to the report.

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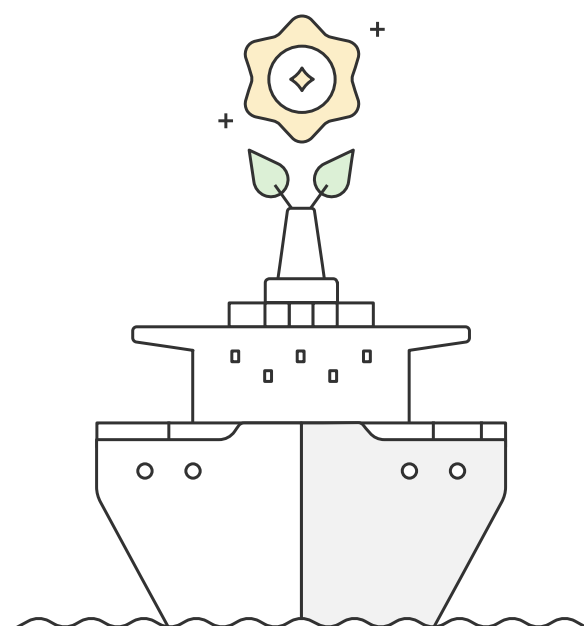
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Abbreviations

AC	Air conditioning
ALS	Air lubrication system
CapEx	Capital expenditure
CFD	Computational fluid dynamics
CO ₂	Carbon dioxide
EET	Energy efficiency technology
GHG	Greenhouse gas
MMMCZCS	Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
LED	Light-emitting diode
NH ₃	Ammonia
NM	Nautical miles
N ₂ O	Nitrous oxide
PID	Propulsion improvement device
PTI/PTO	Power take-in/power take-out
TEU	Twenty-foot equivalent unit
VFD	Variable frequency drive
VLSFO	Very low-sulfur fuel oil
WHR	Waste heat recovery



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Appendix: Energy efficiency technologies

This appendix contains further information about the EETs selected for consideration in our study. The appendix is split into five subsections according to the different EET categories: hull and propulsion system, hotel load and air conditioning (AC), machinery, waste heat recovery (WHR), and other areas.

For some EETs (mainly those in the hull and propulsion category), we share some technical results from analyses specific to our 15,000 TEU ammonia-fueled vessel design. For others, we offer a more general or qualitative overview of how each technology works to improve energy efficiency and other relevant considerations for ship design and operation. Unless otherwise specified, these insights are based on experience from previous projects – extrapolated to the characteristics of this vessel design, where appropriate.

Hull and propulsion system

Hull form optimization

For this part of the study, we considered the benefit of optimizing the vessel's hull form and bow shape for its speed profile and relevant sea conditions. Energy savings from this approach will depend on the starting hull form. For this study, we used an 'off-the-shelf' design as the baseline.

In previous projects we had used computational fluid dynamics (CFD) optimization and resistance analysis to compare a conventional bulbous bow to an optimized bow with a vertical stem. An additional aspect of the CFD analysis was the simulation of the vessel behavior in waves, representing more realistic operational conditions than the calm water conditions which are traditionally considered during the hull form optimization process.

Given a vessel traveling at 18 knots in calm water and four-meter regular head waves, and based on previous projects, we estimate that the optimized vertical stem design could offer:

- 1.4% reduction in overall resistance
- 7% reduction in residual resistance due to improved wave formation
- Slight increase in viscous resistance (wetted surface +0.5%)
- Reduced net power requirement

We concluded that the vertical stem performs better than the conventional bow in waves above 1.5 meters, and is less sensitive to draft and trim variations. The speed profile (14-18 knots with wave height of 2-3 meters) is also optimal for the vessel's typical range.

Future work building on this analysis could include a full-scale validation of the resistance reduction and further CFD optimization, including simulations in waves.

Optimization of bow thrusters and scallop fairings

For the purposes of this study, we assume that the bow thruster openings increase the vessel's overall resistance by 3-5% across its full speed range. Here, hull form design is critical to energy savings – thruster tunnels must align with the streamlines to minimize drag. Speed and loading conditions also influence resistance, but hull form is the primary factor.

For this section, we analyzed the impact of the following enhancements based on experience from previous projects:

- Installation of bow thruster grids on the thruster tunnel opening to reduce resistance (see Figure 3)
- Scallop fairings shaped aft of tunnel openings to smooth flow and further reduce resistance (see Figure 4)



Figure 3: Illustrative example of flow impact of bow thruster grids (image source: Foreship).

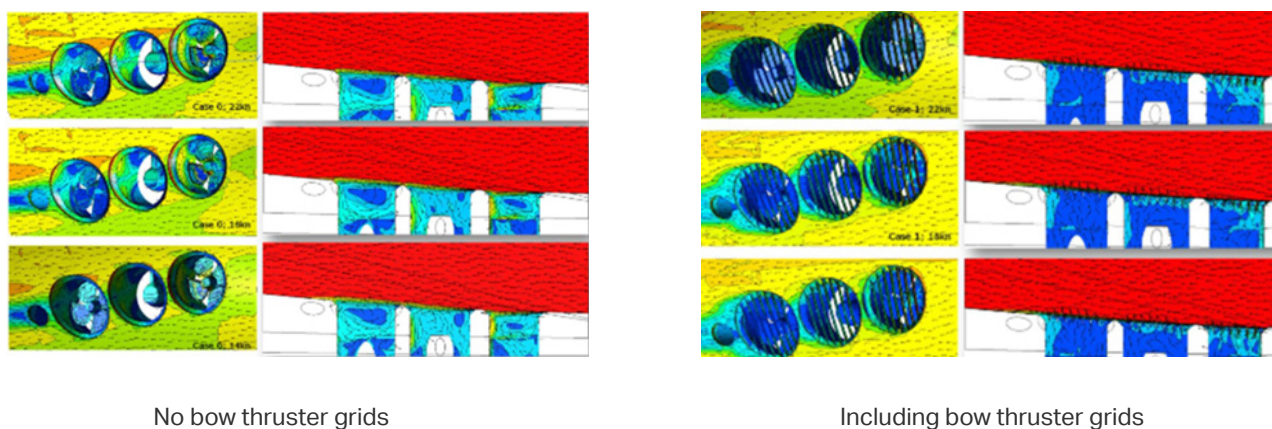
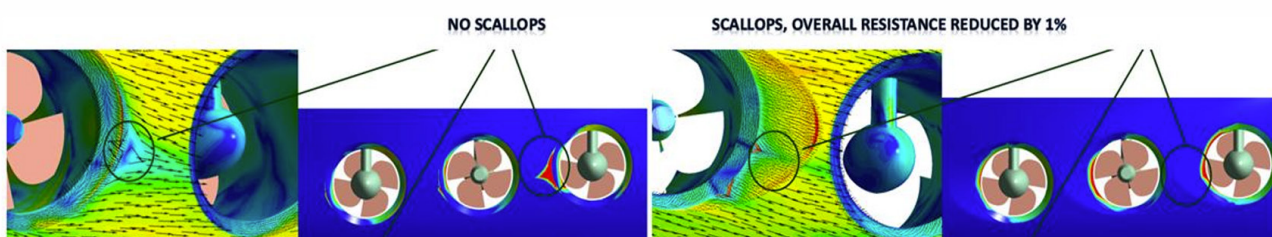


Figure 4: Illustrative example of flow impact of scallops (image source: Foreship).



We found that optimal scallop fairings typically reduced resistance by 0-0.5% across speeds and loading conditions. The fairings do not affect thruster side force.

At the same time, a well-designed hull form pushes the bow thruster opening resistance towards the lower end of the 3-5% range. Thruster grids reduce parasitic drag, contributing to a 0.5% resistance gain. However, the optimized grids reduced the thruster side force by around 10%, which is undesirable.

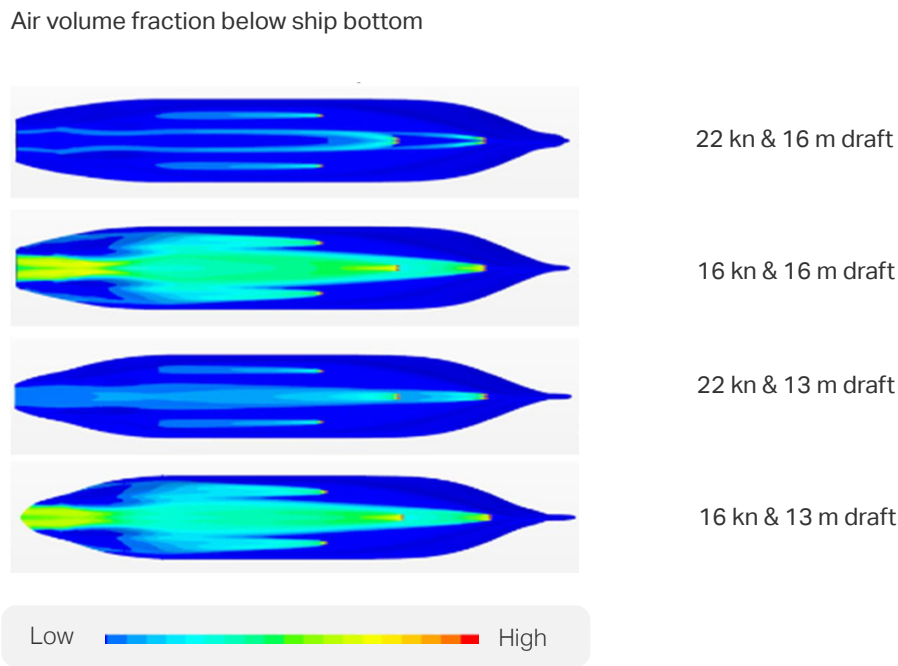
Therefore, optimizations of the bow thrusters and scallop fairings must ensure that bow tunnel integration minimizes interference with hull flow. Furthermore, comprehensive CFD validation is required to refine the full-scale resistance impacts.

Optimization of air lubrication systems (ALS)

Air lubrication systems (ALS) reduce vessels' resistance in seawater – thereby saving energy – by trapping a layer of small air bubbles close to the hull surface (see Figure 5).¹² Active ALS use compressors to create the air bubble layer, while passive ALS use ducting to generate the air bubbles under pressure. The latter approach is often more suitable for shallow-draft ships due to a reduced head that needs to be overcome.



Figure 5: Illustrative example showing air bubble distribution for a vessel using an active air lubrication system (image source: Foreship).



Potential fuel savings from an active ALS for our vessel design were estimated based on a CFD methodology developed and validated in previous projects. Passive systems are not feasible due to the vessel's 15.5-meter draft. Using this methodology, we analyzed the impact of an active ALS in the following scenarios:

- Draft: 13 meters (ballast) and 16 meters (full load)
- Speed: 16 knots and 18 knots
- Air volume: 8 kg/second and 12 kg/second

Table 6 summarizes the estimated net resistance reduction from the ALS for our design, depending on vessel speed and loading conditions in calm water. Higher hydrostatic pressure at deeper draft results in smaller air bubbles and increased demand for compressor power. When it comes to fuel savings, we found that absolute savings (in kW) remain relatively constant, while relative savings decrease as speed increases.

Table 6: Estimated net resistance reduction potential from active air lubrication system for the 15,000 TEU ammonia-fueled vessel design.

Net resistance reduction		
Speed	Ballast (13 m)	Full load (16 m)
16 kn	10%	6%
18 kn	6%	4%



Further optimization and validation of this analysis could include feasibility studies, increasing the number of air distribution boxes for better wetted surface coverage, and using onboard data to verify the system's long-term performance.

Bow wind shield

We investigated the impact of a wind shield installed on the bow to reduce wind resistance. Our aim was to find a configuration that would achieve the following:

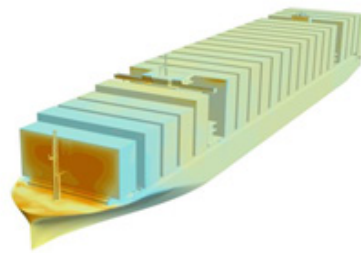
- **Reduce drag:** Minimize aerodynamic/hydrodynamic drag to lower the vessel's propulsion power requirements.
- **Maintain visibility:** Ensure compliance with SOLAS visibility standards, considering a two-meter stern-down trim condition.
- **Enhance ammonia venting:** Improve venting by thinning the boundary layer and reducing turbulence near the ammonia vent mast.
- **Structural and weight efficiency:** Use standard plate thickness (12 mm with a 20% allowance for stiffeners) to ensure the shield can be manufactured with a reasonable weight.

We used CFD to model multiple shield geometries on the ship's front section, assuming a draft of 15.5 meters. Our analysis assessed drag reduction, dynamic pressure distribution, and boundary layer behavior. We assumed a ship traveling at 15 knots with an apparent wind speed of 20 knots, and tested wind angles of 0°, 15°, and 30°.

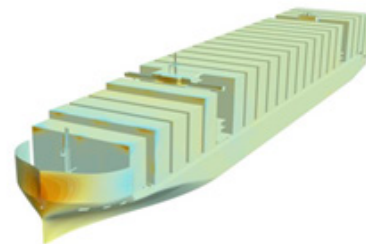
We adjusted the shield height and shape to optimize performance while ensuring that the conning position's visibility remains unobstructed. Two shield configurations shown in Figure 6 (designated as Case G_II and Case C_IV) emerged as leading candidates when compared to the original design (Case 0).

Figure 6: Modeled wind pressure for original (Case 0) and optimized (Case G_II, Case C_IV) bow wind shield designs (image source: Seaspan).

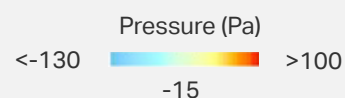
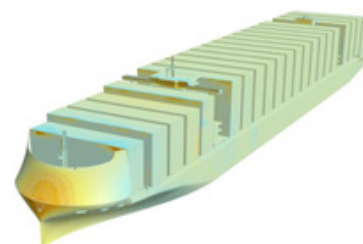
Case 0, headwind



Case G_II, headwind



Case C_IV, headwind



Our simulations indicate that these optimized shield designs reduce the vessels' average required propulsion power by approximately 1.7% under the modeled conditions. Power savings would be higher under stronger wind conditions and lower with lower wind speeds.

Both optimized designs were effective in reducing high-pressure zones and achieving a thinner, less chaotic boundary layer. These impacts both assist with drag reduction and improve ammonia venting. While both designs offer comparable performance, Case C_IV is structurally simpler to build and so potentially more cost-effective.

In summary, this analysis validates the concept of an optimized bow wind shield that meets key functional and regulatory requirements, while providing measurable energy savings. Our results support the further integration of such designs into full-ship models.

Weight optimization

Lowering the vessel's overall weight can reduce fuel consumption. We considered the following weight optimization approaches:

- **Smaller engine sizes:** Evaluate power solutions that meet performance needs with a reduced mass.
- **Improved steel tolerances:** Optimize structural designs to minimize excess material while maintaining safety.
- **Reduce component weights:** Identify non-critical systems or parts where weight savings can be implemented without affecting functionality.

In general, the benefit of weight reductions can be achieved by a draft reduction, or allowing for a more streamlined hull form with a reduced underwater volume.

To quantify the power savings from reduced lightweight, we can use the Admiralty Coefficient (A_c). This constant is defined as:

$$A_c = \frac{D^{\frac{2}{3}} \times V^3}{P_s}$$

Where D is displacement, V is speed, and P_s is shaft power.

With a constant A_c , the shaft power decreases as the displacement decreases, allowing an energy saving.

Overall, an effective weight optimization strategy must balance direct displacement reduction with design flexibility to achieve the best speed-power performance. This will vary from vessel to vessel.

Stator fin and other propulsion improvement devices (PIDs)

Propulsion improvement devices (PIDs) are specialized components that are integrated into the vessel's propulsion system to enhance energy efficiency. These devices work by optimizing the flow field around the propeller, recovering lost energy, and reducing turbulence and flow separation (see Figure 7). These impacts create a more homogeneous wake field, lower resistance, and improved speed-power performance.

When considering how these solutions could be implemented in our vessel design, we had the following baseline considerations:

- Locate the rudder and propeller as far aft as possible to maximize baseline propulsion efficiency.
- Optimize the stern hull form for the best compromise between minimizing hull resistance and maximizing propulsion efficiency.
- Prior to integrating any PID, ensure that the hull form and entire propulsion line are fully optimized for maximum efficiency.



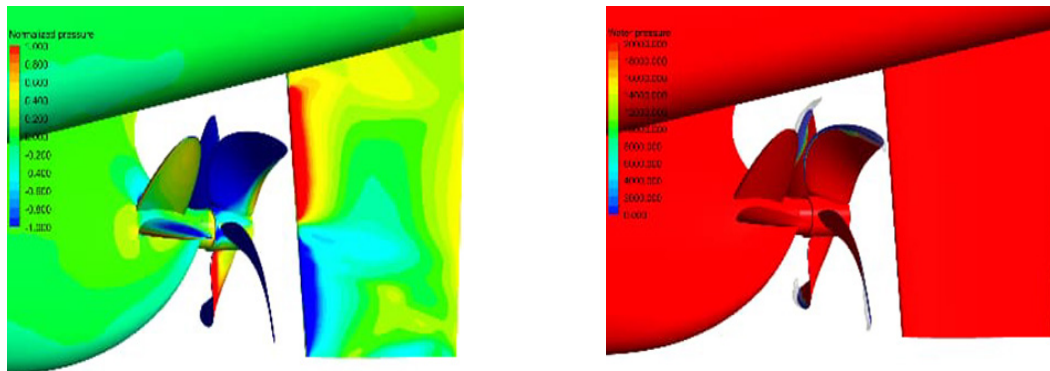
PIDs can be placed either ahead of or behind the propeller. Typical examples of the former include pre-swirl stators (see Figure 7), while solutions such as twisted rudder blades and rudder bulbs fall into the latter category. We chose to investigate a strategy of placing devices both ahead of and behind the propeller, while ensuring that each component enhances the overall system performance.

PIDs ahead of the propeller improve the wake field by conditioning the inflow ahead of the propeller, making it more homogeneous. For our vessel design, we estimated that installing a pre-swirl stator ahead of the propeller would improve propulsion efficiency by approximately 4-6% under varied operational conditions.

PIDs behind the propeller recover the propeller's rotational losses and eliminate the hub vortex. For our study, we investigated using a combination of a rudder bulb, twisted rudder blades, and a propeller hub cap. We estimated that this solution would improve propulsion efficiency by approximately 1-3% across the full range of speeds and loading conditions. A post-swirl stator may optionally be added to the rudder bulb to further recover rotational energy, but this may slightly increase resistance.

Overall, we found that combined implementation of these PIDs can yield cumulative efficiency gains. These measures offer additional propulsion savings on top of baseline hull and propulsion optimizations, contributing to overall energy savings. Final integration of PIDs should follow comprehensive baseline optimization to ensure that the improved flow conditions are fully exploited.

Figure 7: Illustrative example of pressure flow (left: normalized pressure, right: cavitation pressure) for a pre-swirl stator design (image source: Foreship).



EETs for hotel load and air conditioning (AC)

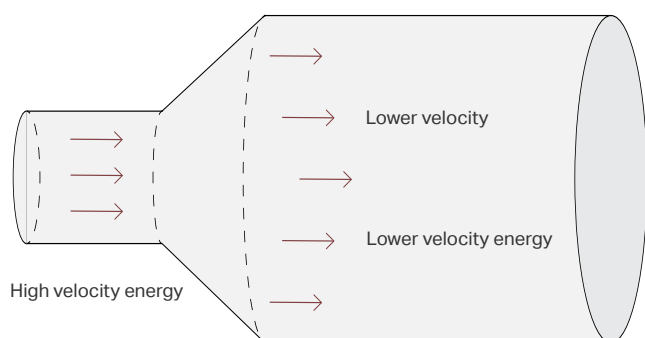
System design optimization

Minimizing energy losses in continuously operating systems – such as ventilation and AC – can improve the vessel's energy efficiency. Relevant strategies for this area include:

- Use straight, streamlined pipe and duct layouts.
- Avoid sharp bends and tight corners.
- Employ larger-diameter pipes and ducts to reduce friction (see Figure 8).

These approaches lower flow resistance and thereby energy consumption, leading to improved system performance and reduced operational costs.

Figure 8: Conceptual illustration of larger pipe diameters reducing flow velocity and thereby friction.



Smart climate control

Smart climate control technologies help match cooling outputs to actual demand – reducing energy use while enhancing indoor air quality. Examples of such smart technologies include intelligent AC management and sensor integration.

- Intelligent AC management systems use occupancy-based controls to dynamically adjust cooling and activate 'eco' modes during low-occupancy periods.
- Sensor integration refers to the use of CO₂ sensors to monitor real-time occupancy of areas on the vessel, and adjust fresh air supply accordingly.

These technologies help to ensure that energy for climate control is used only where and when it is actually needed.

Waste energy recovery

As it vaporizes, ammonia stored at -33°C extracts heat from the surrounding area. This energy can be recovered and reused for e.g., AC cooling – reducing reliance on conventional cooling, lowering auxiliary power needs, and enhancing overall energy efficiency.

Thermal envelope enhancements

These technologies improve the vessel's energy efficiency by allowing passive temperature regulation, reducing the need to spend energy on heating and cooling. Options in this category include:

- **High-performance windows:** Double-glazed windows with reflective coatings reduce solar heat gain and thermal transmittance.
- **Thermal insulation:** Thermal insulation of all AC-exposed surfaces and interfaces, focusing on heat-intensive zones like engine rooms.

Reefer container energy optimization

Reefer containers require energy to maintain refrigeration, and therefore optimizing the energy demand from these containers represents an opportunity for energy savings.

For our design, we aimed to prioritize the placement of reefer containers on the deck rather than in the hold. We estimated that reefers on the open deck use about 4.5 kW per container, while those in the hold use about 6 kW per container due to the hold ventilation power demands. Therefore, placing more reefer containers on the deck can reduce power consumption and enhance vessel-wide energy efficiency. However, the cargo contents should also be considered when deciding where to place the reefers.



EETs for machinery

Table 7: Summary of selected energy efficiency technologies for machinery.

Technology	Description	Energy efficiency benefits	Operational impact	Other considerations
Adaptive cooling and ventilation	- Systems to adjust cooling and airflow based on operational mode (at sea, in port, shore power) - Engine room ventilation using high-efficiency fans with VFDs and smart controls	- Reduces energy use by matching system output to actual thermal demand - Reduces fan power consumption through optimized duct design and adaptive speed control	- Maintains safe machinery temperatures across all operational modes - Reduces wear on ventilation equipment, lowering maintenance needs	- Requires careful coordination between operational modes and control systems
Waste heat recovery	- Regenerative lube oil heat exchangers reuse heat from outgoing oil to preheat incoming oil - EGBs recover steam from both main and auxiliary engine exhausts	- Decreases demand for heating energy via regenerative heat exchange - Additional steam generation from auxiliary engines enhances onboard power efficiency	- Enhances thermal system efficiency and reduces reliance on auxiliary heating - Supports continuous power generation from waste heat	- Some systems (e.g., regenerative exchangers, EGBs) require precise engineering and integration
Passive oil treatment	- Filtering lube and fuel oil using passive systems without motors or preheating	- Elimination of rotating parts and preheating cuts energy use in oil treatment	- Simplifies maintenance and increases system reliability	n/a
Smart lighting	- Smart lighting (e.g., motion-sensor or automatically timed) in crew and storage areas	- Minor but cumulative energy savings from automated lighting control	- Improves crew convenience and safety	n/a
Wastewater treatment	- Advanced systems (e.g., MBR, MBBR) to ensure high-quality effluent and environmental compliance	- Estimated direct energy savings are limited, but technology supports broader sustainability goals	- Ensures compliance with environmental regulations and reduces discharge risks	- Primary function of wastewater treatment is to meet discharge standards, not energy efficiency

VFDs = variable frequency drives, EGBs = exhaust gas boilers, MBR = membrane bioreactor, MBBR = moving bed bioreactor



EETs for waste heat recovery (WHR)

Table 8: Summary of selected energy efficiency technologies for waste heat recovery.

Technology	Description	Energy efficiency benefits	Operational impact	Other considerations
Sliding steam pressure	- Allows steam system pressure to gradually decline instead of maintaining a constant nominal pressure	- Reduces boiler running hours by avoiding continuous steam generation - Reduces energy consumption by minimizing unnecessary boiler operation	- Reduces boiler wear and operational hours - Simplifies steam system management during low-demand periods	- Energy savings are greater for high-load vessels such as cruise ships, less so for container ships - Requires careful pressure management to avoid performance issues
HT-water WHR	- Captures waste heat from HT cooling water - Integrates recovered heat into a common WHR loop for use in e.g., potable water production, AC heating, tank heating, absorption chillers	- Recycles thermal energy that would otherwise be lost - Reduces demand for auxiliary heating systems	- Enhances system integration and supports multiple onboard consumers - Improves thermal management across vessel systems	- System complexity increases with integration of multiple consumers - Requires robust control logic for optimal performance
Heat-to-power generators	- Use ORC (or similar systems) to convert engine waste heat into electricity - For this study, we used a 300 kW ORC unit as a reference for estimating potential energy savings	- Decreases auxiliary fuel consumption	- Adds onboard power generation capacity - Reduces load on generators and improves redundancy	- Installing and maintaining ORC systems requires space and technical expertise - May not always be possible extract the nominal power - Best suited for vessels with consistent high thermal loads
Power and steam turbines	- Steam turbine generators convert excess steam into electricity - Steam expanders are a cost-effective alternative that generate power by expanding high-pressure steam	- Harness excess steam to generate power, improving overall energy recovery and reducing fuel use	- Provide flexible power generation options - Can be tailored to steam availability and vessel needs	- Technology selection depends on cost, space, and steam availability - Expanders offer lower output than generators

HT = high-temperature, WHR = waste heat recovery, AC = air conditioning, ORC = organic Rankine cycle



EETs for other areas

Table 9: Summary of selected energy efficiency technologies for other areas.

Technology	Description	Energy efficiency benefits	Operational impact	Other considerations
Freshwater production	- Instead of evaporators, use single- and double-pass reverse osmosis units with integrated pressure converters for technical water production	- Saves heat energy by avoiding evaporation and enables integration with WHR systems	- Simplifies water production and reduces thermal system load	- Energy savings are indirect – main value lies in integration with WHR
Auxiliary engine optimization	- Selecting engines based on vessel power profile - Operating engines near optimal SFOC to improve fuel efficiency	- For our study, we estimated that operating auxiliary engines at 90% is ~4% more efficient than operation at 75% load, and ~11% more efficient than operation at 50% load	- Reduce fuel consumption and engine wear, especially in port operations	- Low-load operation leads to efficiency loss
Stacked auxiliary engine operation	- Keeps other engines at optimal load while one engine adjusts to load changes	- Maintains efficiency by keeping most engines at optimal SFOC	- Reduce fuel consumption and engine wear, especially in port operations	- Benefits depend on load profile and engine management
Efficient electrical motors	- Ensure that all continuously running motors meet high efficiency standards - (IE3 or better)	- Reduce energy losses and adapt motor output to actual demand	n/a	- Example standards: EU 2019/1781 and 2021/341
Variable frequency drives (VFDs)	- Allow dynamic adjustment of motor speed based on demand, for motors of ≥10 kW	- Reduce energy losses and adapt motor output to actual demand	- Enhance system responsiveness and reduce unnecessary energy use	- Demand and efficiency gains will be influenced by external factors (e.g., seawater temperature) - Example standards: EU 2019/1781 and 2021/341

WHR = waste heat recovery, SFOC = specific fuel oil consumption, LED = light-emitting diodes, SOFC = solid oxide fuel cell, PEM = proton-exchange membrane



Fuel mass flow meters	- Coriolis-type meters installed on bunkering lines and fuel consumers for precise monitoring	- Enable operational optimization through accurate fuel tracking	- Improve diagnostics and maintenance planning	- No direct savings, but critical for optimization and can support compliance with e.g., EU MRV and IMO DCS
LED lighting	- Ship-wide LED installation with centralized control for energy-efficient lighting	- Reduces energy consumption and maintenance for lighting	- Enhances visibility and safety together with lower energy use	- Energy savings are minor
Power take-in/power take-out (PTI/PTO) system	- Uses shaft generators powered by the main engine instead of by auxiliary engines	- Saves fuel as the main engine is more efficient than auxiliary engines	- Reduces auxiliary engine runtime and maintenance	- Reducing the number of ammonia-fueled engines can lower the safety risks from ammonia as fuel
Energy management systems	- Real-time monitoring and advisory software system to help optimize energy use and voyage planning	- Support continuous efficiency improvement through data-driven decisions	- Provide actionable insights for crew and operators	n/a
Fuel cells	- Includes SOFC and PEM technologies	- Fuel cells can be up to 20% more efficient than internal combustion engines¹³ - Based on a previous study,¹³ we estimate that ammonia-powered SOFCs can offer ~60% peak efficiency	- Compact and efficient nature is relevant for ammonia-fueled vessels	- Efficiency declines over time¹³



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