ENERGY EFFICIENCY AND DECARBONIZATION TECHNICAL GUIDE

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Maritime Administration

Glosten

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Acknowledgements and Contributors

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Definitions and Abbreviations

Term	Definition
$/kWh	dollars per kilowatt hour
A3C	PMW technology's proprietary cryogenic carbon capture process
ABS	American Bureau of Shipping (classification society)
AC	alternating current
ACC	absorption carbon capture
ACE	advanced flow controlling and energy saving
AFC	alkaline fuel cell
AiP	approval in principle
ALS	air lubrication system
ASTM	ASTM International (formerly American Society for Testing and Materials)
BIMCO	Baltic and International Maritime Council
bkW	brake kilowatt, power delivered to the engine shaft
BLDC	brushless direct current
BOP	balance of plant
CAV	constant air volume
CCC	cryogenic carbon capture
CCUS	carbon capture, utilization, and storage
CePV	CO_2e performance value
CFD	computational fluid dynamics
CG-ENG	USCG Office of Design and Engineering Standards
CGH_2	compressed gaseous hydrogen
CH_4	methane
CII	carbon intensity indicator
CNG	compressed natural gas
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
COTS	commercial off-the-shelf
CPP	controllable pitch propeller
CPV	CO_2 performance value
CRP	contra-rotating propellers
CTV	crew transfer vessels
DC	direct current
DEP	diesel-electric propulsion
DF	dual fuel
DG	diesel-generator
dLUC	direct land-use change
DME	dimethyl ether
DMFC	direct methanol fuel cell
DNV	Det Norske Veritas (classification society, formerly DNV-GL)
DOE	U.S. Department of Energy
DP	dynamic positioning
DRI	Desiccant Rotors International

Term	Definition
DWT	deadweight tonnage
EDLC	electric double layer capacitor
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
Ef	efficiency factor
EF_f	fuel emission factor
EGR	exhaust gas recirculation
EIF	entry into force
ENI	European Number of Identification
ERV	energy recovery ventilators
ET	efficiency technology
FAME	fatty acid methyl esters
FC	fuel cell
FCM	fuel consumption monitoring
FOG	biogenic feedstocks including vegetable oils, waste fats, oils, and greases
FPP	fixed pitch propeller
FT	fuel technology
FTD	Fischer-Tropsch diesel
G	guarantees of origin
GAO	U.S. Government Accountability Office
GHG	greenhouse gas
H_2	hydrogen
HFO	heavy fuel oil, or fuel oil with >2.0% sulfur, corresponding to ISO 8217:2017 residual grades
HHI	Hyundai Heavy Industries
hp	horsepower
HTL	hydrothermal liquefaction
HVAC	heating, ventilation, and air conditioning
ICCT	International Council on Clean Transportation
ICE	internal combustion engine
IEEC	international energy efficiency certificate
IGF Code	International Code of Safety for ships using gases or other low-flashpoint fuels
iLUC	indirect land-use change
IMO	International Maritime Organization
IR	infrared radiation
IRENA	International Renewable Energy Agency
kg	kilogram
km	kilometer
KM CDR	Kansai Mitsubishi Carbon Dioxide Recovery Process
kW	kilowatt
kWh	kilowatt hour
LARS	launch and recovery system
LDC	least developed countries
LEG	liquefied ethane gas
LEL	lower explosive limit

Term	Definition
LFO	light fuel oil
LH_2	liquefied hydrogen
LHV	lower heating value, at 25 °C and 1 atmosphere (1.01 bar)
LIC	lithium-ion capacitor
Li-ion	lithium-ion
LFP	lithium-iron-phosphate
LNG	liquefied natural gas
LPDF	low pressure dual fuel
LPG	liquefied petroleum gas
LR	Lloyd's Register (classification society)
LVOC	liquefied volatile organic compound
MARPOL	International Convention for the Prevention of Pollution from Ships
MBM	market based measures
MCFC	molten carbonate fuel cell
MCR	maximum continuous rating
CH_3OH	Methanol, methyl alcohol
MEPC	Marine Environment Protection Committee
MGO	marine gas oil, or ultra-low sulfur fuel oil (ULSFO) with ≤0.1% sulfur, corresponding to ISO 8217:2017 residual or distillate grades
MJ	megajoule
MW	megawatt
MWh	megawatt hour
N_2O	nitrous oxide
NOx	nitrogen oxides
oCCS	onboard carbon capture and storage
OM	operational measures
OPS	onshore power supply
ORC	organic Rankine cycle
PAFC	phosphoric acid fuel cell
PCB	printed circuit board
PBCF	propeller boss cap fins
PDD	pseudo direct drive
PEM	polymer electrolyte membrane
PEM-FC	polymer electrolyte membrane fuel cell
PIL	Pacific International Lines
PM	particulate matter
PTG	power turbine generator
PTI	power take-in
PTO	power take-off
R&D	research and development
RE	renewable energy
RF_e	energy reduction factor (as a value from 0 to 1)
RINA	Registro Italiano Navale (classification society)
RoRo	roll on, roll off (vehicle transport)
ROI	return on investment
ROV	remotely operated vehicle

Term	Definition
rpm	revolutions per minute
SBC	shore-side battery charging
ScES	supercapacitor energy storage
SCO_2	supercritical carbon dioxide
SCR	selective catalytic reduction
SDARI	Shanghai Merchant Ship Design and Research Institute
SDS-F	semi-duct system with contra fins
SEEMP	ship energy efficiency management plan
SFC	specific fuel consumption
SIDS	small island developing states
SMES	superconducting magnetic storage
SMR	steam methane reformation
SOFC	solid oxide fuel cell
SOLAS	International Convention for the Safety of Life at Sea
SOV	surface operation vessels
SOx	sulfur oxides
STF	Sanoyas Tandem Fin
STG	steam turbine generator
STP	standard temperature and pressure, 0 °C and 1 atmosphere (1.01 bar)
TBT	tributyltin
TEU	twenty-foot equivalent unit
TRA	technology readiness assessment
TRL	technology readiness level
TtW	tank-to-wake
USD	U.S. dollar
UV	ultraviolet
VAV	variable air volume
VFD	variable frequency drive
VOC	volatile organic compound
VRV	variable refrigerant volume
VSG	variable speed generator
VVT	variable volume temperature
WHR	waste heat recovery
WISAMO	Wing Sail Mobility Project
WSC	World Shipping Council
WSF	Washington State Ferries
WtT	well-to-tank
WtW	well-to-wake

Overview

The marine industry has entered a period of rapidly changing vessel energy technologies, fuels, and operations. The momentum behind international regulations such as IMO's EEXI, EEDI, and CII, as well as growing pressure in the US to regulate and reduce greenhouse gas emissions, is pushing many energy options from nascent beginnings to full commercial adoption. Vessel owners and operators are challenged to stay current with the technology landscape and which solutions fit with a specific vessel's characteristics and operating profile. This guide serves as a reference for US and international owners/operators alike but is geared toward the vessel types that are characteristic of the US flag merchant fleet.

The guide focuses on the state of energy efficiency and fuel technologies available, and overviews emerging technologies and operational measures that may contribute to improving energy efficiency and reducing GHG emissions in the long-term. The guide is organized into the following parts:

- **Introduction.** Provides background on regulatory mandates and guidelines, market-based measures, a technology category overview, and a Guide Navigator.
- **Part 1 – Evaluation Methodology.** Describes how each technology or measure is evaluated with respect to energy and emission reduction potential, technology readiness, and overall vessel performance.
- **Part 2 – Technology Evaluation.** Evaluates or overviews all considered technologies, broken down by the categories Efficiency Technology (ET) (including renewable energy), Fuel Technology (FT), and Operational Measures (OM).
- **Part 3 – Technology Stacking.** Explores how some technology combinations can be readily stacked (with complementary outcomes), are practical to stack (no complementary benefits but are compatible), or are impractical to stack (detriment to each technology's effectiveness when stacked).
- **Part 4 – Case Studies.** Examines six vessel types, their baseline emissions performance, and possible technology implementation to reduce the vessel's energy and emissions. Vessels were selected to represent large sections of the US flag merchant fleet.

This guide serves as a starting point for owners/operators to consider the overall landscape of energy efficiency, fuel, and operational measures available, and how the emissions performance of their fleet, in singular or diverse trades, can be improved in the most effective manner.

A guide navigator is linked here, and on all pages from Part 1 onward, to quickly navigate through the guide:

Link to Guide Navigator

References

Technical references, technologies, and vessel deployments mentioned in this guide are maintained on the platform Airtable to provide current hyperlinks to each reference and enable periodic updates that track with industry developments. These references are indicated with the following nomenclature throughout the guide, where "№" is the reference index:

- References: [A№]
- Technologies: [B№]
- Deployments: [C№]

Static lists of references, technologies, and vessel deployment list are provided in the appendices.

References

Online List with Hyperlinks

Static list: Appendix A

Technologies

Online List with Hyperlinks

Static list: Appendix B

Deployments

Online List with Hyperlinks

Static list: Appendix C

Introduction

Moving goods and people over the water on marine vessels, like any means of transportation, consumes energy and fuel. The *efficiency* of marine vessels can be considered in a number of possible ways often depending on one's perspective. The ***vessel operator*** may measure efficiency in terms of specific fuel oil consumption (SFC), which is the amount of fuel the vessel consumes at a given speed, draft, and required power condition. The ***fleet manager*** may measure efficiency as fuel consumption per ton-mile per year. The ***international community*** now favors energy efficiency in terms of carbon emissions per transport work (unit of economic output), also known as carbon intensity. Each of these efficiency definitions are legitimate and appropriate for the application.

Generally, all methods are trying to determine 'how much *net work/energy I get out* for how much *fuel/electricity I use*.' There are many opportunities to improve efficiency and decarbonize vessels. This can happen by reducing energy wasted on the vessel propulsion system, improving the flow of electricity to various onboard demands, or switching to a fuel and consumers with an reduced lifecycle carbon emissions. These approaches are all explored in this guide.

The amount of propulsion power required is a function of the desired speed, hull efficiency, propeller efficiency, and prime mover efficiency, as well as level of redundancy and safety factors. Numerous factors will affect the efficiency of each. Figure 1 illustrates how energy losses for an example vessel are distributed, assuming a conventional diesel-electric propulsion system using petroleum-based marine fuel. Due to internal combustion engine thermal efficiency limitations, a significant portion of energy is lost to heat via exhaust and radiation. The remaining fuel energy available for electrical power has subsequent losses through each step of energy conversion, before finally reaching vessel demands: hotel loads, vessel loads, and propulsion.

Figure 1 is a helpful visual map for where *wasted* energy can provide opportunities for savings. In this example, propulsion energy dominates the electrical demand, and the propeller losses are nearly equal to the useful energy applied to propulsion. Reducing propeller losses is an enormous opportunity to improve efficiency. Such technologies as pre- and post-swirl devices, as well as various propeller configurations, can have appreciable impacts on those propeller losses. Waste heat is another significant opportunity. Capturing waste energy or improving the efficiency of the engine are two ways to benefit from this. Moderate investments in these loss areas can return savings over the entire life of the vessel and, in some cases, can have short payback times.

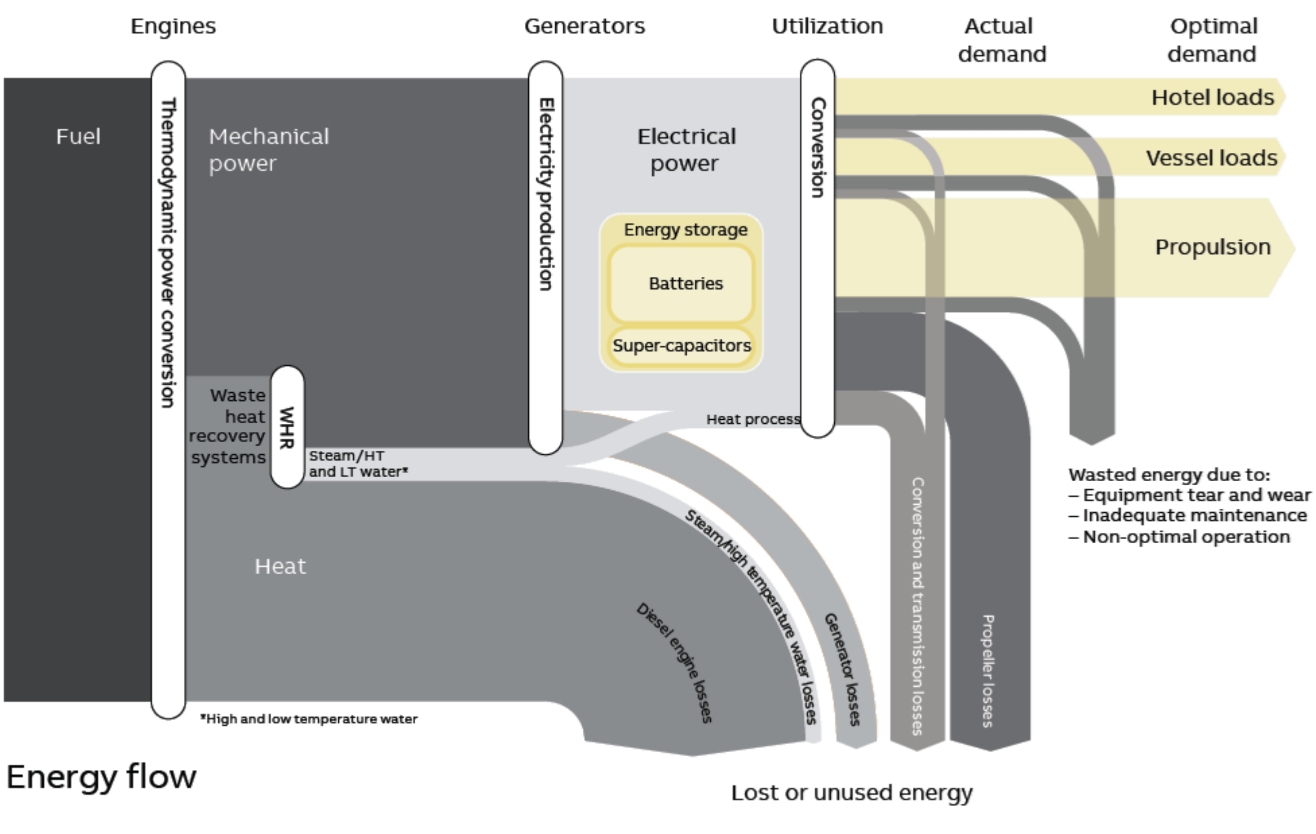


Figure 1: Energy breakdown for a diesel-electric vessel (source: ABB)

Regulatory Mandates & Guidelines

While international and domestic targets for GHG emissions reductions, global temperature rise limits, and production/adoption of zero-carbon fuels continue to become more prominent, IMO regulations have either entered into force or are slated to enter into force over the next year. These regulations largely apply to vessels engaged in international commerce and are required to carry an International Energy Efficiency Certificate (IEEC) (i.e., vessels of 400 gross tonnage and above), per MARPOL Annex VI, Chapter 2, Regulation 6 [A1].

Targets being established on the international level and in regional communities, such as the declaration by 14 countries (including the United States) at the COP26 climate conference (Glasgow, November 2021) to reduce global maritime GHG emissions to zero by 2050, will likely influence stricter emissions and energy regulations to materialize in the next 5-10 years [A2].

International Maritime Organization (IMO) Mandates

Under the Initial Greenhouse Gas (GHG) Strategy (Resolution MEPC.304(72), adopted April 2018 at MEPC's 72nd session), IMO established the following ambitions for international shipping:

- Reduce carbon intensity (CO_2 emissions per transport work) by at least 40% by 2030.
- Reduce carbon intensity by at least 70% by 2050.
- Reduce total annual GHG emissions by at least 50% by 2050, compared to 2008.
- Carbon intensity of ships to decline through implementation of further phases of the Energy Efficiency Design Index for new ships.

Some experts have contended that these goals are inadequate to align with the imperative set of the Paris Agreement to limit global warming to 1.5 °C (compared to pre-industrial levels). IMO is slated to consider a final draft Revised IMO GHG Strategy at MEPC's 80th session (June 2023), but it is uncertain whether the above ambitions will be tightened further to align with the vision for zero emissions shipping by 2050.

Energy Efficiency Design Index (EEDI) for New Ships

The IMO Energy Efficiency Design Index (EEDI) requirements are in the 2021 Revised MARPOL Annex VI (Resolution MEPC.328(76)), under Regulations 22 and 24. The IMO regulations and supporting resolutions are summarized in Table 1, including entry into force (EIF) dates, vessel applicability, and schedule. EEDI is the first globally binding climate measure to be adopted since the Kyoto Protocol, and made mandatory for new ships at the 62nd session of IMO's Marine Environment Protection Committee (MEPC 62). The EEDI provides a specific numerical figure for an individual ship design, expressed in grams of CO_2 per ship's capacity mile (the smaller the EEDI, the more energy efficient the ship's design). The attained EEDI is calculated by the following concept formula, based on the technical design parameters for a given ship:

$$Attained\ EEDI = \frac{power\ installed\ \times\ specific\ fuel\ consumption\ \times\ CO_2\ conversion\ factor}{available\ capacity\ (DWT\ or\ GT)\ \times\ speed}$$

The EEDI is the ratio of ship's "cost to the society" in the form of its CO_2 emissions divided by the "benefits to the society" represented by the transport work done by the ship. It represents the amount of CO_2 generated by a ship while doing one ton-mile of transport work. The EEDI for new ships aims at promoting the use of more energy-efficient (less polluting) equipment and engines. The EEDI requires a minimum energy efficiency level per capacity mile for different ship type and size segments. EEDI is intended to stimulate continued innovation and technical development of all the components influencing the fuel efficiency of a ship from its design phase.

The EEDI calculation is based on assumptions regarding the specific fuel consumption (SFC) of the engines (in g/kWh) compared to the power installed on the ship. For new ships, the attained EEDI value represents a measure of the "design" efficiency of the ship, but it does not give any indication concerning the operational efficiency. In this respect, two sister ships with the same EEDI may have different emissions depending on their load factor, sea conditions, and the way the ship is operated. Attained EEDI is a static design measure, focusing on the tank-to-wake (TtW) part of the CO_2 emission lifecycle.

Attained EEDI is compared to the required EEDI using a reference line for the vessel type and size:

$$Attained\ EEDI \leq Required\ EEDI = \left(1 - \frac{x}{100}\right) \times Reference\ line\ value$$

The reduction factor '*x*' for different vessel types and sizes is scheduled in four phases (Phase 0 – Phase 3), which take effect in accordance with the schedule in Table 1. Reduction factors for each schedule phase vary by vessel type and size, summarized in Regulation 24 of the 2021 Revised MARPOL Annex VI.

Detailed calculations for attained EEDI are provided in Resolution MEPC.308(73) and its amendments[A3][A4][A5].

Table 1: IMO EEDI Regulation Summary

<table>
<tr><th colspan="4">Relevant Documents</th></tr>
<tr><th>Document</th><th>Title</th><th>Status</th><th>Ref</th></tr>
<tr><td>Resolution MEPC.328(76) (2021 Revised MARPOL Annex VI)</td><td>Regulation 22: Attained Energy Efficiency Design Index (Attained EEDI)</td><td>Revision EIF 1 Nov 2022*</td><td>[A6]</td></tr>
<tr><td>Resolution MEPC.328(76) (2021 Revised MARPOL Annex VI)</td><td>Regulation 24: Required EEDI</td><td>Revision EIF 1 Nov 2022*</td><td>[A6]</td></tr>
<tr><td>Resolution MEPC.308(73)</td><td>Annex 5: 2018 Guidelines on the Method of Calculation of the Attained EEDI for New Ships</td><td>Adopted 26 Oct 2018</td><td>[A3]</td></tr>
<tr><td>Resolution MEPC.322(74)</td><td>Annex 16: Amendments to the 2018 Guidelines</td><td>Adopted 17 May 2019</td><td>[A4]</td></tr>
<tr><td>Resolution MEPC.332(76)</td><td>Annex 5: Amendments to the 2018 Guidelines</td><td>Adopted 17 June 2021</td><td>[A5]</td></tr>
<tr><th colspan="4">Applicability of Required EEDI</th></tr>
<tr><td colspan="4">All ships of 400 gross tonnage and above engaged in international voyages, of conventional (i.e., diesel-mechanical) propulsion and following types/sizes:
- Bulk carrier (10,000 DWT and above)
- Gas carrier (2,000 DWT and above)
- Tanker (4,000 DWT and above)
- Containership (10,000 DWT and above)
- General cargo ship (3,000 DWT and above)
- Refrigerated cargo carrier (3,000 DWT and above)
- Combination carrier (4,000 DWT and above)
- LNG carrier (10,000 DWT and above)
- Ro-ro vehicle carrier (10,000 DWT and above)
- Ro-ro cargo ship (1,000 DWT and above)
- Ro-ro passenger ship (250 DWT and above)</td></tr>
<tr><td colspan="4">All cruise passenger ships of 400 gross tonnage and above engaged in international voyages, having non-conventional propulsion, and 25,000 DWT and above.</td></tr>
<tr><td colspan="4">All LNG carriers of 400 gross tonnage and above engaged in international voyages, having non-conventional propulsion, and 10,000 DWT and above.</td></tr>
<tr><th colspan="4">Schedule</th></tr>
<tr><th>Phase</th><th colspan="3">Schedule (Table 1 of 2021 Revised MARPOL Annex VI)</th></tr>
<tr><td>0</td><td colspan="3">1 Jan 2013 to 31 Dec 2014 – elapsed</td></tr>
<tr><td>1</td><td colspan="3">1 Jan 2015 to 31 Dec 2019 – elapsed</td></tr>
<tr><td>2</td><td colspan="3">1 Jan 2020 to 31 Mar 2022 – elapsed (for certain vessel types/sizes, see Reg 24 [A6])
1 Jan 2020 to 31 Dec 2024 – ACTIVE (for other vessel types/sizes)</td></tr>
<tr><td>3</td><td colspan="3">1 April 2022 onward - ACTIVE (for certain vessel types see Reg 24 [A6])
1 Jan 2025 onward – forthcoming (for other vessel types/sizes)</td></tr>
</table>

*Prior MARPOL Annex VI regulations for EEDI have been in-force since 2013 [A7].

Energy Efficiency Existing Ship Index (EEXI)

The IMO Energy Efficiency Existing Ship Index (EEXI) applies to the same set of vessel types and sizes as EEDI but for existing vessels that do not have an EEDI Technical File. For existing ships that do have an EEDI Technical File, the attained EEDI needs to be verified to be equal to or lower than the require EEXI. EEXI requirements are in the 2021 Revised

MARPOL Annex VI, under Regulations 23 and 25. The IMO regulations and supporting resolutions are summarized in Table 2, including entry into force (EIF) dates and vessel applicability. While the EEXI amendments to MARPOL Annex VI enter into force 1 November 2022, the first EEXI certification period comes into effect 1 January 2023.

EEXI is calculated using the same parameters as EEDI and is also a static measure, focusing on the TtW part of the CO_2 emission lifecycle. Unlike EEDI, existing vessels under EEXI do not have a phase-in period for increasing reduction factors, instead having fixed reduction factors for various ship types and sizes.

Table 2: IMO EEXI Regulation Summary

Relevant Documents			
Document	**Title**	**Status**	**Ref**
Resolution MEPC.328(76) (2021 Revised MARPOL Annex VI)	Regulation 23: Attained Energy Efficiency Existing Ship Index (Attained EEXI)	EIF on 1 Nov 2022	[A6]
Resolution MEPC.328(76) (2021 Revised MARPOL Annex VI)	Regulation 25: Required EEXI	EIF on 1 Nov 2022	[A6]
Resolution MEPC.350(78)	2022 Guidelines on the Method of Calculation of the Attained EEXI	Adopted 10 June 2022	[A8]
Resolution MEPC.351(78)	2022 Guidelines on Survey and Certification of the Attained EEXI	Adopted 10 June 2022 Takes effect 1 Jan 2023	[A8]
Applicability of Required EEXI			
All ships of 400 gross tonnage and above engaged in international voyages, of conventional (i.e., diesel-mechanical) propulsion and following types/sizes: - Bulk carrier (10,000 DWT and above) - Gas carrier (2,000 DWT and above) - Tanker (4,000 DWT and above) - Containership (10,000 DWT and above) - General cargo ship (3,000 DWT and above) - Refrigerated cargo carrier (3,000 DWT and above) - Combination carrier (4,000 DWT and above) - LNG carrier (10,000 DWT and above) - Ro-ro vehicle carrier (10,000 DWT and above) - Ro-ro cargo ship (1,000 DWT and above) - Ro-ro passenger ship (250 DWT and above)			
All cruise passenger ships of 400 gross tonnage and above engaged in international voyages, having non-conventional propulsion, and 25,000 DWT and above.			
All LNG carriers of 400 gross tonnage and above engaged in international voyages, having non-conventional propulsion, and 10,000 DWT and above.			
Reduction Factors (no schedule for existing vessels)			
Defined in Table 3 of Revised MARPOL Annex VI.			

Carbon Intensity Indicator (CII)

The IMO has also developed the Carbon Intensity Indicator (CII), an operational technical measure that provides information on the efficiency of a ship while in operation, with respect to CO_2 emissions from a TtW perspective. The CII requirements are in the 2021 Revised MARPOL Annex VI, under Regulation 28. This IMO regulation and supporting resolutions (providing guidance for calculating CII, vessel type reference lines, ratings, and correction factors/voyage adjustments) are summarized in Table 3, including entry into force (EIF) dates and vessel applicability.

Where EEDI and EEXI are a snapshot evaluation of emissions performance, the CII is a progressive improvement measure to be calculated and reported year over year. CII is based on the actual operational characteristics of the vessel, specifically the vessel's fuel consumption data and achieved transport work data, resulting in a figure of CO_2 emissions per ton-nautical mile. The attained CII calculation is summarized as follows:

$$Attained\ CII = \frac{annual\ fuel\ consumption\ \times CO_2\ conversion\ factor}{available\ capacity\ (DWT\ or\ GT)\ \times\ distance}$$

At the end of each calendar year, a vessel's performance against vessel-specific ratings must be determined (ratings are A, B, C, D, and E), and whether corrective action is required for inferior performance. As such, CII compliance requires long-term planning by operators, and likely a re-assessment and revision of a vessel's Ship Energy Efficiency Management Plan (SEEMP).

Attained operational CII is compared to the required operational CII using a reference value, CII_R, for the vessel type and size:

$$Attained\ CII \leq Required\ CII = \left(1 - \frac{z}{100}\right) \times CII_R$$

The reduction factor '*z*' is an annual reduction factor. This differs from the reduction factor *x* for EEDI (phased values for different vessel types/sizes) and reduction factor *y* for EEXI (fixed values for different vessel types/sizes) in that the CII reduction factors increase year over year, ensuring continuous improvement of carbon intensity.

CII is not limited to new vessels and can be used to measure the 'real' energy efficiency of a ship in operation (expressed through carbon intensity) and gauge the effects of any changes, such as hull and propeller cleaning, slow steaming, and improved voyage planning. CII can also be improved by increasing the amount of transport work done per distance, vessel improvements, or operational measures. However, as the CII calculation depends on ship activities and operations, it will vary over time and with voyage characteristics. It therefore cannot be used to establish a fixed figure of performance.

Table 3: IMO Operational CII Regulation Summary

Relevant Documents			
Document	**Title**	**Status**	**Ref**
Resolution MEPC.328(76) (2021 Revised MARPOL Annex VI)	Regulation 28: Operational Carbon Intensity	EIF on 1 Nov 2022 Takes effect 1 Jan 2023 First reporting 1 April 2024	[A6]
Resolution MEPC.348(78)	2022 Guidelines for Administration Verification of Ship Fuel Oil Consumption Data and Operational Carbon Intensity	Adopted 10 June 2022	[A8]
Resolution MEPC.352(78)	2022 Guidelines on Operational Carbon Intensity Indicators and the Calculation Methods (CII Guidelines, G1)	Adopted 10 June 2022	[A8]
Resolution MEPC.353(78)	2022 Guidelines on the Reference Lines for Use with Operational Carbon Intensity Indicators (CII Reference Lines Guidelines, G2)	Adopted 10 June 2022	[A8]
Resolution MEPC.354(78)	2022 Guidelines on the Operational Carbon Intensity Rating of Ships (CII Rating Guidelines, G4)	Adopted 10 June 2022	[A8]
Resolution MEPC.355(78)	2022 Interim Guidelines on Correction Factors and Voyage Adjustments for CII Calculations (CII Guidelines, G5)	Adopted 10 June 2022	[A8]
Applicability of Required CII			
All ships falling into categories of Table 2 of 2021 Revised MARPOL Annex VI (Regulation 24) that are 5,000 gross tonnage and above, irrespective of propulsion type.			
Schedule			
Schedule and values for annual reduction factors are not included in the 2022 set of guidelines for CII. 2021 Guidelines are provided in Resolution MEPC.338(76) [A9]			

Ship Energy Efficiency Management Plan (SEEMP)

The Ship Energy Efficiency Management Plan (SEEMP) is the consolidating document that lays out how a vessel will monitor and improve its efficiency performance. Vessels have been required to carry a SEEMP under the currently in-force MARPOL Annex VI since 2013, but certain vessels will be required to meet new SEEMP requirements under the 2021 Revised MARPOL Annex VI. The revised requirements are under Regulations 26 of the 2021 Revised MARPOL Annex VI. The IMO regulation and supporting resolutions are summarized in Table 4, including entry into force (EIF) date and vessel applicability.

For vessels subject to operational CII (see Table 4), the revised SEEMP regulation requires the following details on compliance with CII to be included:

1. Methodology to calculate the vessel's attained CII.
2. The required CII for the following three years.
3. An implementation plan for achieving the required CII for the following three years.
4. A procedure for self-evaluation and improvement of carbon intensity performance.

The revised SEEMP is the instrument by which corrective actions due to inferior CII performance are implemented. Inferior CII performance for a vessel is addressed through a review and update to the vessel's SEEMP, incorporating a plan to achieve the required CII for that vessel. As required CII values adjust annually with increasing reduction factors, the SEEMP is expected to account for progressive changes to the vessel's performance.

Table 4: IMO SEEMP Regulation Summary

Relevant Documents			
Document	**Title**	**Status**	**Link**
Resolution MEPC.328(76) (2021 Revised MARPOL Annex VI)	Regulation 26: Ship Energy Efficiency Management Plan (SEEMP)	Revision EIF 1 Nov 2022* Takes effect 1 Jan 2023	[A6]
Resolution MEPC.346(78)	2022 Guidelines for the Development of a SEEMP	Adopted 10 June 2022	[A8]
Resolution MEPC.347(78)	Guidelines for the Verification and Company Audits by the Administration of Part III of the SEEMP	Adopted 10 June 2022	[A8]
Applicability of SEEMP, Regulation 26, Part 3			
All ship falling into categories of Table 2 of 2021 Revised MARPOL Annex VI (Regulation 24) that are 5,000 gross tonnage and above, irrespective of propulsion type.			

*Prior MARPOL Annex VI regulations for EEDI have been in-force since 2013 [A7].

Market-Based Measures

Market Based Measures (MBM) are policy instruments that incentivize polluters to reduce emissions using markets, price, and other economic mechanisms. While there is international consensus that externalities such as climate change are directly correlated to greenhouse gas (GHG) emissions from human activity, and that climate change has severe environmental and economic consequences, the cost of fossil fuels do not reflect the cost of these 'negative externalities'. MBMs such as emissions cap-and-trade schemes or carbon taxes (levies) are possible mechanisms in addition to mandatory or prescriptive regulations that can drive industrial or consumer choices to reduce emissions. These two MBMs are discussed here, as well as financial measures.

Cap-and-Trade

Emissions trading, often known as cap-and-trade, is a government-mandated MBM which seeks to limit or reduce a pollutant through an economic incentive. Under such a scheme, the governing authority issues permits to emit specific amounts of the pollutant over a given period. Each polluter is given a permit, equivalent to their emissions. If they want to increase their emissions, they need to purchase permits on the open market. If a polluter reduces their emissions sufficiently, they can sell permits on the market to another polluter who knows their emissions will increase. In theory, the polluters who can most cost effectively reduce their emissions will do so and, therefore, the cost to society will be the lowest. Cap-and-trade systems provide a precise emission control strategy, but create uncertain and potentially volatile emission pricing and revenues if not appropriately controlled. The administrator may be challenged to collect and distribute funds in a fair and transparent manner, and investment decisions by polluters become less certain and potentially more financially risky.

Emissions trading has been implemented with varying degrees of success in many countries and regions but has not been broadly mandated in the maritime industry. Launched in 2005, the EU Emissions Trading System (EU ETS) is the world's first supranational ETS, which includes 27 EU member states and three states from the European Economic Area-European Free Trade Association (EEA-EFTA): Iceland, Liechtenstein, and Norway. The EU ETS is one of the EU's key policies for reducing carbon emissions. Three phases have been completed between 2005 and 2020, and Phase 4 started in 2021. Phase 4 adopts a more ambitious cap under the European Green Deal, targeting at least 55% net reduction in greenhouse gas emissions by 2030 (the 'Fit for 55' package) [A10]. Phase 4 proposes a revision to the EU ETS to achieve the revised target and may incorporate the shipping trade to and from EU ports in the ETS cap-and-trade system. The vessel size threshold for implementation is also still under discussion.

Carbon Tax

Pollution taxes set levies on each ton (or kg) of a generated GHG pollutant (e.g., CO_2), and are a more direct way of regulating GHG emissions. While cost of the taxes may incentivize polluters to reduce emissions, the cost of implementing emissions-reducing technologies is often higher. In many schemes, the taxes are collected in an R&D fund that is reinvested to offset the cost of emissions-reducing technologies and strategies. The Norwegian NOx Fund is an example of a program that has been successful in reducing emissions on a national basis, including the maritime sector. The agreement was initiated in 2008 between 15 business organizations and the Ministry of the Environment. As of 2019, the NOx Fund has paid out USD$468 million for NOx reduction measures, and reduced NOx emissions within Norway by 40,000 metric tons ([A11]). The fund, which supports up to 80% of the cost of projects, has invested heavily in such technology as LNG for ship propulsion. From 2008 to 2017 the fund supported conversion or construction of over 70 LNG vessels bringing the total up from only 3 LNG vessels in 2008 [A12].

A similar maritime carbon tax, either at national or international levels, could be effective at accelerating technology development and motivating emitters to improve their operations. A Carbon tax or levy system provides precise revenue collection, but generally lacks precise emission control, and therefore a clear emission reduction trajectory.

Carbon levies are an ongoing discussion on the IMO level, especially since 2021. The appropriate value for a carbon tax comprises a wide range. The vessel size threshold for implementation (400 GT or 5,000 GT) has also not been determined and will require further discussion. In 2021, the International Chamber of Shipping (ICS) proposed to IMO a tax of USD$2 per metric ton marine fuel consumed, or approximately $0.67 per metric ton CO_2 [A13]. The primary objective of this proposed amount is to initiate a USD$5 billion R&D fund for accelerating emissions-reducing technologies.

Conversely, the Marshall Islands and the Solomon Islands proposed a universal levy to IMO starting at USD$100 per metric ton carbon dioxide-equivalent (CO_2e) in 2025, increasing to $250-300 by 2030 [A14]. The $250-$300 range marks the high end of proposed rates, and could serve several purposes: make carbon-zero and carbon-neutral fuels cost-competitive with conventional marine fuels, provide aid to small island developing states (SIDS) and least developed countries (LDC) that will see accelerated adverse impacts from global warming, and establish R&D funds to accelerate technology development.

While international consensus on carbon tax has not been reached, and a timeline for an initial implementation is unclear, the end-goal of a carbon tax will drive the agreed rate, if a universal tax is mandated at all.

Shipping organizations like the World Shipping Council (WSC) and Baltic and International Maritime Council (BIMCO) have stressed that market-based measures such as a carbon tax should not be adopted as the sole method of reducing emissions, instead being coordinated with progressive energy efficiency improvements and fuel reduction mandates. With EEDI in-force, and EEXI and CII taking effect in 2023, hesitation from shipping organizations to mandate market-based measures is now subsiding. Several shipping organizations are now actively engaging in MBM discussions at IMO, possibly increasing the likelihood of implementation in the coming years.

Financial Measures

The financial sector is now taking an active role in decarbonizing global shipping. Under the Poseidon Principles, a self-governing climate agreement launched in 2019, a large group of ship financiers are taking emission performance into account in their decision-making for their underwriting portfolios. Signatories include 27 major banks, representing approximately 15% of global shipping finance value [A15][A16]. The Poseidon Principles Association seeks to align "ship finance goals with society's goals." The following four principles constitute that goal:

1. Assessment of climate alignment. Signatories to measure carbon intensity of their shipping portfolio and assess performance relative to decarbonization pathways established by the Association.
2. Accountability. Signatories to use un-biased information, primarily from classification societies and IMO-recognized organizations, to assess and report climate alignment of their portfolios.
3. Enforcement. Signatories to implement standardized covenant clauses that are contractual in new business activities, ensuring access to necessary carbon intensity data.
4. Transparency. Climate alignment scores from each signatory's portfolio will be annually published.

The Poseidon Principles are coupled with the Sea Cargo Charter, which establishes a framework for shipping companies to align their operations with ship financiers' climate alignment baselines for achieving emissions reduction goals. The Sea Cargo Charter currently applies to bulk ship charters, with signatories including 34 major dry and liquid bulk charterers and operators [A17].

An expansion of the Poseidon Principles now includes marine insurers, broadening the initiative's immersion across the financial system that supports global shipping.

Major financial initiatives like the Poseidon Principles and its supporting instruments are complementary to regulatory mandates and should accelerate the uptake of emissions-reducing measures across the global industry.

Technology Categories Overview

The Energy Efficiency and Decarbonization Guide organizes technologies into the following categories: Efficiency Technology (including Renewable Energy), Fuel Technology, and Operational Measures.

Efficiency (ET)

Efficiency Technology (ET) measures directly reduce the amount of total energy required by the vessel to operate under normal conditions. ET measures can reduce the propulsion power, which is the primary energy consumer on most vessels, the electrical power required for all shipboard systems, or both.

Renewable Energy is a sub-category of ET, focused on technologies that harness energy from the environment: wind, wave, and solar.

Fuel Technology (FT)

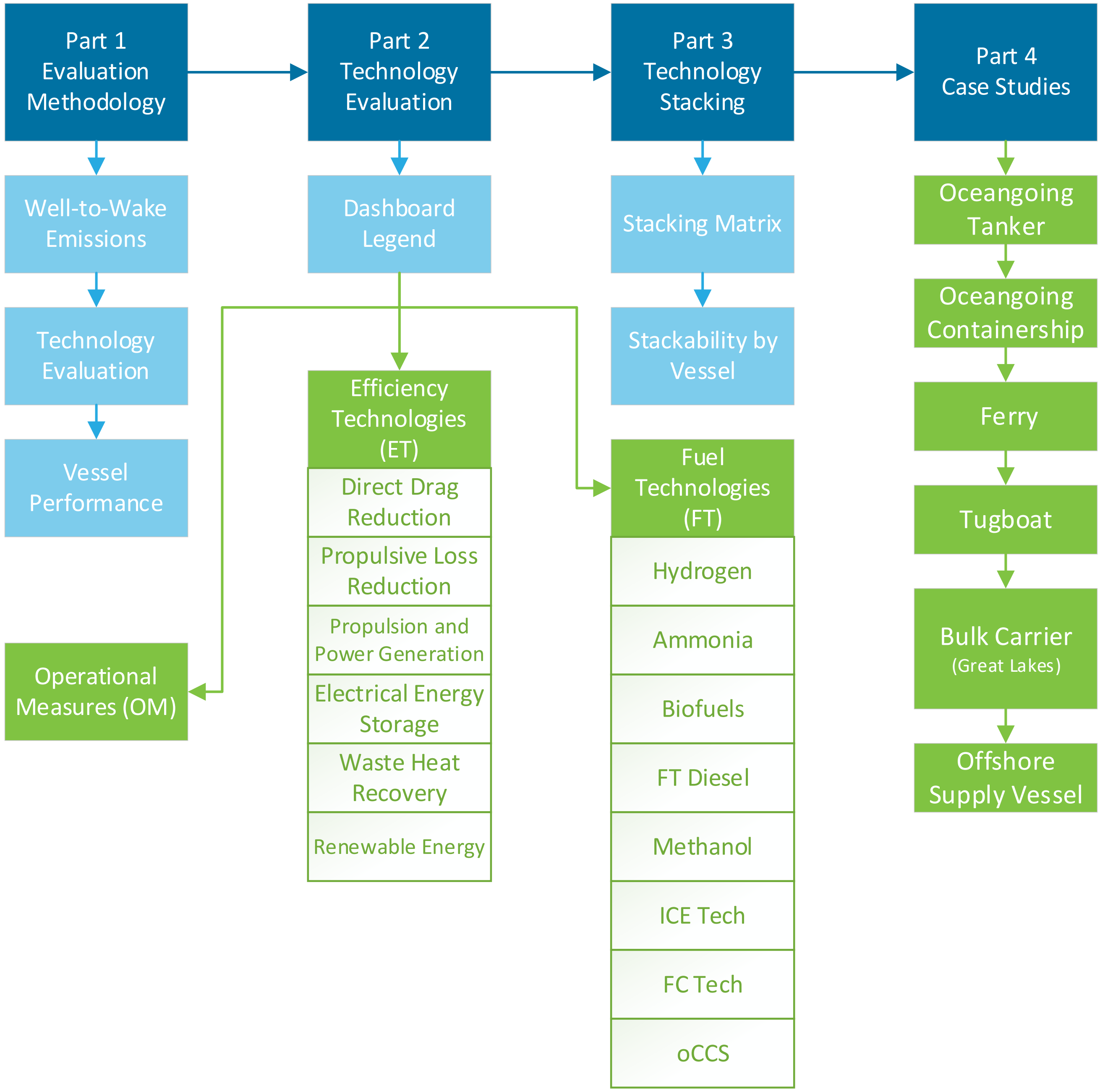
Fuel Technology (FT) measures include both the alternative fuels that can reduce a vessel's Well-to-Wake (WtW) emissions and the energy converters which utilize the fuel, such as specialized internal combustion engines (ICE) and fuel cells (FC). While onboard carbon capture and storage (oCCS) is not strictly a FT, it is included in this technology category.

Operational Measures (OM)

Operational measures (OM) can be implemented to reduce fuel consumption, independent of changes to the vessel's energy efficiency or fuel configuration. These include data capture and analysis for operational improvements, fuel consumption monitoring, voyage optimization, predictive maintenance, and partial or full vessel autonomy.

Guide Navigator

Use the following flowchart and hyperlinks to navigate sections of the guide most applicable to your decarbonization planning.



Part 1 – Evaluation Methodology

1.1 Well-to-Wake Emissions vs Tank-to-Wake Emissions

This guide evaluates greenhouse gas (GHG) emissions on the Well-to-Wake (WtW) basis, which includes Tank-to-Wake (TtW) emissions, sometimes called "stack-only". TtW emissions are reported next to overall WtW emissions for more operations-oriented assessments of vessel and fleet emissions.

There are two GHG emissions definitions to consider: straight carbon dioxide (CO_2), and carbon dioxide-equivalent (CO_2e). In this guide, CO_2e includes two additional GHG constituents: methane (CH_4), nitrous oxide (N_2O). The radiative forcing of each, or potential to trap heat, is equated to the amount of CO_2 generating an equivalent amount of radiative forcing. The global warming potential (GWP) of each constituent is based on a 100-year timescale, consistent with the 2020 Fourth IMO GHG Study 2020 [A18]. A 20-year timescale for determining global warming potential is also used in some literature (GWP20) and has merit when evaluating the near-term impact of GHG emissions. Only CO_2e values using the 100-year timescales are considered in this guide (GWP100).

Emissions in both CO_2 and CO_2e are reported throughout the guide, giving the reader the opportunity to use the data that is most relevant to their own evaluations.

While CO_2e emissions are often measured or evaluated based on TtW emissions, WtW emissions capture the complete lifecycle impact of an operation, from extraction through consumption. By focusing on WtW emissions, the global and temporal impacts of GHG releases are considered from an absolute perspective. TtW emissions are useful for evaluating the local impact of criteria pollutants (e.g., carbon monoxide – CO, nitrogen oxides – NOx, sulfur oxides – SOx, and particulate matter – PM) on the environment and human health, and GHG figures for the TtW segment in this guide can be applied accordingly.

Depending on the fuel type and consumer (propulsion or ship service power), stack CO_2e releases can sometimes represent less than half of the total GHG intensity incurred by a vessel's operations. The actual environmental impact of a vessel's operations, particularly global warming, is therefore underestimated if the related Well-to-Tank (WtT) emissions have an appreciable GHG component that is not considered. WtT emissions, or source emissions, include feedstock extraction/cultivation, early processing/transformation at the source, feedstock transport, feedstock conversion to product fuel, product fuel transport, product fuel storage, local delivery, retail storage, and dispensing (including bunkering).

GHG emissions are therefore reported in the following ways:

- Emission type: straight carbon dioxide (CO_2) vs carbon dioxide equivalent (CO_2e).
- Emissions lifecycle: WtT (source) segment vs TtW (stack) segment, summed to total WtW (lifecycle) emissions.
- Baseline: lifecycle segments compared to marine gas oil (MGO) as a conventional marine fuel, defined below.

MGO is generalized as ultra-low sulfur fuel oil (ULSFO) with ≤0.1% sulfur, corresponding to ISO 8217:2017 residual or distillate grades. The other marine fuel considered in this guide is heavy fuel oil (HFO), generalized as fuel oil with >2.0% sulfur, corresponding to ISO 8217:2017 residual grades.

The importance of distinguishing between TtW (stack-only) and WtW (lifecycle) emissions is demonstrated in the following comparison between fossil-derived (gray) liquified natural gas and biomass-derived (green) Fischer Tropsch diesel as alternatives to MGO.

Lifecycle Emissions Comparison Example: LNG vs Fischer Tropsch Diesel

A comparison example of the WtW value chains of fossil-based liquified natural gas (LNG) and sustainable biomass Fischer Tropsch diesel (FTD) illustrates key differences in the WtW GHG intensity of different fuels from both how they are sourced (WtT) and consumed (TtW).

A typical WtW value chain for producing, transporting, and consuming marine, fossil-based, LNG is shown in Figure 2. The cumulative WtT segment of extraction/production, feedstock transport, processing (purification & liquefaction), product transport, storage, and bunkering of LNG results in net release of CO_2e emissions, in addition to the TtW emissions of onboard storage, fuel transfer, and combustion on board the vessel.

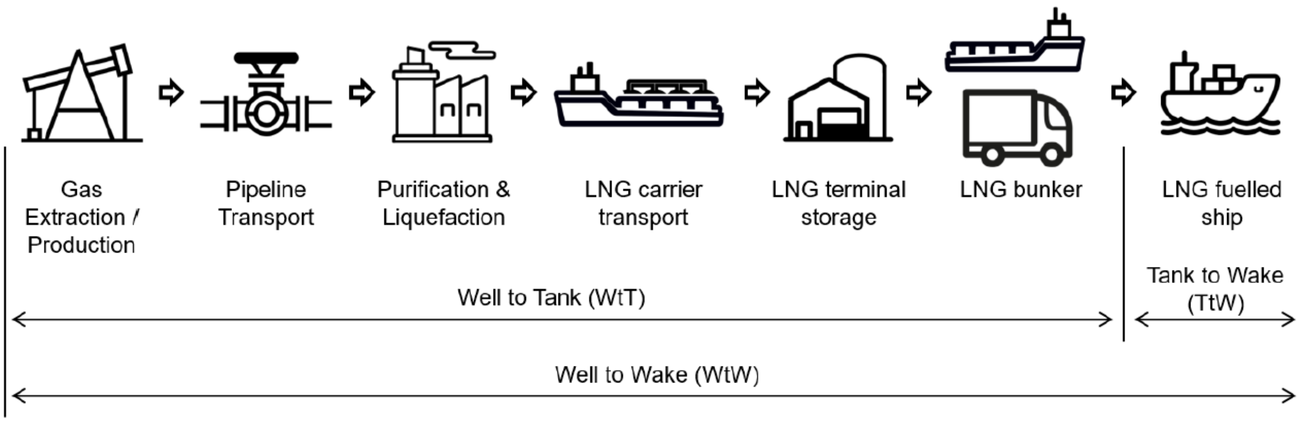


Figure 2: **Typical emissions lifecycle of fossil-based LNG for marine use (Source: Journal of Marine Science and Engineering)**

The net release of CO_2e throughout the LNG value chain (WtW, comprising WtT and TtW) is shown in Figure 3, with CO_2 in light gray, CO_2e in dark gray, and the MGO baseline (reported as CO_2e) as diamond markers (The unit Fuel Emission Factor EF_f as used in this guide is defined in the next section on CO2 and CO2e Reduction Potential. Natural gas undergoing liquefaction to LNG is assumed to be sourced in the US. While natural gas, assumed to be consumed in a low pressure dual fuel (LPDF) engine, has a lower TtW CO_2e emission factor than MGO by CO_2e, it's WtT CO_2e emission factor is higher than MGO. By including the WtT segment, the WtW emissions of LNG approaches that of MGO.

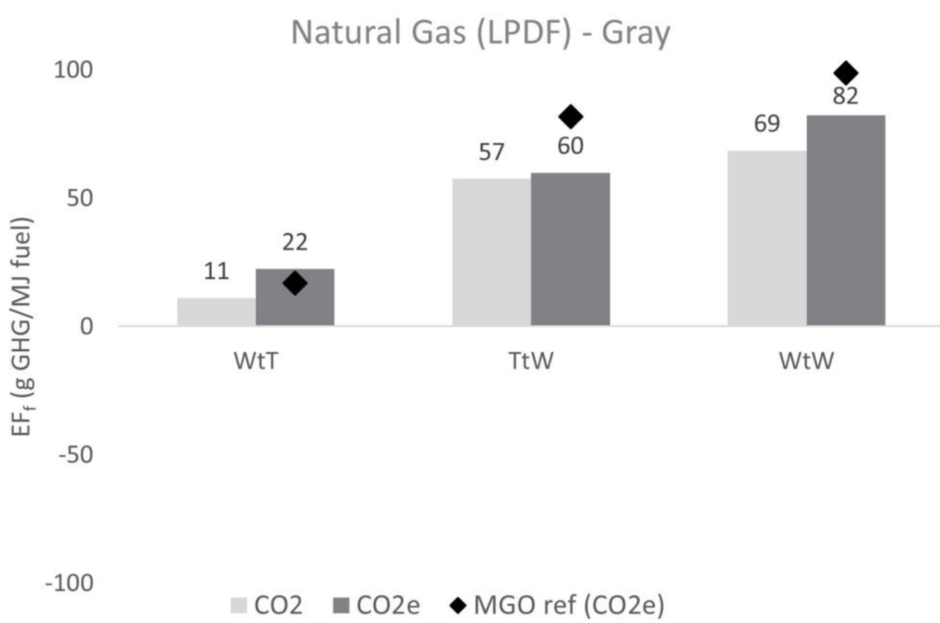


Figure 3: **Lifecycle CO_2 and CO_2e emission factors for fossil-based natural gas, diesel cycle (low pressure dual fuel – LPDF)**

A corresponding WtW value chain for a biofuel-type diesel is shown Figure 4, representative of sustainable biomass FTD. The extraction of biofuel-type diesel from a biomass source has a net decrease in CO_2e emissions, as significant CO_2 could be captured in the raw biogenic feedstock, followed by CO_2 released in feedstock transport through bunkering.

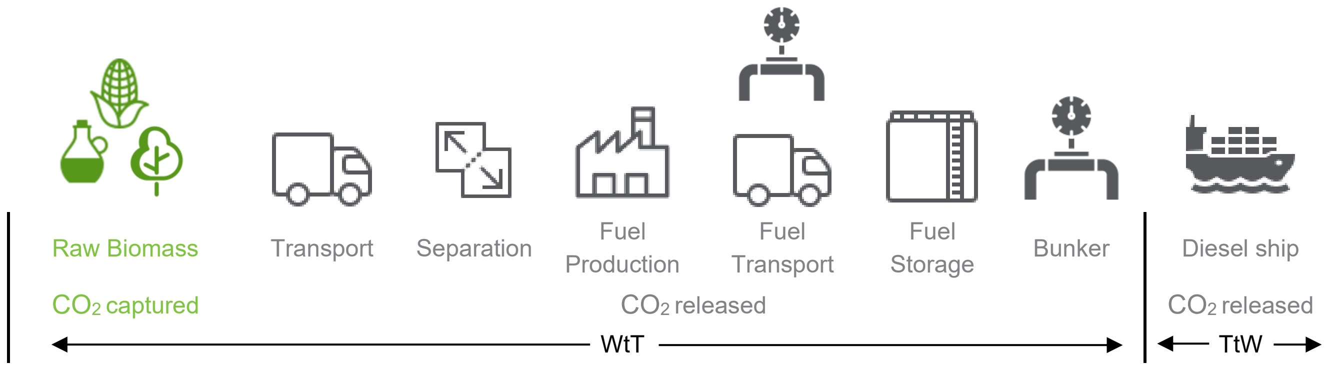


Figure 4: Typical emissions lifecycle of bio-fuel type diesel for marine use

The net release of CO_2e throughout the sustainable biomass FTD value chain (WtW, comprising WtT and TtW) is shown in Figure 5. The TtW CO_2e emissions of sustainable biomass FTD combustion is similar to MGO, and higher than LNG. From a TtW perspective, FTD would appear to have a more consequential impact on GHG emissions. However, the biogenic uptake of carbon from biomass sources in the WtT segment results in a negative CO_2e emission factor. This carbon uptake offsets the TtW CO_2e emissions, resulting in WtW emissions that are dramatically lower than MGO.

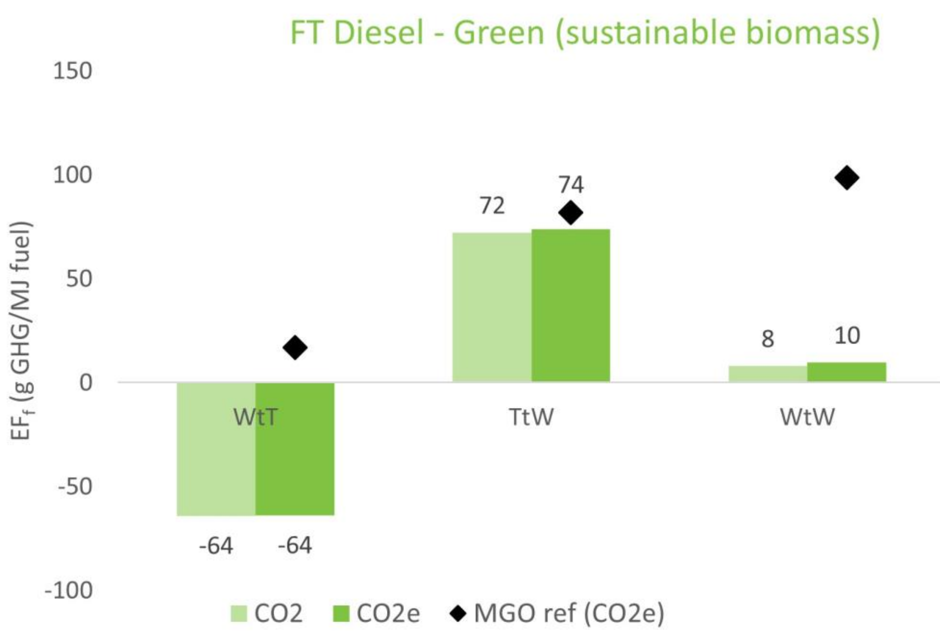


Figure 5: Lifecycle CO_2 and CO_2e emission factors for green (sustainable biomass) FTD

When considering both WtT and TtW emission factors of fossil-based LNG vs sustainable biomass FTD, the importance of evaluating WtW emissions becomes clear. LNG does have lower TtW GHG emissions than both MGO and FTD, but its high WtT emissions diminishes its overall GHG reduction potential. Conversely, sustainable biomass FTD's net reduction in WtT emissions improves its overall GHG reduction potential over MGO and LNG, by a significant factor:

- The TtW emission factor ratio for fossil-based LNG over sustainable biomass FTD from Figure 3 and Figure 5 is 0.83 (60/74 grams CO_2e/MJ fuel), indicating FTD to emit more GHG in its use as a marine fuel.
- The overall WtW emission factor ratio for fossil-based LNG over sustainable biomass FTD is 8.2, indicating fossil-based LNG emits more lifecycle GHG in its use as a marine fuel than a biofuel-type diesel.

The reporting of both WtW and its TtW segment in this guide allows the reader to perform GHG emissions evaluations as needed for their operation. WtW figures are especially necessary for considering fuel types with widely disparate WtT and TtW characteristics.

1.2 Technology Evaluation

Technology Readiness Level

Each technology presented in this guide has undergone a Technology Readiness Assessment (TRA) to determine its Technology Readiness Level (TRL). The TRL scale shown in Figure 6 was developed based on the US Government Accountability Office (GAO) [A19] best practices and adapted from the US Department of Energy's TRL scale to be specifically applied for marine technology evaluation. Each energy efficiency technology and fuel technology has been assessed for its readiness and assigned a TRL.

Generally, TRAs are conducted to give a snapshot of a technology's maturity. Scale of development and testing, analytical fidelity, and operational environmental considerations all play a role in determining the readiness. The associated TRL serves to condense this information into a single value which represents the technology's overall stage of development.

The TRL scale in this guide was developed for the maritime industry and references both the vessel-specific environment as well as class or regulatory approval across each of the levels. Similar to how the original TRL scale was developed for aerospace technologies, this TRL scale verifies technologies across relevant marine applications. Understanding a specific technology's readiness can help reduce technical risk and minimize unknown future costs associated with uptake.

	TRL	Explanation
Concept	1	Basic principles observed and reported
	2	Technology concept with planned application formulated
	3	Process tested for proof of concept in controlled environment
Development	4	**Prototype** tested in industrial setting (non-marine environment)
	5	**Prototype** tested in marine setting (relevant environment)
	6	**Pilot** tested in marine setting (relevant environment)
Commercial	7	**Demonstration** on marine vessel as partial-system, with vessel-specific approval (operational environment)
	8	**Demonstration** on marine vessel as full-system, with vessel-specifc approval (operational environment)
	9	**Commercial installation** on marine vessel, with type approval (operational envrionment)

Figure 6: TRL scale implemented in guide

CO_2 and CO_2e Reduction Potential

Two measures of Reduction Potential are considered:

- For energy efficiency technologies, an Energy Reduction Factor, RF_e as a value from 0 to 1.
- For fuel technologies, a Fuel Emission Factor, EF_f, in terms of WtT, TtW, and cumulative WtW.

Both energy efficiency and fuel technologies are factored into overall decarbonization performance for a vessel. Their relationship to determining a vessel performance, when single or multiple technologies are combined, is detailed in the next section, Vessel Performance.

Energy Reduction Factor (RF_e)

For each energy efficiency technology (ET) included in this guide, manufacturer and third-party data are used to develop a percent reduction range, which corresponds to the portion of energy that can potentially be saved by implementing the technology. The magnitude of the range indicates the confidence in potential energy reductions achieved by a given technology and its variable reduction impact for different vessel types and their characteristics.

Percent reduction is defined as the amount of energy that is reduced by the technology relative to the total energy demand of the vessel, i.e., propulsion load plus ship service load. A technology that can reduce the overall vessel's energy demand by 10 % to 15% has a reduction range from -10 to -15%. This is illustrated in the Percent Reduction plot on the left in Figure 7, with the minimal energy reduction as a solid bar, and the reduction range as a patterned bar.

The Energy Reduction Factor (RF_e) is the resulting portion of energy for vessel operations still required after technology implementation, against the vessel's baseline energy. For a technology reduction range of -10 to -15%, the reduction factor RF_e is a range of 0.85 to 0.90. This is illustrated in the Reduction Factor plot on the right in Figure 7, as the solid bar plus the patterned range bar.

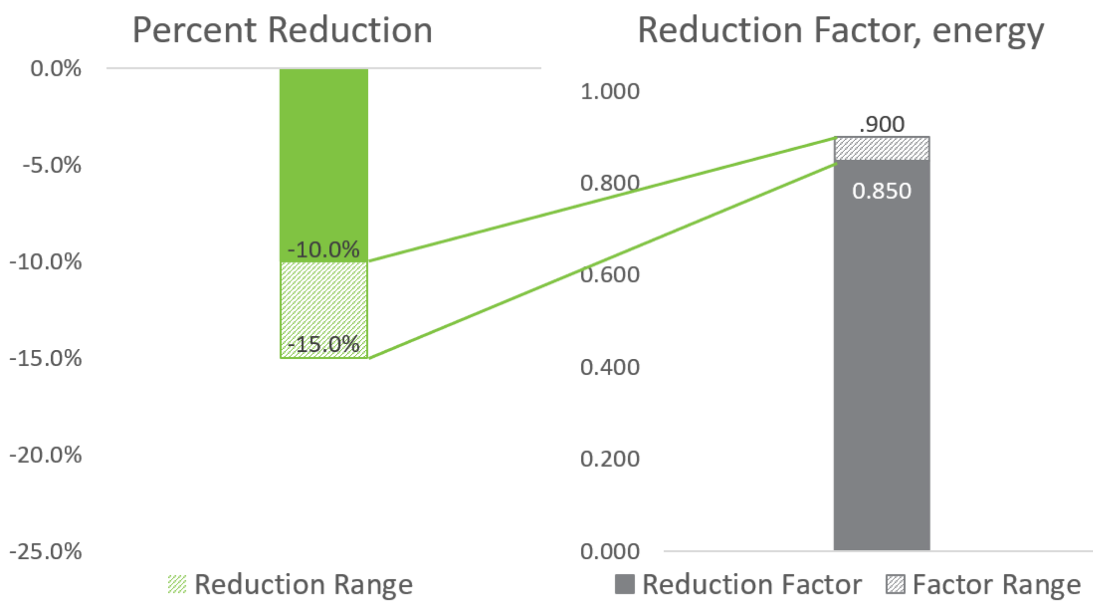


Figure 7: Generic percent reduction and reduction factor plots

In most cases, energy efficiency measures will reduce a vessel's overall energy, resulting in a negative percent reduction range and Efficiency Factor of less than 1.0. In some cases, however, an energy efficiency measure may increase the vessel's energy (e.g., powered equipment that adds to the ship service load, or hull appendages that can increase vessel drag). Such technologies will have a percent reduction range that spans zero (e.g., reduction range of +5/-15%), and an Efficiency Factor range that spans 1.0 (e.g., E_F of 0.85/1.05).

For the sake of simplicity, the reduction range and efficiency factor focus on the net operating impact of the technology only. The embedded energy of manufacturing, shipping, and installing various technologies are ignored. This embedded energy may be nontrivial in some cases, but evaluating embedded energy would require a detailed analysis into the supply chain of each technology reviewed in this guide and is outside its scope.

Fuel Technology Emission Factor (EF_f)

WtW Fuel Emission Factor (EF_f) is calculated for each fuel technology considered in this guide, based on the fuel's carbon content and lifecycle GHG emissions. GHG emissions is primarily defined in the Fourth IMO GHG Study 2020 as the combined emissions of CO_2, CH_4, and N_2O, expressed as CO_2-equivalent, or CO_2e [A18]. The 100-year global warming potential (GWP100) of each constituent is based on a baseline GWP for CO_2 of 1 and are provided in Table 5. Both CO_2 and total CO_2e emission factors are reported for fuels throughout this guide to facilitate different types of emissions performance evaluations.

Table 5: 100-year global warming potential for different GHGs

Greenhouse Gas	GWP100
Carbon dioxide (CO_2)	1
Methane (CH_4) - fossil	29.8
Nitrous oxide (N_2O)	273

For some fuels, multiple WtT sourcing paths are considered to demonstrate the different reduction potential based on how the fuel is extracted (or type of primary feedstock), produced, and processed.

The Fuel Emission Factor is expressed either on a mass per energy basis (grams per megajoule fuel energy) or as a unitless value, tons GHG (CO_2 or CO_2e) per ton fuel consumed. Fuel Emission Factor as applied in this guide is adopted from the definition in IMO Resolution MEPC.308(73) and its amendments [A3], which provides guidelines on calculating attained EEDI for new ships, as well as the Fourth IMO GHG Study 2020 [A18], but this guide expands EF_f values to both CO_2 and CO_2e. EF_f as a unitless mass per mass value (tons emission per tons fuel) can be multiplied by a vessel's fuel consumption in tons (on an annual or absolute basis) to estimate the mass CO_2 or CO_2e impact of the vessel. This is detailed in the next section.

Where Emission Factor is assessed for fuels that are prospective alternatives to marine petroleum-based fuels, the provided EF_f is independent of specific fuel consumption (SFC) for that fuel. Notional SFC values are provided for each alternative fuel to perform the Vessel Performance calculations discussed in the next section.

WtW Emission Factor in this guide is divided into WtT and TtW segments, comprised of the following sub-segments:

1. WtT: Emissions from extraction, production, storage, transport and bunkering.
2. TtW: Emissions from storage onboard, fuel transfer, and combustion/consumption.

The sum of the two segments equals the total WtW Emission Factor of a given fuel:

$$EF_{f\,(WtW)} = EF_{f\,(WtT)} + EC_{f\,(TtW)}$$

This breakdown helps clarify how different areas of a fuel's life cycle contribute to its total GHG impact, and thus reduction potential.

The significance of WtW Emission Factors is illustrated in the plots in Figure 8, comparing conventional marine gasoil (MGO) with green Fischer Tropsch diesel (FTD). MGO and FTD have similar heating values [A20] and both meet ASTM D975 (standard specification for diesel fuel), so this side-by-side comparison is acceptable without adjusting for the SFC of each fuel.

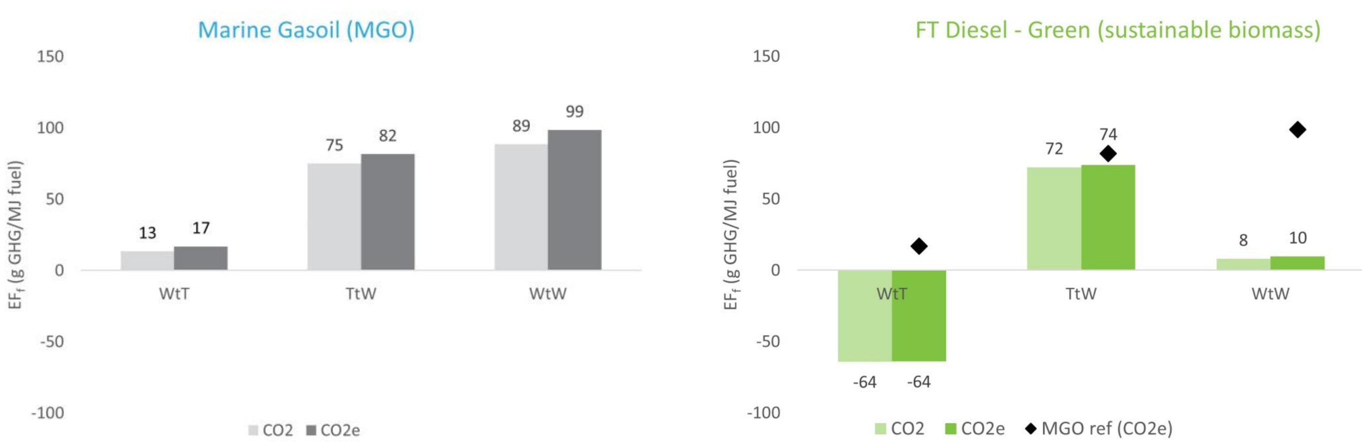


Figure 8: Comparison of WtW emissions factors for fossil-based MGO and green FTD

1.3 Vessel Performance

Vessel Performance is evaluated on a vessel-specific basis and considers single or stacked energy efficiency technologies and fuel technologies integrated into one vessel. Vessel performance shifts from the reduction potential of individual technologies or fuels to actual estimated emissions reductions. These values are used to directly calculate estimated GHG emissions resulting from implementing decarbonization measures, and how reductions stack against the Initial IMO Strategy on Reductions of GHG Emissions from Ships as adopted by Resolution MEPC.304(72) in April 2018 [A21]: 40% carbon intensity reduction for 2030 and 70% carbon intensity reduction for 2050. Vessel performance for specific vessels is examined in Part 4 – Case Studies.

Vessel Performance Against Initial IMO GHG Strategy Goals

With IMO requirements for EEDI in-force since 2013, and EEXI and CII requirements entering into force in November 2022, vessel owners are actively planning or implementing measures to meet those requirements. This guide provides operators metrics to further evaluate their emissions and energy reduction performance in ways that are not captured by the IMO requirements. The CO_2e performance value, tons CO_2e (or CO_2 only), and GHG intensity percent reduction values presented in the following sections can be used for the following purposes:

- To estimate actual fuel and emissions savings from implementing certain technologies, analyzing operating cost, lifecycle cost and net present value of technology implementation.
- To estimate potential impacts of carbon taxes or other market-based measures for a baseline operation vs a reduced emissions operation due to technology implementation.
- To raise private or public funding for technology implementation.
- To report to company stakeholders and public audiences the emissions reduction potential of planned technology investments, in tangible terms.
- To align corporate sustainability strategies with domestic and international emissions reduction goals.

CO_2e Performance Value (WtW GHG intensity)

CO_2e Performance Value (CePV) is a composite of reduction potentials for 1) energy efficiency and 2) fuel technology measures, and represents the GHG intensity for a vessel's decarbonization program. CePV is a unitless value: tons CO_2e/tons fuel. This unitless value is derived by multiplying an emission factor in mass per unit energy (kg/MJ) by the lower heating value (LHV in MJ/kg) for that fuel.

For CePV calculations that incorporate alternative fuels, a specific fuel consumption (SFC) ratio of the selected fuel technology to the baseline vessel fuel oil is added to account for differing energy densities of marine fuels. The CePV is calculated as follows:

$$\mathrm{CePV} = \mathrm{EF}_{\mathrm{f(WtW)}} \times \mathrm{RF_e} \times \mathrm{SFC_{FT}}/\mathrm{SFC_{FO}}$$

In tons CO_2e / tons fuel

Where

$EF_{f(WtW)}$ is the sum of WtT and TtW Emission Factors for a fuel (tons CO_2e / tons fuel).

RFe is the overall reduction factor, taken as a composite of each technology's percent reduction, weighted by the operating modes benefiting from the technology. This is demonstrated in Part 4 – Case Studies.

SFC_{FT} is the composite specific fuel consumption for the selected fuel, in g/kWh.

SFC_{FO} is the composite specific fuel consumption for the vessel's baseline fuel (MGO or HFO), in g/kWh.

For vessel performance evaluations where no fuel technology is incorporated, the SFC ratio is one.

CPV can be determined on a CO_2-only basis by applying the CO_2 emission factor for a fuel in way of the CO_2e factor.

CO_2e Emissions (Tons)

CO_2e emissions (in tons) are calculated by multiplying the CePV by a vessel's baseline fuel oil consumption over a selected time period:

$$\mathrm{CO_2e} = \mathrm{CePV} \times \mathrm{FO}$$

Where

CePV is CO_2e Performance Value with decarbonization measures implemented.

FO is tons fuel oil, over a selected time period.

Vessel Performance calculations in Part 4 – Case Studies determined on an annual basis, i.e., the selected period is one year.

Tons CO_2-only can also be determined using a CO_2 emission factor to determine the CO_2 Performance Value (CPV) for a vessel.

GHG Intensity Percent Reduction

GHG Intensity percent reduction can be calculated by comparing the baseline CO_2e Performance Value (CePV) to the vessel's baseline fuel Emission Factor, for each fuel used:

$$\text{GHG intensity \% reduction} = \frac{EF_{f(baseline)} - \text{CePV}}{EF_{f(baseline)}}$$

Where

$EF_{f(baseline)}$ is the vessel's original emission factor without decarbonization measures implemented.

CePV is CO_2e Performance Value with decarbonization measures implemented.

GHG intensity % reduction can be calculated for both CO_2 and CO_2e, using CPV and CePV, respectively.

Part 2 – Technology Evaluation

Dashboard Legend

Summary dashboards throughout the guide provide a “snap-shot” for each technology, summarized in the Dashboard Legend linked through the button below. A dashboard is provided for each Efficiency Technology (ET) and each Fuel Technology (FT). The dashboard legend can be accessed on each dashboard page by double-clicking the Dashboard Legend button.

Internal Combustion Engine (ICE) and Fuel Cell (FC) technology sections do not have full dashboards, as many of their details are included in the fuel-type sections, but each includes a section on Key Factors.

Link to Dashboard Legend

Link to Guide Navigator

2.1 Efficiency Technologies (ET)

As ship design has evolved and shipboard technologies have modernized, both mechanically and electrically, the opportunities to improve energy efficiency has gradually increased. Some of these opportunities are limited once the vessel has been constructed and some are ready retrofit options that can reduce energy and save on fuel costs. As always, there must be careful consideration given to implementation cost vs return on investment (ROI), particularly as compared to other energy efficiency solutions.

The Efficiency Technologies (ET) considered in this guide are summarized in Table 6, including the results of the technology evaluation. Each technology evaluation is detailed in the technology's section of the guide, which can be viewed by clicking on the name in the first column.

Table 6: Efficiency Technologies (ET) Summary

Technology	Reduction Factor RF_e	TRL	Newbuild		Retrofit		OpEx
			Compatible	CapEx	Compatible	CapEx	
Anti-Fouling Coatings	0.960 – 0.990	9	✓	$	✓	$	-$
Nanocoatings	0.920 – 1.000	7	✓	$	○	$$	-$
Hull Cleaning/ Maintenance	0.830 – 0.940	9	–	–	✓	–	-$/$$
Hull Form Optimization	0.800 – 0.960	9	✓	$	⊗	–	-$/$$
Air Lubrication	0.920 – 1.020	9	✓	$	○	$$$	-$/$$
Propellers	0.850 – 0.970	9	✓	$$	○	$$$	-$/$$
Pre-Swirl Devices	0.920 – 0.970	9	✓	$	✓	$	-$
Post-Swirl Devices	0.920 – 0.980	9	✓	$	✓	$	-$
Diesel-Electric Propulsion	0.720 – 1.100	9	✓	$$	○	$$$	-$/$$
Variable Speed Generator	0.700 – 1.100	8	✓	$$	○	$$$	-$/$$
PTO/PTI	0.750 – 1.000	9	✓	$$	⊗	–	-$/$$
Magnetic Gearing	*overview only*						
PCB Stator Motor	*overview only*						
Hybrid Mechanical/Electrical	0.840 – 1.310	9	✓	$$$	○	$$$	-$/$$
Battery (All-Electric)	1.240 – 1.310	8	✓	$$$	○	$$$	-$/$$
Shore Power	*overview only*						
ScES	*overview only*						
SMES	*overview only*						
Waste Heat Recovery	0.790 – 0.980	8-9	✓	$$	⊗	$$$	-$/$$
HVAC Optimization	0.900 – 1.000	6-9	✓	$/$$	○	$$	-$
Kite Sails	0.850 – 1.000	7	✓	$	✓	$$	-$/$$
Rotor Sails	0.875 – 1.000	9	✓	$$	✓	$$	-$/$$
Rigid Wingsails	0.100 – 0.950	7	✓	$$	⊗	$$$	-$/$$
Flexible Sails	0.100 – 0.950	3	✓	$$	⊗	$$$	-$/$$
Inflatable Sails	0.800 – 1.000	3	✓	$$	○	$$	-$/$$
Wave-Assisted Propulsion	0.850 – 1.000	8	✓	$$	○	$$	-$/$$
Solar Power	0.980 – 1.000	5-8	✓	$/$$	○	$/$$	-$

DIRECT DRAG REDUCTION

Navigation:

Advanced Hull Coatings	Hull Form Optimization	Hull Cleaning and Maintenance
	Air Lubrication	

Reducing overall hull resistance reduces the required propulsion power for a given speed. For most commercial vessels, the majority of that resistance comes from viscous effects (viscous pressure + friction) between the hull and the water. As speeds increase, the effects of wave-making become more significant. Figure 9 shows the resistance curves (total = viscous + wave-making) for a typical large commercial vessel.

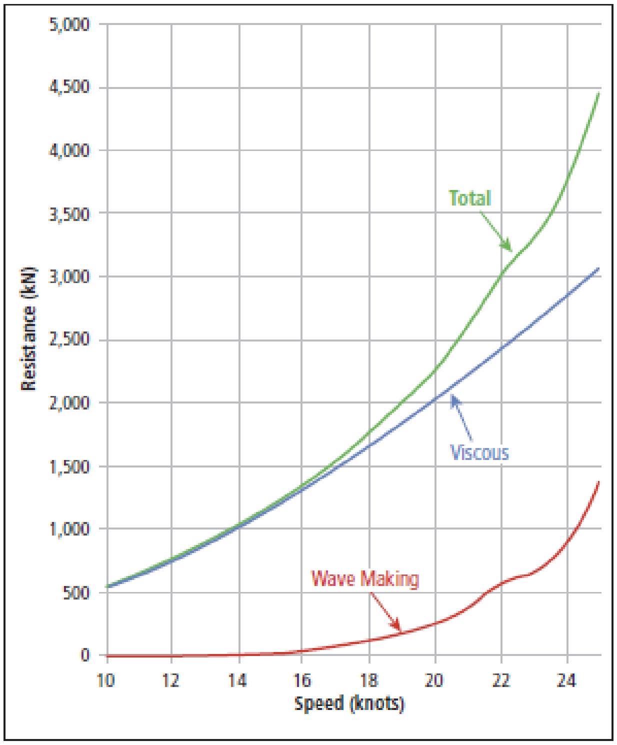


Figure 9: Typical resistance curve for a large commercial vessel (source: ABS)

The vessel designer must consider all effects on resistance and balance these against the vessel's primary mission requirements. Because viscosity effects are dominant, most methods for reducing resistance focus on reducing friction resistance.

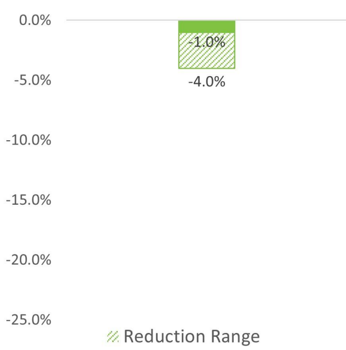
Advanced Hull Coatings

As a vessel operates, its hull will gradually become rougher as marine organisms grow on the underwater surface. Hull biofouling can occur very rapidly in warmer climates, especially when the vessel is stationary, either at dock or at anchor. The roughness of the marine growth disrupts the flow of water over the vessel surface, resulting in increased resistance.

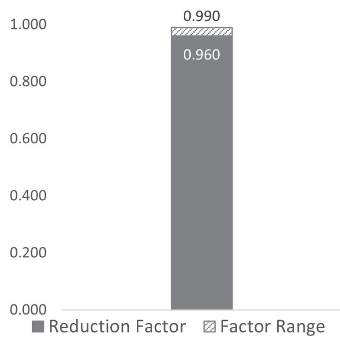
Advanced hull coatings – paired with a hull cleaning and maintenance schedule – can be an effective means for preventing and minimizing this growth, reducing drag and improving overall fuel consumption (assuming no changes on the vessel speed profile).

Anti-Fouling Coatings

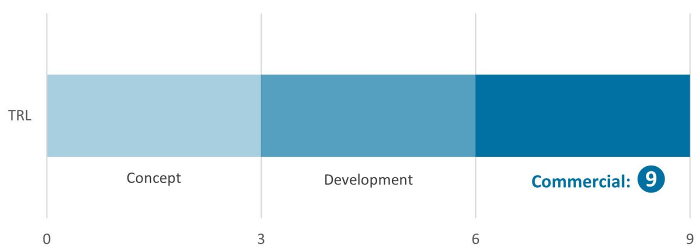
PERCENT REDUCTION



REDUCTION FACTOR (RF_e)



TRL



APPLICATIONS

MW	Duty					
>10	Continuous	general	general	general	marginal	marginal
	Intermittent		general	general	general	general
1-10	Continuous	general	general	general	marginal	marginal
	Intermittent		general	general	general	general
<1	Intermittent		general	general	general	general

MW: Propulsion Power plant size, in MW

Compatibility: general / marginal / poor

INTEGRATION

		OpEx	CapEx
Newbuild	✓	-$	$
Retrofit	✓		$

KEY FACTORS

- Best for vessels frequently in-transit with idle/low-speed periods
- Non-metallic selective biocides have reduced environmental impact
- Foul-release coatings prevent attachment without any biocidal effect
- Experienced contractor with proper equipiment recommended
- May require more frequent/less rigorous in-water hull cleanings

[Link to Dashboard Legend](#)

Overview

Surface roughness has a significant effect on frictional resistance for a ship's hull. Adding an antifoulant coating to the hull can help reduce this resistance and improve overall performance.

Roughness can be described on both the macro- and the micro-level as seen in Figure 10. It can be caused by both physical imperfections and the accumulation of biological growth. Large marine organisms such as barnacles and mussels, as well as slimes and grasses, can attach themselves to the hull causing drag. Over time, such hull accumulations will progressively increase resistance, and therefore fuel consumption of the vessel.

The material used to coat the hull of a ship below the waterline serves several purposes. The primary purpose is to prevent corrosion of the steel hull. A secondary purpose is to inhibit the growth of marine organisms on the exterior of the hull by means of anti-fouling.

Historically, tributyltin (TBT) was added to marine paints to inhibit the growth of organisms on the ship's hull. While effective at inhibiting growth, TBT is biocidal and therefore damaging to the marine environment. The use of TBT has now been banned by many countries and the IMO [A22]. Many suppliers have agreed to stop selling antifouling coatings containing TBT and alternative coatings utilizing copper as the biocide are more prominent. However, copper antifoulant coatings can be problematic when separated from the hull by potentially releasing harmful copper into the environment.

A different biocide approach is using selective action for specific marine growth classes. Selektope® is one example of a biocide now being incorporated into antifouling products [B1]. Selektope® targets receptors on barnacle larvae, temporarily altering their behavior to prevent hull attachment. **Selektope® is non-metallic and therefore will have reduced environmental impacts on the non-targeted organisms.**

An alternative strategy to biocides is the use of foul-release hull coating. Using advanced materials, modern foul-release coatings are designed to prevent organisms from attaching or remaining attached to the hull. When the ship is stationary, the organisms can attach themselves to the hull of a ship, but when the ship gets above a certain threshold velocity, the hydrodynamic forces strip the growth away. In this sense, the hulls are 'self-polishing' and do not poison the organism.

There are two general compositions of foul-release coatings: silicone-based and fluoropolymer-based. Both work by releasing organisms from the hull surface while underway. Silicone will provide an 'intermediate' level of friction reduction and fluoropolymer will provide a higher level leading to greater improvements to vessel efficiency.

For some operators, the reduced friction from advanced hull coatings can also allow increased speed without an added fuel penalty. Depending on the trade, the commercial benefits of increased speed may outweigh fuel savings at the original operating speed.

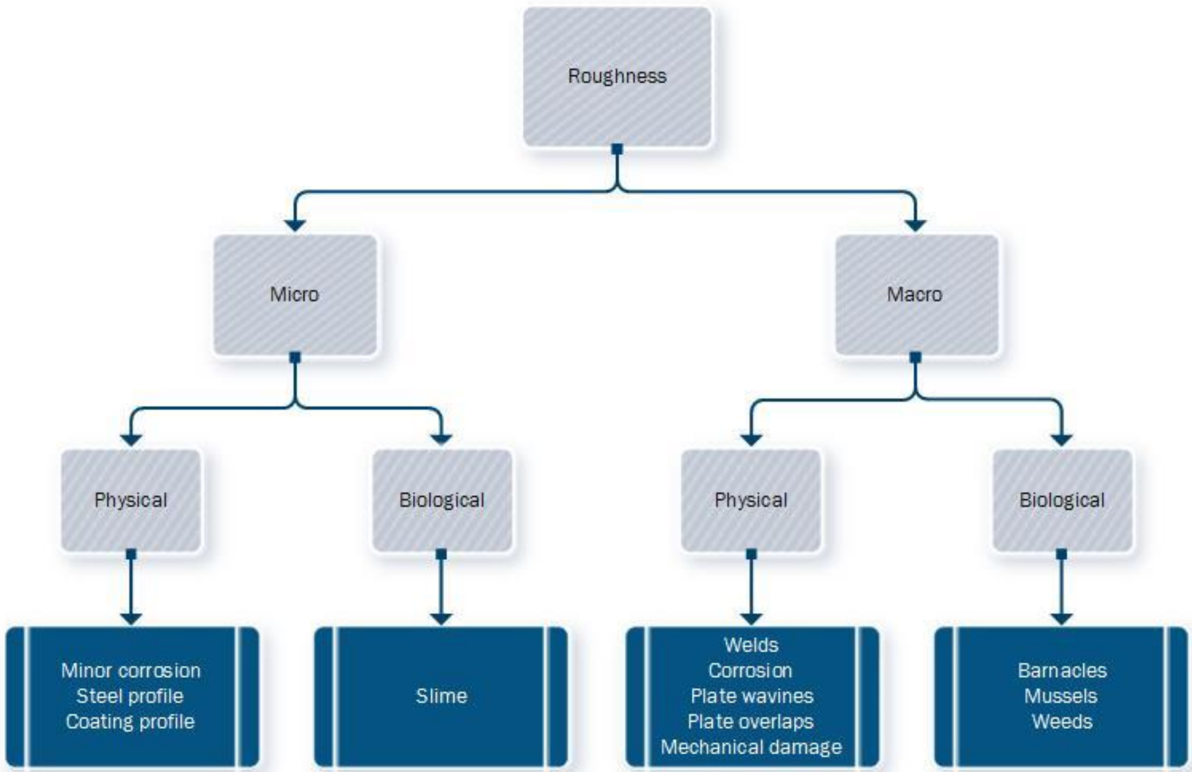


Figure 10: Types of surface roughness affecting hull friction

The roughness of the applied coating also affects vessel efficiency. Advanced foul-release coatings have lower hull roughness than traditional biocidal coatings and maintain this lower hull roughness more effectively, maintaining the improvement in efficiency over the drydocking interval. Biocidal coatings are more prone to mechanical damage and roughening.

The performance of any coating system, including foul-release, will diminish over time. Organisms will find a way to attach to imperfections or damaged areas of the coating, increasing hull resistance. Coatings are usually renewed on the dry-docking schedule, typically 60 months for most cargo vessels and more frequently for many passenger vessels.

The quality of the application is very important to lifecycle performance. Foul release coatings may require less paint to be added at future drydockings, following the first application. This can potentially reduce time needed in drydock, as well as costs for paint and labor.

Figure 11: Coating being applied to the vessel hull (Source: Seatrade Maritime News)

More frequent cleanings may also be required, but the cleaning process is less rigorous due to the nature of the coating. An experienced contractor is recommended for application of foul-release coatings to ensure proper performance, but widespread uptake of these coatings has increased the availability of such contractors.

For optimal performance, the owner must plan for and carry out continuous monitoring, inspections, and maintenance of hull coating integrity at periodic intervals.

Reduction Potential (as % of total energy demand): -1 to -4%

- Applying an effective antifouling coating has been tested to decrease hull resistance by up to 8%, but typical energy and fuel consumption reduction ranges between **1 and 4%** [A23].

TRL: 9

- Antifouling coatings are available from several paint companies and widely adopted across vessel types and trades.

Applications

- Suitable for all vessels, seawater and freshwater alike. Particularly beneficial in warm and seawater environments where marine growth advances aggressively.
- **Savings are maximized for vessels that are frequently in-transit, while also experiencing idle or low-speed periods when marine growth can accumulate.**
- Stena Line's new E-Flexer passenger/RoPax ferries have hulls coated with a paint that incorporates the Selektope® formula to reduce marine life build-up [C1]. Coatings containing Selektope® have been applied on over 500 vessels [B2].

Integration & Cost

✓ general compatibility for newbuild

✓ general compatibility for retrofit

$ minor newbuild CapEx

$ minor retrofit CapEx

-$ moderate OpEx savings

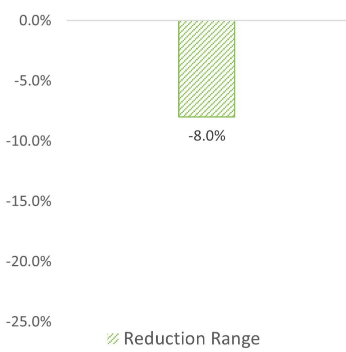
- The first-time application cost of foul release coatings is higher than that of traditional coatings. This is driven by the material costs as well as the skilled labor required.
- Additionally, dedicated equipment is required for installing foul-release coatings, as they are not compatible with other paint types. New spray lines and cleaned (or new) pumps are required.
- For replacing traditional coatings with a foul-release coating on an existing vessel, more surface preparation may be required due to compatibility issues.

Link to Guide Navigator

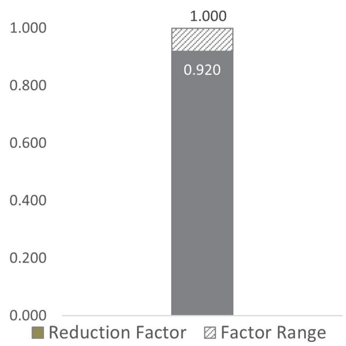
Nanocoatings

Link to Dashboard Legend

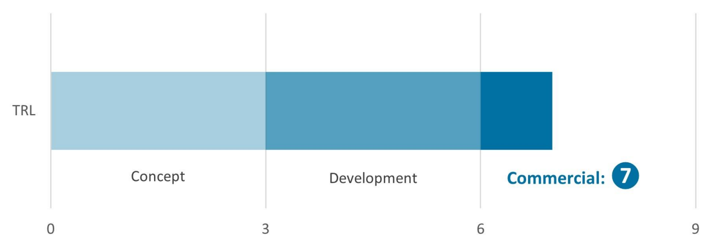
PERCENT REDUCTION



REDUCTION FACTOR (RFe)



TRL



APPLICATIONS

MW	Duty					
>10	Continuous	✓	✓	✓	✓	✓
	Intermittent		✓	✓	✓	✓
1-10	Continuous	✓	✓	✓	✓	✓
	Intermittent		✓	✓	✓	✓
<1	Intermittent		✓	✓	✓	✓

MW: Propulsion Power plant size, in MW

Compatibility: ✓ general ○ marginal ⊗ poor

INTEGRATION

		OpEx	CapEx
Newbuild	✓	-$	$
Retrofit	○		$$

KEY FACTORS

- Applied as either an additive treatment or complete coating system
- Reduces hull friction by retaining water in the nanolayer
- At least one manufacturer has class type approvals
- Application not supposed to require specialized equipment/training
- Compatibility with foul-release (self-polishing) coatings not known

Overview

Nanocoatings are generally defined as coatings that are measured on the nanoscale, or in the range of 1-100 nanometers thick. **They are applied as either an additive treatment to new and existing coatings (such as Nano-Clear system [B3]) or incorporated as a complete coating system replacement (such as Nippon Paint Marine's FASTAR system [B4]).** Numerous benefits are touted for nanocoatings: reduced hull friction, extended UV resistance, biofouling prevention, and enhanced appearance. One developer claims that nanocoatings can reduce maintenance by 50%, but a method for quantifying this performance is not detailed [B3].

Hull friction can be reduced by essentially retaining water in the nanolayer of the surface treatment, mimicking the behavior of marine animal skin. While nanocoating itself is not a biocide or self-polishing material, it does reduce elution (or the washing-away) of biocide agents in antifouling coatings, extending the functional life of coatings that rely on those biocides [B4].

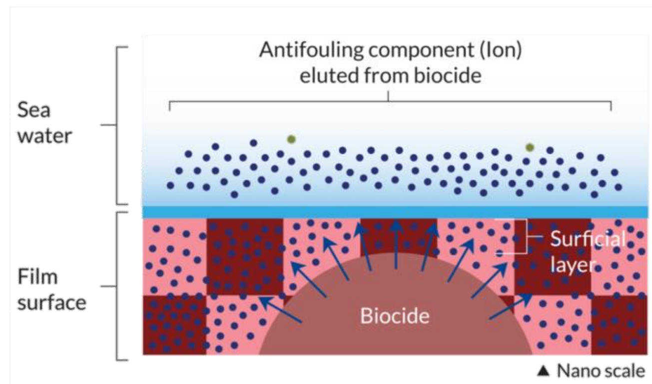


Figure 12: Nanocoating representation (source: Nippon Paint Marine)

Link to Guide Navigator

Reduction Potential (as % of total energy demand): 0 to -8%

- Nippon Paint Marine's FASTAR reports reducing energy and fuel consumption by 8% [B4]. Testing data is not publicly available.

TRL: 7

- Nanocoating systems have been ordered and applied on commercial vessels.
- **Nippon Paint Marine's FASTAR has received class society type approvals, with trial application on over 20 vessels as of 2021**.
- COSCO Shipping plans to coat it's VLCC fleet with the FASTAR system [C2], and Iskenderun selected FASTAR for five Panamax bulkers [C3].

Applications

- Widely applicable for vessels of various sizes and types of service.
- Nanocoatings are best applied to new or blasted surfaces when integrated into an antifouling product, or freshly coated vessels when used as an additive layer.
- The effectiveness of nanocoatings when applied over existing bottom coating is not well understood, but is approved by some developers.

Integration & Cost

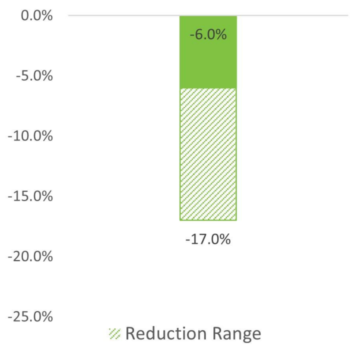
✓	**general compatibility for newbuild**	$	**minor newbuild CapEx**
○	**marginal compatibility for retrofit**	$	**minor retrofit CapEx**
		-$	**moderate OpEx savings**

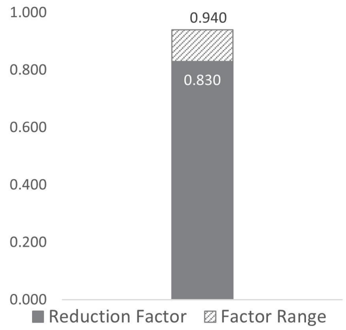
- Actual cost data of nanocoating-based systems has not been collected. As an emerging technology, material cost is likely higher than other antifouling coatings. This may be offset by reduced coating thickness for some applications.
- **Application is not supposed to require any specialized equipment or training.**
- Nanocoating as an additive process is less suitable for hull coatings that have already been in service. Nanocoating integrated into an antifouling product may be applied over existing coating, but is recommended by manufacturers to be applied over a blasted surface.
- **Nanocoating is generally associated with biocidal antifouling coatings, and its compatibility with foul-release (self-polishing) coatings was not examined.**

Link to Guide Navigator

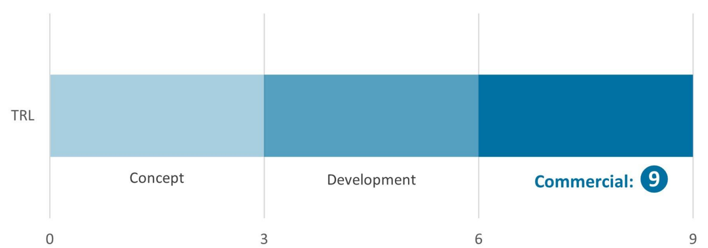
Hull Cleaning and Maintenance

PERCENT REDUCTION | **REDUCTION FACTOR (RF_e)**





TRL



APPLICATIONS

MW	Duty					
>10	Continuous	general	general	marginal	marginal	marginal
	Intermittent		general	general	general	general
1-10	Continuous	general	marginal	marginal	marginal	marginal
	Intermittent		general	general	general	general
<1	Intermittent		general	general	general	general

MW: Propulsion Power plant size, in MW

Compatibility: general | marginal | poor

INTEGRATION

		OpEx	CapEx
Newbuild	-	-$/-$$	-
Retrofit	general		-

KEY FACTORS

- Fuel consumption monitoring can indicate cleaning is needed
- Cleaning must be done in accordance with environmental regs
- Savings of 12% yielded in cleaning vs not cleaning sister vessels
- Most vessels should plan for routine hull inspections at minimum
- Vessels with frequent anchorage/lay-ups more suscetible to fouling
- Cleaning is OpEx-driven cost, no real CapEx

Link to Dashboard Legend

Overview

Hull cleanings and maintenance are effective in mitigating marine build-up but are expensive to carry out routinely. Marine growth on a hull increases the friction between the hull and the water. Severe fouling, particularly macrofouling, can dramatically increase resistance. Modeling in one study estimates that a 136-m frigate hull covered in 10% barnacle fouling may require up to an extra 36% engine power to maintain the same speed [A24].

Underwater hull inspection should be carried out as part of a vessel's routine maintenance, and cleaning should follow depending on the condition of the hull surface. The frequency will depend on many operational factors. Generally, any time a vessel is temporarily taken out of service should be coordinated with an underwater inspection before return to service, with adequate margin allowed for hull cleaning if required. Cleaning during scheduled drydocking is preferred, where the bottom can be thoroughly cleaned and recoated as required. If significant biofouling is identified outside of the drydock schedule, underwater cleaning may be appropriate.

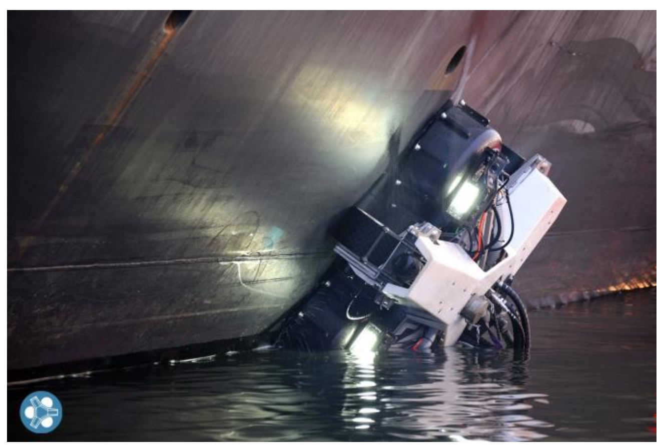


Figure 13: A Fleet Cleaner robot cleans the side of a vessel's hull (Source: Fleet Cleaner [B5])

If there is no established maintenance plan, condition-based maintenance serves to address when to perform maintenance by measuring the condition against a known baseline. For hull maintenance, this can be done in multiple ways:

1. Direct observation by divers in port or at anchorage.
2. Observed increase in fuel consumption over time.

Direct observation will be most effective if the qualitative observation can be correlated to a known threshold value. A skilled contractor can help with this, but the owner should have some correlated data to independently verify the contractor's findings. **Fuel consumption monitoring is an indirect method for assessing the marine growth on the hull compared to a baseline.**

Hull cleaning must be done in accordance with local environmental regulations, as they apply to cleaning in or out of the water. To the owner, there are no disadvantages to cleaning the hull on a reasonable schedule outside of immediate cost, and cleanings can help early identification of other hull condition issues such as damage or wastage. This cleaning cost itself is typically offset by savings in both fuel and a reduction in coating repair while in drydock.

Alternative hull cleaning schemes, such as using underwater robots, are being considered to help reduce costs but are not yet widely available [A25]. Figure 14 shows such a remotely-operated vehicle (ROV) cleaning the hull of a vessel. The service savings from using a diver-less ROV likely won't be realized until availability increases.

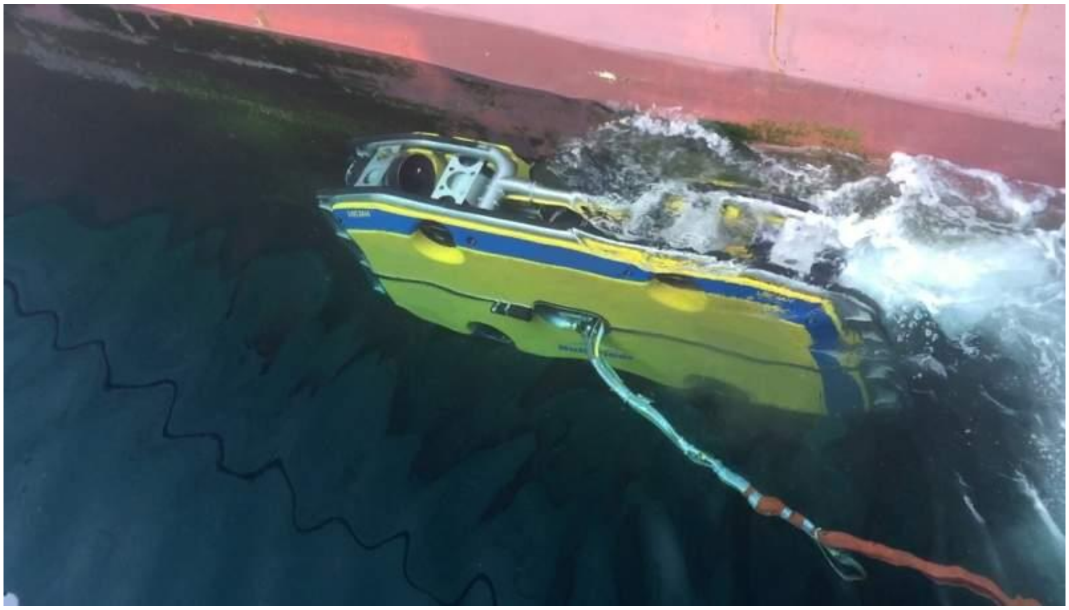


Figure 14: HullWiper's underwater hull cleaning technology uses adjustable seawater jets under variable pressure as the means of cleaning (Source: HullWiper [B6])

Reduction Potential (as % of total energy demand): -6 to -18%

- For underwater cleanings, fuel consumption can be reduced by **6-10%** in the short term depending on the degree of biofouling, and around **7%** several months after cleaning [A26].
- Cleaning during drydocking yielded approximately 17% fuel savings, compared to 9% for underwater cleaning during service [A26].
- **Aframax tankers saw 12% lower fuel consumption from cleaning compared to control sister vessels** [A26].

TRL: 9

- Hull cleaning and maintenance are widely practiced in the industry and the benefits are well documented.
- ROV-based cleaning is emerging as a cost-saving alternative but is not yet widely available.

Applications

- **Most vessels should plan for routine hull inspections, and cleanings as needed. Scheduling this work can be challenging by limited shipyard or drydock availability**.
- **Vessels with frequent anchorage or lay-up periods are more susceptible to macrofouling and should proactively plan underwater hull inspections around these inactive periods.**
- Vessels that have high utilization in transit, or dock in freshwater environments, are less likely to experience biofouling and may require less frequent inspections.
- Vessels with non-biocidal foul release coatings may require more frequent cleaning.

Integration & Cost

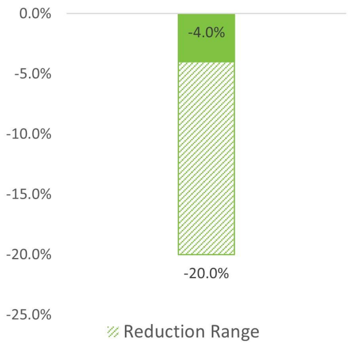
–	**not applicable to newbuilds**	–	**CapEx cost not applicable**
✓	**general compatibility for retrofit**	-$/-$$	**moderate to significant OpEx savings**

- The cost-to-benefit ratio is extremely low for hull inspections and maintenance, particularly if vessel is already out of service.
- Hull cleaning generally requires either underwater divers or drydocking. If not scheduled, drydocking can have major direct and commercial costs. Planning inspections and maintenance ahead will help mitigate their direct costs.
- **No CapEx cost unless operator purchases own hull cleaning equipment.**

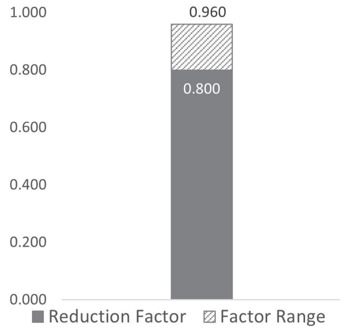
Link to Guide Navigator

Hull Form Optimization

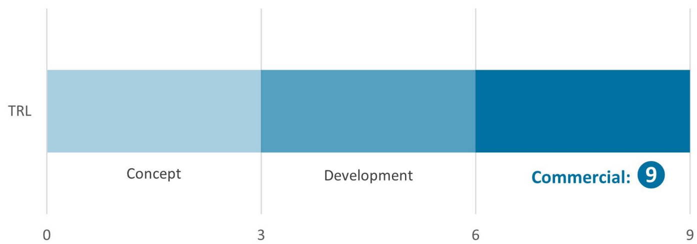
PERCENT REDUCTION



REDUCTION FACTOR (RF$_e$)



TRL



APPLICATIONS

MW	Duty					
>10	Continuous	general	general	general	general	general
	Intermittent		general	general	general	general
1-10	Continuous	general	general	general	general	general
	Intermittent		general	general	general	general
<1	Intermittent		general	marginal	general	marginal

MW: Propulsion Power plant size, in MW

Compatibility: general, marginal, poor

INTEGRATION

		OpEx	CapEx
Newbuild	general	-$/-$$	$
Retrofit	poor		-

KEY FACTORS

- Different outcomes can be prioritized with optimization parameters
- Decision-making on hull form driven by analysis, not instinct
- 3-8% energy savings if starting from reasonable baseline geometry
- $50-100k typical cost, depending on geometry constraints and variations

Link to Dashboard Legend

Overview

Hull form optimization is common across the marine industry and is often reevaluated throughout the course of a project as constraints change and the machinery arrangement is developed. Hull form optimization is a highly effective tool for reducing hull total resistance for a given speed on new vessels, if implemented early in the design process. In practical terms, it cannot be used to improve an existing vessel's hull form unless major conversions to bow or stern shape are planned.

While the tools now exist, many ships are designed without enough consideration for a vessel's total resistance (viscous and wave-making), even though the largest component of total life cycle cost is typically fuel. Designing a hull using an optimization framework can produce the most efficient possible form within the requirements of the vessel design.

Hull forms are designed to meet a complex and conflicting set of requirements: the hull needs to provide enough buoyancy to support the weight of the vessel while also providing enough space for the interior arrangements, machinery, and cargo or payload. Additionally, each vessel must have enough stability and good seakeeping for all weather conditions that it will encounter. Multiple trims should be considered during the design process to ensure the hull is considered across a variety of load conditions. A well-designed vessel should do all the above while maintaining the least possible resistance for maximum speed at minimum power, and meeting the contractual speed requirement.

The optimization process takes a baseline hull and uses a computer algorithm to vary the shape within the bounds defined by the designer. The algorithm allows the computer to produce faired hulls with buildable shapes. The designer can define additional constraints on the hulls to ensure each candidate hull form meets the desired stability and possibly seakeeping criteria. The computer program produces a multitude of variations, each having a small variation in geometry. For each hull form, the algorithm will predict the resistance using Computational Fluid Dynamics (CFD). The computer code can recognize trends and explore promising modifications using the resistance results of each shape change. A typical optimization process analyses thousands of hull forms, resulting in hulls with significantly reduced resistance over the baseline hull. The designer will select the best hull form from a small group of 'semi-finalists'.

Optimization parameters can lead to differing hull forms for vessels with identical missions and design criteria. For example, an owner may wish to optimize for resistance, but also for constructability, to reduce capital cost. This process could lead to a vessel with chines (a chine is a sharp change in angle in the cross section of a hull and is considered simpler to construct than a gradually curving cross section) and a flat keel (Figure 15, right). Alternatively, a design may require a low resistance hull form that also minimizes underwater-radiated noise leading to a different hull form (Figure 15, left). In this way, the process is leveraged to consider multiple competing design requirements while minimizing resistance.

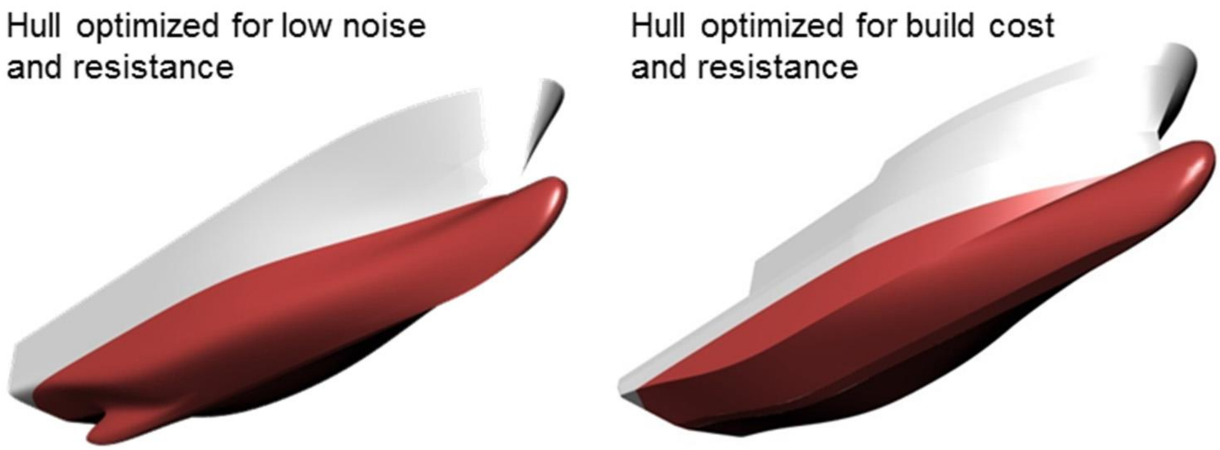


Figure 15: Comparison of two research vessel hull forms optimized to minimize resistance: low noise on left versus build cost on right (Source: Glosten)

This formal optimization process is separate from targeted analysis such as using advanced tools like CFD. These analyses have limited capabilities as a design tool, instead geared toward evaluation and validation of hull geometry, whereas hull optimization is specifically a design tool. **Formal hull form optimization is a significant departure from the days when naval architects used intuition and experience to improve hull forms**. In some ways, the optimization process requires the architect to let go of ownership of designing or refining a hull with traditional methods. Experience has shown, repeatedly, that formal computer-based optimization will outperform a good starting hull form by a significant margin. Resistance improvements of 5-20% over the initial hull form are common.

The optimization process takes time, upwards of 6-8 weeks, and must be accounted for in the schedule. The process must also be carefully planned and managed by the designer, including establishing geometry constraints, stability limitations, and design objectives. If the process is initiated too late in the schedule, there is much less flexibility to vary the hull form without affecting arrangements. If not done properly, the optimized hull form can increase the expense of building the vessel. This can be minimized, or mostly avoided, if the designer incorporates constructability factors into the constraints of the optimization.

For well-informed owners the upfront costs for hull form optimization will be considered in the context of the lifecycle of the vessel, where design optimization will have a tremendous long-term benefit. For most vessels, the payback time will be very rapid, possibly within a year, and continue to benefit the owner for the life of the vessel.

Reduction Potential (as % of total energy demand): -3 to -20%

- **Minimizing hull resistance through optimization can typically improve fuel consumption by 3-8%.**
- If done properly and early enough in the design process, reductions in hull resistance can make a vessel up to 20% more energy efficient [A27].

TRL: 9

- Hull form optimization is available as a service from multiple international companies.
- Several computational fluid dynamic (CFD) software packages exist and support hull shape development by assessing hydrodynamic performance.

Applications

- The best results will be seen for commercial vessels that are normal in transit and operating at above 10 knots, where resistance effects are more significant.

Integration & Cost

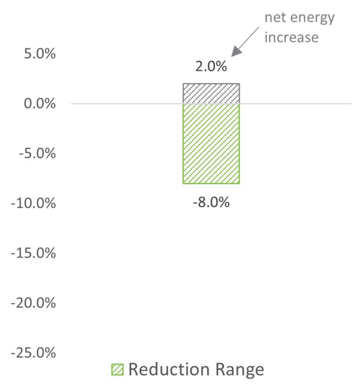
✓	general compatibility for newbuild	$	minor newbuild CapEx
⊗	poor compatibility for retrofit	–	retrofit CapEx N/A
		-$/-$$	moderate to significant OpEx savings

- **Approximately USD$50,000-100,000 for newbuild optimization.** This does not include naval architect costs for planning the optimization contract, managing the process, and implementing the results.
- Cost generally scales with complexity/constraints of optimization, not vessel size. Payback period is therefore longer for small vessels that often idle, given lower annual fuel costs.

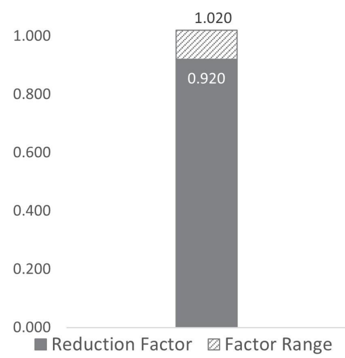
Link to Guide Navigator

Air Lubrication

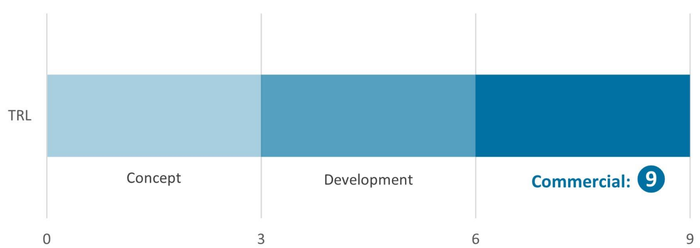
PERCENT REDUCTION



REDUCTION FACTOR (RFe)



TRL



APPLICATIONS

MW	Duty					
>10	Continuous	general	marginal	marginal	poor	poor
	Intermittent		poor	poor	poor	poor
1-10	Continuous	general	marginal	marginal	poor	poor
	Intermittent		poor	poor	poor	poor
<1	Intermittent		poor	poor	poor	poor

MW: Propulsion Power plant size, in MW

Compatibility: general marginal poor

INTEGRATION

		OpEx	CapEx
Newbuild	general	-$/-$$	$
Retrofit	marginal		$$$

KEY FACTORS

- Large air compressors required for bubble-making
- Approved installations from multiple class societies
- Suitable for vessels with large flat bottom areas
- Moderate investment for newbuilds, significant for retrofits
- Increased vessel speeds equate to higher net energy reduction
- Rough weather can diminish effectiveness at across all operational speeds

Link to Dashboard Legend

Overview

Air lubrication uses compressed air released over the bottom of a vessel hull to reduce the friction incurred by the passing water. The reduced friction results in reduced propulsion power requirements, and therefore reduced energy and fuel consumption, assuming the vessel speed doesn't change. Air lubrication systems (ALS) typically consist of machinery and piping common to marine vessels: air compressors, air reservoirs, and distribution piping. Three primary methods have been developed: air bubble (bubbles distributed across the bottom hull), air cavity (recessed cavity filled continuously with air), and air cushion (deep cavity with pressurized air to lift the hull and reduce draft).

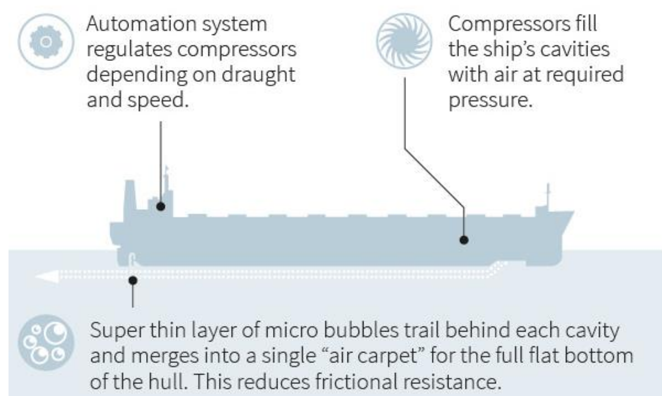


Figure 16: Simplified representation of air lubrication process (Source: vesselfinder.net)

Air Bubble

Air bubble ALS does not form a continuous layer of air on the hull surface, but rather a sheet of small bubbles. The sheet of air bubbles reduces the effects of skin friction at the boundary layer when evenly distributed on the hull surface. A typical arrangement uses an array of air release units located on the bottom shell near the bow, distributing air bubbles to flow aft along the full length of the flat bottom while the vessel is underway. For large oceangoing vessels,10-18 air release units integrated in the hull structure is typical. For cruise ships, Silverstream Technologies [B7] arranges air release units in a V-array that maximizes air coverage transversely and as far forward as practical (Figure 17). ALS developers have indicated that entrained air flowing into propellers improves propulsive efficiency and reduces noise and vibration, though independent reporting on these claims has not been identified.

Air compressors are used to generate the feed of bubbles to the release units, and drives a system's power consumption. While a properly sized and operated bubble ALS can achieve a net energy savings, it will increase the ship service load while running. The air compressor load can be significant and should be evaluated for how much it increases the ship service load compared to the vessel's generator capacity. This is less challenging for a vessel with diesel-electric propulsion, where the propulsion and ship service power come from the same source, so the ALS load on the power plant will be directly offset by propulsion savings.

The air compressor equipment also requires dedicated space, and for some ALS systems the compressor capacity must be distributed across multiple compressors to be located close to the air release units. The equipment arrangement could be readily planned into a newbuild, but may not be feasible in many retrofits.

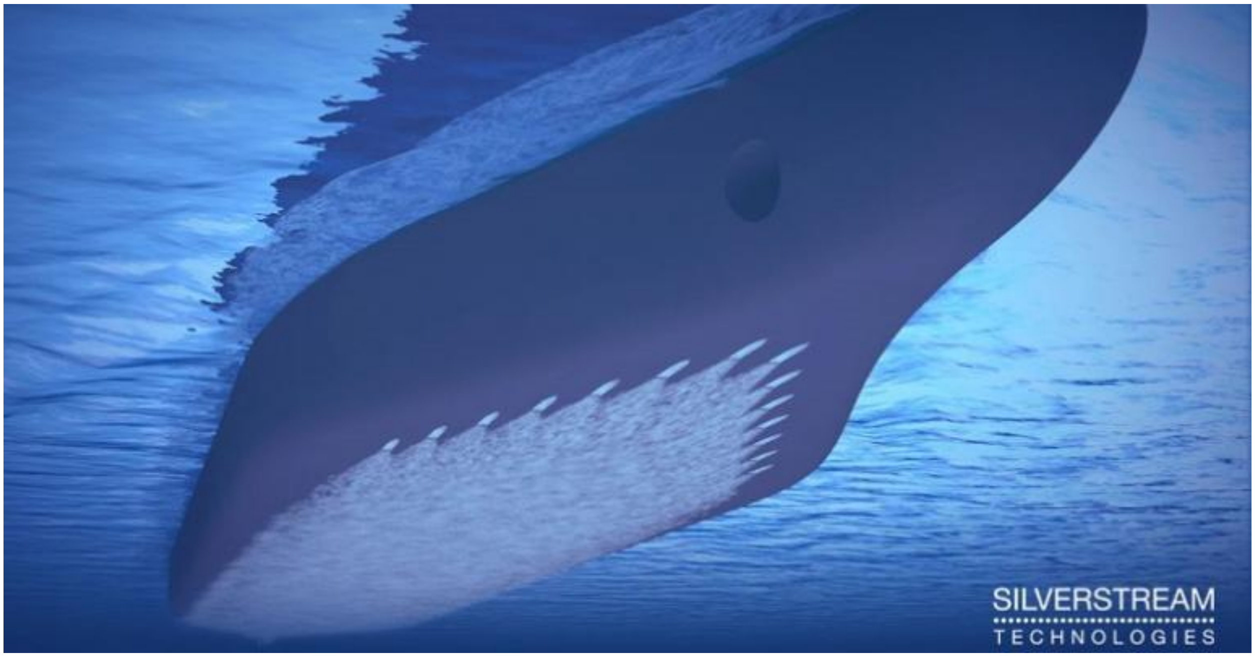


Figure 17: V-array of 14 air release units (Source: Silverstream via seatrade-maritime.com [B7])

Several manufacturers, including major shipyards (Daewoo Shipbuilding & Marine Engineering and Samsung Heavy Industries in South Korea, Mitsubishi Heavy Industries in Japan), now offer bubble ALS as a fully commercial product, with systems installed on a variety of vessels with large flat bottom areas. Vessel types include cruise ships, containerships, product tankers, and LNG carriers. One operator reported optimizing the system for 18 knots, with net energy savings starting at speeds above 10 knots. Net savings increase with increased vessel speed, and will drive payback period for integrating a bubble ALS.

Low-end speeds (below 10 knots) may allow air to detach from the hull or escape from the sides in rough weather; at the high-end (above 15 knots), rough weather could allow air detachment near the stern, diminishing any potential efficiency benefits at the propeller.

As the most mature air lubrication technology, bubble ALS is selected for reduction potential and readiness level evaluation in this guide.

Air Cavity

Air cavity requires a bounded section on the hull to entrap air and eliminate contact with water over a large area. Air cavity ALS is more complicated to integrate, as it requires significant modifications (retrofit) or purpose-built structure (newbuild) to entrap the air at the hull, increasing structural complexity and cost of construction. DK Group designed and tested an air cavity system in 2008, but it was determined to not be successful in waves, as air would not remain trapped in the air cavity as intended. The most recent air cavity concept was a corrugated hull bottom developed by Damen Shipyards, demonstrated on the *Ecoliner* (European Number of Identification (ENI): 2336631) in 2015 [C4].

There have been no publicly announced air cavity projects since the *Ecoliner* in 2015, so air cavity ALS is not evaluated for reduction potential or readiness level in this guide.

Air Cushion

Air cushion takes a large volume of air to elevate the vessel, combining energy savings from both a reduced draft and a reduced wetted surface area. High-flow blowers are combined with a novel hull geometry, with elements of both monohull and catamaran design, to enclose an air cushion at a pressure sufficient to physically lift the vessel and reduced its draft.

SES-X is the primary developer of the air cushion technology [B8], and has demonstrated it for the BB Green project's *AiriEl* (Figure 18), an 80-passenger prototype ferry operating in Sweden [C5]. Air cushion was also implemented on the surface effect ship *CWind Pioneer*, which also utilizes hybrid mechanical/electrical power [C6].

Air cushion is currently being developed for small, high-speed work boats and passenger vessels, with plans for scaling to larger vessels unclear. SES-X claims up to 50% reduction in total energy, but the technology requires more uptake to evaluate its broader reduction potential across different vessel types and characteristics.

Given its current state of development, Air Cushion is not evaluated for reduction potential or readiness level in this guide.

Figure 18: BB Green project *AiriEl* (Source: International Institute of Marine Surveying)

Reduction Potential (as % of total energy demand): +2 to -8%

- Bubble ALS developers advertise net fuel savings ranges of 5-10%.
- The highest claimed net energy peak savings for a specific vessel are 5% on a 238m class of RoRo carriers [A28][C7], and **8%** on a 347m cruise ship [C8], however these claims have not been independently verified.
- Independent study of a bubble ALS system installed by Silverstream Technologies on a product tanker reported **3.8-4.3%** savings in laden and ballast conditions, respectively [A29].
- Where installed on a vessel that operates at lower speeds (below 10 knots), or operates on a normally transiting vessel while loitering or on-station, the system could result in a net increase in energy consumption due to power required to run the compressors. This potential additional (increased) energy requirement is vessel- and situation-specific, but we have assumed here a net increase of up to **2%** for the bubble ALS when operating outside design conditions.

TRL: 9

- Bubble ALS is fully deployed and widely available for marine vessels.
- **Multiple classification societies have approved installations (ABS, LR, RINA)**. ABS released a Guide on Air Lubrication Technology in 2019 [A30].
- Uptake is still growing, but several vessel trades have demonstrated energy savings by integrating ALS.

Applications

- **Suitable for vessels with large flat bottom hulls (air bubble): LNG carriers, RoRos, cruise ships, and some containerships.** Savings are maximized where vessels have large flat bottom to wetted area ratios and speeds exceeding 10 knots. Savings may be achievable on oil tankers and bulk carriers, but there has been limited uptake in that market.
- Air release units installed on containerships as install-ready design, indicating acceptable impact on resistance when not operating.

Link to Guide Navigator

- Deep draft vessels are less optimal due to the higher head pressure the air must overcome to release over the hull, therefore increasing the power input to generate the compressed air. Further, slow vessel speeds offer a slower return on investment due to overall lower fuel savings.
- Bubble ALS available from both mature developers (Silverstream Technologies [B8], and major shipyards with in-house technology (DSME, SHI, MHI).

Integration & Cost

✓	**general compatibility for newbuild**	$	**minor newbuild CapEx**
○	**marginal compatible for retrofit**	$$$	**significant retrofit CapEx**
		-$/-$$	**moderate to significant OpEx savings**

- **Moderate capital investment for newbuilds (air release units readily integrated).**
- **Significant capital investment for retrofits** (air release units require major structure modifications and close class involvement).
- Due to consistent air pressure requirement and high temperature compressed air, distributed compressor arrangement preferred to centralized system. Distributed system has greater impact on machinery arrangements by locating equipment throughout the vessel.
- Compressor equipment generally all commercial off-the-shelf (COTS), not increasing cost with proprietary components.
- **Speed and portion of time underway is proportional to payback time on initial capital investment for speeds.**

Link to Guide Navigator

PROPULSIVE LOSS REDUCTION

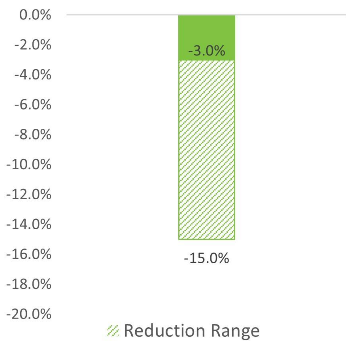
Navigation:

Propellers:	Large Diameter, Slow Speed	Ducted
	Controllable Pitch	Podded & Azimuthing
Pre-Swirl Devices:	Stator	Pre-Swirl Ducts
Post-Swirl Devices:	Rudder Thrust Fins	Asymmetric Rudders
	Costa Bulbs	Propeller Boss Cap Fins

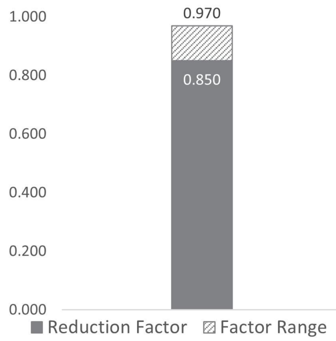
Increasing propulsor efficiency is one of the most straightforward ways to save energy onboard. Several factors influence a propulsor's overall efficiency, including wake characteristics, interactions between the hull and propeller, propeller type and characteristics, and interactions with the propeller flow field and the rudder or other downstream appendages. Most of these factors should be considered in propeller selection and hull design. However, project constraints such as design budget, designer capability, schedule, construction cost, and vessel trade/mission may prevent optimizing propulsor efficiency.

Propellers

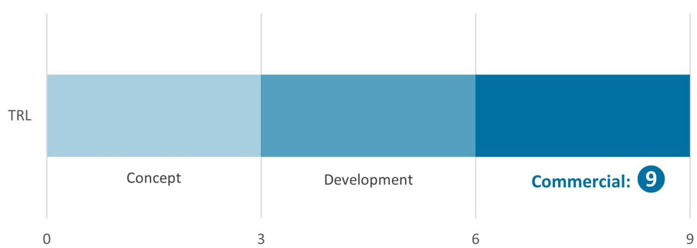
PERCENT REDUCTION



REDUCTION FACTOR (RF_e)



TRL



APPLICATIONS

MW	Duty					
>10	Continuous	✓	✓	✓	✓	✓
	Intermittent		✓	✓	✓	✓
1-10	Continuous	✓	✓	✓	✓	✓
	Intermittent		✓	✓	✓	✓
<1	Intermittent		✓	✓	✓	✓

MW: Propulsion Power plant size, in MW

Compatibility: ✓ general ○ marginal ⊗ poor

INTEGRATION

		OpEx	CapEx
Newbuild	✓	-$/-$$	$$/$$$*
Retrofit	○		$$$

*$$ for propellers, duct, CPP, $$$ for CRP, pods/azimuthing thrusters

KEY FACTORS

- As indicated above, propeller-efficiency solutions can fit almost any vessel
- Due to geometry and drivetrain constraints, solutions best for newbuild
- Some solutions like CPP are efficient across many operating points, not optimized for one
- Podded/azimuthing thrusters increasingly used in niche applications
- CPP, CRP, Podded/azimuthing increase maintenance due to moving parts

Link to Dashboard Legend

Overview

Propellers are foil-shaped devices that use input rotational power to generate lift, and thus thrust, to propel a vessel in most vessel operations. They represent a broad range of devices that vary depending on vessel needs and service. Identical vessel designs might select different propellers based on their operating profiles, typical loads, and environmental conditions.

Large Diameter, Low Speed Propellers

Generally, large diameter, low speed propellers with fewer blades offer higher efficiency than other propeller solutions. The propeller design should balance the propeller size and speed with other design factors such as hull geometry, reasonable clearances, engine speed, powertrain drive type, and draft. This propeller type is best-coupled with reduced vessel speed to match the design operating point of the propeller.

Figure 19: MAITA propeller (Source: Oshima [B9])

Large-diameter, low-speed propellers are adopted across the marine industry, most common in deep-draft, oceangoing vessels. A vessel's trade and operating profile must be compatible with slower steaming speeds, reduced by up to 25% to utilize a low-speed propeller. For trades based on express shipping services, there may not be a financial case to implement this propeller type. However, where fleet logistics can accommodate longer voyages and reduced down-time, low-speed propellers may be a good match.

Figure 20: ***YM Mobility*** **(IMO no. 9457737) retrofitted with large-diameter, low-speed propeller in 2021 (source: Wartsila [C9])**

Ducted Propellers

Sometimes referred to as a Kort Nozzle (by way of recognition of the Kort Propulsion Company's initial patents and long association with this type of propeller), ducted propellers improve propeller efficiency in two ways: first, by increasing the efficiency of the propeller itself, and secondly, by producing lift using the tapered form of the nozzle to generate forward thrust. The thrust from the nozzle alone can account for as much as 40% of total thrust from the ducted propeller assembly [A31].

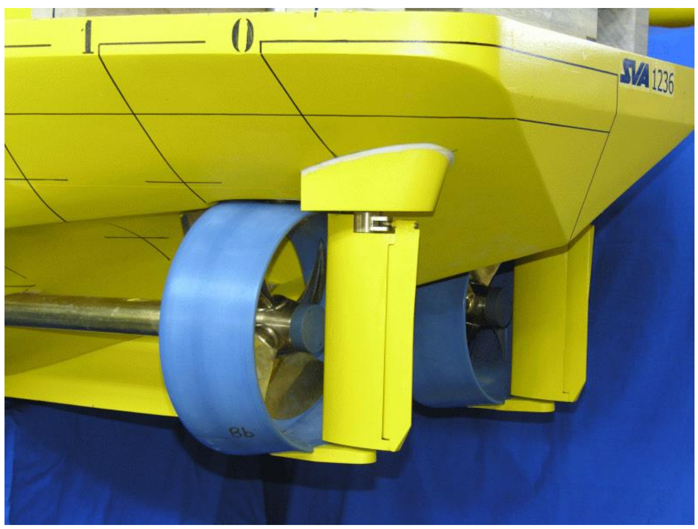


Figure 21: Ducted propellers on a model with high-lift rudders (source: SVA)

The cross section of the duct itself is foil shaped (Figure 22), accelerating the flow and causing lift which further increases the thrust. As vessel speeds increase beyond 10 knots, this effect is diminished due to additional drag on the duct. The propeller selected should be optimized to work within the duct and at planned vessel design speeds. The duct may be either fixed or steerable. In the case of a steerable duct, this may be in addition to a conventional rudder or as a substitution for providing all steering force.

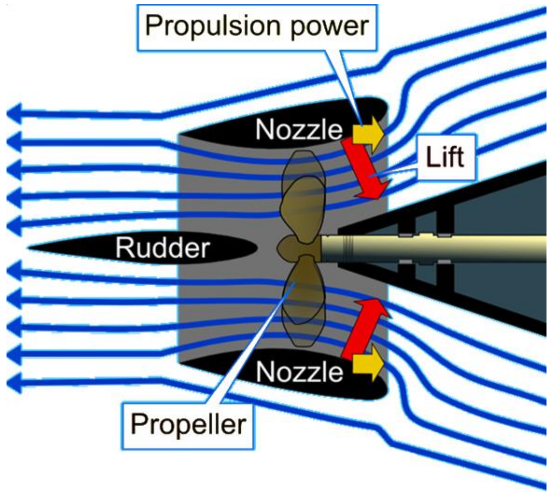


Figure 22: Kort nozzle (source: Wikimedia)

Controllable Pitch Propellers

Replacing a fixed pitch propeller (FPP) with a controllable pitch propeller (CPP) can maximize engine performance by controlling the propeller pitch according to the specific load needed and environmental conditions present. Each blade is rotated in tandem with the other blades, typically with hydraulic power. It can be adapted to most vessel types, but often has high capital costs and increased mechanical maintenance.

FPPs have an additional degree of freedom over fixed pitch propellers in that the pitch of the blades can be adjusted to suit the vessel speed and propeller loading. However, some FPP systems operate at constant speed, particularly when coupled with shaft-driven generators, eliminating a degree of freedom. While ideal for electrical power generation when coupled with a shaft-driven generator, cavitation can be increased on the back and face of the propeller for certain propulsion conditions (rpm, vessel speed, and pressure).

When compared to a FPP operating at its ideal design point, a CPP will be *less* efficient. CPP imparts additional drag at the hub and increases overall propeller weight. However, CPPs offer greater efficiency over FPPs in off-design conditions. The efficiency of CPPs are optimized if operated on a 'combinator curve', whereby pitch and speed are maximized for each point on the curve**. For a given speed-power point, the peak efficiency of a CPP will be inferior to a FPP selected for that point, but will have an improved efficiency across multiple operating points**.

Figure 23: CPP system installed on Washington State Ferries vessels (source: travelswithtowhee.com)

Contra-Rotating Propellers

Contra-Rotating Propellers (CRP) use a single prime mover to drive multiple, coaxial propellers rotating in opposite directions on a common shaft. Much like a pre-swirl device, CRPs increase propulsion efficiency by exploiting the rotating field of the upstream propeller to condition the wake of the downstream propeller.

Contra-rotating propellers are rare in commercial ships where the added efficiency gains must be great enough to overcome the cost and complexity.

A simplified variation of the CRP is a twin propeller, or double propeller, where two propellers are attached to the same shaft, but blades are slightly offset to improve the interaction of the two and improve the flow conditions across the trailing propeller. These are advantageous when there is limited room for a larger propeller diameter due to draft or hull geometry constraints. However, this arrangement adds weight to the driveline, requiring increased ratings for bearings, shafting, couplers, and other driveline components.

Figure 24: CRP mounted separately on azimuthing pod and stern drive (source: ABB)

Podded & Azimuthing Propulsors

Podded and azimuthing propulsors are some of the most complicated propulsion solutions as they combine the steering and drive equipment into a single device. Most of the equipment for the gearing and drivetrain is housed exterior to the hull, saving space inside the vessel.

Functionally, podded propulsors and azimuthing propulsors are very similar. For podded propulsors, the motor is housed within the pod and directly drives the propeller. As such, the motor must be protected from water ingress as it sits outside the hull below the waterline.

For azimuthing propulsors, also known as Z-drives and L-drives, the motor is housed within the hull and connected to the propeller through a series of shafts and gears. Types of azimuth thrusters include bottom mount, top mount, swing-up, retractable, and containerized.

These propellers provide a nearly seamless transition between pushing and pulling, and can even be positioned outside of the vessel wake where the flow is cleaner to improve efficiency, especially during pulling. Both types of thrusters can sit farther below the stern of the ship, helping to increase maneuverability.

While available and used across nearly all types of vessels, workboats and large passenger vessels employ this technology most frequently. Increasingly, the technology is being applied to more niche marine application such as icebreaking.

Figure 25: ABB's Azipod® steering and propulsion system (source: ABB)

Reduction Potential (as % of total energy demand): -3 to -15%

- Operator Yang Ming Marine Transport reported energy savings of 3 to 5% after retrofitting two ships with Wartsila slow steaming propellers, coupled with Wartsila's EnergoProFin boss cap. This modification requires the vessels to reduce operating speed from 24 to 18 knots [A32]. The propellers are fixed pitch (FPP), and 27% lighter than the original propeller, enabled by the slower rotational speed and resulting load reductions on the propeller blades.
- Ducted propellers have reported up to 15% propeller efficiency improvement at design speed or 5% savings in bollard pull, based on Wartsila's high performance nozzle [A33]. The vessel type is not specified.
- Podded & Azimuthing Propellers have typical energy savings of 10 to 15% over a shaftline FPP, with some manufacturers claiming higher efficiencies in specific applications such as longliner fishing [A34].

TRL: 9

- All propeller technologies considered here have been widely adopted on hundreds, sometimes thousands of vessels with regulatory approval. Oshima's MAITA propellers (FPP) alone have been adopted on over 200 vessels [B9].
- Developers continue to improve existing products, with potential for higher savings to be achieved in the future.

Applications

Large diameter, low speed propellers:

- Ideal for deep-draft vessels to accommodate large wheel diameter, and basic maneuvering requirements.
- Not suitable for shallow-draft vessels, or those that require quick changes in thrust for maneuvering or accelerating.

Ducted propellers:

- Widely used on vessels with heavily-loaded, small diameter propellers, where maximizing thrust to diameter ratio is critical and low speeds are typical.
- Slow speed fishing vessels that also benefit from protecting propeller from nets and lines in the water.
- Optimized nozzle geometry has expanded suitability to larger vessels, including ocean service vessels, research vessels, and offshore supply vessels.

CPP:

- Deployed on tankers, containerships, bulkers, car ferries, and RoRos where maintaining constant engine speed but varying thrust is desirable.

CRP:

- Often Coupled with podded propulsors, CRP are useful on vessels with limited draft, achieving more thrust in a limited wheel diameter while operating at an optimal rotational speed for the propeller.

Podded & azimuthing propulsors:

- Vessels with rigorous DP requirements benefit from azimuthing propulsion, as do harbor tugs and work boats needing to change thrust direction quickly for assist operations.
- Azimuthing propellers often combined with duct to increase bollard pull on work boats.
- Podded propellers are beneficial when hull geometry limits space for drivetrain equipment inside vessel. Podded propulsors like ABB's Azipod® [B10] are common on cruise ships, offering favorable efficiencies at high speeds, improved maneuverability, and more space for auxiliary equipment and crew quarters.

Integration & Cost

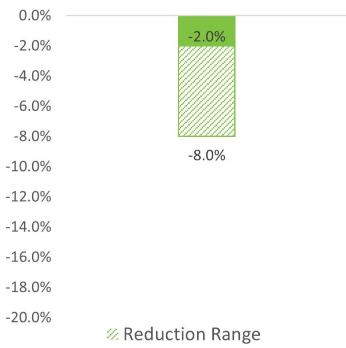
✓	**general compatibility for newbuild**	$$	**moderate newbuild CapEx for propellers, ducts, CPP**
○	**marginal compatibility for retrofit**	$$$	**significant newbuild cost for CRP, pods/azimuthing**
		$$$	**significant retrofit CapEx**
		-$/-$$	**moderate to significant OpEx savings**

- **Most propeller technologies best-suited for integration on newbuild design. Geometry and drivetrain constraints may make retrofit infeasible, particularly for podded and azimuthing propulsors.**
- CPP systems have been retrofitted on fixed pitch drives, but require adequate space for hydraulic equipment and increased complexity to propeller, shafting, and stern tube.
- For large diameter, low speed propellers, equipment is broadly available, not increasing cost significantly.
- CPP, CRP, and podded/azimuthing propellers have high capital costs and require additional design planning and shipyard installation.
- **CPP, CRP increase maintenance requirements and cost with additional moving parts.**
- **Podded and azimuthing propulsors increase equipment maintenance**, and are more difficult to inspect and maintain with critical equipment located outside the hull. This introduces risk of downtime in event of failure, and redundancy for safe return to port on one propulsor is recommended.
- Savings correspond to fuel savings from propulsion energy reduction potential.

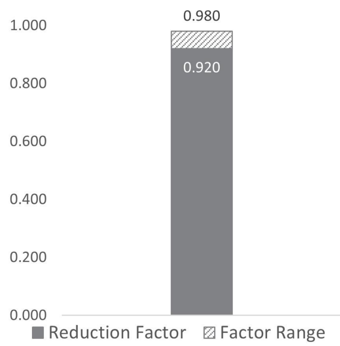
Link to Guide Navigator

Pre-Swirl Devices

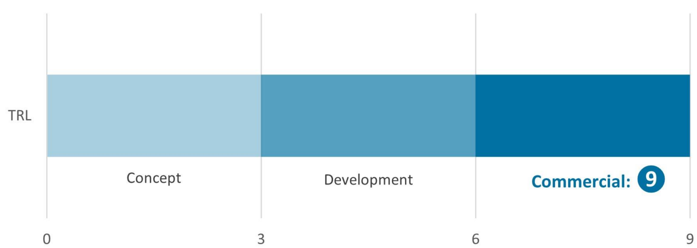
PERCENT REDUCTION



REDUCTION FACTOR (RFₑ)



TRL



APPLICATIONS

MW	Duty					
>10	Continuous	general	marginal	marginal	general	marginal
	Intermittent		poor	poor	marginal	poor
1-10	Continuous	general	marginal	marginal	general	marginal
	Intermittent		poor	poor	marginal	poor
<1	Intermittent		poor	poor	marginal	poor

MW: Propulsion Power plant size, in MW

Compatibility: ✓ general ◯ marginal ⊗ poor

INTEGRATION

		OpEx	CapEx
Newbuild	✓	-$	$
Retrofit	✓		$

KEY FACTORS

- Pre-swirl stators ideal for fast cargo ships, such as containerships
- Pre-swirl ducts suitable for slow cargo ships, such as tankers and bulkers
- Propeller should be optimized to match with pre-swirl technology
- Stators and ducts can be combined on slow vessels.
- Propeller optimization needed to maximize savings, particularly on retrofits

Link to Dashboard Legend

Overview

Pre-swirl devices condition the flow entering the propeller by establishing a higher uniformity that improves the loading on and propulsive efficiency of the propeller. This is accomplished by accelerating the flow in the upper part of the propeller disc and minimizing the tangential velocity components in the wake field. They are typically fixed and can be added to either newbuilds or retrofits for a relatively low cost.

Stators

Also known as fixed guide vanes, a pre-swirl stator is a set of fins on the propeller inlet fairing ahead of the propeller that improve flow to the propeller thus improving performance.

Figure 26: Pre-swirl stator (source: gCaptain)

While they increase the drag of the hull, these stators add a twist to the flow in the direction opposite of the propeller, which increases the angle of attack on the propeller blades. This stator rotational flow counteracts the propeller's rotational flow so the water behind the propeller has less circumferential momentum which would otherwise result in propulsive efficiency losses.

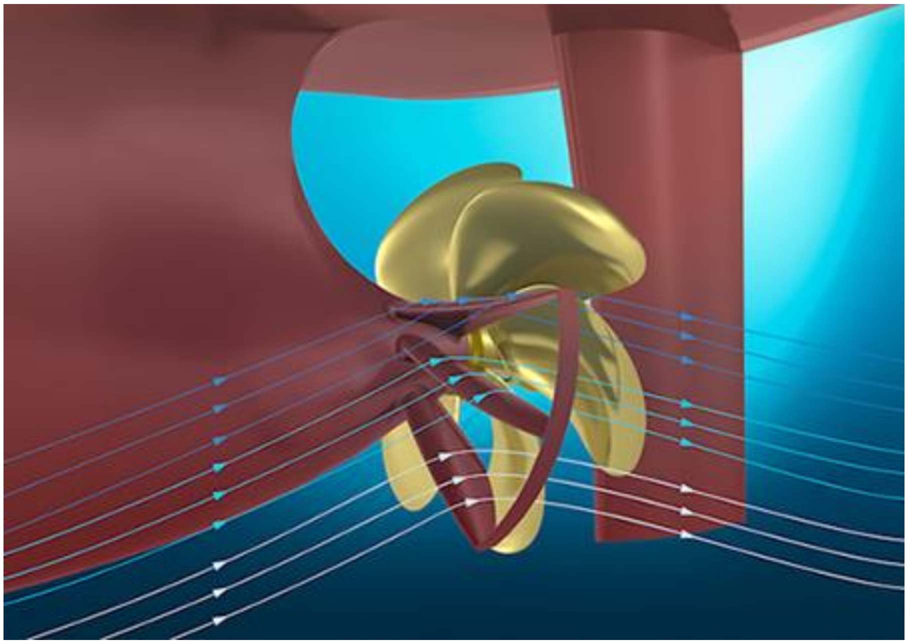


Figure 27: Wartsila pre-swirl stator (source: Wartsila [B11])

Pre-Swirl Ducts

Pre-swirl ducts operate in a similar fashion to pre-swirl stators, adjusting the incoming flow to the propeller and increasing its efficiency, but are typically better suited for slower flow applications. Variations are shown in Figure 28 and Figure 29. The wake equalizing duct has a half-circle duct on either side of the hull leading into the propeller flow, helping direct the flow into the propeller blades, and away from the hub. The Becker Mewis duct by Becker Marine Systems uses a round duct supported by a series of fins to straighten and accelerate the flow into the propeller [B12].

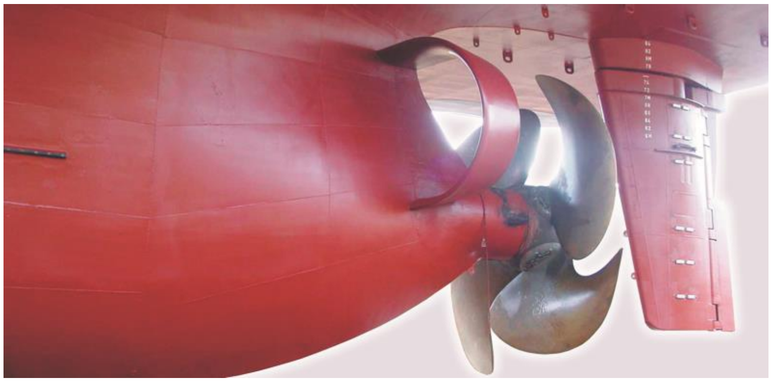


Figure 28: A Schneekluth wake equalizing duct, a type of pre-swirl duct (source: Wartsila [B15])

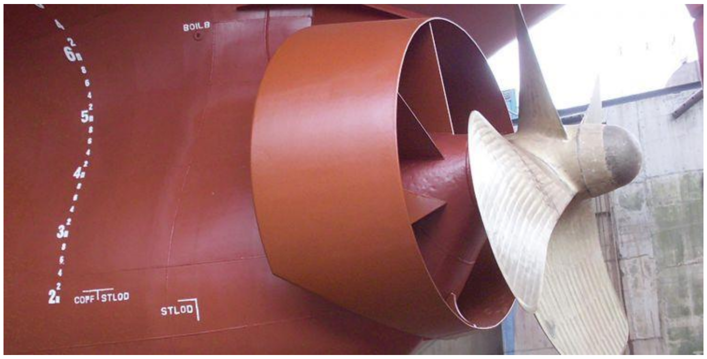


Figure 29: Becker Mewis Duct (source: Becker Marine Systems [B12])

Reduction Potential (as % of total energy demand): -2 to -8%

- MAN claims vessels will typically see 3 to 5% improvement in fuel consumption with pre-swirl fins [A35].

- Kawasaki Semi-Duct System with contra Fins (SDS-F) claims 2 to 7% energy savings with its semi-duct and contra fin pre-swirl device. SDS-F has been installed on five oil tankers [B13].
- **For vessels with high block coefficients, such as tankers and bulkers, pre-swirl stators and accelerating ducts can be combined for even further fuel savings**. For example, Sanoyas claims 8% reduction in fuel consumption by combining their Sanoyas Tandem Fins (STF) system with the Advanced flow Controlling and Energy saving (ACE) DUCT system to control the bilge vortex ahead of the propeller [B14].
- Wartsila claims up to 10% fuel savings for new pre-swirl concept EnergoFlow, but technology has not been demonstrated yet [B11].

TRL: 9

- Static stators and ducts are well established and widely adopted.
- New adaptations of devices such as retractable fins continue to gain improvements in many operational cases.
- Wake equalizing ducts have been installed on over 1,800 ships, including bulkers, containerships, and tankers [C10].

Applications

- **Pre-swirl stators are best suited for fast vessels with highly loaded propellers, such as containerships**.
- **Ducts are better suited for vessels operating under 20 knots, including bulkers, general cargo ships, and tankers**.
- **Ideally, the propeller is optimized to operate behind stators as they will impart higher loading on the propeller as a result of the stator induced twisted flow.**
- **Applicable for both newbuilds and retrofits, though propeller geometry should still be optimized to maximize energy savings.**
- Not suitable for vessels with non-conventional propulsors (pods, azimuthing thrusters, CPP, CRP), including cruise ships and most passenger vessels.

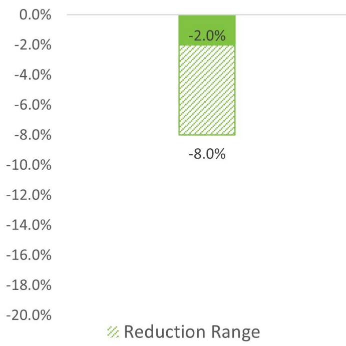
Integration & Cost

✓ **general compatibility for newbuild**	$ **minor newbuild CapEx**
✓ **general compatibility for retrofit**	$ **minor retrofit CapEx**
	-$ **moderate OpEx savings**

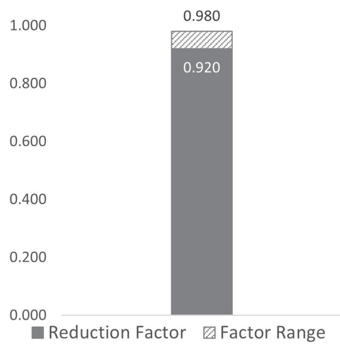
- Readily integrated on newbuild designs.
- Generally compatible as retrofit as appendages are passive devices and mount to the hull exterior. Propeller re-design and replacement may be necessary to maximize efficiency.
- Wartsila claims 1-2 years payback period for new pre-swirl device [B11].

Post-Swirl Devices

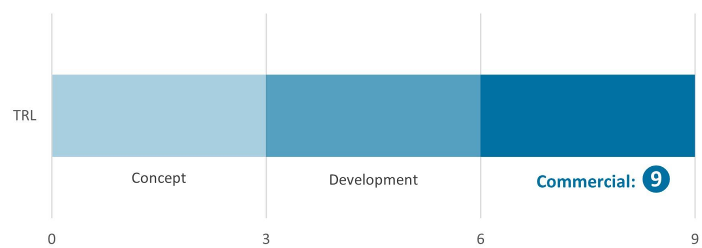
PERCENT REDUCTION



REDUCTION FACTOR (RF_e)



TRL



APPLICATIONS

MW	Duty	Vessel 1	Vessel 2	Vessel 3	Vessel 4	Vessel 5
>10	Continuous	general	general	marginal	general	marginal
	Intermittent		poor	poor	marginal	poor
1-10	Continuous	general	marginal	marginal	general	marginal
	Intermittent		poor	poor	marginal	poor
<1	Intermittent		poor	poor	marginal	poor

MW: Propulsion Power plant size, in MW

Compatibility: general / marginal / poor

INTEGRATION

		OpEx	CapEx
Newbuild	general	-$	$
Retrofit	general		$

KEY FACTORS

- Multiple post-swirl devices can be integrated together to maximize benefits
- Savings are primarily achieved by "straightening" flow out of propeller, and generating thrust from propeller-induced momentum
- Most devices ideal for fast cargo ships and passenger vessels
- Readily retrofittable as passive hull appendages
- Low installation cost enables short payback period, as low as one year

Link to Dashboard Legend

Overview

Post-swirl devices work by capturing some of the rotational energy that remains in the flow downstream of the propeller and turning it into thrust. They can also be used to correct detrimental flow patterns, such as hub vortices, or to improve rudder lift and maneuvering while reducing noise and vibration. **Often, post-swirl devices provide multiple overlapping benefits by integrating multiple downstream appendages into a single device**. They impact the hull wake field and modifications to the wake field impinged by the propeller slipstream, so they are primarily attempting to recover energy that would otherwise be lost. Depending on the device, they may be applied to both retrofits and newbuilds.

Rudder Thrust Fins

Rudder thrust fins are foils attached directly to the rudder to help capture energy and convert it to thrust that would otherwise be lost from the flow exiting the propeller. To optimize flow and reduce the potential for structural issues, the fins should not be attached to the pivoting rudder blade. Rudder thrust fins should ideally be attached to the rudder horn (the fixed surface at the leading edge of the rudder). Consequently, rudder thrust fins are not suited for all rudder types.

Figure 30: Hyundai (HHI) thrust fins attached to a ship's rudder (source: HHI)

While the state of rudder thrust fins has advanced significantly in recent years, developers continue to make incremental improvements, including updates to the angle of attack and the foil orientation.

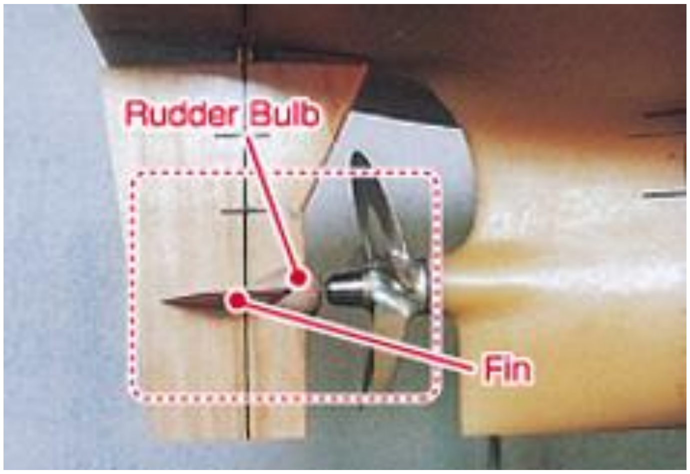


Figure 31: Rudder thrust fins paired with rudder bulb (source: Kawasaki)

Asymmetric Rudders

Asymmetric rudders take advantage of the angular momentum component of the flow after leaving the propeller. They can be paired with other pre- and post-swirl solutions such as Costa bulbs or a modified propeller cap (see next page) to further improve efficiency. They are typically employed on newbuilds but may be suitable for retrofit under some circumstances.

Figure 32: Van der Velden asymmetric rudder technology (source: Damen [B16])

A variation of the asymmetric rudder is the Gate Rudder®, developed by Kamome Propeller, which uses two separate rudders placed on either side of the propeller, rather than behind the propeller. The two “gates” mimic a nozzle to add thrust, but also provide steering by being actuated on two linked rudders. The Gate Rudder® concept is shown in Figure 33 [B17], and was tested on the containership MV *Shigenobu* (IMO no. 9826873) [C11] in parallel to its sister vessel fitted with a flap rudder. Kamome Propeller also reported improved turning radius and reduced noise in machinery spaces.

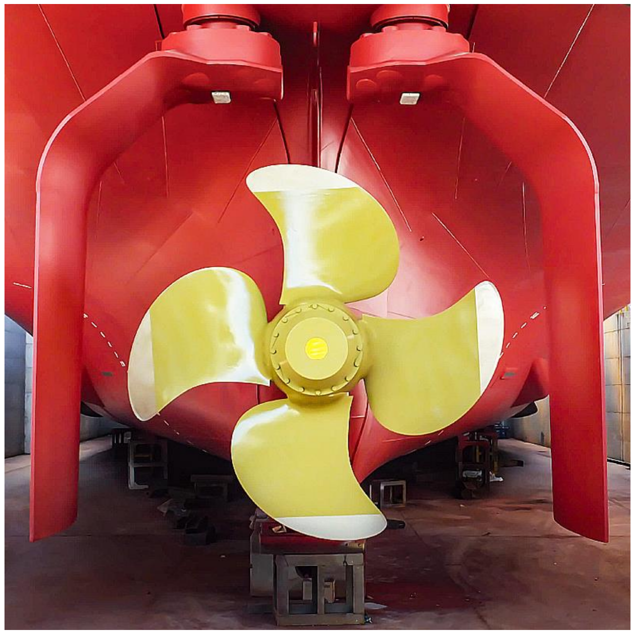


Figure 33: Kamome Gate Rudder® for increasing thrust and reducing rudder resistance (source: Kamome Propeller)

Costa Bulbs

Costa or rudder bulbs help condition the flow behind the propeller hub where there are often losses. This helps accelerate the flow past the rudder increasing thrust and improving propulsive efficiency. It also reduces cavitation, rotational losses in the slipstream, and hub vortex losses as well as improving noise and vibration conditions.

Figure 34: Kongsberg Promas propulsion system with costa bulb (left, source: Kongsberg [B18]) and Brunvoll integrated costa bulb (right, source: Brunvoll [B19])

Propeller Boss Cap Fins

Propeller Boss Cap Fins (PBCF) are added to the rear cap of the propeller and vastly reduce the hub vortex behind it. PBCFs are static blades attached to the propeller boss cap at an angle that transmit vortex energy into usable thrust. Given the difference in flow velocity between the top and bottom of the propeller blade, especially at the root, a strong vortex forms behind the propeller boss cap. By adding small fins to the boss cap, the flow is redirected and some of the rotational energy is converted into thrust and eliminates the hub vortex. Given their simplicity and ease of installation, they have a very fast payback period.

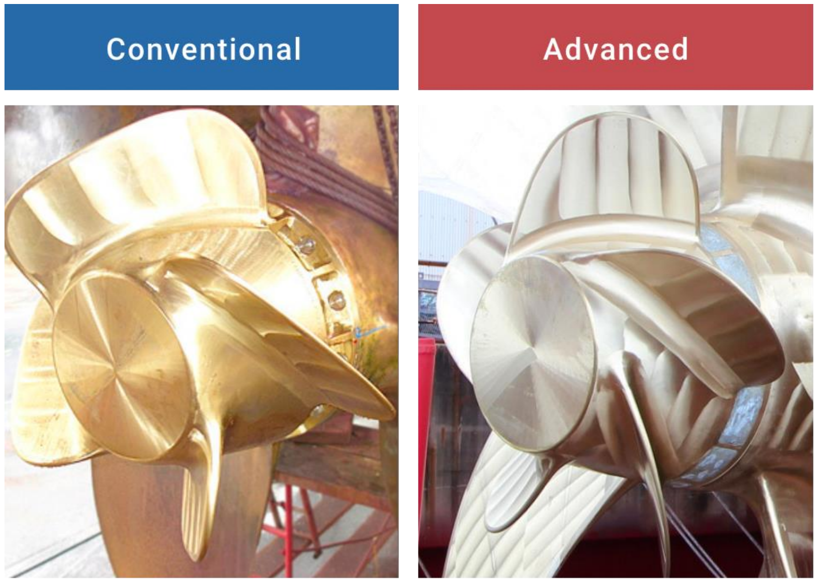


Figure 35: Conventional [left] and advanced [right] PBCF (source: PBCF [B20])

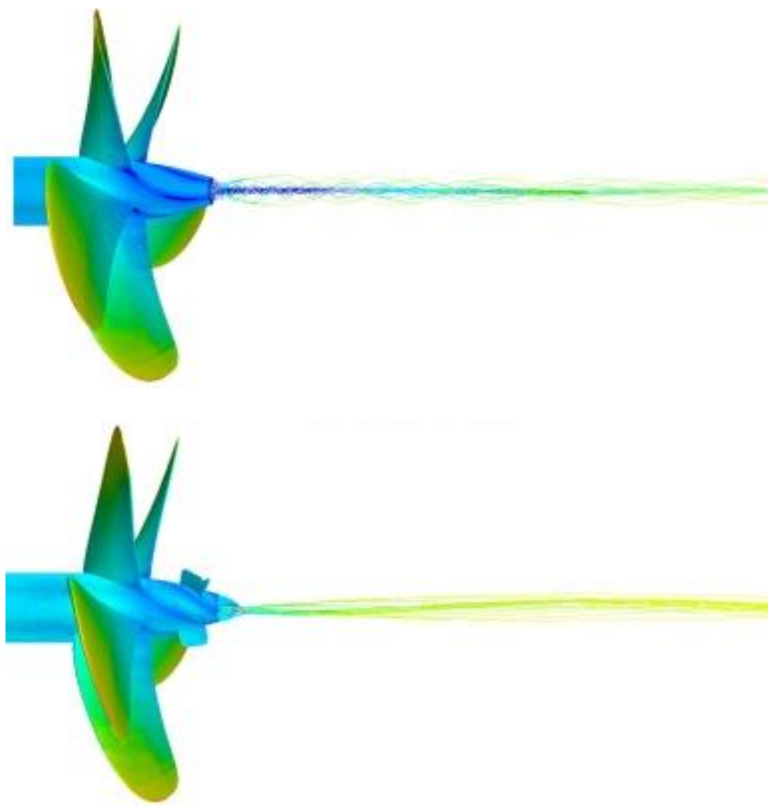


Figure 36: Comparison of propeller streamlines: without PBCF on top, with PBCF on bottom (source: Applied Ocean Research)

Reduction Potential (as % of total energy demand): -2 to -8%

Reduction potentials in this section are based on vendor claims, and have not been independently verified.

- Based on CFD simulations, model experiments, and real ship conditions, the energy savings from rudder thrust fins can be 3 to 7%.
- Gate Rudder® claimed to reduce fuel consumption by 14% in a sister ship trial, though an independent CFD and model test study indicated savings of 3 to 8% should be expected, varying based on hull geometry [A36]). A separate study estimated 7 to 8% energy savings.

- The addition of a costa bulb typically is estimated to reduce vessel fuel consumption by 2-4% [A37].
- Adding PBCFs can reduce vessel fuel consumption by 3-5%. Recent improvements to the original PBCF design has yielded a design with an additional 2% in fuel savings [A38].

TRL: 9

- Similar to propeller energy saving devices, various post-swirl devices are installed on thousands of vessels. PBCFs alone are installed on thousands of vessels, with over 300 installations since 2017 [A38].
- New optimizations of these devices continue to gain improvements in many operational cases.

Applications

- **Rudder fins, costa bulbs, and asymmetric rudders (including twin Gate Rudders) are generally installed on fast cargo ships and passenger vessels. In particular, costa bulbs are suitable at speeds from 14 knots and up [B21].**
- Highest savings achieved on large, deep draft propeller wheels.
- Multiple post-swirl devices can be coupled to improve performance, including PBCFs with asymmetric rudders, as well as costa bulbs.

Integration & Cost:

✓	**general compatibility for newbuild**	$	**minor newbuild CapEx**
✓	**general compatibility for retrofit**	$	**minor* retrofit CapEx**
		-$	**moderate OpEx savings**

*rudder modifications such as asymmetric rudders or gate rudders may have more significant retrofit CapEx

- **As exterior appendages, retrofit requires drydocking but does not impact internal machinery spaces or equipment.**
- While asymmetric and gate rudders require rudder replacement, costa bulbs can be retrofitted onto existing rudders with modification to the propeller and hub.
- **Payback period claimed to be less than one year for asymmetric rudders [B21]**
- Retrofit installation of PBCF in particular can be very straightforward, installed in hours [A39].

Link to Guide Navigator

PROPULSION AND POWER GENERATION

Navigation:

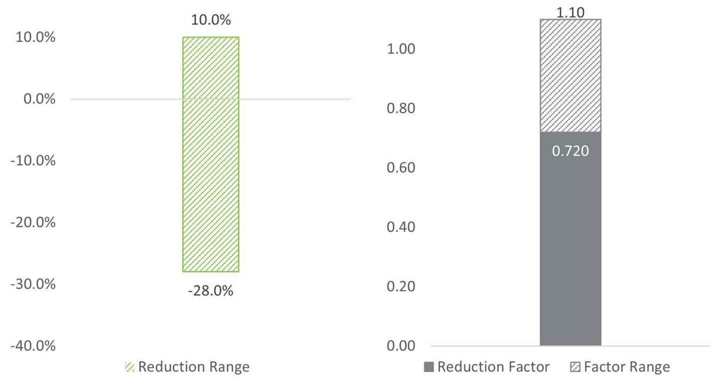
Diesel-Electric Propulsion	Variable Speed Generator	Power Take-Off/Power Take-In
Magnetic Gearing	PCB Motor Stator	

Onboard power generation, for propulsion or non-propulsion ship service loads, is a major source of energy losses. This is particularly true for propulsion power, which typically makes up most of the energy consumption aboard a marine vessel. Propulsion internal combustion engines and propulsion diesel-generators are often sized for maximum expected loads, and therefore may not be optimized for the dominant load cases a vessel experiences. Various forms of electrification enable prime movers to run at near-optimal loads and speeds, including variable speed generators (VSG), power take-off and power take-in (PTO/PTI), and electrical energy storage devices. These technologies are details in the following sections.

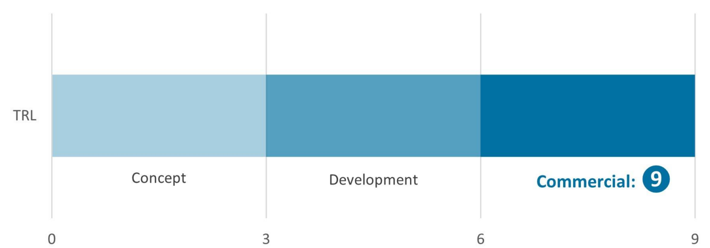
Link to Guide Navigator

Diesel-Electric Propulsion (DEP)

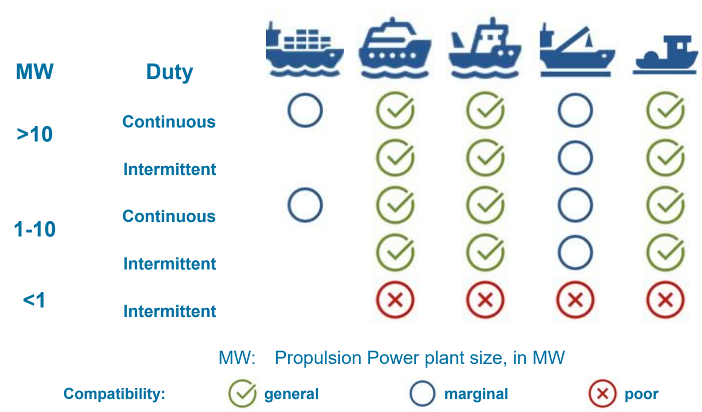
PERCENT REDUCTION | **REDUCTION FACTOR (RF_e)**



TRL



APPLICATIONS



INTEGRATION

		OpEx	CapEx
Newbuild	general	-$/-$$	$$
Retrofit	marginal		$$$

KEY FACTORS

- Particularly well-suited for vessels variable load ops/significant aux loads
- Potential for energy savings on large vessels with highly variable routes
- DEP vessel is electrified, compatible with integration of batteries/fuel cells
- May increase vessel's energy demand if not matched with vessel ops/loads
- Improved reduction potential when coupled with VSG or PTO/PTI
- Difficult to integrate as retrofit due to footprint and impact on auxiliaries
- Total cost of DEP equipment higher than equivalent diesel mechanical plant

Link to Dashboard Legend

Overview

Fixed speed diesel-electric propulsion is considered in this section. Variable speed diesel-electric propulsion is considered in the next section.

One of the primary challenges with diesel engines is matching the right engine to the right task. This is particularly challenging when trying to optimize fuel consumption. Diesel engines typically have optimal fuel consumption in the power ranges between 70-90% of maximum continuous rating (MCR). To maximize the efficiency and minimize energy, a diesel engine should spend as much time as possible operating at or near its best efficiency point.

Diesel-electric propulsion (DEP) is an alternative arrangement to diesel-mechanical propulsion. A representative topology of DEP is provided in Figure 37. **DEP is used widely across vessel types, but is particularly well-suited for operations with variable loads and/or significant auxiliary loads**. Large vessels in specific trades can also implement DEP, such as cruise ships and gas tankers, particularly where there are large electric consumers in addition to main vessel propulsion.

A vessel operating on a fixed route and schedule will have a clearly defined operating point that a main diesel-mechanical propulsion engine can be optimized for. However, a vessel may have multiple routes or routes changing with trade. Consequently, the load profile of the engine may not have a consistently dominant operating point. It is also common in sizing an engine for maximum power to be the driving input, resulting in low efficiency at other operating points. A vessel may have a contractual requirement to operate at a certain maximum speed, or to have a maximum bollard pull. However, for that same vessel, it may spend a majority of its operating time at a low or medium power level.

On many types of vessels, there may be very high demands for services other than propulsion for transit. Large passenger vessels such as cruise ships and car ferries can have very large hotel loads with significant fluctuation. This also applies to many work vessels that have high auxiliary loads for special equipment or station keeping.

DEP uses a set of diesel-generators (DG) to power a vessel's propulsion as well as all auxiliary and hotel loads. While DEP introduces some efficiency losses by introducing conversion and switchgear equipment between the prime mover and propulsion electric motors, it offers more plant flexibility, redundancy, and optimization of the engine operating point. The number and size of diesel-generators can be optimized to meet all anticipated power demands, and modern power management systems can optimize fuel consumption for each load case.

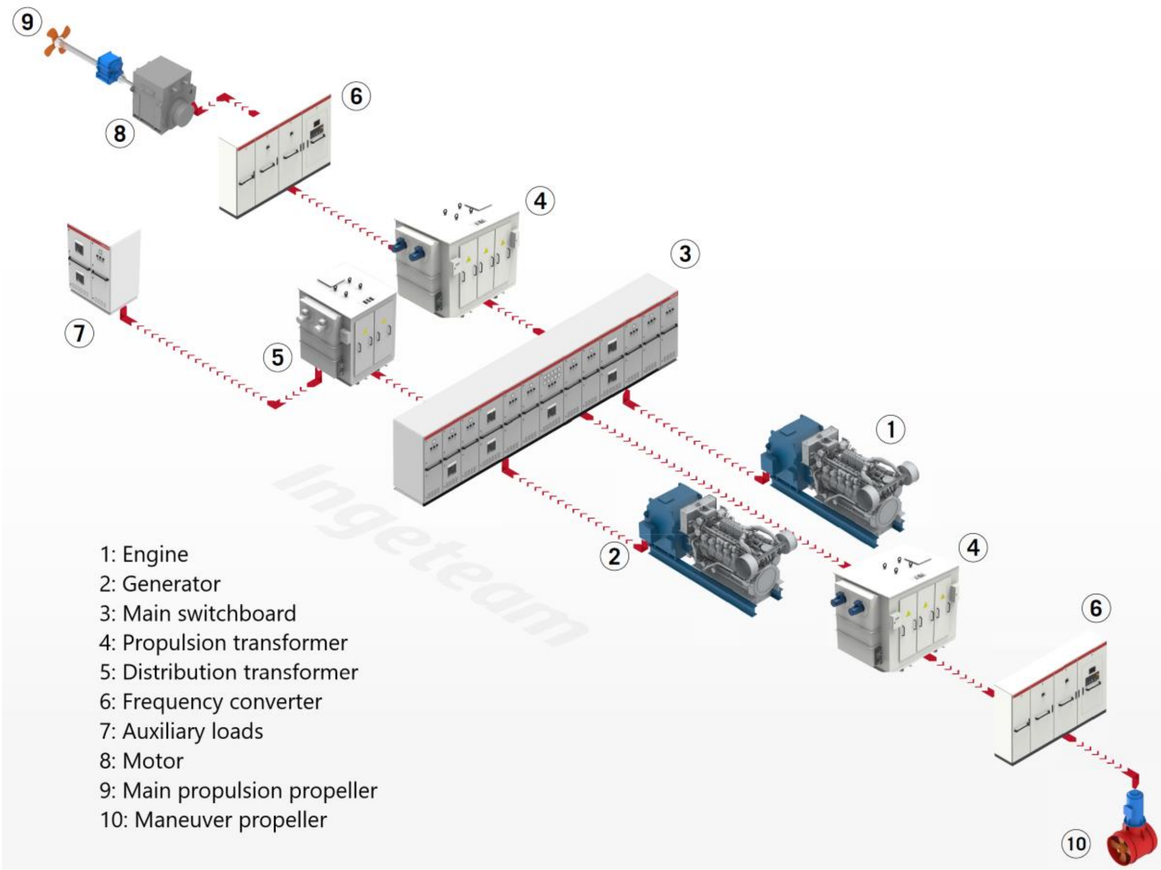


Figure 37: Typical diesel-electric propulsion topology with AC switchboard (source: Ingeteam [B22])

A power plant configured for diesel-electric is considered electrified, so it can also be readily adapted to electric-based technologies like batteries and fuel cells. Vessels that are built with DEP now will be easier to update with electric-based technologies in the future, particularly if switchboards and the electric plant are configured for other power inputs.

DEP is not suitable for all vessel types and operations, and may actually increase a vessel's total energy demand if not matched appropriately. Depending on the conversion and switchgear arrangement, these losses, and thus energy increase, could be as high as 10%, as illustrated in Figure 38.

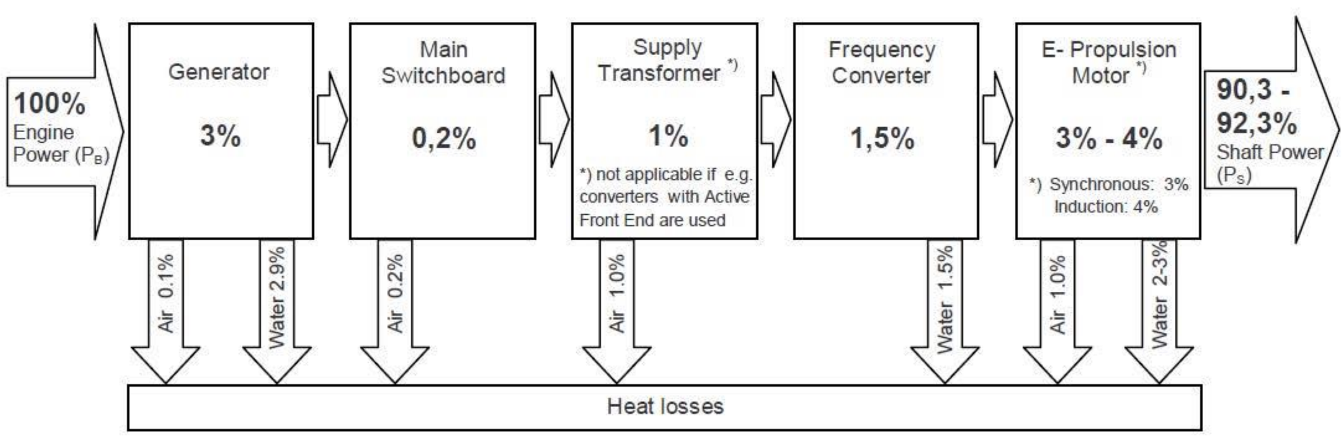


Figure 38: Typical energy losses of a diesel-electric power generation and propulsion plant (source: MAN)

Reduction Potential (as % of total energy demand): +10 to -28%

- Reduction potential is highly dependent on vessel type, load profile, ratio of propulsion and auxiliary loads.
- Work boats with highly variable loads that operate at idle or loiterer speeds could achieve upwards of 28% total energy reduction compared to diesel-mechanical propulsion [A40].
- If DEP is not matched appropriately, net increase in total energy could be as high as 10%.

TRL: 9

- Fixed speed DEP is broadly adopted across vessel sizes and types, and has been in full commercial operation for decades.
- It is well proven what vessel types and load profiles are best-suited for DEP integration.

Applications

- Suitable for vessels with highly variable load profile and significant portion of energy consumed by auxiliary and hotel loads.
- Work boats and small vessels with significant loiter or idle time are an ideal match.
- **Large vessels with varying trade routes and/or significant auxiliary loads (e.g., cruise ships LNG carriers) can benefit from DEP over a diesel-mechanical propulsion plant**.
- Vessels with high loads and little variability are better matched with diesel-mechanical propulsion optimized for vessel specifics.
- **Reduction potential can be further improved by switching to variable speed DEP or coupling with power take-off and power take-in (PTO/PTI), as discussed in next sections.**

Integration & Cost

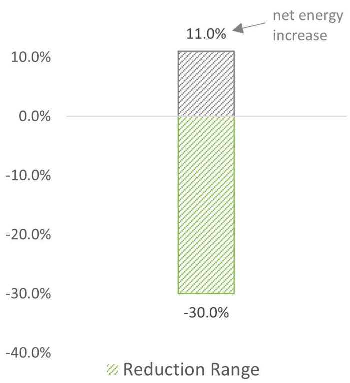
✓	**general compatibility for newbuild**	$$	**moderate newbuild CapEx**
○	**marginal compatibility for retrofit**	$$$	**significant retrofit CapEx**
		-$/-$$	**moderate to significant OpEx savings**

- DEP electrical equipment is generally less centralized but has a larger footprint than direct diesel-mechanical propulsion.
- **Difficult/expensive to integrate as retrofit, due to higher footprint of equipment and impact on many auxiliary systems.**
- Can be challenging to integrate on small vessels with limited machinery space.
- **Total cost of DEP generators and electrical conversion equipment is higher than equivalent direct diesel-mechanical propulsion with ship service diesel-generators.**
- Allows for future integration of electric-based technologies, if additional capacity and space is allocated in electrical plant.
- Appropriate duty-rated generators widely available, power equipment is available from multiple vendors, allowing for thorough selection process/owner preference.

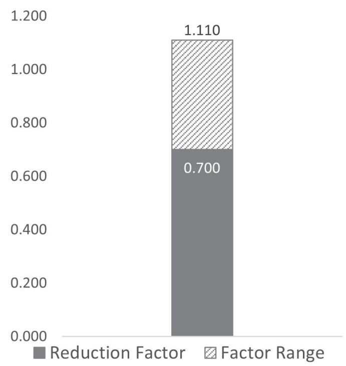
Link to Guide Navigator

Variable Speed Generator (VSG)

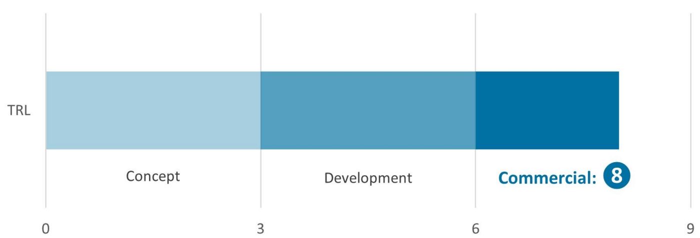
PERCENT REDUCTION



REDUCTION FACTOR (RF_e)



TRL



APPLICATIONS

MW	Duty					
>10	Continuous	poor	marginal	general	marginal	general
	Intermittent		general	general	marginal	general
1-10	Continuous	poor	marginal	marginal	marginal	marginal
	Intermittent		general	general	marginal	general
<1	Intermittent		poor	poor	poor	poor

MW: Propulsion Power plant size, in MW

Compatibility: general marginal poor

INTEGRATION

		OpEx	CapEx
Newbuild	general	-$/-$$	$$
Retrofit	marginal		$$$

KEY FACTORS

- Optimal engine loading with VSG can reduce wear and maintenance
- Isolation through DC bus reduces harmonic distortion issues
- Improved RF_e over fixed speed DEP if matched with highly variable/low loads
- Slightly smaller equipment more readily retrofitted than fixed speed DEP
- May allow for fewer generators due to optimized sizing

Link to Dashboard Legend

Overview

Fixed-speed diesel-generators operate at different, set speeds (e.g., 900 rpm, 1800 rpm, or 3600 rpm) to create the required frequency for a system (e.g., 50 Hz or 60 Hz). Unfortunately, unlike propulsion ICE, which can vary their speed to match power demand, fixed-speed generators cannot. The resulting high mechanical losses when operating at low power levels means lower efficiency and higher wear when compared to propulsion engines.

In contrast to conventional fixed-speed diesel-generators, variable speed generators (VSG) run over a range of rpm to match the speed of one or multiple generators to the required electrical load. VSGs typically connect to a DC bus through rectifiers, which then converts the DC electricity to a standard frequency power output (VSGs can also connect through an AC bus with frequency converters, however this limits the direct connection of variable speed devices such as VFDs). Diesel-electric plants are often loaded below the engine's MCR, so by matching speed to load, VSGs perform at their optimal speed for a given load, minimizing brake specific fuel consumption and wear on the engines. VSG also allows for more intelligent load sharing between multiple generators, and can be highly responsive to load changes if a spinning reserve (running engines at a slightly higher speed than optimal for a given load) is programmed into the power management system.

Optimal loading of the engines should also reduce maintenance, as less wear is experienced when engines are loaded at an optimal speed vs fixed speed at reduced load.

When comparing the efficiency to a fixed speed DEP system, the improvement of a VSG will depend on the amount of time that the engines will spend at partial load. A highly optimized DEP plant that has a very predictable operational profile will see little gain from a VSG arrangement. However, most DEP plants have unpredictable loads and should see moderate to significant benefits from switching to variable speed. As can be seen in Figure 39, the fuel savings between fixed-speed and variable-speed generators is significant at lower loads. Therefore, an evaluation of the load profile of the vessel should be done prior to selection of VSGs.

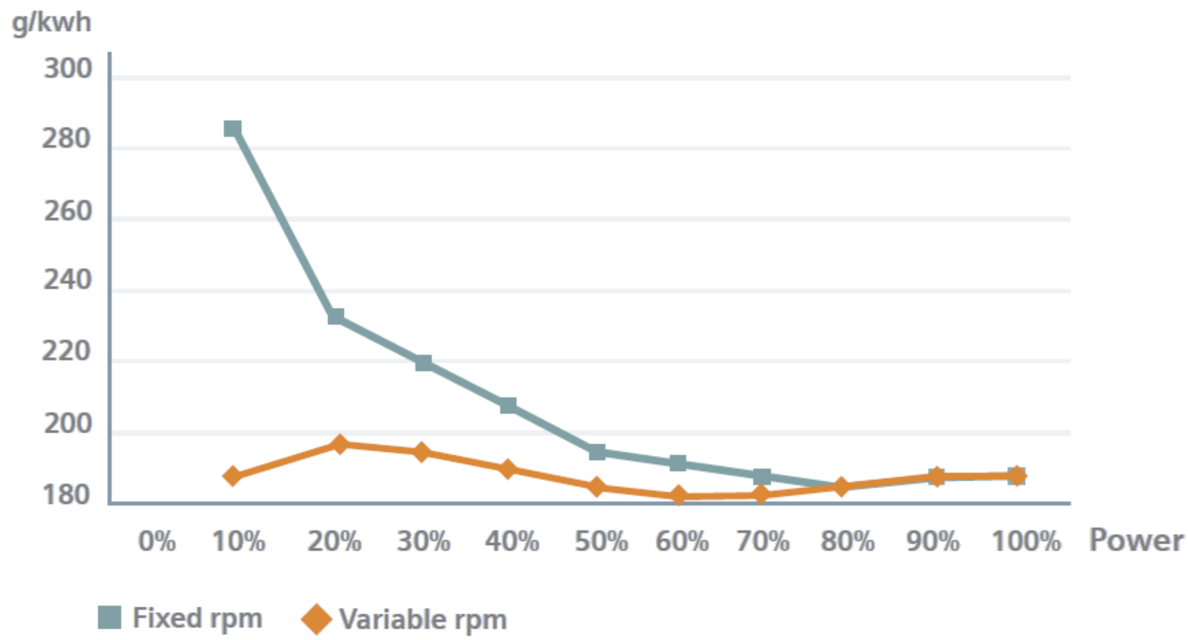


Figure 39: Specific fuel consumption for variable speed vs fixed speed diesel-generators (source: Siemens)

With increased volume of installations, the cost of VSG systems is approaching the cost of fixed speed DEP systems and they may well become the standard solution. This has been seen with variable speed motors, which are now fairly standard, even in small sizes, but were a premium product when first introduced.

Major power equipment developers such as ABB, Ingeteam, and Siemens have worked to optimize the size of conversion hardware for VSG applications. In some cases, the switchboard and transformer equipment are actually smaller in footprint than a comparable synchronous system, making it attractive for small vessels that often operate below the rated load of the generator plant.

By isolating VSG generators through a DC bus, the electrical architecture can also reduce harmonic distortion issues that come from other variable frequency devices such as propulsors and winch motors, as those devices can also connect to the DC bus through dedicated transformers. This is a secondary advantage for vessels with equipment that is sensitive to harmonic distortion such as research and hydrographic survey vessels.

Reduction Potential (as % of total energy demand): +11 to -30%

- **Reduction potential is similar to DEP, but improved when VSG is matched with vessel loads that are highly variable and often operate at low loads**.
- Work boats with high variably loads could achieve even higher energy savings than fixed speed DEP, upwards of 30% [A40].
- Ingeteam also reports the potential 30% savings with VSG and DC bus, if matched with the right vessel load profile [B22].
- Similar power conversion losses to synchronous DEP, with additional 1% assumed for asynchronous AC to DC bus conversion.

TRL: 8

- VSG is a fully commercial solution and is growing in uptake across multiple trades and vessel types.
- Class societies and flag states are familiar with VSG DEP and have a regulatory framework for reviewing these types of propulsion plants.

Applications

- Similar suitability to synchronous DEP.
- Ideal for vessels that spend lots of time at low or moderate generator loads.
- May be suitable for large vessels that do not expect to normally operate near MCR of diesel-generators.

Integration & Cost

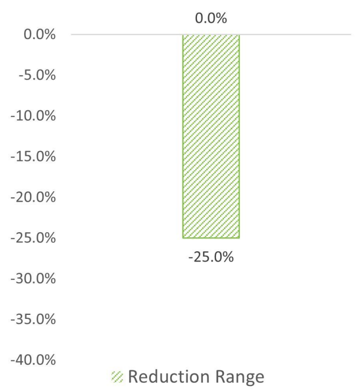
✓	**general compatibility for newbuild**	$$	**moderate newbuild CapEx**
○	**marginal compatibility for retrofit**	$$$	**significant retrofit CapEx**
		-$/-$$	**moderate to significant OpEx savings**

- **May be more readily retrofitted than synchronous DEP with slightly smaller equipment footprint.**
- VSG combined with a DC bus allows for more ready integration with batteries or fuel cells.
- **May allow for fewer generators due to optimized sizing and incorporation of spinning reserve.**
- No paralleling synchronization required when connected through a DC bus.

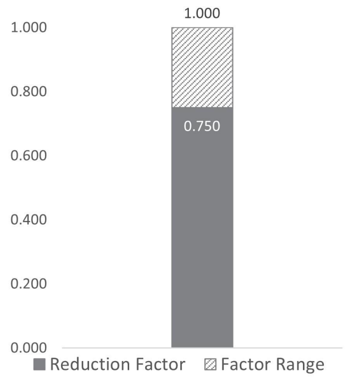
Link to Guide Navigator

Power Take-Off/Power Take-In (PTO/PTI)

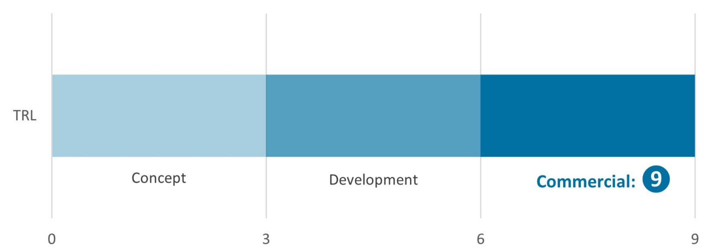
PERCENT REDUCTION



REDUCTION FACTOR (RFₑ)



TRL



APPLICATIONS

MW	Duty					
>10	Continuous	general	general	marginal	general	marginal
	Intermittent		general	marginal	general	marginal
1-10	Continuous	general	general	marginal	general	marginal
	Intermittent		marginal	marginal	marginal	marginal
<1	Intermittent		poor	poor	poor	poor

MW: Propulsion Power plant size, in MW

Compatibility: general, marginal, poor

INTEGRATION

		OpEx	CapEx
Newbuild	general	-$/-$$	$$
Repower	general		$$
Retrofit	poor		

KEY FACTORS

- Frequency converter advances make PTO/PTI more broadly suitable
- Energy savings depend on operating profile and PTO/PTI mode exercised
- Energy reductions for both continuous and intermittent operation
- May simplify repower by reducing size of new prime mover
- Reduced engine and generator maintenance by improved load management

Link to Dashboard Legend

Overview

Power takeoff (PTO) and Power take-in (PTI) technology serves as a hybrid between diesel-mechanical and diesel-electric propulsion. By integrating a main shaft-generator between the main propulsor (diesel engine or main electric motor), energy can be transferred in multiple modes to optimize the vessel's propulsion and auxiliary operations. PTI modes include:

- Propulsion boost: re-direct power from auxiliary generators to the shaft-generator, typically through a frequency converter, to augment propulsion power. Generally, does not improve overall fuel efficiency but improves operational flexibility.
- Diesel-electric: re-direct power from auxiliary generators to the shaft-generator to provide 100% propulsion power, to avoid operating the propulsion engine at low loads and allow safe return-to-port flexibility in event of propulsion engine failure.
- Fully electric: where energy storage is incorporated, re-direct power from batteries directly to the shaft-generator to provide 100% electric propulsion and/or auxiliary power.

PTO modes include:

- Parallel: re-direct power from propulsion engine to the switchboard, via the shaft-generator, to augment auxiliary generator power and optimize propulsion engine and diesel-generator operating points.
- Diesel-mechanical: re-direct power from propulsion engine to switchboard via the shaft-generator, to provide 100% auxiliary power, optimizing propulsion engine performance and avoiding operation of auxiliary diesel-generators at low loads.

These modes are illustrated in Ingeteam topology diagrams, shown in Figure 40.

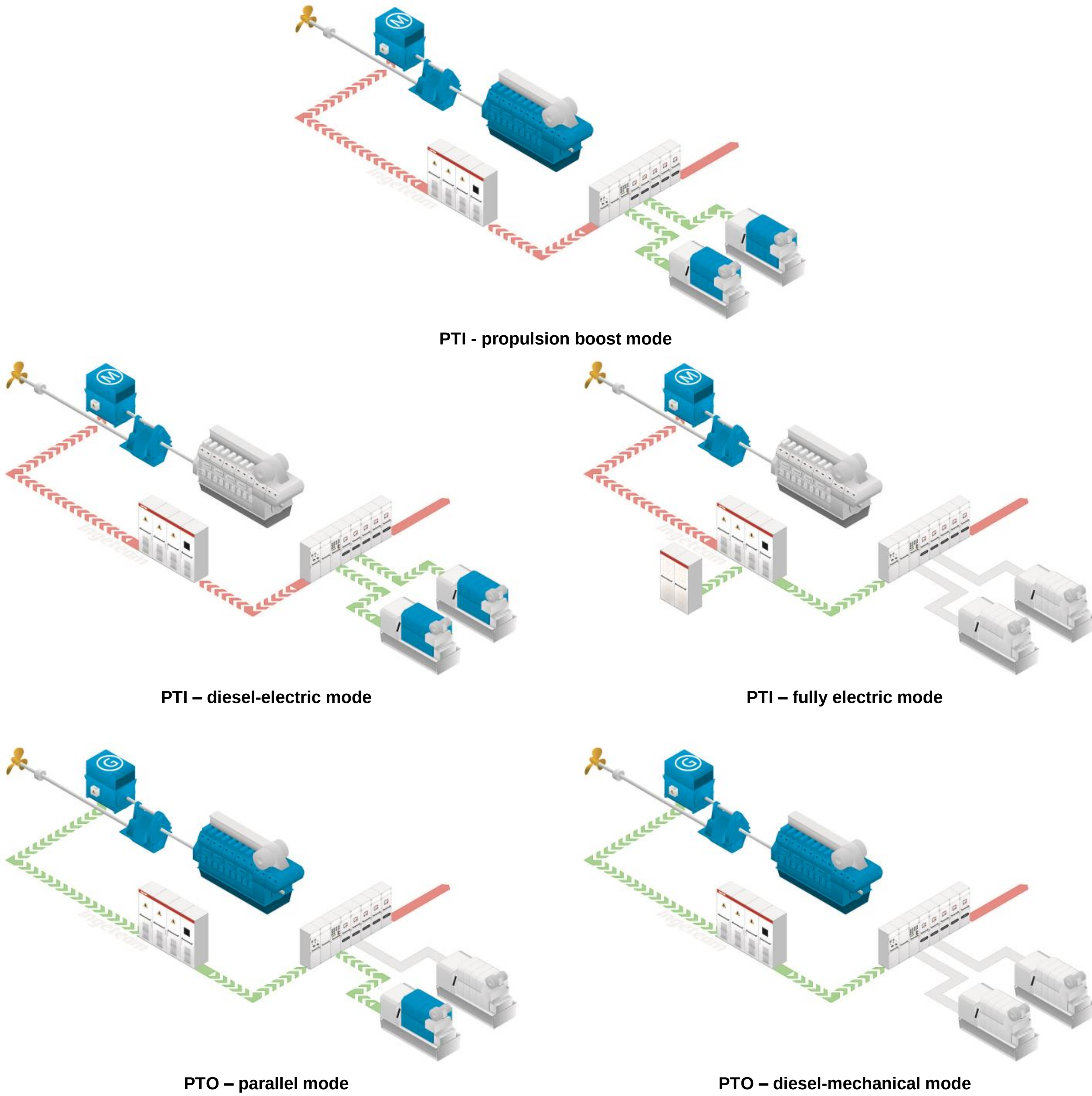


Figure 40: Various PTI and PTO topologies (source: Ingeteam [B22])

If energy storage is incorporated, additional electric modes of propulsion are possible, for both propulsion and auxiliary power.

Early adopters of propulsion PTO/PTI typically integrated the equipment with either controllable pitch propellers or only operating in certain speed ranges due to the cost and availability of large capacity frequency converters.

With frequency converter technology much more affordable and scalable, motor-generators for PTO/PTI purposes are now broadly suitable for slow speed propulsion plants [A41], and can be utilized over a wider range of engine speeds (for PTO) and propeller speeds (for PTI). Power integration can also be simplified by use of an induction motor-generator rather than synchronous arrangement, as offered by GE Power Conversion [B23].

PTO/PTI integration allows both propulsion engines and auxiliary generators to operate within their most optimal range for fuel consumption. Unlike diesel-electric propulsion, PTO/PTI can reduce energy needs over a wide range of propulsion and auxiliary load points. In PTO mode, the power transferred to the ship's switchboard can prevent additional generators from coming online while maintain existing generators at the peak operating point. In PTI mode, generator power can boost the propulsion engine, maximizing propeller thrust while not overloading the propulsion engine. A dual PTO/PTI arrangement is shown in Figure 41.

PTO/PTI may allow for a lower installed power for both propulsion and ship service generators, and possibly reduce the quantity of generators installed to meet peak auxiliary load conditions.

While shaft-generators are widely adopted on large vessels (>10MW) with slow speed propulsion engines, the technology also provides an alternative to diesel-electric only for vessels with wide-ranging operating profiles coupled with significant propulsion loads.

A PTI-only "hybrid" solution, developed by Caterpillar, implements a booster motor for diesel-electric operation at low operating loads. This configuration does not offer the full operational flexibility of a motor generator, but may be more readily integrated on smaller work boats that have diesel-mechanical propulsion [B24].

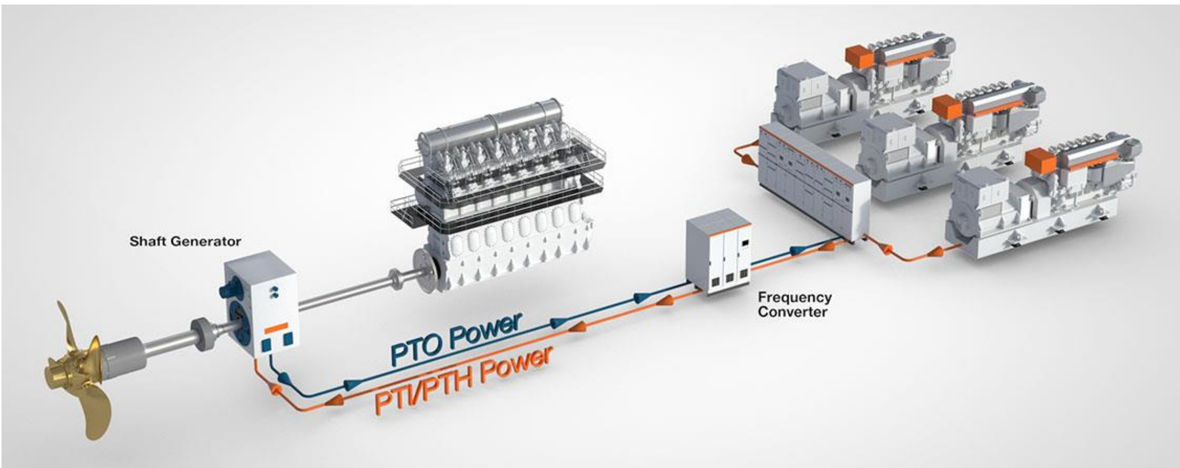


Figure 41: Shaft-generator shown in both PTO and PTI operation (source: Wartsila [B25])

Reduction Potential (as % of total energy demand): 0 to -25%

- **Energy savings highly dependent on vessel's operating profile and PTO/PTI mode exercised, and therefore may be highly intermittent**:
  - Propulsion boost won't reduce full consumption, as it is increasing energy consumption.
  - Parallel mode can optimize fuel consumption for medium- and high-speed generators
  - Diesel-electric (propulsion engine offline), or diesel-mechanical (auxiliary generators offline) modes can maximize savings by avoiding inefficient operating points on propulsion or auxiliary engines.
- Improved efficiency with modern frequency converter technology.

TRL: 9

- Widely adopted on oceangoing cargo vessels, with 150 installations in past decade by one manufacturer alone [B26].
- Increased uptake in other trades due to improved availability of frequency converter technology.

Applications

- Newbuilds with diesel-mechanical propulsion.
- Repower projects to reduce propulsion plant and/or auxiliary generator size.
- **Energy reductions for both continuous and intermittent operation, and wide range of engine operating points.**
- Not compatible with DEP unless re-powered to be diesel-mechanical propulsion.
- Not suitable for vessels with limited space availability.
- Potential for integration on workboats with battery-hybrid systems [A42].

Integration & Cost

✓	general compatibility for newbuild	$$	moderate newbuild CapEx
✓	general compatibility for repower	$$	moderate repower CapEx
⊗	not compatible for general retrofit	-$/-$$	moderate to significant OpEx savings

- Newbuild cost of additional equipment may be offset by reducing propulsion engine or ship service generator size. Additional savings are possible if quantity of generators can be reduced.
- **May simplify repower project by reducing size of new prime movers and therefore offsetting CapEx. Several shaft-generator positions available from different manufacturers, improving retrofit flexibility**.
- Generally not compatible for retrofit that doesn't include repower.
- **Reduces engine and generator maintenance by increasing hours at optimal load and possibly decreasing overall hours.**

Magnetic Gearing

Key Factors

- Eliminates frictional losses, reduces maintenance and noise, potential to increase reliability.
- Configured as either standalone magnetic gearbox or combination gearbox/electric motor.
- Magnetic gears for vessel drivetrains have not been developed, thrusters only available in 15 kW or 25 kW sizes.
- Wind energy, aerospace, rail, and ocean energy applications could enable vessel drivetrain development.

Overview

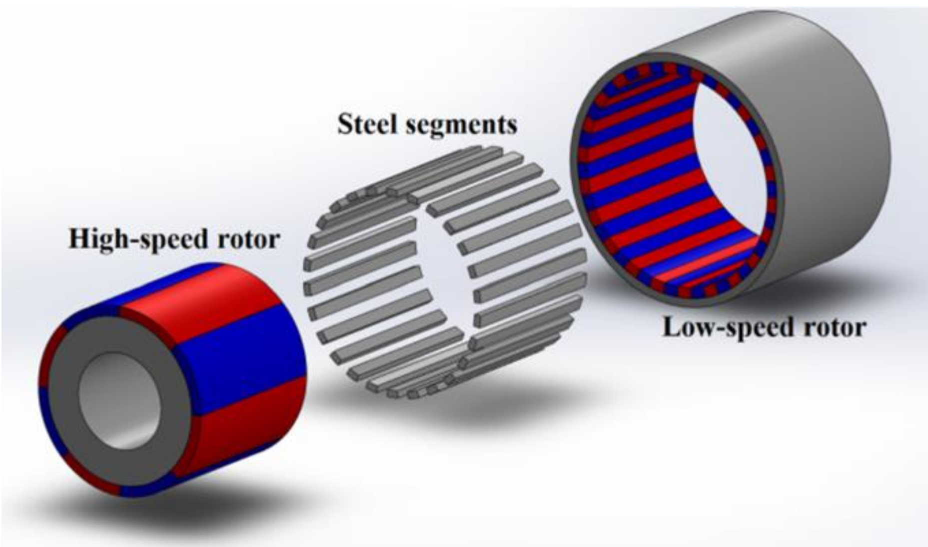


Figure 42: Exploded view of magnetic gear assembly (source: Springer Link)

Mechanical gears have long been the convention in marine drivetrains for changing the speed and direction of the driving shaft. While a proven and reliable technique, mechanical gears also introduce efficiency losses, require lubrication, are subject to wear, and can be damaged in an over-torque condition. Magnetic gearing is emerging as an alternative technology that may be developed for marine drive applications.

Magnetic gears have three rings: two magnet rings arranged in alternating polarity sections in the radial direction, and a center steel ring that alters the magnetic field between the magnet rings. The inner magnet ring is coupled to one shaft, and either the center steel ring or the outer magnet ring is coupled to another shaft, with the other ring being rotationally fixed. An exploded view is shown in Figure 42, where the inner ring has fewer, larger magnets as the high-speed rotor, and the outer ring has more, smaller magnets as the low-speed rotor. The gear ratio is determined by the magnet ratio between the inner and outer rings. The geometry shown aligns both shafts as colinear, similar to the input/output arrangement of a planetary gear.

Magnetic gears have no contact surfaces, as there is an air gap between spinning surfaces, requiring no oil lubrication and minimal maintenance. Marine single reduction gearboxes typically experience 1 to 2% energy losses due to friction, which would be eliminated with magnetic gearing. The elimination of contact friction also makes magnetic gears very quiet. Magnetic gears may be capable of accommodating higher gear ratios (the ratio of smaller magnets in one ring to large magnets in the other ring) within a reasonable volume, whereas high gear ratios may require multiple gearboxes in mechanical drivetrains.

Magnomatics has developed the Pseudo Direct Drive (PDD) [B27], which couples its magnetic gear technology with a permanent magnet motor into a single device. The PDD, shown both as a standalone unit and installed on a remotely operated vehicle (ROV) in Figure 43, is available in 15 kW and 25 kW thrusters. Larger capacities have not been developed, limiting its applications to ROVs, submersibles, and other electrically-powered small vehicles.

Magnetic gearing can also be coupled with electronic controls to form electromagnetics that enable continuously variable gear ratios. Variable ratio magnetic gearing has been demonstrated on road vehicles, and could offer efficiency gains on marine vessels if scaled accordingly.

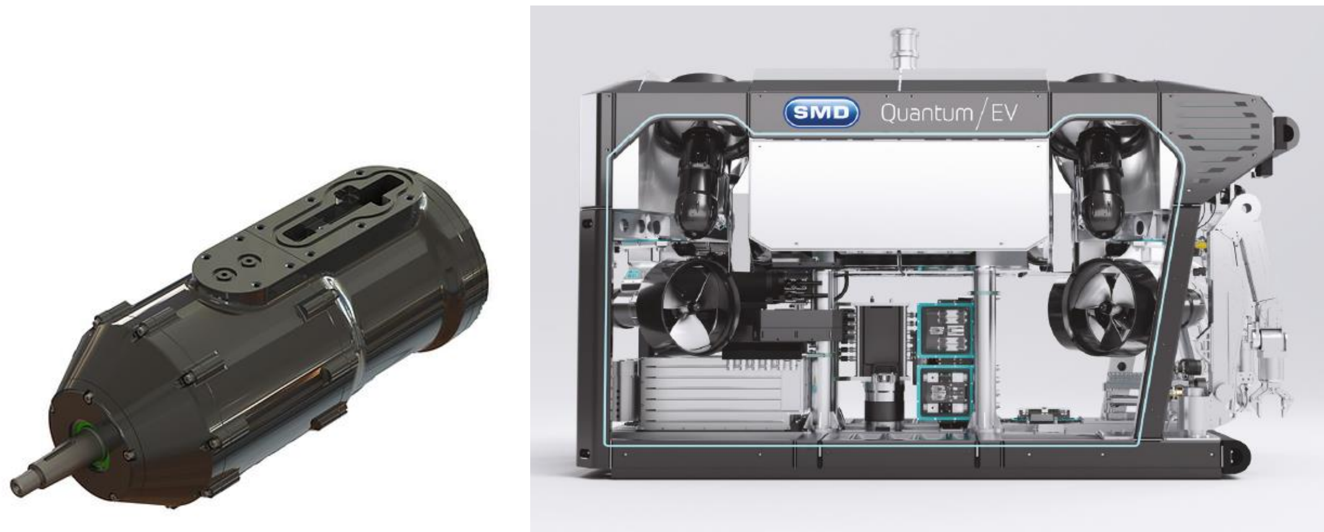


Figure 43: The Pseudo Direct Drive is a combination magnetic gear and electric motor (sources: Magnomatics and SMD)

Magnetic gears or combination gear-motors have not yet been developed for vessel propulsion, but have the potential to improve efficiency and vessel operations. Drivetrain magnetic gears would reduce system losses, noise, and maintenance. Combination gear-motors similar to Magnomatic's PDD could simplify podded and azimuthing propellers and also reduce mechanical losses. Magnomatics is also exploring solutions for wind energy, aerospace, rail, and ocean energy, which could accelerate development a vessel drivetrain solution [B28].

Printed Circuit Board (PCB) Stator Motor

Key Factors

- Motor size and weight significantly reduced with precision printing of copper stators.
- 3 hp motor has been demonstrated onboard a vessel: 66% weight reduction, negligible efficiency gain.
- Developer has stated technology is ready for up to 15 kW motor size.
- Multiple PCB stators and rotors may be stacked to increase torque and power.
- Further development/testing required to demonstrate efficiency improvements at commercial scale.
- If scalable to large (>15 kW) motors, weight reductions alone could appreciably reduce vessel energy.

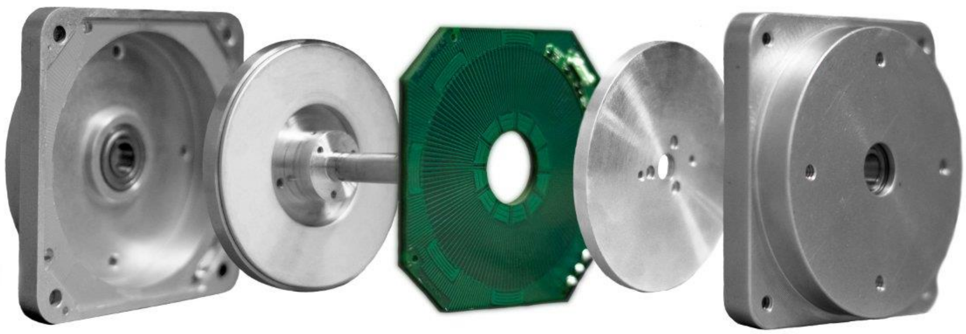


Figure 44: PCB motor stator assembly (source: Maritime Executive)

Conventional motor windings are constrained in their load capacity by uniform wire diameter and geometry, and are not space or weight efficient. By using printed circuit board (PCB) technology, geometries and winding patterns consisting of copper-etched conductors can be optimized in stators to reduce weight, improve efficiency, and improve motion quality (by eliminating cogging between rotor magnets and stator slots). ECM, a leading developer of PCB stators, uses a proprietary software called PrintStator to turn customer motor requirements into an optimized stator design [B29]. By coupling algorithm-based software with PCB fabrication, a custom motor can be designed and built rapidly. The printed copper stator can be made ultra-thin while still containing precise copper geometries, encapsulated in PCB composite material. A comparison of a PCB stator motor geometry to conventional induction and brushless DC motors (BLDC) is shown in Figure 45. The PCB resembles a thin disc, taking up less space and considerably less weight and materials.

While PCB stator motors do increase the radial size over a conventional motor, ECM indicates that multiple stator/rotor disc assemblies can be stacked on a single shaft to multiply torque within a radial area and volume normally occupied by a conventional motor. A stacked assembly is shown in Figure 46.

Figure 45: PCB stator motor geometry compared to conventional motor types (source: ECM)

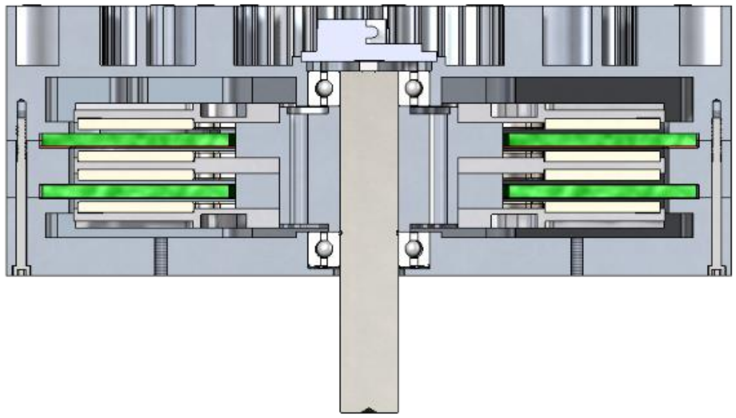


Figure 46: Stacked PCB stators within one motor housing (source: ECM)

A feasibility study on the Training Ship *Kennedy* replaced a 3 hp air handler motor with a 3 hp PCB stator motor supplied by ECM. The project demonstrated the technology's readiness for marine installations and reported a 66% equipment weight reduction (15 kg compared to 45 kg). Efficiency was not appreciably improved, which ECM attributed to internal motor losses that could be improved and the use of a standard motor controller rather than a fast-switching controller [A43]. A comparison of the motor designs and installed arrangement is shown in Figure 47. ABS collaborated on the project and issued a statement of maturity for the technology.

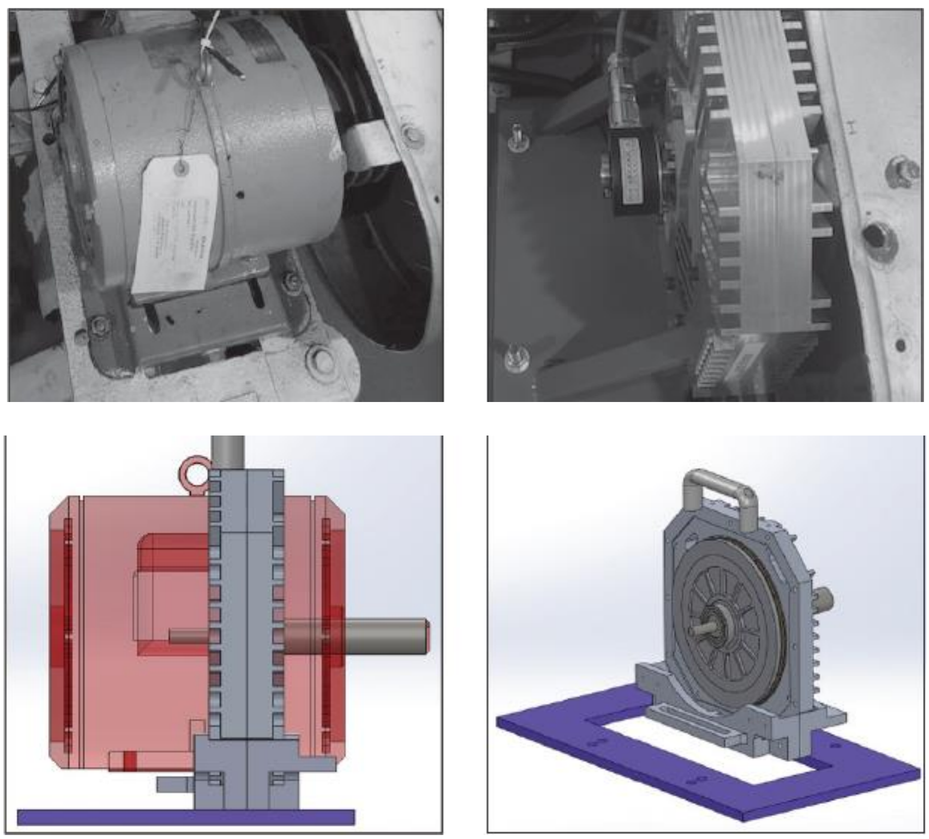


Figure 47: Conventional air handler motor replaced with PCB stator motor on the Training Ship *Kennedy* (source: ECM)

Scaling potential of the PCB stator motors has not been detailed by ECM or other developers. The *Kennedy* air handler study indicates that smaller motors (5 HP and below) could be feasibly replaced with a PCB stator motor. If the technology's fabrication process could be scaled to larger motor sizes (e.g., pumps, fans, winches, hydraulic equipment, or even electrical propulsion), it could play an appreciable role in vessel weight reduction, which indirectly reduces vessel energy consumption. ECM has stated that its technology is ready for manufacturing motors up to 15 kW, and is developing methods to manufacture motors larger than 15 kW.

More testing on integer hp/kW-scale motors is needed to determine whether PCB stator motors reliably increase efficiency.

Link to Guide Navigator

ELECTRICAL ENERGY STORAGE

Navigation:

Hybrid Mechanical/Electrical	Battery (All-Electric)
Supercapacitor Energy Storage (ScES)	Superconducting Magnetic Storage (SMES)
Shore Power	

Electrical energy storage is an important technology enabler that allows other efficiency solutions to be possible. For example, hybrid mechanical/electrical systems utilize energy storage to maximize the efficiency of a vessel's prime mover. Energy storage also allows a vessel to maximize the benefit from other power sources such as wind, solar, regeneration, shore power from the electrical grid, fuel cells, and plug-in (swappable) power packs.

Numerous technological improvements to electrical energy storage have occurred in recent years driven by the growing adoption of electric vehicles, power grid stabilization and frequency regulation, renewable energy, and portable electronics. These parallel development paths have driven down costs and encouraged further adoption. In particular, the cost of batteries has fallen while their storage capacity has been improving steadily. The marine industry is already benefitting from these improvements.

Onboard renewable energy sources, such as wind or solar, are intermittent and cannot be dispatched "on-demand." This can stress the grid when they make up a larger part of the overall energy mix, but energy storage offers a means to address this, allowing a greater capacity of renewable energy sources to be integrated without available power being negatively affected.

New electrical energy storage solutions continue to emerge and mature. Multiple groups are developing offshore charging stations collocated with offshore wind installations to both take advantage of an offshore power generation source and potentially reduce vessel congestion and air pollution in-port. Maersk Supply Service's venture company Stillstrom, in partnership with Ørsted, seeks to develop charging stations at offshore wind farms, with plans to test a pilot installation sometime in 2022 [B30]. A representation of the Stillstrom power buoy is shown in Figure 48. Electrical characteristics such as voltage and capacity (kVA) have not been released. Power buoys that are planned for charging at offshore wind sites could be adapted to anchorage applications to provide shore power while vessels are awaiting an available berth or next voyage instructions. For electrified vessels, this reduces emissions while idle, essentially allowing cold ironing while at anchor. The overall reduction in emissions (Well-to-Wake) depends on whether the buoy-provided power is sourced from renewable inputs such as wind or hydroelectric.

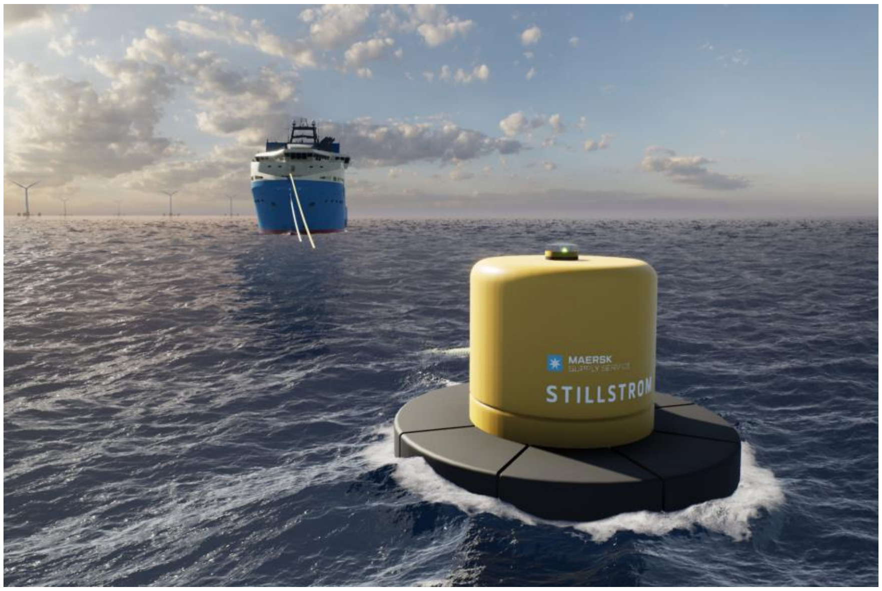
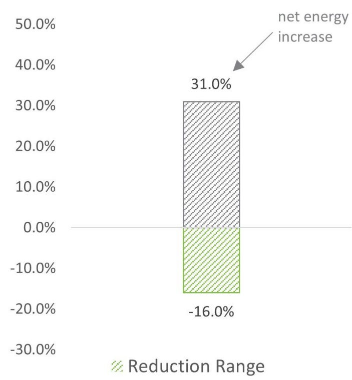


Figure 48: Stillstrom power buoy at Offshore wind site (image source: Maersk Supply Service)

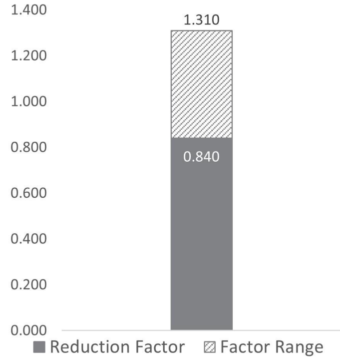
Link to Guide Navigator

Hybrid Mechanical/Electrical

PERCENT REDUCTION



REDUCTION FACTOR (RF_e)



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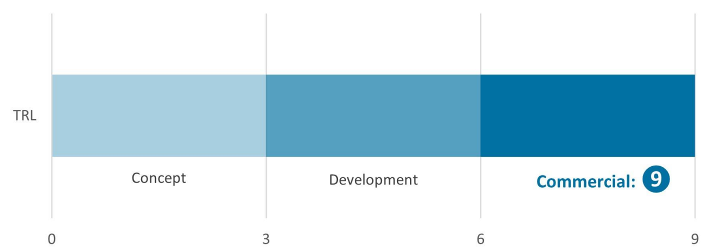


APPLICATIONS

MW	Duty					
>10	Continuous	poor	poor	poor	poor	poor
	Intermittent		marginal	marginal	poor	general
1-10	Continuous	poor	general	marginal	poor	marginal
	Intermittent		general	marginal	marginal	general
<1	Intermittent		general	marginal	marginal	general

MW: Propulsion Power plant size, in MW

Compatibility: general marginal poor

INTEGRATION

		OpEx	CapEx
Newbuild	general	-$/-$$	$$$
Retrofit	marginal		$$$

KEY FACTORS

- Main engines may be downsized if supplemented by electric power
- Overall energy may be increased when using batteries charged from shore
- Phased-in battery capacity is feasible, enabling advanced capabilities
- Class societies now carry notation for hybrid vessels using batteries
- Hybrid not ideal for oceangoing vessels with engine loads already optimized
- Batteries typically installed below deck, displacing machinery and fuel
- Maintenance cost can be reduced by lowering operating hours on ICEs

Link to Dashboard Legend

Overview

Vessels with hybrid powertrains are seeing increased uptake across multiple vessel types and trades. There are many power systems that are described as “hybrid”. For the purpose of clarity in this guide, marine hybrid propulsion refers to propulsion solutions that combine mechanical and electrical elements, including but not limited to energy storage, to optimize efficiency. Hybrid conversions provide a pathway for vessels to meet reduced emissions goals without switching to a new vessel type, and maintaining some elements of a vessel’s existing powertrain and electrical infrastructure.

The battery technologies available for integration in hybrid mechanical/electrical systems are detailed in the next section.

A hybrid system can be configured as “series hybrid” or “parallel hybrid”. Either arrangement may be more appropriate for a given application depending on project goals and vessel specifics. These configurations are described as follows.

Series Hybrid

Series hybrid resembles a diesel-electric propulsion (DEP) plant but with energy storage. This configuration is represented in Figure 49 for a small vessel propulsion system. The propellers are driven entirely by electric motors while diesel-generators (DG) are used to provide propulsion power and auxiliary power. A battery bank or banks can be charged by the diesel-driven generator, shore power, and/or other sources (e.g., wind, solar, shaft regeneration, etc.). The batteries are charged when there is low power demand and discharged when the power demand is high. As such, the diesel engines can operate near their optimal efficiency point under most conditions, rather than having to follow load changes and operating over a range of load points and corresponding fuel efficiencies that are sub-optimal.

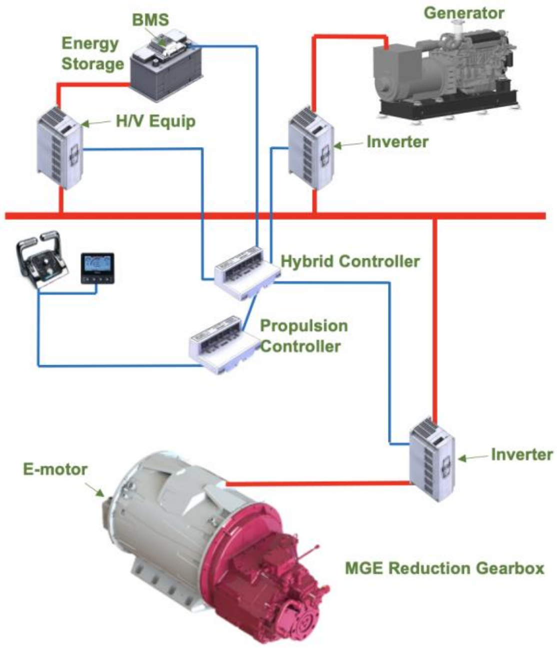


Figure 49: Series hybrid electric plant (source: TwinDisc [B31])

The improved efficiency of a Series Hybrid system comes from the improved efficiency of the diesel-driven generators. Fuel savings can also come from charging the battery bank from shore while at the dock. If other electrical power generation sources are available, such as wind or solar, these too can trickle charge the battery while the vessel is underway to offset fuel consumption.

Parallel Hybrid

A parallel hybrid system blends elements of a conventional propulsion system with a small diesel-electric system. This configuration is represented in Figure 50 for a small vessel propulsion system. Parallel hybrid is well-suited for applications where there is a large range of power demands for propulsion or other auxiliary loads, with multiple operating modes that differ significantly in their power demand. In some cases, this is also considered a hybrid propulsion system in that it combines multiple mechanical inputs to propellers.

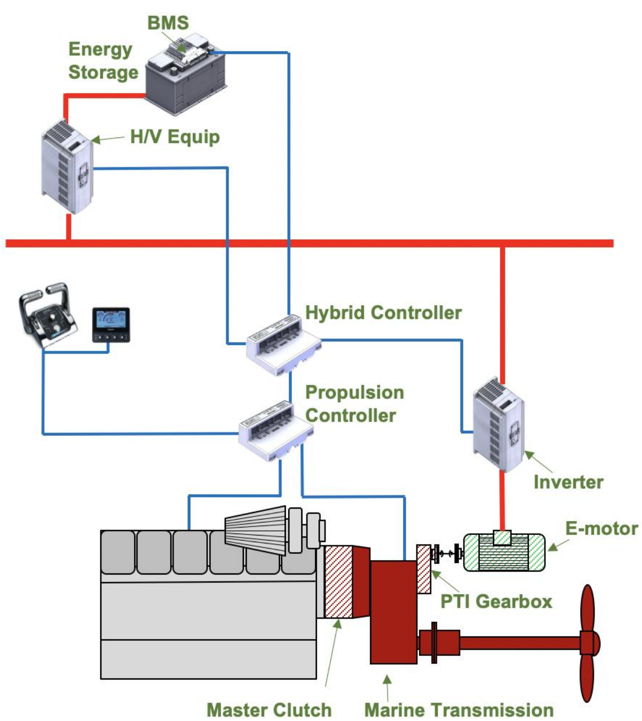


Figure 50: Parallel hybrid electric plant (source: TwinDisc [B31])

Link to Guide Navigator

Harbor-assist and escort tugs are prime candidates for a parallel hybrid configuration. These vessels are used for moving and braking large oceangoing vessels and typically require high-power diesel engines, driving large-diameter propellers, to provide the significant thrust forces to control the vessel under assist. However, peak power is only needed around 5 to 15% of the vessel's operating time with the remainder of the time spent transiting at low power or loitering. A parallel hybrid system is well suited to this task since it can allow the vessel to operate partially or fully on battery when transiting or loitering, producing little to no emissions and low noise. When peak power is needed, the main engines and electric motors can work in parallel to deliver an added boost of power. **In some cases, this can allow the main engines to be downsized due to the supplemental power provided by the electric motor**.

As with the series hybrid system, efficiency can be gained by operating all the diesel engines (auxiliary diesel-generators and propulsion) at their optimal efficiency point. Fuel can also be saved by charging the batteries from shore or with an alternative electrical power generation source.

In some cases, the parallel hybrid concept is used without the energy storage option to lower cost. This can still be an attractive option from an emissions and energy savings point of view and can be planned for a future retrofit with batteries.

Reduction Potential (as % of total energy demand): -16 to +31%

- The reduction potential spans both Series Hybrid and Parallel Hybrid. It is referenced from a baseline non-hybrid vessel, either diesel-electric or diesel-mechanical (geared or direct) drive.
- Reduction savings depend on size of energy storage plant (as supplement for peak-shaving or full electric operation), and the availability of shore power to charge batteries in lieu of charging from onboard diesel-driven generators.
- Washington State Ferries (WSF) is converting 16 ferries to hybrid mechanical/electrical systems. Shore charging is not yet available, so short-term fuel savings are expected to be between 8-16% [C12]. 16% represents the best reduction potential on an energy basis by improving operating efficiency of the propulsion plant and auxiliary loads. **While partial or fully electric power with shore charging would reduce fuel consumption further, it can increase overall energy due to energy losses associated with battery systems**. Battery systems can experience electrical losses through the following: shore cabling (in case of shore charging), AC switchboards and transformers, charging rectifiers, thermal losses in the batteries during charging, thermal losses during discharging, and DC bus losses. This is represented by the 31% energy increase, discussed in the Reduction Potential portion of the next section on Battery (All-Electric).

TRL: 9

- **Many hybrid installations, such as the *Stena Jutlandica* (IMO no. 9125944), are being phased in for battery capacity, with range or power output increasing in staggered installations [C13]**.
- *Vision of the Fjords* (IMO no. 9784192) was delivered in 2018 as a diesel-electric hybrid that can operate propulsion on 100% battery power, and was classed by DNV [C14].
- *CWIND Pioneer* was delivered in 2021 as a crew transfer vessel coupling hybrid mechanical/electrical power with air cushion technology to further reduce propulsion energy, and was classed by Bureau Veritas including Electric Hybrid notation [C6].
- **Several classification societies carry a notation for hybrid mechanical/electrical vessels, for example: "DNV Battery(Power)" and "Bureau Veritas Electric Hybrid".**
- Many packages enabling hybrid operation exist, with vessel demonstrations planned or in operation. Siemens, ABB, Ingeteam, and others offer power electronics to integrate energy storage and propulsion equipment. Most approvals are on an individual vessel basis, though commercial approval of technologies is expected to grow quickly.
- Planned commercial projects such as the WSF electrification will bring hybrid mechanical/electrical to full commercial readiness in coming years.

Applications

- Best suited for inland and coastal vessels with frequent stops to allow for charging. Work boats that loiter or are at dock are also candidates for hybrid drivetrains.
- **Uptake increasing for service operation vessels (SOV) and crew transfer vessels (CTV), to enable low or zero emissions service to wind farm installations.**
- As energy density increases and cost decreases with battery advancements, more vessels will be compatible for newbuild hybrid or retrofit.

- **Oceangoing vessels with long ranges not ideal for integration due to low power density of batteries used in hybrid arrangement, and diesel propulsion engines already optimized for efficiency at the dominant load.**

Integration & Cost

✓	**general compatibility for newbuild**	$$$	**significant newbuild CapEx**
○	**marginal compatibility for retrofit**	$$$	**significant retrofit CapEx**
		-$/-$$	**moderate to significant OpEx savings**

- **At low energy density, battery storage requires large volumes below deck, displacing machinery and fuel storage.**
- Best-suited for newbuild vessels with arrangements and electrical systems designed specifically for hybrid power.
- Power electronics for hybrid mechanical/electrical may actually be smaller than conventional DEP equipment. A diesel-electric vessel is more readily retrofitted to hybrid than a diesel-mechanical, which may not have appropriate space available in the right locations. Large vessels are more suitable as their machinery spaces allow for more flexibility, as demonstrated on the WSF electrification project.
- Equipment costs, particularly for energy storage, are very high. Similarly, power electronics are more expensive than equivalent capacity DEP equipment. Costs continue to improve with technology advancements and production scale.
- Weight to store energy is increased by switching to batteries in lieu of liquid fuel.
- **Maintenance cost can be reduced by lower operating hours on main diesel engines and diesel-generators.**

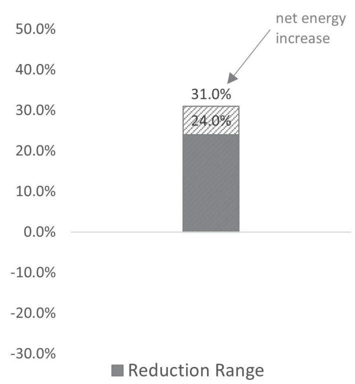
Useful Resources

- ABS: Guide for Hybrid Electric Power Systems for Marine and Offshore Applications [A44].
- ABS: Practical Considerations for Hybrid Electric Power Systems Onboard Vessels [A45].

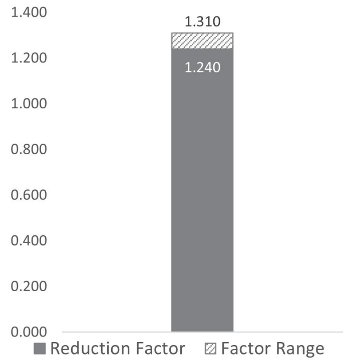
Link to Guide Navigator

Battery (All-Electric)

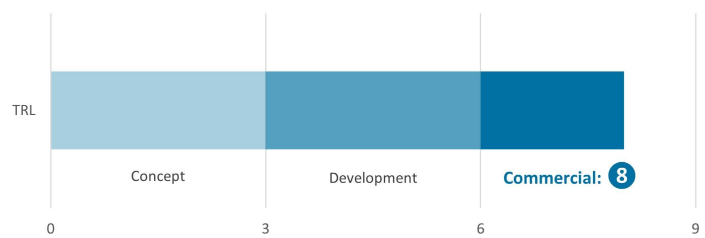
PERCENT REDUCTION



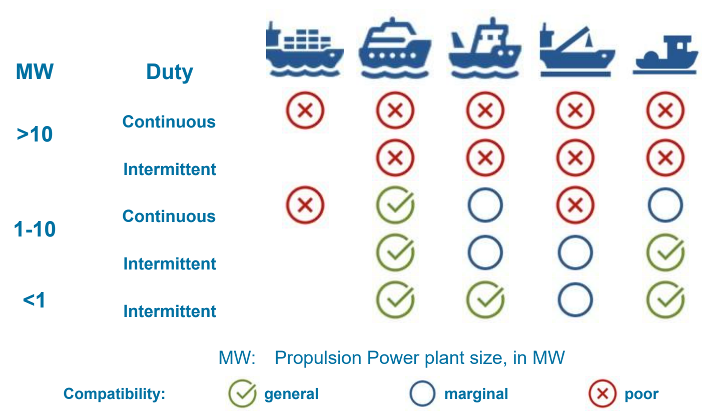
REDUCTION FACTOR (RFe)



TRL



APPLICATIONS



INTEGRATION

		OpEx	CapEx
Newbuild	✓	-$/-$$	$$$
Retrofit	○		$$$

KEY FACTORS

- Charging infrastructure may dictate amount of battery capacity needed
- Source of power for grid charging impacts overall emissions reductions
- Li-ion batteries have been selected for short routes with charging at dock
- Flow batteries have potential to be more scalable across marine trades
- Full-battery systems increase total energy needed, estimated at 24-31%
- Type approved battery systems exist for Li-Ion and LiFePO manufacturers
- Rapid charging at shore may be necessary but shortens battery life

Link to Dashboard Legend

Overview

Battery (all-electric) vessels have matured quickly in recent years and have numerous deployments globally. As battery costs come down, they will increasingly be included in power plants for full propulsion power, as well as efficiency optimization. While lithium-ion batteries currently dominate in marine installations, a multitude of other chemistries might have potential to become commercially viable and see uptake as energy storage options.

For niche applications, batteries can provide a full energy storage solution, allowing a vessel to achieve zero tank-to-wake (TtW) emissions during operation. In these cases, the stored energy is used for both propulsion and auxiliary power. The battery system must provide adequate energy for at least one trip, if not multiple round trips. Shore charging can occur when the vessel is at the dock. **Charging infrastructure must be carefully considered to fit the vessel's operational needs, and may dictate the amount of onboard storage required if charging cannot be made available at one or multiple routine docking points.** A representative topology of all-electric is provided in Figure 51.

While an electric vessel has negligible TtW emissions, and high 'round-trip' battery efficiency (defined later in this section), the grid-based electricity for battery charging may have a thermal efficiency that is comparable to or worse than a marine diesel engine. Average thermal efficiency for US non-renewable electrical plants is estimated between 30 and 44%, as shown in Figure 52 [A47]. This compares to thermal efficiencies between 40% and 50% for marine diesel engines, as shown in Figure 53 (or up to 55% for the largest, most efficient slow-speed engines).

There are several potential efficiency losses between grid power generation and the vessel's propeller:

- 6% transmission losses in US electrical infrastructure (based on 94% average efficiency [A46]).
- 5-10% round-trip battery charge/discharge losses, including both charging equipment losses and internal battery losses (assuming 90% efficiency for a given battery type and use).
- 5-10% losses between battery output and propulsion shaft (via drives, converters, shafting, gearing). These potential losses are characterized in Part 4, Case Study 3 and Case Study 4.

These electrical losses result in an increase in energy consumption for all-electric power, not a reduction.

When combined with a grid thermal efficiency of up to 44%, about 33 to 35% of a non-renewable energy source is transmitted to the propeller in a battery-powered vessel. For a typical 4-stroke diesel-mechanical vessel with up to 45% thermal efficiency and about 2% transmission (shafting and gearing) losses, about 44% of the fuel energy is transmitted to the propeller. This disparity highlights the importance of the electricity source for achieving emissions reductions with battery-powered propulsion.

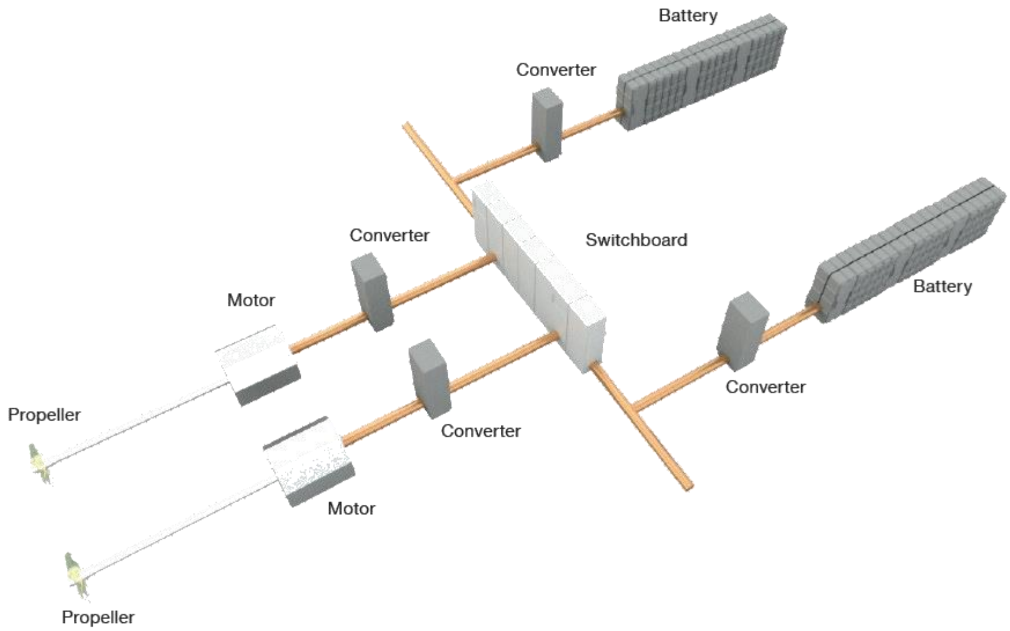


Figure 51: Typical battery (all-electric) topology with AC switchboard (source: MAN-ES)

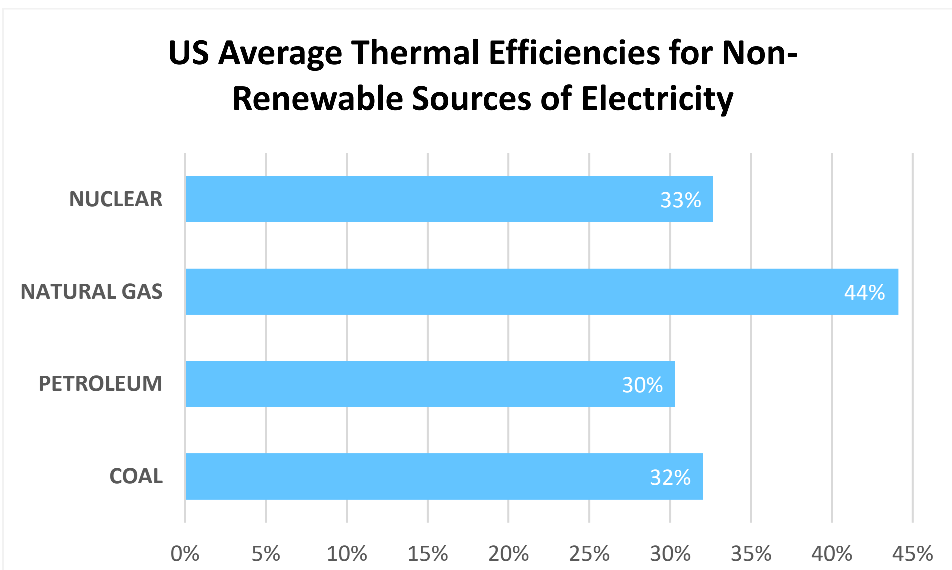


Figure 52: Thermal efficiencies for US non-renewable grid power, 2020 (source: Energy Information Administration (EIA))

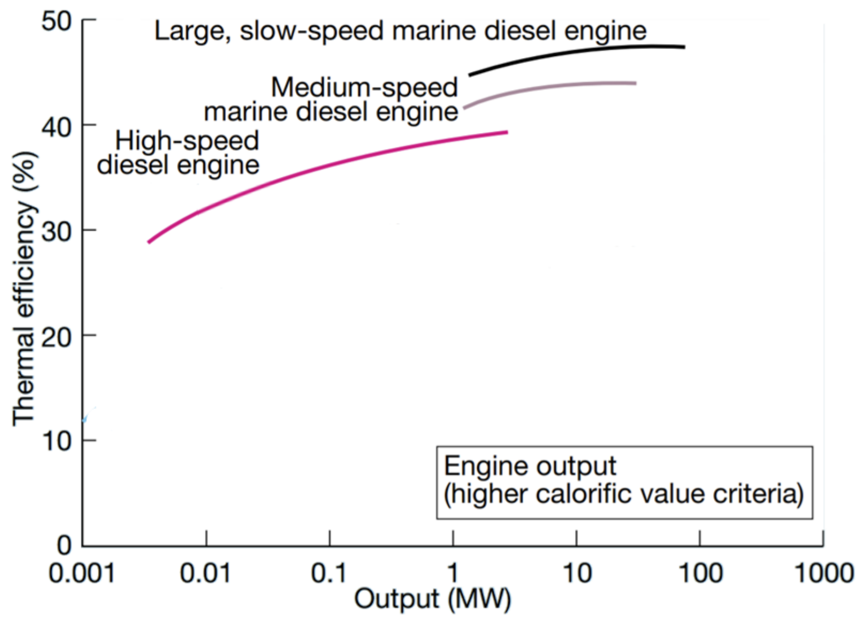


Figure 53: Thermal efficiencies of various size marine diesel engines from 2010 (source: adapted from MHI Technical Review).

In 2021, the US electrical grid was about 39% renewables and nuclear (with negligible greenhouse gas emissions), while the remaining energy came from fossil sources: natural gas, coal, and petroleum. This breakdown is shown in Figure 54. **The source of power available for grid charging of an all-electric vessel will directly impact the overall emissions reductions of that vessel**. Utility power that is partially or wholly sourced from renewables will have a corresponding energy savings as related to GHG release. As grid power becomes more influenced by carbon-neutral sources, all-electric vessels' reduction in GHG-emitting energy will improve accordingly.

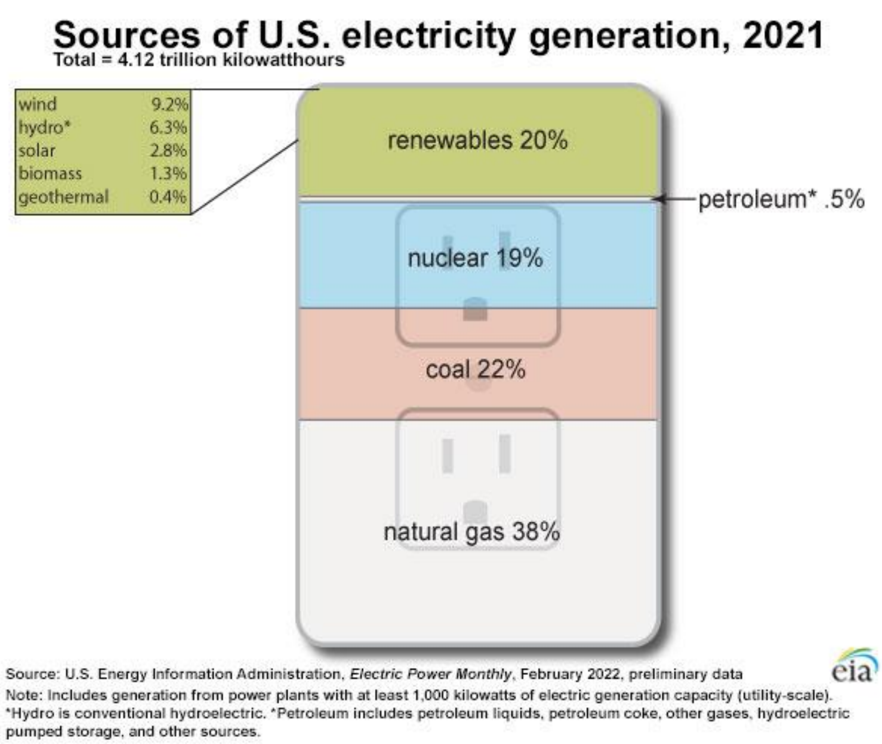


Figure 54: US distribution of grid energy sources (source: EIA)

Key characteristics that should be considered when evaluating battery options for an installation are described in Table 7.

Table 7: Key battery characteristics

Name	Unit	Description
Specific energy	Wh	The amount of energy that can be stored for a given weight (kg).
Power	kW or MW	The amount of peak power that is available from a battery for a given weight or volume.
Round-trip efficiency	%	The amount of energy released from a battery compared to the energy put into the battery. It is usually expressed as a percentage. For example, if 1 kilowatt-hour of energy is put into a battery when it is fully charged, and 0.9 kilowatt-hours of energy are released when it is fully discharged, then the battery has a round-trip efficiency of 90%. Most energy loss is through internal resistance and comes out as heat. The efficiency depends on other operations conditions, including how quickly it is charged or discharged.
Capacity	amp-hours, kilowatt-hours, or megawatt-hours (for very large batteries).	The coulometric capacity, or total amp-hours available when the battery is discharged at a certain discharge current (specified as C-rate) from 100% state-of-charge to the cut-off voltage. Capacity is calculated by multiplying the discharge current (in amps) by the discharge time (in hours) and decreases with increasing C-rate.
Cycle life	Discharge cycles	The number of discharge-charge cycles the battery can experience before it fails to meet specific performance criteria. Cycle life is estimated for specific charge and discharge conditions. The actual operating life of the battery is affected by the cycle rate and depth of discharge, as well as other conditions such as temperature and humidity. A higher depth of discharge corresponds to a reduced cycle life.
Cost	$/kWh	The cost must be understood as cell cost, pack cost, module cost, or system cost. System cost in the most important to understand because it includes the electrical processing and monitoring equipment needed to operate the system. The cost can vary widely, but USD$500 to USD$1,000/kWh is a generally accepted range for marine batteries to-date depending on the size and complexity of the system [A48].
Safety	None	Stored energy comes with the inherent risk of sudden, unexpected release of that energy due to a failure in the system. Battery technologies vary greatly, and therefore the risks associated with different types of batteries are different. The risk concern with batteries is smoke and fire or toxic chemical release which can be an extreme hazard on a ship. When selecting a particular type of battery, it is important to understand the potential safety issues that it presents in the application and the marine environment in general. Regulations surrounding battery storage have not kept up with the advancements of battery technology. Due diligence beyond regulatory requirements is necessary to ensure safe design and operation of batteries.

Lithium-ion batteries are the dominant commercially developed battery chemistry for marine applications, largely due to their high energy density (gravimetric and volumetric) coupled with favorable cycle life characteristics, as well as the maturity of corresponding safety and energy management systems. A comparison of Lithium-ion energy density to other common chemistries is provided in Figure 55.

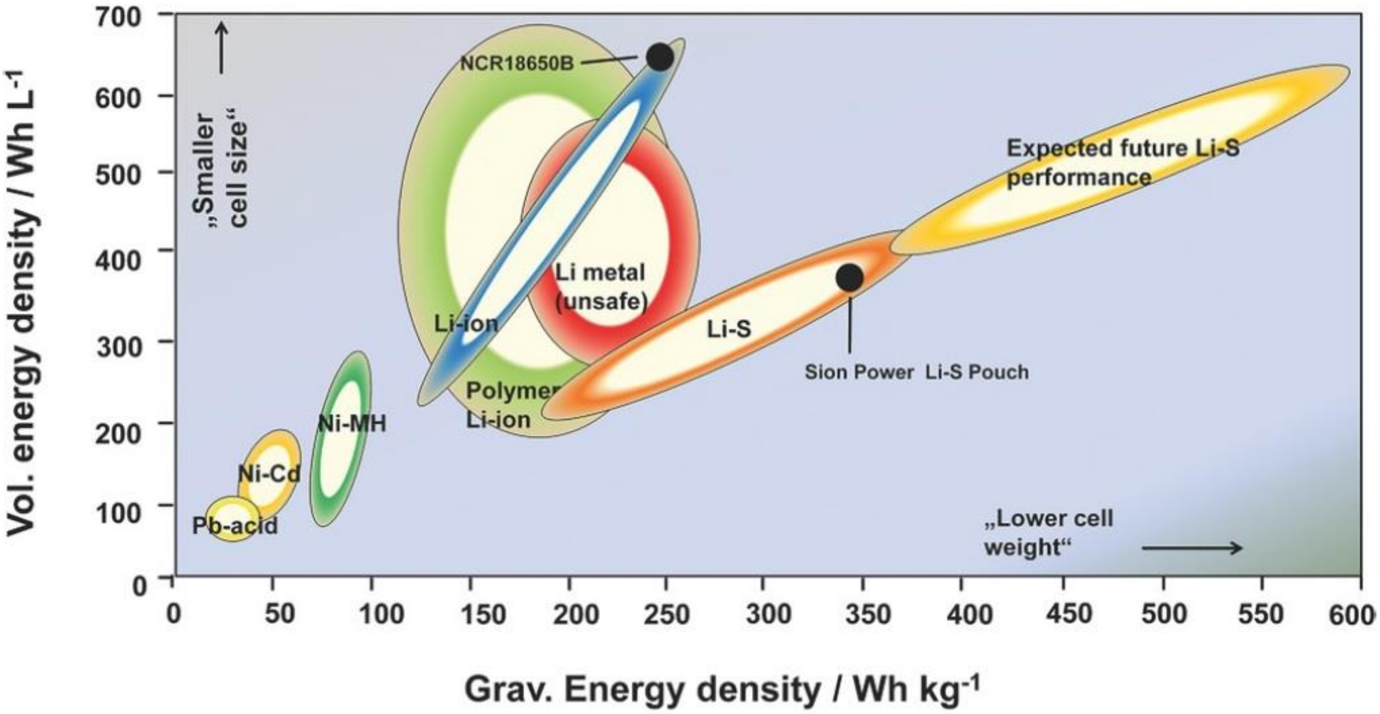


Figure 55: Energy density comparison of various battery chemistries (source: Hagen, et al.)

Praxis Automation Technology has developed a lithium-iron-phosphate (LFP) battery system for marine vessels, and received type approval from DNV in 2021 [B32]. The Praxis system was installed on its first vessel in 2022, the hybrid aquaculture support vessel *Maurel* that uses an in-line motor/generator for battery charging and discharging [C15]. There has not been broader uptake of LFP yet. Lithium polymer batteries are seeing increased uptake in the auto EV industry, but are not currently being scaled for commercial vessel power.

Nascent battery technologies with potential for future uptake are also overviewed in this section:

- Sodium sulfur.
- Zinc hybrid cathode (Znyth™).
- Flow Redox.

Lithium-Ion

Much like the batteries of the portable electronics industry, all-electric vessels typically employ lithium-ion (li-ion) battery chemistry. They are ideal for transportation due to their high energy and power density, and their relatively high cycle life (including resistance to memory effects). Historically, li-ion batteries have been quite expensive, but recent improvements and economies of scale from the electronics and automotive sectors have helped drive down cost. An increasing number of suppliers have developed systems specifically for the marine market.

Li-ion batteries are most often selected for vessels that run short, repetitive routes to allow for charging between runs as the vessel's range is limited by the battery capacity onboard. Batteries have already been deployed as 100% of power on passenger ferries, car ferries, catamarans, and a short-sea, 2,000-ton coal carrier in China.

The three primary Li-ion battery chemistries are nickel-manganese-cobalt (NMC), lithium-iron-phosphate (LFP), and lithium-titanate-oxide (LTO). Some key characteristics for these battery chemistries are compared in Table 8. NMC is the most prominent chemistry being used in all-electric and hybrid-electric propulsion, and also has the highest specific energy of the three. However, LFP and LTO both have certain advantages in terms of life cycle and safety, which are also important characteristics for implementing on a marine vessel. LTO uses expensive materials, but has a high cycle life and is generally more stable than the other chemistries.

Table 8: Li-ion chemistry comparison

Chemistry	Specific Energy (Wh/kg)	Cycle Life	Safety	Capital Cost
NMC	150 – 220	1,000 – 5,000	relatively unstable	high

Chemistry	Specific Energy (Wh/kg)	Cycle Life	Safety	Capital Cost
LFP	90 – 160	3,000 – 5,000	stable	moderate
LTO	50 – 80	3,000 – 7,000	very stable	high

100% repower with li-ion batteries has also been proven in the US, with the *Gee's Bend Ferry* in Gees Bend, Alabama being retrofitted with 2 banks of 135 kWh batteries and new electric propulsion motors. The ferry, shown in Figure 56, has been in operation since 2019. The Gee's Bend route is ideal for battery power, as the cross-river transit is very short, and charging infrastructure could be installed at both terminals. The battery capacity was sized to charge on only one side, providing flexibility in the event of charging equipment downtime on one side or the other. The *Gee's Bend Ferry* has NMC batteries coupled with 480 VAC induction motors for propulsion.

Figure 56: ***Gee's Bend Ferry*, the first all-electric ferry to operate in the US (source: workboat.com)**

Larger projects are now being planned including Stena Line's *Stena Elektra*, a 215-meter RoPax vessel with 70 MWh of battery capacity, shown in Figure 57 [C16]. The project is on a longer time scale, with vessel order planned by 2025 and delivery by 2030.

Figure 57: Rendering of Stena Line's all-electric RoPax, *Elektra* (source: offshore-energy.biz)

Not all li-ion battery-types are inherently safe. For many, the safety is managed by a sophisticated control and monitoring system that constantly looks at battery conditions and can shut them down if anomalies occur. Integrating batteries on a marine vessel must be done with an understanding of the inherent risks and failure modes of the particular chemistry. In most cases, battery storage compartments require specific gas monitoring, fire monitoring, and suppression systems; these should be designed in cooperation with regulatory bodies and in accordance with applicable rules and regulations. Several high-profile vessel battery fires have highlighted the importance of rigorous safety and detections to be in place.

Other Chemistries

Several battery chemistries are developing rapidly, but have generally not been configured, tested, or evaluated as marine power systems. These include sodium sulfur, zinc hybrid cathode (e.g., Znyth™), and flow redox batteries. Each offers unique levels of energy density, cycle life, safety, and cost, and could be matched to vessel applications once risk assessments for marine operation have been carried out, and required safety measures are well-defined. A few of these battery types are discussed below.

Sodium Sulfur. At first glance, these batteries seem quite attractive for large-scale energy storage on a ship. They are widely used for very large grid-scale storage projects (multi-MWh). They have a high round-trip efficiency, high energy density, long cycle life, and a low cost. However, they operate at a high temperature (300-350ºC) and contain molten sodium, which is highly flammable in oxidizing atmospheres like air or water. Use in a marine application is not recommended without a complete risk analysis and development of chemistry-specific safety systems.

Zinc hybrid cathode (Znyth™). This early-stage battery technology under development by Eos Energy Enterprises is claimed to be a solution with very low cost, long cycle life, high energy and power density, high efficiency (80%), and inherently safe chemistry. Eos Energy claims the chemistry does not require any temperature conditioning and is nonflammable. Their initial product is a containerized battery system that is highly scalable, capable of 10 MW output from a single container. The technology seems suitable for medium- to large-scale marine storage applications but is still unproven and Eos is not publicly targeting marine applications [B33].

Redox Flow Batteries. Redox flow batteries are similar to fuel cells but reversible and consist of a closed process loop. In a flow battery, two chemicals are stored in separate containers, which are separated by a membrane. During discharge they are pumped through a membrane and produce a current. During charging, the process is reversed. There are many different types of flow batteries, and it is an area of significant research and development. Flow batteries do not have a limit on cycle life and their capacity can be scaled by increasing the storage tank size. These characteristics make flow batteries an interesting prospect for marine applications.

Flow batteries are characterized by moderate efficiency, moderate power density, moderate energy density, and low cost. A possibly arrangement would be for the flow fluids to be charged shore-side and bunkered to tanks on the vessel, like a fuel. **This could enable zero emission vessels that are more scalable, as the energy would be stored in hull tanks rather than** battery banks. The developer Portliner is specifically targeting marine applications. Their vanadium redox flow battery system, called an "electro engine", converts charged electrolyte energy into electricity. The electrolyte anolyte and catholyte, stored at ambient pressure and temperature, flow through half cells to generate electricity for powering an electric vessel [B34]. Portliner has developed 52-meter and 110-meter vessel concepts powered by redox flow battery plants.

Figure 58: Portliner 52-meter cargo ship concept, powered by flow batteries (source: Portliner)

Reduction Potential (as % of total energy demand): +24 to +31%

- Reduction potential estimated for li-ion battery systems. Other future batteries may have different energy efficiency characteristics and corresponding energy potentials.
- **Due to added losses in electrical transmission from electrical source (grid power or otherwise) to propeller, marine battery power actually increases the total energy needed.**
- **Assuming 6% grid transmission loss, 10% roundtrip charging efficiency (both charging and battery internal efficiencies), and 5 to 10% onboard mechanical and electrical conversion losses, total energy increase is 24% to 31%.**
- Battery reduction potential is combined with emissions factors for available utility power to determine a CO_2 or CO_2e performance value for all-electric vessels.
- If shore electricity is sourced locally rather than from the grid, such as a local solar power array, transmission loss may be reduced.

TRL: 8

- Battery power systems continue to be developed for and deployed on marine vessels. However, integration design and regulatory approval varies project to project, particularly in the US, due in part to limited marine approvals and the absence of a well-defined regulatory framework from USCG.
- Uptake in Europe is ahead of the US, with dozens of all-electric vessels in operation. As such, US shipyards are lagging in experience building/retrofitting vessels with battery power systems.
- **Energy storage system manufacturers Corvus, Leclanché, and Spear have li-ion batteries type approved by DNV and other class societies [B35][B36][B37]. Corvus systems have been installed on numerous classed vessels, and the company has a long order book for upcoming installations.**
- **Becker Marine Systems and Praxis Automation Technology have LFP energy storage systems type approved by DNV [A32][A38].**
- As more type-approved battery packs and systems become available, the regulatory process for electric vessel approval will improve.

Applications

- Full all-electric uptake has primarily been on passenger vessels with short, routine transits and reliable electrical infrastructure.

- **Rapid charging is often required for the operations of battery-powered vessels, but this practice actually shortens the overall life of many batteries (degradation/aging), including Li-ion. Overnight slow charging is preferred.** Charging frequency and operations will need to be carefully considered, as will the realities of backup generators in the event of equipment failures.
- Norled's *MF Ampere* (IMO no. 9683611) operates between Lavik and Oppedal, Norway [C17]. The 80-meter (262 feet) vessel carries 120 cars and 360 passengers on the 9 km route, transiting 34 times per day. The vessel has two 520 kWh battery packs on board and each shore charging station has a 410kWh battery pack to improve charging capabilities and simplify power infrastructure requirements. *Ampere*'s electrical architecture is shown in Figure 59.
- Asahi Tanker's bunker vessel *Asahi* (IMO no. 9952270), delivered in early 2022, is demonstrating full all-electric propulsion for short-distance cargo vessels [C18]. The new vessel, shown in Figure 60, has 3.5 MWh of energy storage, and an estimated range of 100 km.

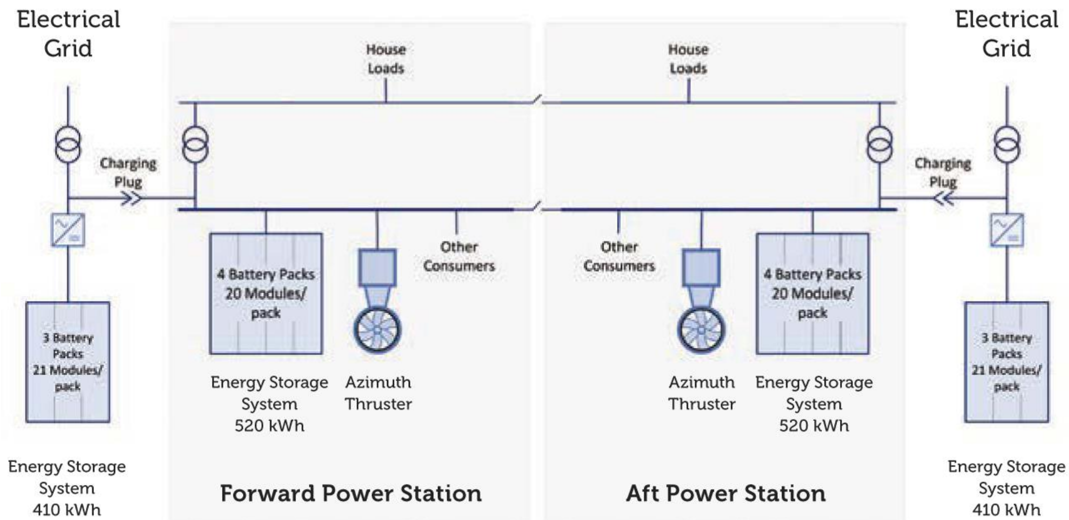


Figure 59: Line diagram of the Ampere drive systems (image courtesy of Corvus Energy)

Figure 60: Asahi Tanker's all-electric bunker tanker was delivered in early 2022 (source: Reuters)

Link to Guide Navigator

Integration & Cost

✓	general compatibility for newbuild	$$$	significant newbuild CapEx
○	marginal compatibility for retrofit	$$$	significant retrofit CapEx
		-$/-$$	moderate to significant OpEx savings

- All-electric systems can have high CapEx, partially offset by the elimination of mechanical systems such as fuel oil, lubricating oil, and engine starting.
- **Battery systems generally reduce OpEx, but extent of savings depends on relative cost of electricity and fuel in the region. Commercial batteries have a finite operating life (generally 5 to 10 years, depending on specific design and operating parameters), but have minimal maintenance costs between replacement**.
- Charging infrastructure costs can be significant. Installing shore-side batteries may increase equipment capital cost but simplify upgrades needed to the upstream infrastructure.

Useful Resources

- DNV: A guide to use of batteries in shipping [A49].
- ABS: Guide for Hybrid Electric Power Systems for Marine and Offshore Applications [A44].
- ABS: Practical Considerations for Hybrid Electric Power Systems Onboard Vessels [A45].
- ABS: Guide for Lithium-ion Batteries in the Marine and Offshore Industries [A50].
- ASTM F3353-19: Standard Guide for Shipboard Use of Lithium-Ion (Li-ion) Batteries.
- USCG CG-ENG Policy Letter 02-19: Design Guidance for Lithium-Ion Battery Installations Onboard Commercial Vessels [A51].

Shore Power

Figure 61: Wärtsilä/Cavotec DC shore charging and mooring system with 690VAC input (source: Wartsila)

Key Factors

- **Delivering electrical power from utilities to vessel batteries involves a number of technical and economic challenges**
- **Shore batteries are often appropriate to minimize utility upgrades and lifecycle costs**
- **Physical charging interfaces are complex and not fully standardized**

Overview

There are two main types of shore power: the onshore power supply (OPS), also known as cold ironing, and the shore-side battery charging (SBC). OPS and SBC are defined as follows:

- OPS: Supply of electrical power to ships at berth, directly to the receiving ship, from a shore-side electrical power source, at a given voltage and frequency (AC or DC, LV or HV), feeding the onboard main distribution switchboard. OPS replaces primarily the onboard electricity generation from auxiliary generators.
- SBC: Charging of onboard Battery Energy Storage Systems (BESS) by shore power supply (AC or DC, LV or HV), using a connection protocol suitable for the specific BESS onboard, at a specified charging power.

To understand the challenges associated with shore charging systems, the basic scale of propulsion power and energy consumption needs to be considered. A small ferry might use 100 kWh of energy in 20-30 minutes. This is comparable to the energy used by an electric car over hundreds of miles. A larger car ferry or small cargo vessel can easily require 10 times that energy, consuming multiple megawatts of power. Currently, battery installations sized to store enough energy for a day or week of ship operation would be impractical in terms of size, weight, and cost. This results in typical electric marine vehicles charging between short voyages, instead of overnight as is more common with road vehicles.

This constraint creates a challenge for the shore electrical systems, which must be able to recharge vessel batteries within the timeframe allowed by a ship's operational requirements – such as passenger and car unloading and loading for a ferry. Whereas electric road vehicles might be able to recharge over several hours, battery-electric ships may need to be recharged in as little as 10-20 minutes, depending on the vessel's operations. The combination of high energy use and short charging time results in charger ratings ranging from 2 to 15 MW, one or two orders of magnitude higher than typical passenger vehicle chargers. This results in several safety and interface challenges discussed in more detail below.

Utility Requirements and Shore Batteries

Separate from the vessel design requirements for the vessel and charging equipment, these high charging powers drive impacts on the electrical utilities available and the OPS system. First, utility infrastructure must be checked to see if distribution to the marine terminal is capable of delivering the desired power level. Utility system upgrades could be required to meet the vessels needs or to prevent unacceptable power quality impacts to other utility consumers.

Another consideration is the cost of electrical power. In addition to charging for the energy used, say USD$0.06/kWh, utilities assess demand charges based on the peak power drawn during some monitoring period (e.g., monthly). Costs will vary regionally and based on the specific schedule but could be on the order of USD$10/kW/month. In other words, a vessel that charges at a rate of 10MW could pay a premium on the order of USD$1.2M/year in demand charges in addition to paying for energy consumed, unless a different demand rate is negotiated with the utility provider.

Both economic and infrastructure impacts can be mitigated by implementing shore-side batteries with an SBC system. Shore-side batteries are charged while the vessel is away from dock. During charging of the ship at dock, the shore-side battery system is discharged to the vessel in parallel with utility power to achieve the required charging rate. A combination battery and utility shore charging system topology is shown in Figure 62. This spreads the vessel's energy consumption over a longer period, reducing demand charges and the required rating of the utility supply. Installing and maintaining shore-side batteries increases both capital and operating costs and may be a challenge to arrange in crowded terminals. Nevertheless, it is often the option with lowest lifecycle cost. In the previous example, say shore-side batteries are charged at a rate of 3 MW while the vessel is in operation. The vessel could then be charged at a rate of 7 MW from batteries and 3 MW directly from utility power. Annual demand charges could be reduced from USD$1.2M to USD$360K.

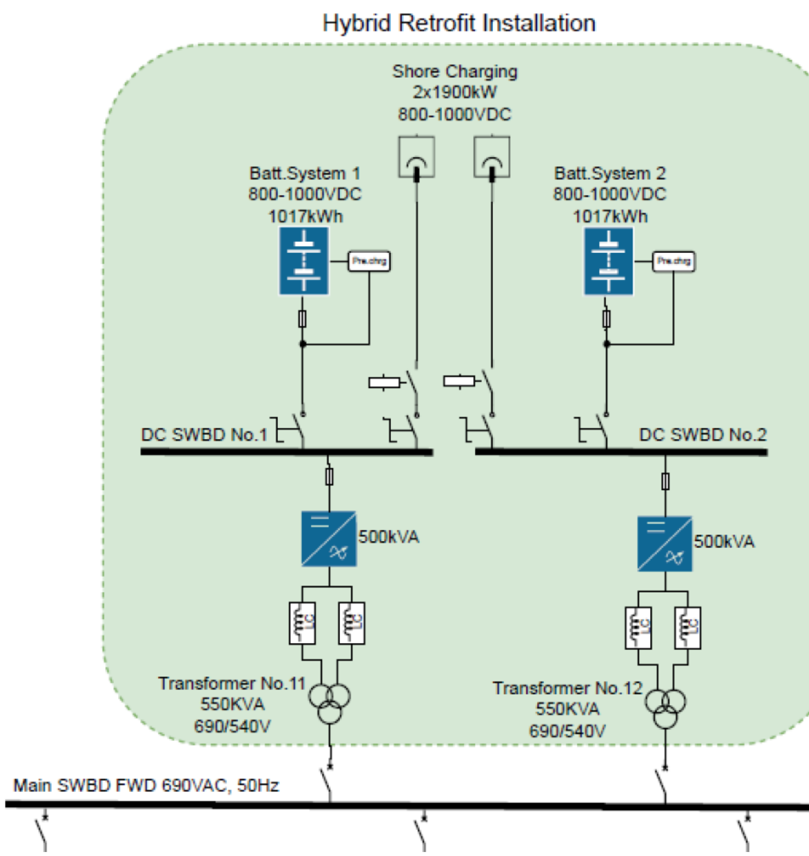


Figure 62: Battery and utility shore charging system (source: Westcon)

Battery swapping (BS) can also be implemented, where battery modules are charged shore-side while the vessel is away from the dock. Then when the vessel docks, discharged batteries are removed from the vessel and swapped with fully-charged, identical battery modules from shore. This system can reduce the complexity of the shore power system, particularly the over-water interface, but requires a specialized vessel design to enable battery swapping.

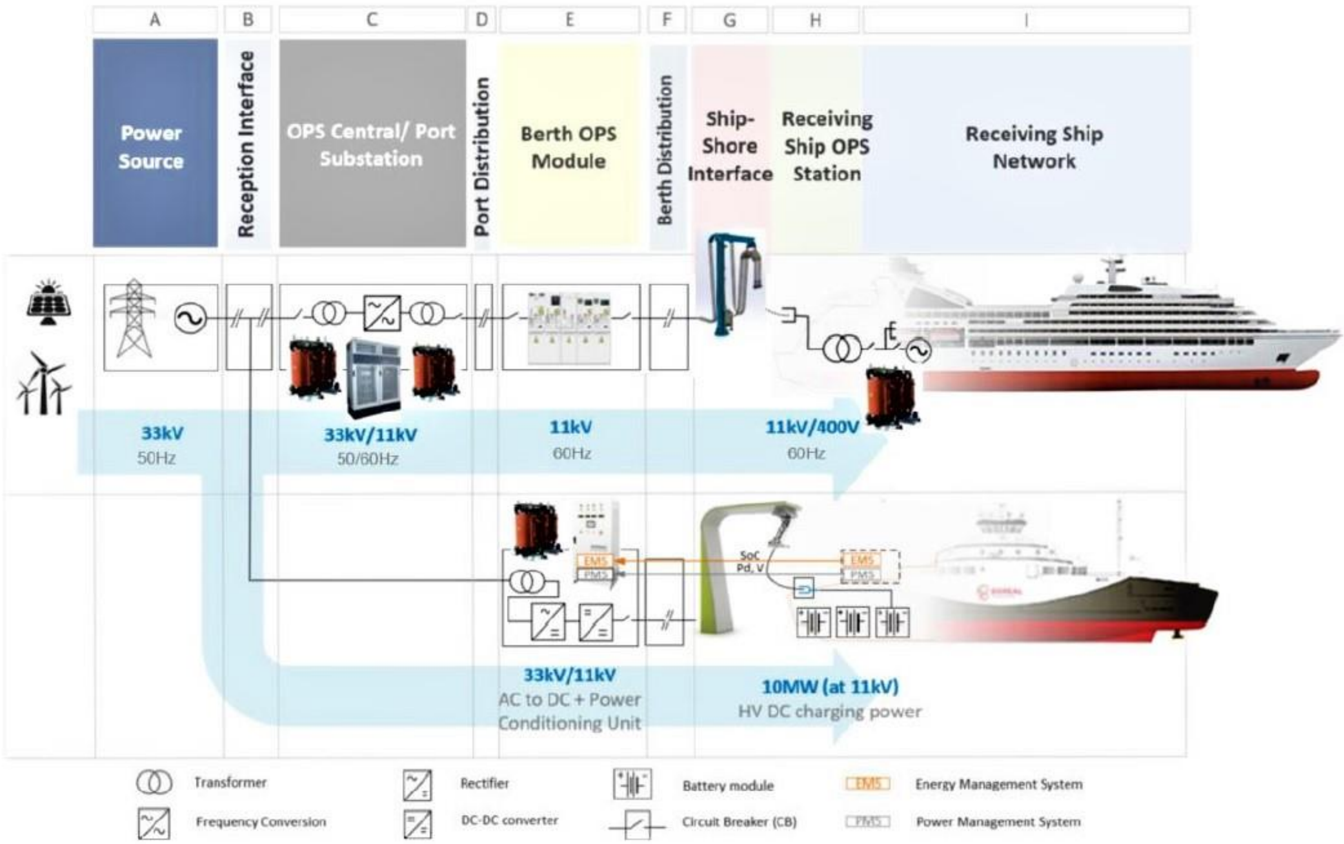


Figure 63: **Generic perspective of key infrastructure elements for shore power (source: EMSA)**

A further challenge to solve with OPS systems is the physical charging interface. In limited applications where overnight charging is feasible, it would be possible to use conventional shore power cables and sockets, if sized appropriately to supply both in-port loads and battery -recharging power. However, most applications will call for rapidly charging during operations. This need for speed and the multi-megawatt scale of the charging operation calls for specialized equipment, such as the Cavotec ferry charging system shown in Figure 64 [B39]. Chargers must be capable of reliably and automatically connecting within seconds of a vessel's arrival at berth – any time spent connecting and disconnecting is time lost from charging, with a corresponding increase in the required power rating and utility demand charges. Automatic operation also eliminates the safety hazards that would be associated with frequent manual handling of plugs and cables.

Automatic chargers must also be designed with consideration for vessel motions. This includes both slow changes such as tidal variation and fast changes such as ship roll, pitch, and heave due to waves. Depending on the vessel and terminal, this may require a charging apparatus that moves with multiple degrees of freedom or reliance on movable marine structures such as ramps and floats.

Bow-loading ferries can present a particular challenge, where limited ship/shore interface space is already allocated to passenger or vehicle movement. Even if an otherwise-suitable position is located in both ship and shore arrangements, arc-flash safety zones around the electrical connection point may encroach on passenger or crew areas.

It may not be feasible to meet all of the above constraints without adding new in-water infrastructure. This should be incorporated into project plans as early as possible, bringing in appropriate civil engineering and environmental consultants to join design teams. Permitting requirements can be critical path and should be identified during project conceptual development.

Figure 64: Cavotec 2 x 1,900 kW, 1000VDC SBC system for e-ferry in Nesodden, Norway, with 690VAC vessel charging (source: Cavotec)

Standardization

Shore power installation should be designed to established maritime standards. The existing and relevant standards for OPS and SBC are provided in Table 9 [A52]. OPS standards are better established than SBC standards, with several IEC/IEEE, IMO, and EN standards in place for OPS installations. High-voltage shore connections (HVSC) in particular have a robust framework of standards: most notable IEC 62613 series and IEC/IEEE series 80005. Table 9 standards are categorized as follows:

- Green represents present/existing standards specific to shore power installations.
- Yellow represents relevant standards that could be applied to shore power.
- Red represents aspects of shore power for which standards are still to be developed.

The IMO Sub-Committee on Ship Systems and Equipment (SSE) is currently finalizing the Guidelines on safe operation of OPS service in port for ships engaged on international voyages, which will further inform the implementation of shore power systems.

Table 9: Shore power standards summary (source: EMSA)

SSE Type		Interconnectivity	Interoperability	Data Communication	International/EU Regulatory
OPS (Onshore Power Supply)	High-Voltage Shore Connection (**HVSC**)	IEC 62613-1:2016 (General) IEC 62613-2:2016 (Connector geometry/ dimensions)	IEC/IEEE 80005-1 (HVSC)	IEC/IEEE 80005-2 (Data Communication)	IMO OPS Guidelines EU AFID
	Low-Voltage Shore Connection (**LVSC**)	IEC 60309-5	IEC/IEEE 80005-3 (under review/development)	IEC/IEEE 80005-2	IMO OPS Guidelines already refer
	LVSC – Inland Waterways (IW)	EN 15869-2:2019 (up 125A) EN 16840: 2017 (above 250A)		Possible application of IEC/IEEE 80005-2	CCNR CESNI – ES-TRIN2019
	Recreational Craft/ Marinas	IEC 60309-2	Not standardized	Not standardized	Not relevant international standard applicable to
SBC (Shore-side Battery Charging)	SBC-AC (AC charging)	IEC 60309-5/ IEC 62613-2 AC connection (As standard OPS connectivity)	IEC/IEEE 80005 series As OPS – ship-side charging.	Not standardized (possible development/ applicability for IEC/IEEE 80005-2 or ISO15118)	No applicable international regulatory instrument applicable to SBC
	SBC-DC (DC Charging)	Not standardized	Not standardized		

Supercapacitor Energy Storage (ScES)

- **Not well-suited as primary energy storage due to low energy density, approximately 1/10 of li-ion batteries.**
- **Multiple possible applications in marine systems for starting systems, managing peak power, and extending battery life.**

Supercapacitor are used as an alternative approach to energy storage, with some key characteristics that differentiate them from batteries. Supercapacitors store energy in an electric field, and are therefore not dependent on temperature in the charging and discharging processes. Supercapacitor Energy Storage (ScES) has some advantages over batteries [A53]:

- High current discharge rate, similar to battery C rating, due to minimal internal resistance.
- High cycle life, in millions rather than thousands of charge/discharge cycles.
- Performance not degraded by charging or discharging under low-temperature conditions.
- Not subject to thermal runaway as oxygen is not released. Combustion could therefore occur at high temperatures, but is not fed with increasing amounts of oxygen to accelerate further combustion.

Capacitors in ScES are arranged similarly to batteries: multiple capacitors are combined in series for a desired voltage and parallel for a current capacity, forming capacitor modules that then manage power characteristics and safety monitoring. These modules resemble battery assemblies, as shown in Figure 65, and are further combined to form banks required for system capacity.

Figure 65: Eaton XLM supercapacitor module (source: Eaton)

ScES can be divided into two primary categories: electric double layer capacitor (EDLC) and li-ion capacitor (LIC). These capacitors are different in the electrode material and type of ions being passed through the capacitor electrolyte.

- EDLC: symmetrical capacitors using the same material for both electrodes with positive and negative ions forming exclusively from activated carbon.
- LIC: asymmetrical capacitors, as a hybrid between a li-ion battery and an EDLC. LIC has a battery-type anode with lithium-doped carbon, enabling higher energy density. It maintains an activated carbon cathode, enabling higher energy discharge. LIC needs to operate a minimum voltage to avoid damaging the capacitor.

A comparison of EDLC, LIC, and li-ion battery processes is shown in Figure 66.

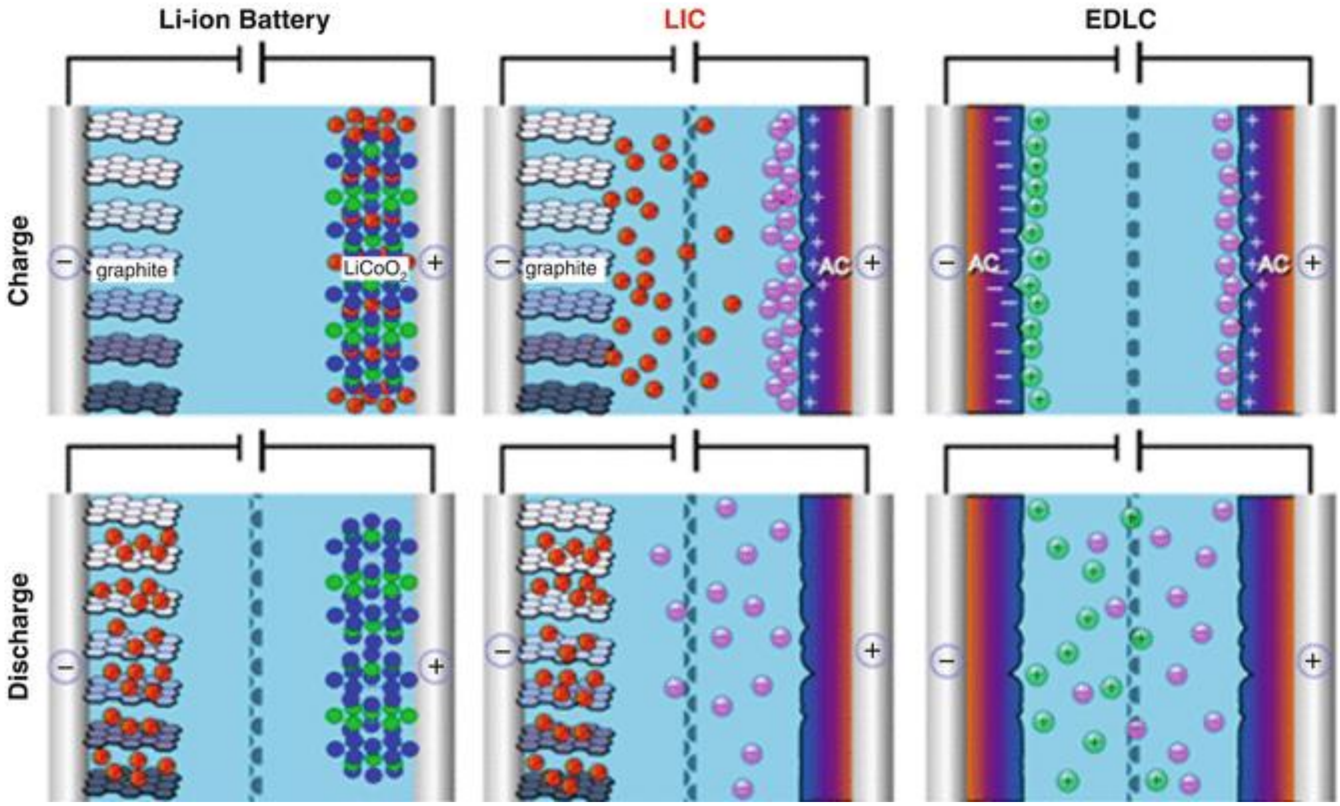


Figure 66: EDLC and LIC supercapacitor processes compared to li-ion batteries (source: Naoi)

While ScES is feasible as a standalone energy source, its low energy density makes it impractical for primary vessel energy storage. Supercapacitor energy density is estimated at approximately 5-10 Wh/kg, compared to 150-220 Wh/kg for li-ion batteries. Its advantages noted above, particularly high energy discharge, make ScES more suitable for integration with other power management processes, supporting power generation or energy storage.

Potential Marine Applications

While current ScES technologies are not well-suited for primary vessel energy storage, there are several system applications where ScES can improve electrical functionality or operating life:

- Engine starting. Supercapacitor tolerance to low temperatures ensures flexible operation in different environmental conditions.
- Peak demand supplement for all-electric or hybrid vessels. Peak battery output capacity of electric vessels may be reduced if supplemented with ScES, and battery life can be extended by not having to accommodate brief pulses in power. A simple network concept for ScES in a hybrid mechanical-electrical plant is shown in Figure 67.
- Dynamic positioning (DP) supplement for offshore and oceangoing vessels would allow for downsizing of diesel-generators (DG) driving propulsion equipment, and enabling faster response to DP commands with high-density power.

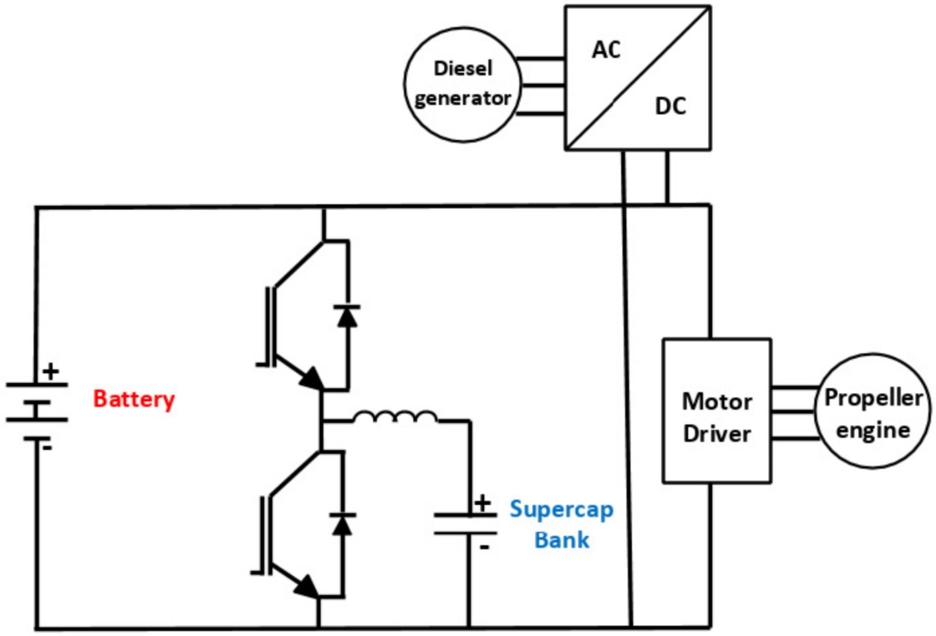


Figure 67: Supercapacitor energy storage in hybrid mechanical/electrical propulsion plant (source: Eaton)

There is also growing interest in implementing ScES in marine heavy-lifting equipment to accommodate high peak loads, as well as offshore renewable energy storage to operate as a buffer reservoir of energy to smooth the output being supplied to the grid [A53].

Superconducting Magnetic Energy Storage (SMES)

Superconducting Magnetic Energy Storage (SMES) is a technology originally envisioned for load-leveling in shore-side, grid-scale systems, but has more recently been considered for pulsed power (or spinning reserve) and peak shaving to optimize electrical systems. SMES uses a cryogenically cooled coil, or cryostat, which forms a magnetic field when current is passed through it. Superconductivity is reached when electrical resistance is essentially zero. In SMES, the cryogenic temperature allows the coil to reach a critical superconducting state, where the circuit, after being charged, can be closed indefinitely to retain energy in both magnetic and electric forms. SMES consists of the following components [A54]:

- Superconducting coil. Closed loop that can be cooled to critical superconductivity, charged with input power, and maintained in an infinite loop to store magnetic energy until needed.
- Power conditioning system. Creates a positive voltage across the coil for charging, and a virtual load for discharging, enabling integration with an AC power system.
- Cryogenic refrigerator. Reduces coil temperature to approximately -269 °C to reach superconductivity. Helium/nitrogen mixture is used as coolant to achieve the necessary temperature.

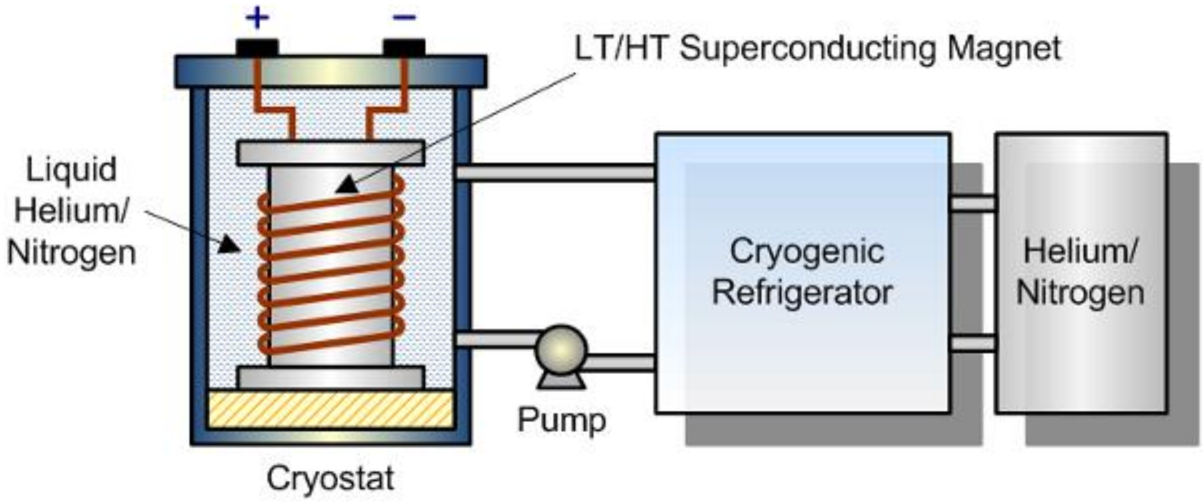


Figure 68: Superconducting magnetic energy storage illustration (source: ESES Lab)

SMES has similar advantages to ScES in that it can discharge energy almost instantly (and faster than ScES), and be cycled innumerable times without losing storage capacity. However, ScES has low energy density, and has a significant ancillary load to maintain the cryogenic, superconducting state of the coil. There are currently no marine-focused developments using superconductors for energy storage. With similar applications to ScES, SMES is not expected to be adapted to marine vessels in the near future.

Link to Guide Navigator

WASTE HEAT RECOVERY

While modern marine diesel engines have been optimized for efficiency, especially so with slow-speed engines, there is still a significant amount of quality heat that is generated and lost from the process. The largest (2-stroke, 60+ MW), most efficient slow-speed diesel engines today reject at least 45% of the fuel energy as waste heat. The waste heat rejection is even higher for the remainder of marine diesel engines (less than 60 MW), at around 50 to 55% of fuel energy rejected. Approximately half of the waste heat (25% of fuel energy) is to exhaust gas, with remaining 25% of wasted fuel energy going to lube oil cooling (approx. 5%), air cooling (approx. 16-17%), and a small amount as radiated heat (approx. 0.5%). Capturing some of the energy of waste heat can significantly increase a ship's overall efficiency, reducing operational costs and emissions.

There are several methods of power recovery from engine waste heat, called waste heat recovery (WHR), provided in the navigation table below. These methods all involve conversion of thermal energy to mechanical energy using a thermodynamic power cycle. Some are mature technologies for marine vessels, such as steam generators, while others are still in the development stage, such as supercritical CO_2 and Organic Rankine Cycle. Other methods that are not being appreciably developed for marine applications are not considered.

Navigation:

Mature Technologies:	Power Turbine Generator (PTG)	Steam Turbine Generator (STG)
	PTG + STG	
Developing Technologies:	Organic Rankine Cycle (ORC)	Supercritical CO_2 (SCO_2)

When evaluating WHR options for an installation, the following vessel characteristics should be considered:

Waste Heat Availability. All methods work well with exhaust heat. Some will also work with lower temperature cooling water, but will require more space on the vessel. Consideration must be given to other waste heat demands (fuel heating, cargo heating, hotel and auxiliary heating, etc.). Generally, lower temperature waste heat will still be available after electrical power is converted but may not be adequate for some applications.

Vessel Size. Some WHR methods are appropriate for smaller vessels, but smaller vessels will have greater size restrictions. WHR will generally work best with larger medium-speed and slow-speed engines.

Vessel Load Profile. Steady operation at a relatively high load is ideal (e.g., trans-ocean or large coastwise vessels). A higher number of operating days will have a faster payback time.

Available Space. Some methods will be more space intensive than others.

Retrofitability. Not all methods are ideal for retrofit.

Crew/Operations. Some systems are higher maintenance and higher complexity than others. Conversely some (e.g., steam systems) may mesh well with existing crew capabilities and skills.

Power Demand. For some vessels (e.g., containerships with high refrigeration loads) there may be a relatively high underway power demand, which can be supplemented or entirely powered by WHR. Conversely, some may not have a high auxiliary power demand underway in which case WHR may not be appropriate, or the vessel propulsion may be outfitted with a shaft-generator for propulsion. Augmenting propulsion can be used either for speed boost or to reduce the load on the main engines.

The applicability of WHR is dependent on engine operation. It should be configured for an engine that is operating continuously, consistently, and at a high enough load that the WHR system can function efficiently. Vessels are not typically designed around a specific exhaust gas minimum temperature, so it should be noted that many vessels may not be suitable for WHR.

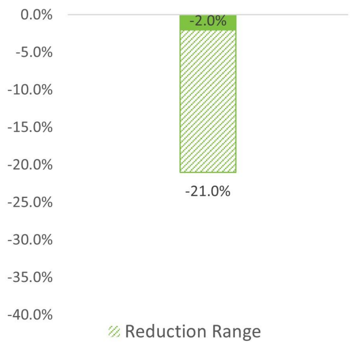
This section focuses on WHR for energy conversion. Waste heat can also be captured for heating purposes. While not detailed in this guide, waste heat for heating can be an effective means of increasing vessel efficiency. Heat can be captured from engine exhaust or hot water from jacket cooling, and can be used for heating fuel, hotel heating (potable hot water, water-making, space heating), and cargo heating, such as on crude oil tankers.

[Link to Guide Navigator](#)

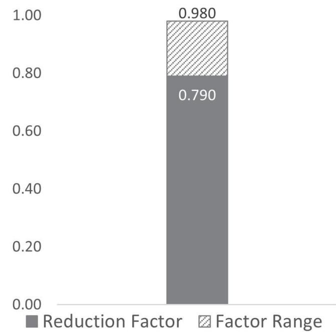
Waste Heat Recovery Systems

[Link to Dashboard Legend](#)

PERCENT REDUCTION



REDUCTION FACTOR (RF_e)



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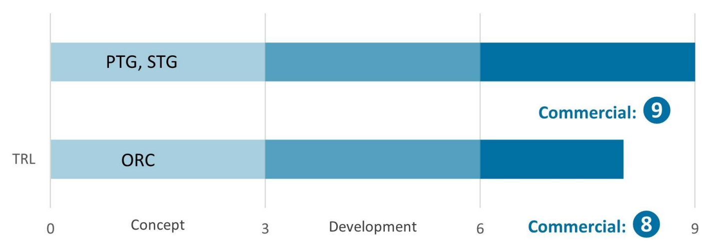


APPLICATIONS

MW	Duty					
>10	Continuous	general	general	marginal	general	marginal
	Intermittent		poor	poor	poor	poor
1-10	Continuous	general	general	marginal	general	marginal
	Intermittent		poor	poor	poor	poor
<1	Intermittent		poor	poor	poor	poor

MW: Propulsion Power plant size, in MW

Compatibility: ✓ general ○ marginal ⊗ poor

INTEGRATION

		OpEx	CapEx
Newbuild	✓	-$/-$$	$$
Retrofit	⊗		-

KEY FACTORS

- WHR is primarily for electrical power, but can also supplement propulsion
- STG is more complex than PTG, but can increase heat recovery.
- ORC may be more compact and readily integrated on medium vessels
- ORC has modular design, allowing custom scaling with standard equipment
- Most suitable for engines that operated at steady load, not intermittent
- Retrofit of steam and exhaust systems not practical
- ORC's low-temperature compatibility and compactness make it feasible for retrofit, though heat recovery may be reduced

Overview – Direct Exhaust and Steam Systems

Power Turbine Generator (PTG)

One of the simplest and least expensive WHR methods are power turbine generators (PTG), also known as exhaust gas turbine generators. At 40% engine MCR and above, a bypass valve re-directs exhaust to drive a turbine generator, or power turbine (Figure 69) [A55]. Typically, a PTG would be connected electrically in parallel with the vessel's ship service diesel-generators. **If the vessel cannot utilize the additional power provided by the PTG due to low electrical demand, then the system can be configured to provide propulsion shaft power via a power take-in (PTI) device**. PTGs can be retrofitted but are more suitable as a new vessel installation. Compared to larger, more complex steam systems the PTG is relatively simple and compact. It should be noted that the use of a PTG reduces the amount of exhaust gas, and therefore energy, available to the engine turbocharger. This can decrease the turbocharger's efficiency.

A PTG requires integration with the engine via software controls as well as the exhaust system. The exhaust piping will require two valves in order to provide bypass control for operation of the power turbine. The outlet temperature of the exhaust gas after the turbine will have a lower limit of around 150 ºC (~300 ºF) to prevent the condensing of gases and the formation of sulfuric acid in the system, which can have corrosive effects on the exhaust piping and equipment. For low-content sulfur fuel, the risk of sulfuric acid formation is lessened.

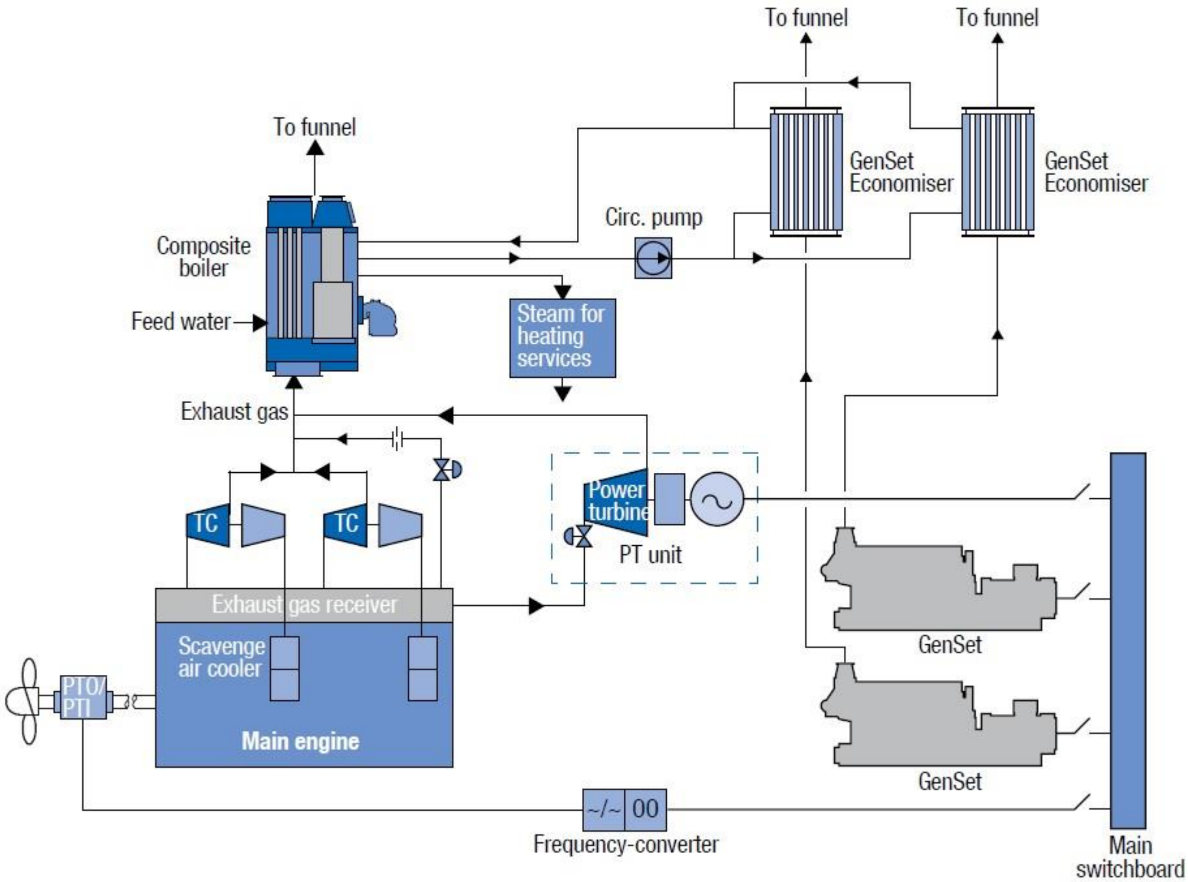


Figure 69: Power turbine generator schematic (source: MAN)

Steam Turbine Generator (STG)

Many large vessels with slow speed diesel engines have exhaust gas boilers, also known as economizers, for providing fuel or cargo heating. The steam from the economizers can also be used for driving a steam turbine generator (STG) for auxiliary and/or propulsion power. Exhaust gas from the turbochargers and bypass stream are combined and then sent to the STG economizer. The application is similar to a PTG with the steam turbine providing power in parallel to generators, or power to the propulsion shaft. There can be enough waste heat for steam generation at loads greater than 30 to 35% of MCR, though efficiencies are greater at peak loads [A55]. If there are other waste heat demands, such as heating, then steam for power generation must be limited accordingly. The steam turbine can be mounted on a compact skid, as shown in Figure 70. **STGs are more complex than PTGs, but can also achieve higher rates of energy recovery.**

Figure 70: Curtiss-Wright steam turbine generator (source: Curtiss-Wright)

The two primary arrangements for STG are single pressure and dual pressure systems:

- Single pressure is the simplest and most compact steam cycle and will only use exhaust gas heat to generate steam for power. Typically, the boiler (economizer) will have a preheater, evaporator, and super-heater section in the stack, and the turbine will have a single stage. A single pressure schematic is shown in Figure 71.
- Additional efficiency can be gained by adding a second pressure stage to the system. A second source of waste heat is typically needed for preheating the feedwater coming out of the hot well. Using exhaust gas to preheat the feedwater risks cooling the exhaust to the point that it becomes corrosive due to condensation. Instead, waste heat from jacket water or scavenge air can be used as a preheating source if available. If other waste heat is not available, feed water can be preheated using low-pressure steam, although this reduces overall steam production. Steam for heating would come from the high-pressure steam drum, and low-pressure steam would be used for the steam turbine. A dual pressure schematic is shown in Figure 72.

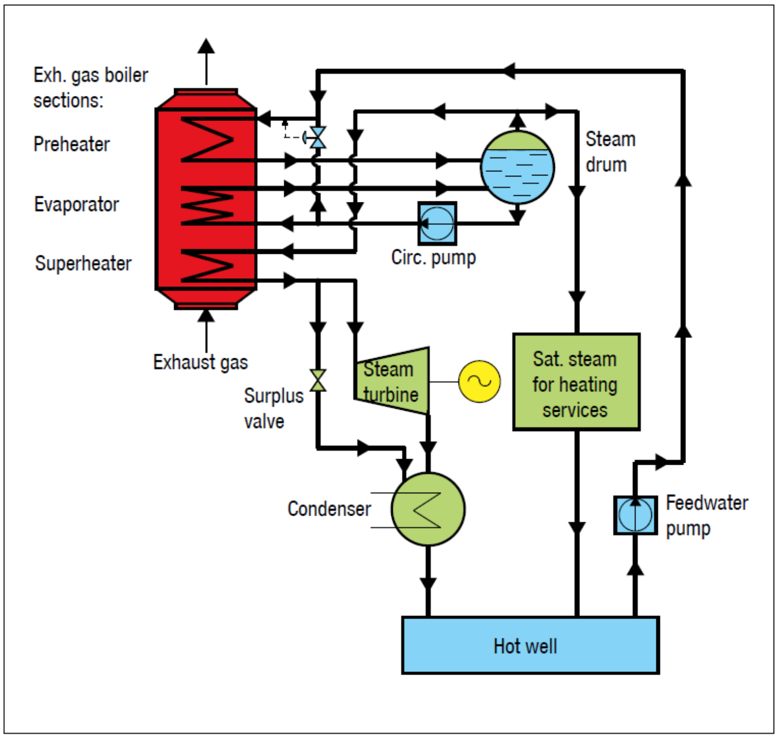


Figure 71: Process diagram for single pressure exhaust gas boiler utilizing STG (source: MAN)

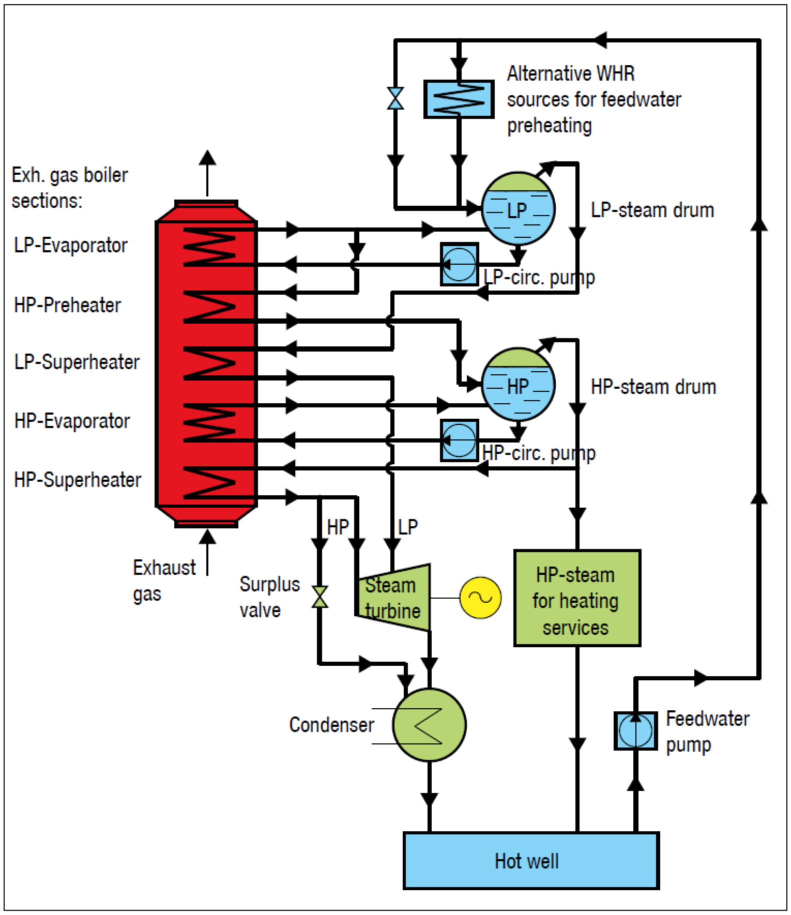


Figure 72: Process diagram for dual pressure exhaust gas boiler utilizing STG (source: MAN)

Combined PTG + STG

A PTG and STG can be paired to further recover heat energy from engine exhaust. Both turbines can be mounted on the same skid, and are coupled to drive a single generator. These systems are best suited for vessels with both a significant propulsion load and a high electrical demand. For example, a containership carrying a large portion of refrigerated cargo has lots of waste heat energy available from its propulsion plant, and needs significant electricity to power its cargo support systems. A schematic of a combined power turbine and steam turbine generator is shown in Figure 73.

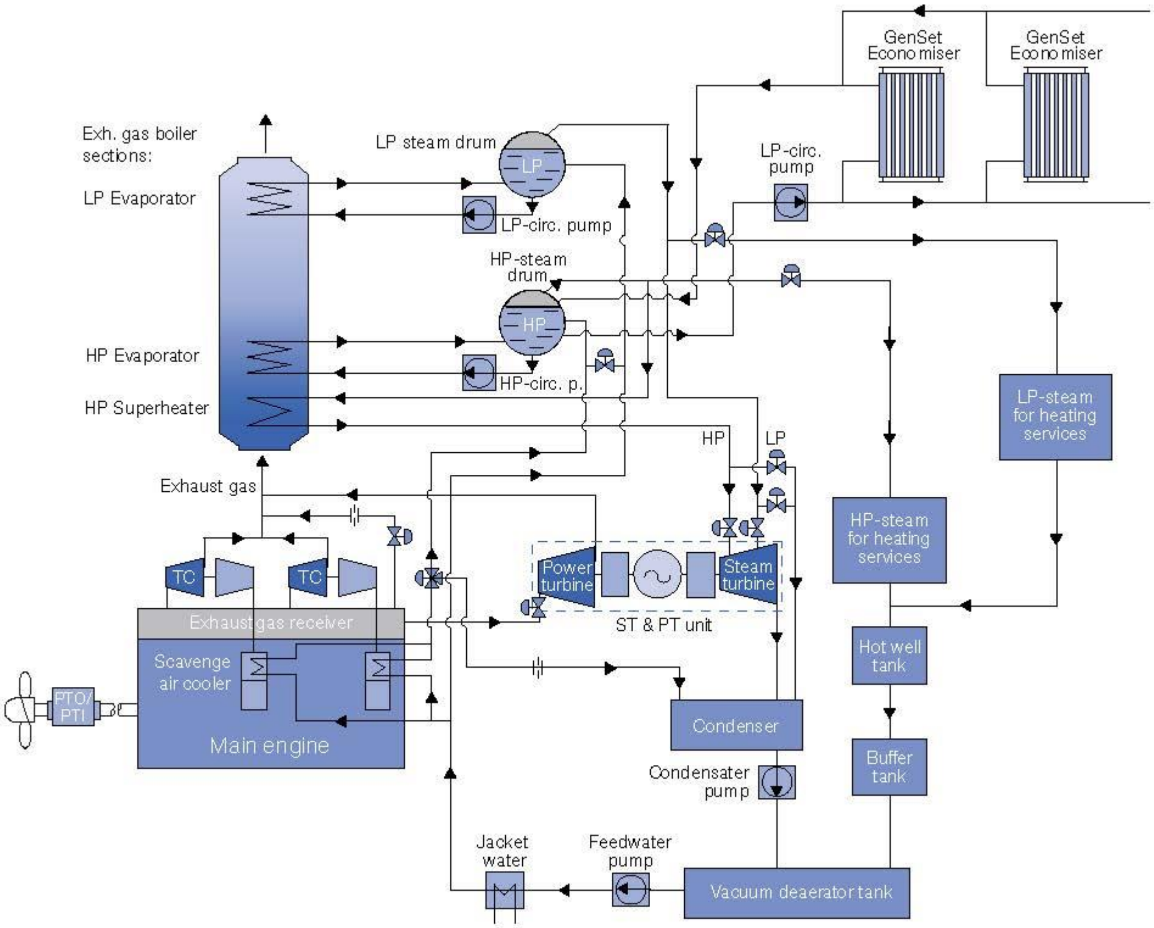


Figure 73: **Combined PTG + STG schematic (source: MAN)**

Organic Rankine Cycle (ORC)

Waste heat recovery with an organic Rankine cycle (ORC) works on the same principle as the steam cycle only the working fluid is typically a refrigerant with a lower boiling temperature than water. This allows more compact, and potentially more efficient capture of waste heat compared to steam. Since the working fluids have lower boiling points, they are capable of capturing useful work from much lower temperature sources of waste heat, such as jacket cooling water and charge air-cooling loops. A simple ORC diagram is shown in Figure 74.

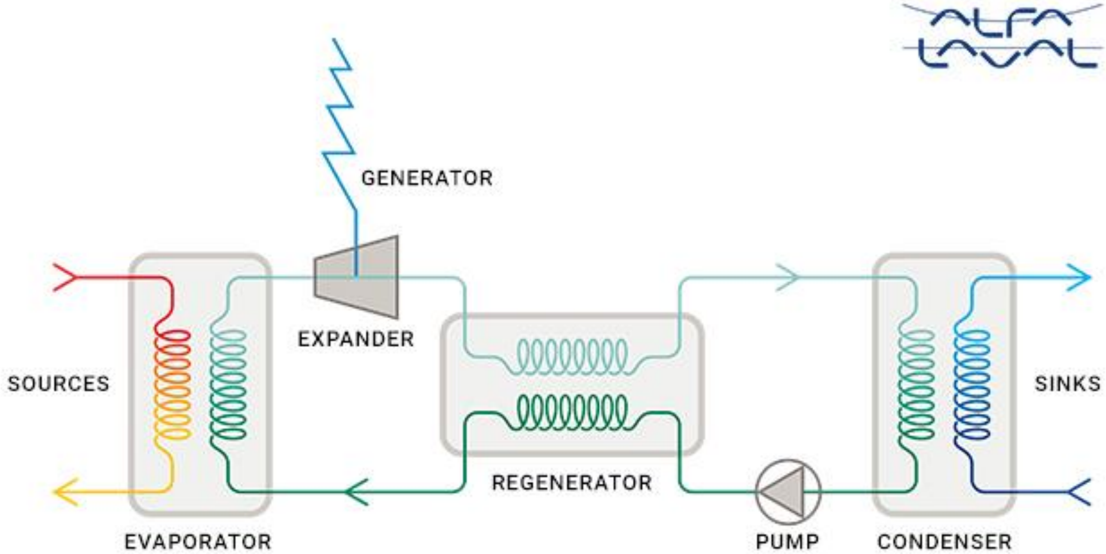


Figure 74: **Simple ORC system diagram (source: Alfa Laval)**

If the system is capturing exhaust waste heat, integration will require an exhaust bypass like the PTG and STG systems above. An exhaust gas boiler (economizer) will need to be installed to capture heat for the ORC. **The footprint may be smaller for an ORC system, and the installation may be less expensive due to less piping and equipment. Most of the system piping can be integrated on the ORC skid.** Due to the lower temperature ranges required for an ORC system, more energy can be recovered at low engine loads, improving the overall efficiency of the system. When recovering heat from both exhaust gas (high quality heat source) and jacket water (low quality heat source), one study estimated 10% fuel savings is achievable [A56]. When recovering heat from jacket water only, the savings will be diminished, as the exhaust gas energy will not be available for recovery.

While development for marine applications has been slow to proceed, Alfa Laval announced its E-PowerPack in 2022, an ORC system for power recovery (Figure 75). It is claimed to recover 9 to 18% of thermal energy for electrical power, with output modules of 100 kW and 200 kW [B40]. Climeon's HeatPower 300 Marine ORC has been installed on a Maersk containership as well as several cruise ships, with an output range scalable from modules of 150 kW each [B41]). Climeon claims up to 5% fuel savings by implementing a HeatPower system [A57]. **These modular approaches make scaling readily achievable without using a custom or poorly matched capacity.**

A shipboard R&D testing program from a third different developer has been ongoing on the Training Ship *Golden Bear* (IMO no. 8834407). Data and results from the project have not been publicly reported [A58].

Figure 75: Alfa Laval e-PowerPack ORC system (source: Alfa Laval)

Figure 76: Climeon HeatPower system, installed on Viking Line's *Glory*, IMO no. 9827877 (source: gcaptain.com [C19])

Supercritical CO_2 (SCO_2)

Supercritical CO_2 (SCO_2) systems are a closed cycle (closed system) energy recovery system similar to an ORC, using the Rankine power cycle, but implementing high-pressure, supercritical CO_2 (supplied with the system) as the heat transfer fluid. While the installed cost could be similar to a conventional steam recovery plant, the operational and maintenance costs are claimed to be reduced. SCO_2 has similar benefits to ORC in that it can recover heat from lower temperature "low quality" sources (e.g., jacket cooling water), and can be more compactly packaged for installation.

While SCO_2 may be suitable for onboard heat recovery and therefore energy reduction potential, development for marine applications is not yet being commercially pursued. Echogen Power Systems has been exploring a marinized system concept, but has not established a timeline for technology readiness [B42].

Reduction Potential (as % of total energy demand): -2 to -21%

- Reduction potential depends on percentage of the vessel's total installed propulsion power. Values here assume propulsion power constitutes 60 to 80% of the vessel's total power profile.
- PTG and STG technologies have the following energy recovery and corresponding reduction potential [A55]:

System	Heat Recovery Rate (% of MCR)	Reduction Potential (% of total energy)
PTG	3 to 5%	1.8 to 4%
Single Pressure STG	4 to 7%	2.4 to 5.6%
Dual Pressure STG	5 to 8%	3 to 6.4%
PTG + STG	8 to 11%	6.4 to 8.8%

- To fully capitalize on the waste heat available from a PTG-STG generator, there must be sufficient electrical demand under normal operating conditions.
- Alfa Laval claims 9 to 18% thermal energy recovery with its e-PowerPack ORC system. This has not been verified with independent test data.
- Climeon claims up to 5% overall fuel savings with its HeatPower ORC system.

TRL: PTG, STG – 9 ORC – 8

- PTG, STG, and combination PTG + STG systems are commercially mature and available from several manufacturers, including MAN [A55] and MHI [B43]. These systems have been installed on hundreds of commercial shipping vessels.
- Climeon's HeatPower ORC system has been installed and is operating on a containership and multiple cruise ships. The systems installed on the *Scarlet Lady* (IMO no. 9804801) and *Valiant Lady* (IMO no. 9805336) are sized for the vessel's full exhaust stream [C20][C21]. These installations qualify ORC technology as a TRL 8.

Applications

- Most suitable for vessels with large propulsion loads, but sufficient auxiliary electrical loads to benefit from recovered energy. Recovered energy can also be fed back into propulsion shaft via power take-in (PTI).
- **Most suitable for vessels with propulsion engines operating in a continuous, high-load profile. Intermittent or variable engine operation will diminish WHR effectiveness and make it difficult to optimize.** Auxiliary engines not ideal due to cycling and multiple-engine exhaust configuration.
- Ideal for large vessels with high electrical loads, such as cruise ships, and cargo/containerships with refrigerated cargo.
- ORC systems are more compact than conventional WHR systems, making them feasible for some medium vessels or large vessels with limited space for additional machinery, e.g., cruise ships.

Integration & Cost

✓ **general compatibility for newbuild** | **$$** **moderate newbuild CapEx**

⊗ **poor compatibility for retrofit*** | **–** **retrofit CapEx N/A**

-$/-$$ **moderate to significant OpEx savings**

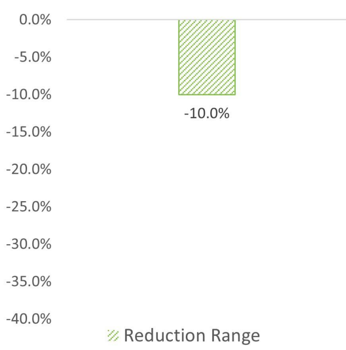
*retrofit compatibility and cost are for most WHR systems. ORC may be retrofittable if it does not integrate with existing exhaust system, but will have diminished heat recovery potential.

- **Conventional steam and exhaust WHR require integration with exhaust system, which requires careful engineering and exhaust stack arrangement planning.**
- PTG system does not require steam piping, only exhaust piping modifications.
- STG system requires steam piping as well as exhaust piping modifications.
- Difficult to retrofit existing exhaust system with WHR equipment. **ORC may be more suitable for retrofit if only recovering heat from low-temperature circuits.**
- ORC can recover heat from low temperature circuits, such as jacket cooling water, not requiring integration with exhaust lines. Heat recovery from exhaust gas plus jacket water cooling has greatest potential for energy recovery, though.

Link to Guide Navigator

HVAC Optimization

PERCENT REDUCTION



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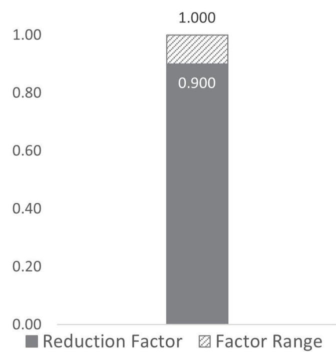

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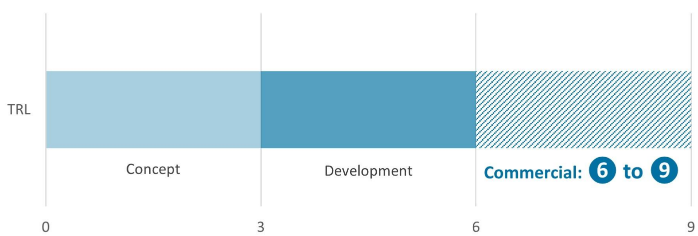


APPLICATIONS

MW	Duty					
>10	Continuous	✓	✓	✓	✓	✓
	Intermittent		✓	✓	✓	✓
1-10	Continuous	✓	✓	✓	✓	○
	Intermittent		✓	✓	✓	○
<1	Intermittent		○	○	○	○

MW: Propulsion Power plant size, in MW

Compatibility: ✓ general ○ marginal ⊗ poor

INTEGRATION

		OpEx	CapEx
Newbuild	✓	-$	$/$$
Retrofit	○		$$

KEY FACTORS

- Energy recovery ventilators like enthalpy wheels are difficult to configure
- Reduction potential dependent on HVAC's portion of total vessel energy
- Cruise ships have highest reduction potential with significant HVAC loads
- Reduced costs and low arrangement impact make VFDs broadly applicable
- Possible harmonic distortion from large VFDs to be assessed during design

Link to Dashboard Legend

Overview

Methods of improving energy consumption in heating, ventilation, and air-conditioning (HVAC) systems can vary widely, from simply implementing variable frequency drives for large fans to completely rethinking the vessel-wide heating and cooling system. The most significant energy reductions can be achieved on vessels with large hotel loads, such as cruise ships and ferries.

Variable Frequency Drive (VFD) Control

The use of VFDs to match operations of pumps and fans with actual demands is one of the most straightforward ways to improve energy consumption. Engine room ventilation can be adjusted based on engine load operating point (and required combustion air), space temperature, or some logic-based combination. For vessels that operate at a reduced plant load for significant periods, or operate in cooler climes for part of the year, significant energy is wasted by running engine room fans at a fixed speed continuously.

Vessels with large HVAC plants to support passenger services and accommodations can benefit the most from VFD control. VFD control of air handler fans allows turndown based on ambient temperature conditions and passenger load. VFD control of chilled water systems allows turndown at low demand period of the day or throughout the year, and can be implemented on both the chilled water circuit and the seawater cooling circuit.

The cube relationship between velocity (liquid flow or air flow) to power illustrates how small adjustments in pump and fan speed can result in dramatic energy savings for that individual consumer (Figure 77).

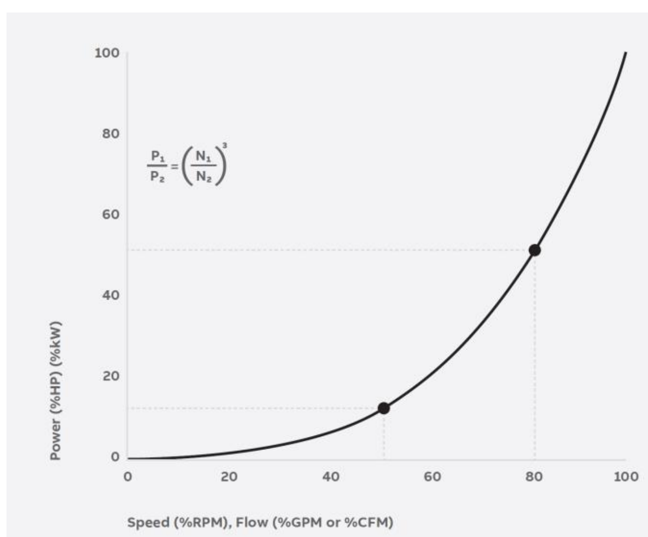


Figure 77: Speed vs flow relationship to power (source: ABB)

Guidance for implementing VFD control on pumps, fans, and compressors is available from ABB's Energy Efficiency Handbook [A59], which also details VFD use on chiller compressors. If applied correctly, VFD control of a chiller with centrifugal compressors can reduce the energy demand by up to 25%, as shown in Figure 78.

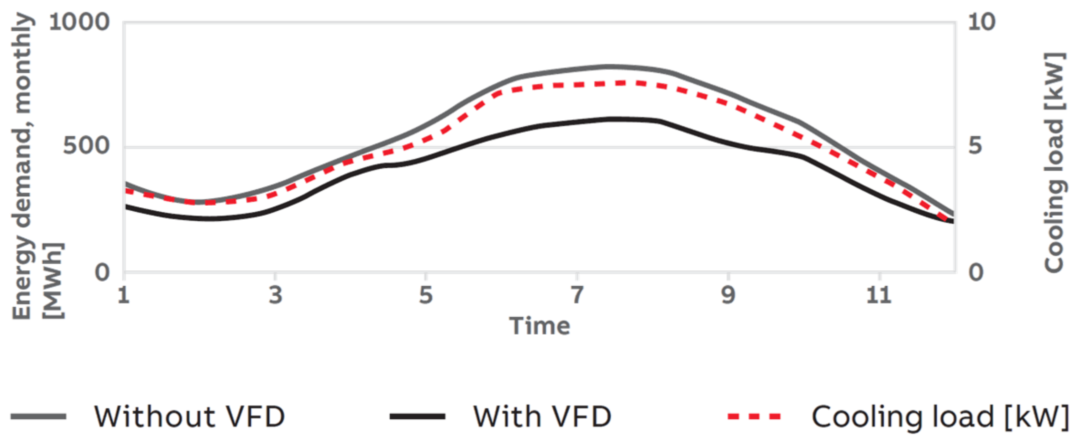


Figure 78: Energy savings with VFD-controlled chiller compressors (source: ABB)

VFD use in HVAC systems can be challenging on vessels with limited space, such as small vessels or special purpose vessels with large mission-specific equipment. While VFD compactness has improved, drives are still larger than a corresponding single-frequency motor controller. Many VFD manufacturers also have limits for allowable ambient temperatures in spaces where the drives are installed, and the equipment must be located in a way to ensure adequate cooling of internal electronics while operating.

Equipment Direct Cooling

Many power consumers with significant heat rejection, such as electronics and motors, are available as water-cooled options. Water-cooled options are more effective at removing rejected heat than air-cooled, and water cooling can also improve equipment efficiency as equipment temperatures are more readily controlled. Selecting water-cooled options for alternators, large motors, drives, and switchboards will reduce the ventilation load in machinery spaces or HVAC load in conditioned equipment rooms. Water-cooling does require additional piping, equipment, and maintenance, and must be accounted for during drydocking periods where the final heat sink (sea water) may not be available.

Energy Recovery Ventilators

Energy recovery ventilators (ERV) can recover significant sensible and latent energy by crossing exhaust air with incoming fresh air (Figure 79). The two ducts must meet at a heat recovery wheel, or enthalpy wheel, where exhaust air provides either pre-cooling or pre-heating of the fresh air. If velocities are reduced across the wheel, upwards of 80% of energy can be recovered from the exiting air stream [B44].

ERVs are challenging to integrate, especially on vessels with limited space. Enthalpy wheels are large pieces of equipment, and ducting must be specifically arranged for joining two flows at the wheel. This can increase duct lengths, and therefore fan loads to achieve the required pressure to exhaust and supply the necessary ventilation.

One manufacturer, Dessicant Rotors International (DRI), offers enthalpy wheels, constructed with marine grade materials, for flows of 160 to 20,000 CFM [B45].

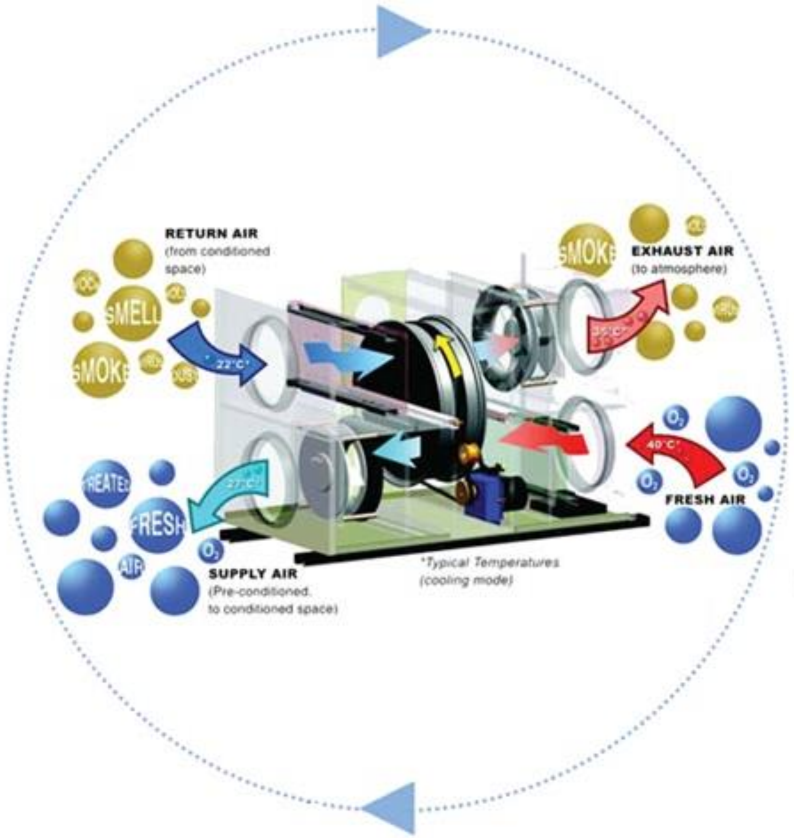


Figure 79: Energy recovery ventilator using enthalpy wheel (source: DRI)

Smart HVAC Control with Variable-Based Systems

Smart control and monitoring of large HVAC systems can both optimize energy consumption and help the operator understand where usage inefficiencies are occurring. Programs like TimeSchedule by Hvacon Marine Systems [B46] incorporate passenger occupancy and schedules to match cooling and heating distribution more closely with space usage.

Traditional constant air volume (CAV) ventilation systems are easy to design and install, but are ineffective at minimizing energy to meet heating and cooling needs. Pairing smart HVAC controls with a variable air volume (VAV), variable volume and temperature (VVT), or variable refrigerant volume (VRV) system may reduce energy consumption and improve crew/passenger comfort. Where CAV systems maintain the air volume regardless of cooling and heating loads, variable-based systems can adjust to changes in both outdoor conditions and heat gains in individual spaces or zones.

VAV is achieved with variable speed fans, as discussed above, and VVT is achieved by modulating the supply air temperature based on existing conditions.

VRV is a multi-split system that distributes refrigerant throughout the vessel, rather than chilled water, eliminating a secondary circuit in the cooling system and its associated energy losses. It is best suited for smaller vessels where the extent of refrigerant distribution is limited and cooling/heating demands are low.

Infrared Heating

Improved long infrared radiation (IR) heating may become an energy saving alternative to forced air convection heating. IR heating is performed by directly heating the contents (and occupants) of the space through radiation, rather than heating indirectly through ventilation air. Black Sun Heating claims 80% heat transmission through radiation and 20% transmission through convection but has only been adopted on small vessels and land-based applications [B47] .

Reduction Potential (as % of total energy demand): 0 to -10%

- **Reduction potential depends largely on portion of overall vessel energy that is consumed by HVAC systems.** HVAC can be up to 30% of a vessel's total energy consumption, such as on large cruise ships [A60], but most vessels have much smaller relative HVAC loads.
- Reduction potential also depends on what element of HVAC is being optimized: air flow, hydronic circuits, refrigeration cycles, heating, or some combination.

- Switching to VFD pump control can save up to 30% energy in chilled water systems [A59].
- Fans comprise up to 40% of HVAC system load but are often run at inefficient operating points.

TRL: Various, depending on technology

- 9: VFD control of HVAC fans, pumps, and compressors are well-established on marine systems and are offered by a variety of manufacturers.
- 9: Direct water cooling is broadly available on large motors and electrical equipment.
- 6: Energy recovery ventilators have started to enter into marine applications, but are not widely adopted or proven at a range of HVAC scales.
- 7: Smart HVAC control is not widely adopted, but HVAC is a marine system that is primed for integration of feedback data and learning functionality.

Applications

- VFD control of fans, pumps, and chiller compressors on most marine commercial vessels. Energy for engine room ventilation on all vessels can be appreciably reduced if controlled by temperature, pressure, or engine load.
- **Passenger vessels and particularly cruise ships have highest potential for energy reductions by HVAC optimization.** In addition to variable control, energy recovery from exhaust air may be implemented where space is available.
- Small vessels with limited space and weight may only implement limited HVAC improvements, as VFD cabinets are large and often have limitations for where they can be installed. ERVs are likely only implemented on very large vessels with flexible fan room space.

Integration & Cost

✓	**general compatibility for newbuild**	$/$$	**minor to moderate newbuild CapEx**
○	**marginal compatibility for retrofit**	$$	**moderate retrofit CapEx**
		-$	**moderate OpEx savings**

- HVAC design is typically tailored for a specific vessel and depend on the vessel's arrangement and HVAC demands. It might be more challenging to integrate HVAC improvements on existing vessels.
- **VFD cost has improved in recent years, and they have minimal impact on other ship's systems and arrangement in newbuilds**. Retrofitting with VFDs is more challenging and may incur additional costs to integrate in existing machinery or electronics spaces.
- **Large VFD loads may introduce harmonic distortion issues on existing vessels, and should be assessed on newbuild designs and retrofits alike.**
- Moderate fuel savings can be achieved, but depend highly on vessel characteristics and portion of vessel's load required by HVAC.

Link to Guide Navigator

RENEWABLE ENERGY

Navigation:

Wind-Assisted Propulsion:	Kite Sails	Rotor Sails
	Rigid Wingsails	Flexible Sails
	Inflatable Sails	
Renewable Energy:	Wave-Assisted Propulsion	Solar Power

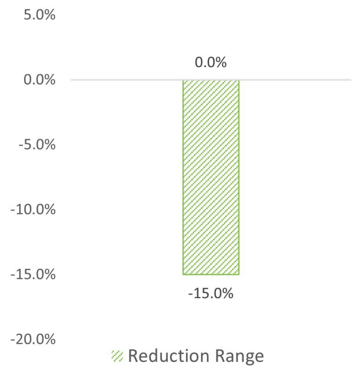
Several solutions have been developed to harness renewable energy on marine vessels. Wind propulsion has been modernized, taking many concepts of conventional sailing and adapting them to commercial, powered vessels. Rotor sails, on the other hand, utilize the Magnus effect to harness wind energy in a completely different way. Each sail technology has its own advantages, but they generally are best-suited for commercial shipping on long-range transits, rather than short routes and passenger-service operations.

Niche solutions include wave-assisted propulsion, which uses pitching of the vessel in waves to generate thrust, and solar power, which supplements onboard power generation with electricity from photovoltaic cells.

Link to Guide Navigator

Kite Sails

PERCENT REDUCTION



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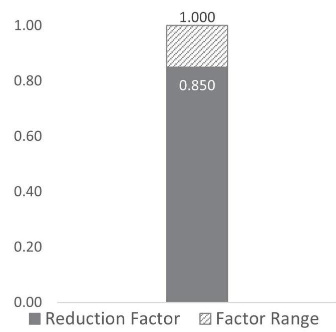

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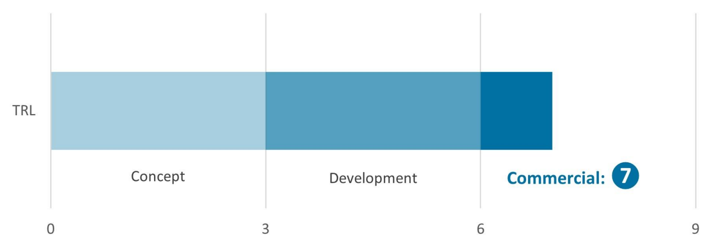


APPLICATIONS

MW	Duty					
>10	Continuous	general	marginal	poor	marginal	poor
	Intermittent		poor	poor	poor	poor
1-10	Continuous	general	marginal	poor	marginal	poor
	Intermittent		poor	poor	poor	poor
<1	Intermittent		poor	poor	poor	poor

MW: Propulsion Power plant size, in MW

Compatibility: ✓ general ○ marginal ⊗ poor

INTEGRATION

		OpEx	CapEx
Newbuild	✓	-$/-$$	$
Retrofit	✓		$$

KEY FACTORS

- Operates hundreds of meters over vessel for favorable wind characteristics
- Thrust not available within 50 degrees of upwind heading
- Can be readily retracted and stowed in unfavorable conditions
- Multiple onboard demonstrations installed but no commercial uptake yet
- Not suitable for vessels with changing routes, or trades
- Packaged product simplifies installation and makes suitable for retrofit

Link to Dashboard Legend

Overview

Kite sails consist of a large kite and towline that mount to the vessel's bow, a launch and recovery system (LARS), and a control system to optimize the kite's thrust performance. The kite operates by the same basic principle as other sails and wings: lift is generated as air passes over the curved surface. The magnitude of the lifting forces is related to the air speed passing over the 'wing', with higher speeds generating higher forces. The lifting force from the kite is transferred to the vessel through tension in the towline.

The effectiveness of a kite sail depends on wind direction relative to the vessel heading. **When a vessel is on a relatively upwind heading (within 50 degrees of wind direction) the kite sails thrust may induce drag on the vessel**, as shown in Figure 80. In these conditions, kite sails have the advantage of being fully retractable. They also take up limited deck space, and limit the heeling moment incurred by the force vector acting through the towline connection point at deck level.

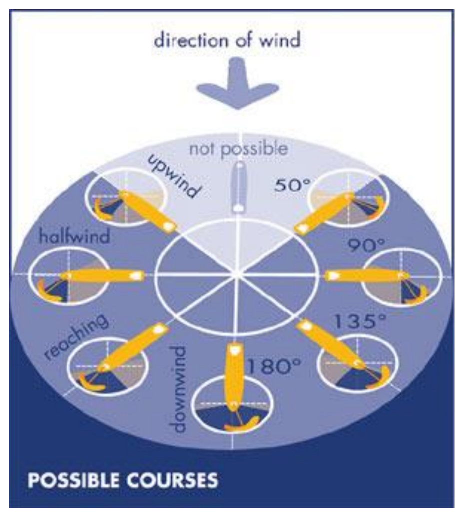


Figure 80 Kite sail possible courses relative to wind direction (source: Skysails via noaa.gov)

Kite sails are unique from many sail technologies in that the kite is not fixed in a single position or direction relative to the vessel. The kite is controlled to fly in a figure-eight pattern around a central position, increasing relative wind speed that translates to improved thrust. SkySails, the early developer of kite sails, has claimed 25 times the power generated per sail area over conventional sails [A48]. **At a height hundreds of meters above the vessel, the kite experiences more favorable wind characteristics**, upwards of 45% higher wind velocity than in the space just above the vessel. The wind velocity and power relationship, as well as a kite sail's figure-eight pattern, is shown in Figure 81.

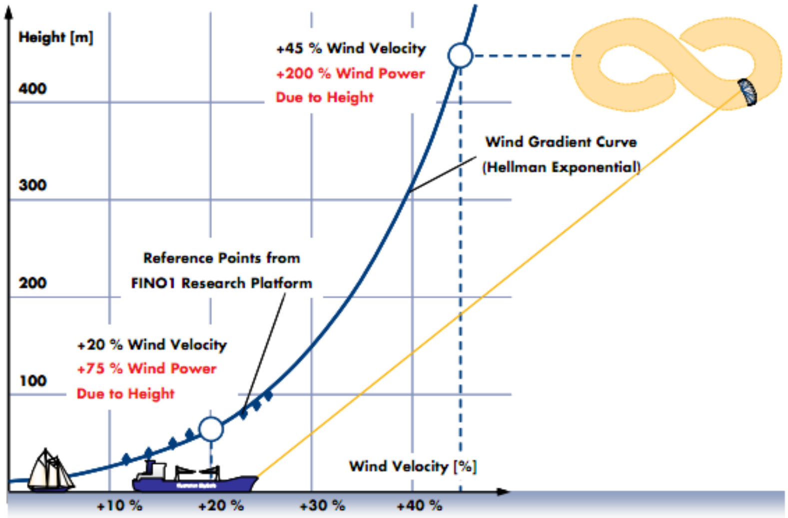


Figure 81: Kite sail flow characteristics (source: Skysails via wattnow.org)

Since their first installations on cargo vessels in 2007 and 2009, SkySails has diversified its business units and pivoted towards landside power generation. As a power generation source, a kite sail does not depend on wind direction to be effective. New SkySails marine installations have not been announced in recent years.

Airseas, a spinoff of AirBus, has coupled their proprietary EcoRouting software with their Seawing kite sail to enhance the sail's performance [B49]. The software optimizes the ship's route to achieve the most favorable conditions. Airseas claims fuel savings of 10-40% by flying the sail at an altitude of 200m, however independent test data is not available [C22]. A Seawing and LARS with a 500 m^2 sail area, weighing 120 tons as a single unit, was installed on the RoRo *Ville de Bordeaux* (IMO no. 9270842) in December 2021 for performance testing [C22]. This installation is shown in Figure 82.

Figure 82: Seawing's kite sail installation on *Ville de Bordeaux*, IMO no. 9270842 (source: heavyliftnews.com)

Reduction Potential (as % of total energy demand): 0 to -15%

- SkySails installation on MS *Beluga* (IMO no. 9399129) tested to achieve up to 10-15% savings, though the conditions of those results were not reported [C23]. WINTECC project reported 5% savings across over average route mix for same vessel [A61].
- Airseas claims 10-40% potential fuel savings, partnered with Bureau Veritas to test first installation on RoRo *Ville de Bordeaux* (IMO no. 9270842) [A62][B49].
- **While kite sail could induce drag in unfavorable wind conditions, it can be retracted and stowed, limiting impacts to the vessel's weight and potential changes to trim and stability**.

TRL: 7

- Systems installed on multiple vessels as demonstration, including M/V *Beluga* (SkySails, IMO no. 9399129) and *Ville de Bordeaux* (Airseas' Seawing, IMO no. 9270842), but **technology has not seen commercial uptake.**
- Seawing system ordered for K Line's first LNG-powered bulker, scheduled for delivery in 2024 [C24].
- Seawing and K-Line granted approval-in-principle by ClassNK in 2020 [A63].

Applications

- Best-suited for vessels on consistent, long-distance voyages with reliable weather patterns. Routes in prevailing wind regions are particularly suitable.
- **Vessels with changing routes may only sometimes be able to utilize kite sails.**
- Not compatible with service and towing vessels that operate under varying trades or contracts.
- Energy savings for ships operating on the Great Lakes limited due to varying wind conditions throughout year.

Integration & Cost

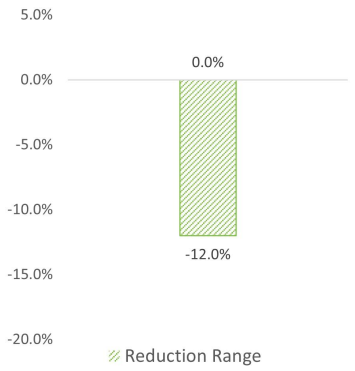
✓	**general compatibility for newbuild**	$	**moderate newbuild CapEx**
✓	**general compatibility for retrofit**	$$	**moderate retrofit CapEx**
		-$/-$$	**moderate to significant OpEx savings**

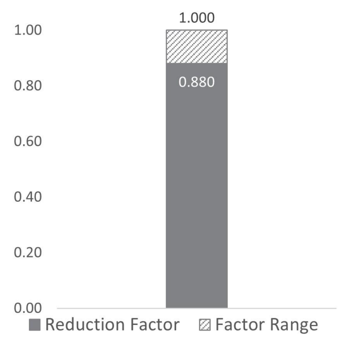
- **Kite sails are packaged products, primarily requiring a foundation and power to integrate**. Little to no impact on auxiliary systems and vessel arrangements, making it suitable for retrofit.
- Location on vessel bow ideal for vessels with stern pilothouse, does not interfere with cargo operations.
- Challenging to integrate or retrofit on vessels with forward pilothouses and limited deck area in bow.

Link to Guide Navigator

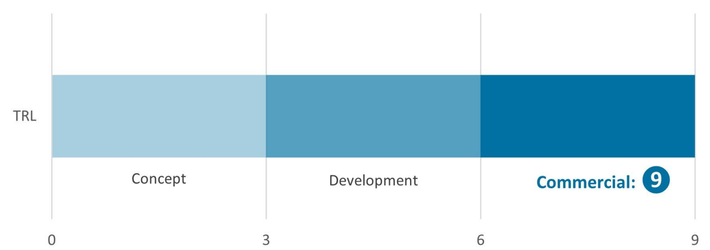
Rotor Sails

PERCENT REDUCTION | **REDUCTION FACTOR (RFₑ)**





TRL



APPLICATIONS

MW	Duty					
>10	Continuous	general	general	marginal	general	marginal
	Intermittent		marginal	marginal	general	marginal
1-10	Continuous	general	general	poor	general	poor
	Intermittent		marginal	poor	marginal	poor
<1	Intermittent		poor	poor	poor	poor

MW: Propulsion Power plant size, in MW

Compatibility: ✓ general ◯ marginal ⊗ poor

INTEGRATION

		OpEx	CapEx
Newbuild	✓	-$/-$$	$$
Retrofit	✓		$$

KEY FACTORS

- Maximum propulsion contribution with wind direction across beam
- Foldable to stow during cargo operations, waterway navigation, rough seas
- Net energy reductions up to 30% advertised but not verified
- Norsepower technology type approved by DNV in 2018
- Best suited for vessels regularly underway in open water
- Not suitable for vessels regularly on station or loitering, inland operations
- Minimal impacts below deck, primarily electrical capacity and distribution

Link to Dashboard Legend

Overview

Rotor sails are vertically oriented spinning cylinders that attach to the vessel's deck to make a virtual sail. Originally called Flettner rotors, rotor sails use the Magnus effect, where the spinning cylinder creates high- and low-pressure areas perpendicular to the flow of wind, generating a resultant lift force. A rotor sail's Magnus effect is represented in Figure 83. If aligned with the advancing direction of the vessel, the sail's lift force supplements thrust force.

The component of lift that contributes to propulsion is maximized when experiencing wind across the vessel's beam, where the wind direction is perpendicular to the vessel's heading. The propulsion component diminishes as wind direction rotates away from perpendicular, either aft or forward, until wind direction is parallel with heading, and thus no force component contributes to thrust. Rotor sails are particularly advantageous in that they generate some propulsion at all wind directions relative to heading, at varying magnitude, except for a tail wind or head wind.

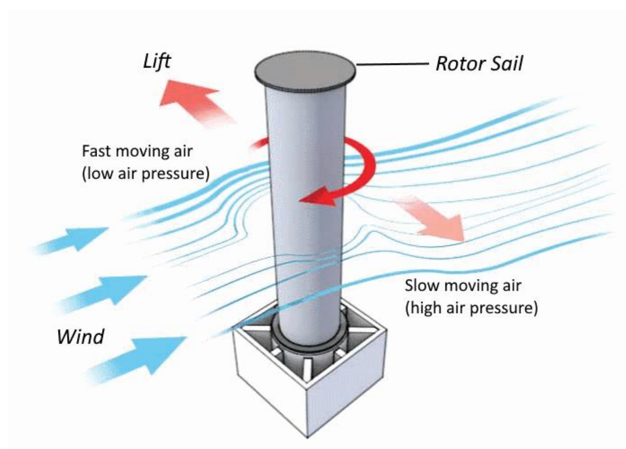


Figure 83: Rotor sail Magnus effect (source: amusingplanet.com)

Rotor sails are simple mechanically, powered by a vertical motor and supported by a foundation attached to the vessel's deck. The direction of rotation must be reversible to provide thrust from both starboard or port winds. A rotor sail can produce 8-10 times the force of a conventional sail of the same area. While a rotor sail will increase the air draft of a vessel, it does not require the same significant height or width to achieve an effective thrust force as a conventional sail.

Rotors sails are generally installed in sets of two or four, staggered longitudinally to avoid interfering air flow and sometimes located in pairs port and starboard to balance the additional weight of the rotor and its foundation. **While rotor sails do increase the air draft of a vessel, they have been configured by multiple manufacturers to fold to a stowed position. This allows positioning under cranes,**

navigating under bridges, or transiting in adverse weather conditions. Folding rotor sails are depicted on a bulk carrier during cargo operations in Figure 84.

Figure 84: Rendering of Anemoi folding rotor sails on bulk carrier (source: Marine Log)

While Flettner rotors were first installed on a vessel in the 1920s, commercial development didn't gain momentum until the turn of the 21st century. Rotor sails were installed on the newbuild *E-Ship 1* (IMO no. 9417141) a wind turbine carrier, in 2010, with the technology custom designed and built by Enercon, the vessel owner [C25]. Norsepower [B50] was founded in 2012, and installed its first commercial rotor sails, two 18-meter units, on the RoRo M/V *Estraden* (IMO no. 9181077) in 2014-2015 [C26]. Anemoi [B51] installed its first rotor sails, four 16-meter units, on the bulk carrier m/v *Afros* (IMO no. 9746803) in 2018 [C27]. The *Afros* installation includes a rail system to allow flexibility in cargo operations. Both manufacturers have since developed folding designs and commercialized their product lines, with Norsepower delivering the first commercial folding rotors to the *SC Connector* (IMO no. 9131993) in 2021, shown in Figure 85 [C28].

Figure 85: *SC Connector* RoRo with Norsepower folding rotor sails (source: Norsepower)

Link to Guide Navigator

Reduction Potential (as % of total energy demand): 0 to -12.5%

- Reduction potential maximized when wind direction is perpendicular to the vessel heading (across the beam), where lift force aligns with vessel heading, but reduced savings still achieved at other wind directions.
- Fuel savings of 12.5% reported by manufacturer Anemoi for bulk carrier m/v *Afros.*
- Fuel savings of 8.2% reported by manufacturer Norsepower for product tanker *Timberwolf* [A64].
- **Theoretical fuel savings of 20-30% have been advertised but not verified.**
- Lift force increases proportionally with rotor diameter and height, but constrained by stability, arrangement, and cost limitations.

TRL: 9

- Installed on over 10 ships over past decade, maturing from prototype installation to full commercial.
- Two manufacturers have delivered equipment for commercial operation, with DSME developing their own technology to install on newbuilds constructed at their shipyards [B52].
- Installed on vessels with class approval from DNV and LR.
- **Norsepower technology is type approved by DNV** [A65], and other manufacturers have achieved approval-in-principle, including Korean shipbuilders DSME and HHI [A66].

Applications

- **Best suited for large vessels that are regularly underway in open water**, particularly for oceangoing vessels on long transits, passenger ships, and vessels engaged in coastal shipping.
- Bulk carrier vessels are seen to have potential for wide uptake of rotor sails, as indicated by joint development project by Oldendorrf Carrier, Anemoi, Lloyd's Register (LR), and Shanghai Merchant Ship Design and Research Institute (SDARI) [A67].
- **Smaller vessels that are regularly on station or loitering, such as work boats and service vessels, will have negligible savings.**
- Inland vessels with limited exposure to wind will have negligible savings under most operations.

Integration & Cost

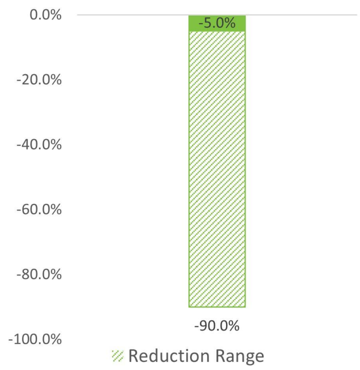
✓	**general compatibility for newbuild**	$$	**moderate newbuild CapEx**
✓	**general compatibility for retrofit**	$$	**moderate retrofit CapEx**
		-$/-$$	**moderate to significant OpEx savings**

- Proven as both newbuild and retrofit technology with multiple installations in both cases.
- "Wind-ready" arrangements available for future installation, including foundations or rails.
- **Integration primarily above deck, with limited modifications to machinery spaces and auxiliary systems. Cost for newbuild or retrofit is therefore similar.**
- Folding installations require new or increased hydraulic system capacity to actuate equipment.
- Rotor motors require electrical input, increasing load on generators. For DEP vessels, this will be offset by reduced propulsion load.
- Norsepower rotor sails are available in five sizes, varying from 30 to 143 kW rated power, all compatible with low voltage networks (380-690 volts AC) [A68].

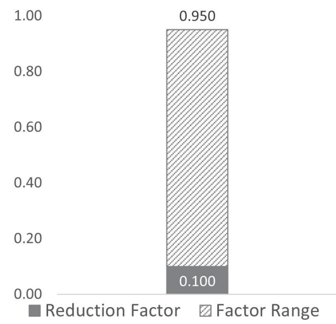
Link to Guide Navigator

Rigid Wingsails

PERCENT REDUCTION



REDUCTION FACTOR (RFₑ)



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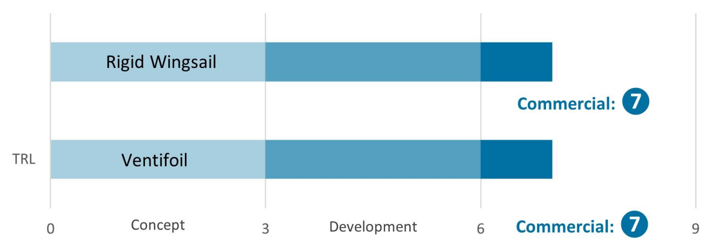


APPLICATIONS

MW	Duty					
>10	Continuous	marginal	marginal	poor	marginal	poor
	Intermittent		marginal	poor	marginal	poor
1-10	Continuous	marginal	marginal	poor	poor	poor
	Intermittent		poor	poor	poor	poor
<1	Intermittent		poor	poor	poor	poor

MW: Propulsion Power plant size, in MW

Compatibility: general / marginal / poor

INTEGRATION

		OpEx	CapEx
Newbuild	✓ (general)	-$/-$$	$$
Retrofit	✗ (poor)		$$$

KEY FACTORS

- May impart high heeling moment, impacting vessel motions and stability
- Different features include solar panels and retractable/foldable wings
- Ventifoil developed for different installation configurations, including retrofit
- Reduction potential depends on extent of installation, primarily sail area
- Four-sail system installed on newbuild VLCC (*New Aden*, IMO no. 9331359)
- Not suitable for vessels with on-deck cargo operations (container/bulk)
- Most designs require newbuild vessel specifically designed for technology
- OpEx savings proportionate to installation size, i.e. capital investment

Link to Dashboard Legend

Overview

Rigid wingsails more closely resemble traditional cloth sails than the previously discussed wind technologies and operate in a similar fashion to cloth sails. A wingsail is essentially an airfoil (similar to an airplane wing) attached vertically to a mast on the main deck.

The angle of attack and camber are adjusted by rotating either the leading or trailing edge of the wingsail around the mast. The sail shape and direction relative to the wind determines the direction and magnitude of thrust imparted on the vessel. If wind conditions allow, a forward or reverse thrust can be developed. If angle of attack cannot be optimized through the rotation of the wingsail, the vessel's heading can be changed for a maximum thrust, analogous to traditional tacking or jibing. Where the wingsail is providing thrust that is supplemental to main thrust from propulsion, adjustments to the heading to benefit the sail thrust may degrade the net energy reductions by increasing main propulsion energy.

While these sails are easy to operate (especially with development of automated controls) and very efficient, they require deck space in highly utilized areas, making them unsuitable for many vessel types and arrangements. **They also may impart a significant heeling moment due to their height above deck, having adverse effects on vessel motions and potentially stability**.

Figure 86: Ventifoil container units installed on *Lady Christina*, IMO no. 9201815 (source: tradewindsnews.com)

There are numerous developers competing to commercialize rigid wingsails. Most developers are advancing unique features that either improve the energy reduction potential or enhance the equipment's practicality for commercial shipping:

- Eco Marine Power's Aquarius MRE system, adapted from their EnergySail concept, **integrates the wingsail with solar panels and energy storage to maximize energy recovery** [B53].

- Wallenius Wilhelmsen is **developing a telescoping sail for their Orcelle Wind RoRo concept** [B54], as well as a folding and tiling sail for the Oceanbird cargo ship concept [B55].
- The Windship groups three wings onto a single mast fixture to reduce deck area interference [B56].
- Econowind's Ventifoil **is foldable and optimizes air flow by pumping air away from the boundary layer** on the trailing edge [B67].

These technology variations are shown in Figure 87.

Figure 87: Various rigid wingsail technologies, clockwise from upper left: Aquarius MRE (Eco Marine Power), Orcelle Wind (Wallenius Wilhelmsen), Wingship (Wingship), and Ventifoil retrofit (Econowind)

The Ventifoil technology is unique in several aspects. First, it uses an internal fan to circulate boundary layer air away from the sail through vents, improving flow characteristics and consequently thrust generation. Second, **Ventifoil has been developed to be configurable for different applications: a flat-rack package for ISO corner fittings, a containerized unit** as shown in Figure 86, and standalone units to be installed on a foundation, as installed on the MV *Ankie* (IMO no. 9331359) in Figure 87 [C29].

The VLCC *New Aden* (IMO no. 9912000) is a newbuild tanker fitted with four 40-meter wingsails [C30]. The technology was developed in cooperation between the owner, China Merchants Group, Dalian Shipbuilding's R&D department, and Guangwei Composite Materials. The *New Aden* is shown in Figure 88.

Figure 88: VLCC *New Aden* (IMO no. 9912000) fitted with four 40-meter wingsails (source: Marine Log)

The other leading manufacturers have coupled their wingsail technologies with purpose-designed vessel concepts, and have not advanced toward prototype or demonstration installations.

Reduction Potential (as % of total energy demand): -5 to -90%

- **Reduction potential depends on extent of installation, including sail area and number of masts.**
- Wingsail can either supplement or completely replace traditional propulsion, however most vessel trades and services would not be commercially viable under wind power only.
- MOL estimates 5 to 8% fuel savings for single sail installation on Wind Challenger concept [B58].
- BAR Technologies estimates 30% fuel savings for WindWings technology integrated on large bulkers or tankers, when combined with route optimization [B59].
- Wallenius Wilhelmsen is targeting up to 90% emissions reductions for the wind-power-only Orcelle Wind project, assumed to be through main propulsion energy reduction, and therefore fuel reduction. This would indicate emissions reductions for GHG as well as criteria emissions. The remaining emissions are presumably for powering auxiliary loads and systems onboard [B54].

TRL Rigid Wingsail: 7 Ventifoil: 7

- Econowind's Ventifoil has been demonstrated as a containerized and permanent retrofit technology on commercial cargo vessels. MV *Ankie* (IMO no. 9331359) retrofit qualifies as a TRL 7.
- **Four 40-meter (1,200 m2 total sail area) wingsails are installed on the New Aden (IMO no. 9912000) under China Classification Society oversight.**
- Other wingsail technologies have achieved class society approval-in-principle, but have not installed or tested equipment on a marine vessel:
  - WindWings gains DNV AiP [B59].
  - Aquarius MRE gains ClassNK AiP [B53].
  - Wind Challenger gains ClassNK AiP [B58].
- Some technologies have been tested in laboratory environments, but most are still in concept planning.

Applications

- Primarily suited for large oceangoing vessels with flexibility in on-deck arrangements. RoRos and some tankers are new design candidates for incorporating wingsails.
- **Vessels with on-deck cargo operations, such as containerships and bulk carriers, are generally not compatible**.
- Requires access to favorable wind conditions, offers more directional flexibility than kite sails but less than rotor sails.
- Not suitable for service vessels, particularly small inland/coastal vessels, with limited deck space and variable route patterns.

Integration & Cost

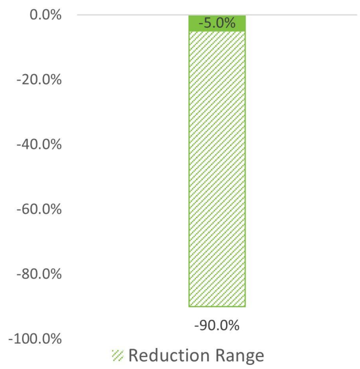
✓	**general compatibility for newbuild**	$$	**moderate newbuild CapEx**
⊗	**poor compatibility for retrofit***	$$$	**significant retrofit CapEx***
		-$/-$$	**moderate to significant OpEx savings**

*retrofit compatibility and cost are for most rigid wingsails. Ventifoil technology is proven as a retrofit solution and may cost less to install.

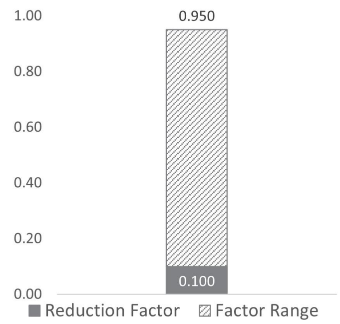
- Rigid wingsails generally take up considerable deck space which may affect vessel operations.
- Power input is minimal, primarily for controlling wingsail position such as angle of attack to optimize flow and thrust.
    - Exception is Ventifoil which requires power for mechanical blowers to circulate air. A 16-meter ventifoil requires 38 kW power (400-460 volts AC) for a claimed 200 kW reduction in propulsion power [A69].
- Compatibility for retrofit is poor for most wingsails, and technologies are generally being developed for newbuild concepts.
- Retrofit specifically for Ventifoil technology has been proven, but likely not compatible with many vessel types.
- **To maximize the benefits of wingsails, a vessel would likely have to be specifically designed for their implementation**. Retrofit would be challenging due to the deck space required, existing mission requirements and ship-to-shore interfaces, and stability impacts of installing heavy equipment high above the deck.
- Combined capital expense of both equipment package and incorporation into design and construction is expected to be high. May be offset if vessel can downsize or eliminate conventional propulsion plant.
- **Operating expense savings depends on size of installation, and is proportional to the CapEx, i.e., larger expensive installations will yield greater energy reductions and OpEx savings.**

Flexible Sails

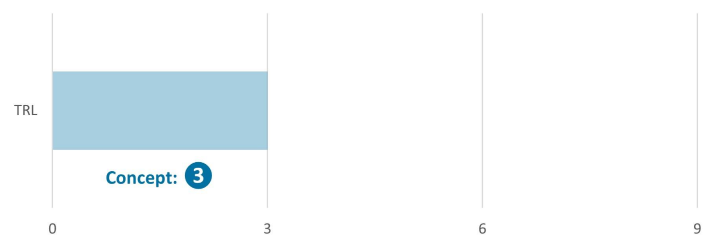
PERCENT REDUCTION



REDUCTION FACTOR (RFₑ)



TRL



APPLICATIONS

MW	Duty					
>10	Continuous	marginal	marginal	marginal	marginal	poor
	Intermittent		marginal	poor	marginal	poor
1-10	Continuous	marginal	marginal	poor	poor	poor
	Intermittent		poor	poor	poor	poor
<1	Intermittent		poor	poor	poor	poor

MW: Propulsion Power plant size, in MW

Compatibility: general marginal poor

INTEGRATION

		OpEx	CapEx
Newbuild	general	-$/-$$	$$
Retrofit	poor		$$$

KEY FACTORS

- Primarily being developed for luxury small-sized cruise and yacht industries
- Commercial concepts include Neoliner and Dykstra's WASP
- Reduction potential depends on extent of installation, primarily sail area
- Not suitable for vessels with on-deck cargo operations (container/bulk)
- Most designs require newbuild vessel specifically designed for technology
- OpEx savings proportionate to installation size, i.e. capital investment

Link to Dashboard Legend

Overview

Modern flexible sail technologies are also being pursued by developers but are primarily geared toward the luxury small-sized cruise and yacht industries. While conventional cloth sails have been in-use for centuries, modern marine-commercial technologies are still in the concept stage of development.

Synthetic sails are advantageous in that they are lightweight, using modern materials that are robust and readily repairable, and they are effective at providing thrust through a wide range of wind directions. Scaling from luxury small-sized cruise and yacht applications to commercial vessels, particularly those engaged in oceangoing trade, is challenging. This is due to the sail area, mast height, and amount of sail material becoming cumbersome to deploy, requiring more specialized equipment with high capacities and load ratings. To be an effective system for modern vessel crews, automation is of utmost importance for launch/retrieval and operation under varying wind conditions.

Neoline's Neoliner concept is a leading example of flexible sail commercial development, shown in Figure 89. The Neoliner is a 136-meter concept that has partnered with Michelin to transport tires in a transatlantic trade from Canada to France [B59]. Michelin plans to start the trade in 2023 using conventional cargo ships, with the ambition of eventually using a wind-powered Neoliner.

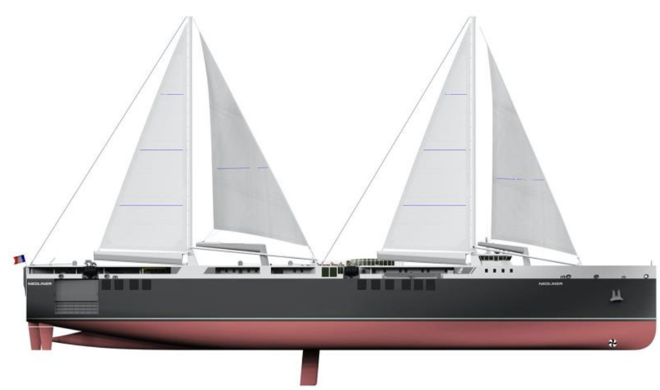


Figure 89: Neoliner cargo ship concept (source: greencarcongress.com)

Dykstra has developed the WASP (formerly Ecoliner) concept, a 138-meter cargo ship with 4,000 m² sail area, shown in Figure 90 [B60]. Dykstra plans to use its proven Dynarig technology, notable for its use on the sailing yacht *Maltese Falcon*.

Most other developers are primarily focused on the luxury cruise and yacht industry.

Figure 90: WASP cargo ship concept (source: Dykstra)

Reduction Potential (as % of total energy demand): -5 to -90%

- **Assumed similar reduction to potential to rigid wingsails, based on extent of installation and whether sail power is supplemental or a replacement for propulsion**. A 90% fuel reduction due to reduced main propulsion energy corresponds with a 90% reduction in energy.
- Lightweight materials used in flexible sails may improve energy reduction by reducing weight.

TRL: 3

- Sail technology is mature, but adaption to commercial shipping requires more development and testing.
- Commercial shipping designs are becoming more abundant but still in concept stage.

Applications

Applications are similar to rigid wingsails:

- Primarily suited for large oceangoing vessels with flexibility in on-deck arrangements.
- **Vessels with on-deck cargo operations, such as containerships and bulk carriers, are generally not compatible**.
- Requires access to favorable wind conditions, offers more directional flexibility than kite sails but less than rotor sails.
- Not suitable for service vessels, particularly small inland/coastal vessels, with limited deck space and variable route patterns.

Integration & Cost

✓	**general compatibility for newbuild**	$$	**moderate newbuild CapEx**
⊗	**poor compatibility for retrofit***	$$$	**significant retrofit CapEx**
		-$/-$$	**moderate to significant OpEx savings**

Integration & cost considerations are similar to rigid wingsails:

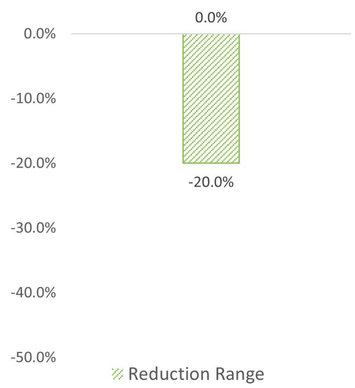
- Flexible sails generally take up considerable deck space which may affect vessel operations.
- Power input is minimal, primarily for controlling sail position such as angle of attack to optimize flow and thrust.
- Compatibility for retrofit is poor, and technologies are generally being developed for newbuild concepts.

- **To maximize the benefits of flexible sails, a vessel would likely have to be specifically designed for their implementation**. Retrofit would be challenging due to the deck space required, existing mission requirements and ship-to-shore interfaces, and stability impacts of installing heavy equipment high above the deck.
- Combined capital expense of both equipment package and incorporation into design and construction is expected to be high. May be offset if vessel can downsize or eliminate conventional propulsion plant.
- **Operating expense savings depends on size of installation, and is proportional to the CapEx, i.e., larger expensive installations will yield greater energy reductions and OpEx savings.**

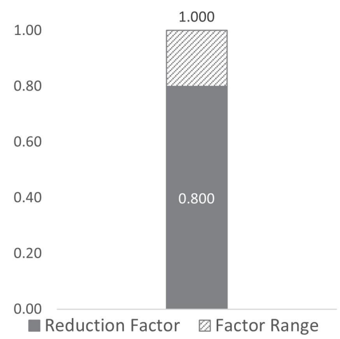
Link to Guide Navigator

Inflatable Sails

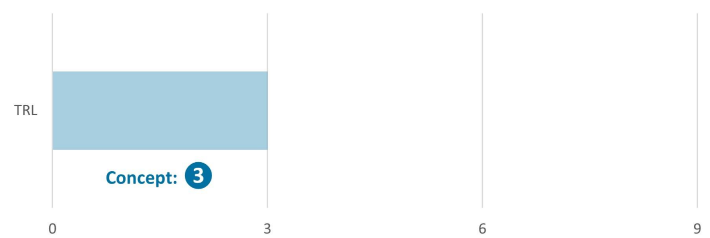
PERCENT REDUCTION



REDUCTION FACTOR (RFe)



TRL



APPLICATIONS

MW	Duty					
>10	Continuous	general	general	marginal	marginal	marginal
	Intermittent		marginal	poor	marginal	poor
1-10	Continuous	general	marginal	marginal	marginal	poor
	Intermittent		marginal	poor	marginal	poor
<1	Intermittent		poor	poor	poor	poor

MW: Propulsion Power plant size, in MW

Compatibility: general marginal poor

INTEGRATION

		OpEx	CapEx
Newbuild	general	-$/-$$	$$
Retrofit	marginal		$$

KEY FACTORS

- Sails are fully retractable, allowing cargo operations on deck
- At concept level, readiness could improve if Michelin pilot is successful
- Could be adapted to service vessels in addition to cargo vessels
- Planned as propulsion booster, not majority replacement

Link to Dashboard Legend

Overview

An intriguing alternative to rigid wingsails is an emerging inflatable sail technology. The concept is still nascent, but has the potential to eliminate or reduce some of the drawbacks of rigid sail approaches. Michelin Group announced the Wing Sail Mobility project, or WISAMO, in 2021 [B61].

WISAMO was first demonstrated on a 40-foot sailing yacht, and is now planned for a 100 m^2 sail area pilot on the RoRo containership MN *Pelican* (IMO no. 9170999) for some time in 2022 or 2023 [C31]. The WISAMO technology is shown in a concept rendering in Figure 91. The sail and mast is essentially a telescoping system with no internal structure.

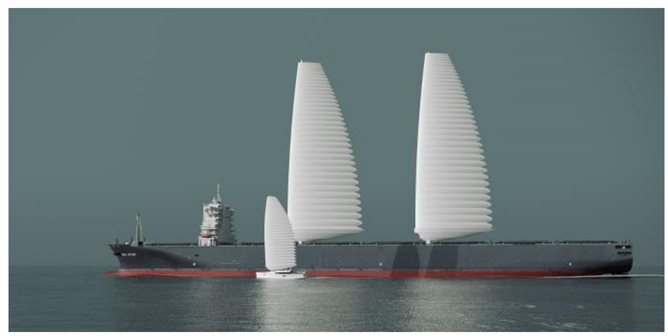


Figure 91: WISAMO inflatable sails (source: Michelin via cnn.com)

Inflated Wing Sails has deployed prototype systems for recreational sailing, and is exploring commercial shipping applications [B62].

Inflatable sails have a couple of key advantages over rigid wingsails or flexible mast-mounted sails. **The inflatable structure allows sails to be fully retracted when in port or under unfavorable wind conditions.** This is ideal for cargo ships that have on-deck operations, such as containerships and bulk carriers. Without a rigid structure, weight and space required for the sail is considerably reduced.

However, the robustness and durability of the sail material is not known and should undergo rigorous endurance testing prior to commercial uptake. Details on the deployment and retraction systems are also not publicly available. These systems would need to operate reliably in a marine environment.

Reduction Potential (as % of total energy demand): 0 to -20%

- Michelin is predicting 20% fuel savings for WISAMO system.
- Inflated Wing Sails is predicting 15% fuel savings.
- Currently no projects planning full propulsion replacement with inflatable sails.

TRL: 3

- Inflatable sails are currently at a concept stage with limited developers pursuing commercial solutions.
- Testing on small sailing yachts indicates proof of concept, but not scalability.
- **Technology readiness could improve quickly if prototype testing planned for 2022/2023 is successful**.

Applications

- Suitable for most oceangoing vessels, with lessened impact on deck arrangements, and ability to fully retract and stow for in-port cargo operations.
- **May have limited applicability for service vessels given more deck arrangement flexibility, but still not ideal for variable route patterns.**

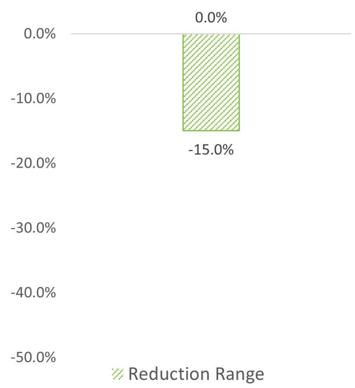
Integration & Cost

✓	**general compatibility for newbuild**	$$	**moderate newbuild CapEx**
○	**marginal compatibility for retrofit**	$$	**moderate retrofit CapEx**
		-$/-$$	**moderate to significant OpEx savings**

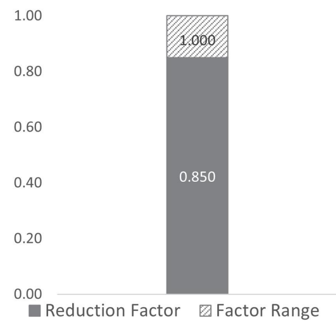
- While space above deck is occupied when sails are deployed, stowed condition should have little to no impact on deck operations.
- **Currently planned as supplemental to propulsion, requiring less deck space and improving retrofit compatibility over rigid sail technologies.**
- Discrete power input required to inflate and deflate sails. Operational power for controls not detailed in public materials.
- May not require vessel design to be specifically adapted to sail arrangement.

Wave-Assisted Propulsion

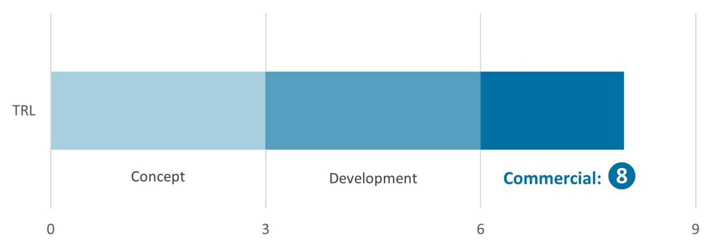
PERCENT REDUCTION



REDUCTION FACTOR (RFₑ)



TRL



APPLICATIONS

MW	Duty					
>10	Continuous	poor	poor	poor	poor	poor
	Intermittent		poor	poor	poor	poor
1-10	Continuous	general	general	general	marginal	marginal
	Intermittent		general	marginal	poor	poor
<1	Intermittent		poor	poor	poor	poor

MW: Propulsion Power plant size, in MW

Compatibility: general, marginal, poor

INTEGRATION

		OpEx	CapEx
Newbuild	general	-$/-$$	$$
Retrofit	marginal		$$

KEY FACTORS

- Retractable foils to not induce calm-water drag or interfere with docking
- Bow foils provide pitch damping in heavy seas
- Suitable for vessels under 200 meters with adequate pitching motion
- Can be retrofitted but requires suitable bow geometry for machinery
- Deployed with motors, but no input power once deployed.

Link to Dashboard Legend

Overview

Concepts and prototypes of thrust-generating bow foils have been around for more than a century. A bow foil consists of a pair of horizontal hydrofoil wings that convert movement of water over the surface to useful thrust. Thrust is generated by a combination of the wave and resulting pitching of the vessel. A variation of the bow foil was demonstrated on the 9.5-meter *Suntory Mermaid II*, which has two hydrofoils fixed between its catamaran hulls that propelled the vessel from Hawaii to Japan in 2008 at an average speed of 1.5 knots (Figure 92).

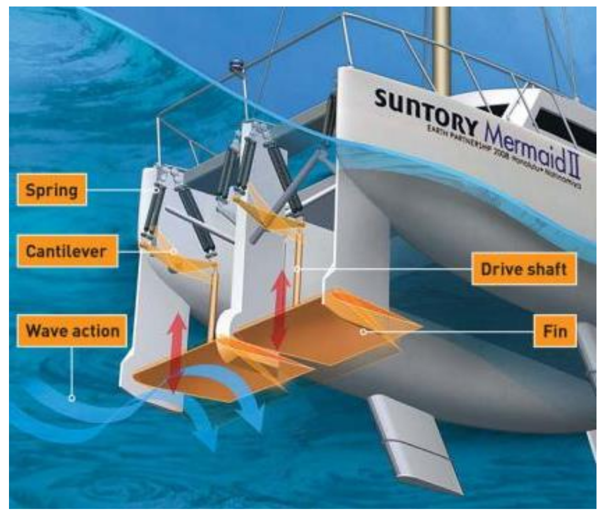


Figure 92: *Suntory Mermaid* hydrofoil propulsion technology (source: proboat.com)

Demonstrations have evolved from fixed appendages to fully retractable systems. **Retractable foils are necessary to not induce resistance in calm waters or interfere with docking procedures**. Wavefoil is the only technology developer with a fully retractable bow foil product, shown in Figure 93 [B63]. Wavefoil deployed a full-scale system on the 45-meter passenger vessel MF *Teistin* (IMO no. 9226102) in 2019 [C32]. The *Teistin* is on an interisland service in the Faroe Islands, operating regularly in heavy seas and strong tidal current. The conditions are ideal for testing a bow foil installation, and Wavefoil initially reported 10% fuel savings on the *Teistin*'s normal route.

Wavefoil has partnered with EireComposites and I P Huse to manufacture the composite foils and retracting machinery, respectively, for its largest model [A70]. The WF5910 model is intended for vessels between 100 and 200m in length. Wavefoil claims the technology is best paired with vessels under 200m, indicating pitching motion that is less prominent on larger vessels may be critical to generating appreciable thrust. It is therefore assumed that the technology does not scale well to larger cargo vessels with limited pitching motion.

In addition to thrust, bow foils generate a damping force in the vertical direction which can reduce vessel motions in a heavy seaway, and thus improve seakeeping. Passenger vessels in particular could benefit from reduced pitching motion, even without major propulsion savings.

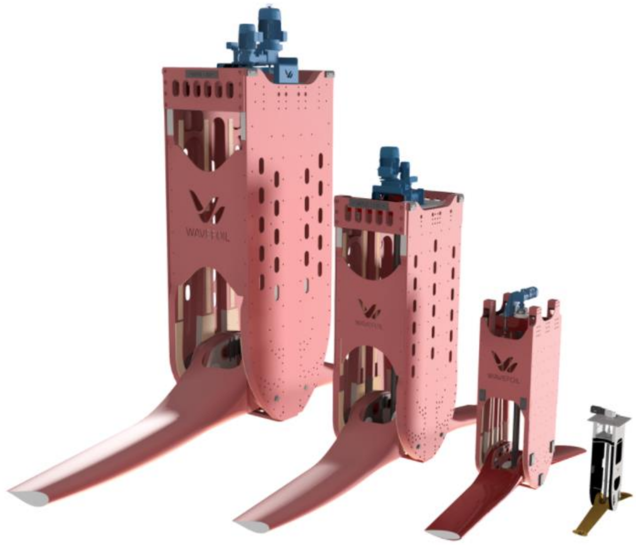


Figure 93: Wavefoil's retractable bow foils in multiple sizes (source: marinelink.com)

Reduction Potential (as % of total energy demand): 0 to -15%

- 10% fuel savings initially reported by Wavefoil on first demonstration, claims up to 15% savings are possible [C32].
- Reduction potential dependent on pitching motion of vessel and exposure to wave-rich seas.

TRL: 8

- Full-scale system demonstrated on 45-meter MF *Teistin* (IMO no. 9226102).
- Pilot installations completed on small passenger and ambulance vessels where pitch damping is primary benefit.
- Only one major equipment developer.

Applications

- **Suitable for vessels under 200-meter with reasonable pitching motion.**
- Not suitable for achieving energy reductions on large cargo vessels, cruise ships or inland vessels with minimal pitching.
- Highest savings on vessels that are normally in transit. No energy reduction while loitering or operating on-station.
- Pitch damping ideal for small passenger vessels, as well as ambulance vessels servicing remote areas.

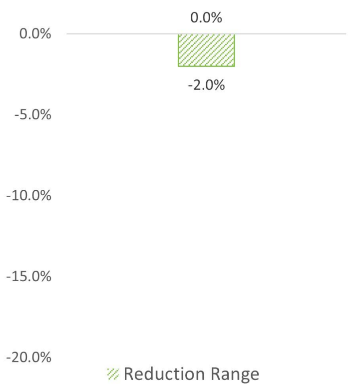
Integration & Cost

✓	**general compatibility for newbuild**	$$	**moderate newbuild CapEx**
○	**marginal compatibility for retrofit**	$$	**moderate retrofit CapEx**
		-$/-$$	**moderate to significant OpEx savings**

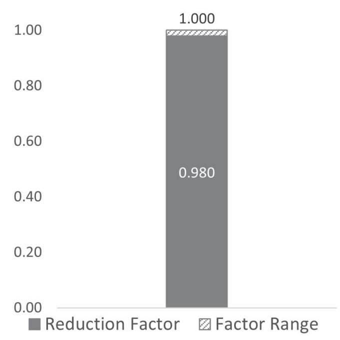
- Retractable arrangement improves versatility but increases size and cost of integration.
- **Proven to be retrofitted, but requires suitable bow geometry and space for retracting mechanism.**
- **Device uses electrical motors to deploy, but is passive once deployed.** Motors are shown on top of units in Figure 93.

Solar Power

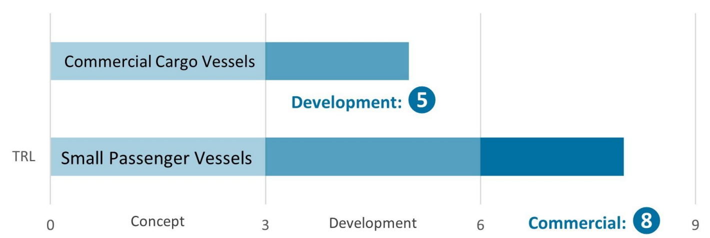
PERCENT REDUCTION



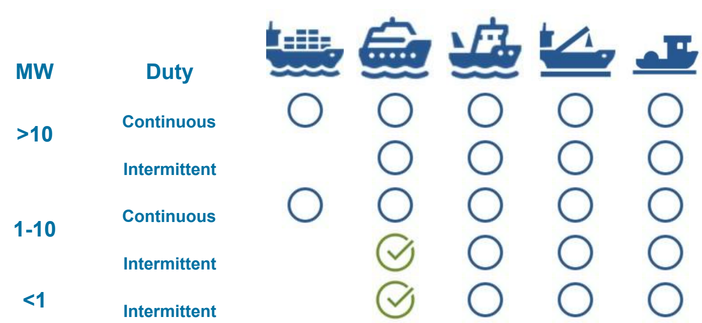
REDUCTION FACTOR (RFₑ)



TRL



APPLICATIONS



MW: Propulsion Power plant size, in MW

Compatibility: general marginal poor

INTEGRATION

		OpEx	CapEx
Newbuild	✓ (general)	-$	$/$$
Retrofit	○ (marginal)		$/$$

KEY FACTORS

- Difficult to locate surface area for useful solar power generation
- Solar on most vessels expected to achieve less than 2% energy reduction
- Small passenger vessels with light operations may be 100% solar-powered
- Retrofit is feasible, but not practical to install solar panels in many locations

Link to Dashboard Legend

Overview

Onboard solar power (utilizing solar panels) is capable of providing part of a vessel's electricity generation for auxiliary loads, but not likely as a stand-alone power source. Directly harnessing solar energy onboard has been demonstrated on several vessels, however, the incident solar radiation is generally not adequate for propulsion of large or power-intense commercial vessels. Most vessels utilizing solar power are in a hybrid arrangement, with other renewable energy sources such as wind used to provide power.

Vessels with solar power need to employ energy storage to effectively utilize the solar energy, as irradiance is only available during daylight hours and solar panels have a relatively low energy density per area. For vessels operating in areas with high solar irradiance and transiting short distance, solar may have more operational upside.

The amount of power that can be harnessed depends greatly on a vessel's surface availability, particularly surfaces that are oriented near horizontal. Vessels with horizontal areas that serve as working decks cannot convert large areas for solar power, and vertical surfaces are not effective at absorbing energy through long periods of daylight, and also depend on the direction of the vessel to ensure exposure to irradiance.

The passenger ferry *Aditya*, developed by Navalt Boats was successful in designing a horizontal roof and overhang over the main deck, achieving up to 20kW of power generation for the 2 x 20 kW propulsion motors. The 20-meter, 75-passenger ferry has an operating speed of 5.5 knots, and has 6 hours of operational endurance in ideal sun conditions. On low irradiance days, *Aditya* relies on shore charging to accomplish a reduced endurance of 4.5 hours [C33]. *Aditya* is shown in Figure 94.

Figure 94: *Aditya* passenger ferry with 20 kW of solar capacity (source: ewnsnews.com)

Ocius® was an early developer of solar-hybrid passenger vessels, including the *Solar Sailor* and *Solar Albatross*, but has since pivoted toward autonomous vessels and drones [B64]. Ocius® vessels are still in operation, however it is unknown to what extent the solar systems are being utilized. Other projects like the MS *Tûranor PlanetSolar* (IMO no. 8681630) are impressive in their utilization of solar power (the *PlanetSolar* circumnavigated the globe on solar power only from 2010 to 2012), but do not directly translate to commercial applications.

Both NYK Line and Nissan have demonstrated small solar projects by retrofitting car carriers with roof arrays of solar panels. The NYK Line project, installed on the *Auriga Leader* (IMO no. 9402718), only generated solar power equivalent to 0.05% of the vessel's propulsion and 1% of the auxiliary loads [C34]. Even if the size of the solar panel array was scaled up by an order of magnitude, it would be difficult to justify the cost of the installation compared to other energy efficiency opportunities.

NYK Line's Ecoship 2050 is a far more ambitious project, evolving from the EcoShip 2030 concept. The Ecoship 2050 concept is shown in Figure 95, maximizes surface area dedicated to solar panels with 9,000 m^2 utilized, and estimates 12% of its total energy demand planned to be generated from the solar panel arrays [B65]. This design is an idealized arrangement for solar power. **Most vessels across all types could not dedicate the same relative area to solar panels, yielding lower percentage of energy reduction**.

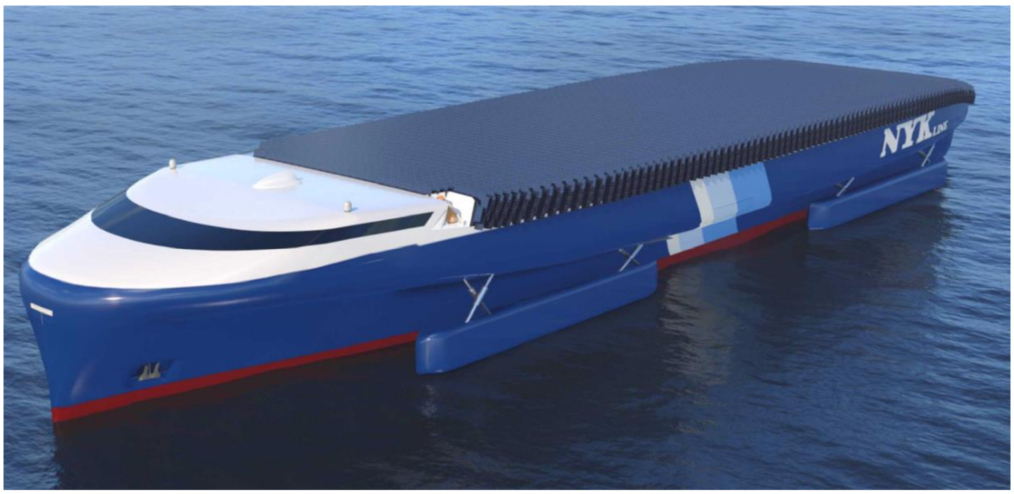


Figure 95: Ecoship 2050 concept with 9,000 m^2 of solar panels (source: NYK Line)

Installation of solar panels on commercial vessels will likely remain a niche application since many vessels cannot accommodate solar panels on deck.

Reduction Potential (as % of total energy demand): Commercial Vessels – 0 to -2% (Small Passenger Vessels – 0 to -100%)

- 12% is maximum electricity production using solar panels, based on idealized vessel concept, **but most vessels expected to achieve less than 2% electricity production**.
- Electricity production potential using solar panels highly dependent on vessel arrangement and availability of surfaces to mount panels.
- Small passenger vessels may achieve up to 100% energy reduction if operating profile is conducive to pure solar power.

TRL: Commercial Vessels – 5 (Small Passenger Vessels – 8)

- Solar panel technologies are mature and broadly proven in landside applications, but their demonstration and practicality on marine commercial vessels is limited.
- **Some small passenger vessels have demonstrated pure or hybrid solar power where transit distance and operating speed are limited.**
- Small-scale installations on commercial vessels have been technically successful but not yielded appreciable energy improvements.

Applications

- Suitable for niche operations, e.g., small passenger vessels with very low power demand.

- Feasible to install on most vessels at some scale, but generally not justified by low power generated.

Integration & Cost

✓	**general compatibility for newbuild**	$/$$	**minor to moderate newbuild CapEx**
○	**marginal compatibility for retrofit**	$/$$	**minor to moderate retrofit CapEx***
		-$	**moderate OpEx savings**

*costs are for commercial vessel applications. Some small passenger vessels may have relatively high CapEx to install but corresponding high OpEx savings from reduced fuel/electricity demand

- Solar panels can be readily incorporated into newbuild designs, primarily requiring deck or structural space and electrical interface.
- Photovoltaic (PV) panels typically consist of layered semi-conducting material such as silicon, and are commercially available globally.
- Material selection of metallic components to reduce corrosion is critical for marine applications, as well as electrical protection from salt air.
- Integration would require DC/DC converters for a DC bus, or a DC/AC inverter for an AC bus. A conceptual one-line power diagram for solar panel integration is shown in Figure 96.
- **Existing vessels may be retrofitted with solar panels, but finding adequate space may be challenging on many vessel arrangements.**
- Installation cost is dependent on size of array, with most installations being limited by available space.
- Except for a commercial vessel arranged with solar power as a design priority, electricity production using solar panels will be limited to less than 2% of vessel load, limiting OpEx savings.

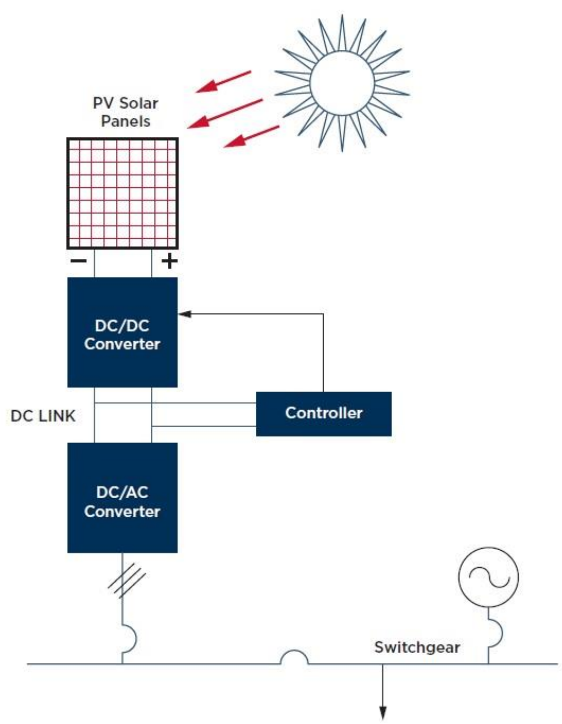


Figure 96: Conceptual one-line diagram for PV solar panel integration (source: ABS)

2.2 Fuel Technologies (FT)

Fuel technologies are fundamental to reducing criteria pollutants and GHG emissions that align with long-term goals, both national and international. While energy efficiency measures can reduce the energy and corresponding fuel required for various vessel operations, only zero-carbon and low-carbon fuels (from a Well-to-Wake perspective) can help bring vessel GHG emissions to near-zero levels.

In the context of this report, fuel technologies both encompass alternative fuels and the equipment (energy converter) that consumes the fuel and converts it into meaningful power for vessel operations. While the technology readiness level (TRL) of each fuel and each fuel consumer can be evaluated individually, their overall commercial readiness depends on the readiness of the corresponding feature, e.g., green hydrogen as a marine fuel only becomes commercially viable when hydrogen fuel cells or internal combustion engines achieve corresponding technology readiness.

Alternative fuels in this section are characterized by both their Fuel Emission Factor (Well-to-Tank and cumulative Well-to-Wake) and their specific fuel consumption value (SFC). A notional SFC for each fuel is established to normalize fuels based on their potential to generate power for vessel propulsion and auxiliary loads.

The energy density landscape of different marine fuels is illustrated in a graphic developed by DNV (for SEA-LNG), shown in Figure 97. Compressed and liquefied fuels that require specialized storage have arrows representing energy density adjusted for those storage arrangements. This graphic will be referred to throughout the Fuel Technologies section.

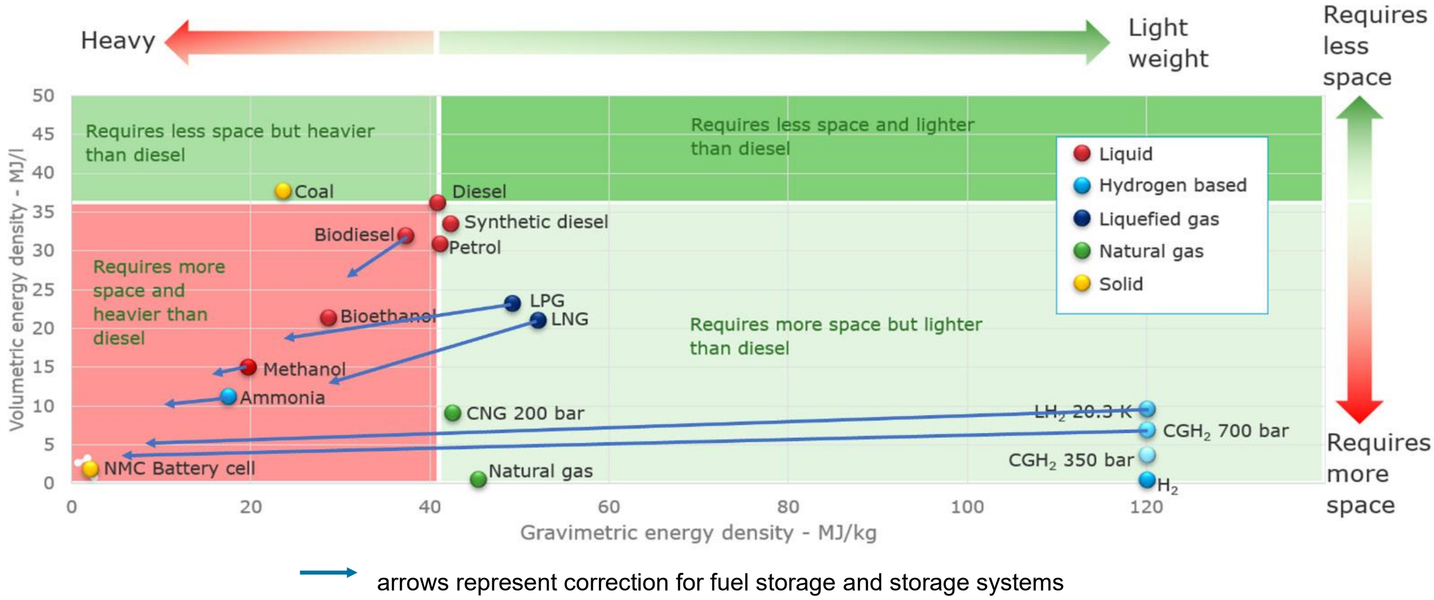


Figure 97: Energy densities for different energy carriers (source: DNV)

Ultimately, conventional marine fuels like MGO and HFO are superior to essentially all alternative fuels in terms of energy density. As a result, more mass of alternative fuels must be consumed to achieve the equal energy yielded of a baseline conventional fuel. Some drop-in biofuels are the exception, which have equivalent or slightly better energy density than their petroleum-based counterparts. SFC is reported for each fuel type detailed in this section, and it's use in CO_2 and CO_2e Performance Value (CPV, CePV) calculations is further detailed in Section 1.3.

The Fuel Technologies (FT) considered in this guide are summarized in Table 10, including the results of the technology evaluation. Each technology evaluation is detailed in the technology's section of the guide, which can be viewed by clicking on the name in the first column.

Table 10: Fuel Technologies (FT) Summary

Technology	Consumer	WtW Emission Factor EF_f g CO_2e /MJ fuel		TRL	Newbuild	Retrofit	OpEx
		gray	green				
Transitional Fuels	*overview only*						
Hydrogen	Fuel Cell	71	0.2	7-8	✓	✗	$$$ (gray)
	ICE	78	25				
Ammonia	Fuel Cell	241	21	4	✓	✗	$$$ (gray)
	ICE	199	44				
Biofuels	*overview only*						
Fischer Tropsch Diesel	ICE	103	10	4	✓	✓	$$$ (green)
Methanol	ICE	96	29	8	✓	✓	$$ (gray) $$$ (green)
ICE Technology	-	-	-	4/5/8*	-	-	-
Fuel Cell Technology	-	-	-	9/4**	-	-	-
Fuel-Ready Vessel Design	*overview only*						
oCCS - absorption	-	54 – 58	-	5	○	✗	$$
oCCS - cryogenic	-	48 – 52	-	3			
Marine Nuclear Power	*overview only*						

* ICE technology TRL values are for hydrogen (4), ammonia (5), and methanol (8), respectively.

** FC technology TRL values are for PEM-FC (9) and all other fuel cell types (4) respectively.

Fuel Colors

Color Categorization

There are a variety of published approaches to applying a color scale to fuel types. This guide uses a simple approach: green fuels are those derived from sustainable or renewable sources; gray fuels are those derived from fossil-based sources. The color applied to a fuel is a categorization of how the fuel is sourced (feedstock and pathway), and not directly reflective of a numerical GHG intensity. Carbon intensity is instead characterized by the emission factors provided for each fuel in this guide. Fuel colors and example fuel sources are provided Table 11. A definition for blue fuels is also provided. Blue fuels are not reviewed in this guide, as the readiness of fuel production coupled with carbon capture, utilization and/or storage (CCUS) does not indicate whether it will play a major role in marine fuel supply chains.

Table 11 Fuel color definitions

Fuel Color	Definition	Example Energy Sources
Green	A fuel derived from a sustainable, renewable, or established nuclear source.	• Sustainable biogenic sources ○ Agriculture: oil/sugar/starch crops, lignocellulosic crops ○ Waste: industrial organic waste, food waste, municipal solids organic waste, animal waste ○ Residues: crop, forest ○ Forestry: sustainable wood extractives ○ Aquaculture: microalgae, macroalgae • Renewable electricity for generating electrofuels* (wind, solar, hydroelectric, geothermal, biomass, etc.) • Nuclear electricity (uranium) for generating electrofuels*
Gray	A fuel derived from a fossil-based source.	• Crude oil • Natural gas • Coal • Fossil wastes (fossil-based plastics) • Fossil-based electricity for generating electrofuels*
Blue	A fuel derived from gray sources coupled with carbon capture, utilization and/or storage (CCUS).	• Land-based CCUS not reviewed in this guide *A notional capture percentage can be applied to estimate blue fuel emission factors. See sub-section on* Blue Hydrogen *for more information.*

*Electrofuels are fuels produced by water electrolysis using electricity from any source, e.g., hydrogen from water electrolysis and its derivatives (e-methanol, e-ammonia).

This guide does not evaluate biofuels derived from feedstocks that displace other crops and therefore diminish their lifecycle potential to reduce GHG emissions. By requiring land use change (direct, dLUC, or indirect, iLUC) for production, the categorization of these fuels as sustainable or non-sustainable is ambiguous. Such fuels include first-generation biofuels produced from soy oil or palm oil, and hydrotreated bio-oils and biodiesel/FAME (transesterification of bio-oils) produced from sugar or corn (ethanol).

Composite Fuels

This guide focuses on emissions characteristics for fuels that are assumed to be either 100% green or 100% gray. In reality, many fuels that become available to the marine market may be a composite of sources, i.e., a feedstock/pathway blend. If the percent composition of a fuel is known, the composite fuel's emissions factors can be determined by multiplying each component percentage by that source's emission factor, and summing the factors to produce a composite emission factor.

The following example demonstrates estimating a composite emission factor, using emission factors provided in the section on Hydrogen:

- A supplier's hydrogen product is reported to be 75% gray hydrogen (steam reforming of natural gas), and 25% green hydrogen (water electrolysis using renewable electricity).
- The hydrogen will be consumed in a vessel's marine fuel cell plant.
- Gray component emission factors:
    - WtT: 0.75 × 71 g CO_2e/MJ = 53.25 g CO_2e/MJ.
    - TtW: 0.75 × 0 g CO_2e/MJ = 0 g CO_2e/MJ.

- Green component emission factors:
  - WtT: 0.25 × 0 g CO_2e/MJ = 0 g CO_2e/MJ.
  - TtW: 0.25 × 0 g CO_2e/MJ = 0 g CO_2e/MJ.
- Composite emission factors:
  - WtT: 53.25 + 0 = **53.25 g CO_2e/MJ**.
  - TtW: 0 + 0 = **0 g CO_2e/MJ**.
  - WtW: 53.25 + 0 = **53.25 g CO_2e/MJ**.

Transitional Fuels

Carbon-based fuels with characteristics that result in reduced TtW emissions are taking the place of conventional marine fuels to varying degrees. These fuels are considered transitional fuels, as they have the potential to moderately reduce GHG emissions, but are limited in their long-term potential to achieve the GHG reduction goals set out by IMO. Natural gas, which is primarily methane, CH_4 (approximately 75% to 95% depending on the region of production), is the most prominent transitional fuel, and has been adopted as the primary fuel on over 750 marine vessels. Other transitional fuels discussed in this guide are ethane, petroleum gas, and dimethyl ether. These fuels are described in terms of their primary characteristics as marine fuels, and their advantages and drawbacks in that application. As transitional fuels, however, they are not evaluated for technology readiness or emissions reduction potential.

Natural Gas (Primarily Methane)

Natural gas, consisting of 75% to 90% methane (CH_4), can be stored in the maritime industry as either a liquid (LNG) or compressed gas (CNG). Natural gas has the benefit of containing very little sulfur, making it ideal as a fuel for reducing SOx and NOx emissions from combustion. It's potential to reduce GHG emissions on a lifecycle basis is less significant.

Natural gas's lower heating value (LHV) is 50 MJ/kg, giving a higher energy than MGO on a mass basis. However, natural gas liquefies at -162 °C (at atmospheric pressure), requiring cryogenic range of temperatures and insulated storage to maintain it in a liquid state at low pressure (less than 10 bar). Storage as a compressed gas requires less energy, but reduces the storage capacity for a given volume envelope. In the case of marine vessels, the volume required for fuel storage is constrained by the vessel size, complexity, carrying capacity, and stability characteristics. When adjusted for storage factors, the gravimetric energy density of LNG is estimated at 28 MJ/kg, or two thirds that of MGO. The adjusted volumetric energy density of LNG is about 13 MJ/liter, or one third that of MGO [A71]. As a compressed gas, CNG actually has a higher gravimetric energy density than MGO, but a volumetric density of about 9 MJ/liter, or one fourth that of MGO.

Physical properties of methane are provided in Table 12.

Table 12 Methane physical properties

Fuel	Flammable Range (%)	LHV* (MJ/kg)	Boiling temperature (°C)	Autoignition temperature (°C)
Methane	5 - 17	50.1	-162	537

Natural gas as a marine fuel is primarily combusted in dual fuel (DF) internal combustion engines (ICE), either in an Otto cycle (theoretical) where pre-combustion of a pilot fuel provides the spark ignition of natural gas, or in a Diesel cycle (theoretical) where the pilot fuel is pre-injected into the cylinder along with natural gas to enable compression ignition. In an Otto cycle dual fuel engine, a small portion of pilot fuel is required to provide the sparking energy, approximately 1 to 2% by mass. In the diesel cycle, fuel is either injected at low pressure or high pressure. For low-pressure injection, less than 1% pilot fuel is required, but a high compression ratio is required for ignition. For high pressure injection, a higher fraction of pilot fuel is required, around 4-5%, but does not require the same high compression ratio of a low-pressure injection system [A72]. The pilot fuel portion for these natural gas injection types is generally smaller than that of other alternative fuels like ammonia and methanol.

Marine approved dual fuel ICEs are available for each of these combustion types, comprising over 750 ships in operation or on order. Natural gas as a marine fuel and its associated engine technologies is fully commercialized.

The crux of natural gas as a decarbonizing fuel is its high WtT (source) GHG emissions. Fossil-based natural gas, or gray natural gas, is primarily derived from petroleum refining or direct shale gas extraction. It contains less carbon per unit energy than MGO and other conventional marine fuels, meaning it can reduce TtW emissions.

However, the extraction and production of fossil-based natural gas has a high carbon intensity. The lifecycle fuel emission factors for gray LNG (WtT, TtW, and cumulative WtW) are shown in Figure 98. When looking at CO_2 only, LNG has a lower WtT value than MGO (11.1 g CO_2/MJ compared to 13.5 g CO_2/MJ). However, when including other GHGs and their CO-equivalent, WtT emissions for natural gas is 30% higher than MGO (22.4 g GHG/MJ compared to 16.9 g GHG/MJ). This is primarily due to the incidental release of methane during natural gas extraction and production. Unreacted methane has 30 times the 100-year global warming potential of carbon dioxide, so even small amounts of methane release during the WtT segment can have significant impacts on the carbon intensity of natural gas as a fuel.

The WtW emission factor for LNG is still lower than MGO, but by a smaller factor than its TtW emission factor: 83% of MGO for WtW GHG emissions, compared to 72% of MGO for TtW.

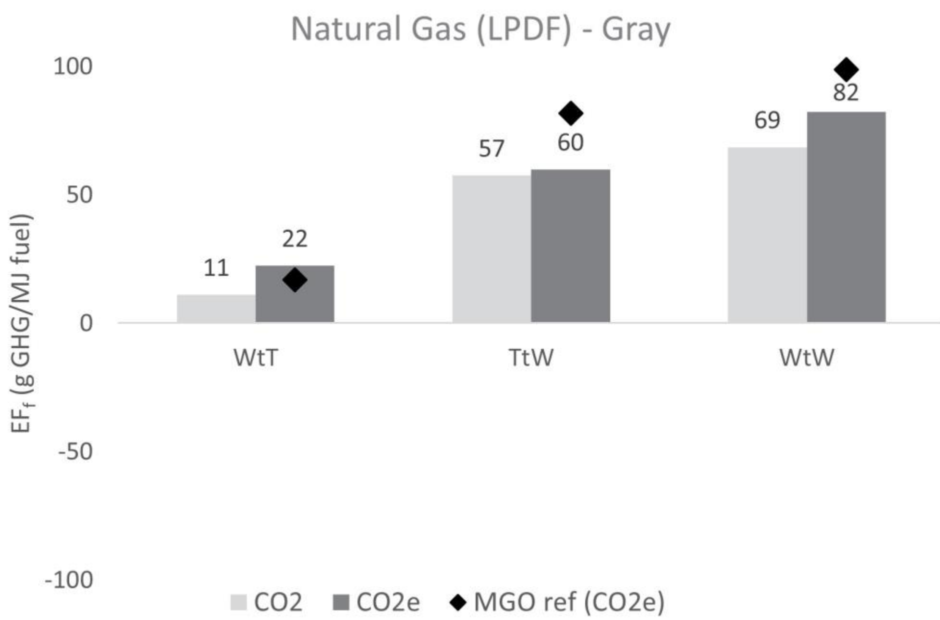


Figure 98: Lifecycle CO_2 and CO_2e emission factors for fossil-based natural gas, diesel cycle (low pressure dual fuel, LPDF)

Natural gas combustion also results in some amount of methane slip due to unburned fuel. If engine performance is not carefully managed in dual fuel engines burning natural gas, increased release of unburned methane could increase natural gas's TtW emission factor closer to that of MGO.

Bio-methane, or renewable natural gas (RNG) has potential to replace some of the demand for gray natural gas and provide a pathway to reducing WtW GHG emissions of LNG- and CNG-fueled vessels. RNG can be sourced from landfill biogas, sewage waste, or agricultural waste. RNG projects in the US have steadily increased over the past 15 years, as shown in Figure 99, but the scale of these projects is still limited, and primarily used for offsetting land-based (residential, commercial, vehicle) demands for natural gas. Synthetic natural gas (SNG) is also a more sustainable form of natural gas, produced by methanation, or the combination of CO_2 and H_2 that can be sourced from renewable electricity. Until sustainable feedstocks for natural gas are pursued more broadly, natural gas remains a transitional marine fuel rather than long-term decarbonizing fuel.

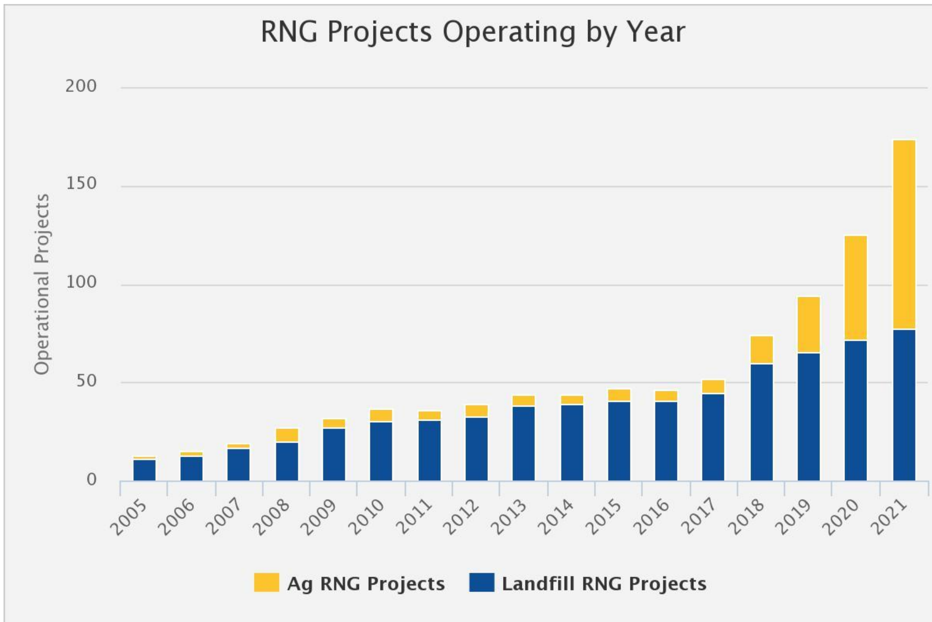


Figure 99: Landfill and agriculture RNG projects in the US (source: epa.gov)

Petroleum Gas (Propane, Butane)

Petroleum gas is a flammable mixture of hydrocarbons. There are predominantly two substances comprising liquefied petroleum gas (LPG): propane (C_3H_8), butane (C_4H_{10}). Propylene (C_3H_6) and other hydrocarbon compounds are also sometimes present. LPG carriers carry propane and butane as separate grades, as well as mixtures of commonly accepted ratios. Commercial grades of petroleum gas are either pure (100% propane or 100% butane) or representative (95% propane or 95% butane). Petroleum gas liquefies at a higher temperature than LNG, depending on the propane/butane composition. At 20 °C, it can be compressed to 8.4 bar to remain a liquid. This gives petroleum gas a storage advantage over natural gas: no cryogenic conditioning is required to maintain its liquid state.

Petroluem gas's LHV is around 45-46 MJ/kg, between natural gas and MGO. When adjusting for storage factors to keep it liquefied, LPG's gravimetric energy density is estimated at 24 MJ/kg, or just over one half that of MGO. The adjusted volumetric energy density is about 19 MJ/liter, higher than LNG but again only one half of MGO. In effect, LPG's properties allow more straightforward storage onboard vessels than LNG, but it cannot compete with MGO on energy density or storage practicality.

Petroleum gas's carbon content is about 0.83, higher than methane at 0.75, making it less practical for reducing GHG emissions.

Table 13 Propane and butane physical properties

Fuel	Flammable Range (%)	LHV* (MJ/kg)	Boiling temperature (°C)	Autoignition temperature (°C)
Propane	2 - 10	46.3	-42	450
Butane	2 - 9	45.7	-1	288

While there has been limited commercial uptake of LPG in the marine industry, dual fuel (DF) engines burning methane can be readily adapted to burn propane-butane. The first LPG-fueled vessel entered service in 2020, a BW LPG product carrier with its fuel supply systems retrofitted to enable propulsion engines to burn petroleum gas [C35]. LPG is advantageous in that there is no potential for methane slip. BW LPG has since ordered 15 Wartsila LPG fuel supply systems for new and retrofit projects.

Efforts to produce petroleum gas from sustainable sources are increasing, but a reliable, scalable pathway has not been established.

Figure 100: Pressurized LPG storage tanks installed on the *BW Gemini*, IMO no. 9703007 (source: BW LPG)

Ethane

Ethane (C_2H_6) is a hydrocarbon primarily used as a feedstock for ethylene in plastics production, and its production and consumption has gradually increased in the United States [A73]. Ethane liquefies at -89 °C (at atmospheric pressure). Ethane has also increasingly been used as a blending fuel with natural gas for grid power generation, due to its similar physical properties as shown in Table 14. Ethane has a lower methane number, making it less resistant to engine knock. Engine knock is discussed more in the section on ICE Technology. Ethane also has a higher carbon content than methane (0.8 vs 0.75), making it less practical for reducing GHG emissions.

Table 14 Ethane physical properties

Fuel	Flammable Range (%)	Methane Number*	LHV* (MJ/kg)	Boiling temperature (°C)	Autoignition temperature (°C)
Ethane	3 - 12	43	47.6	-89	515

*Methane number and LHV for ethane sourced from Wartsila.com

When it was determined that Evergas LNG-fueled product carriers on order would be exporting liquefied ethane gas (LEG), Wartsila worked with the vessel owner to develop and test a gas vaporizer and mixing unit to enable the vessels to also burn ethane from the cargo tank boiloff. Evergas's Dragon class *INEOS INTREPID* (IMO no. 9685449) became the first vessel powered by ethane in 2016 [C36], and did not require separate bunkering of LNG when transporting ethane as a cargo. With engines re-optimized for ethane, the new vessel class has enhanced fuel flexibility and reduced power consumption by not having to power its auxiliary LNG equipment when burning ethane from cargo tank boiloff.

The Dragon class conversion was a successful demonstration project for ethane as a marine fuel, but broader commercial development has not been pursued. Without significant combustion benefits that distinguish ethane from natural gas, its role as a marine fuel will be limited to fueling gas carriers on boiloff, or for blending with liquid and other gas fuels for improved engine performance.

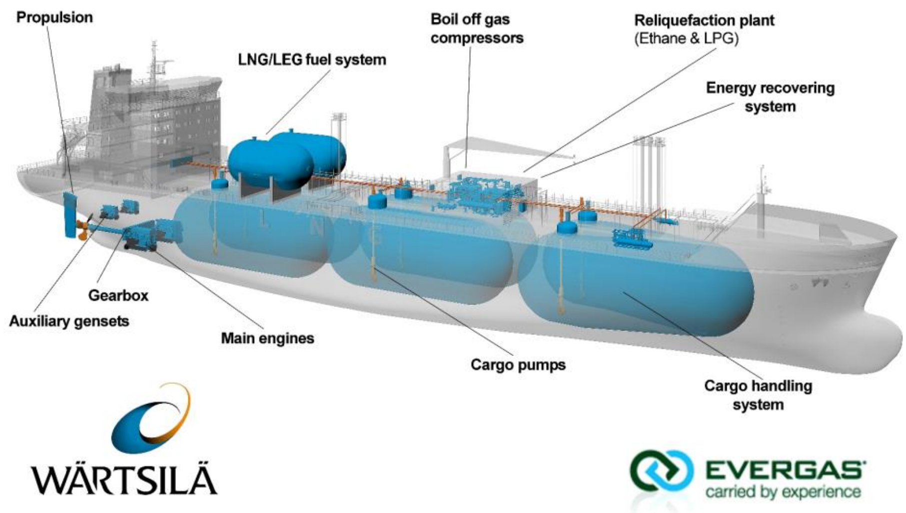


Figure 101: Evergas product carrier converted to burn ethane, stored in liquid form (source: Wartsila)

Dimethyl Ether

Dimethyl ether (DME) can be produced from biomass, methanol, and fossil fuels. DME can be produced directly from synthesis gas produced from natural gas, coal, or biomass, or indirectly from methanol via a dehydration reaction. Due to its combustion properties, it is largely considered as a blending fuel, and is not practical as a neat fuel (monofuel) or primary component in dual fuel use. Dimethyl ether from biomass is discussed as a blending fuel for reducing GHG emissions in the section on Biofuels.

VOC

In the maritime industry, the term volatile organic compounds (VOC) means the natural mixture of organic vapors that are released from crude oil and petroleum products during loading, storage, and transport. VOCs are found in the ullage, or head space, of cargo tanks and may contain small components of the cargo, including heavier hydrocarbons. The longer the cargo tank contains VOC gas, the larger the fraction of heavier hydrocarbons that will be present in the VOC mixture.

VOCs are seeing some increased interest as a marine fuel. VOCs are vented from oil carrier storage tanks during loading and storage and have harmful effects to human health. Some regions in the US regulate or prohibit the release of VOCs in ports near population centers. Liquefied VOCs (LVOC), sometimes referred to as a non-methane VOC (NMVOC), are the most viable VOC for fuel applications. If VOCs that would normally be vented to atmosphere are instead recovered and liquefied, they could offset fuel demand on oil carriers. An LVOC system would consist of two-stage condenser, pressurized storage, an evaporator, and fuel mixing unit. Semi-VOCs (SVOC) are less suitable to be repurposed as a marine fuel.

The Swiss engine manufacturer WinGD has tested capturing, processing, and mixing LVOC with LNG for combustion in a marine engine, optimizing the blend to minimize engine knock from the VOCs, which have a low methane number. The WinGD recovery and mixing system is represented in Figure 102.

VOCs are not scalable to be a replacement marine fuel, but they do have potential to reduce fuel consumption onboard crude oil and product tankers.

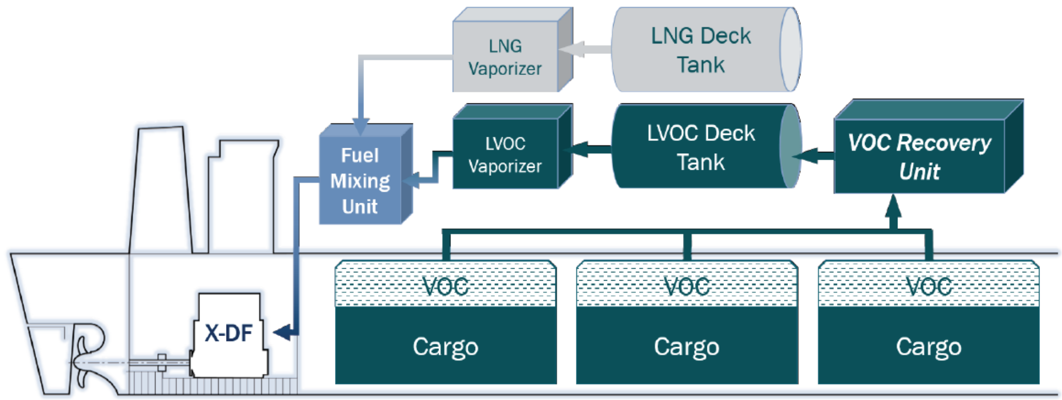


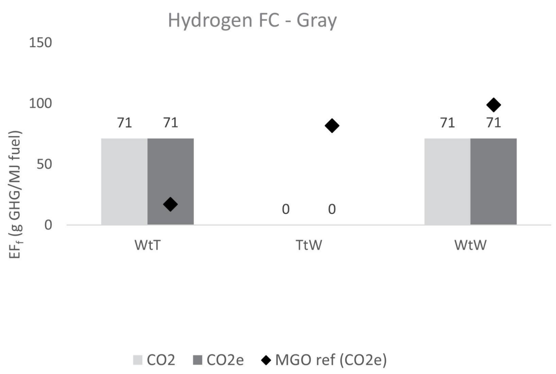
Figure 102: Concept diagram of WinGD VOC recovery fuel system (source: WinGD)

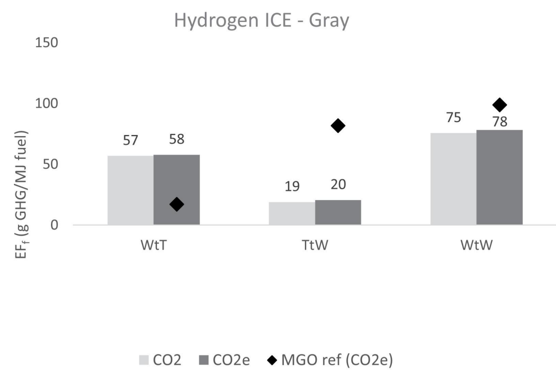
Link to Guide Navigator

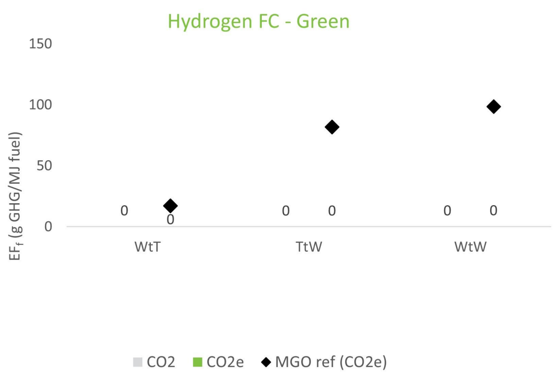
Hydrogen

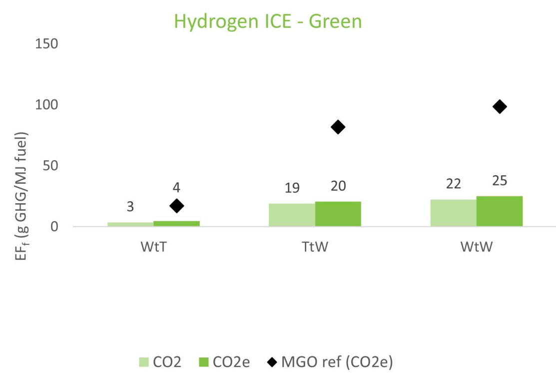
gray H_2 | green H_2 | fuel cell | internal combustion engine

FUEL EMISSION FACTOR (EF_f)

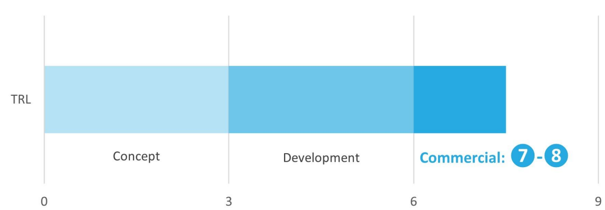








TRL



KEY FACTORS

- Available as fuel for either fuel cells or internal combustion engines
- 7.6 times MGO tank volume required for LH_2 (low pressure)
- Gray hydrogen is abundant, green hydrogen is not
- US-flagged vessels using hydrogen as a fuel will be reviewed case-by-case
- Medium-speed, 4-stroke ICE currently burn up to 75% hydrogen
- Vessel range and fueling schedule dictates compatibility
- Classed vessels have been delivered with plans to run on H2
- Gray hydrogen estimated to be 1 to 2.5 times price of MGO on energy basis

APPLICATIONS

MW	Duty	Vessel type 1	Vessel type 2	Vessel type 3	Vessel type 4	Vessel type 5
>10	Continuous	poor	poor	poor	poor	general
	Intermittent		poor	poor	poor	general
1-10	Continuous	marginal	marginal	marginal	marginal	general
	Intermittent		marginal	marginal	marginal	general
<1	Intermittent		marginal	poor	marginal	marginal

MW: Propulsion power plant size, in MW

general compatibility | marginal compatibility | poor compatibility

INTEGRATION

		OpEx	CapEx
Newbuild	general	$$$ (gray)	-
Retrofit	poor		-

Link to Dashboard Legend

Figure 103: Cryo storage system for liquefied hydrogen (source: MAN Energy Solutions)

Overview

Hydrogen has high decarbonizing potential as a zero-carbon marine fuel. **Hydrogen can either be consumed in a fuel cell for onboard electrical generation, applicable to an electrified vessel, or combusted in a diesel- or otto-cycle internal combustion engine (ICE), applicable to a diesel-mechanical propulsion vessel**. The advantages and limits of each of these hydrogen power sources are detailed in the guide sections on Fuel Cell and ICE .

Hydrogen (H_2) exists as the lightest gas at standard temperature and pressure (0 °C, 1 atm). For fuel purposes, hydrogen can be stored as either liquid (LH_2) or compressed gas (CGH_2). Hydrogen has a very high gravimetric energy density: it's lower heating value (LHV) is about 120 MJ/kg, or three times that of MGO. However, hydrogen liquifies at -253 °C (at atmospheric pressure), requiring cryogenic liquefaction and storage to maintain it in a liquid state. When adjusted for storage factors, the gravimetric energy density of liquid hydrogen is estimated at about 8 MJ/kg, or only one fifth that of MGO. The adjusted volumetric energy density of liquid hydrogen is about 5 MJ/liter, or one seventh that of MGO [A71]. As a compressed gas, the adjusted gravimetric and volumetric energy densities of hydrogen are even lower, but CGH_2 is less expensive to supply and store onboard. A typical pressure range for storage is 250 to 700 bar.

The physical properties of hydrogen are provided in Table 15.

Table 15: Hydrogen physical properties, atmospheric pressure

Fuel	Flammable Range (%)	Methane Number	LHV (MJ/kg)	Boiling temperature (°C)	Autoignition temperature (°C)
Hydrogen	4 - 75	0	120	-253	>500

This aspect of storage-adjusted energy density is the primary challenge to adopting hydrogen as a marine fuel. **The tank volume required for liquid hydrogen fuel is 7.6 times that of MGO** [A74]. For vessels with any significant range, such as oceangoing cargo ships, it is simply impractical to carry the required mass and volume of stored hydrogen needed for long-distance transits. Liquefied or compressed hydrogen take up significant volume by itself, with additional space required for cylindrical storage tanks separate from hull structure.

Liquefied hydrogen has improved volume density, but tanks must be well-insulated to maintain the fuel's cryogenic state. For cargo ships, the net added mass and volume over conventional marine bunkers would reduce the cargo capacity, impacting a vessel's commercial viability. For smaller vessels with long ranges, there simply isn't enough space to accommodate both the hydrogen fuel and the non-structural storage tanks. For passenger vessels, storage tanks are prohibited by most class rules from being located below enclosed decks or under passenger areas, creating arrangement, weight, and stability challenges.

Production

The second challenge to adopting hydrogen as a sustainable marine fuel is how it is produced.

Gray Hydrogen

Approximately 98% of hydrogen produced annually around the globe is sourced from emissions-intensive sources, primarily through syngas reformation of natural gas, secondarily through coal or oil processing [A75]. Steam methane reformation (SMR) is used to produce hydrogen used in oil refining as well as the production of the chemicals ammonia and methanol, which collectively makeup the bulk of hydrogen demand.

Unabated SMR releases 8.5 tons CO_2e per ton H_2 produced. This production GHG intensity, a component of Well-to-Tank emissions, is twice the Well-to-Wake GHG intensity of MGO, which releases approximately 4.2 tons CO_2e per ton MGO consumed [A76]. When correcting for specific fuel consumption (SFC) of each fuel, Well-to-wake CO_2 release of gray hydrogen is about 88% that of MGO. This illustrates why it is important to consider the source of hydrogen fuel to determine whether its lifecycle carbon intensity will reduce a vessel's GHG emissions, and by how much. The SMR hydrogen lifecycle is shown in Figure 104.

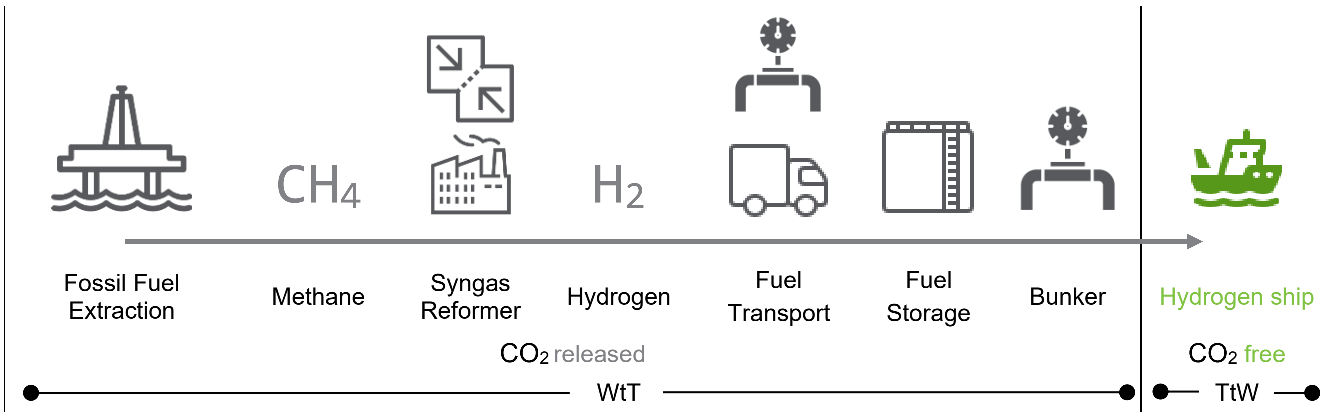


Figure 104: Hydrogen CO_2 lifecycle from natural gas and steam methane reformation (gray)

Blue Hydrogen

The carbon intensity of SMR hydrogen production can be offset by abatement via carbon capture, utilization, and/or storage (CCUS). Land-based CCUS is not reviewed in this guide, but a useful resource is the International Energy Agency's page on CCUS [A77].

The efficacy of carbon capture for producing blue hydrogen is dependent on a multitude of factors, including capture technology, storage method, location, and electricity source. To estimate the WtT emission factor for blue hydrogen at a high level, a notional overall capture percentage can be applied to the WtT emission factor of gray hydrogen. For example, if 80% overall capture is assumed, a WtT emission factor of EF_f of 71 g/MJ CO_2e for gray hydrogen would be reduced to 14.2 g/MJ CO_2e.

Green Hydrogen

The leading method for producing green hydrogen is through water electrolysis. Essentially the reverse of fuel cell redox reactions (detailed in the guide section on Fuel Cell Technology), water electrolysis generates hydrogen by passing water through a polymer electrolyte membrane (PEM) and applying direct electrical current. Oxygen is generated as a byproduct. Water electrolysis production of hydrogen is energy-intensive, so it is only viable as a low-carbon production method if the power is from a renewable source, such as hydroelectric, wind, or solar.

Solid oxide electrolyzers are maturing and could improve the energy intensity of producing hydrogen from renewables. The efficiency of solid oxide water electrolysis is estimated at 80%, compared to 65% of PEM or alkali low-temperature water electrolysis [A74].

If electricity with the global average carbon intensity is used for hydrogen production, it could actually release three times as much CO_2 as that produced by SMR [A75]. Whereas if renewable electricity is used, the production component of CO_2 release from hydrogen is essentially eliminated. Guarantees of origin (G) certificates may be necessary when sourcing green hydrogen [A76]. The green hydrogen CO_2 lifecycle is shown in Figure 105.

Green hydrogen can also be produced through biomass fermentation, using sustainable feedstocks. This production method is challenging by scaling issues and is not covered in this guide.

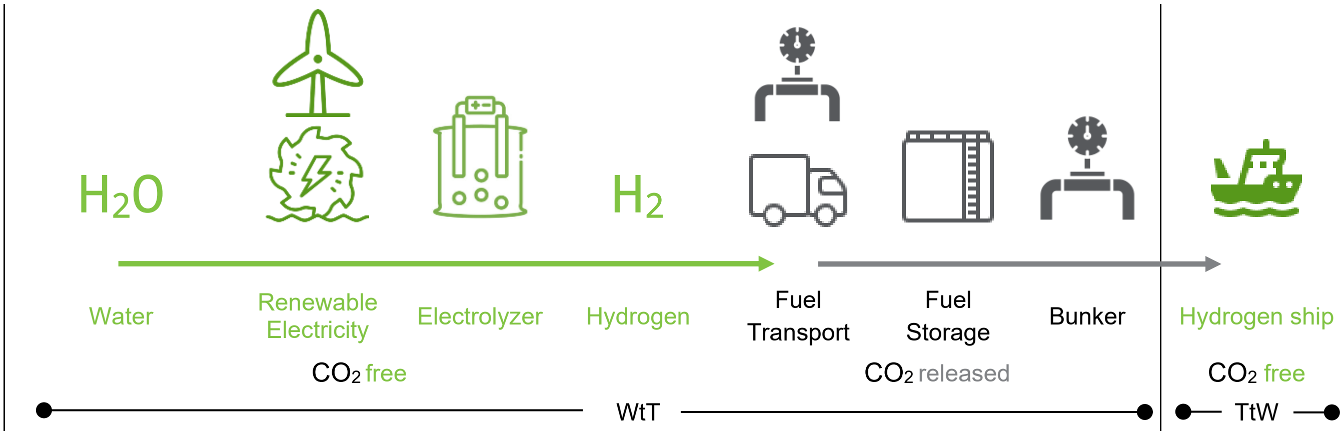


Figure 105: Hydrogen CO_2 lifecycle from renewable water electrolysis (green)

Safety

The third challenge with hydrogen is safety. Hydrogen is flammable over a wide range of concentrations in air (4-75% by volume), and has a minimum ignition energy of only 0.017 mJ in air mixtures. These flammable characteristics require that hydrogen storage, transfer, bunkering, and service arrangements onboard a vessel be carefully planned. For hydrogen vessels using either compressed or liquid hydrogen, a tall vent mast from any hydrogen storage is required to elevate vented hydrogen away from vessel openings and sources of ignition. This mast height depends on the hazardous area requirements used for the system design, and setback distances to protect crew or persons from thermal radiation from ignited hydrogen at the vent. In the case of liquid storage, the cryogenic hydrogen is always boiling off, resulting in the continuous presence of hydrogen gas at the vessel's vent mast. Fortunately, due to its low density, hydrogen rises rapidly and disperses in air, reducing the chances of hydrogen accumulating in explosive mixtures on the vessel. Where hydrogen is supplied to a machinery space containing either fuel cells or ICEs, Lower explosive limit (LEL) detection and piping containment are critical elements of the hydrogen safety system.

Until the regulatory framework for hydrogen as a marine fuel matures, hydrogen system design must be carefully coordinated with the vessel's flag state and classification society from a project's inception. The USCG Office of Design and Engineering Standards (CG-ENG) is overseeing hydrogen installations on US-flagged vessels. **Because USCG regulations under the CFR do not presently consider hydrogen or fuel cells for vessel power, designs will be reviewed on a case-by-case basis**. A design basis agreement (DBA) with CG-ENG of standards and requirements should be adopted at the inception of a project, and should consider applicable areas of IMO's International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code) [A78]. The IGF Code is focused on the use of low-flashpoint fuels on ships, and is useful for designing hydrogen systems. Some hydrogen equipment developers are pursuing USCG and class type approval, which should help streamline regulatory review.

Reduction Potential: Gray and Green Hydrogen

Emission factors EF_f for hydrogen consumers are provided in Table 16 (g GHG/MJ fuel) and Table 17 (tons GHG/ton fuel), developed using the following assumptions:

- Lower heating value of hydrogen for calculating mass/mass EF_f values is assumed to be 120 MJ/kg.
- Gray hydrogen is assumed to be produced by 100% SMR.
- Green hydrogen is assumed to be produced by water electrolysis using 100% renewable electricity.
- EF_f values are provided for both CO_2 and CO_2e, and broken into segments of Well-to-Tank (WtT), Tank-to-Wake (TtW), and the lifecycle sum: Well-to-Wake (WtW).
- WtT storage and transportation emissions are based around cryogenic liquid hydrogen.
- Fuel cell EF_f values are based on 100% hydrogen fuel.
- **ICE EF_f values assume dual fuel (DF) engines, 4-stroke medium-speed, combusting hydrogen in gas mode (diesel cycle), which are being commercialized to burn up to 75% hydrogen fuel content** [B66]. The EF_f values are therefore based on a 75/25 H_2/MGO ratio. Otto cycle ICE are believed to be able to burn up to 100% hydrogen, but these are still in the developmental stage of readiness.
- Transportation emissions are incorporated in WtT EF_f for all fuel categories, assuming 100 km roundtrip trucking (laden and empty) from terminal storage to vessel [A79].
- Fuel Cell (FC) specific fuel consumption is assumed to be 67 g/kWh (based on 0.8 Nm3/kWh, [A80]).

- ICE specific fuel consumption estimated by converting LHV to power output, assuming a thermal efficiency of 48%. This assumption corresponds to the LHV/SFC ratios for MGO, methanol, and natural gas reported in the Fourth IMO GHG Study 2020 [A18].

Table 16: Hydrogen reduction potential: emission factors in grams GHG/MJ fuel

Fuel Composition	Consumer	CO_2 Emissions Factor EF_f (g CO_2/MJ fuel)*			CO_2e Emissions Factor EF_f (g CO_2e/MJ fuel)*			Specific Fuel Consumption
%H2 / %MGO	FC/ICE	WtT	TtW	WtW	WtT	TtW	WtW	SFC (g/kWh)
Gray 100/0	Fuel Cell	71.1	0.0	**71.1**	71.2	0.0	**71.2**	67
Gray 75/25	ICE	56.7	18.8	**75.5**	57.6	20.4	**78.1**	63
Green 100/0	Fuel Cell	0.1	0.0	**0.1**	0.2	0.0	**0.2**	67
Green 75/25	ICE	3.5	18.8	**22.2**	4.4	20.4	**24.8**	63

*EF_f Sources: ABS Sustainability White Paper: Hydrogen as Marine Fuel [A76].

ICCT Briefing: Update: Accounting for Well-to-Wake Carbon Dioxide Equivalent Emissions in Maritime Transportation Climate Policies [A81].

Journal of Marine Science and Engineering: Life Cycle Assessment of LNG Fueled Vessel in Domestic Services [A79].

Table 17: Hydrogen reduction potential: emission factors in tons GHG/ton fuel

Fuel Composition	Consumer	CO_2 Emissions Factor EF_f (tons CO_2/ton fuel)*			CO_2e Emissions Factor EF_f (tons CO_2e/ton fuel)*			Specific Fuel Consumption
%H2 / %MGO	FC/ICE	WtT	TtW	WtW	WtT	TtW	WtW	SFC (g/kWh)
Gray 100/0	Fuel Cell	8.53	0.00	**8.53**	8.544	0.00	**8.54**	67
Gray 75/25	ICE	6.54	0.80	**7.34**	6.59	0.87	**7.46**	63
Green 100/0	Fuel Cell	0.01	0.00	**0.01**	0.03	0.00	**0.03**	67
Green 75/25	ICE	0.15	0.80	**0.96**	0.20	0.87	**1.07**	63

*EF_f Sources: See Table 16 notes.

TRL: 7.5

- Hydrogen is actively being used as a fuel on numerous private vessels, and multiple commercial vessels have been launched.
- Most installations are one-off projects, with equipment that is undergoing type approval review. Regulatory review is currently on a case-by-case basis.
- The regulatory framework should mature rapidly with the number of projects in the pipeline.
- IMO's IGF Code does not specifically address hydrogen as a marine fuel, but prescriptive elements and guidance from the document can be applied for a hydrogen-fueled vessel. IMO and flag states have not developed regulations specific to hydrogen as a fuel, but IMO's guidelines for alternative approaches, MSC.1/Circ.1455, can serve as guidance [A82].
- Guides from multiple class societies have been developed for hydrogen-fueled vessels.
- Class rules and guidance for fuel cells are detailed in the section on Fuel Cell Technology.
- Hydrogen bunkering is not widely available, particularly at the scale needed for ports and commercial vessels. Compressed hydrogen is a more widely traded commodity than liquid, and most active hydrogen projects are focused on compressed hydrogen as a fuel. Liquid hydrogen infrastructure is a more ambitious endeavor and requires liquid hydrogen projects to move forward in tandem with value chain development.
- Programs like Green Hydrogen Blue Danube in Europe [A83] and DOE's Hydrogen Shot in the US [A84] should help propel hydrogen infrastructure in the coming decade.

Applications

- **Hydrogen fuel is best-suited for inland or near-shore vessels with small-to-medium range requirements**.
- Ocean service and cargo vessels will typically not be able to accommodate the storage volume and weight needed for hydrogen as a propulsion fuel. Auxiliary diesel power may be more suitable for replacement by hydrogen fuel cells or generators driven by hydrogen engines.
- The first classed vessel powered by hydrogen, the car ferry MF *Hydra*, was delivered to Norled in Norway in summer 2021, and is now in service [C37]. *Hydra* is capable of being powered by 2x200 kW Ballard FCwave™ fuel cells or 2x440kW diesel-generators. It is operating on the diesel-generators until the hydrogen bunkering infrastructure is in-place.
- **The first US-based commercial ferry *Sea Change* was launched in fall 2021, and is undergoing final USCG approvals**. *Sea Change* is powered by Cummins fuel cell racks totaling 360 kW power rating [C38].
- The HydroTug is a harbor tug being developed by CMB Tech and Angle Belgian Corporation for the Port of Antwerp [C39]. The HydroTug will be powered by BeHydro DF, 4-stroke, diesel-cycle engines burning hydrogen in gas mode and will include 400 kg of CGH_2 onboard storage.

Integration & Cost

✓	**general compatibility for newbuild**	⊗	**poor compatibility for retrofit**
$$$	**significant OpEx cost (gray H_2)**	–	**no CapEx costs***

*Fuels themselves are not considered under CapEx. CapEx is considered for the equipment and technologies that utilize the fuels, in guide sections on Fuel Cell Technology and ICE Technology.

- Hydrogen as a fuel is estimated to be 3 to 7 times the price of MGO on a mass basis, based on gray hydrogen as the source [A76]. **On an energy basis, this range is closer to 1 to 2.5 times the price of MGO.**
- Production cost ranges for green hydrogen and gray hydrogen are provided in Table 18. These ranges, provided for 2020 and estimated for 2030, are sourced from the International Energy Agency (IEA) Global Hydrogen Review 2021 [A85].
- Until blue and green hydrogen production pathways become clearer, it is difficult to estimate the OpEx of utilizing fuels from these sources.
- Hydrogen storage for both compressed and liquid hydrogen requires specialized tanks for either high pressure and/or low temperature. These capital costs are considered along with fuel consumer/auxiliary equipment costs in the sections on Fuel Cell Technology and ICE Technology.

Table 18: Hydrogen production cost comparison on an energy basis, based on IEA estimates for 2020 and 2030

Fuel	LHV	2020 Production Cost Per MJ	2030 Production Cost Per MJ
Gray hydrogen - natural gas	120	$0.004 - $0.014	$0.005 - $0.020
Green hydrogen - electrolysis		$0.025 - $0.070	$0.011 - $0.033

Useful Resources

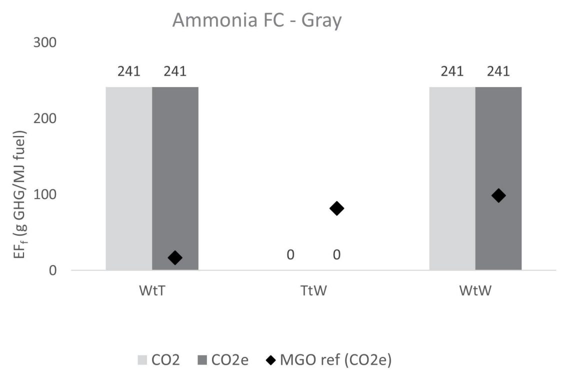
- ABS Sustainability Whitepaper: Hydrogen as a Marine Fuel [A76].
- International Energy Agency: Webpage on Hydrogen [A86].
- DNV Handbook for Hydrogen-Fuelled Vessels [A87].

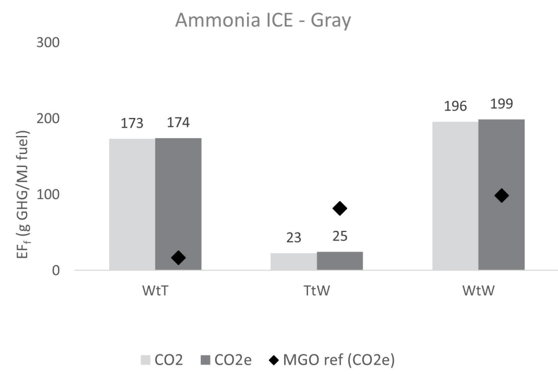
Link to Guide Navigator

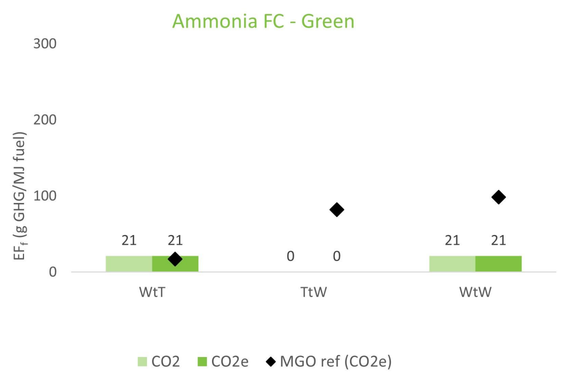
Ammonia

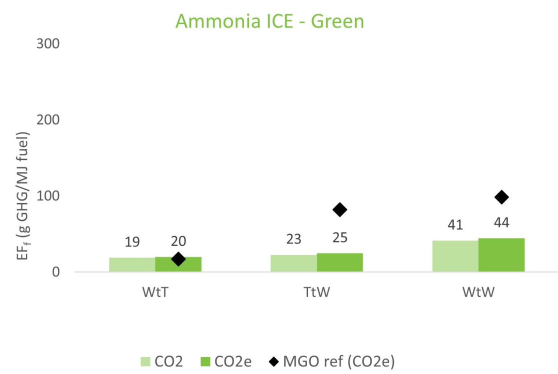
gray NH_3 | green NH_3 | fuel cell | internal combustion engine

FUEL EMISSION FACTOR (EFf)









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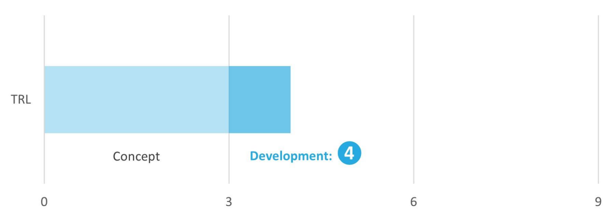


KEY FACTORS

- Cooled or compressed to a liquid, more readily stored onboard than H_2
- 4 times MGO tank volume required
- Available as fuel for either fuel cells or internal combustion engines
- N_2O develops during combustion, increasing GHG emissions
- More flammable than MGO, less flammable than H_2
- Human exposure can cause serious respiratory symptoms
- Multiple engine manufacturers developing medium and slow-speed engines
- 5x more expensive producing from renewable electrolysis than natural gas

APPLICATIONS

MW	Duty					
>10	Continuous	○	○	○	○	✓
	Intermittent		○	○	○	✓
1-10	Continuous	✓	✓	○	✓	✓
	Intermittent		✓	○	✓	✓
<1	Intermittent		○	○	○	○

MW: Propulsion power plant size, in MW

✓ general compatibility ○ marginal compatibility ✗ poor compatibility

INTEGRATION

		OpEx	CapEx
Newbuild	✓	$$$ (gray)	-
Retrofit	✗		-

Link to Dashboard Legend

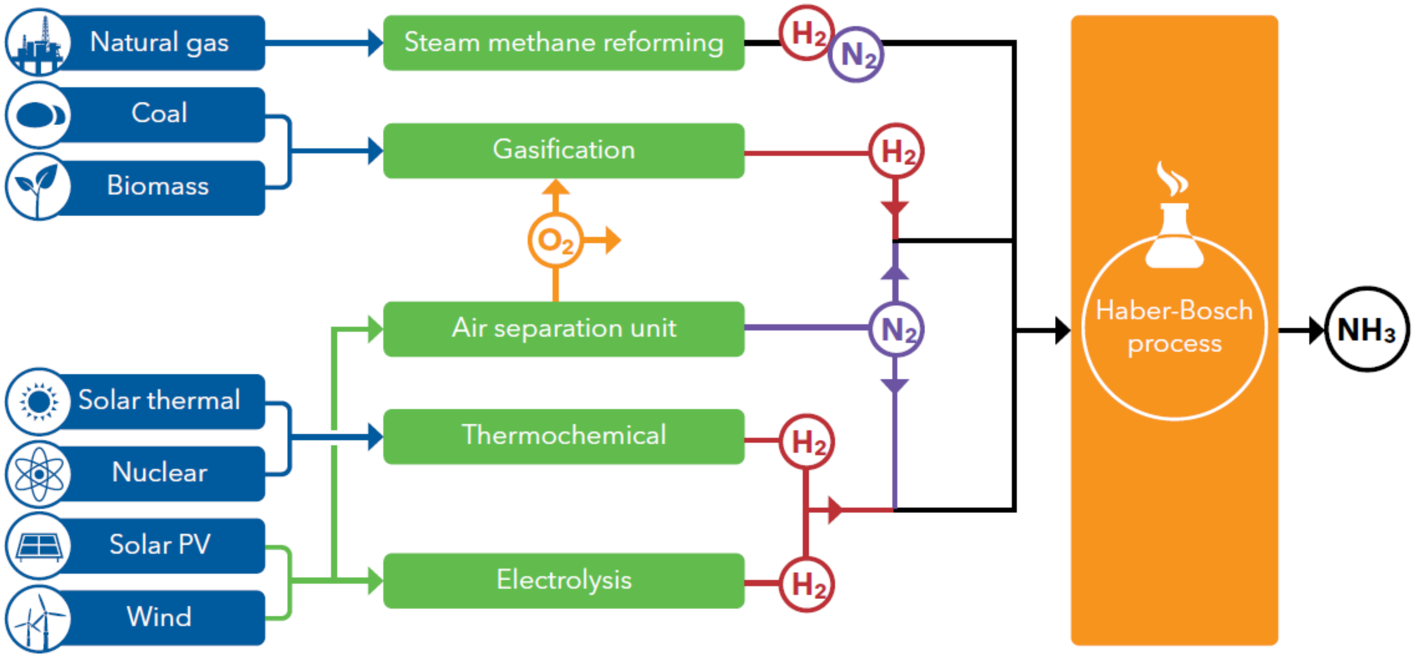


Figure 106: Ammonia production pathways (source: DNV)

Overview

Ammonia is an emerging alternative to petroleum-based marine fuels. This guide focuses on anhydrous ammonia (NH_3), rather than ammonia as a water-dissolved solution. Ammonia is known as an indirect hydrogen storage medium, combining with nitrogen to improve physical properties over pure hydrogen. **Ammonia's liquefies at -33 °C (at atmospheric pressure), compared to -273 °C for pure hydrogen. At 20 °C, ammonia can be compressed to 8.6 bar to remain a liquid**. Liquefied ammonia is 50% more energy dense than liquefied hydrogen on a volumetric basis [A76][A88]. However, at 12.7 MJ/L, it has 35% the volumetric energy density of MGO. These properties make onboard storage of liquefied ammonia much more practical than hydrogen, particularly for vessels with longer range requirements, but still considerably less volume-efficient than MGO. **The tank volume required for ammonia fuel is 4.1 times that of MGO** [A74]. Safety aspects of storage and handling are discussed later in this section.

The physical properties of hydrogen are provided in Table 15.

Table 19: Ammonia physical properties, atmospheric pressure

Fuel	Flammable Range (%)	LHV (MJ/kg)	Boiling temperature (°C)	Autoignition temperature (°C)
Ammonia	15 – 28	18.6	-33	651

Similar to hydrogen, **ammonia can be consumed in either a fuel cell for onboard electrical generation, or combusted in a diesel- or otto-cycle ICE**. In fuel cells, it can be used either indirectly, requiring cracking of hydrogen from nitrogen, or directly. These processes are discussed further in the section on Fuel Cell Technology. Having a low cetane characteristic (slow combustion speed) and slow flame propagation, ammonia requires a pilot fuel for ignition in diesel-cycle engines. As such, ammonia ICEs are primarily being developed in dual fuel configurations. These engine technologies are discussed further in the section on ICE Technology.

A key drawback of ammonia is the inclusion of nitrogen in its composition. NOx compounds can form during both combustion in an ICE and oxidation in a fuel cell, depending on the redox scheme. Early testing of ammonia/diesel blends by Wartsila in a 4-stroke engine, however, indicates ammonia can reduce NOx emissions by up to 50%. MAN has reported similar results in 2-stroke engine testing. Using ammonia as a marine fuel likely does not eliminate the need for selective catalytic reduction (SCR) or exhaust gas recirculation (EGR) to bring NOx emissions below regulated levels. Ammonia combustion can also result in ammonia slip, or the passing of un-combusted ammonia through the SCR. Ammonia slip can result in costly corrosion, but can be controlled if the SCR system includes a catalyst that oxidizes ammonia to nonreactive compounds.

Further research is necessary to clarify the quantity and type of emissions resulting from burning ammonia in varying ratios with other fuels. The application of exhaust gas aftertreatment systems seems to be a promising solution in the case of unavoidable NOx emissions and ammonia slip.

The development of N_2O during ammonia combustion, a greenhouse gas with 273 times the global warming potential of CO_2, is not well understood. Engine manufacturers need to research N_2O generation when combusting ammonia in different engine types and load profiles to characterize whether reductions of CO_2 emissions are being undermined by N_2O emissions. For any climate benefit to be achieved by using green ammonia, issues with N_2O emissions must be solved. Stringent N_2O emission regulations could ensure that DF engines burning ammonia are compatible with IMO's long-term goal of climate-neutral maritime shipping.

Production

While ammonia as a zero-carbon fuel, the production of most ammonia has a significant well-to-tank GHG component. Ammonia is typically produced by combining hydrogen and nitrogen under high temperature and pressure in the Haber-Bosch reaction (Figure 107). The possible sources of hydrogen, as shown in Figure 106, are highly varied, and include natural gas and coal for gray ammonia, and biomass for green ammonia. Nitrogen used in the Haber-Bosch reaction can be taken from air through a process called air separation, whereby air is first liquified and then separated into its constituents. The WtT emissions factor of ammonia is primarily determined by how the hydrogen is obtained. Ammonia production pathways summarized in this guide therefore align with hydrogen: gray, blue, and green. Additional energy is needed for both the air separation and Haber-Bosch reaction to generate the ammonia itself, so the production emission factor of a certain ammonia pathway will typically be higher than its corresponding hydrogen pathway.

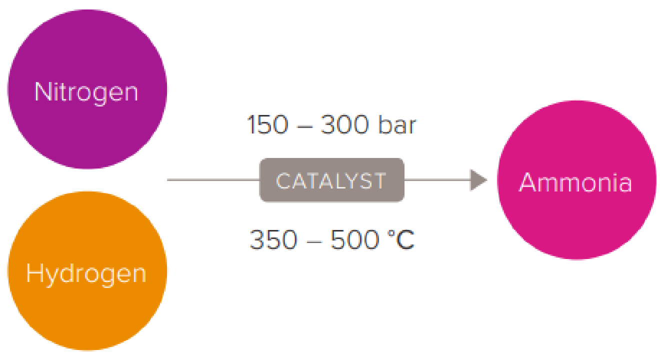


Figure 107: Haber-Bosch reaction (source: The Royal Society)

Gray Ammonia

The hydrogen used for gray ammonia production is primarily developed via steam methane reformation, as described in the Hydrogen section on Production. It is estimated that 90% of the CO_2 emissions from producing gray ammonia are sourced to the hydrogen production itself [A89]. For ammonia that is produced from hydrogen via SMR, it is likely that makeup of grid power (for air separation of nitrogen and the Haber-Bosch reaction) is not primarily from a renewable electricity source. This ammonia fuel pathway is shown in Figure 108, and the lifecycle of CO_2 emissions is shown in

*Assuming ammonia is consumed in a dual fuel ICE, CO_2 and other GHGs are not reduced to zero for the TtW portion of the ammonia fuel lifecycle, as pilot fuel combustion still produces these components.

Figure 109. Using the figure of 8.5 tons CO_2e per ton gray hydrogen produced, gray ammonia should produce approximately 9.4 tons CO_2e per ton ammonia produced.

Hydrogen for ammonia production takes up a large portion of the global demand for hydrogen. Of the 90 million metric tons of hydrogen used annually, approximately 35 million metric tons goes towards ammonia, similar to the portion used in oil refining. Ammonia is the second-highest manufactured chemical behind sulfuric acid.

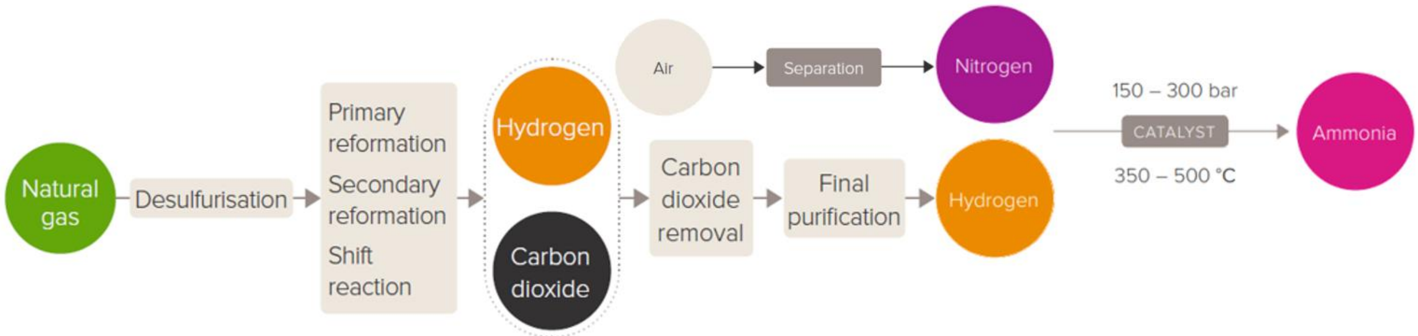
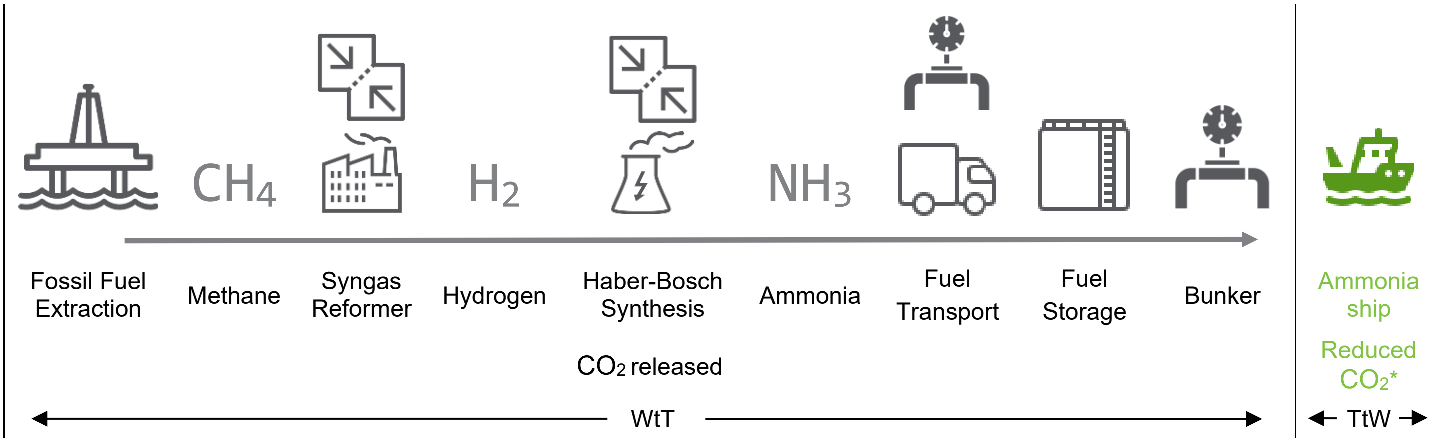


Figure 108: Gray ammonia pathway from natural gas, steam methane reformation to Haber-Bosch (source: The Royal Society)



*Assuming ammonia is consumed in a dual fuel ICE, CO_2 and other GHGs are not reduced to zero for the TtW portion of the ammonia fuel lifecycle, as pilot fuel combustion still produces these components.

Figure 109: Ammonia CO_2 lifecycle from natural gas and SMR to Haber-Bosch (gray)

Blue Ammonia

By capturing of CO_2 from natural gas and SMR, hydrogen production using carbon capture, utilization, and/or storage (CCUS), the WtT emission factor of fossil-derived ammonia can be significantly reduced. Land-based CCUS is not reviewed in this guide, but it should be considered in evaluating ammonia pathways for a vessel using ammonia as a fuel. An approach to estimating WtT emission factor for blue hydrogen, as feedstock to blue ammonia, is discussed in the hydrogen section on Production.

Green Ammonia

Ammonia produced from green hydrogen is primarily through water electrolysis using renewable electricity, which is detailed in the Hydrogen section on Production. The process is then followed by air separation of nitrogen and Haber-Bosch synthesis to combine nitrogen and hydrogen. GHG emissions can be all but eliminated from this production pathway if renewable energy is also used for air separation and Haber-Bosch synthesis, as shown in Figure 110. The lifecycle of GHG emissions for green ammonia is shown in *Assuming ammonia is consumed in a dual fuel ICE, CO_2 and other GHGs are not reduced to zero for the TtW portion of the ammonia fuel lifecycle, as pilot fuel combustion still produces these components.

Figure 111

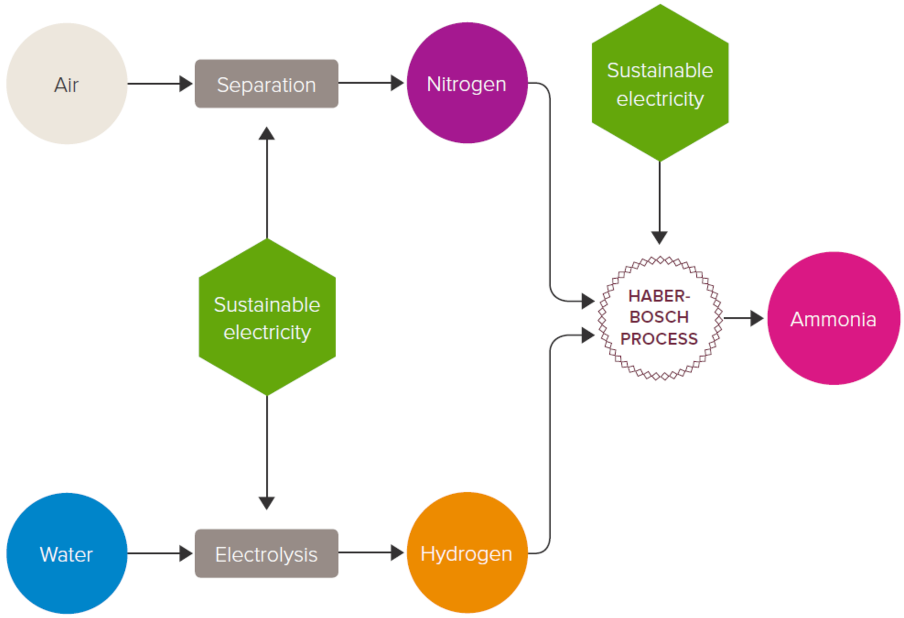
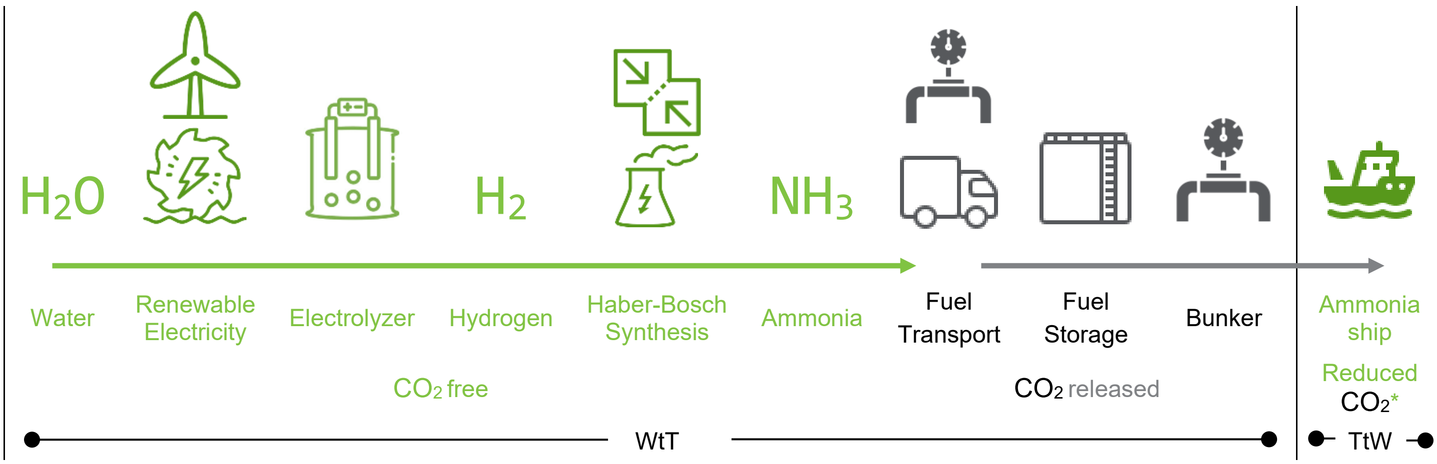


Figure 110: Green ammonia pathway from water electrolysis of hydrogen and air separation of nitrogen using renewable electricity (source: The Royal Society)



*Assuming ammonia is consumed in a dual fuel ICE, CO_2 and other GHGs are not reduced to zero for the TtW portion of the ammonia fuel lifecycle, as pilot fuel combustion still produces these components.

Figure 111: Ammonia CO_2 life cycle from water electrolysis using renewable electricity

Safety

Ammonia does not have the same fire safety concerns of pure hydrogen, but has some other characteristics that must be considered when designing for it as a marine fuel.

Despite the challenges described here, ammonia is not a novel substance on marine vessels. Ammonia is distributed globally as a chemical cargo on liquefied gas carriers (subject to the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk, or IGC Code), and used as a refrigerant, particularly on fish processing vessels. Class societies and flag administrations have established regulations for designing and integrating ammonia systems, and these can be adapted to ammonia fuel systems. An ammonia fueled design should be approached like hydrogen, in that the International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code [A78]) serves as a basis for developing design requirements to coordinate with flag and class for review. Until regulations for ammonia fueled vessels become codified in the US, projects will generally be reviewed on a case-by-case basis by the USCG.

Fire Safety

The flammability range and minimum ignition energy of ammonia and hydrogen are compared in Table 20. These ammonia characteristics correspond to a low risk of fire explosion from ammonia vapors, leaks, or spills. **Ammonia is still a flammable gas at atmospheric pressure and temperature, and is more flammable than MGO, so must remain isolated from ignition sources in both its storage and transfer throughout a vessel**. The ABS Guide for Ammonia-Fueled Vessels provides general guidance for planning hazardous areas around ammonia systems and points of release [A90]. The IGF Code [A78] can be applied to ammonia as a fuel where it can be demonstrated that an equivalent level of safety can be achieved where it differs from natural gas.

Table 20: Flammable properties of ammonia compared to other marine fuels

Fuel	GHS Classification	Flammable Range (%)	Ignition Energy (mJ)	Autoignition temperature (°C)
Hydrogen	H220: extremely flammable gas	4-75	0.017	500 (T1)
Ammonia	*H221: flammable gas*	*15-28*	*680*	*651 (T1)*
Methanol	H225: highly flammable liquid	6-36.5	0.14	470 (T2)
MGO	H226: flammable liquid and vapor	0.7-5	-	-*

*Autoignition temperature not included for MGO due to its flashpoint being over 60 °C.

Toxicity

Ammonia is a toxic substance, and exposure to humans introduces several health hazards. At low levels of exposure, hazards include skin and eye irritation, redness, and exposure to lungs can result in difficult breathing. **At concentrated exposures, respiratory symptoms become more severe, including bronchospasms or pulmonary edema**. Direct contact at high concentrations can cause several chemical burns and permanent eye damage [A88].

A summary of ammonia concentrations in air and their corresponding health effects is provided in Table 21.

Table 21: Ammonia concentration and corresponding health effects (source: Oeko Institut e.V.)

Concentration / time	Effect
10000 ppm	Promptly lethal
5000 – 10000 ppm	Rapidly fatal
700 – 1700 ppm	Incapacitation from tearing of the eyes and coughing
500 ppm for 30 minutes	Upper respiratory tract irritation, tearing of the eyes
134 ppm for 5 minutes	Tearing of the eyes, eye irritation, nasal irritation, throat irritation, chest irritation
140 ppm for 2 hours	Severe irritation, need to leave the exposure area
100 ppm for 2 hours	Nuisance eye and throat irritation
50 – 80 ppm for 2 hours	Perceptible eye and throat
20 – 50 ppm	Mild discomfort, depending on whether an individual is accustomed to smelling ammonia

Source: The Fertilizer institute: Health effects of ammonia, cited in Alfa Laval et al. (2020)

Similar to hazardous area definitions, toxic areas can be defined to reduce the risk of human contact with ammonia. These toxic areas are covered in the ABS Guide for Ammonia-Fueled Vessels, and are summarized here:

- Air intakes, outlets or openings to accommodation spaces, service spaces and control stations are to be located away from potential release points of ammonia the following distances:
  - 25 m from the ammonia vent mast.
  - 10 m from any fuel tank outlet, gas or vapor outlet, or pipe connection point including valves, flanges, crankcase vents, or ventilation outlets from Zone 1 spaces, fuel tank openings, spillage coamings, fuel room entrances and ventilation inlets, and other openings to Zone 1 spaces.

A risk assessment of the design should be carried out to identify risks and ensure their proper mitigation according to appropriate regulations.

Reduction Potential: Gray and Green Ammonia

Emission factors EF_f for ammonia consumers are provided in Table 22 (g GHG/MJ fuel) and Table 23 (tons GHG/ton fuel), developed using the following assumptions:

- Lower heating value of ammonia for calculating mass/mass EF_f values is assumed to be 19.9 MJ/kg.
- Gray ammonia is assumed to be produced 100% from hydrogen via natural gas and SMR followed by Haber-Bosch synthesis.
- Green ammonia is assumed to be produced by water electrolysis from 100% renewable electricity followed by Haber-Bosch synthesis.
- EF_f values are provided for both CO_2 and CO_2e, and broken into segments of Well-to-Tank (WtT), Tank-to-Wake (TtW), and the lifecycle sum: Well-to-Wake (WtW).
- WtT CO_2e values for green ammonia and gray ammonia are derived from the ABS series on Low Carbon Shipping Outlook [A91][A92], and include transportation emissions.
- Fuel cell EF_f values are based on 100% ammonia fuel, cracked into hydrogen prior to use in the fuel cells.
- Differences between CO_2 and CO_2e in WtT emissions for both gray and green ammonia production are assumed to be negligible (CH_4 and N_2O).
- ICE EF_f values assume dual fuel (DF) engines combusting ammonia in gas mode (diesel cycle), which have been tested to burn up to 70% ammonia fuel content for one manufacturer [A93]). The EF_f values are therefore based on a 70/30 NH_3/MGO ratio. One technology consortium is developing 2-stroke engines able to burn up to 95% ammonia, but these are still in the developmental stage of readiness [A94].
- N_2O emissions from combustion of ammonia is assumed negligible, also assuming that stringent N_2O regulations have been implemented to limit their release. Due to the high GWP of N_2O (273 times CO_2), any incidental N_2O evolution could cause large increases to TtW ammonia emissions.
- FC specific fuel consumption assumes ammonia is used indirectly, i.e., ammonia is cracked into hydrogen and nitrogen before hydrogen is used directly in a solid oxide fuel cell (SOFC). The energy required for ammonia cracking would be considered an auxiliary load and would need to be considered as a contributor to the total energy demand of the vessel. This additional energy requirement is not captured in the base SFC values provided here.
- ICE specific fuel consumption estimated by converting LHV to power output, assuming a thermal efficiency of 48%. This assumption corresponds to the LHV/SFC ratios for MGO, methanol, and natural gas reported in the Fourth IMO GHG Study 2020 [A18].

Table 22: Ammonia reduction potential: emission factors in grams GHG/MJ fuel

Fuel Composition	Consumer	CO_2 Emissions Factor EF_f (g CO_2/MJ fuel)*			CO_2e Emissions Factor EF_f (g CO_2e/MJ fuel)			Specific Fuel Consumption
%NH3 / %MGO	FC/ICE	WtT	TtW	WtW	WtT	TtW	WtW	SFC (g/kWh)
Gray 100/0	Fuel Cell	241.4	0.0	**241.4**	241.4	0.0	**241.4**	377
Gray 70/30	ICE	173.0	22.5	**195.5**	174.0	24.5	**198.6**	403
Green 100/0	Fuel Cell	20.9	0.0	**20.9**	20.9	0.0	**20.9**	377
Green 70/30	ICE	18.7	22.5	**41.2**	19.7	24.5	**44.2**	403

*EF_f Sources: ABS Sustainability White Paper: Ammonia as Marine Fuel [A88].

ABS Setting the Course to Low Carbon Shipping: View of the Value Chain [A92].

ICCT Briefing: Update: Accounting for Well-to-Wake Carbon Dioxide Equivalent Emissions in Maritime Transportation Climate Policies [A81].

Journal of Marine Science and Engineering: Life Cycle Assessment of LNG Fueled Vessel in Domestic Services [A79].

Table 23: Ammonia reduction potential: emission factors in tons GHG/ton fuel

Fuel Composition	Consumer	CO_2 Emissions Factor EF$_f$ (tons CO_2/ton fuel)*			CO_2e Emissions Factor EF$_f$ (tons CO_2e/ton fuel)*			Specific Fuel Consumption
%NH3 / %MGO	FC/ICE	WtT	TtW	WtW	WtT	TtW	WtW	SFC (g/kWh)
Gray 100/0	Fuel Cell	4.49	0.00	**4.49**	4.49	0.00	**4.49**	377
Gray 80/20	ICE	3.32	0.96	**4.28**	3.36	1.05	**4.41**	403
Green 100/0	Fuel Cell	0.39	0.00	**0.39**	0.39	0.00	**0.39**	377
Green 80/20	ICE	0.44	0.96	**1.41**	0.49	1.05	**1.54**	403

*EF$_f$ Sources: See Table 12 notes.

TRL: 4

- Demonstration projects are planned, including ammonia fuel cells for auxiliary power, but will not enter service until 2024 and beyond [C40].
- Regulatory framework will follow demonstration projects, similar to the paths hydrogen projects are currently under.
- Class guidance has been published for ammonia-fueled vessels, included in the Useful Resources section below.
- **Multiple engine manufacturers have active ammonia development programs testing both diesel- and Otto-cycle combustion, including MAN, Wartsila, and the Japan Engine Corporation**.
- Ammonia is common on marine vessels (as a cargo and refrigerant), with mature set of rules and regulations for design and safety, including the IGC Code. These can be adapted to ammonia as a marine fuel.

Applications

- Liquefied ammonia has a wider range of applications than pure hydrogen as a more energy-dense storage medium.
- The increased tank volume ratio (4.1 times MGO, [A74]) makes ammonia generally unsuitable for many long-range vessels such as oceangoing freighters and passenger ships (e.g., large cruise ships).
- Suitability on other oceangoing vessels depends on vessel range and available space for additional fuel storage. Smaller passenger vessels and lake freighters with known ranges could be adapted to ammonia fuel.
- The *Viking Energy* (IMO no. 9258442) is planned for retrofit with an ammonia-powered fuel cell as part of the ShipFC program to allow reduced hours operating on diesel. A 2 MW ammonia fuel cell will be installed for hybrid electric operations [C40].

Integration & Cost

✓ **general compatibility for newbuild**

⊗ **poor compatibility for retrofit**

$$ **moderate OpEx cost (gray NH_3)**

– **no CapEx costs***

*Fuels themselves are not considered under CapEx. CapEx is considered for the equipment and technologies that utilize the fuels, in guide sections on Fuel Cell Technology and ICE Technology.

- Ammonia price for gray ammonia compared to MGO is provided in Table 24. These values are based on a price of $300/MT for gray ammonia and $600/MT for MGO. The ammonia value is sourced from DNV's 2020 Ammonia as a Marine Fuel report [A95].

Table 24: Ammonia price comparison on an energy basis

Fuel	LHV	Price Per MJ
MGO	42.7	$0.014*
Gray ammonia (natural gas)	18.6	$0.016

*MGO price based on $600 per ton.

- **The energy cost to produce ammonia from renewable energy is approximately 5 times the energy cost to produce from natural gas**.
- Liquefied ammonia storage requires specialized tanks for reduced temperature, as well as specialized piping to mitigate safety concerns from toxicity and flammability. Ammonia has less critical requirements than liquid hydrogen, which is stored at cryogenic temperature and has a much higher flammability risk. The added capital cost of implementing ammonia fuel storage is considered along with fuel consumer/auxiliary equipment costs in the sections on Fuel Cell Technology and ICE Technology.

Useful Resources

- ABS Sustainability Whitepaper: Ammonia as Marine Fuel [A88].
- Oeko-Institut e.V.: Ammonia as a Marine Fuel [A74].
- ABS: Guide for Ammonia Fueled Vessels [A90].
- DNV White Paper: Ammonia as a Marine Fuel [A95].

Biofuels

Overview

The term biofuel covers a wide range of alternative fuels for use in marine internal combustion engines. A biofuel is any liquid fuel that is carbon-based, primarily hydrocarbons, and sourced from a biogenic feedstock. Biofuels are usually categorized as first-, second-, and third-generation, based on the technology and/or biogenic materials utilized for their production:

- First-generation biofuels are sourced from food crops, such as sugary, starchy, or oily crops.
- Second-generation (advanced) biofuels are sourced from non-food materials, such as wastes, residues, and lignocellulosic biomass.
- Third-generation biofuels are sourced from aquaculture, such as macroalgae including sargassum.

Several production pathways exist to generate biofuel, such as hydrotreating or gasification with synthesis, which determine the fuel's characteristics as well as feasibility to be commercially scaled.

Some biofuels may be suitable as "neat" fuels, i.e., can be combusted in engines without any blending with petroleum fuels. Further, some biofuels are "drop-in" neat fuels requiring no modifications to the engine or its fuel systems for combustion. Other fuels require blending to minimize impacts on engine performance and maintenance.

An overview of different biofuels and their WtW GHG emissions, developed from the Argonne National Laboratory GREET Model data [A96], is provided in Figure 112. The fuels are organized from low WtW emissions on top to high WtW emissions on bottom (with natural gas and petroleum-based fuels on the bottom).

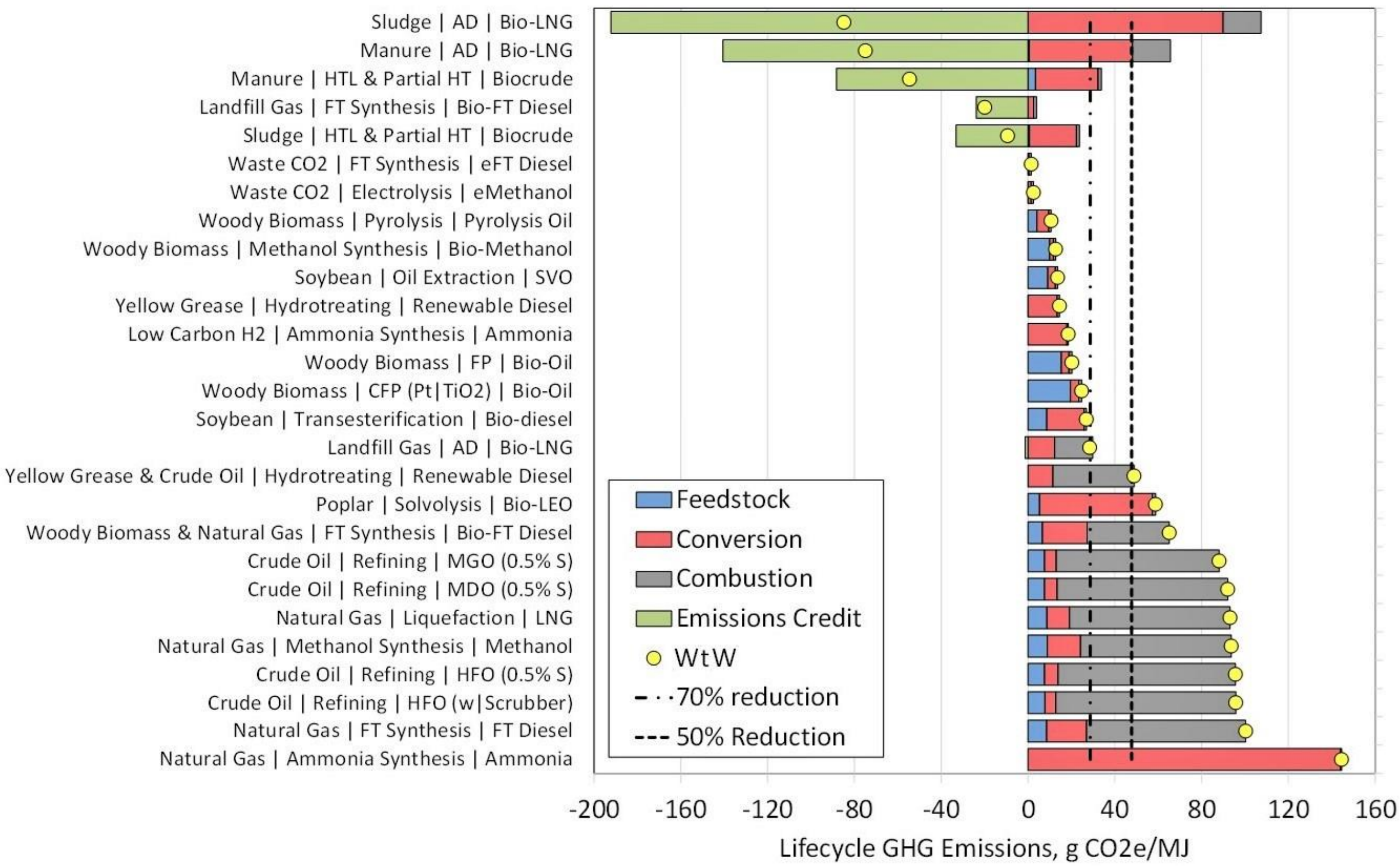


Figure 112: Biofuels and their WtW CO_2e emissions (source: Argonne GREET data)

First-generation (conventional) biofuels include both blends, such as biodiesel, or fatty acid methyl ester (FAME), and neat fuels, such as hydrotreated diesel, including hydrotreated vegetable oil (HVO), hydrotreated esters and fatty acids (HEFA), or hydrotreated renewable oil (HRO). While first-generation biofuels are readily available and proven in road transportation, they have several drawbacks:

- Typically blended with conventional petroleum fuels to be combusted, diminishing GHG reduction potential.
- Blended and neat fuels alike rely on food crop feedstocks, generating emissions from direct and indirect land-use change (dLUC and iLUC) that offset biogenic carbon uptake.
- Depending on composition, first-generation fuels may reduce engine output performance, indirectly increasing GHG emissions.

For these reasons, first-generation biofuels are not detailed in this guide.

Second-generation (advanced) fuels are produced from advanced methods that can be synthesized from a wider variety of feedstocks. These feedstocks are primarily non-food, such as grasses (e.g., miscanthus and switchgrass) food waste (e.g., corn stover), or waste FOG (e.g., used cooking oil). By eliminating food sources as the feedstock and centering on waste materials, second-generation fuels have a significantly reduced emissions from iLUC, improving their WtW emissions performance.

Five biofuels may have promising pathways for the potential for marine commercialization and GHG reduction [A97]:

- Biodiesel, or fatty acid methyl ester (FAME), produced from waste FOG.
- Hydrotreated diesel, including HVO, HEFA, and HRO.
- Dimethyl ether (DME) produced from lignocellulosic feedstock via catalytic synthesis.
- Fischer Tropsch diesel (FTD) by using gasified biomass through Fischer Tropsch synthesis.
- Bio-methanol produced by using gasified biomass and applying methanol synthesis (can also use gasified municipal solid waste (MSW)).

The first three fuels, biodiesel (FAME), hydrotreated diesel, and DME, are overviewed in this section. FTD and Methanol are detailed and evaluated in their own sections, Fischer Tropsch Diesel (FTD) and Methanol.

Fischer Tropsch diesel (FTD) is identified as a particularly promising biofuel of the second-generation group, and was selected as a representative biofuel for further evaluation. There are several key elements that make FTD a promising biofuel:

- FTD is both neat and drop-in, as a 100% replacement fuel fully compatibility with existing marine engines.
- Feedstocks for FTD are non-food, available and scalable, and minimize indirect land use change. Specifically, corn stover (waste from corn crop production) is a reliable pathway in the US, as the largest corn producer in the world.
- The production pathway based on biogenic feedstock (gasification and Fischer Tropsch synthesis) is not fully commercialized, but has potential to advance quickly.

Biodiesel (FAME) from Waste Fats, Oils, and Greases

Biodiesel and FAME are one and the same: the biofuel produced from FOGs via transesterification. Transesterification is the reaction of a lipid, sourced from a FOG feedstock, with an alcohol to form an ester. Second-generation biodiesels do not rely on vegetable sources such as soy oil and palm oil; they are produced from waste materials or other more sustainable feedstocks. FOGs are more difficult to scale than lignocellulosic waste streams, being largely derived from animal sources.

FOG-derived FAME has a mature production pathway, and can significantly reduce well-to-wake GHG emissions. Biodiesel should comply with the requirements set by EN 14214, the standard developed specifically for FAME as a biodiesel.

FAME can, in theory, replace MDO and MGO in low- to medium-speed diesel engines. However, it is more commonly used as a blending component, as biodiesel in neat form can be compromised by cold weather and create problems in older engine systems. FAME’s physical and chemical characteristics depend on the length (number of carbons) and unsaturation level of the fatty acid. Under current supply logistics, the practice of blending FAME into distillate fuels is relatively common; this nearly guarantees that some distillate fuels supplied in the marine market contain FAME. In response, the International Organization for Standardization (ISO) has revised the ISO 8217 standard to provide a wider tolerance and additional specifications for FAME content.

Only blends up to 20% FAME are expected to prevent any engine modifications. The GHG reduction potential of a FAME is significantly diminished by this blending. As a neat fuel, FAME would require several modifications to an engine such as high-quality seals, its fuel systems, and its maintenance procedures, including additives in the fuel to inhibit bacterial growth. Further, degradation during storage may occur without thermal conditioning at lower temperatures, with storage beyond six months not recommended [A97].

FAME is currently estimated to cost 1.3 to 2.2 times MGO on a volume basis.

Hydrotreated Diesel from Waste Fats, Oils, and Greases

Hydrotreated diesel is a true drop-in, neat biofuel, and can also be blended. The production of hydrotreated diesel from FOGs, via hydrotreating, is a commercially mature process. Like FAME, however, hydrotreated diesel production from FOGs is commercially mature but difficult to scale, and has limited availability for the road transportation market.

Hydrotreated diesel has been demonstrated on ferries, containerships, and a cruise ship, and is ready to use in marine engines without any modifications to the engine or fuel system.

Hydrotreated diesel is currently estimated to cost 1.5 to 2.4 times MGO.

Dimethyl Ether from Lignocellulosic Feedstock

DME (C_2H_6O) is primarily produced from lignocellulosic (herbaceous or woody) biomass via gasification and fuel synthesis. Using lignocellulosic biomass as a feedstock, DME as a neat fuel has a high potential for reduction of GHG emissions: nearly zero net WtW when using miscanthus; about 8% that of MGO when using corn stover.

However, due to its low flash point (-41 °C), DME must be blended for use in existing marine engines. A blend of up to 40% has been tested. A blend of this fraction would have significantly higher WtW emissions due to the petroleum component of the blend. DME blends have been measured to effectively reduce other criteria emissions such as PM and SOx, but may actually increase NOx under certain operating conditions.

As a neat fuel, DME would require engine modifications or a dedicated gas-only engine to handle its characteristics as a fuel. MAN has developed a slow-speed engine technology using liquid-gas-injection for combusting DME.

The cost of DME from lignocellulosic feedstock relative to MGO has not been estimated; natural gas-based DME is estimated to cost 0.9 to 1.3 times MGO on a volume basis.

Biofuel Replacements for Heavy Fuel Oil (HFO)

Several biofuels have been considered as potential sustainable replacements for heavy fuel oil (HFO, or fuel oil with >2.0% sulfur, corresponding to ISO 8217:2017 residual grades): straight vegetable oil (SVO, e.g., palm oil or soy oil), bio-oil (upgraded pyrolysis oil), or bio-crude from hydrothermal liquefaction (HTL). All three have varying drawbacks:

- SVO's GHG reductions is offset by its ILUC as a food-based feedstock, has marginal compatibility with existing engines, and has limited studies supporting its use.
- Bio-oil (upgraded pyrolysis oil) and HTL biocrude have poor compatibility with existing engines, and lack almost any evidence supporting their use.

Useful Resources

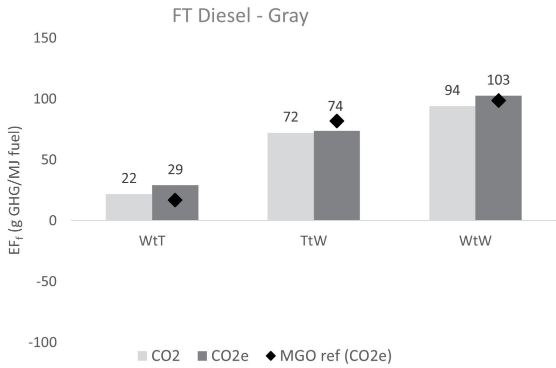
- ICCT Working Paper: The potential of liquid biofuels in reducing ship emissions [A97].
- ABS Sustainability Whitepaper: Biofuels as Marine Fuel [A98].

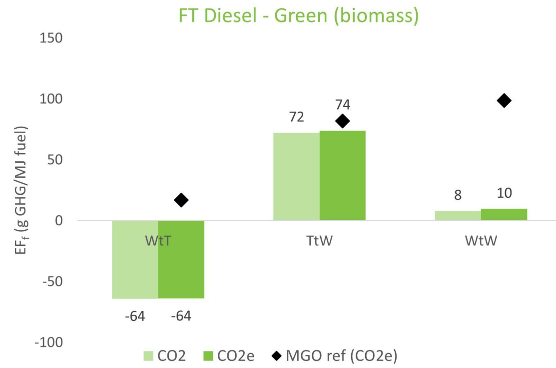
Link to Guide Navigator

Fischer Tropsch Diesel (FTD)

gray **FTD** | green **FTD** | internal combustion engine

FUEL EMISSION FACTOR (EFf)

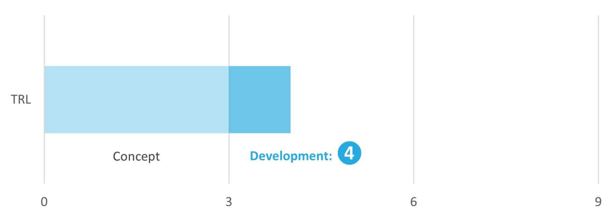




Natural gas as feedstock (image courtesy of businesspartnermagazine.com)

Corn stover as feedstock (image courtesy of beef.unl.edu)

TRL



KEY FACTORS

- FT diesel is both neat (100%) and drop-in replacement for MGO
- Low indirect land use change (iLUC) emissions when produced from non-food feedstocks
- Abundant residuals from US corn production are potential feedstock
- Slightly higher LHV than MGO
- No commercial-scale projects currently planned for corn stover, whereas forest residues now planned for small-scale commercial plants
- Green FTD costs uncertain, initially estimated at 1.5 to 4 times MGO

APPLICATIONS

MW	Duty					
>10	Continuous	✓	✓	✓	✓	✓
	Intermittent		✓	✓	✓	✓
1-10	Continuous	✓	✓	✓	✓	✓
	Intermittent		✓	✓	✓	✓
<1	Intermittent		✓	✓	✓	✓

MW: Propulsion power plant size, in MW

✓ general compatibility ○ marginal compatibility ⊗ poor compatibility

INTEGRATION

		OpEx	CapEx
Newbuild	✓	$$$ (green)	-
Retrofit	✓		-

Link to Dashboard Legend

An introduction to Fischer Tropsch diesel (FTD) from sustainable biomass (a second-generation biofuel) and its promise as emissions-reducing biofuel is provided in the section on Biofuels. In summary, **FTD can be used as a neat, drop-in replacement, it can be produced from non-food feedstocks, which results in negligible iLUC**, and it is well-aligned with the US corn industry and resulting corn stover that is generated as a residue. For these reasons, FTD from biomass (corn stover) is evaluated here.

Production

Fischer Tropsch synthesis can be used to produce diesel from a variety of feedstocks, including natural gas, switchgrass, miscanthus, and corn stover. Synthesis starts with syngas generation, or gasification, from a carbon source, steam and water, creating a hydrogen and carbon monoxide mixture. In the case of corn stover, the biomass must be first broken down at high temperature (thermochemical gasification of solid biomass) to separate the carbon from the biomass. The syngas is passed over a catalyst at an appropriate temperature and pressure to form a hydrocarbon such as diesel. The catalyst and process conditions determine the composition of the end product. The Fischer Tropsch synthesis process is represented in Figure 113.

Corn stover is produced as a residue at about an equal mass rate to the corresponding corn grain produced. At an annual corn production rate of 383 million metric tons in the US (15.1 billion bushels, [A99]), a corresponding 383 million metric tons of corn stover residue are also produced. At a fixed carbon value of 15.7% [A100], and 86% carbon content in diesel, there is potential for approximately 70 million metric tons of diesel to be produced from US corn stover biomass. This compares to 99 million metric tons of annual global demand for marine diesel across all maritime sectors, according to the Fourth IMO GHG Study 2020 [A18]. **While 100% utilization of existing corn stover residues is infeasible, corn stover could replace a portion of global shipping's demand for marine diesel**.

Sustainable FTD's drop-in suitability and compatibility with sustainable feedstocks make it a replacement fuel with notable long-term potential [A97].

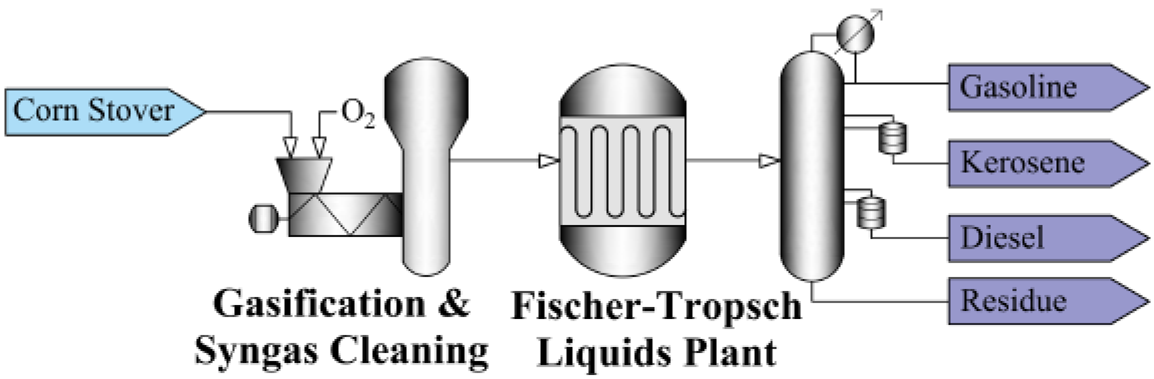


Figure 113: Fischer Tropsch synthesis using corn stover as feedstock (source: Biofuel Research Journal)

Safety

If FTD can meet ISO 8127 requirements as a neat drop-in replacement to marine diesel, it is not expected to introduce any unique safety challenges with its implementation. A marine vessel burning FTD could effectively operate the same as a vessel burning petroleum-based diesel.

Reduction Potential: Gray and Green FTD

Emission factors EF_f for FTD are provided Table 25, developed using the following assumptions:

- **Lower heating value of FTD assumed to be slightly higher than MGO** based on published data: 43.9 MJ/kg vs 42.7 MJ/kg, respectively [A101]. This value is used to calculate mass/mass EF_f values.
- Gray FTD is assumed to be produced using solely natural gas.
- Green FTD is assumed to be produced from FT synthesis using solely corn stover.
- Specific fuel consumption assumed to be equivalent to MGO.
- CO_2-only values for WtT and TtW based on ratio of emissions for natural gas- and biomass-based FTD from Argonne National Laboratory GREET Model data [A96].

Table 25: FTD reduction potential: emission factors in grams GHG/MJ fuel

Fuel Composition	CO_2 Emissions Factor EF_f (g CO_2/MJ fuel)*			CO_2e Emissions Factor EF_f (g CO_2e/MJ fuel)*			Specific Fuel Consumption SFC (g/kWh)		
FTD	**WtT**	**TtW**	**WtW**	**WtT**	**TtW**	**WtW**	**SSD**	**MSD**	**HSD**
Gray (NG)	21.8	72.3	**94.1**	28.9	73.7	**102.6**	165	175	185
Green (CS)	-64.2	72.2	**8.0**	-64.0	73.7	**9.7**	165	175	185

NG = natural gas
CS = corn stover
SSD/MSD/HSD = slow/medium/high speed diesel
*EFf Sources: ICCT Working Paper: The Potential of Liquid Biofuels in Reducing Ship Emissions [A97].
Argonne National Laboratory GREET Model [A96].

Table 26: FTD reduction potential: emission factors in tons GHG/ton fuel

Fuel Composition	CO_2 Emissions Factor EF_f (tons CO_2/ton fuel)*			CO_2e Emissions Factor EF_f (tons CO_2e/ton fuel)*			Specific Fuel Consumption SFC (g/kWh)		
FTD	**WtT**	**TtW**	**WtW**	**WtT**	**TtW**	**WtW**	**SSD**	**MSD**	**HSD**
Gray (NG)	0.94	3.12	**4.07**	1.25	3.19	**4.44**	165	175	185
Green (CS)	-2.78	3.12	**0.35**	-2.77	3.19	**0.42**	165	175	185

*EFf Sources: See Table 15 notes.

TRL: 4

- As FTD readiness is irrespective of industry application, marine-related aspects of TRL scale do not apply to this TRL rating.
- Several small-scall commercial FT production plants are planned in the US and Europe, using forest residues, wood waste, and municipal solid waste. This places TRL at 5-6 for these feedstocks.
- **There are currently no planned commercial FT production projects using corn stover, placing TRL at 3 for that specific feedstock.**
- Varying degrees of readiness for different sustainable feedstocks places overall technology TRL at 4.

Applications

- FTD is a neat drop-in fuel, and can therefore be substituted for petroleum marine fuels on all marine vessels. It is not limited in applicability for any conventional marine vessel types or sizes.

Integration and Cost

✓	**general compatibility for newbuild**	✓	**general compatibility for retrofit**
$$	**moderate OpEx cost (green)***	–	**no CapEx costs**

*Operating cost impact uncertain until green FTD pathway matures. Could be significant increase in operating cost (>5% increase), due to added cost of fuel, at initial adoption on marine vessels, with cost improving over time.

- As neat drop-in fuel, FTD requires no special considerations for integrating on existing and newbuild vessels. Impacts to fuel systems expected to be minor.
- **Lignocellulosic FTD (including corn stover) estimated at 1.5 to 4 times the cost of MGO initially, on an energy basis** [A97].
- Incentives and long-term policy certainty likely needed for scale-up to proceed [A97].

Useful Resources

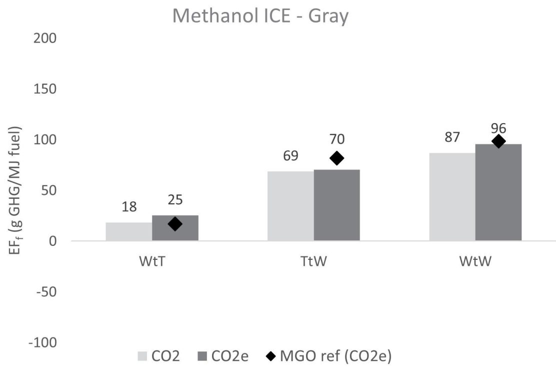
- ICCT Working Paper: The Potential of Liquid Biofuels in Reducing Ship Emissions [A97].
- ABS Sustainability White Paper: Biofuels as Marine Fuel [A98].
- IEA Bioenergy: Advanced Biofuels – Potential for Cost Reduction [A102].

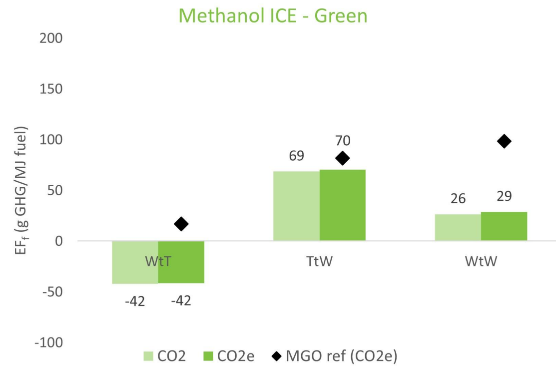
[Link to Guide Navigator]

Methanol

gray CH_3OH | green CH_3OH | internal combustion engine

FUEL EMISSION FACTOR (EFf)

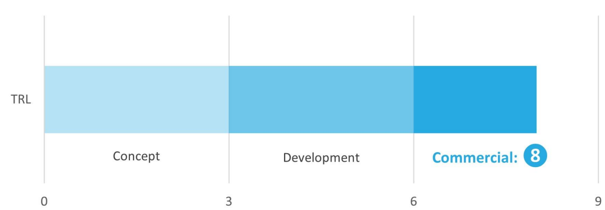




Natural gas as feedstock (image courtesy of businesspartnermagazine.com)

Corn stover as feedstock (image courtesy of beef.unl.edu)

TRL



KEY FACTORS

- Liquid at atmospheric pressure, more readily adapted for bunkering/storage
- 2.3 times MGO tank volume required, less than ammonia and hydrogen
- Small pilot ratio required for combustion, 5% being commercially developed
- Presents human health hazard from contact, inhalation, and ingestion
- Corrosive properties require careful material selection for tanks and piping
- Engine manufacturers developing dual fuel engines first, using methanol
- Suitable for long-range vessels, also being developed for small work boats
- Green methanol production cost is 5+ times cost of gray methanol

APPLICATIONS

MW	Duty					
>10	Continuous	✓	✓	✓	✓	✓
	Intermittent		✓	✓	✓	✓
1-10	Continuous	✓	○	○	✓	○
	Intermittent		○	○	✓	○
<1	Intermittent		○	○	○	○

MW: Propulsion power plant size, in MW

✓ general compatibility ○ marginal compatibility ⊗ poor compatibility

INTEGRATION

		OpEx	CapEx
Newbuild	✓	$$ (gray)	-
Retrofit	✓	$$$ (green)	-

[Link to Dashboard Legend]

Link to Guide Navigator

Overview

Methanol (methyl alcohol, CH_3OH, MeOH) is a carbon-based fuel that has emissions-reducing potential if coupled with carbon capture, sourced from biomass feedstock, or created through water electrolysis from H_2O and CO_2 using renewable electricity. Several global shipping companies are pursuing the commercialization of methanol engines to reduce the lifecycle emissions of their fleets. This is discussed further in the section on ICE . Methanol has an established supply chain, traded as both a general fuel and industrial chemical, but is not fully established as a vessel bunkering fuel. **However, as a liquid at atmospheric pressure (below 65 °C), Methanol could be readily adapted to existing shore-side distribution and bunkering infrastructure**. Methanol as a carbon-based fuel is unique in that it is sulfur free and does not contain carbon-to-carbon bonds. When combusted, it does not generate sulfur oxides (SOx) or particulate matter (PM) as a result, two emissions that are already regulated in the US and internationally [A103]. It also reduces NOx emissions by an estimated 45% compared to conventional fuels on a per unit energy basis. These “clean” characteristics make methanol an attractive replacement to conventional marine fuels.

The physical properties of methanol are provided in Table 15.

Table 27: Methanol physical properties, atmospheric pressure

Fuel	Flammable Range (%)	LHV (MJ/kg)	Flash Point (°C)	Boiling temperature (°C)	Autoignition temperature (°C)
Methanol	6 – 36.5	19.9	11 - 12	65	470

The tank volume required for methanol fuel is 2.3 times that of MGO, with a volumetric energy density of 15.7 MJ/L [A74]. Due to its liquid state at ambient conditions, methanol can be stored in structural hull tanks rather than standalone, pressurized tanks as required for hydrogen, natural gas (methane) and ethane, but requires additional coating and material selection measures due to its corrosiveness. Methanol is classified as toxic to human health when used in onboard systems, but its concentration considered immediately dangerous to life or health (IDLH) is 6,000 ppm, compared to 300 ppm for ammonia [A104].

These corrosion and safety aspects of storage and handling are discussed later in this section.

Like hydrogen and ammonia, methanol can be consumed in either a fuel cell for onboard electrical generation or combusted in a diesel- or otto-cycle ICE. While some pilot projects are planned using methanol in fuel cells on marine vessels, marine technology development has predominantly focused on combustion in ICE applications. As such, this guide focuses on methanol as a combustion fuel, rather than a fuel cell redox fuel. Methanol is more readily combusted than ammonia, having a relatively low minimum ignition energy, but is still characterized by a low cetane number (3) that requires a diesel pilot for ignition. **Compared to hydrogen and ammonia in a diesel-cycle, with 25-30% diesel blend required (4-stroke), only 5% diesel pilot is required in commercial 2-stroke and upcoming 4-stroke dual fuel engines running on methanol in gas mode** [A105].

While less energy-dense than natural gas (LHV of 19 MJ/kg compared to 50 MJ/kg), methanol does not require cryogenic liquefaction or pressurization to be stored onboard as a fuel. Without the related storage complexities, it carries the same tank volume requirement as natural gas, relative to MGO. This makes it a more adaptable fuel for existing vessel designs than natural gas, without a penalty to storage volume required.

Production

As a carbon-based fuel, methanol’s role in GHG reduction hinges on the carbon feedstock used for production.

Gray Methanol

Methanol’s gray production method considered here is through syngas reformation from natural gas (methane) followed by methanol synthesis. Natural gas goes through gasification (i.e., steam methane reformation), producing hydrogen and carbon monoxide as described in the Production section of Fischer Tropsch Diesel (FTD). The hydrogen and carbon monoxide are then synthesized into methanol, which must be further distilled to remove water. As a hygroscopic material, methanol is susceptible to absorbing water if it isn’t handled and stored appropriately. The methane gasification/synthesis/distillation process requires energy and relies on a fossil fuel in natural gas as the feedstock. About 65% of methanol is produced from natural gas. Coal gasification represents the balance of methanol production, with only a small fraction produced via renewable methods [A106]. The SMR methanol lifecycle is shown in Figure 114.

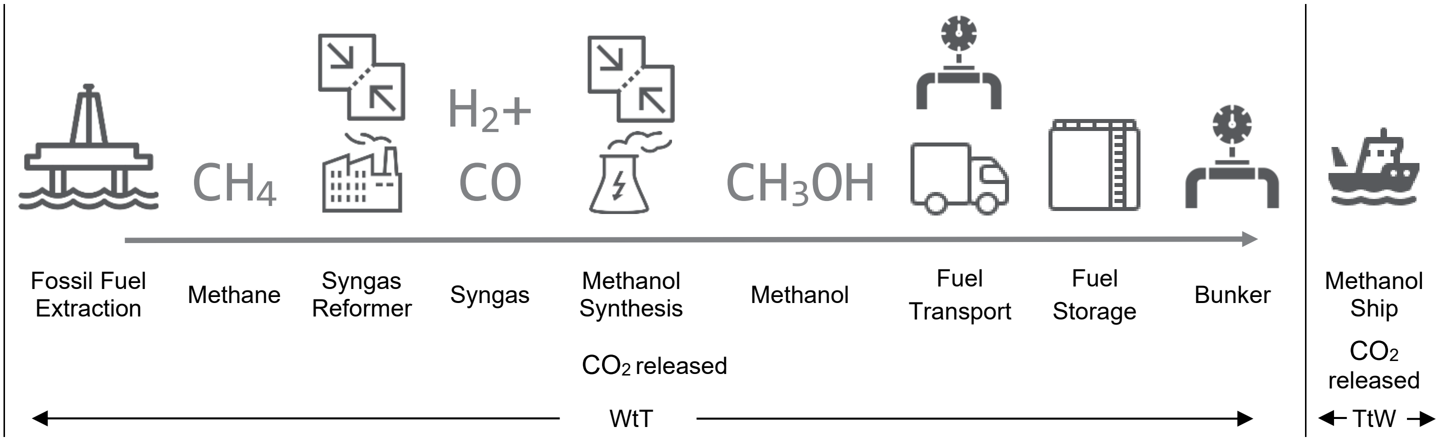


Figure 114: Methanol CO_2 lifecycle from natural gas and steam methane reformation (gray)

Green Methanol

There are two methods of green methanol production: bio-methanol (via gasification of biomass followed by methanol synthesis or reformation of renewable natural gas followed by methanol synthesis) and e-methanol via water electrolysis using renewable electricity and CO_2 hydrogenation.

Bio-methanol is primarily a biofuel. The WtT GHG emissions of bio-methanol vary depending on the energy source to power the process. Renewable electricity for the reformation process will reduce GHG emissions over electricity generated from natural gas or coal. Bio-methanol produced using fossil-based electricity has a lower potential to reduce GHG emissions.

The bio-methanol lifecycle using direct biomass feedstock is shown in Figure 115.

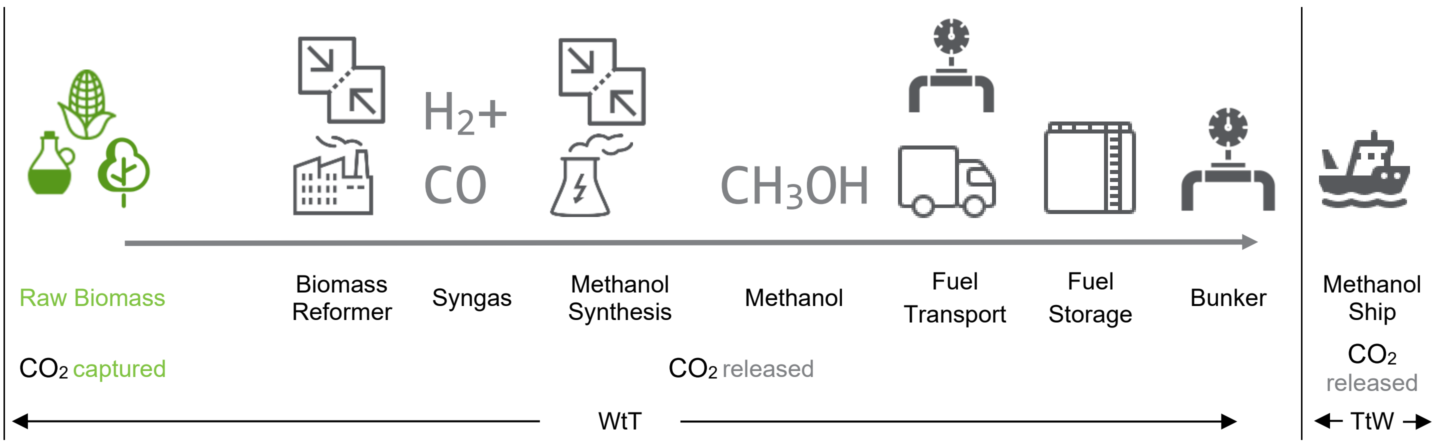


Figure 115: Methanol CO_2 lifecycle from direct biomass gasification/reformation (green)

E-methanol is an electrofuel, using electricity to generate hydrogen, which is then combined with CO_2 through a catalytic process (methanol synthesis). In the case of renewable electricity for the generation of hydrogen, e-methanol would be green. If CO_2 is extracted from a biomass source or direct air capture, the WtT GHG emissions of green e-methanol will be lower than the green hydrogen it is sourced from, as the production process is absorbing CO_2 in addition to generating renewable hydrogen. If fossil-based CO_2 is sourced, such as a bioproduct from syngas reformation, then the net reduction of GHG is diminished, as there is no element of carbon uptake in the cycle.

E-methanol production is more energy intensive than bio-methanol, but the primary feedstock of renewable hydrogen is water, making it more reliably sourced than the various biomass feedstocks under development for bio-methanol. E-methanol requires a much lower amount of biomass to facilitate production. If sufficient renewable electricity is available to the producer, e-methanol could be more readily scaled to commercial production than bio-methanol.

Safety

Methanol as a marine fuel is a lesser fire hazard than hydrogen but is a greater toxicity and human health hazard. Its flammable and toxic properties alike require special planning, design, and precautions.

The IMO released the Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel, or MSC.1/1621, in 2020 [A107], which should be referenced for any vessel design including methanol as a main or auxiliary fuel.

Fire Safety

Methanol as a gas in liquid phase will produce less potentially flammable vapors than straight gas fuels, but it is still considered a low flashpoint fuel. It is classified under the GHS system as H225, or a highly flammable liquid [A74]. Methanol's flammable properties are compared to hydrogen, ammonia, and MGO in Table 20. Its flammable range is wider than ammonia at 6-36.5%, but less than half the range of hydrogen. The ignition energy of 0.14 mJ makes methanol vapor and air mixtures in the flammable range conducive to combustion in the presence of an ignition source. Methanol as a gas fuel in liquid phase will introduce vapor in lower quantities than other gas fuels, but the vapor can be held captive in the tanks rather than vented to a safe location. To avoid explosive atmospheres in methanol tank ullage and at vents, a CO_2-free inert gas system for fuel tanks is recommended in MSC.1/1621. CO_2 must be avoided due to the potential to create corrosive conditions [A103]. Methanol vapor is also heavier than air, introducing the risk of accumulation in low areas in vessel machinery spaces and on deck. Proper ventilation volume and flow path must therefore be considered to ensure flammable quantities of methanol vapor do not accumulate.

Table 28: Flammable properties of methanol compared to other marine fuels

Fuel	GHS Classification	Flammable Range (%)	Ignition Energy (mJ)	Autoignition temperature (°C)
Hydrogen	H220: extremely flammable gas	4-75	0.017	>500 (T1)
Ammonia	H221: flammable gas	15-27	680	651 (T1)
Methanol	*H225: highly flammable liquid*	*6-36.5*	*0.14*	*470 (T2)*
MGO	H226: flammable liquid and vapor	0.7-5	-	-*

*Autoignition temperature not included for MGO due to its flashpoint being over 60 °C.

At an autoignition temperature of 470 °C, the temperature class for electrical equipment installed near potential methanol vapors is T2, requiring a more rigorous rating than for ammonia and hydrogen, which are assigned T1 (autoignition temperatures of 651 °C and 500 °C, respectively).

MSC.1/1621 provides guidance for both fire integrity, arrangements including hazardous areas, as well as firefighting systems prescribed for methanol fuel systems. If a foam-type firefighting system is used, alcohol-resistant foam is necessary to combat methanol fires.

Toxicity

Methanol has a combination of toxic characteristics that make it unique from other marine fuels, conventional and alternative alike. It is like ammonia in that it is toxic if inhaled, but methanol requires 20 times the concentration in air as ammonia to classify as immediately dangerous to life or health. It is also toxic if swallowed, aligning more closely with MGO and HFO (whereas ammonia is not classified as toxic if swallowed, instead resulting in corrosive damage to the mouth, throat and stomach, but not poisoning). Consumption of methanol produces formic acid and formaldehyde, dangerous at a quantity as low as 10 mL [A103]. It is also toxic in contact with skin, but to a lesser severity than ammonia.

This trio of hazards (contact, inhalation, ingestion) requires more careful protection from human exposure on ships than other fuels. A summary of methanol toxic hazards compared to hydrogen, ammonia, and MGO is provided in Table 29. MSC.1/1621 prescribes fuel piping to be double walled, preventing both development of hazardous environments in enclosed spaces as well as conditions toxic to human health. Adequate personal protective equipment for handling methanol spills or leaks is needed, specifically selected for use with methanol. Proper training, taking into account the specific hazards of methanol, is necessary for all crewmembers on methanol-fueled ships.

Table 29: Toxic properties of methanol compared to other marine fuels (source: Oeko-Institut e.V.)

Fuel	Toxic Hazard (GHS Classification)		
	Contact with skin and eyes	Inhalation	Ingestion
Hydrogen	None	None	None
Ammonia	H314: causes severe skin burns and eye damage	H331: toxic	None
Methanol	***H311: toxic***	***H331: toxic***	***H304: toxic***
MGO	None	None	H304: may be fatal

Corrosion

Methanol is a uniquely corrosive marine fuel. Due in part to its high conductivity, methanol can vigorously attack titanium broadly and certain aluminum alloys specifically. Titanium, in the absence of water (as is the case for anhydrous methanol used as fuel), can suffer catastrophic stress corrosion cracking [A108]. **Materials should be carefully selected for both fuel systems as well as on-engine components**. Part of engine conversion for methanol combustion includes updates for material compatibility. Non-metallic components must also be compatible with methanol to ensure seals, joints, and piping internals do not see accelerated degradation [A103].

Methanol storage must also account for its corrosive properties. While the liquid state of methanol permits it to be stored in structural hull tanks, ABS advises either compatible stainless steel (such as duplex or austenitic grades) or methanol-resistant coating [A109]. Zinc is a non-reactive coating that is used on many chemical tankers for storage, and is compatible with methanol fuel storage. A wider variety of metallic materials may be compatible for certain applications, as advised by the Methanol Institute's technical bulletin on compatibility [A108]. Class may also require ventilated cofferdams between methanol tanks and crewed spaces due to its low flashpoint properties.

Methanol can also cause corrosion in the presence of CO_2 and sea air, so inert gas systems for storage tanks should be CO_2 free to mitigate corrosion.

Reduction Potential: Gray and Green Methanol

Emission factors EF_f for ammonia consumers are provided in Table 30 (g GHG/MJ fuel) and Table 31 (tons GHG/ton fuel), developed using the following assumptions:

- Lower heating value of methanol for calculating mass/mass EF_f values is assumed to be 19.9 MJ/kg.
- Gray methanol is assumed to be produced from 100% natural gas, via reformation and methanol synthesis.
- Green methanol is assumed to be produced from 100% biogenic feedstock (corn stover), via gasification and methanol synthesis.
- **ICE EF_f values assume dual fuel (DF) engines combusting methanol in gas mode (diesel cycle), which are being commercialized to burn up to 95% methanol fuel content from one manufacturer** [A105]. This fuel ratio specifically applies to 2-stroke, high pressure engines. The EF_f values are therefore based on a 95/5 CH_3OH /MGO ratio.
- Specific fuel consumption based on the Fourth IMO GHG Study 2020 for slow speed and medium speed diesel [A18]. High speed diesel is not included in the GHG Study for methanol.
- CO_2-only emissions factors are adjusted from CO_2e factors by using CO_2 to CO_2e ratios for methanol published in the Argonne National Laboratory GREET Model [A96].

Table 30: Methanol reduction potential: emission factors in grams GHG/MJ fuel

Fuel Composition	CO_2 Emissions Factor EF_f (g CO_2/MJ fuel)*			CO_2e Emissions Factor EF_f (g CO_2e/MJ fuel)*			Specific Fuel Consumption SFC (g/kWh)	
%CH_3OH / %MGO	WtT	TtW	WtW	WtT	TtW	WtW	SSD	MSD
Gray (NG) 95/5	18.3	68.6	**86.9**	25.3	70.3	**95.6**	350	370
Green (CS) 95/5	-42.2	68.6	**26.4**	-41.5	70.3	**28.8**	350	370

NG = natural gas

CS = corn stover

SSD/MSD/HSD = slow/medium/high speed diesel

*EFf Sources: ICCT Working Paper: The Potential of Liquid Biofuels in Reducing Ship Emissions [A97].

Argonne National Laboratory GREET Model [A96].

Link to Guide Navigator

Table 31: Methanol reduction potential: emission factors in tons GHG/ton fuel

Fuel Composition	CO_2 Emissions Factor EF_f (tons CO_2/ton fuel)*			CO_2e Emissions Factor EF_f (tons CO_2e/ton fuel)*			Specific Fuel Consumption SFC (g/kWh)	
%CH_3OH / %MGO	WtT	TtW	WtW	WtT	TtW	WtW	SSD	MSD
Gray (NG) 95/5	0.38	1.45	**1.83**	0.52	1.49	**2.01**	350	370
Green (CS) 95/5	-0.82	1.45	**0.63**	-0.81	1.49	**0.69**	350	370

*EFf Sources: See Table 20 notes.

TRL: 8

- One commercial RoPax vessel retrofitted in 2015 for running on methanol, converting Wartsila-Sulzer ZA 40S propulsion engines for dual fuel methanol/diesel service [C41].
- As of 2021, thirteen dual-fuel tankers capable of using methanol are in service globally, including four operated by MOL [C42].
- Proman Stena Bulk, a joint venture between Proman Shipping and Stena Bulk, took delivery of the second of six newbuild, methanol-fueled, medium-range tankers in July 2022. The new vessel series are designed with MAN B&W engines [C43].
- Maersk has ordered different models of MAN B&W liquid gas injection methanol (LGIM) series engines [B67] for a total of 19 methanol-fueled vessels [C44].
- **Engine manufacturers including MAN-ES, Wartsila, and WinGD are developing commercial methanol dual fuel solutions, for both conversion and newbuild, with availability to market planned ahead of ammonia and hydrogen versions [B68].**
- Methanol is widely produced as an industrial chemical, but bunkering infrastructure for marine applications is not established.
- Maersk has invested in bio-methanol company WasteFuel to produce 30,000 tons of fuel per year for Maersk's planned methanol containerships [A110].
- Liquid Wind in Sweden is planning multiple e-methanol production projects, using wind or solar energy to produce green hydrogen as a methanol feedstock [A111].

Applications

- Methanol is readily adaptable for vessel retrofit given its simple storage requirements, compared to ammonia and hydrogen.
- The increased tank volume ratio (2.3 times MGO, [A74]) makes methanol more suitable for long-range vessels. Range would still be reduced relative to fossil fuel use.
- Several global shipping companies are pursuing methanol-fueled vessels accordingly. Maersk, Proman Shipping, and Stena Bulk all have orders for methanol cargo vessels, with the latter two having taken delivery.
- **Small vessel methanol projects are also being pursued, including towboats and multipurpose tugs, indicating it may be a versatile fuel across many vessel operations**.

Integration & Cost

✓	**general compatibility for newbuild**	✓	**general compatibility for retrofit**
$$	**minor OpEx cost (gray)**	–	**no CapEx costs***
$$$	**significant OpEx cost (green)**		

*Fuels themselves are not considered under CapEx. CapEx is considered for the equipment and technologies that utilize the fuels, in guide sections on Fuel Cell Technology and ICE Technology.

A comparison of estimated production costs and prices for various methanol pathways is provided in Table 32. Prices for green methanol are approximated by applying the low-end and high-end difference between production cost and price for gray methanol. **Until green methanol production processes mature, they are generally 5+ times the cost of gray methanol to produce.**

- Gray methanol may be competitive in price with MGO on an energy basis, but there are added operational costs for handling the fuel and possibly inerting fuel tanks to mitigate fire risks.
- Production cost and price ranges for gray methanol and various sources of green methanol are provided in Table 32. These ranges, provided for 2021, are sourced from the International Renewable Energy Agency (IRENA) Innovative Outlook on Renewable Methanol Report [A106].

Table 32: Methanol cost and price comparison on an energy basis

Fuel	LHV	Production Cost* Per MJ	Price Per MJ
MGO	42.7	-	$0.014**
Gray methanol	19.9	$0.005 - $0.010	$0.010 - $0.020
Green bio-methanol		$0.023 - $0.051	$0.028 - $0.061
Green e-methanol - biomass		$0.035 - $0.081	$0.040 - $0.091
Green e-methanol - DAC		$0.042 - $0.045	$0.047 - $0.055

*Green methanol production costs do not include potential efficiencies gained by maturing processes.

**MGO price based on $600 per ton.

Useful Resources

- ABS Sustainability Whitepaper: Methanol as Marine Fuel [A103].
- International Renewable Energy Agency (IRENA) Innovation Outlook: Renewable Methanol [A106].
- Methanol Institute Resources on Methanol as a Marine Fuel [A112].
- IMO MSC.1/Circ.1621: Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel [A107].
- ABS: Guide for Methanol and Ethanol Fueled Vessels [A109].

Link to Guide Navigator

ICE Technology

Overview

Engine manufacturers are following the development of commercial marine engines running on natural gas (methane) by adapting mature dual fuel and gas-fuel technologies to other fuel types, as well as developing new technologies to improve design, performance, and reliability. Wartsila, MAN-ES, Caterpillar, WinGD, MTU Solutions, and BeHydro (a joint venture of Anglo Belgium Corporation (ABC) and Compagnie Maritime Belge (CMB)) are all pursuing various alternative fuel projects. Dual fuel engines offer more flexibility and enable an energy transition from fossil fuels to low-carbon and zero-carbon fuels. Compression ignited (diesel cycle) engines are most readily adaptable to marine installations, so most early engines will still require at least a diesel pilot fuel, with the ratio depending on the combustion characteristics of the fuel. The pilot could be either a fossil- or bio-based fuel. The amount of pilot fuel required, and its production pathway, directly impacts the GHG emission reduction potential of the engine technology.

Technologies for different fuels are at varying levels of readiness for marine installations. Methanol has been a primary focus for manufacturers, with engines on order for projects in several markets: commercial containerships, tankers, and wind turbine installation vessels. These engines generally fall in the two-stroke/slow-speed or four-stroke/medium-speed categories. Ammonia engines are also being pursued, but will lag behind methanol products by a few years. Hydrogen as a dual fuel or mono-gas in engines is approaching commercialization with BeHydro’s DZD line (a variant of ABC’s natural gas dual fuel engines), but hydrogen is still in a developmental stage with other engine manufacturers.

Each fuel has its own unique challenges for adapting to marine engines. These fuel-specific challenges are discussed in the next sections. The use of alternative fuels in gas turbines is not considered in this guide.

Hydrogen

Hydrogen has previously been used as a supplement to mono-gas and dual fuel engines to improve thermal efficiency and reduce GHG and other criteria pollutant emissions. It is only more recently that dual fuel engines burning hydrogen in gas mode as the primary fuel, or gas-only engines burning exclusively hydrogen, have been under development for marine applications. While commercialization efforts are underway, the horizon for broad uptake of marine hydrogen ICE is farther out than methanol and ammonia.

Figure 116: BeHydro spark-ignited V12 hydrogen engine (source: BeHydro)

Combustion and Engine Characteristics

Liquefied hydrogen cannot be combusted directly in an ICE due to the cryogenic range of temperatures required for liquefied storage, so it must first be expanded to a gas before being injected into the combustion chamber. This requires additional fuel system equipment to enable hydrogen use in ICEs. This is not applicable in the case of compressed hydrogen storage.

Hydrogen’s flammable properties compared to methane and MGO are provided in Table 33. While it’s high autoignition temperature makes it more suitable for spark ignition in gas-only engines, its high flammability introduces challenges for spark combustion. Hydrogen’s low ignition energy and high flame speed cause the fuel to burn quickly when ignited [A113]. Quick combustion is more difficult to control, and increases engine knock. Low ignition energy can cause untimed ignition of hydrogen in combustion where temperature is poorly controlled, contributing to knocking. Hydrogen's methane number is 0, indicating very low knock resistance.

Table 33: Hydrogen flammable properties compared to methane and MGO

Fuel	Flammable Range (%)	Methane Number	Ignition Energy (mJ)	Autoignition temperature (°C)	Flame Speed (m/s)
Hydrogen	4 - 75	0	0.017	> 500	1.7
Methane	5 - 17	100	-	537	0.4
MGO	0.7 - 5	N/A	-	> 225	-

Hydrogen low knock resistance when used in gas-only engines requires engine modification to optimize the combustion timing. Hydrogen's low ignition energy can result in premature and untimed ignition if temperature is not controlled in the engine's combustion cycle. Poorly controlled knocking can degrade engine efficiency and cause damage to the combustion chamber surfaces.

In the absence of a pilot injection, hydrogen is not conducive to compression ignition. It's autoignition temperature in excess 500 °C requires a high compression ratio for ignition to occur, resulting in larger cylinder sizes and thus a larger engine. By pre-injecting a pilot fuel with a relatively low autoignition temperature, such as MGO in the range of 225-257 °C, hydrogen can be used in a diesel cycle engine. The fraction of pilot fuel to enable compression ignition can be quite small, but a higher ratio of hydrogen may be necessary to control combustion and limit engine knocking. In the case of BeHydro's dual fuel DZD engines (operating in diesel cycle and low-pressure), that ratio is 15-25% diesel to 75-85% hydrogen [B66].

An advantage of hydrogen combustion is a wide range of compatible air to fuel ratios. With a flammable range of 4-75% concentration in air, hydrogen can be combusted at fuel ratios varying from 34:1 as a rich mixture to 180:1 as a lean mixture [A114]. Hydrogen's low volumetric density, however, reduces power output for a given cylinder displacement.

ICE technologies being developed for marine vessels generally have direct injection of the hydrogen fuel into the cylinder. High-pressure injection can help maintain stable combustion in the chamber [B69].

Commercial Development

Engine technologies for hydrogen as a marine fuel are being developed by several major engine manufacturers: ABC (under joint venture BeHydro with CMB [A66], MAN-ES [B70], Wartsila [B71], and Japanese Engine Corporation (J-ENG, under joint venture HyENG with Kawasaki Heavy Industries and Yanmar Power Technology [B69]. For engines that use more than 20% hydrogen, most manufacturers project commercial readiness no earlier than 2025.

BeHydro, however, has operated its first commercial DF engine, running on up to 85% hydrogen in gas mode, since 2020 (the balance 15% being diesel pilot fuel). BeHydro has not announced a release date for its spark-ignited engine line burning hydrogen as a mono-gas. BeHydro features a double-walled hydrogen system to prevent hazardous environments in the engine room. Even if 100% hydrogen utilized, exhaust aftertreatment to remove NOx may still be necessary on hydrogen ICEs, as the development of NOx components from hydrogen combustion is not well documented.

A summary of hydrogen engine developments and their estimated availability is provided in Table 34. Hydrogen engines are generally being developed as newbuilds rather than retrofit kits for existing marine engines.

Table 34: Marine hydrogen engine developments

Manufacturer	Model	H_2 %	Cycle/Stroke	Speed*	Status	Available
BeHydro	DZD	75 - 85	DF diesel, 4-stroke	medium	commercial	2020
BeHydro	-	100	Otto, 4 stroke	medium	development	-
J-ENG	UEC-LSGH	-	DF diesel, 2-stroke	slow	development	2026
J-ENG	-	100	Otto	-	concept	-
MAN-ES	-	20	Otto, 4-stroke	-	prototype**	2021**
MAN-ES	-	100	Otto, 4-stroke	-	concept	2030
Wartsila	34SG	3 - 25	Otto, 4-stroke	medium	commercial	2022
Wartsila	(multiple series)	15 - 25	DF diesel, 4-stroke Otto, 4-stroke	medium	commercial	~2000
Wartsila	-	100	Otto	-	development	2025

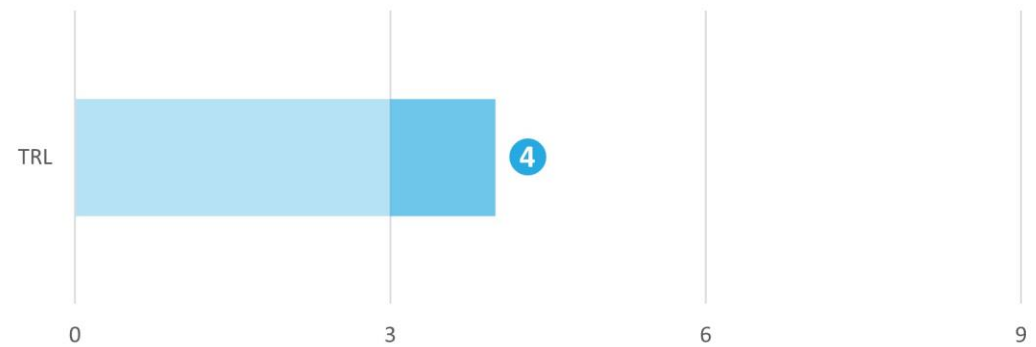
- Speed definitions from Fourth IMO GHG Study: slow <300 rpm, medium 300-900 rpm, high > 900 rpm.

"-" indicates details that have not been disclosed by the manufacturer.

** Prototype year indicates start of testing, not commercial availability.

TRL: 4

Based on the above development programs and projected manufacturer timelines, hydrogen ICEs are at a TRL of 4. When BeHydro's commercial engine is installed and demonstrated on a marine vessel, the TRL assessment will shift accordingly. The CMB.TECH Hydrotug was launched in May 2023 with BeHydro V12 engines, providing the opportunity for hydrogen ICE technology to be demonstrated at full-scale [C39].



Integration and Cost

- **general compatibility for newbuild**
- **poor compatibility for retrofit**
- $$ **moderate OpEx cost**
- $$$ **significant CapEx costs**

Ammonia

The development of ammonia as a marine fuel has grown in the past 5 years, with most engine manufacturers pursuing more aggressive development schedules for ammonia than hydrogen in the 2-stroke market. Ammonia as a fuel in a mono-gas engine will be difficult to achieve due to its flammable properties, so its potential as a zero-GHG emission fuel for ICE use is limited unless coupled with a biofuel pilot. As part of the energy transition in the coming decades, however, uptake of ammonia engines has potential to grow in several maritime trades.

Figure 117: MAN-ES two-stroke engine considered for Ammonia service (source: marineinsight.com)

Combustion and Engine Characteristics

Liquefied ammonia differs from hydrogen in that it is admitted in liquid state to the injection system, where it is then atomized by the high-pressure (600-700 bar) injectors. As a non-cryogenic fuel, ammonia can remain as a liquid through the fuel supply system.

Ammonia's flammable properties compared to methane and MGO are provided in Table 35. At a very high ignition energy (680 mJ compared to 0.017 mJ for hydrogen) and slower flame speed, ammonia is not subject to the same instabilities in the combustion chamber as hydrogen. However, at an even higher autoignition temperature than hydrogen, it cannot be readily combusted as a monofuel using compression ignition. A compression ratio of 35:1 would be necessary for compression ignition combustion. Even for spark ignition in an Otto cycle, a dual fuel mixture is likely necessary due to its flame speed [A74].

Table 35: Ammonia flammable properties compared to methane and MGO

Fuel	Flammable Range (%)	Methane Number	Ignition Energy (mJ)	Autoignition temperature (°C)	Flame Speed (m/s)
Ammonia	15-28	-	680	651	< 0.1*
Methane	5 - 17	100	-	537	0.4
MGO	0.7 - 5	-	-	> 225	-

"-" indicates properties not readily available.

* flame speed is reported at 1 atm and 25 K [A115].

For dual fuel applications, ammonia can be mixed with natural gas or diesel for pilot ignition and combustion improvement. A 9:1 ratio of ammonia (90% ammonia by mass) is practical, which could reduce CO_2 emissions by up to 80% [A74]. Higher ratios may be feasible.

Japan Engine Corporation is part of a project team, including NYK Line, aiming to provide a 2-stroke, slow-speed propulsion engine (dual fuel) burning 95% ammonia for an ammonia carrier scheduled for delivery in 2026. Similarly, IHI Power Systems has partnered with NYK Line and others to provide a 4-stroke engine burning 80% ammonia for auxiliary generators on the 2026 ammonia carrier, as well as engines burning 80% ammonia for a tugboat scheduled for delivery in 2024 [C45][C46].

Wartsila is testing a dual fuel engine at 70% ammonia by mass in gas mode. Wartsila is promoting a mono-gas engine concept burning ammonia by 2023, but has not published technical details [B72].

Ammonia slip, or unreacted ammonia passing through exhaust aftertreatment equipment, is of particular concern when burning ammonia in an ICE. Ammonia slip can cause corrosion and plugging of down-stream exhaust equipment, as well as contribute to stack plume opacity. Ammonia slip may be controlled through several approaches alone or in combination:

high-pressure direct-injection for optimal combustion, increased combustion temperature (which may increase the formation of NOx), and specialized exhaust aftertreatment equipment [A74].

The formation of N_2O during combustion could have significant global-warming impacts. N_2O has 273 times the GWP of CO_2. If N_2O formation is not closely controlled, its release could diminish or negate an ammonia engine's GHG reduction potential. Ammonia engine manufacturers will likely have to test and validate the control of N_2O emissions from combustion [A88].

An ammonia supply system for dual fuel/2-stroke/high-pressure operation has several aspects that must be considered, as shown in Figure 118 and summarized here [B73]:

- Fuel supply system, including high-pressure pump, heater/cooler, and filters.
- Recirculation system for avoiding two-phase ammonia conditions.
- Fuel valve train for isolating fuel system during shutdown and maintenance.
- Nitrogen system for purging and gas-freeing ammonia supply system.
- Double-walled ventilation and ammonia capture system for maintaining safe engine room environment and detecting ammonia leaks.
- Selective catalytic reduction (SCR) technology to control NO_x emissions, as well as ammonia slip.

These systems are generally expected to be supplied by the ICE manufacturer in addition to the engine technology.

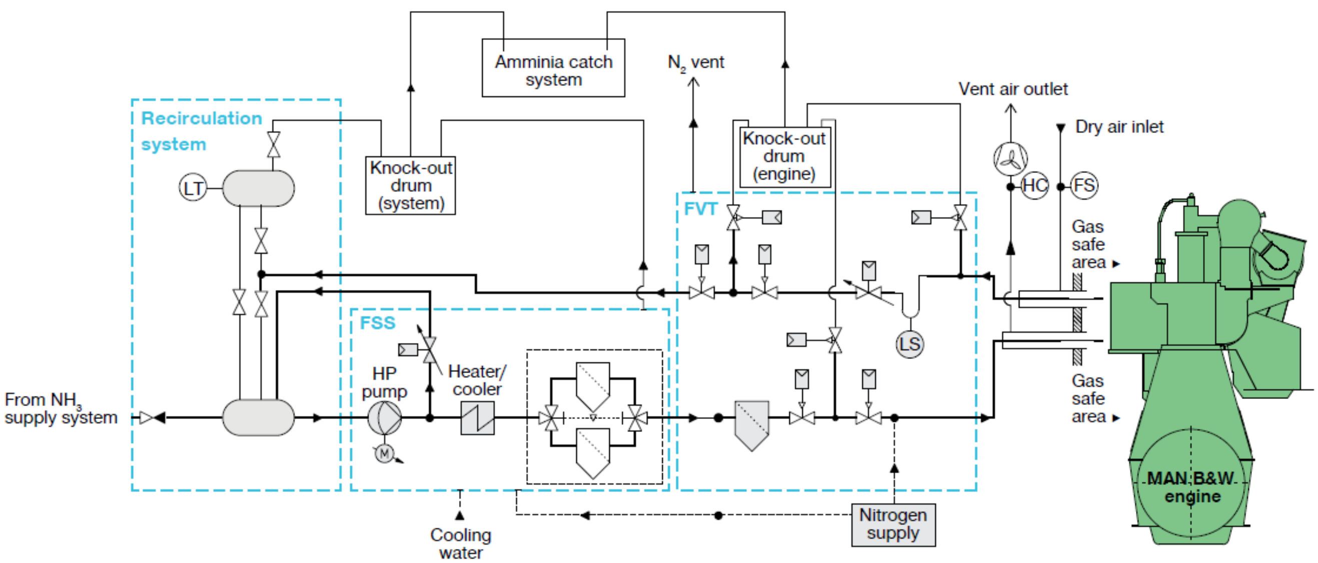


Figure 118: Concept diagram of ammonia high-pressure fuel supply system for 2-stroke, dual fuel engine (source: MAN-ES)

Commercial Development

Most engine manufacturers with future fuel programs are planning ammonia ICE readiness ahead of hydrogen variants. This is reflective of the sense across industry that ammonia has broader applicability, particularly in ocean shipping, than hydrogen. Commercial readiness of ammonia ICE is generally projected around 2024-2025, with the focus primarily on dual fuel diesel-cycle engines. As mentioned above, Wartsila is exploring a mono-gas ammonia technology (running 100% on ammonia), but details are not publicly available.

As an alternative to newbuild ammonia engines, manufacturers are also developing retrofit kits, such as Wartsila's future fuels conversion platform, which optimizes fuel injection and combustion in two-stroke engines, specifically electronically-controlled Wartsila engines [B68]. Ammonia-ready dual fuel engines are also being developed, such as WinGD's X-DF2.0 engine line that is promoted as being ammonia-ready with minor modifications. Four containerships ordered for Pacific International Lines will be delivered with ammonia-ready engines in 2024 [B74][C47].

MAN-ES has partnered with DNV, Electronic FuelTech, and Technical University of Denmark to develop a commercial ammonia engine, based on MAN's liquid gas-injection (ME-LGI) engine line, ready for delivery in 2024 [B75]. Shipping line MOL may be the first customer to install MAN's ammonia engines.

A summary of ammonia engine developments and their estimated availability is provided in Table 36.

Link to Guide Navigator

Table 36: Marine ammonia engine developments

Manufacturer	Model	NH_3 %	Cycle/Stroke	Speed*	Status	Available
J-ENG	UEC-LSJA	95	DF diesel, 2-stroke	slow	development	2025
IHI Power Systems	-	80	DF diesel, 4-stroke	medium	development	2024
MAN-ES	ME-LGI	-	DF diesel, 2-stroke	medium	concept	2024 (newbuild) 2025 (retrofit)
MAN-ES	4T50ME-X	-	DF diesel, 2-stroke	slow	prototype**	2020**
Wartsila	Future Fuels Conversion	-	DF diesel, 2-stroke	-	development	2024 (retrofit)
Wartsila	-	70	DF diesel, 4-stroke	-	prototype**	2021**
Wartsila	-	100	Otto, 4-stroke	-	concept	2025 or later
WinGD	X-DF2.0	-	DF diesel, 2-stroke	slow	development	2024
WinGD	X-Engine	-	2-stroke	slow	concept	2025

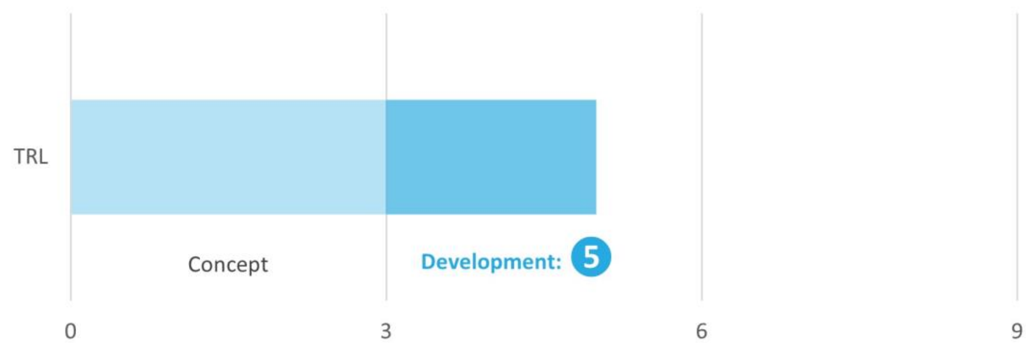
* Speed definitions from Fourth IMO GHG Study: slow <300 rpm, medium 300-900 rpm, high > 900 rpm.

"-" indicates details that have not been disclosed by the manufacturer.

** prototype year indicates start of testing, not commercial availability.

TRL: 5

Based on the above development programs and projected manufacturer timelines, ammonia ICEs are at a TRL of 5.



Integration and Cost

general compatibility for newbuild — **poor compatibility for retrofit**

$$ **moderate OpEx cost** — $$$ **significant CapEx costs**

- Retrofit of ammonia fuel systems, storage, and engine modifications may be more straightforward than hydrogen, but still infeasible for many vessels.
- CapEx of an ammonia fuel package is expected to be less than a hydrogen system (which requires cryogenic storage and more specialized material selection), but more than 5% of the total vessel cost, over a baseline conventional fuel system.

Methanol

Methanol's reasonable storage volume requirements (able to be stored in prismatic hull tanks) and its characteristic as a liquid-state fuel (at atmospheric pressure and ambient temperature) have driven development of methanol combustion technologies ahead of other alternative fuels. With new orders for engines capable of burning up to 95% methanol, coupled with the use of sustainable biomass-derived methanol, vessel operations may reduce GHG emissions by about 70% compared to MGO (assuming 2-stroke, dual fuel, slow-speed diesel). Methanol can also be applied to a broad selection of engine types and sizes, though most engine manufacturers are focusing on adapting their large, slow speed or medium speed engines for methanol. Methanol engines will figure prominently in the immediate marine energy transition, but long-term potential for GHG emissions reduction depends on the development of sustainable fuel pathways.

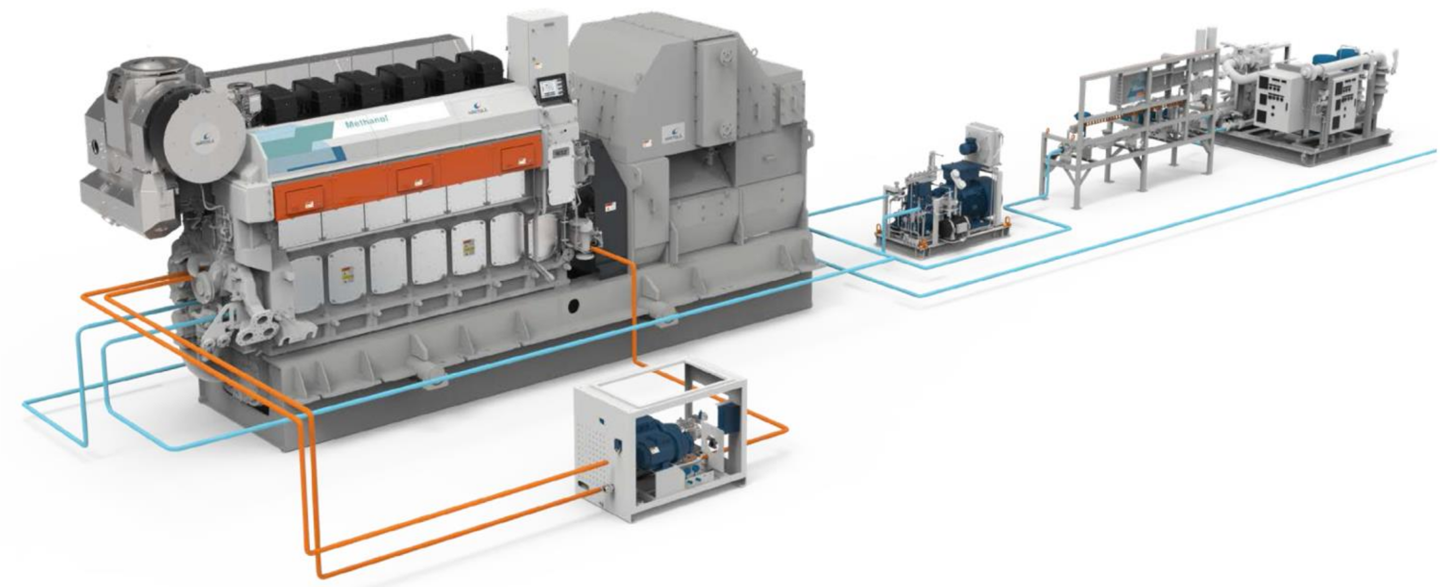


Figure 119: Wartsila 32 methanol engine and MethanolPac fuel system, 4-stroke, diesel dual fuel, high-pressure (source: Wartsila)

Combustion and Engine Characteristics

Methanol is in liquid phase (atmospheric pressure or higher, ambient temperature) through all stages onboard: bunkering, storage, transfer, and engine injection. Methanol is distinctly more flammable than MGO: it's a low flashpoint fuel vaporizing at approximately 11 °C, well below the 60 °C low flashpoint threshold defined by IMO (SOLAS regulation II-2/4, paragraph 2.1.1). At an autoignition temperature 450 °C, methanol is more difficult to use in compression ignition than MGO, but easier than hydrogen, methane, and ammonia alike (autoignition temperatures ranging 500-651 °C). Methanol as a mono-gas fuel does not require the same high compression ratio needed for hydrogen and ammonia.

Burning methanol in a diesel cycle does require special modifications to the engine and supply piping. Due to its toxic and flammable characteristics, methanol must be carried in double-wall piping in machinery spaces, both for transfer as well as on-engine distribution to cylinders.

Methanol engines will typically use high-pressure injection, as is the case for MAN's methanol liquid gas injection system (LGIM) used for 2-stroke, dual fuel engines [B65]. The LGIM fuel supply system brings pressure up to 10 bar through a low-pressure and high-pressure pump in series, followed by the injection valve which boosts pressure up to approximately 600 bar for injection into the cylinder, via hydraulic pressure. To comply with NOx regulations (e.g., IMO Tier III and EPA Tier 4), methanol may need to be mixed with water prior to being fully pressurized for injection.

A typical methanol supply system for dual fuel (2-stroke, high-pressure) operation is summarized here:

- Fuel supply system, including low-pressure and high-pressure pumps, heater/cooler, and filters.
- Fuel valve train for isolating fuel system during shutdown and maintenance.
- Water injection system for controlling NOx formation during combustion.
- Nitrogen system for purging and gas-freeing methanol system.
- Double-walled ventilation system for maintaining safe engine room environment and detecting methanol leaks.

These auxiliary systems are expected to be supplied by ICE manufacturers, such as MAN's integrated system for the LGIM series [B65] and Wartsila's MethanolPac announced for retrofit or newbuild engines [B76].

While the auxiliary systems required for methanol add complexity to the engine, they are generally limited to the fuel supply and injection side, including special electronic controls. The remainder of the engine configuration is generally not impacted, making methanol fuel systems suitable for retrofit as well as newbuilds.

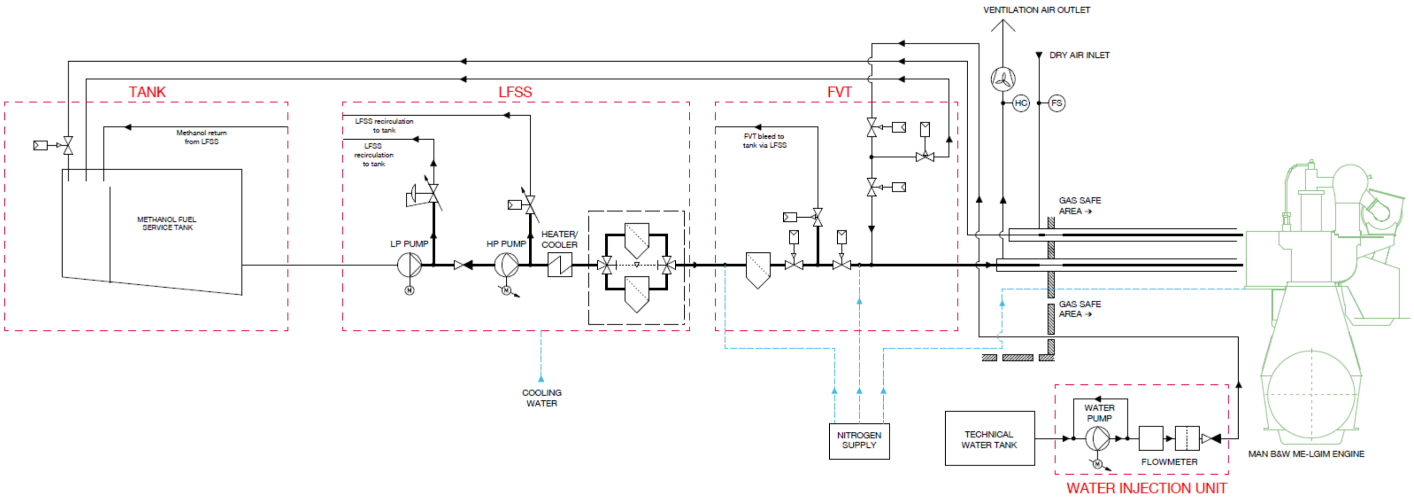


Figure 120: Concept diagram of methanol high-pressure fuel supply system, 2-stroke dual fuel (source: MAN-ES)

Commercial Development

MAN's ME-LGIM liquid-gas engine burning methanol in gas mode has been ordered on multiple A.P Moller-Maersk projects: one 6-cylinder two-stroke engine for a 2,100-TEU project, twelve 8-cylinder two-stroke engines for a 16,000-TEU multi-ship project, and six 8-cylinder engines for a 17,000-TEU multi-ship project [C44]. First deliveries on these projects are in 2023 and the first quarter of 2024, respectively.

The MAN ME-LGIM can operate on up to 95% methanol in gas mode, with the remaining fuel being pilot diesel for proper combustion.

Wartsila's methanol 32 engine was ordered for Van Oord, consisting of five engines for a new wind turbine installation vessel. Delivery is planned for early 2023 [C48]. Wartsila has not announced the fuel blend for the Wartsila 32 package.

Both MAN and Wartsila are also offering retrofit kits for their engines, including the fuel systems described in the previous section. Both MAN's Methanol four-stroke retrofit kit and Wartsila's MethanolPac four-stroke system are expected to be available for delivery in 2024.

While MAN and Wartsila have the most robust methanol ICE programs, other manufacturers are also developing methanol dual fuel technologies. Some methanol manufacturer developments are summarized here:

- WinGD announced plans to release a methanol version of the X-Engine (2-stroke, dual fuel) by 2024 [B77].
- In the high-speed market, ScandiNAOS has developed methanol ICEs (dual fuel, 4-stroke, high-speed, Otto cycle) in the 150-450 kW range, demonstrated on the GreenPilot project [B78].
- Caterpillar announced a methanol development program for their high-speed ICEs [B79].
- Methanol shippers like Proman and Waterfront Shipping have implemented methanol-fueled ICEs on their respective fleets' methanol carriers [C43][C49].

A summary of methanol engine developments and their estimated availability is provided in Table 37.

Table 37: Marine methanol engine developments

Manufacturer	Model	CH_3OH %	Cycle/Stroke	Speed*	Status	Available
Caterpillar	-	-	4-stroke	high	concept	-
MAN B&W	LGIM	95	DF diesel, 2-stroke	slow	commercial	now
MAN-ES	-	-	DF diesel, 4-stroke	medium	concept (retrofit)	2024
ScandiNAOS	MD97	97	Otto, 4-stroke	high	prototype** (retrofit)	2018**
Wartsila	Z40S	100	DF diesel, 4-stroke	medium	Pilot** (retrofit)	2015**
Wartsila	32	-	DF diesel, 4-stroke	medium	commercial	2023

Manufacturer	Model	CH_3OH %	Cycle/Stroke	Speed*	Status	Available
Wartsila	MethanolPac	-	DF diesel, 4-stroke	medium	commercial (retrofit)	-
WinGD	X-Engine	-	DF diesel, 2-stroke	slow	concept	2024

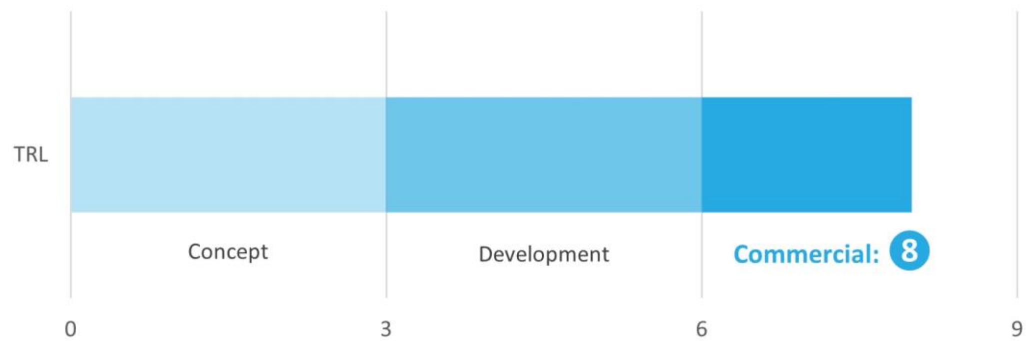
* Speed definitions from Fourth IMO GHG Study: slow <300 rpm, medium 300-900 rpm, high > 900 rpm.

"-" indicates details that have not been disclosed by the manufacturer.

** Prototype/pilot year indicates start of testing, not commercial availability.

TRL: 6

Based on the above commercial developments, namely ME-LGIM engines being in operation on several vessels, a pilot installation in 2015, and several commercial orders scheduled to delivery in 2-3 years, methanol ICE are at a TRL of 8.



Integration and Cost

general compatibility for newbuild — **marginal compatibility for retrofit**

$ **minor OpEx costs** — $$ **moderate CapEx costs**

Fuel Cell Technology

Overview

Fuel cells are emerging as a viable method of carbon-free, pollutant-free high-efficiency electrical power generation for marine applications. Fuel cells are electro-chemical units that operated to convert chemical energy into electrical energy by means of a pair of redox reactions. Fuel cells primarily consist of an anode and a cathode separated by an electrolyte layer. The fuel, often being hydrogen, flows across the surface of the anode, while the oxidizing agent, often being oxygen, flows across the surface of the cathode. An agent on the surface of the anode catalyzes an oxidant reaction, breaking down H_2 molecules into H^+ ions and electrons. The H^+ ions flow across the electrolyte from the anode to the cathode, while the electrons travel the anode to the cathode through an external circuit – in this way work can be performed on a load connected to the external circuit. At the cathode, another catalyst causes H^+ ions, electrons, and oxygen to produce water and release thermal energy from the reaction. A basic representation of the fuel cell process is shown in Figure 121.

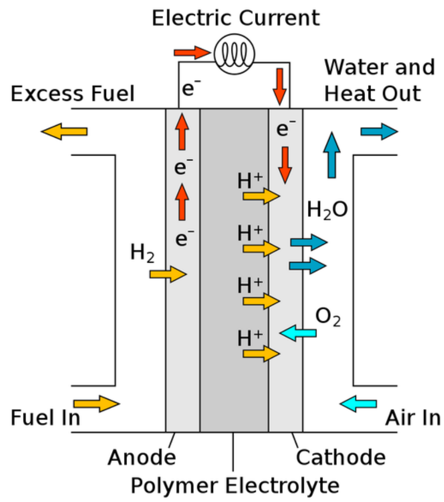


Figure 121: Basic fuel cell chemistry diagram (source: energyeducation.ca)

Fuel cells have high overall efficiency of chemical energy conversion to electrical energy, and thus power. Where a marine diesel engine will convert roughly 45%-50% of the available chemical energy into mechanical energy (up to 55% for the largest, most efficient slow-speed engines), a fuel cell can convert approximately 60% of that energy into electrical energy [A116]. Fuel cells do experience some efficiency degradation over time.

Fuel cells are highly scalable and can be combined with renewable energy sources in a power system, but are not well-suited for rapid changes in load without an intermediate energy buffer. Low temperature fuel cell technologies such as polymer electrolyte membrane (PEM) can reasonably provide load following (adjusting power output to demand), but not to the degree that marine vessel electrical loads vary. Fuel cell power in marine applications should generally be coupled with energy storage systems, such as batteries, to accommodate changing loads in propulsion and ship services.

Several fuel cell chemistries exist in varying degrees of technology readiness for marine applications. These are discussed in the following section.

Fuel Cell Technologies

Fuel cell technologies can be categorized by either temperature or electrolyte material. Low and high temperature categories are as follows:

- Low temperature technologies (below 200 °C):
  - Polymer Electrolyte Membrane Fuel Cell (PEM-FC), also known as Proton Exchange Membrane.
  - Alkaline Fuel Cell (AFC).
  - Phosphoric Acid Fuel Cell (PAFC).
- High temperature technologies (above 500 °C):
  - Molten Carbonate Fuel Cell (MCFC).
  - Solid Oxide Fuel Cell (SOFC).

Each of these fuel cell types are described in following sub-sections. Click the portal button to access a summary comparison of these technologies and their advantages, disadvantages, and marine considerations.

Fuel Cell Summary

Polymer Electrolyte Membrane Fuel Cell (PEM-FC)

PEM-FCs are the most mature technology for marine applications, and typically use hydrogen as a mono-fuel. A PEM-FC utilizes a solid polymer for the electrolyte, and the anode and cathode are constructed of a porous organic molecule impregnated with a catalyst such as platinum [A117]. A noble metal like platinum is required due to the low operating temperature of the reactions, typically less than 120 °C. The use of platinum, however, makes PEM-FC fuel cells sensitive to carbon monoxide contamination, also known as CO poisoning, so care must be taken to ensure the fuel and oxygen sources are free of contaminants. PEM-FCs typically have an overall efficiency of about 60% conversion of chemical energy into electrical power when using direct hydrogen.

PEM-FCs are popular in transportation applications due to their quick start-up and load following (adjusting power output to demand) characteristics, compared to other fuel cell technologies. The use of a solid electrolyte instead of a liquid layer also mitigates concerns over corrosion.

PEM-FCs are arranged into multi-cell stacks, with power capacities of each stack ranging from less than 1 kW to 400 kW. A PEM-FC cell power plant is scaled by combining multiple fuel cell stacks in parallel to achieve the desired power output at a given voltage.

A variation of the PEM-FC is the Direct Methanol Fuel Cell (DMFC), which uses a platinum/ruthenium alloy in way of pure platinum for the catalyst. The methanol is typically mixed with purified water prior to being fed into the anode-side of the fuel cell [A117].

Fuels compatible with PEM-FC include [A118]:

- 100% hydrogen, either directly or reformed from methanol, ethanol, and other light hydrocarbon fuels.
- 100% methanol, as used in PEM-variant DMFC.

Alkaline Fuel Cell (AFC)

AFCs are characterized by an alkaline electrolyte layer that is constructed of a matrix soaked through with an aqueous potassium hydroxide solution. Some AFCs alternatively use an alkaline polymer membrane. AFCs generally operate at lower temperatures than PEM-FC variants, below 100 °C. Due to the alkaline nature of the electrolyte, AFCs are quite sensitive to carbon dioxide and are readily contaminated in its presence. The aqueous electrolyte also requires careful management to ensure optimal performance of the fuel cell.

By using an alkaline electrolyte, the reduction reaction at the AFC cathode is tamer than in acidic environments like PEM-FC, allowing a wide range of catalysts to be used at the electrodes. With a wider availability of materials to support the AFC reaction, the cost of construction for an AFC can be lower than a comparable PEM-FC. Like PEM-FC, AFCs are capable of quick start-up due to their low operating temperature. AFCs operate at similar overall efficiencies to PEM-FCs around 60% but can achieve up to 70% efficiency in optimized conditions.

Stack power ratings for AFCs range from 1 kW to 100 kW.

Fuels compatible with AFC include 100% hydrogen, either directly or reformed from methanol, ethanol, and other light hydrocarbon fuels.

Phosphoric Acid Fuel Cell (PAFC)

PAFC is one of the more mature alternatives to PEM technology, using liquid phosphoric acid in a silicon-carbide matrix together with platinum-impregnated carbon electrodes. PAFCs are less susceptible to contamination from carbon monoxide than PEM-FC, and are tolerant of carbon dioxide. They are sensitive to sulfur contamination, so this must be considered for fuel selection. As a result, PAFC is more tolerant of a variety of fuels and fuel qualities. They are considerably less efficient, however, only achieving 37 to 40% overall efficiency without cogeneration incorporated. Cogeneration is the capture and use of heat from the fuel cell reaction in addition to power. At an operating temperature range of 140 to 200 °C, PAFC has a long start-time, which can be difficult to adapt to typical marine power applications. PAFCs are also challenged by the large amount of platinum required for electrode catalysts, increasing the cost of equipment.

Stack power ratings for liquid PAFCs range from 5 kW up to 400 kW.

Fuels compatible with PAFC include:

- 100% hydrogen, either directly or reformed from methanol, ethanol, and other light hydrocarbon fuels.
- 100% methane (CH_4) due to higher operating temperature, improved with external reformation.
- 100% methanol (CH_3OH) due to higher operating temperature, improved with external reformation.

Molten Carbonate Fuel Cell (MCFC)

MCFCs are a more recent fuel cell development, with commercial development efforts growing in the past few decades. The electrolyte consists of a molten carbonate salt held in a ceramic matrix. A key advantage of MCFC is internal reforming: at a high operating temperature of 600 to 700 °C, methane and other light hydrocarbons can be converted to hydrogen within the fuel cell, eliminating the need for external reforming for fuels that classify as indirect hydrogen carriers. MCFCs have potential to also use carbon monoxide and carbon dioxide as fuels.

The baseline overall efficiency for MCFC is approximately 50%, but up to 85% efficiency can be achieved with thermal cogeneration. High temperature operation makes heat capture through cogeneration possible. High temperature operation also increases corrosion and the breakdown of cell components, decreasing the operating life of an MCFC compared to low-temperature technologies.

Stack power ratings for MCFCs range from 300 kW to 3,000 kW.

Fuels compatible with MCFC include:

- 100% hydrogen, either directly or reformed from methanol, ethanol, and other light hydrocarbon fuels.
- 100% methanol through internal reformation at high temperatures.
- Other hydrocarbons through internal reformation at high temperatures.

Solid Oxide Fuel Cell (SOFC)

SOFCs employ a solid ceramic as the electrolyte. Similar to MCFCs, they operate at very high temperatures, between 500 and 1,000 °C, and are thus able to perform internal reformation of light hydrocarbon fuels. The baseline overall efficiency for SOFC is approximately 55%, but up to 85% efficiency can be achieved with thermal cogeneration, similar to MCFCs.

SOFCs are not sensitive to sulfur or carbon monoxide contamination, but the very high operating temperature requires selection of specialized components rated for that service.

Stack power ratings for MCFCs range from 1 kW to 2,000 kW.

Fuels compatible with SOFC include:

- 100% hydrogen, either directly or reformed from methanol, ethanol, and other light hydrocarbon fuels.
- 100% methanol through internal reformation at high temperatures.
- 100% ammonia.
- Other hydrocarbons through internal reformation at high temperatures.

High temperature technologies like MCFC and SOFC are less ideal for marine applications with transient loads, as they require long start-up time, are slow to respond to load changes, and are expensive at small scales due to the specialized materials required.

Marine Systems

Fuel cells are best integrated into a vessel with electric propulsion and a DC bus switchboard, where the DC power from the fuel cells can be readily converted into AC power for ship's propulsion and auxiliaries. The main machinery spaces of a ship using fuel cells will look different from a conventional vessel with diesel-generators. Fuel cells must be installed in a special fuel cell space that is separated from other machinery spaces. Class societies and IMO guidelines define a fuel cell space as both a Category A space requiring A-60 fire protection, and a Zone 1 hazardous area under the IEC definition [A119]. These requirements preclude the sharing of the fuel cell compartment with other auxiliary systems equipment, while all equipment within the space must be rated appropriately as explosion proof or intrinsically safe. If fuel cells are the sole source of power onboard, then class and flag may require equipment to be segregated between multiple fuel cell spaces for redundancy.

Equipment that supports fuel cell operation, separate from the fuel cell stacks themselves, is referred to as the "balance of plant" (BOP). Non-fuel handling BOP equipment is similar in nature to equipment commonly found on marine vessels, unlike the specialized nature of the fuel cells themselves. However, BOP equipment specific to fuel handling will be quite different from conventional marine fuel systems, given fuels handled such as hydrogen, ammonia, methanol, and other gas fuels. The typical systems to support fuel cell power generation are summarized here:

- Controls for automatic operation of fuel cell equipment.
- Power conversion and energy storage equipment to manage typical vessel load variations.
- Fuel preparation rooms separate from the fuel cell compartments.
- Specialized piping for the fuel, including double-wall ventilation.
- Specialized firefighting systems suitable for the fuel.
- Oxidant supply, including conditioning equipment to remove contaminants.
- Leak detection and ventilation in spaces containing gas fuel.
- Fuel cell exhaust systems.
- Process equipment, including cooling water and water byproduct handling.
- Reforming equipment for use of light hydrocarbons as indirect fuel cell fuel.

These systems need to be designed by an engineering group with experience in fuel cell power and their associated fuel systems. DNV published rules for fuel cell system installations onboard vessels under additional class notations in 2019 [A120]. ABS's Guide for Fuel Cell Power Systems is a useful starting point for considering the unique elements of a fuel cell installation [A119]. The IMO published Interim Guidelines for the Safety of Ships Using Fuel Cell Power Installations in June 2022 [A121]. USCG regulations specific to marine fuel cell installations don't yet exist, but individual projects are advancing USCG's familiarity and experience in reviewing fuel cell power systems.

Commercial Development

Marine technologies by PEM fuel cell developers are entering commercial maturity:

- Ballard's 200 kW FCwave™ PEM module received DNV type approval in April 2022 [B80].
- Cummins HyPM PEM model is designed specifically for marine applications, including the 360 kW HyPM™ PEM system installed on the ferry *Sea Change* [B81][C38].
- PowerCell in cooperation with Siemens Energy have collaborated to integrate the 200 kW PEM module with Siemens BlueDrive power electronics [B82].
- TECO2030's 400 kW PEM module has DNV approval-in-principle as they work toward full type approval. TECO2030 has also developed containerized solutions for their fuel cell system, in 1.6 MW (10-ft container), 3.2 MW (20-ft container), and 6.4 MW (40-ft container) capacities [B83].

Figure 122: Ballard (200kW), Cummins (120 kW), PowerCell (200 kW), and TECO2030 (400 kW) PEM modules

Several development projects are pursuing SOFC technology for marine vessels:

- Bloom Energy is developing SOFC fuel cells for a hydrogen-fueled LNG carrier, in collaboration with Samsung Heavy Industries [B84].
- SOFC4Maritime, a joint development project between Alfa Laval, DTU Energy, Haldor Topsoe, Svitzer, the Maersk Center for Zero Carbon Shipping, and ABS was formed in early 2021 to advance solid oxide fuel cell technology for the maritime industry, with a focus on ammonia as a direct fuel.
- Ammonia is also the selected fuel for the ShipFC project retrofitting the *Viking Energy* (IMO no. 9258442) with a 2 MW system, which will use SOFC technology developed by Prototech [B85].

Table 38: Marine fuel cell technology developments

Manufacturer/ Consortium	Type	Power Rating	Fuel	Approval Status	Deployments
Genevos HPM	PEM	15/40/80 kW	H_2	Lloyds AiP	MV *Shapinsay* (planned) [C50]
Ballard HD	PEM	100 kW	H_2	-	HYSEAS III (planned) [C51]
Cummins HyPM™	PEM	120 kW	H_2	-	*Sea Change* (delivered) [C38]
Ballard FCwave™	PEM	200 kW	H_2	DNV TA	MF *Hydra* (delivered) [C37]
PowerCell	PEM	200 kW	H_2	DNV AiP Lloyds AiP	
Corvus Energy/H2NOR	PEM	320 kW	H_2	-	
TECO2030	PEM	400 kW	H_2	DNV AiP	
Bloom Energy	SOFC	-	H_2	DNV AiP for vessel	
ShipFC	SOFC	2 MW total	NH_3	-	*Viking Energy* (planned) [C40]
SOFC4Maritime	SOFC	-	NH_3	-	

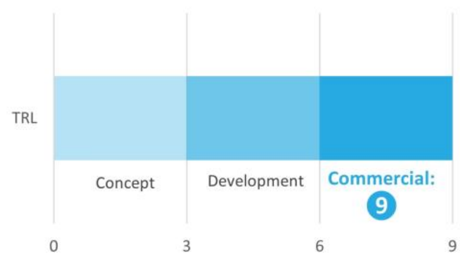
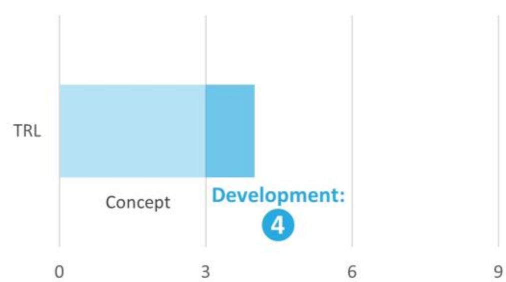
TA: type approval.

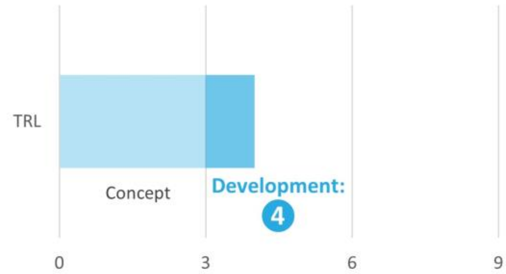
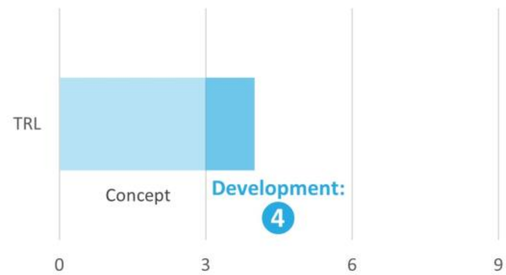
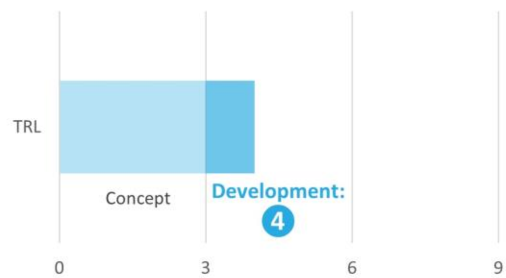
AiP: approval in principle.

TRL: Fuel Cell Technologies

Technology readiness levels for the fuel cell types reviewed above are provided in Table 39.

Table 39: Fuel cell technology readiness levels

Fuel Cell Type	TRL	
Polymer Electrolyte Membrane FC (PEM-FC)		- Type approved equipment installed on marine vessels - Multiple manufacturers offering commercial units - Multiple classes granting equipment approval-in-principle with class guidance for installation
Alkaline FC (AFC)		- Long history of successful installation in aerospace industry - No marine commercial installations or developments to date

Fuel Cell Type	TRL	
Phosphoric Acid FC (PAFC)		- Used in military submarine applications - No marine commercial installations or developments to date
Molten Carbonate FC (MCFC)		- Versatile with different hydrocarbons and hydrogen carrier fuels, temperature enables cogeneration from heat recovery - No marine commercial installations or developments to date
Solid Oxide Fuel Cell (SOFC)		- Versatile with different hydrocarbons and hydrogen carrier fuels, temperature enables cogeneration from heat recovery - No marine commercial installations, but multiple demonstration projects will progress TRL, including ShipFC with *Viking Energy* (IMO no. 9258442) and SOFC4Maritime development

Useful Resources

- US DOE Fuel Cell Technologies Fact Sheet [A116].
- Review of Fuel Cell Power Systems for Maritime Applications [A118].
- ABS Guide for Fuel Cell Power Systems [A119].
- DNV Rules for Fuel Cells [A120].
- IMO MSC.1/Circ.1647: IMO Interim Guidelines for the Safety of Ships Using Fuel Cell Power Installations [A121].
- EG&G Fuel Cell Handbook [A122].
- EMSA/DNV Study on the Use of Fuel Cells in Shipping [A123].

Fuel-Ready Vessel Design

Figure 123: NYK Line ammonia-fuel ready LNG-fueled car carrier concept (source: NYK)

Some owners are safeguarding their newbuild investments against potential future regulations by ordering engines that are either ready for dual fuel operations, or capable of being readily converted when ICE retrofit packages are released for sale.

A.P. Moller-Maersk is an industry leader in this area. Despite the production and distribution pathway for green methanol not being mature (though Maersk is actively funding production and infrastructure development), Maersk has ordered new vessels with dual-fuel (DF) engines capable of running on methanol in gas mode. Nineteen Maersk containerships with MAN's LGIM DF engines have been ordered to date, with a 2,100-TEU feeder scheduled for delivery in mid-2023. If gray or green methanol pathways are delayed, the new vessels can operate on conventional (petroleum) fuels in the interim.

WinGD was selected to provide "ammonia-ready" DF engines (running on natural gas in gas mode) for four new 14,000-TEU Pacific International Lines (PIL) containerships [C47]. The readiness of the engines or scope of future modifications for ammonia conversion is not detailed by WinGD, but it shows that multiple fuels are being considered for oceangoing vessels.

These early movements by Maersk, PIL, and others indicate that the containership trade could be at the forefront of alternative fuel uptake.

Wartsila has announced its Two-Stroke Future Fuels Conversion Platform, The technology will start with natural gas conversion, followed by plans for methanol and ammonia conversion [B68]. It is unclear whether the program will be for dual fuel or monofuel conversion. Wartsila is partnering with the shipping company MSC to install and test the first conversion package onboard one of their vessels in 2023 [C52]. The Future Fuels technology uses a proprietary combustion process that combines aspects of both high pressure and low pressure cycles, and places all fuel preparation equipment on-engine rather than as separate machinery skids. Pressure amplification occurs on-engine, so fuel can be supplied to the engine at low pressure. This has potential to simplify and reduce the cost of an installation, particularly a retrofit [B68]. The Wartsila on-engine conversion concept is shown in Figure 124 for LNG. The on-engine process would be simplified for methanol as a gas fuel in liquid form.

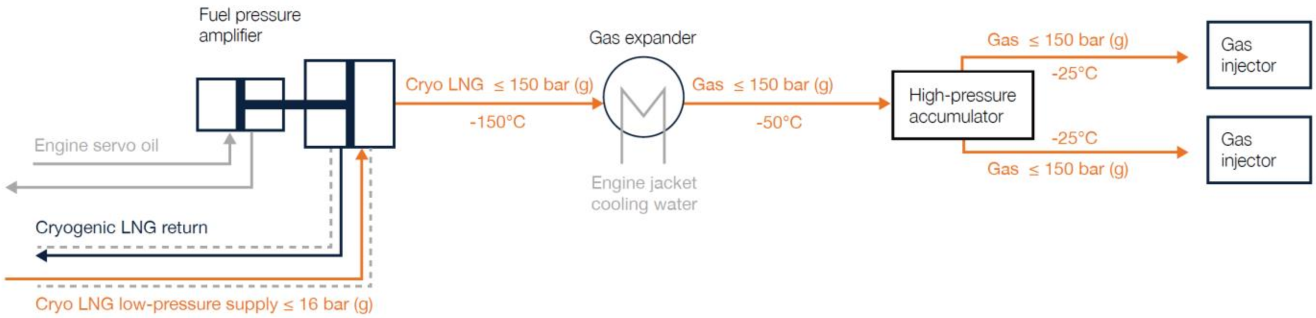


Figure 124: Wartsila Future Fuels on-engine schematic (source: Wartsila)

The engine itself is only one component of designing a fuel-ready vessel. If an owner selects a manufacturer based on their commercial plan for dual fuel capability, they should consult with that manufacturer closely to prepare for the aspects discussed in Table 40.

Table 40: Design aspects to consider for dual fuel capability

Design Aspect	Consideration
Space reservations for equipment	Fuel conditioning and supply equipment may still be under development at the time of vessel construction. Adequate space must be held in reserve, in appropriate locations, with margin to account for possible design changes.
Systems interface points for future equipment	Auxiliary system tie-ins, including power, cooling, ventilation, and communications must all be considered. A future fuel conversion could be similar in scope to a full repower, so advance interface planning can simplify the work.
System sizing margin	For power and auxiliary systems that will interface with future fuel systems, adequate capacity must be designed in advance to accommodate those systems. Pumping and piping systems may have increased power demand with integration of a new fuel supply system, and distribution panels will see increased loads to support new equipment.
Fuel storage	Onboard storage of a future fuel will look different from conventional MGO or HFO, to a degree dependent on the specific fuel. Non-structural cryogenic or compressed tanks (liquid hydrogen and ammonia, respectively), will require space and weight planning, and structural tanks initially used to carry conventional fuel may require protective coating (methanol).

These aspects should be considered for all future dual-fuel options, including methanol, ammonia, and hydrogen. NYK's Ammonia Ready LNG Fueled Vessel (ARLFV) design lays out a possible path to future fuel conversion, and incorporates storage tanks cross compatible with LNG and liquefied ammonia, with adequate energy capacity for a future switch to ammonia [B85]. The tank concept tank arrangement is shown in Figure 123.

Design in accordance with IMO's IGF code [A78] is critical to ensuring future integration is both technically feasible and financially feasible. Some class societies offer guidance and consulting in this area, such as ABS's Guide for Gas and Other Low-Flashpoint Fuel Ready Vessels [A124]. The Suezmax tanker *Kriti Future* (IMO no. 9924326) was delivered as the first "ammonia-ready vessel" in early 2022, recognized as Level 1 ready in that the concept design was reviewed by ABS for alternative fuel readiness [C53]. Full class notation falls under Level 3 readiness, as shown in Table 41.

Table 41: ABS notations for fuel-ready vessels (source: ABS)

List of "Alternate Fuel Ready Level 3" Notations (1 February 2021)	
CNG Fuel Ready Level 3	Methanol Fuel Ready Level 3
LNG Fuel Ready Level 3	Ethanol Fuel Ready Level 3
Ethane Fuel Ready Level 3	Hydrogen Fuel Ready Level 3
LPG Fuel Ready Level 3	Ammonia Fuel Ready Level 3
DME Fuel Ready Level 3	

In addition to engine and fuel systems geared toward future conversion, vessel concepts are being advertised as future-ready or future-proof with regard to fuels. In particular, selection of a diesel-electric plant can simplify future integration, as engine conversion can be phased in across multiple generators, and does not directly impact the propulsion drive train. This is the basis of Conoship's CIP3600 general cargo vessel, which does not tout any fuel-specific features, but deviates from a conventional sea-river design by using a diesel-electric plant. The CIP3600 concept also includes Econowind Ventifoils for assisted propulsion [B87].

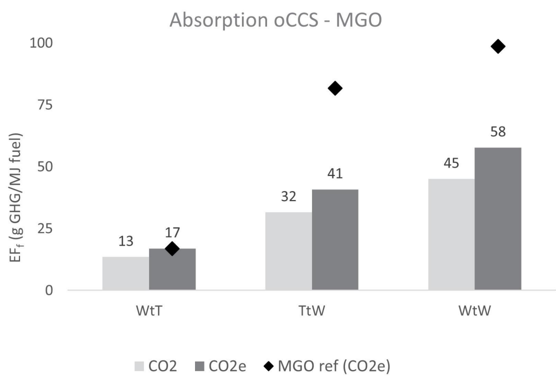
Figure 125: Conoship CIP3600 concept with diesel-electric propulsion (source: Conoship International)

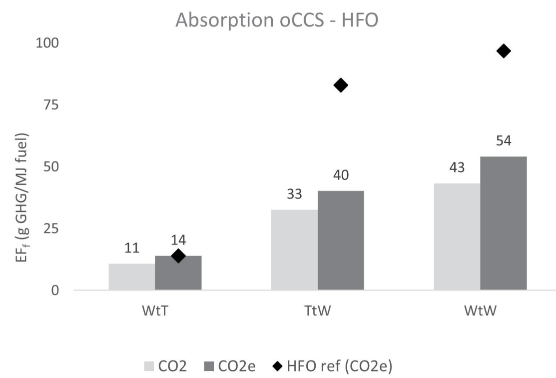
Link to Guide Navigator

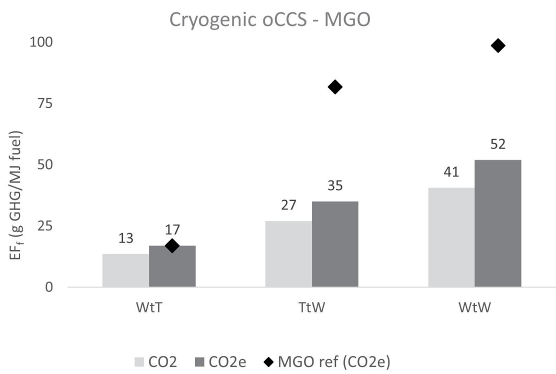
Onboard Carbon Capture and Storage (oCCS)

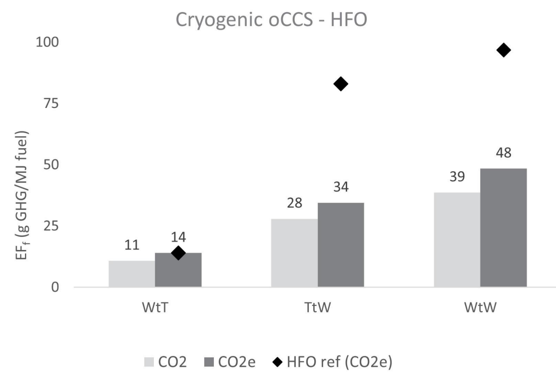
MGO with carbon capture | **HFO** with carbon capture | absorption capture | cryogenic capture

FUEL EMISSION FACTOR (EF$_f$)

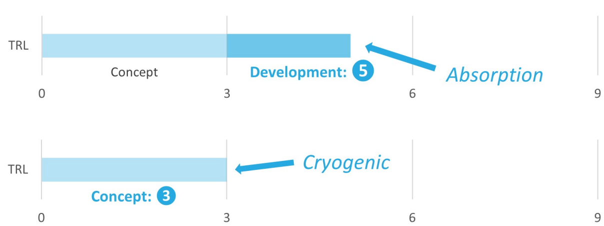








TRL



KEY FACTORS

- Cryogenic with heat recovery may require half power of absorption
- Cryogenic may remove critieria pollutants (SOx, NOx, PM)
- Common absorption solvents are prone to degradation
- Capture rate up of 60-70% in early testing, 90-95% potentially achievable
- ~1:100 scale tested in prototype installed on 230-meter coal carrier
- Best suited for large cargo vessels with available deck space and coastal/lake ranges
- Long-range vessels challenged by required CO_2 storage (space & weight)
- CO_2 storage may significanly reduce cargo capacity or vessel capabilities

APPLICATIONS

MW	Duty					
>10	Continuous	poor	marginal	marginal	marginal	marginal
	Intermittent		marginal	marginal	marginal	marginal
1-10	Continuous	marginal	poor	poor	marginal	poor
	Intermittent		poor	poor	marginal	poor
<1	Intermittent		poor	poor	poor	poor

MW: Propulsion power plant size, in MW

general compatibility | marginal compatibility | poor compatibility

INTEGRATION

		OpEx	CapEx
Newbuild	marginal	$$	$$$
Retrofit	poor		$$$

Link to Dashboard Legend

Overview

Two methods of onboard carbon capture and storage (oCCS) are being adapted for marine suitability: absorption carbon capture and cryogenic carbon capture. Absorption capture is a chemical absorption process, while cryogenic capture is physical separation. These processes are considered post-combustion carbon capture, which are challenged by the low partial pressure of CO_2 in the exhaust gas. Both methods are focused on the same underlying objective: capture CO_2 emissions in-situ from the vessel's stack and store it onboard until it can be offloaded in port or at an offshore facility. For vessels that are consuming a fossil fuel with high carbon intensity, CCS enables GHG emissions reductions without modifying the method of power generation, or switching to a different fuel with lower GHG intensity but higher commodity cost.

The challenge in marine and offshore environments is the handling and storage of captured CO_2. Both cryogenic and absorption methods require significant power to liquefy or solidify the captured CO_2 for storage. Storing CO_2 in gaseous form onboard is not viable due to space requirements.

CO_2 transforms directly from a gas to a solid, known as deposition or desublimation, when cooled at atmospheric pressure to -78 °C. It can also be solidified by interaction with other chemicals. To transport CO_2 in a liquid state, it needs to be stored at 0.7 MPa and -50 °C. If the liquefied CO_2 is to be stored onboard, the storage space needs to be considered based on the expected capture volume for the voyage. One ton of liquefied CO_2 occupies approximately one m^2 volume.

One maritime research group is testing a modified SOx scrubber to also absorb CO_2, possibly simplifying the integration of oCCS onboard vessels already fitted with a SOx scrubber or planning for a future integration with one.

Any carbon capture process relies on mature infrastructure to store, transport, and dispose the captured CO_2, disposal methods including permanent sequestration or industry utilization. The land-based infrastructure and value chain side of the carbon capture lifecycle are not detailed in this guide. However, projects in the UK, Norway, and other North Sea countries are planning or developing the infrastructure necessary to make oCCS possible.

Aside from locating and integrating complicated process equipment with existing ship's systems, oCCS also requires storage of a significant mass of captured CO_2 onboard. This is discussed in the oCCS section on Integration.

Absorption Carbon Capture

Absorption carbon capture (ACC) uses an amine-based solvent to absorb CO_2 from the exhaust gas. ACC is more developed than Cryogenic carbon capture (CCC) in industrial settings, having been used for decades in gas plants. The exhaust gas is first cooled, passed through a filter, and then reacted with the solvent to separate the CO_2 before the exhaust is released to atmosphere. The solvent, or absorbent, then goes through a regeneration process in which the CO_2 is released by steam heating, and the absorbent is recycled to the absorption process to continue CO_2 removal. A basic diagram of the process is shown in Figure 126.

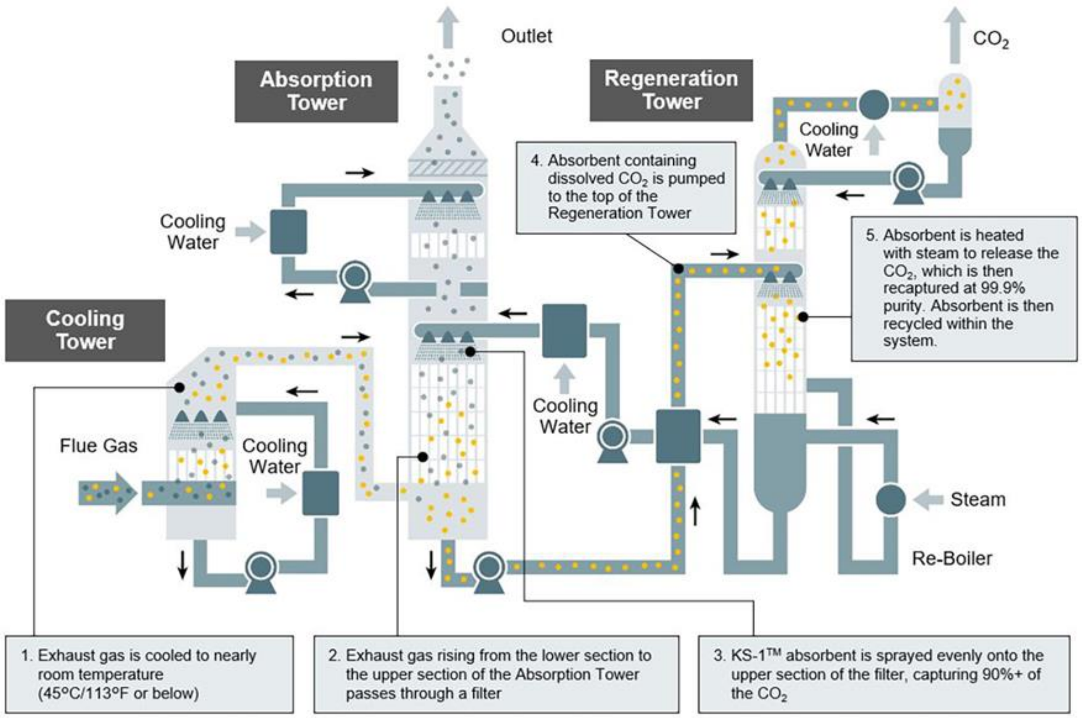


Figure 126: Absorption carbon capture process (source: MHI)

ACC does require a chemical solvent to be carried onboard and potentially handled by a vessel's crew. Alkanolamines as a solution are the most common amine for carbon capture, including monoethanolamine. **Alkanolamines are prone to degradation, particularly at elevated temperatures, and in the presence of other components common to a marine exhaust stream** (NOx, SOx, and particulate matter). Alkanolamines degraded by the exhaust stream can form compounds that may be harmful to the environment and human health [A128]. Potassium carbonate is also proven as a solvent, being less volatile and reactive than alkanolamines, but also slower to react with CO_2 in an exhaust stream.

ACC is estimated to have a theoretical CO_2 capture rate of 90-99%, and is sensitive to NOx and SOx impurities [A126].

Building on their proprietary KS-1™ solvent, which is likely monoethanolamine-based, Mitsubishi Heavy Industries (MHI) has developed KS-21™ to have lower volatility and improved resistance to degradation [B88]. Advances in solvent chemistry and equipment technology alike may improve the effectiveness and environmental safety of ACC systems in the marine environment.

Cryogenic Carbon Capture

Cryogenic carbon capture (CCC) separates CO_2 from the exhaust gas plume of a fossil fuel (or other carbon-based fuel) by desublimation (the direct phase change from gas to solid) of the CO_2 to a solid followed by heat transfer to a pressurized liquid. A basic diagram of the process is shown in Figure 127. CCC technology uses specialized heat exchangers and a series of heat recovery stages to achieve the separation in an energy-efficient manner, producing pressurized liquid CO_2. **The heat recovery system, or heat integration, may reduce 50% of auxiliary power required to operate the equipment compared to amine absorption carbon capture** [A125].

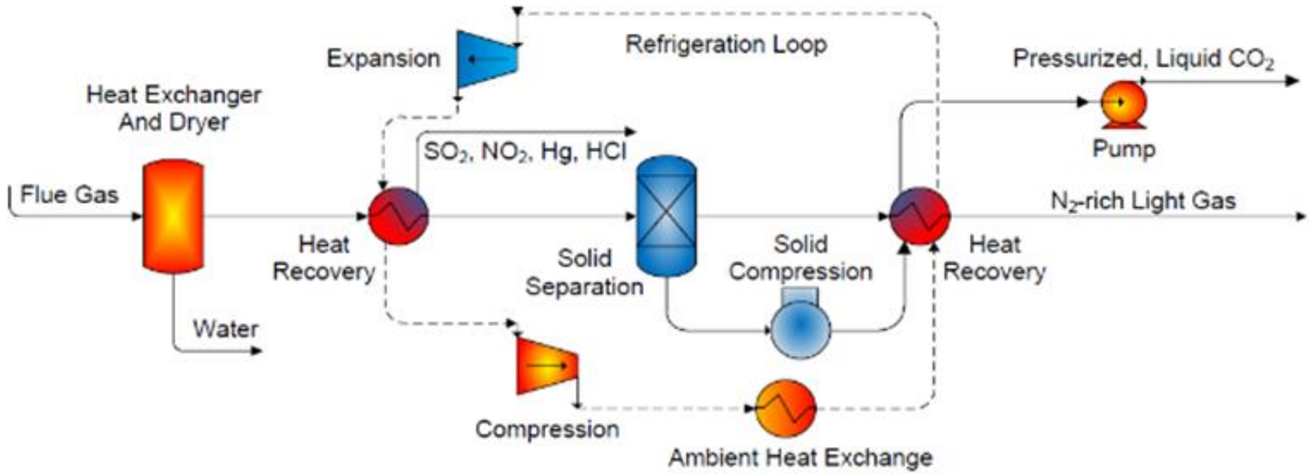


Figure 127: Cryogenic carbon capture process (source: NETL)

CCC was initially targeted toward coal-fired power pollutants, and several US-based pilot demonstrations by SES Innovations have been successful. **A key benefit of CCC is the removal of other harmful emissions, possibly enabling CCC to replace other exhaust gas cleaning systems that are currently mandated by regulations**, such as scrubbers for SOx and selective catalytic reduction systems for NOx.

CCC is advantageous in that it does not require a reacting chemical to separate CO_2, thus avoiding potential for harmful byproducts from forming, but it is energy-intensive to cool the exhaust gas adequately to extract CO_2. Heat integration is necessary to optimize the carbon capture and offset the energy input, the overall energy benefit is significantly diminished.

CCC is estimated to have a theoretical CO_2 capture rate of 90-99%, and is potentially sensitive to SOx and water moisture impurities [A126].

One developer, PMW Technology, is seeking to simplify the process by circulating metal beads to cool the flue gas and then separate carbon dioxide by it adhering to the beads as frost. A basic diagram of this process, known as A3C, is shown in Figure 128, In a case study with the UK Department of Transport, PMW estimated the CO_2 abatement cost of the A3C process to be 50% of using ammonia as a marine fuel [A127].

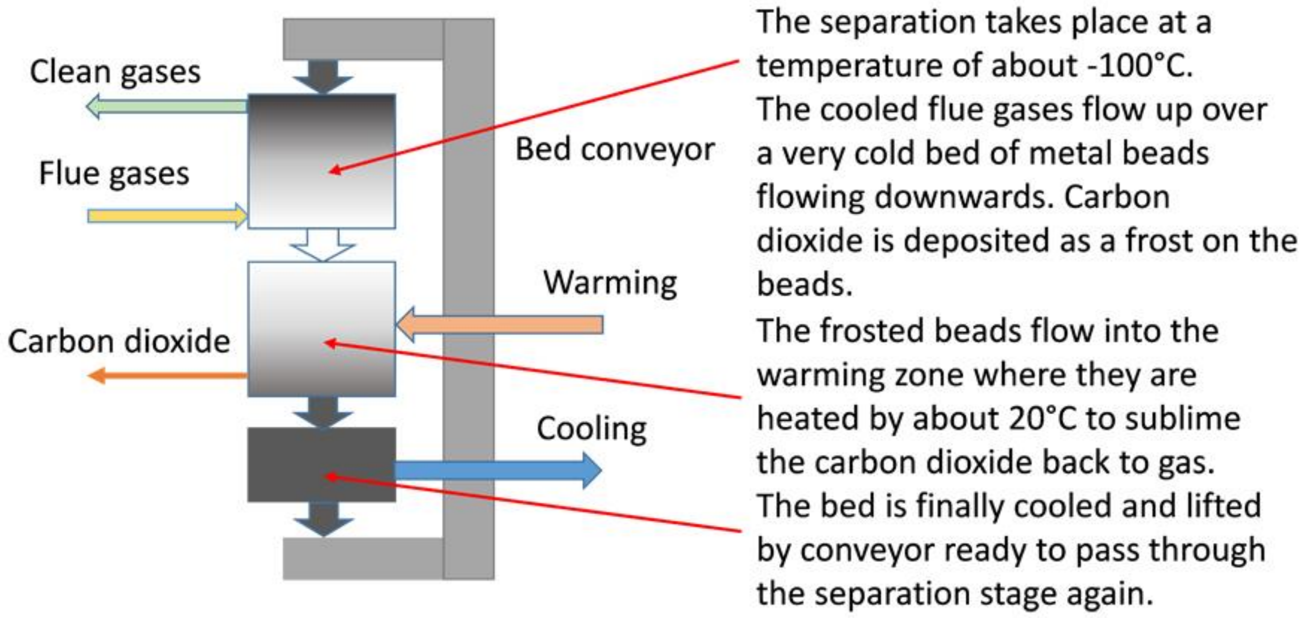


Figure 128: PMW Technology's metal bead cryogenic CO_2 separation process (source: PMW Technology)

Carbon Capture with SOx Scrubbers

Scrubber technologies that were designed for SOx absorption are now being evaluated to capture and remove CO_2 from exhaust gas as a secondary function. In 2021, an Alfa Laval PureSOx scrubber was modified and tested on a newbuild Japanese vessel to absorb CO_2 in addition to SOx, in collaboration with Japan's National Maritime Research Institute [B89]. The project indicated initial success in removing CO_2 from the auxiliary engine exhaust stream while the PureSOx operated in closed loop. Actual results of the testing were not published.

As discussed in the next section, coupling carbon capture with other exhaust management technologies could simplify oCCS integration on new and existing vessels.

Figure 129: Alfa Laval has tested its SOx scrubber technology to absorb CO_2 (source: Alfa Laval via rivieramm.com)

Commercial Development

Absorption

Onboard demonstration projects are moving forward with ACC technology. MHI formed a consortium with K Line and ClassNK to install and test their Kansai Mitsubishi Carbon Dioxide Recovery (KM CDR) Process™ [B90] onboard the coal carrier *Corona Utility* (IMO no. 9748021, [C54]). The system was installed in 2021, as shown in Figure 130, and has been undergoing onboard testing and performance analysis. The CC-Ocean system is a small-scale prototype, capturing approximately 0.1 ton CO_2/day, or less than 1% of the ship's daily output of CO_2 emissions. MHI **has reported a 65% capture rate, but estimate up to 90% capture is possible** [A129]. The CC-Ocean project notably does not include bulk CO_2 storage onboard, limiting the project to capture analysis only.

The EverLoNG project seeks to implement carbon capture technology on LNG-fueled vessels, starting with the semi-submersible *Sleipnir* (IMO no. 9781425) and an LNG carrier operated by TotalEnergies [B91]. The *Sleipner* platform is shown in Figure 131, with a concept for carbon capture towers shown in Figure 132.

The planned EverLoNG prototype is based on TNO's research in solvent-based ACC technology. TNO is the Netherlands' national applied scientific research organization. EverLoNG represents a diverse set of stakeholders, including equipment manufacturers, research institutes, government organizations, and three classification societies (DNV, Bureau Veritas, and Lloyd's Register). EverLoNG seeks to use ACC to reduce a vessel's emissions by at least 70%. Hereema, the operator of the *Sleipner* platform, has indicated a target full-scale installation by 2024 [C55].

Figure 130: MHI absorption carbon capture system installed as part of CC-Ocean project (source: MHI)

Figure 131: Hereema *Sleipner*, planned for carbon capture integration under EverLoNG project (source: Hereema)

Hereema is also partnered on Conoship International's DerisCO_2 project, which aims to configure an ACC system specifically for handling exhaust from LNG-fueled engines.

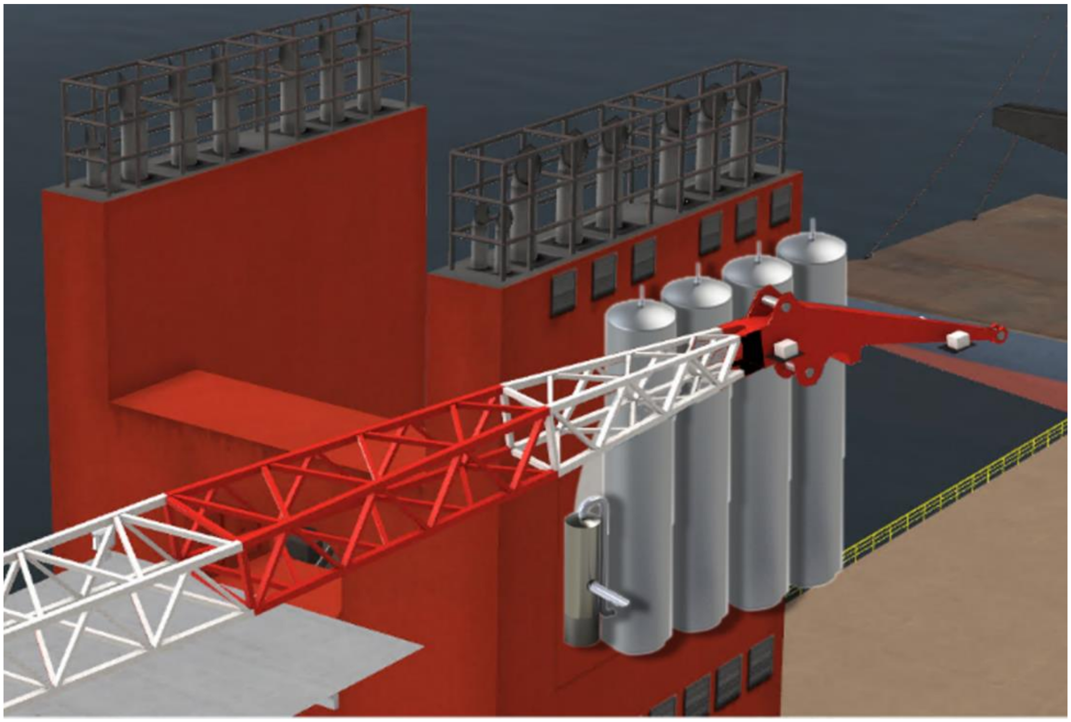


Figure 132: Carbon capture concept on board the Hereema *Sleipner* (source: Hereema)

Cryogenic

At least two companies have developed patents for unique CCC processes and are also exploring marine applications: SES Innovations (a Chart Industries company) in the US and PMW Technology's A3C system in the UK. Chart Industries has partnered with TECO2030 to integrate the SES Innovations technology into the TECO Future Funnel program [B92]. A comprehensive technology like Future Funnel with CCS would enable owners and operators to meet current emissions regulations while also readying their vessels for future GHG emissions requirements. Technical details on the SES system are limited.

PMW's novel metal bead technology has potential to simplify the cryogenic process, reducing the footprint and difficult of integrating equipment onboard [B93]. PMW Technology is seeking to build a pilot system followed by an onboard demonstrator in 2023, but has not announced any partners to advance as a marine-capable technology.

Reduction Potential:

Emission factors EF_f for implementation of oCCS are provided in Table 42 (g GHG/MJ fuel) and Table 43 (tons GHG/ton fuel), developed using the following assumptions:

- Lower heating value for calculating mass/mass EF_f values are assumed to be 42.7 MJ/kg for MGO and 40.2 MJ/kg for HFO.
- Emission factors are reported for Absorption (ACC) with capture rate is assumed to be 70%, based on EverLoNG objective of 70% capture [B91] and MHI pilot results reported at 65% capture [A129].
- Emission factors for Cryogenic (CCC) capture rate assumed to be equivalent to ACC, for the sake of proper comparison.
- oCCS assumed to only capture CO_2, with other GHG components released unaffected by process.
- ACC additional auxiliary load for 70% capture rate assumed to be 40% of total vessel energy. CCC auxiliary load assumed to be one half of ACC, or 20%, based on NETL estimate [A125]. **Developer data on equipment electrical loads is not available**.
- Emission factors reported for both MGO and HFO, given large vessels that may use carbon capture typically use residual fuels.
- oCCS is estimated to be capable of 90% to 99% capture rate for both ACC and CCC [A126], but this performance has not been demonstrated in a shipboard application.

Table 42: oCCS reduction potential at 70% capture rate: emission factors in grams GHG/MJ fuel

oCCS Type	Fuel	CO_2 Emissions Factor EF_f (g CO_2/MJ fuel)			CO_2e Emissions Factor EF_f (g CO_2e/MJ fuel)		
		WtT	TtW	WtW	WtT	TtW	WtW
Absorption	MGO	13.5	31.5	**45.0**	16.9	40.8	**57.7**
Absorption	HFO	10.7	32.5	**43.3**	13.9	40.2	**54.1**
Cryogenic	MGO	13.5	27.0	**40.5**	16.9	35.0	**51.9**
Cryogenic	HFO	10.7	27.9	**38.6**	13.9	34.4	**48.3**

Table 43: oCCS reduction potential at 70% capture rate: emission factors in tons GHG/ton fuel

oCCS Type	Fuel	CO_2 Emissions Factor EF_f (tons CO_2/ton fuel)			CO_2e Emissions Factor EF_f (tons CO_2e/ton fuel)		
		WtT	TtW	WtW	WtT	TtW	WtW
Absorption	MGO	0.58	1.35	**1.92**	0.72	1.74	**2.46**
Absorption	HFO	0.43	1.31	**1.74**	0.56	1.62	**2.17**
Cryogenic	MGO	0.58	1.15	**1.73**	0.72	1.49	**2.22**
Cryogenic	HFO	0.43	1.12	**1.55**	0.56	1.38	**1.94**

TRL: Absorption – 5, Cryogenic – 3

- **ACC has been installed at a <1:100 scale on the *Corona Utility* (IMO no. 9748021), for testing and analysis purposes**.
- ACC integration is planned on multiple LNG-fueled vessels through EverLoNG, but other installation projects are not publicly known.
- CCC is being studied as a marine solution with no full-scale or fully operational shipboard projects currently active. SES Innovations has successfully demonstrated their technology up to 1 metric ton CO_2/day captured in industrial settings [A130].
- ABS released a white paper on Carbon Capture, Utilization, and Storage in 2021 as an introductory document [A131], indicating growing interest but still nascent state of the technology for marine vessels.

Applications

- **oCCS best-suited for large cargo vessels with space available for both enlarged exhaust casings as well as on-deck compressed or liquid CO_2 storage. Vessels include coastal cargo vessels and lake freighters**.
- **CO_2 storage requirements may preclude long-range, oceangoing vessels without enough space and weight margin.**
- Many cruise ships, small passenger vessels, work boats, and special purpose vessels will not be able to incorporate added stack equipment and storage; vessels of this type primarily use ULSD due to limited space to integrate SOx scrubbers.

Integration

○ **marginal compatibility for newbuild** ⊗ **poor compatibility for retrofit**

$$$ **significant OpEx cost** $$$ **significant CapEx costs**

- oCCS requires modified designs for exhaust system, stack structure, or possibly separate dedicated towers for pre-cooling and CO_2 removal equipment. Applicable across all vessel types.
- **Onboard CO_2 storage onboard may reduce cargo capacity or vessel capabilities significantly.** The impact on stability should be investigated, as well as how the oCCS system is impacted by engine load variations and vessel motions.

- Existing vessels unlikely to have space and load capacity to accommodate oCCS stack modifications and onboard storage. MGO combustion produces approximately 3.2 tons CO_2 per ton fuel consumed; HFO produces 3.1 tons CO_2 per ton fuel.
- Assuming auxiliary loads of 20-40% to run oCCS systems at a 70% capture rate, without improving fuel efficiency as a post-combustion technology, OpEx estimated to be significant. Potential loss of revenue due to lost cargo capacity not considered, but could make oCCS economically infeasible.
- Cost of mechanical and electrical equipment, integration to systems, structure, and CO_2 storage for oCCS system would require significant capital investment for newbuild installation, more-so for retrofit installation.

Useful Resources

- PMW Technology: Evaluation of the Marine Application of Advanced Carbon Capture Technology [A127].
- MHI Presentation: Overview of “CC-Ocean’ project [A129].
- ABS Whitepaper: Carbon Capture, Utilization, and Storage [A131].
- Research Report: Large-scale CO_2 shipping and marine emissions management for carbon capture, utilization, and storage [A132].

Marine Nuclear Power

Overview

Nuclear Power has been in use on ships since the USS Nautilus first sailed in 1955 with the historic message “Underway on nuclear power.” However, with few exceptions, subsequent use has been limited to military vessels. In contrast with some other decarbonization technologies, nuclear power plants offer exceptional endurance and energy density. There are active efforts to adapt some of the newest advanced reactor designs for use on ships.

Unfortunately, any use of nuclear power for propulsion or power generation in commercial marine projects must overcome steep technical, regulatory, commercial, and logistical challenges. Perhaps uniquely among marine decarbonization technologies, it would also face intense political opposition. Commercial power generation will be a useful bellwether here: if the world embraces massive expansion of nuclear power generation on land, commercial marine power will be a step closer to being practical.

Historically, pressurized water reactors (PWR) have been most common, both for terrestrial power generation and as a shipboard power source. Most recent efforts seek to mature alternative reactor designs to mitigate historical challenges with PWRs.

Molten salt reactors (MSR) are one such alternative design and is under development by multiple companies, including some seeking to adapt terrestrial reactor designs for shipboard use.

Technologies

Pressurized Water Reactor

Pressurized water reactors (PWR) operate with water as coolant, maintained as a liquid by generating high pressures (~155 bar) with a steam bubble generated by electric heaters in the pressurizer. To make power, heat from the "primary" loop circulating through the reactor core boils water in a steam generator, which is converted to useful work in a "secondary" steam plant. The steam plant operates on the Rankine cycle. Seawater cools the condenser. A nuclear ship engine room bears many similarities to conventionally powered steam ships. A typical PWR plant is shown in Figure 133.

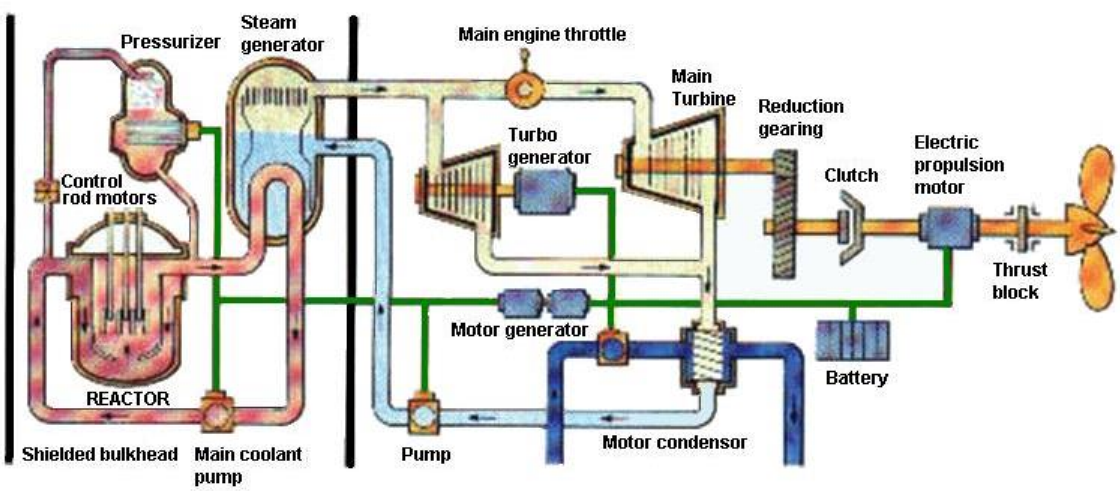


Figure 133: Typical Shipboard PWR Propulsion Plant (source: fas.org)

PWRs are a mature and proven technology but are not without drawbacks and challenges. One drawback is that the high operating pressure requires primary loop reactor components to be heavy and expensive pressure vessels.

Additionally, PWRs used for commercial power generation are typically fueled with low enriched uranium (LEU). This requires frequent refueling, typically every 2-3 years. Naval reactors, operating on high enriched uranium (HEU), can be designed with life-of-ship cores, but HEU is not allowed in civilian applications due to the risk of nuclear weapons proliferation. Refueling outages in commercial nuclear plants are at least 30-40 days long [A133]. Potential difficulties in arranging both fuel handling equipment and spent fuel storage onboard would likely push the refueling duration of a commercial shipboard PWR to at least a year.

Construction costs and refueling logistics suggest that even if regulatory and political challenges were solved, PWRs are unlikely to be developed for use in commercial marine propulsion plants.

Molten Salt Reactor

A nascent technology for commercial marine nuclear is the molten salt reactor (MSR). MSRs can use a molten salt fluid (liquid at 400 °C and above) as both the reactor coolant and the carrier of nuclear fuel. Molten salts at these operational temperatures remain liquid at ambient pressure – a major design benefit which avoids heavy pressure vessels seen in PWRs. MSRs are attractive based on the anticipation they may require a lighter regulatory regime than conventional PWR. This will not be known until MSR technologies approach a commercial maturity for marine applications.

MSRs envelop a wide design space, with many tradeoffs between nuclear, thermal, and chemical design considerations. No fewer than seven companies are developing MSR reactors, using a variety of salt compositions and fuel elements. Critical details to understand about any proposed MSR technology include:

- the size and complexity of the associated chemical processing equipment.
- radiation levels during operation and maintenance.
- fueling frequency, storage, and bunkering methodology.
- nuclear proliferation risk.

One major challenge in adapting nuclear technology from commercial power generation onto ships is a large mismatch in typical power ratings. Whereas the biggest ships in the world might use between 10-80 MW of propulsive power, mature PWR designs are on the order of 1000 MW. Fortunately, much of the current technology development is oriented around the idea of smaller, modular reactors. In terrestrial applications, this is foreseen to offer advantages in manufacturing and allow a standardized design to be used at sites with a wide range of power requirements. Maturation of modular reactor designs may be a major development for shipboard applications, as the rating of one or two modules may better align with typical propulsion needs. Relatively little information is publicly available about the projected sizes of modules under development. Sources indicate that Terrapower, the nuclear developer for the Core Power concept, is developing a small variant of their design with a minimum rating of 30 MW [A134].

In addition to power matching and modular production, MSRs are promoted by their developers to have the following advantages compared to PWRs:

- Operation at ambient pressure increases safety.
- Fuel is contained within the coolant, reducing chance of loss of coolant.
- High temperature (400-700 °C) process increases thermal efficiency.
- In event of failure, molten salt containing nuclear fuel cools to a solid, reducing risk of a contaminated leak.
- Life-of-ship fuel capacity.

From a technical perspective alone, marine MSRs are not expected to be ready for commercial deployment any time soon. Seaborg has ambitiously estimated a commercial prototype of their Power Barge concept by 2024, but has no plans for marine propulsion power [B94]. Core Power is pursuing nuclear electric ships as one application for their MSR technology [B95] but has not announced a timeline for that development. Terrapower's Molten Chloride Reactor Experiment is projected to start operation in 2025. This demonstrator project should significantly advance this technology, but substantial further development will still be required to scale and adapt the basic nuclear process. Core Power has also acknowledged that regulatory hurdles will require significant work and renewed international cooperation [A135].

Figure 134: CORE POWER molten salt reactor concept (source: energytrend.com)

Applications

- Large cargo ships. Given the likely reactor sizes, only the biggest ships in the world will have sufficient propulsion loads for nuclear propulsion to be a good fit.
- Miscellaneous vessels with both large power and endurance requirements. Nuclear icebreakers have been in Russian service since 1975, but other governments and private companies have not pursued non-combatant vessels.
- Floating nuclear power production (FNPP). Floating nuclear power plant concepts are under development, including Seaborg's Power Barge. Russia commissioned the 70-MW floating plant *Akademik Lomonosov* in 2020 as the first of its kind [C56]. FNPP are not relevant to marine vessel decarbonization but may function in the marine commercial environment before commercial nuclear vessels.

Key Design Considerations

Aside from the development of the reactor technology itself, many design details will need to be considered to develop a reactor into a complete shipboard power plant and integrate that plant into a ship design. For example:

- Reactor compartment. All reactor types will require a dedicated compartment with heavy radiation shielding and other safety features. It should be immediately forward of the engine room.
- Secondary plant. The type, complexity, efficiency, and arrangement of the Rankine cycle plant must be developed. Steam can be used to drive turbines that mechanically spin propellers via reduction gears. Alternatively, a steam-electric plant could eliminate a significant number of mechanical components and replace them with motors, switchgear, and power conversion equipment. Superheaters, economizers, and multiple-expansion turbines can trade space, weight, and capital cost for improved operating efficiency.
- Alternative power cycles. MSR designs have proposed to take advantage of the higher operating temperatures to use innovative power cycles. One example is the supercritical CO_2 Brayton cycle. While this is an exciting technology with many potential benefits, it is a separate development effort from the reactor itself and has a low TRL today.
- Backup power. Restarting a nuclear plant after a planned or unplanned shutdown can require significantly more power than starting a diesel engine. Passively storing energy (e.g. diesel air start cylinders) will not be possible. This may have a significant impact to the size and redundancy requirements for emergency diesel installations.

2.3 Operational Measures (OM)

Operational Measures (OM) have been demonstrated to reduce fuel consumption and improve the energy efficiency of vessels. Such reductions are typically concurrent with increased on-time arrivals and decreased maintenance cycles. This section provides an overview of several such operational measures. The vessel operator/owner is encouraged to engage in OM in tandem with energy efficiency technologies and fuel technologies for the most cost, safety, and emissions effective solution.

Data Management and Software Landscape

The maritime industry continues to engage in data management and feedback. In 2020, Kongsberg identified an estimated 400 maritime software offerings, summarized in Figure 135 through Figure 139. Many of these software suites include operational measures that can reduce fuel consumption and the resulting emissions. The next sections look at OM that might be onboard the ship, focused on the voyage, and combinations of both.

Figure 135: Maritime software landscape: administrative and personnel (source: Kongsberg)

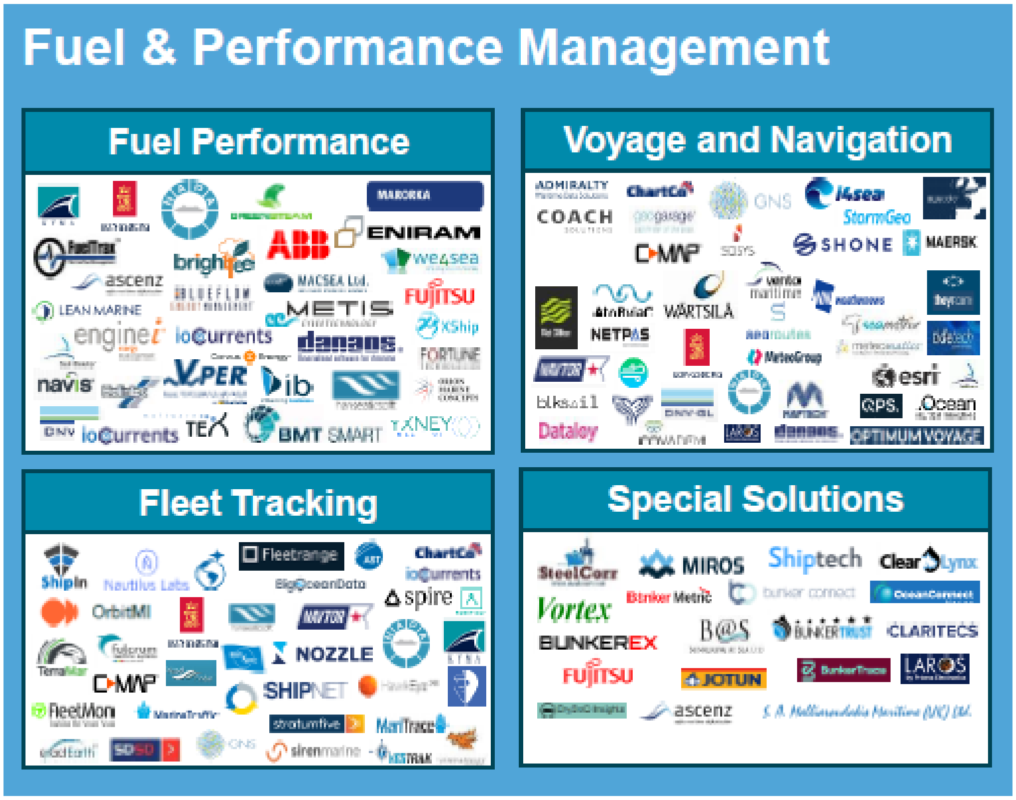


Figure 136: **Maritime software landscape: fuel and performance management (source: Kongsberg)**

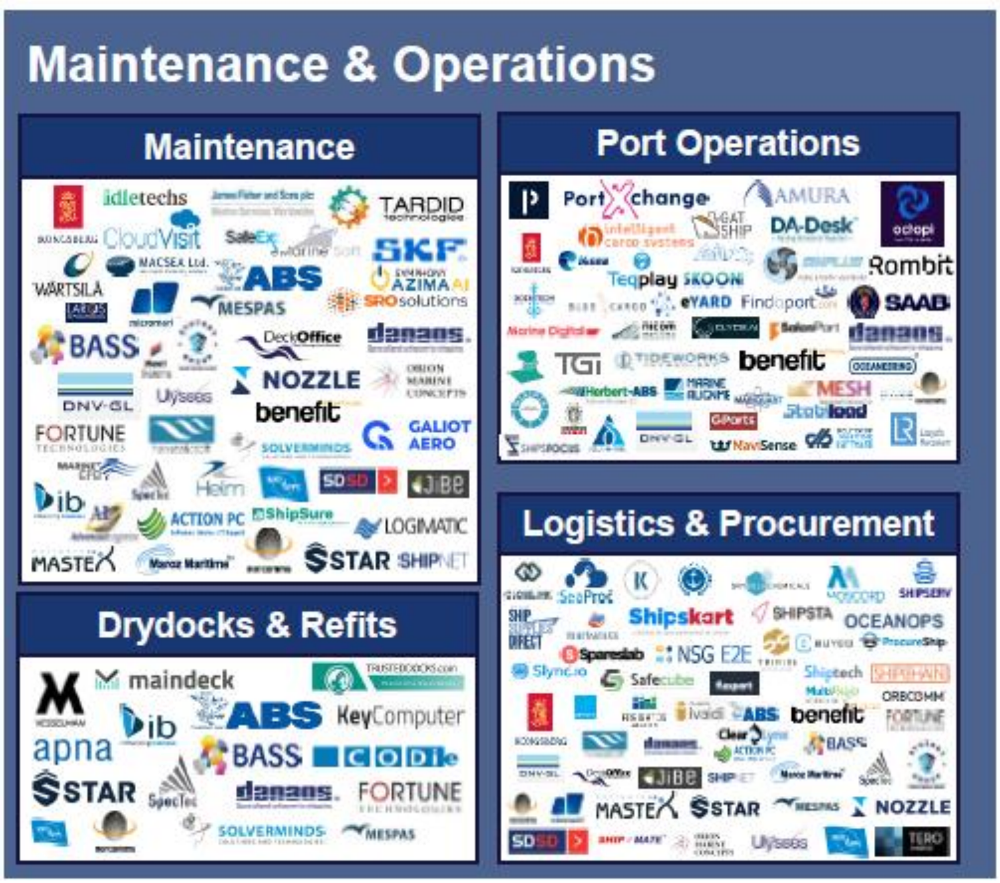


Figure 137: **Maritime software landscape: maintenance and operations (source: Kongsberg)**

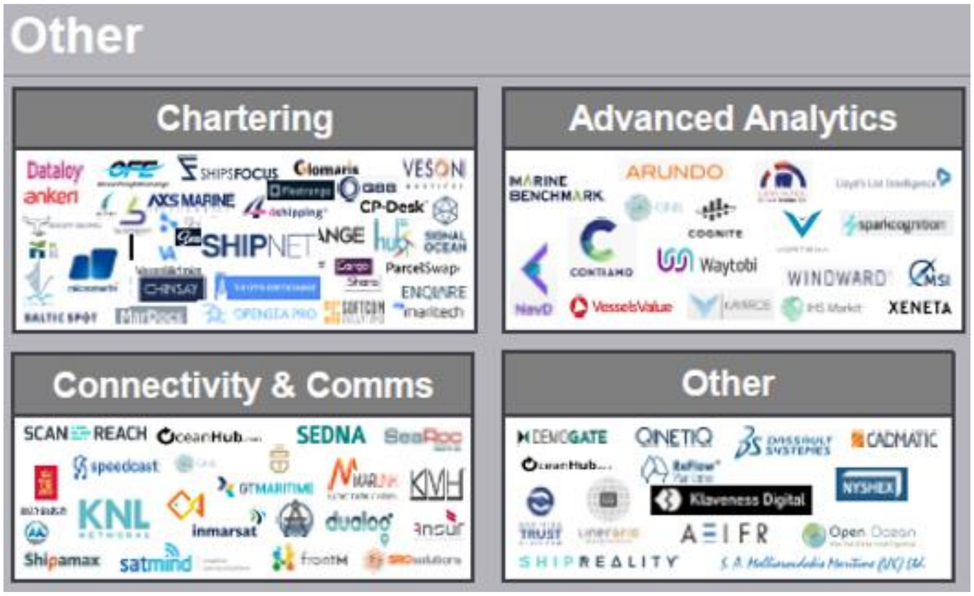


Figure 138: Maritime software landscape: other (source: Kongsberg)

Figure 139: Maritime software landscape: fleet management systems (source: Kongsberg)

Artificial Intelligence & Data Modeling

Data management in the maritime sector incorporates advanced data modeling including artificial intelligence and predictive modeling. Weather optimization and vessel positioning algorithms, as discussed below, employ such tools.

Blockchain technologies are also used in the maritime sector, primarily at this time related to tracking payments, optimization of space on ships, tracking cargos, and clearing customs. Closely related to decarbonization is the use of blockchain technology for tracking fuel oil bunker specifications, quantities, and payment.

Onboard Data Capture

Capture of environmental and machinery data can be expensive and challenging. Every captured point, such as an exhaust temperature or anemometer, requires engineering, sensor procurement and installation, wiring, calibration, commissioning, and routine recalibration and service. Every point requires programming including defining a set-point and any responses, integration into a user interface, and determining storage and archive functions.

A single engine might have 1,000 points of captured data. A marine vessel might have as many as 10,000 points. The storage and access of this data can be a challenging management effort. As a result, points installation and data management is often limited to that required to gain regulatory approval for essential operations, such as reduced crewing/uncrewed operations or dynamic positioning. Feedback to the user is often limited to responding to off setpoint parameters and basic trend analysis such as a rising engine exhaust temperature over hours or days.

Implementation of onboard data capture measures tend to focus on fuel reductions and performance improvements that quickly pay back needed capital investment and can support any ongoing maintenance fees and costs.

Fuel Consumption Monitoring

Fuel consumption monitoring provides ship operators with real-time data typically paired with vessel speed. A key aspect is that fuel consumption generally increases by the cube (third power) of vessel speed, meaning that modest reductions in speed can have significant impacts on fuel consumption.

Real-time Fuel Consumption Monitoring (FCM) is typically accomplished by installing flow meters on the fuel supply and return piping of each marine engine. Such meters can be 'mass flow' type or 'volume flow' type with specific gravity and temperature corrections. At a minimum, such data is transferred to vessel operators in units such as gallons or liters per hour. More advanced systems will pair fuel consumption with speed through water, shaft and engine rpm, and shaft torque in order to provide more insightful efficiency metrics.

There are commercial services that use weather routing to suggest shaft rpm at various points in the voyage for optimal fuel economy over a voyage. Some of these pair with FCM for real-time adjustments. These can even directly control rpm on a real time basis as well as adjust rpm in conjunction with rudder angles.

Ancillary benefits of fuel consumption monitoring include:

- Marine technology evaluation: Real-time FCM allows owners to independently and accurately evaluate the effectiveness of various technologies or strategies. Questions such as 'does it work?' and 'how much does it save?' can be answered to assist in investment decisions.
- Route optimization: By overlaying real-time FCM data with route maps, tidal and weather data, it is possible to optimize a vessel's route for time of day, time of year or weather conditions to minimize fuel use. Various software packages are available to streamline this process.
- Environmental compliance: Tracking fuel consumption, including various grades of fuels, is required when entering areas that restrict consumption of certain fuels. In addition, fuel consumption monitoring is a key element in complying with the upcoming IMO CII requirements.
- Operational efficiency and logistics: Knowing 'distance to empty' or 'time to empty' can help operators improve dispatching and assist with logistics planning.
- Predictive maintenance: Trending fuel consumption over time can be used to develop effective hull cleaning and propeller polishing schedules, and to diagnose potential engine issues early. Combining engine run time with fuel burn rates allows operators to estimate workloads on engines more accurately to optimize maintenance cycles and overhaul dates.
- Automatic speed pilot: Combining FCM with autopilot can maximize fuel savings by traveling at the minimum required speed for an on-time arrival. These systems continuously monitor speed, engine rpm, power output, and fuel consumption. As sea conditions change, propulsion power is adjusted automatically to maintain the optimum speed for the requested arrival time. This can prevent the potentially wasteful practice of arriving early and loitering while waiting for a berth.
- Over the air reporting: Many vendors of FCM systems recognize that there are numerous reporting requirements that can be automated with the right software. Fuel usage information can be transmitted from the vessel to the fleet office, in near real time. This can relieve crews of onerous paperwork and provide the owner with an excellent monitoring and verification tool.

With the exception of automated systems, actual savings are highly dependent on vessel operators. Actual savings will be dependent on the type of operation, type of system, training, and operator behavior. Payback times will be faster for operations with the highest fuel use.

There are significant limitations to technology that is 'pushed' onto vessel crew. The FCM provides the information, but it is up to the operator to use it appropriately. To maximize returns from FCM systems it is incumbent on owners to encourage buy-in through training, financial incentives, reduction of routine tasks (automated reporting), and competition.

Voyage Optimization

Voyage planning has always been an integral part of marine operations. Traditional voyage planning involves plotting a vessel's intended route on paper or electronic charts, shown as a series of course headings and waypoints. Historically, this was done to determine the total distance of a voyage, estimate cost and schedule, and to prepare accordingly in terms of crewing, fuel, and provisions.

Over the years, voyage planning has evolved into a detailed risk management process considering numerous factors such as safety and storm avoidance, on-time arrival, vessel and cargo conditions (including draft and trim), fuel consumption, fuel management, vessel speed, etc. Though it can take many forms and is carried out in varying degrees of formality and sophistication, virtually all commercial vessel operators today use voyage planning tools to reduce uncertainty and manage some or all of the following:

- Navigation risk / human error.
- Health and safety risk.
- Schedule risk.
- Economic/business risk.
- Cargo risk.
- Environmental risk.
- Regulatory risk.

On board the vessel, voyage planning generally involves navigation tools such as Electronic Chart Display and Information Systems (ECDIS) and ARPA (Automatic Radar Plotting Aid) enabled radar systems, both of which are typically integrated with real-time AIS (Automatic Identification System) and GPS (Global Positioning System) data. Fuel consumption monitoring systems may also be integrated. Real-time weather routing services and associated software programs are now standard through satellite connectivity. At the administrative level, voyage planning is often about strategic, business, and logistics planning.

Some of these tools can be used to rapidly evaluate the feasibility of a new service route, a new cargo opportunity, or a new vessel by providing accurate cost and schedule information in advance. Modern voyage planning is a process that allows vessel operators to identify risks and opportunities that may not be readily apparent, and thereby, to select the most efficient and/or appropriate pathways in their operations. Speed Optimization, Weather Routing, Positioning Algorithms, Pool Adjustments, and Virtual Arrivals are interrelated components of Voyage Optimization.

Speed Optimization

The amount of fuel a vessel burns is highly sensitive to the speed that the vessel is traveling since the speed-power relationship for a marine vessel is typically a cubic function (i.e. doubling the speed requires 8 times more power). Roughly, a 10% speed reduction will decrease fuel consumption by over 20%, and a 20% speed reduction will use 45% less fuel. However, the slower speed requires more voyage time, with the result being that the fuel savings is based on the square function (doubling speed results in 4 times fuel consumption). These fuel savings have led to substantial use of speed reduction (i.e. ‘slow-steaming’), especially when fuel prices are high.

Market drivers and commercial factors can discourage slow steaming in some cases. Contracts and charter agreements can have speed requirements, machinery may not operate well at lower loads, and fleet size can be affected if speeds are reduced too much. Maximizing savings requires the fleet manager and the operator to balance all of the factors within their control to find the optimum voyage speed. This is a dynamic process and must be continually adjusted.

The optimal economical operating speed will depend on many factors such as:

- Expected arrival day and time as set in charter agreement.
- Fuel cost.
- Fuel efficiency of the vessel.
- Daily operating cost.
- Operating profitability.
- Vessel’s future contracts.
- Current market conditions.
- Design speed of the ship (hull speed).
- Low load operability of the main engine(s).
- Weather conditions.

Weather Routing

Planning a voyage around known weather conditions has always been an integral part of voyage planning. In recent decades the sophistication and accuracy of weather forecasting has been revolutionized with tools such as weather satellites, sophisticated ocean buoys, supercomputer climate models, and inexpensive computation. Weather routing combines forecasting tools, electronic charts and maps, and simulation software into an integrated package that can quickly, and in near real time simulate thousands of potential routes and speeds to find the safest most economic route and speed for a given vessel.

The goal of weather routing is to select an optimal course between two or more ports that provides the safest passage and reliable on-time arrival while accounting for actual wind, wave, and current conditions expected during the voyage. In the last several years the focus has shifted from routes that are ‘fast and safe’ to routes that are ‘efficient and safe’. Weather routing and voyage performance management are closely linked to provide optimal speed with minimum risk to crew, passengers, ship, and its cargo.

Weather routing is typically provided as a service to the vessel operator on a per-voyage basis. The cost and sophistication of services will vary. Some can offer customized services that model a particular vessel’s characteristics, incorporating engine fuel maps, vessel seakeeping characteristics, and real operating parameters. Others use generic characteristics based on vessel type and size.

Communication with the vessel can be as simple as sending voyage recommendations via email or as complex as integration with onboard computer software or integration with shore-side management systems. Onboard computers provide the added benefit of allowing the master to interact with the tool to account for changes that happen in real time.

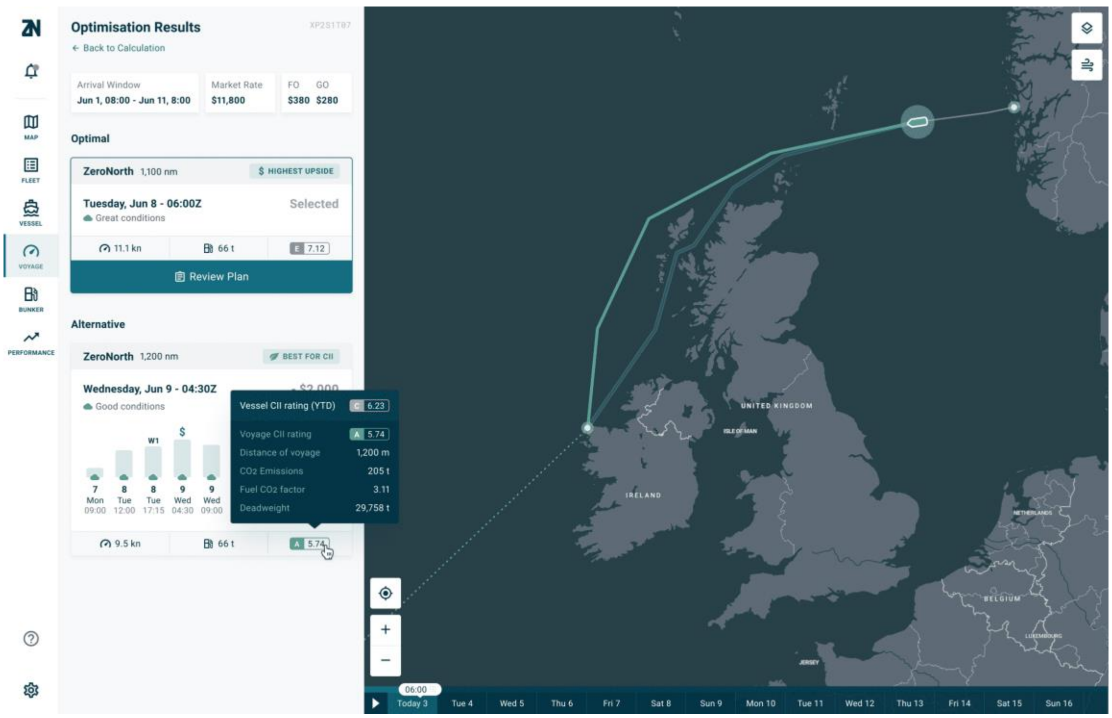


Figure 140: Screenshot example from a commercial weather routing system. (source: marineinsight.com)

Virtual Arrival

Vessels under charter are typically required to arrive at the specified port no later than a certain date and time, or else face financial penalties. However, delays in a port or at a specific terminal mean that often a vessel will make best speed at significant fuel consumption only to then wait for days before commencing cargo operations.

Virtual arrival is a means to allow a vessel to meet its charter obligation by demonstrating that it could in fact meet that obligation, and instead slow-down to a fuel-efficient speed to arrive at a later time. Figure 141 is an example from the Oil Companies International Marine Forum (OCIMF) guide on virtual arrivals.

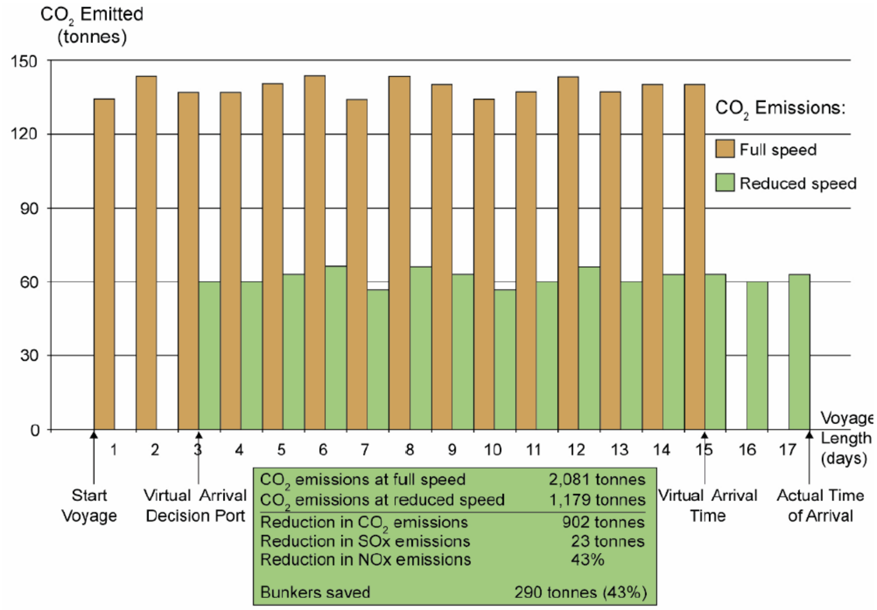


Figure 141: Example of fuel/emissions reduction from virtual arrival (source: OCIMF)

Positioning Algorithms

Services are offered that identify strategic vessel positioning based on algorithms that predict most likely and profitable cargo movements. For example, a vessel dropping off cargo in Charleston, South Carolina might slow steam towards New Jersey or the US Gulf at best economy depending on predicted next charter. Such movements reduce fuel consumption and put vessel in a favorable position to win the charter.

Pool Adjustments

Vessel operators will pool vessels together in order to service charter contracts. In such pools, it can be difficult to determine which vessels are performing most efficiently as different cargo movements are subject to different parcel sizes and distances, different vessel speeds and drafts, and weather conditions. Services are offered that normalize such differences in order to motivate companies and individual vessels within the pool to operate efficiently. The data is then used to assign profits between vessels within the pool.

Predictive Maintenance

Onboard monitoring of propulsion, power generation, and service systems can identify and even predict off-efficiency operations that can result in excessive fuel consumption and emissions. Generally, such monitoring services identify necessary maintenance and repair based on metrics such as temperatures, pressures, vibration, and fuel consumption. This approach is sometimes implemented instead of, or in combination with, an hours-based maintenance and service approach.

A primary focus of predictive maintenance is to reduce unplanned repairs that can reduce marine vessel availability or require less efficient operations and fuel consumption. Also important is the reduction of unnecessary service and maintenance that is costly and can be time intensive.

The extent of data monitoring can vary widely. Big data and artificial intelligence are being used to compare large datasets to identify trends in machinery performance and increase prediction of failures and reductions in efficiency. Regardless of the extent of data monitoring, such programs can reduce ship fuel consumption and emissions.

Real-time monitoring and reporting of onboard diagnostics are certain to be adopted industry wide due to their broad applicability for improving operational and maintenance scheduling while reducing downtime and overall costs. Outfitting either a new or existing propulsion plant onboard can offer live status updates and assessment of performance while underway to help keep all equipment running optimally. Adding these systems is relatively simple but requires additional investment to add the marine diagnostic sensors and reporting system. Pressure, cycle (for fatigue monitoring), speed, and electrical load/characteristic sensors deployed across the vessel will help make the goal of having system-wide information possible. The data from these probes can be analyzed onboard or shore-side to assess equipment health and update existing maintenance schedules.

Autonomy

Marine vessels are continuing to increase reliance on automation and autonomy to reduce crewing and increase efficiency. Periodically unattended machinery rooms have been commonplace for many years now. Autonomous bridge aids, such as advanced autopilots are increasingly in use. Fully autonomous vessels have been demonstrated on oceanic voyages.

Autonomous operations are typically paired with increased use of data and algorithms that tend to reduce fuel consumption. To the extent that reduced crewing results in smaller accommodations and reduced services, such as removal of a full-service galley, marine vessels will be smaller and more efficient.

Part 3 – Technology Stacking

The Efficiency Technologies (ET) and Fuel Technologies (FT) detailed in Part 2 are standalone measures to improve energy efficiency or reduce GHG emissions. In many cases, these technologies can be "stacked" together to further improve vessel performance, both within Efficiency Technologies and between Efficiency Technologies and Fuel Technologies.

Stacked technologies may improve the individual reduction potential of one or multiple technologies, being complementary in their integration, and the technologies together can improve a vessel's CO_2 or CO_2e performance value (CPV, CePV) discussed in Section 1.3. The complementary and combined reduction effects of stacked technologies are illustrated in Part 4 vessel-specific case studies.

The stackability matrix provided in Section 3.3 is limited to one-to-one stackability. This does not exclude the stacking of more than two technologies; rather, stacking of more than two technologies requires vessel-specific characteristics to be considered to determine overall stackability. Stacking of more than two technologies is illustrated in Part 4.

3.1 Stackability Rating

The ability to stack different technologies will depend on the specific characteristics of a subject vessel, but some general considerations can assist an owner or operator in planning. There are three different stackability ratings considered, shown in Table 44.

Table 44: Stackability ratings

Symbol	Description	Guidance
✓	Technologies are **readily stackable**, may be complementary in improving reduction potential of each technology	Review technologies together for enhanced performance
○	Technologies **are practical to stack**, with no complementary benefits aside from combined reduction potential	Review technologies independently, should not impact each other
⊗	Technologies **are impractical to stack**, and may conflict or increase vessel's energy requirements	Avoid stacking unless vessel-specific analysis proves compatibility

3.2 Stackability Factors

Several factors can dictate whether two or more technologies can be stacked. Some technologies are also ineligible for stackability due to their technology readiness, or universally stackable due to the way in which they interact with the vessel design.

Technology Readiness

Technologies that have not entered the commercial phase of development, TRL 7 – 9, are not included in the stackability review. As these technologies continue to mature in their own right, they may be considered eligible for stacking on newbuild or existing vessels.

Only technologies with a TRL of 7 or above are included in the stacking matrix provided in Section 3.3.

General Stackability

Several technologies considered in this guide are generally stackable. They are readily combined with other technologies, as their integration is not related to factors provided below: service/duty, vessel drivetrain/electrical plant, and arrangement on vessel. These technologies are shown with green icons in the section after the Stacking Matrix.

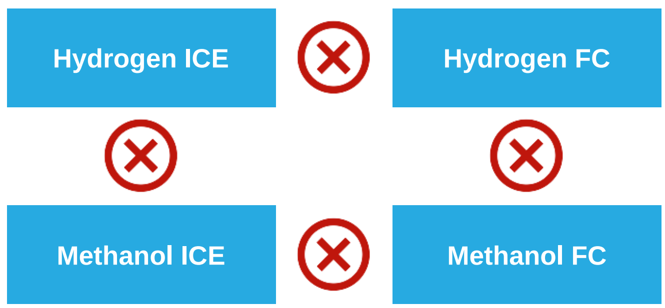
Regardless of technology stacking, technologies that are generally stackable will not be compatible with certain vessel types, trades, or sizes. Likewise, stacking these technologies with certain other technologies may not be practical on specific vessels. All available stacking configurations must be weighed against the vessel-specific characteristics.

Fuel Technology Stacking

Stacking between different fuel technologies is not covered in the stacking matrix in Section 3.3, so fuel technologies are only provided as rows, not columns. Fuel stacking is limited in the following ways:

- Different consumers (internal combustion engines – ICE, and fuel cells – FC) are not considered stackable for a single fuel. All alternative fuels require a consumer, either ICE or FC. While multiple consumers for a single fuel is possible, it is not practical on most vessels. This does not preclude a FC system using an alternative fuel from being combined with a diesel-generators for a hybrid power generation system onboard.
- Multiple alternative fuels are not considered stackable, given the complex nature of storage and systems required for each fuel type. While it may be possible to use multiple alternative (non-conventional) fuels, practical constraints will preclude it on most vessels.

The four fuel technologies with TRL 7 or above have been consolidated into four categories as shown below, and are not considered for stackability between one another:



Vessel Service and Duty

As detailed in Part 2, a vessel's planned service (oceangoing vs coastal or inland, long-range vs short-range) and duty (continuous vs intermittent) can impact the compatibility of a given ET or FT. Similarly, two technologies that are only compatible with widely different vessel types will not be readily stackable as they don't overlap on their general applicability to vessel characteristics.

For example, waste heat recovery (WHR) has its highest reduction potential when coupled with a continuously loaded main engine operating close to its MCR. It is therefore not practical to stack waste heat recovery with variable speed generators, which have their highest reduction potential when operated under variable loads where engine speed can be optimized to match the load.

Conversely, hydrogen fuel is best-suited for vessels that operate in near-coastal and inland trades. Hybrid mechanical/electrical drivetrains are also best-suited for these trades, making these technologies (one energy efficiency, one fuel) readily stackable. They also have compatible electrical plant requirements, as hydrogen fuel cells, the most mature hydrogen technology, must integrate with an electrified vessel to provide propulsion power.

Vessel Drivetrain and Electrical Plant

A vessel's propulsion drivetrain and its electrical plant will determine whether certain technologies can be stacked and integrated on the vessel. For technologies that directly interface with a diesel-mechanical system, they cannot be stacked with technologies that that are exclusively implemented on diesel-electric or fully-electric vessels. Likewise technologies that input electricity at scales that are intended for propulsion cannot be stacked with technologies that require a diesel-mechanical plant, unless a bridging technology like power take-in (PTO) is implemented.

For example, PTO/PTI motor-generators cannot be stacked with battery (all-electric) propulsion, as PTO/PTI requires propulsion with multiple inputs, and an all-electric vessel will only be driven by electric motors.

Conversely, PTO generators typically connect to large prime movers, and WHR see their highest energy recovery from large exhaust systems operating under consistent loads. These technologies are therefore readily stackable.

It should be noted that a system that operates primarily in PTI mode will see reduced exhaust output from the engine exhaust, reducing the recovery potential from the WHR system.

Arrangement on Vessel

Each technology's arrangement requirements can dictate whether they are stackable with other technologies, or whether stacking is impractical. Technologies that occupy the same space, either on-deck, in a machinery space, or attached to the hull, are difficult to stack given the physical conflict that may arise. Similarly, multiple systems that must generally be located in machinery spaces may not be stackable on a vessel with limited deck space for additional machinery. In most cases, arrangement alone will not make two technologies complementary in their stacking, merely compatible. But arrangement can make two technologies impractical or flat-out not possible to stack.

For example, rigid wingsails and rotor sails both occupy space on-deck, and require unimpeded exposure to air flow across the equipment. These technologies therefore are not practical to stack, as they would inhibit each other's effectiveness and would be difficult to arrange on most vessel decks.

Conversely, diesel-electric propulsion and kite sails occupy completely different areas on the vessel, one aft (on most vessels), and one forward. The two technologies therefore are practical to stack, though they do not complement each other in any way.

Cost

Cost is a critical factor for evaluating multiple energy or fuel technologies on a vessel, newbuild or retrofit. The cost impacts of any stacked technology combination will be very vessel-specific, and cannot be readily generalized. Cost is therefore not considered in the stacking matrix in Section 3.3. A comprehensive cost analysis, both capital cost and lifecycle cost, should be performed for any single technology or multiple stacked technologies before being considered for implementation.

3.3 Technology Stackability

Stacking Matrix

	Diesel Electric Propulsion	Variable Speed Generators	PTO/PTI	Hybrid Mech/Elec	Battery Electric	Kite Sails	Rotor Sails	Rigid Wingsails	Wave-Assisted Propulsion	Waste Heat Recovery
Diesel Electric Propulsion	–	✓	✗	✓	✗	○	○	○	○	✗
Variable Speed Generators	✓	–	✗	○	✗	○	○	○	○	✗
PTO/PTI	✗	✗	–	○	✗	○	○	○	○	✓
Hybrid Mech/Elec	✓	○	○	–	✗	○	○	○	○	✗
Battery Electric	✗	✗	✗	✗	–	○	○	○	○	✗
Kite Sails	○	○	○	○	○	–	○	○	○	○
Rotor Sails	○	○	○	○	○	○	–	✗	○	○
Rigid Wingsails	○	○	○	○	○	○	✗	–	○	○
Wave-Assisted Propulsion	○	○	○	○	○	○	○	○	–	✗
Waste Heat Recovery	✗	✗	✓	✗	✗	○	○	○	✗	–
Hydrogen ICE	○	○	✗	○	✗	✗	○	✗	○	✗
Methanol ICE	✓	✓	✓	✓	✗	○	○	○	○	○
Hydrogen FC	✗	✗	○	✓	✓	✗	○	✗	○	✗
Methanol FC	✗	✗	○	✓	✓	○	○	○	○	✗

Technologies with General Stackability

Direct Drag Reduction	Advanced Hull Coatings	Hull Cleaning & Maintenance	Hull Form Optimization	Air Lubrication
Propulsive Loss Reduction	Propellers	Pre-Swirl Devices	Post-Swirl Devices	
Other Technologies	Solar Power	HVAC Optimization		

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3.4 Vessel Types and Sizes Most Suitable for Stacking

A vessel stackability table for different vessel types and sizes is shown in Table 45. These scores are derived from the applications tables for every technology considered appropriate for stacking, with higher numbers representing vessel types/sizes that are suitable for a wide-range of technologies, and low numbers representing vessel types/sizes that are more difficult to integrate with single technologies, and therefore multiple stacked technologies.

Only applications tables for technologies with TRL 7 and above are used to derive the vessel stackability scores.

Table 45: Vessel stackability table

MW	Duty					
>10	Continuous	29	28	23	25	20
	Intermittent		22	20	22	21
1-10	Continuous	31	32	24	25	21
	Intermittent		26	21	21	22
<1	Intermittent		17	14	16	15

MW: Propulsion power plant size, in MW

Key highlights of the stackability by vessel type and size are provided below.

Vessel Types with High Stackability

Medium to Large Oceangoing Cargo Vessels
(continuous duty)

1+ MW

Stackability Score: 29-31

- Ready to accommodate various stacking combinations.
- Large size and available space can accommodate multiple technologies.
- Oceangoing transits tend to have more reliable propulsion loads, electrical loads, and consistent environmental conditions. These characteristics allow for better planning of energy efficiency and fuel technologies.
- Specific technologies that may stack well:
    - Renewable energy (wind-assisted propulsion, wave-assisted propulsion, solar power).
    - PTO/PTI.
    - WHR power generation technologies.
    - Methanol fuel.
    - Propulsive loss reduction and direct drag reduction technologies.

Medium to Large Passenger Vessels
(continuous duty)

1+ MW

Stackability Score: 29-31

- Ready to accommodate various stacking combinations.
- Straightforward machinery and arrangements can accommodate stacking combinations.
- Flexible with different propulsion plant configurations, including diesel-mechanical, diesel-electric, energy storage.

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- Transits are typically routine and scheduled, allowing for highly predictable energy reductions by integrating technologies.
- Specific technologies that may stack well:
  - Propulsion and power generation technologies (diesel-electric propulsion - DEP, and variable speed generators - VSG).
  - Hybrid mechanical/electrical.
  - HVAC optimization.
  - Wave-assisted propulsion for medium-size vessels.
  - Propulsive loss reduction and direct drag reduction technologies.

Medium to Large Lake Freighters
(continuous duty)

1+ MW

Stackability Score: 25

- Ready to accommodate some stacking combinations.
- Large size and available space can accommodate multiple technologies.
- Lake transits tend to have consistent propulsion loads, electrical loads, and environmental conditions. These characteristics allow for better planning of energy efficiency and fuel technologies.
- Less conducive for renewable energy technologies.
- Less susceptible to hull-fouling, therefore less potential benefit from anti-fouling coatings and hull cleaning.
- Slow speeds and deep hulls not ideal for air lubrication.
- Specific technologies that may stack well:
  - PTO/PTI.
  - WHR power generation technologies.
  - Methanol fuel.
  - Some drag reduction measures.

Medium Passenger Vessels
(intermittent duty)

1-10 MW

Stackability Score: 26

- Ready to accommodate some stacking combinations.
- Reasonable size and available space can accommodate multiple technologies.
- Flexible with different propulsion plant configurations, including diesel-mechanical, diesel-electric, energy storage.
- Intermittent operation makes vessels suitable for propulsion and power generation optimization measures.
- Transits are typically routine and scheduled, allowing for highly predictable energy reductions by integrating technologies.
- Specific technologies that may stack well:
  - Propulsion and power generation technologies (diesel-electric propulsion - DEP, and variable speed generators - VSG).
  - Hybrid mechanical/electrical.
  - All-electric with alternative power generation, including fuel cells and solar power.
  - HVAC optimization.
  - Propulsive loss reduction and direct drag reduction technologies.

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Oceangoing Service Vessels
(continuous duty)

1+ MW

Stackability Score: 23-24

- Ready to accommodate some stacking combinations.
- Reasonable size may accommodate multiple technologies, but space is more limited due to mission equipment.
- Flexible with different propulsion plant configurations, including diesel-mechanical, diesel-electric.
- Intermittent operation makes vessels suitable for propulsion and power generation optimization measures.
- Transits may be highly variable, making it more difficult to optimize energy improvements for vessel's load profile.
- Specific technologies that may stack well:
    - Propulsion and power generation technologies (diesel-electric propulsion - DEP, and variable speed generators - VSG).
    - Hybrid mechanical/electrical.
    - Propulsive loss reduction and direct drag reduction technologies.

Vessels Types with Marginal Stackability

Other vessel types and sizes may not be as readily suitable for technology stacking, and vessel specifics will be required to determine what technology or combination of technologies may be both feasible and practical for energy and emissions reductions. These vessel types are summarized here:

- Large, intermittent duty passenger vessels (stackability score: 22).
- Large and medium intermittent duty oceangoing service vessels (stackability score (20-21).
- Medium to large inland/coastal service vessels (stackability score: 20-22).

Vessel Types with Low Stackability

Small vessels (<1 MW propulsion plant) are often difficult to stack efficiency and fuel technologies, due to their limited available space and (typically) intermittent load profile. To maximize stacking opportunities, small vessels may need to be designed as a newbuild, purpose-built for the technologies considered. The energy/emissions benefits of multiple technologies may be outweighed by the cost or technical risk to execute the design.

The stackability score for small, intermittent duty vessels ranges from 14 to 17.

Part 4 – Case Studies

Six vessel types have been selected as case studies for determining the following characteristics:

- CO_2 and CO_2e Performance Values (CPV, CePV): baseline vs improved vessel (decarbonization).
- Annual tons CO_2 and CO_2e: baseline vs improved vessel (decarbonization).
- GHG emissions percent (%) change: baseline CPV/CePV vs improved vessel CPV/CePV (decarbonization).

4.1 Vessel Case Studies

Selected Vessels Overview

The vessel types were selected based on their representation in the US flag merchant fleet of self-propelled vessels. Fleet representation was estimated from MARAD's National Transportation Statistics 2021 reports [A136][A137] and the ICCT's 2019 Great Lakes-St. Lawrence Seaway Ship Emissions Inventory [A138].

The case study vessels and their respective US fleet representation are provided in Table 46. Vessel characteristics for each case study vessel are provided in Table 47.

Table 46: Vessel type and representation in US fleet

Type	US Fleet Representation
Oceangoing Tanker	35% of US oceangoing vessels over 1,000 GT (50% of deadweight tonnage)
Oceangoing Containership	36% of US oceangoing vessels over 1,000 GT 38% of deadweight tonnage)
Ferry	17% of US commercial self-propelled vessels
Towboat-Tugboat	62% of US commercial self-propelled vessels
Offshore Supply Vessel	17% of US commercial self-propelled vessels
Ore Bulk Carrier	35% of US commercial vessels operating on the Great Lakes and St. Lawrence Seaway (GL/SLS) (40% of all vessels operating on the GL/SLS)

Table 47: Summary of vessel characteristics

Type	Classification	Length Overall (m)	Capacity	Propulsion
Oceangoing Tanker	Medium Range (MR) Tanker	186	50,000 MT (DWT)	Diesel-mechanical, single screw
Oceangoing Containership	2,400 TEU	215	38,000 MT (DWT)	Diesel-mechanical, single screw
Ferry	144-carr ferry	110	9,292 (GT)	Diesel-mechanical, double-end single screw
Tugboat	Azimuth Stern Drive (ASD) Escort Tug	30	196 (GT)	Diesel-mechanical, twin screw
Bulk Carrier (Great Lakes)	Ore Carrier	305	93,645 MT (DWT)	Diesel-mechanical, twin screw
Offshore Supply Vessel	Refueling Vessel	96	4,880 (GT)	Diesel-mechanical, twin screw

Technology Selection

Technology selection for each case study vessel is carried out considering several key factors:

- **Technology readiness.** As discussed in the section on Technology Stacking (Part 3), only technologies with TRL 7 and above are considered for vessel case studies.
- **Stackability.** Technologies that are either readily stackable or practical to stack are considered for combination in the vessel case studies.
- **Vessel operations.** The specific trade or operating profile of a vessel determines which technologies may have the most reduction potential, and which may have negligible impact or even an energy penalty.
- **Existing baseline technologies.** Some technologies already commonly exist on certain baseline vessels. As such, these are considered already included in the vessel's baseline performance, not providing additional reduction potential. For example, oceangoing vessels typically have optimized hull forms and anti-fouling coating, so those benefits are already realized.

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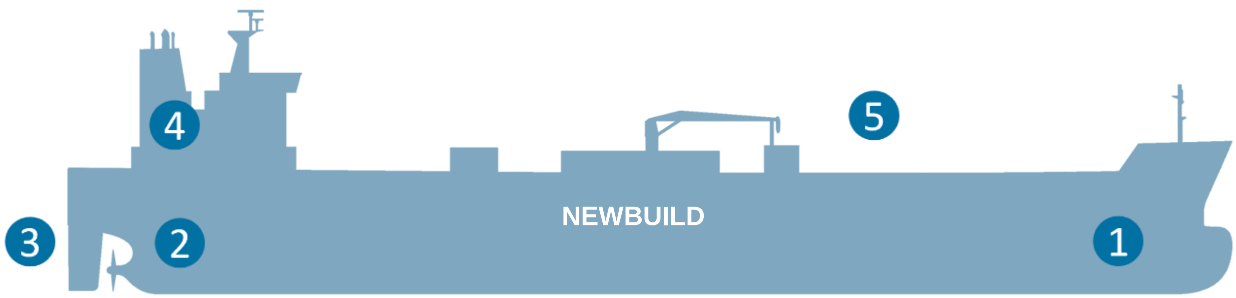
Case Study 1: Oceangoing Tanker



Overview

The vessel selected for Oceangoing Tanker is a medium range (MR) product tanker as a newbuild. At a DWT capacity of 50,000 MT, a MR product tanker is the approximate median vessel of the US-flagged tanker fleet.

The vessel's operating region is North America between the US Gulf Coast and US West Coast.

A summary of the vessel's decarbonization results compared to the vessel baseline is provided in Table 48. The selected efficiency technologies resulted in an estimated 13% reduction in WtW GHG intensity for HFO, the propulsion plant fuel, and a 4% reduction in WtW GHG intensity for MGO, the electrical plant fuel.

Table 48: Oceangoing tanker results summary (WtW)

		Propulsion		Electrical	
Parameter	**Unit**	**Baseline**	**Decarbonized Result**	**Baseline**	**Decarbonized Result**
Fuel	-	HFO	HFO	MGO	MGO
CO_2 Emission Factor EF_f,	MT/MT	3.55	3.55	3.78	3.78
CO_2e Emission Factor EF_f,	MT/MT	3.89	3.89	4.21	4.21
Reduction Factor RF_e	-	1.00	0.87	1.00	0.96
CO_2 Performance Value CPV	MT/MT	3.55	3.08	3.78	3.63
CO_2e Performance Value CePV	MT/MT	3.89	3.38	4.21	4.04
Annual Fuel Consumption	MT	7,671	6,653	887	851
CO_2 Emissions	MT	27,232	23,627	3,354	3,220
CO_2e Emissions	MT	29,840	25,928	3,733	3,583
Total Emissions		**Baseline**		**Decarbonized Result**	
CO_2	MT	30,585		26,846	
CO_2e	MT	33,574		29,511	
GHG Intensity % Change		**HFO**		**MGO**	
CO_2	%	-13%		-4.0%	
CO_2e	%	-13%		-4.0%	

Improved performance in green

Vessel Particulars

The MR product tanker vessel particulars are provided in Table 49. This case study assumes the MR product tanker is a newbuild construction.

Table 49: Oceangoing tanker particulars

Particular	Value	Notes
Capacity (DWT)	50,000 MT	
Length Overall	186 m	
Beam	32 m	
Draft (Load Line)	11 m	
Design Speed	14.5 knots	At 80% MCR
Propulsion Plant		
Type	Diesel-mechanical	
Power	1 x 7,300 kW MCR	1 x two-stroke, slow speed diesel
Fuel	HFO	
SFC (g/kWh)	175	Average value for all engine loads, from Fourth IMO GHG Study 2020
Electrical Plant		
Type	Diesel-generators	AC switchboard
Power	3 x 1,000 kWe	3 x four-stroke, medium speed diesel-generators
Fuel	MGO	
SFC (g/kWh)	175	Average value for all engine loads, from Fourth IMO GHG Study 2020

Operating Profile

Operating Modes

The vessel's operating profile consists of two modes:

- SERVICE mode. Transporting petroleum products between New Orleans, LA and Long Beach, CA.
- IDLE mode. Extended idle, at anchor or dock, operating on diesel-generators.

These operating modes are summarized in Table 50. Operating modes are detailed in Table 51 through Table 52, including all details necessary to estimate annual fuel consumption for the vessel.

Table 50: Oceangoing tanker operating modes overview

Mode	Description	Hours Per Cycle	Cycles Per Year	Equivalent Days Per Year
SERVICE	New Orleans/Long Beach (NOLA/LB) trade	720	12	360
IDLE	Extended idle, running on generators	120	1	5

Table 51: Service mode details: New Orleans/Long Beach trade

Location	Condition	Speed (kts)	Distance (nm)	Duration (hr)	Propulsion Load (bkW)	Electrical Load (bkW)
New Orleans, LA	Maneuver	8	16	2	1,095	500
	Idle/anchor	0	0	12	0	300
	Cargo ops	0	0	32	0	1500
	Maneuver	8	16	2	1,095	500
Laden voyage	Transit	14.5	4,524	312	5,840	500
Long Beach, CA	Maneuver	8	16	2	1,095	500
	Idle/anchor	0	0	12	0	300
	Cargo ops	0	0	32	0	1500
	Maneuver	8	16	2	1,095	500
Ballast voyage	Transit	14.5	4,524	312	5,840	500
Total				720		

Table 52: Idle mode details: extended idle running on generators, at anchorage or docks

Location	Condition	Speed (kts)	Distance (nm)	Duration (hr)	Propulsion Load (bkW)	Electrical Load (bkW)
Anchorage/dock	Idle/anchor	0	0	120	0	300
Total				120		

Baseline Fuel Consumption, CO_2/CO_2e Performance Values, and Annual Emissions

Fuel Consumption

The estimated fuel consumption for each operating mode is calculated and provided in Table 53. The fuel per cycle and per year are both provided, based on the operating mode summary in Table 50.

These estimates are simplified, and apply the base SFC for each engine type across all operating modes. Actual fuel consumption will vary based on specific engine fuel curves and the engine loading at each operating condition.

Table 53: Oceangoing tanker fuel consumption by modes

Mode	Description	Propulsion - HFO (MT)		Electrical - MGO (MT)	
		per cycle	per year	per cycle	per year
SERVICE	NOLA/LB trade	639	7,671	73.4	880
IDLE	Extended idle	0	0	6.3	6.3
	Annual Total	*Tons HFO*	*7,671*	*Tons MGO*	*887*

Baseline CPV and Annual CO_2 Emissions

The vessel's baseline WtW CO_2 performance values for each fuel (CPV), and resulting CO_2 emissions per year can be calculated, using the equation for CPV and tons CO_2 (see Section 1.2):

$$\mathrm{CPV} = \mathrm{EF}_{\mathrm{f(WtW)}} \times (\mathrm{RF}_{\mathrm{e1}} \times \mathrm{RF}_{\mathrm{e2}} \times \ldots \mathrm{RF}_{\mathrm{en}}) \times \mathrm{SFC}_{\mathrm{FT}}/\mathrm{SFC}_{\mathrm{FO}}$$

$$\text{tons } \mathrm{CO}_2 = \mathrm{CPV} \times \mathrm{FO}$$

The resulting CPV and tons CO_2 are summarized in Table 54. For calculating TtW emissions only, the values EF_f can be replaced with their TtW components: 3.11 for HFO, 3.21 for MGO.

Table 54: Oceangoing tanker annual CO_2 emissions, baseline

Fuel	LHV (MJ/kg)	EF_f, WtW (MT CO_2/ MT fuel)	RF_e	SFC_{FT}/SFC_{FO}	CPV (MT CO_2/ MT fuel)	Annual Fuel (MT)	WtW CO_2 (MT)
HFO	40.2	3.55	1	1	3.55	7,671	27,232
MGO	42.7	3.78	1	1	3.78	887	3,353
						Total Tons CO_2	*30,585*

Baseline CePV and Annual CO_2e Emissions

The vessel's baseline CO_2e performance values for each fuel (CePV), and resulting CO_2e emissions per year can be calculated, using the equation for CePV and tons CO_2e (see Section 1.2):

$$\mathrm{CePV} = \mathrm{EF}_{\mathrm{f(WtW)}} \times (\mathrm{RF}_{\mathrm{e1}} \times \mathrm{RF}_{\mathrm{e2}} \times \ldots \mathrm{RF}_{\mathrm{en}}) \times \mathrm{SFC}_{\mathrm{FT}}/\mathrm{SFC}_{\mathrm{FO}}$$

$$\text{tons } \mathrm{CO}_2 e = \mathrm{CePV} \times \mathrm{FO}$$

The resulting CePV and tons CO_2e are summarized in Table 55. For calculating TtW emissions only, the values EF_f can be replaced with their TtW components: 3.33 for HFO, 3.49 for MGO.

Table 55: Oceangoing tanker annual CO_2e emissions, baseline

Fuel	LHV (MJ/kg)	EF_f, WtW (MT CO_2e/ MT fuel)	RF_e	SFC_{FT}/ SFC_{FO}	CePV (MT CO_2e/ MT fuel)	Annual Fuel (MT)	WtW CO_2e (MT)
HFO	40.2	3.89	1	1	3.89	7,671	29,840
MGO	42.7	4.21	1	1	4.21	887	3,734
						Total Tons CO_2e	*33,574*

Technology Implementation

The baseline MR product tanker is assumed to already have the following efficiency technologies included in its design:

- Antifouling coating on hull.
- Routine hull cleaning & maintenance.
- Hull form optimization.

The following efficiency technologies were selected for implementation on the vessel:

1. Nanocoatings: Nippon Paint Marine FASTAR coating.
2. Pre-swirl device: Sanoyas tandem fins and duct.
3. Post-swirl device: Kongsberg Promas bulb.

4. Waste heat recovery: MAN power turbine generator (PTG).
5. Rotor Sails: Norsepower rotors.

The efficiency technologies and their reduction factor RF_e characteristics for the vessel are provided in Table 56.

Table 56: Oceangoing tanker reduction factors RF_e

Technology	Energy Category	Operating Conditions	Propulsion % Reduction Base	Propulsion % Reduction Weighted*	Electrical % Reduction Base	Electrical % Reduction Weighted[1]
Nanocoatings	Propulsion/ HFO	Maneuver	0.0%	0.0%	-	-
		Transit	-3.0%	-3.0%	-	-
Pre-Swirl Device	Propulsion/ HFO	Maneuver	0.0%	0.0%	-	-
		Transit	-3.0%	-3.0%	-	-
Post-Swirl Device	Propulsion/ HFO	Maneuver	0.0%	0.0%	-	-
		Transit	-3.0%	-3.0%	-	-
Waste Heat Recovery (PTG)	Electrical/ MGO	Maneuver	-	-	-0.8%	0.0%
		Transit	-	-	-4.0%	-4.0%
Rotor Sails	Propulsion/ HFO	Transit	-5.0%	-5.0%	-	-
			% Reduction by Operating Condition		**% Reduction by Operating Condition**	
		Maneuver	0.0%		0.0%	
		Idle/anchor	0.0%		0.0%	
		Cargo ops	0.0%		0.0%	
		Transit	-13.3%		-4.0%	
		Total % Reduction (∑)	**-13.3%**		**-4.0%**	
		Total RF_e	**0.867**		**0.960**	

*Weighted % reduction is scaled based on the fraction of energy that is consumed for a given operating condition.

No fuel technologies were selected for the MR product tanker. Propulsion ICEs using methanol (CH_3OH) as fuel would be the most compatible with the vessel's operating profile. However, methanol's gravimetric and volumetric energy densities (2 times the mass and 2.6 times the volume of methanol over HFO) make it not desirable for the vessel's 4,500 n.m. voyage.

Nanocoatings

Nanocoatings were selected based on their suitability for vessels that operate over long distances at consistent speeds. Nanocoatings are best-suited for newbuilds where they can be applied in tandem with an antifouling coating.

- Energy category: propulsion, affecting HFO consumption.
- Operating conditions: maneuvering and transit.
- Percent reduction: 0% while maneuvering, 3% while transiting at service speed.
  - Assumed percent reduction is reduced from Nippon Paint Holdings' claim of 8% [B4].
  - Assumed negligible effect while maneuvering.

Pre-Swirl Device

Two pre-swirl devices were selected based on their suitability for vessels that operate over long distances, operating at speeds under 20 knots. In this case, two complimentary technologies from one manufacturer, Sanoyas tandem fins and a duct, were included to maximize the pre-swirl benefit.

- Energy category: propulsion, affecting HFO consumption.
- Operating conditions: maneuvering and full steam.

- Percent reduction: 0% while maneuvering, 3% while transiting at service speed of 14.5 kts.
    - Assumed percent reduction is reduced from Sanoyas' claim of 8% [B14].
    - Assumed negligible effect while maneuvering.

Post-Swirl Device

A Kongsberg Promas bulb, a type of Costa bulb, was selected based on its suitability for deep draft vessels operating at speeds of 14 knots and up.

- Energy category: propulsion, affecting HFO consumption.
- Operating conditions: maneuvering and full steam.
- Percent reduction: 0% while maneuvering, 3% while transiting at service speed of 14.5 kts.
    - Assumed negligible effect while maneuvering.
    - Assumed percent reduction is reduced from Kongsberg data for a chemical tanker claim of 8% [B18].

Waste Heat Recovery

An MAN power turbine generator was selected based on its compactness (compared to other WHR systems), and the vessel's high engine loading while transiting at full-steam.

- Energy category: electrical, affecting MGO consumption.
- Operating conditions: maneuvering and full steam.
- Percent reduction: 0.8% while maneuvering, 4% while transiting at service speed of 14.5 kts.
    - Assumed percent reduction is based on MAN reported ranges and engine loading compared to MCR [A55].

Rotor Sails

Norsepower rotor sails were selected based on the vessel's trade route, which primarily sees coastal wind in varying directions, and Norsepower's previous success installing rotor sails on the product tanker *Timberwolf* (IMO no. 9319686, ex *Maersk Pelican*).

- Energy category: propulsion, affecting HFO consumption.
- Operating conditions: full steam.
- Percent reduction: 8% while transiting full-steam.
    - Assumed percent reduction is based on Norsepower reported savings, verified by Lloyd's Register [B50].

Improved Vessel Fuel Consumption, CO_2/CO_2e Performance Values, and Annual Emissions

The total reduction factors RF_e from Table 56 are applied to calculate improved vessel CPV and CePV values from implementing efficiency technologies on the vessel. CPV/CePV values are then used to calculate the annual tons CO_2 and CO_2e emitted after technology implementation. The results are provided in Table 57 and Table 58.

Improved Vessel CPV and Annual CO_2 Emissions

Table 57: Oceangoing tanker CPV and CO_2 emissions, result

Fuel	LHV (MJ/kg)	EF_f, WtW (MT CO_2/ MT fuel)	RF_e	SFC_{FT}/ SFC_{FO}	CPV (MT CO_2/ MT fuel)	Baseline Annual Fuel (MT)	WtW CO_2 (MT)
HFO	40.2	3.55	0.867	1	3.08	7,671	23,627
MGO	42.7	3.78	0.960	1	3.63	887	3,220
						Total Tons CO_2	*26,846*

Improved Vessel CePV and Annual CO_2e Emissions

Table 58: Oceangoing tanker CePV and CO_2e emissions, improved vessel

Fuel	LHV (MJ/kg)	EF_f, WtW (MT CO_2e/ MT fuel)	RF_e	SFC_{FT}/ SFC_{FO}	CePV (MT CO_2e/ MT fuel)	Baseline Annual Fuel (MT)	WtW CO_2e (MT)
HFO	40.2	3.89	0.867	1	3.38	7,671	25,928
MGO	42.7	4.21	0.960	1	4.04	887	3,583
						Total Tons CO_2e	*29,511*

GHG Intensity Reduction

The GHG intensity percent reduction for each fuel is calculated using the following equation:

$$\text{GHG \% reduction} = \frac{EF_{f(baseline)} - \text{CPV}}{EF_{f(baseline)}}$$

Where

$EF_{f(baseline)}$ is the vessel's original emission factor without decarbonization measures implemented.

CPV is CO_2 Performance Value with decarbonization measures implemented.

The GHG percent reductions by fuel (HFO and MGO) and emission (CO_2 and CO_2e) for the MR product tanker are provided in Table 59. The GHG is reduced (indicated by a green negative value) for both propulsion and electrical.

Table 59: Oceangoing tanker GHG intensity reduction, WtW

Fuel	Baseline CO_2 EF_f	Baseline CO_2e EF_f	Improved Vessel CPV	Improved Vessel CePV	CO_2 % Change	CO_2e % Change
Propulsion (HFO)	3.55	3.89	3.08	3.38	-13%	-13%
Electrical (MGO)	3.78	4.21	3.63	4.04	-4%	-4%

Capital Expenditure (CapEx) and Operational Expenditure (OpEx)

CapEx

The selected efficiency technologies could have combined CapEx of approximately 5% to 13% of the original vessel cost. The estimated CapEx impacts are provided in Table 60.

Table 60: Oceangoing tanker estimated CapEx

Category	Technology	CapEx (% of vessel cost)	CapEx Impact
Hull coating	Nanocoating	< 1%	Minor
Pre-swirl devices	Tandem fins and duct	< 1%	Minor
Post-swirl device	Promas bulb	< 1%	Minor
Waste heat recovery	Power turbine generator	1-5%	Moderate
Wind power	Rotor sails (2)	1-5%	Moderate
Total		*5% - 13%*	*Significant Cost*

Link to Guide Navigator

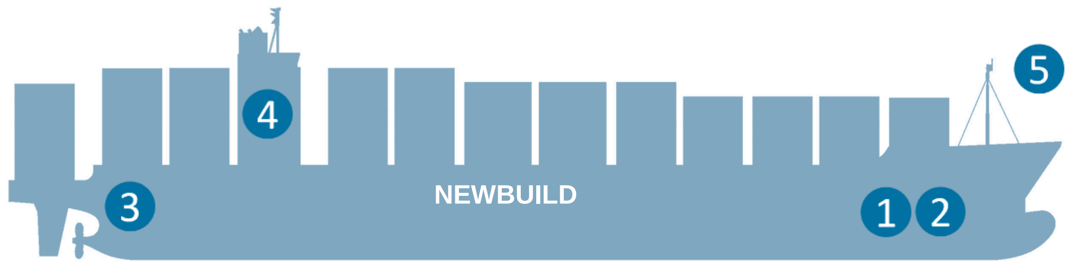
OpEx

The selected efficiency technologies are estimated to save fuel by 12.3% annually, having a significant impact on OpEx. The estimated fuel savings are provided in Table 61.

Table 61: Oceangoing tanker estimated OpEx impact

Annual Fuel Baseline (MT)	Annual Fuel Improved Vessel (MT)	Fuel Expense Change	OpEx Impact
8,558	7,505	-12.3%	Significant Savings

Case Study 2: Oceangoing Containership



1 Nanocoatings
2 Air Lubrication
3 Pre-Swirl Device
4 Waste Heat Recovery
5 Kite Sail

Overview

The vessel selected for Oceangoing Containership is a 2,400 TEU ship. At a DWT capacity of 38,000 MT, a 2,400 TEU ship is the approximate median vessel of the US-flagged containership fleet.

The vessel's operating region is the Pacific Ocean between Los Angeles and two ports in Hawaii: Honolulu and Kawaihae.

A summary of the vessel's decarbonization results compared to the vessel baseline is provided in Table 62. The selected efficiency technologies resulted in an estimated 15% reduction in WtW GHG intensity for HFO, the propulsion plant fuel, and a 5.4% reduction in WtW GHG intensity for MGO, the electrical plant fuel.

Table 62: Oceangoing containership results summary (WtW)

Parameter	Unit	Propulsion		Electrical	
		Baseline	Decarbonized Result	Baseline	Decarbonized Result
Fuel	-	HFO	HFO	MGO	MGO
CO_2 Emission Factor EF_f,	MT/MT	3.55	3.55	3.78	3.78
CO_2e Emission Factor EF_f,	MT/MT	3.89	3.89	4.21	4.21
Reduction Factor RF_e	-	1.00	0.85	1.00	0.95
CO_2 Performance Value CPV	MT/MT	3.55	3.01	3.78	3.58
CO_2e Performance Value CePV	MT/MT	3.89	3.30	4.21	3.98
Annual Fuel Consumption	MT	18,868	15,994	3,109	2,943
CO_2 Emissions	MT	66,981	56,793	11,752	11,130
CO_2e Emissions	MT	73,421	62,264	13,090	12,374
Total Emissions		**Baseline**		**Decarbonized Result**	
CO_2	MT	78,733		67,923	
CO_2e	MT	86,485		74,638	
GHG Intensity % Change		**HFO**		**MGO**	
CO_2	%	-15%		-5.4%	
CO_2e	%	-15%		-5.4%	

Improved performance in green

Vessel Particulars

The 2,400 TEU ship particulars are provided in Table 63. This case study assumes the containership is a newbuild construction.

Table 63: Oceangoing containership particulars

Particular	Value	Notes
Capacity (DWT) Length Overall Beam Draft (Load Line) Design Speed	38,000 MT 217 m 32 m 11 m 23 knots	
Propulsion Plant		
Type Power Fuel SFC (g/kWh)	Diesel-mechanical 1 x 28,880 kW MCR HFO 175	 1 x two-stroke, slow speed diesel MAN 8K80MCC Average value for all engine loads, from Fourth IMO GHG Study 2020
Electrical Plant		
Type Power Fuel SFC (g/kWh)	Diesel-generators 2 x 1,450 kWe 2 x 1,290 kWe MGO 175	AC switchboard 4 x four-stroke, medium speed diesel-generators Average value for all engine loads, from Fourth IMO GHG Study 2020

Operating Profile

Operating Modes

The vessel's operating profile consists of two modes:

- SERVICE mode. Transporting containers (standard and refrigerated) between Los Angeles, CA and Honolulu, HI/Kawaihae, HI.
- IDLE mode. Extended idle, at anchor, operating on diesel-generators.

These operating modes are summarized in Table 64. Operating modes are detailed in Table 65 and Table 66, including all details necessary to estimate annual fuel consumption for the vessel. When the vessel is in port doing cargo operations in Los Angeles, it is assumed to be connected to shore power. The GHG emissions associated with shore power electricity are not included in this case study.

Table 64: Oceangoing containership operating modes overview

Mode	Description	Hours Per Cycle	Cycles Per Year	Equivalent Days Per Year
SERVICE	Los Angeles/Hawaii trade	360	24	360
IDLE	Extended idle, running on generators	120	1	5

Table 65: Service mode details: Los Angeles/Hawaii trade

Location	Condition	Speed (kts)	Distance (nm)	Duration (hr)	Propulsion Load (bkW)	Electrical Load (bkW)
Los Angeles, CA	Maneuver	8	16	2	4,332	2,672
	Idle/anchor	0	0	4	0	1,918
	Cargo ops	0	0	16	0	0
	Maneuver	8	16	2	4,332	3,494
Laden voyage (full steam)	Transit	23	2,300	100	25,992	2,466
Honolulu, HI	Maneuver	8	16	2	4,332	3,494
	Idle/anchor	0	0	4	0	2,192
	Cargo ops	0	0	12	0	2,192
	Maneuver	8	16	2	4,332	3,083
Laden voyage	Transit	24	168	7	25,992	2,192
Kawaihae, HI	Maneuver	8	16	2	4,332	3,083
	Idle/anchor	0	0	4	0	1,918
	Cargo ops	0	0	10	0	1,918
	Maneuver	8	8	1	4,332	2,672
Ballast voyage (slow steam)	Transit	11.5	2,208	192	8,664	1,918
Total				360		

Table 66: Idle mode details: extended idle running on generators, at anchorage

Location	Condition	Speed (kts)	Distance (nm)	Duration (hr)	Propulsion Load (bkW)	Electrical Load (bkW)
Anchorage/dock	Idle/anchor	0	0	120	0	1,233
Total				120		

Baseline Fuel Consumption, CO_2/CO_2e Performance Values, and Annual Emissions

Fuel Consumption

The estimated fuel consumption for each operating mode is calculated and provided in Table 67. The fuel per cycle and per year are both provided, based on the operating mode summary in Table 64.

These estimates are simplified, and apply the base SFC for each engine type across all operating modes. Actual fuel consumption will vary based on specific engine fuel curves and the engine loading at each operating condition.

Table 67: Oceangoing containership fuel consumption by mode

Mode	Description	Propulsion - HFO (MT)		Electrical - MGO (MT)	
		per cycle	per year	per cycle	per year
SERVICE	Los Angeles/Hawaii trade	786	18,868	129	3,083
IDLE	Extended idle	0	0	26	26
	Annual Total	*Tons HFO*	*18,868*	*Tons MGO*	*3,109*

Baseline CPV and Annual CO_2 Emissions

The resulting CPV and tons CO_2 are summarized in Table 68. For calculating TtW emissions only, the values EF_f can be replaced with their TtW components: 3.11 for HFO, 3.21 for MGO.

Table 68: Oceangoing containership annual CO_2 emissions, baseline

Fuel	LHV (MJ/kg)	EF_f, WtW (MT CO_2/ MT fuel)	RF_e	SFC_{FT}/ SFC_{FO}	CPV (MT CO_2/ MT fuel)	Annual Fuel (MT)	WtW CO_2 (MT)
HFO	40.2	3.55	1	1	3.55	18,868	66,981
MGO	42.7	3.78	1	1	3.78	3,109	11,752
						Total Tons CO_2	*78,733*

Baseline CePV and Annual CO_2e Emissions

The resulting CePV and tons CO_2e are summarized in Table 69. For calculating TtW emissions only, the values EF_f can be replaced with their TtW components: 3.33 for HFO, 3.49 for MGO.

Table 69: Oceangoing containership annual CO_2e emissions, baseline

Fuel	LHV (MJ/kg)	EF_f, WtW (MT CO_2e/ MT fuel)	RF_e	SFC_{FT}/SFC_{FO}	CePV (MT CO_2e/ MT fuel)	Annual Fuel (MT)	WtW CO_2e (MT)
HFO	40.2	3.89	1	1	3.89	18,868	73,397
MGO	42.7	4.21	1	1	4.21	3,109	13,089
						Total Tons CO_2e	*86,485*

Technology Implementation

The baseline 2,400-TEU ship is assumed to already have the following efficiency technologies included in its design:

- Antifouling coating on hull.
- Routine hull cleaning & maintenance.
- Hull form optimization.

The following efficiency technologies were selected for implementation on the vessel:

1. Nanocoatings: Nippon FASTAR coating.
2. Air Lubrication: Silverstream system.
3. Pre-swirl device: Schneekluth wake equalizing duct.
4. Waste heat recovery: MAN steam turbine generator (STG).
5. Kite Sail: Airseas Seawing.

The efficiency technologies and their reduction factor RF_e characteristics for the vessel are provided in Table 70.

Table 70: Oceangoing containership reduction factors RF_e

Technology	Energy Category	Operating Conditions	Propulsion % Reduction Base	Propulsion % Reduction Weighted*	Electrical % Reduction Base	Electrical % Reduction Weighted*
Nanocoatings	Propulsion/ HFO	Maneuver	0.0%	0.0%	-	-
		Transit	-3.0%	-3.0%	-	-
Air Lubrication	Propulsion/ HFO	Transit	-6.0%	-5.9%	-	-
Pre-Swirl Device	Propulsion/ HFO	Maneuver	0.0%	0.0%	-	-
		Transit	-1.5%	-1.5%	-	-
Waste Heat Recovery (STG)	Electrical/ MGO	Maneuver	-	-	-0.9%	0.0%
		Transit	-	-	-5.4%	-5.3%
Kite Sail	Propulsion/ HFO	Transit	-10.0%	-5.7%**	-	-
			% Reduction by Operating Condition		% Reduction by Operating Condition	
		Maneuver	0%		0%	
		Idle/anchor	0%		0%	
		Cargo ops	0%		0%	
		Transit	-15.2%		-5.3%	
Total % Reduction (∑)			**-15.2%**		**-5.4%**	
Total RF_e			**0.848**		**0.946**	

*Weighted % reduction is scaled based on the fraction of energy that is consumed for a given operating condition

**Kite sail is only operable during trans-ocean transit from East to West, weighted % reduction is therefore decreased from base value proportionally.

No fuel technologies were selected for the 2,400-TEU ship. Propulsion ICEs using methanol (CH_3OH) as fuel would be the most compatible with the vessel's operating profile. However, methanol's gravimetric and volumetric energy densities (2 times the mass and 2.6 times the volume of methanol over HFO) make it not desirable for the vessel's 4,600 n.m. roundtrip voyage without reasonable intermediate refueling locations.

Nanocoatings

Nanocoating was selected based on their suitability for vessels that operate over long distances at consistent speeds. Nanocoating is best-suited for newbuilds where they can be applied in tandem with an antifouling coating.

- Energy category: propulsion, affecting HFO consumption.
- Operating conditions: maneuvering and transit.
- Percent reduction: 0% while maneuvering, 3% while transiting at service speed.
  - Assumed percent reduction is reduced from Nippon Paint Holdings' claim of 8% [B4].
  - Assumed negligible effect while maneuvering.

Air Lubrication

An air lubrication system (ALS) was selected base on its suitability for large oceangoing vessels, particularly that operate at higher transit speeds. ALS is best-suited for newbuilds where air release units are readily integrated in the hull structure during construction.

- Energy category: propulsion, affecting HFO consumption.
- Operating conditions: transit, not operable at lower speeds.

- Percent reduction: 6% while transiting at service speed.
  - Assumed percent reduction is based on Silverstream's claim of 5-10%, noting large containerships would likely fall at the lower end of that range [C57].
  - Not effective at lower speeds so assumed not operable.

Pre-Swirl Device

A Schneekluth wake equalizing duct (WED) was selected based on its significant uptake in containerships around the capacity of the selected vessel. Ducts have minimal impact on arrangement and construction as they are mounted exterior to the hull and are passive devices. While up to 12% savings has been indicated by Schneekluth, their study of a 2,500-TEU vessel operating in ocean trade would see around 1.5% fuel savings. As a new construction, hull, propeller, and rudder interactions can be optimized, possibly increasing savings.

- Energy category: propulsion, affecting prime mover consumption.
- Operating conditions: maneuvering and transit.
- Percent reduction: 0% while maneuvering, 1.5% while transiting at service speed of 23 kts.
  - Assumed percent reduction is based on Schneekluth's study of a 2,500 TEU ship [A139].
  - Assumed negligible effect while maneuvering.

Waste Heat Recovery

An MAN single pressure steam turbine generator (STG) was selected based on the vessel size and availability of propulsion exhaust heat. Machinery space will be more limited on a 2,400 TEU containership than higher-capacity vessels, making it difficult to integrate a secondary steam pressure stage for preheating feedwater.

- Energy category: electrical, affecting MGO consumption.
- Operating conditions: maneuvering and full steam.
- Percent reduction: 0.9% while maneuvering, 5.4% while transiting at service speed of 23 kts.
  - Assumed percent reduction is based on MAN reported ranges and engine loading compared to MCR [A55].

Kite Sail

An Airseas Seawing was selected based on the vessel's trade route, which primarily sees easterly and northeasterly trade winds. The kite sail would provide a propulsive effect for the westward transit from Los Angeles to Honolulu, and could be retracted and stowed for the return eastward transit

- Energy category: propulsion, affecting HFO consumption.
- Operating conditions: full steam, westward transit.
- Percent reduction: 10% during westward transit, not deployed during eastward transit.
  - Assumed percent reduction is based on Airseas' claim of 10-40% [B49].

Improved Vessel Fuel Consumption, CO_2/CO_2e Performance Values, and Annual Emissions

The total reduction factors RF_e from Table 70 are applied to calculate improved vessel CPV and CePV values from implementing efficiency technologies on the vessel. CPV/CePV values are then used to calculate the annual tons CO_2 and CO_2e emitted after technology implementation. The results are provided in Table 71 and Table 72.

Improved Vessel CPV and Annual CO_2 Emissions

Table 71: Oceangoing containership CPV and CO_2 emissions, improved vessel

Fuel	LHV (MJ/kg)	EF_f, WtW ($MT\ CO_2$/ MT fuel)	RF_e	SFC_{FT}/ SFC_{FO}	CPV ($MT\ CO_2$/ MT fuel)	Baseline Annual Fuel (MT)	WtW CO_2 (MT)
HFO	40.2	3.55	0.848	1	3.01	18,868	56,793
MGO	42.7	3.78	0.946	1	3.58	3,109	11,130
						Total Tons CO_2	*67,923*

Improved Vessel CePV and Annual CO_2e Emissions

Table 72: Oceangoing containership CePV and CO_2e emissions, improved vessel

Fuel	LHV (MJ/kg)	EF_f, WtW ($MT\ CO_2e$/ MT fuel)	RF_e	SFC_{FT}/ SFC_{FO}	CePV ($MT\ CO_2e$/ MT fuel)	Baseline Annual Fuel (MT)	WtW CO_2e (MT)
HFO	40.2	3.89	0.848	1	3.30	18,868	62,264
MGO	42.7	4.21	0.946	1	3.98	3,109	12,374
						Total Tons CO_2e	*74,638*

GHG Intensity Reduction

The GHG intensity percent reductions by fuel (HFO and MGO) and emission (CO_2 and CO_2e) for the 2,400-TEU ship are provided in Table 73. The GHG intensity is reduced (indicated by a green negative value) for both propulsion and electrical.

Table 73: Oceangoing containership GHG intensity percent reduction, WtW

Fuel	Baseline CO_2 EF_f	Baseline CO_2e EF_f	Improved Vessel CPV	Improved Vessel CePV	CO_2 % Change	CO_2e % Change
Propulsion (HFO)	3.55	3.89	3.01	3.30	-15%	-15%
Electrical (MGO)	3.78	4.21	3.58	3.98	-5.4%	-5.4%

Capital Expenditure (CapEx) and Operational Expenditure (OpEx)

CapEx

The selected efficiency technologies could have combined CapEx of approximately 5% to 17% of the original vessel cost. The estimated CapEx impacts are provided in Table 74.

Table 74: Oceangoing containership estimated CapEx

Category	Technology	CapEx (% of vessel cost)	CapEx Impact
Hull coating	Nanocoating	< 1%	Minor
Air lubrication	Air bubble	1-5%	Moderate
Pre-swirl device	Wake equalizing duct	< 1%	Minor
Waste heat recovery	Steam turbine generator	1-5%	Moderate
Wind power	Kite sail	1-5%	Moderate
Total		*5% - 17%*	*Significant Cost*

OpEx

The selected efficiency technologies are estimated to save fuel by 13.8% annually, having a significant impact on OpEx. The estimated fuel savings are provided in Table 75.

Table 75: Oceangoing containership estimated OpEx impact

Annual Fuel Baseline (MT)	Annual Fuel Improved Vessel (MT)	Fuel Expense Change	OpEx Impact
21,977	18,937	-13.8%	Significant Savings

Case Study 3: Ferry

1 Hybrid: Battery (All-Electric)

2 Hybrid: Diesel-Electric

Overview

The vessel selected for ferry is a 110-meter, double-ender car ferry as a retrofit. A ferry of this size is typical in US-based regional ferry services, which are generally the largest emitters among ferry fleets. The baseline vessel has diesel-mechanical propulsion with ship service diesel-generators.

The vessel's operating region is Washington State's Puget Sound, operating in two-point service between population centers.

A summary of the vessel's decarbonization results compared to the vessel baseline is provided in Table 76. Hybrid mechanical-electrical with battery storage was implemented on the vessel, with diesel-generators also installed to supplement battery power for propulsion and auxiliary loads in the diesel-electric configuration. The utilization is assumed as a flat 75% battery (all-electric) and 25% diesel-electric across all operating modes and conditions.

The selected efficiency technologies resulted in an estimated 44% reduction in WtW CO_2e GHG intensity (50% reduction in CO_2 intensity) for the propulsion plant and 45% reduction in WtW CO_2e GHG intensity (51% reduction in CO_2 intensity) for the electrical plant. Given the vessel's route, environmental conditions, and characteristics, no other efficiency technologies were implemented.

Table 76: Car ferry results summary (WtW)

Parameter	Unit	Propulsion		Electrical	
		Baseline	Decarbonized Result	Baseline	Decarbonized Result
Energy Source	-	MGO	Battery/MGO	MGO	Battery/MGO
All-Electric (75% utilization)					
CO_2 Emission Factor EF_f	MT/MT	3.78	0.89	3.78	0.89
CO_2e Emission Factor EF_f	MT/MT	4.21	1.28	4.21	1.28
Reduction Factor RF_e	-	1.00	1.19	1.00	1.16
CO_2 Performance Value CPV	MT/MT	3.78	1.06	3.78	1.04
CO_2e Performance Value CePV	MT/MT	4.21	1.52	4.21	1.49
Diesel-Electric (25% utilization)					
CO_2 Emission Factor EF_f	MT/MT	3.78	3.78	3.78	3.78
CO_2e Emission Factor EF_f	MT/MT	4.21	4.21	4.21	4.21
Reduction Factor RF_e	-	1.00	1.15	1.00	1.12
CO_2 Performance Value CPV	MT/MT	3.78	4.33	3.78	4.23
CO_2e Performance Value CePV	MT/MT	4.21	4.82	4.21	4.71
Overall Results					
Annual Fuel Consumption	MT	2,103	602	527	147
CO_2 Emissions	MT	7,953	3,948	1,992	968

Parameter	Unit	Propulsion Baseline	Propulsion Decarbonized Result	Electrical Baseline	Electrical Decarbonized Result
CO_2e Emissions	MT	8,855	4,932	2,218	1,209
Total Emissions		**Baseline**		**Decarbonized Result**	
CO_2	MT	9,941		4,917	
CO_2e	MT	11,072		6,141	
Overall GHG Intensity % Change		**Propulsion**		**Electrical**	
CO_2	%	-50%		-51%	
CO_2e	%	-44%		-45%	

Improved performance in green

Degraded performance in red

Vessel Particulars

The 110-meter car ferry particulars are provided in Table 77. This case study assumes the car ferry is being retrofitted.

Table 77: Car ferry particulars

Particular	Value	Notes
Capacity (GT)	9,292	
Length Overall	110 m	
Beam	25 m	
Draft (Load Line)	5 m	Summer
Service Speed	16 knots	
Propulsion Plant		
Type	Diesel-mechanical	
Power	2 x 2,500 kW	2 x four-stroke, medium speed diesel
Fuel	MGO	
SFC (g/kWh)	175	Average value for all engine loads, from Fourth IMO GHG Study (post-2001)
Electrical Plant		
Type	Diesel-generators	AC switchboard
Power	3 x 341 kWe	3 x four-stroke, high speed diesel-generators
Fuel	MGO	
SFC (g/kWh)	185	Average value for all engine loads, from Fourth IMO GHG Study (post-2001)

Operating Profile

Operating Modes

The vessel's operating profile consists of three modes:

- SERVICE mode. Transiting between Seattle, WA and Bremerton, WA.

- IDLE mode. Daily idle between operating periods, connected to shore power.
- MAINTENANCE mode. Unplanned out-of-service for maintenance or repair, connected to shore power.

These operating modes are summarized in Table 78.

Table 78: Car ferry operating modes overview

Mode	Description	Hours Per Cycle	Cycles Per Year	Equivalent Days Per Year
SERVICE	Seattle/Bremerton ferry service	2.67	2,520	280
IDLE	Daily idle between operating periods	5.33	360	80
MAINTENANCE	Unplanned out-of-service	24	5	5

Operating modes are detailed in Table 79 through Table 81, including all details necessary to estimate annual fuel consumption for the vessel.

Table 79: Service mode details: Seattle/Bremerton ferry service

Location	Condition	Speed (kts)	Distance (nm)	Duration (min)	Propulsion Load (bkW)	Electrical Load (bkW)
Seattle, WA	Dock	0	0	18	275	375
	Accelerate	0-16	1.0	2	2,365	443
	Transit	16	14.5	55	2,365	443
	Maneuver	16-0	1.5	5	660	375
Bremerton, WA	Dock	0	0	18	275	375
	Accelerate	0-16	1.0	2	2,365	443
	Transit	16	14.5	55	2,365	443
	Maneuver	16-0	1.5	5	660	375
Total (min)				160		
Total (hr)				2.67		

Table 80: Idle mode details: daily idle between operating periods, connected to shore power

Location	Condition	Speed (kts)	Distance (nm)	Duration (min)	Propulsion Load (bkW)	Electrical Load (bkW)
Maintenance Facility	Dock	0	0	320	0	0
Total (min)				320		
Total (hr)				5.33		

Table 81: Maintenance mode details: unplanned out-of-service, connected to shore power

Location	Condition	Speed (kts)	Distance (nm)	Duration (min)	Propulsion Load (bkW)	Electrical Load (bkW)
Maintenance Facility	Dock	0	0	1,440	0	150
Total (min)				1,440		
Total (hr)				24		

Baseline Fuel Consumption, CO_2/CO_2e Performance Values, and Annual Emissions

Fuel Consumption

The estimated fuel consumption for each operating mode is calculated and provided in Table 82. The fuel per cycle and per year are both provided, based on the operating mode summary in Table 79.

These estimates are simplified and apply the base SFC for each engine type across all operating modes. Actual fuel consumption will vary based on specific engine fuel curves and the engine loading at each operating condition.

Table 82: Car ferry fuel consumption by mode

Mode	Description	Propulsion - MGO (MT)		Electrical - MGO (MT)	
		per cycle	per year	per cycle	per year
SERVICE	Seattle/Bremerton service	0.83	2,103	0.21	527
IDLE	Daily idle	0	0	0	0
MAINTENANCE	Unplanned out-of-service	0	0	0	0
	Annual Total	*Tons MGO*	*2,103*	*Tons MGO*	*527*

Baseline CPV and Annual CO_2 Emissions

The resulting CPV and tons CO_2 are summarized in Table 83. For calculating TtW emissions only, the value EF_f can be replaced with its TtW components: 3.21 for MGO.

Table 83: Car ferry annual CO_2 emissions, baseline

Fuel	LHV (MJ/kg)	EF_f, WtW (MT CO_2/ MT fuel)	RF_e	SFC_{FT}/ SFC_{FO}	CPV (MT CO_2/ MT fuel)	Annual Fuel (MT)	WtW CO_2 (MT)
MGO (propulsion)	42.7	3.78	1	1	3.78	2,103	7,949
MGO (electrical)	42.7	3.78	1	1	3.78	527	1,992
						Total Tons CO_2	*9,941*

Baseline CePV and Annual CO_2e Emissions

The resulting CePV and tons CO_2e are summarized in Table 84. For calculating TtW emissions only, the value EF_f can be replaced with its TtW component: 3.49 for MGO.

Table 84: Car ferry annual CO_2e emissions, baseline

Fuel	LHV (MJ/kg)	EF_f, WtW (MT CO_2e/ MT fuel)	RF_e	SFC_{FT}/ SFC_{FO}	CPV (MT CO_2e/ MT fuel)	Annual Fuel (MT)	WtW CO_2e (MT)
MGO (propulsion)	42.7	4.21	1	1	4.21	2,103	8,854
MGO (electrical)	42.7	4.21	1	1	4.21	527	2,219
						Total Tons CO_2e	*11,072*

Technology Implementation

The baseline car ferry is assumed to already have the following efficiency technologies included in its design:

- Antifouling coating on hull.

- Routine hull cleaning & maintenance.
- Controllable pitch propellers.

The following efficiency technologies were selected for implementation on the vessel:

1. Hybrid mechanical/electrical: battery storage with redundant diesel-electric plant.

Retrofit with battery energy storage for a hybrid mechanical/electrical plant is a significant modification, so other efficiency technologies were not considered for integration on this subject vessel.

The car ferry's operation during Idle and Maintenance modes is not expected to change with the hybrid mechanical/electrical integration, so these operating modes are not included in the evaluation of reduction factors and emission factors.

Reduction Factors RF_e

The efficiency technologies and their reduction factor RF_e characteristics for the vessel are provided in Table 85 (all-electric) and Table 86 (diesel-electric). RF_e differ between all-electric operation and diesel-electric operation, based on switchgear, transformers, and converters required for each operating mode. Similarly, RF_e also differ between power to the propulsion plant and the electrical plant.

Table 85: Car ferry reduction factors RF_e, all-electric

Technology	Energy Category	Operating Conditions	Propulsion		Electrical	
			% Reduction		% Reduction	
			Base	Weighted*	Base	Weighted*
All-electric	Propulsion/ Electrical	Dock	16.1%	0.6%	13.3%	0.5%
		Accelerate	19.0%	0.6%	16.2%	0.5%
		Transit	19.0%	17.3%	16.2%	14.7%
		Maneuver	19.0%	0.4%	16.2%	0.4%
			% Reduction by Operating Condition		**% Reduction by Operating Condition**	
		Dock	1%		0%	
		Accelerate	1%		1%	
		Transit	17%		15%	
		Maneuver	0%		0%	
		Total % Reduction (∑)	18.9%		16.1%	
		Total RF_e	1.189		1.161	

*Weighted % reduction is scaled based on the fraction of energy that is consumed for a given operating condition

Table 86: Car ferry reduction factors RF_e, diesel-electric

Technology	Energy Category	Operating Conditions	Propulsion % Reduction Base	Propulsion % Reduction Weighted*	Electrical % Reduction Base	Electrical % Reduction Weighted*
Diesel-electric	Propulsion/ Electrical	Dock	14.6%	0.5%	11.8%	0.4%
		Accelerate	14.6%	0.5%	11.8%	0.4%
		Transit	14.6%	13.2%	11.8%	10.8%
		Maneuver	14.6%	0.3%	11.8%	0.3%
			% Reduction by Operating Condition		% Reduction by Operating Condition	
		Dock	1%		0%	
		Accelerate	0%		0%	
		Transit	13%		11%	
		Maneuver	0%		0%	
Total % Reduction (∑)			14.6%		11.8%	
Total RF_e			1.146		1.118	

*Weighted % reduction is scaled based on the fraction of energy that is consumed for a given operating condition

As shown in Table 85 and Table 86, total RF_e values for both all-electric and diesel-electric operation are increased over the baseline of zero. This is due to introduced losses in the vessel's fully electric plant. The makeup of these losses and how they impact the RF_e values are detailed below.

The RF_e values are determined based on the following assumptions and calculations:

All-electric:

- Charging infrastructure available at both route terminals.
- Battery-only power utilized 75% of time across all operating conditions.
- Dock: assumed that electricity for propulsion comes directly from shore power in parallel to battery charging.
    - Electrical losses (series) and resulting RF_e:

ID	Component	Efficiency Propulsion	Efficiency Electrical
A	Shore cabling (AC)	98.8%	
B	Shore switchboard (AC)	99.5%	
C	MV/LV transformer (AC)	99.4%	
D	Switchboard rectifier (AC/DC)	95.8%	
E	Propulsion inverter (DC/AC)	96.3%	-
F	VFD for propulsion (AC)	98.0%	-
G	Propulsion motor – permanent magnet (AC)	97.5%	-
H	Ship service inverter (DC/AC)	-	95.3%
I	Ship service transformer (AC)	-	98.9%
$RF_e = 1/(A×B×C×D×E×F×G)$ =		1.161	-
$RF_e = 1/(A×B×C×D×H×I)$ =		-	1.133

- Accelerate/transit/maneuvering: assumed that electricity for propulsion comes from stored energy in batteries.
    - Electrical efficiencies and resulting RF_e:

ID	Component	Efficiency	
		Propulsion	Electrical
Charging			
A	Shore cabling (AC)	98.8%	
B	Shore switchboard (AC)	99.5%	
C	Transformer, MV/LV (AC)	99.4%	
D	Charging rectifier (AC/DC)	98.6%	
E	Battery charging (DC)	97.6%	
Discharging			
F	Battery discharging (DC)	97.6%	
G	DC bus (DC)	99.5%	
H	Propulsion inverter (DC/AC)	96.3%	-
I	VFD for propulsion (AC)	98.0%	-
J	Propulsion motor – permanent magnet (AC)	97.5%	-
K	Ship service inverter (DC/AC)	-	95.3%
L	Ship service transformer (AC)	-	98.9%
$RF_e = 1/(A×B×C×D×E×F×G×H×I×J) =$		1.190	-
$RF_e = 1/(A×B×C×D×E×F×G×K×L) =$		-	1.162

- Adjusted RF_e is calculated based on the percent of baseline fuel (and energy) consumed at each operating condition.
- Total RF_e for all-electric is calculated by taking the product of the adjusted RF_e for all-electric operating conditions (propulsion and electrical, respectively).

Diesel-electric:

- Diesel-only power utilized 25% of time across all operating conditions.
- Use of batteries for peak shaving and other load management in tandem with diesel-generators not considered.
- All conditions (dock/accelerate/transit/maneuvering): assumed that electricity comes from diesel-generators for both propulsion and electrical power.
    - Electrical efficiencies and resulting RF_e:

ID	Component	Efficiency	
		Propulsion	Electrical
A	Alternator (AC)	96.8%	
B	Switchboard rectifier (AC/DC)	98.0%	
C	Propulsion inverter (DC/AC)	96.3%	-
D	VFD for propulsion (AC)	98.0%	-
E	Propulsion motor – permanent magnet (AC)	97.5%	-
F	Ship service inverter (DC/AC)	-	95.3%
G	Ship service transformer (AC)	-	98.9%
$RF_e = 1/(A×B×C×D×E) =$		1.146	-
$RF_e = 1/(A×B×F×G) =$		-	1.118

- Adjusted RF_e is calculated based on the percent of baseline fuel (and energy) consumed at each operating condition.

- Total RF_e for diesel-electric is calculated by taking the product of the adjusted RF_e for all diesel-electric operating conditions (propulsion and electrical, respectively).

Emission Factors EF_f

The use of battery storage for all-electric propulsion and auxiliary loads requires a review of the land-side utility sources for power and their GHG emission impacts. Batteries do not emit any GHG emissions when discharged, but it is unclear whether shore power emissions will be regarded as WtT or TtW by regulators. Either way, shore power electricity contributes to the WtW emissions of a battery-electric propulsion system, so utility electricity emissions are summarized as WtW emissions in this case study.

Overall emission factors for all-electric and diesel-electric operation are provided in Table 87.

Table 87: Car ferry emission factors EF_f for batteries and MGO

Energy Source	% Utilization	CO_2 EF_f, WtW ($MT\ CO_2/MT$ fuel)	CO_2e EF_f, WtW ($MT\ CO_2e/MT$ fuel)	SFC (g/kWh)	% of energy consumption
All-electric	75%				
Propulsion/Electrical (batteries)		0.89	1.28	-	100%
Diesel-electric	25%	3.78	4.21		
Propulsion (MGO)				175	80%
Electrical (MGO)				185	20%

Because it is assumed the car ferry can charge batteries at both route terminals, the electrical utility at each terminal must be considered:

All-electric:

- All-electric EF_f values are used to calculate emissions from the baseline MGO consumption that is being replaced. EF_f values reported in MT/MT are therefore derived from g/MJ values using the LHV for MGO: 42.7 MJ/kg.
- Seattle:
  - Assumed 97% renewable electricity and 3% natural gas electricity.
  - Represents 37.5% of total energy utilization (75% all-electric divided by 2).
- Bremerton:
  - Assumed 40% renewable, 32% natural gas, and 27% coal electricity.
- Resulting EF_f values for utility electricity:

Electricity Source	Fraction	WtW EF_f (MT/MT) CO_2	WtW EF_f (MT/MT) CO_2e
Seattle			
Renewable	97%	0.00	0.00
Natural gas	3%	2.14	4.35
Weighted average		*0.06*	*0.13*
Bremerton			
Renewable	40%	0.00	0.00
Natural gas	32%	2.14	4.35
Coal	27%	3.77	3.77
Weighted average		*1.72*	*2.43*
Overall Value	*100% Battery*	*0.89*	*1.28*

Diesel-electric:

- Assumed that MGO will continue to be used for diesel-electric operations.
- Baseline EF_f values for MGO:

Fuel	Fraction	WtW EF_f (MT/MT)	
		CO_2	CO_2e
MGO	*100% of DEP*	*3.78*	*4.21*

Hybrid Mechanical/Electrical

A hybrid mechanical/electrical system would be a significant undertaking as a retrofit, but the size and arrangement of the selected 110-meter car ferry makes such an integration feasible. Several elements must be integrated on the vessel, as well as upgrades to shore infrastructure to enable terminal charging.

The arrangement evaluated here is a series hybrid (see section on Hybrid Mechanical/Electrical, page 70) that fully electrifies the power sources: high-capacity batteries providing propulsion and ship service power in conjunction with large diesel-generators. The system would be a plug-in hybrid, where all battery energy would be coming from shore power rather than onboard charging from the diesel-generators, though this capability could be built into the vessel's electrical system. Vessel modifications are summarized here:

- Repower. Replacement of diesel-mechanical propulsion engines (one each end) with main diesel-generators of similar diesel-electric propulsion (DEP) capacity, 2,500 kWe each. The new diesel-generators also replace the three original ship service diesel-generators.
- Electrification. Replacement of conventional AC main switchboard with DC switchboard (1000 VDC) capable of taking shore, generator, and battery inputs at varying voltages and voltage types. Includes new drives, inverters, rectifiers, switchgear, and battery charging electronics.
- Energy storage. Two redundant battery banks each capable of sufficient capacity (approximately 5,000 kWh) and output to power the vessel's propulsion and ship service electrical demands.
- Shore power conversion. Transformers for both battery charging and shore power-to-propulsion while at either route terminal.

A simplified single-line diagram similar to this vessel's hybrid system is shown in Figure 142, notably without shore power conversion and charging electronics shown.

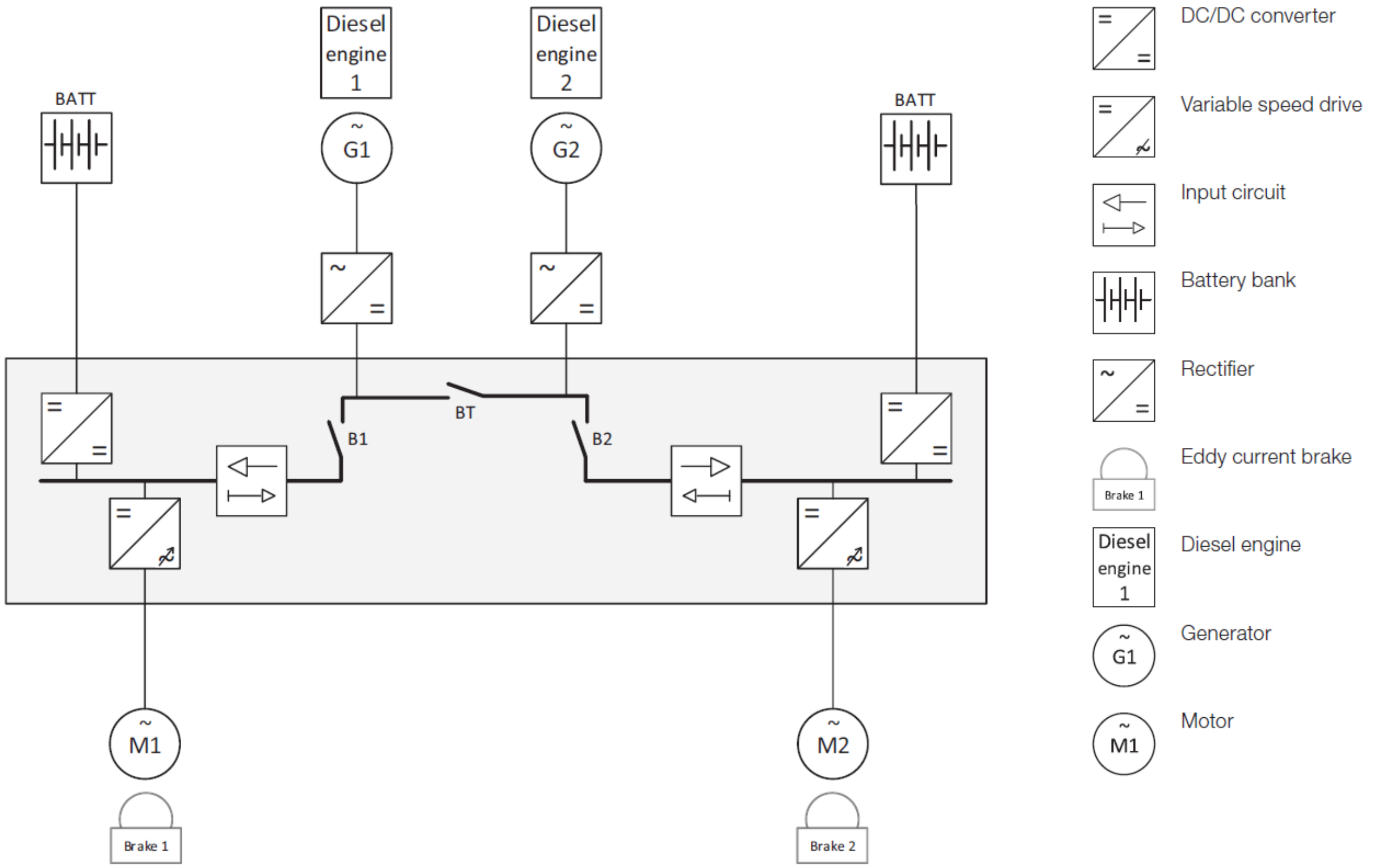


Figure 142: Simple hybrid mechanical/electric single line diagram, minus shore power charging electronics (Source: adapted from ABB)

The above modifications are limited to the vessel, and do not consider shore power infrastructure upgrades. The ability to charge a vessel of this size in 18-minute dockside windows is a complex undertaking, requiring design of both the electrical and physical interface with the ship, conversion equipment from high voltage to low voltage, and electronic controls and safeties to ensure the reliability of the system.

While a full all-electric configuration would be simpler and more readily integrated than full hybrid mechanical/electrical, the backup reliability of diesel power generation on a large passenger vessel, operating in a high-traffic region, is important to reduce operational risk and ensure long-term success of the project. Most passenger vessel fleets also require flexibility among their vessels, where maintenance or repairs requires vessel swapping to reduce out-of-service time on service routes. A full hybrid vessel can be shifted to different routes and services without having to be limited by energy storage capacity or availability of charging infrastructure.

This case study assumes that battery-electric power would be utilized exclusively for 75% of operational time, capable of power across all service operating conditions. Diesel-generators will be utilized for the remaining 25% of operating time. This accounts for adverse weather conditions, shore infrastructure downtime, and backup operation in routes with different load profiles and shore infrastructure. The energy and emissions reduction potential could be increased further by increasing battery-electric uptime, reducing the need to consume diesel fuel.

Improved Vessel Fuel Consumption, CO_2/CO_2e Performance Values, and Annual Emissions

The total reduction factors RF_e from Table 85/Table 86 and the emission factors EF_f from Table 87 are applied to calculate improved vessel CPV and CePV values from implementing these measures on the vessel. CPV/CePV values are then used to calculate annual tons CO_2 and CO_2e emitted after technology implementation. The results are provided in Table 88 and Table 89.

Improved Vessel CPV and Annual CO_2 Emissions

Table 88: Car ferry CPV and CO_2 emissions, improved vessel

Energy Source	% Utilization	LHV (MJ/kg)	EF_f, WtW (MT CO_2/ MT fuel)	RF_e	SFC_{FT}/ SFC_{FO}	CPV (MT CO_2/ MT fuel)	Baseline Annual Fuel (MT)	WtW CO_2 (MT)
Battery-electric (propulsion)	75%	-	0.89	1.189	1	1.06	2,103	1,672
Battery-electric (electrical)				1.161		1.04	527	411
Diesel-electric (propulsion)	25%	42.7	3.78	1.146	1	4.33	2,103	2,276
Diesel-electric (electrical)				1.118		4.23	527	557
Tons CO_2 (battery-electric, 75% utilization)								*2,083*
Tons CO_2 (diesel-electric, 25% utilization)								*2,834*
Total Tons CO_2								*4,917*

Improved Vessel CePV and Annual CO_2e Emissions

Table 89: Car ferry CePV and CO_2e emissions, improved vessel

Energy Source	% Utilization	LHV (MJ/kg)	EF_f, WtW (MT CO_2e/ MT fuel)	RF_e	SFC_{FT}/ SFC_{FO}	CePV (MT CO_2e/ MT fuel)	Baseline Annual Fuel (MT)	WtW CO_2e (MT)
Battery-electric	75%							
(propulsion)		-	1.28	1.189	1	1.52	2,103	2,397
(electrical)				1.161		1.49	527	589
Diesel-electric	25%							
(propulsion)		42.7	4.21	1.146	1	4.82	2,103	2,534
(electrical)				1.118		4.71	527	621
Tons CO_2 (battery-electric, 75% utilization)								*2,986*
Tons CO_2 (diesel-electric, 25% utilization)								*3,155*
Total Tons CO_2								*6,141*

GHG Intensity Reduction

The GHG percent reductions by energy source (battery-electric and diesel-electric) and consumer (propulsion and electrical) for the car ferry are provided in Table 90. Battery-electric operations reduce the vessel's GHG intensity (indicated by a green negative value), while diesel-electric operations increase the vessel's GHG intensity (indicated by a red positive value). Because battery-electric has a much higher utilization, however, the overall GHG intensity for both propulsion and electrical are reduced, summarized at the end of the table.

Link to Guide Navigator

Table 90: Car ferry GHG intensity percent reduction, WtW

Energy Source	% Utilization	Baseline CO_2 EF_f	Baseline CO_2e EF_f	Improved Vessel CPV	Improved Vessel CPVe	CO_2 % Change	CO_2e % Change
Battery-electric	75%						
(propulsion)		3.78	4.21	1.06	1.52	-72%	-73%
(electrical)		3.78	4.21	1.04	1.49	-64%	-65%
Diesel-electric	25%						
(propulsion)		3.78	4.21	4.33	4.82	15%	15%
(electrical)				4.23	4.71	12%	12%
Overall GHG Intensity % Change (propulsion)						-50%	-44%
Overall GHG Intensity % Change (electrical)						-51%	-45%

Capital Expenditure (CapEx) and Operational Expenditure (OpEx)

CapEx

The selected efficiency technologies could have combined CapEx of approximately 10% to 20% of the original vessel cost. The estimated CapEx impacts are provided in Table 91.

Table 91: Car ferry estimated CapEx

Category	Technology	CapEx (% of vessel cost)	CapEx Impact
Hybrid mech./elect.	Battery storage with DEP	10-20%	Significant Cost
Total		*10% - 20%*	*Significant Cost*

OpEx

The selected efficiency technologies are estimated to save fuel by 71.5% annually, having a significant impact on OpEx. The estimated fuel savings are provided in Table 92. The conversion to shore charging electrical will have an added utility cost that is not estimated here, but is expected to only partially offset the significant fuel savings.

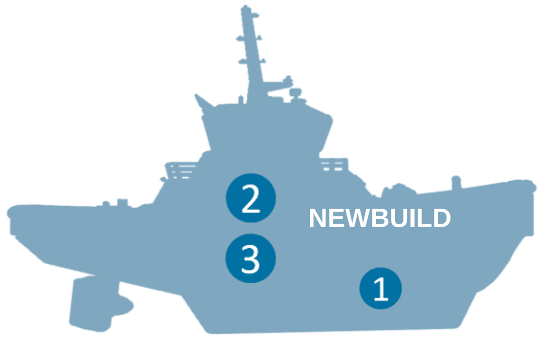
Table 92: Car ferry estimated OpEx impact

Annual Fuel Baseline (MT)	Annual Fuel Improved Vessel (MT)	Fuel Expense Change	OpEx Impact
2,630	750	-71.5%	Significant Savings*

*Savings do not account for added utility cost of shore charging, but this is expected to only partially offset OpEx savings from fuel reduction.

Link to Guide Navigator

Case Study 4: Tugboat



1. Anti-fouling coating
2. Hydrogen fuel cells
3. Battery-electric system

Overview

The vessel selected for the Towboat/Tugboat category is a 30-meter escort tug with azimuthing stern drive (ASD), as a newbuild. Towboats and tugboats represent 62% of US commercial self-propelled vessels.

The vessel's operating region is the San Francisco Bay Area, escorting tank vessels from region's Zone 1 station outside the Golden Gate Bridge to an oil terminal in Zone 6 in Martinez, CA.

A summary of the vessel's decarbonization results compared to the vessel baseline is provided in Table 93. The analysis is for a tugboat operating on fuel cells powered by hydrogen, with a battery system to delivery power and accommodate frequent and abrupt load changes typical of a tugboat. The drivetrain is upgraded to an all-electric configuration over the diesel-mechanical baseline. Based on plans for compressed green hydrogen to be available as a marine fuel in San Francisco, these results assume that the new escort tug will operate on 100% green hydrogen. Where a composite fuel that is a mixture of green and gray (or blue) fuel pathways is utilized, composite emission factors EF_f can be determined, as discussed in the section on Composite Fuels.

The selected fuel technology of fuel cells powered by hydrogen resulted in an estimated 99.7% to 99.9% reduction in WtW GHG intensity for the entire vessel. Anti-fouling coating had a negligible effect on the GHG intensity, due to the vessel typically operating at low speeds.

Table 93: Escort tug results summary using green hydrogen (WtW)

Parameter	Unit	Propulsion		Electrical	
		Baseline	Decarbonized Result	Baseline	Decarbonized Result
Fuel	-	MGO	H_2	MGO	H_2
CO_2 Emission Factor EF_f,	MT/MT	3.78	0.01	3.78	0.01
CO_2e Emission Factor EF_f,	MT/MT	4.21	0.03	4.21	0.03
Reduction Factor RF_e	-	1.000	1.156	1.000	1.135
CO_2 Performance Value CPV	MT/MT	3.78	0.004	3.78	0.004
CO_2e Performance Value CePV	MT/MT	4.21	0.013	4.21	0.012
Annual Fuel Consumption	MT	1,777	744	367	151
CO_2 Emissions	MT	6,717	7.1	1,387	1.5
CO_2e Emissions	MT	7,481	23.1	1,545	4.4
Total Emissions		**Baseline**		**Decarbonized Result**	
CO_2	MT	8,104		8.6	
CO_2e	MT	9,026		27.5	

Parameter	Unit	Propulsion		Electrical	
		Baseline	Decarbonized Result	Baseline	Decarbonized Result
GHG Intensity % Change		**Propulsion**		**Electrical**	
CO_2	%	-99.9%		-99.9%	
CO_2e	%	-99.7%		-99.7%	

Improved performance in green
Degraded performance in red

Vessel Particulars

The escort tug particulars are provided in Table 94. This case study assumes the tug is a newbuild.

Table 94: Tugboat particulars

Particular	Value	Notes
Capacity (GT)	196	
Length Overall	30 m	
Beam	12 m	
Draft (Load Line)	6 m	
Service Speed	15 knots	
Propulsion Plant		
Type	Diesel-mechanical	
Power	2 x 2,500 kW MCR	2 x four-stroke, high speed diesel
Fuel	MGO	
SFC (g/kWh)	185	Average value for all engine loads, from Fourth IMO GHG Study (post-2001)
Electrical Plant		
Type	Diesel-generators	AC switchboard
Power	2 x 250 kWe	2 x four-stroke, high speed diesel generators
Fuel	MGO	
SFC (g/kWh)	185	Average value for all engine loads, from Fourth IMO GHG Study (post-2001)

Operating Profile

Operating Modes

The vessel's operating profile consists of two modes:

- SERVICE mode. Tanker escort operation from San Francisco Zone 1 to Martinez, CA in Zone 6, including transit to and from the service route, and idle time on station.
- DOCK mode. Tie-up between service shifts, at dock on shore power.

These operating modes are summarized in Table 95.

Table 95: Escort tug operating modes overview

Mode	Description	Hours Per Cycle	Cycles Per Year	Equivalent Days Per Year
SERVICE	Tanker escort from Zone 1 to Zone 6	14	365	213
DOCK	Tie-up between shifts, on shore power	10	365	152

Operating modes are detailed in Table 96 and Table 97, including all details necessary to estimate annual fuel consumption for the vessel.

Table 96: Service mode details: San Francisco Zone 1 to Zone 6 tanker escort

Location	Condition	Speed (kts)	Distance (nm)	Duration (hr)	Propulsion Load (bkW)	Electrical Load (bkW)
San Francisco	Transit	12	9	0.75	3,000	396
Zone 1	Idle	0	0	4.00	500	180
	Maneuver	4	2	0.50	3,750	480
Zone 1 to Zone 6	Escort	8	25	3.25	1,500	540
Zone 6	Escort	6	8	1.75	2,500	540
Martinez	Maneuver	4	2	0.50	3,750	396
	Transit	12	34	3.00	3,000	396
San Francisco	Idle	0	0	0.25	250	180
Total				14		

Table 97: Dock mode details: tie-up at dock on shore power

Location	Condition	Speed (kts)	Distance (nm)	Duration (hr)	Propulsion Load (bkW)	Electrical Load (bkW)
San Francisco	Shore power	0	0	10	0	0
Total				10		

Baseline Fuel Consumption, CO_2/CO_2e Performance Values, and Annual Emissions

Fuel Consumption

The estimated fuel consumption for each operating mode is calculated and provided in Table 98. The fuel per cycle and per year are both provided, based on the operating mode summary in Table 95.

These estimates are simplified, and apply the base SFC for each engine type across all operating modes. Actual fuel consumption will vary based on specific engine fuel curves and the engine loading at each operating condition.

Table 98: Escort tug fuel consumption by mode

Mode	Description	Propulsion - MGO (MT)		Electrical - MGO (MT)	
		per cycle	per year	per cycle	per year
SERVICE	Tanker escort to Zone 6	4.9	1,777	1.0	367
DOCK	Tie-up on shore power	0	0	0	0
	Annual Total	*Tons MGO*	*1,777*	*Tons MGO*	*367*

Baseline CPV and Annual CO_2 Emissions

The resulting CPV and tons CO_2 are summarized in Table 99. For calculating TtW emissions only, the value EF_f can be replaced with its TtW components: 3.21 for MGO.

Table 99: Escort tug annual CO_2 emissions, baseline

Fuel	LHV (MJ/kg)	EF_f, WtW (MT CO_2/ MT fuel)	RF_e	SFC_{FT}/ SFC_{FO}	CPV (MT CO_2/ MT fuel)	Annual Fuel (MT)	WtW CO_2 (MT)
MGO (propulsion)	42.7	3.78	1	1	3.78	1,777	6,717
MGO (electrical)	42.7	3.78	1	1	3.78	367	1,387
						Total Tons CO_2	*8,104*

Baseline CePV and Annual CO_2e Emissions

The resulting CePV and tons CO_2e are summarized in Table 110. For calculating TtW emissions only, the value EF_f can be replaced with its TtW component: 3.49 for MGO.

Table 100: Escort tug annual CO_2e emissions, baseline

Fuel	LHV (MJ/kg)	EF_f, WtW (MT CO_2e/ MT fuel)	RF_e	SFC_{FT}/ SFC_{FO}	CePV (MT CO_2e/ MT fuel)	Annual Fuel (MT)	WtW CO_2e (MT)
MGO (propulsion)	42.7	4.21	1	1	4.21	1,777	7,481
MGO (electrical)	42.7	4.21	1	1	4.21	367	1,545
						Total Tons CO_2e	*9,026*

Technology Implementation

The baseline escort tug is assumed to already have the following efficiency technologies included in its design:

- Ducted, azimuthing propellers.

The following efficiency technologies were selected for implementation on the vessel:

1. Anti-fouling coating.
2. All-electric drivetrain: battery-electric, small storage capacity and high-power output.
    - Li-ion battery system coupled with below fuel cell system to account for transient loads.

The following fuel technologies were selected for implementation:

2. All-electric drivetrain: fuel cells powered by hydrogen as the energy source, used to charge small-capacity battery system for an all-electric drive train.

The combination of a battery-electric system with fuel cells powered by hydrogen replaces the baseline diesel-mechanical propulsion plant.

Reduction Factors RF_e

The efficiency technologies and their reduction factor RF_e characteristics for the vessel are provided in Table 101.

Table 101: Escort tug reduction factors RF_e

Technology	Energy Category	Operating Conditions	Propulsion		Electrical	
			% Reduction		% Reduction	
			Base	Weighted*	Base	Weighted*
Anti-fouling coating	Propulsion	Transit	-1.0%	-0.4%	-	-
		Escort	-0.5%	-0.2%	-	-
Battery-electric	Propulsion & Electrical	Transit	16.3%	7.0%	13.5%	5.8%
		Idle	16.3%	1.3%	13.5%	1.1%
		Maneuver	16.3%	2.3%	13.5%	1.9%
		Escort	16.3%	5.7%	13.5%	4.8%
			% Reduction by Operating Condition		% Reduction by Operating Condition	
		Transit	6.5%		5.8%	
		Idle	1.3%		1.1%	
		Maneuver	2.3%		1.9%	
		Escort	5.5%		4.8%	
		Total % Reduction (∑)	+15.6%		+13.5%	
		Total RF_e	1.156		1.135	

*Weighted % reduction is scaled based on the fraction of energy that is consumed for a given operating condition.

As shown in Table 101, total RF_e values are increased over the baseline of 1 due to introduced losses from battery-electric power. The RF_e values are determined based on the following assumptions and calculations:

- All operating conditions: assumed that electricity for propulsion and electrical systems come from stored energy in batteries that are charged by hydrogen fuel cells:
  a. Electrical losses and resulting percent reduction:

ID	Component	Efficiency	
		Propulsion	Electrical
Charging batteries			
A	Fuel cell to battery converter (DC/DC)	98.6%	
B	Battery charging (DC)	97.6%	
Discharging batteries			
C	Battery discharging (DC)	97.6%	
D	DC bus (DC)	99.5%	
E	Propulsion inverter (DC/AC)	96.3%	-
F	VFD for propulsion (AC)	98.0%	-
G	Propulsion motor – permanent magnet (AC)	97.5%	-
H	Ship service inverter (DC/AC)	-	95.3%
I	ship service transformer (AC)	-	98.9%
% Red = 1/(A×B×C×D×E×F×G)-1 =		+16.3%	-
% Red = 1/(A×B×C×D×H×I)-1 =		-	+13.5%

Emission Factors EF_f

Hydrogen fuel cells were selected as a fuel technology for both propulsion and electrical power. With projects in development to provide compressed green hydrogen to the San Francisco waterfront for marine vessel fueling [A140], it is assumed that this fuel will be available for a hydrogen-powered escort tug operating in the region. Green hydrogen emission factors EF_f, and specific fuel consumption in a hydrogen fuel cell, are provided in Table 102. These values are taken directly from the guide section on Hydrogen.

Table 102: Escort tug emission factors EF_f for green hydrogen

Fuel	CO_2 EF_f, WtW (MT CO_2/MT fuel)	CO_2e EF_f, WtW (MT CO_2e/MT fuel)	SFC (g/kWh)	% of vessel consumption
Green H_2 (propulsion & electrical)	0.01	0.03	67	100%

Anti-Fouling Coating

An escort tug runs in intermittent service, with periods of tie-up at the dock a routine part of the operation. As such, anti-fouling coating is advised to limit marine growth and maintenance on the vessel's hull. Escort tugs do not transit or perform escort duties at high speeds, so the resistance reductions may be nominal (up to 1% assumed for 12-knot transit), but maintenance and coating replacement costs likely justify the coating upgrade.

- Energy category: propulsion.
- Operating conditions: transit and escort.
- Percent reduction: 1% while transiting at service speed of 12 kts, 0.5% while escorting at speeds of 6-8 kts.

Fuel Cells Powered by Hydrogen and Battery-Electric

Fuel cells powered by hydrogen are selected as an alternative fuel for the escort tug. At approximately 6 MT of MGO consumed per roundtrip by both propulsion and electrical demands in service mode, the equivalent mass of hydrogen alone would be only 2.1 MT, however adjusting for storage could require up to 6 to 8 times the mass of MGO for the combined hydrogen and storage equipment [A71]. 700 bar compressed hydrogen requires about 8 times the volume of an equivalent amount of energy in MGO [A76], and additional storage for tanks, frames, and storage equipment could increase that volume by 2 to 3 times. As a result, stored hydrogen could require 16 to 24 times as much space onboard as MGO. A comparison of compressed hydrogen energy densities to MGO is provided in Table 103.

Table 103: Compressed hydrogen energy density compared to MGO

Fuel		MGO	Hydrogen (700 bar)	Factor
Mass density (kg/m^3)		860	42	
LHV (MJ/kg)	Fuel only	42.7	120	2.8 times more dense
	H_2 + storage	-	6	7 times less dense
Volumetric density (MJ/L)	Fuel only	38.4	4.8	8 times less dense
	H_2 + storage	-	1.6 to 2.4	16 to 24 times less dense

Hydrogen could be stored below deck on a tugboat, offsetting structural volume originally reserved for fuel tanks. A representation of this arrangement is shown on the Port of Antwerp's Hydrotug design in Figure 143. The *Hydrotug* design uses hydrogen ICE, but the tank storage configuration on a fuel cell tug would be similar.

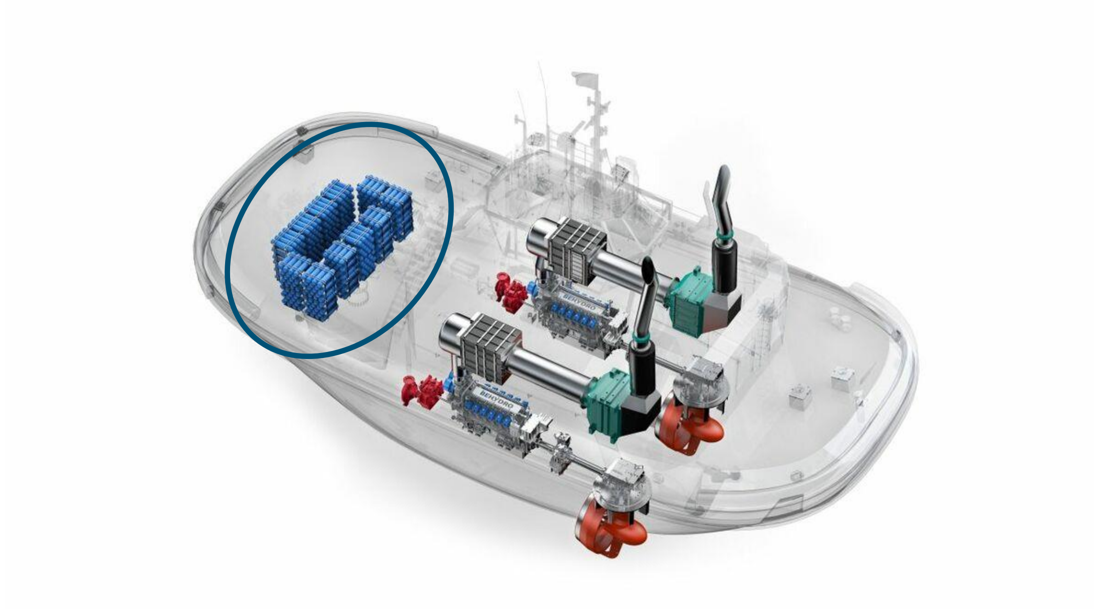


Figure 143: *Hydrotug* with compressed hydrogen shown below aft working deck (source: rivieramm.com)

While the 8 times mass and 16 to 24 times volume ratios indicated above would reduce the energy capacity of a 30-meter escort tug, a typical vessel of this type could accommodate the reduced fuel energy capacity. There is usually plenty of surplus fuel available for the operating profile considered here. However, the changes would increase the fueling frequency by a factor of 3, which has added operational costs that have not been quantified. A comparison of MGO storage capacity to hydrogen storage capacity is shown in Table 104.

Table 104: Escort tug compressed hydrogen fuel storage capacity compared to MGO

Fuel	MGO	Hydrogen (700 bar)
Volume Storage (m^3)	275	11 to 17
Mass Storage (MT)	235	33
Fuel per cycle (MT)	5.9	2.1
Cycles between fueling (25% fuel reserve)	29	11

Fuel cell banks and discharge batteries would replace the baseline arrangement of two propulsion engines and 2 diesel-generators, occupying similar machinery spaces onboard. A conceptual one-line power diagram of this powertrain is provided in Figure 144. On a work boat in this service, the fuel cells could be located in a single space (versus segregated spaces as required on passenger vessels), reducing the potential changes to machinery space arrangement. The elimination of diesel exhaust equipment could further accommodate the fuel cell balance of plant (BOP) required for 100% hydrogen fuel cell power.

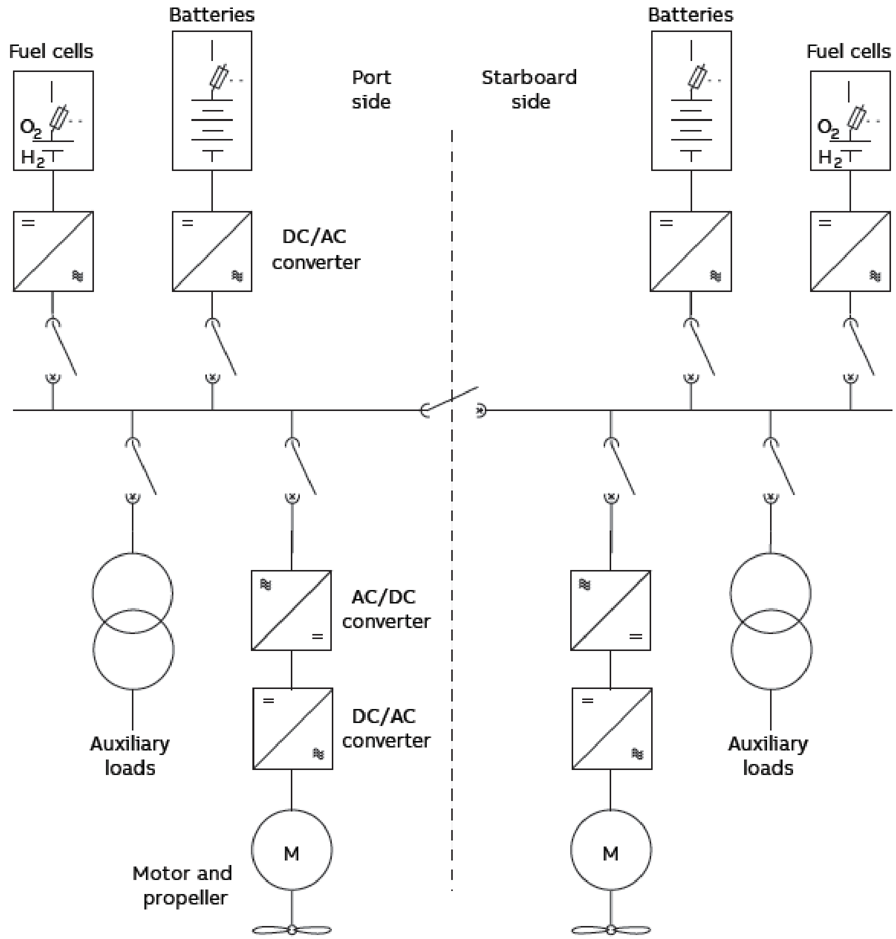


Figure 144: Conceptual one-line diagram with battery-electric power using hydrogen fuel cells (source: ABB)

Improved Vessel Fuel Consumption, CO_2/CO_2e Performance Values, and Annual Emissions

The total reduction factors RF_e from Table 101 and the emission factors EF_f from Table 102 are applied to calculate improved vessel CPV and CePV values from implementing these measures on the vessel. CPV/CePV values are then used to calculate the annual tons CO_2 and CO_2e emitted after technology implementation. The results are provided in Table 105 and Table 106.

Improved Vessel CPV and Annual CO_2 Emissions

Table 105: Escort tug CPV and CO_2 emissions, improved vessel

Fuel	LHV (MJ/kg)	EF_f, WtW (MT CO_2/ MT fuel)	RF_e	SFC_{FT}/ SFC_{FO}	CPV (MT CO_2/ MT fuel)	Baseline Annual Fuel (MT)	WtW CO_2 (MT)
Green H_2 (propulsion)	120	0.01	1.156	0.36	0.004	1,777 (MGO)	7.1
Green H_2 (electrical)	120	0.01	1.135	0.36	0.004	367	1.5
					Total Tons CO_2 (using green H_2)		*8.6*

Improved Vessel CePV and Annual CO_2e Emissions

Table 106: Escort tug CePV and CO_2e emissions, improved vessel

Fuel	LHV (MJ/kg)	EF_f, WtW (MT CO_2e/ MT fuel)	RF_e	SFC_{FT}/ SFC_{FO}	CePV (MT CO_2e/ MT fuel)	Baseline Annual Fuel (MT)	WtW CO_2e (MT)
Green H_2 (propulsion)	120	0.03	1.156	0.36	0.013	1,777 (MGO)	23.1
Green H_2 (electrical)	120	0.03	1.135	0.36	0.012	367	4.4
						Total Tons CO_2e (using green H_2)	*27.5*

GHG Intensity Reduction

The carbon intensity percent reductions by fuel and consumer (green hydrogen for propulsion and electrical) and emission (CO_2 and CO_2e) for the escort tug are provided in Table 107. The GHG intensity is reduced to near-zero (indicated by a green negative percent value) for both propulsion and electrical emissions, due to the very low emission factors of green hydrogen.

Table 107: Escort tug GHG intensity percent reduction

Fuel	Baseline CO_2 EF_f	Baseline CO_2e EF_f	Improved Vessel CPV	Improved Vessel CPVe	CO_2 % Change	CO_2e % Change
Green H_2 (propulsion)	3.78	4.21	0.004	0.013	-99.9%	-99.7%
Green H_2 (electrical)	3.78	4.21	0.004	0.012	-99.9%	-99.7%

Capital Expenditure (CapEx) and Operational Expenditure (OpEx)

CapEx

The selected efficiency technologies could have a wide-ranging total CapEx, depending on vessel design specifics and developers selected. The range is estimated at approximately 40% to 80% additional to the original vessel cost. Fuel cells powered by hydrogen, high pressure storage systems, safety systems, and the battery system are all expected to be significant expenditures that would drive the overall cost of the vessel. The estimated CapEx impacts are provided in Table 108.

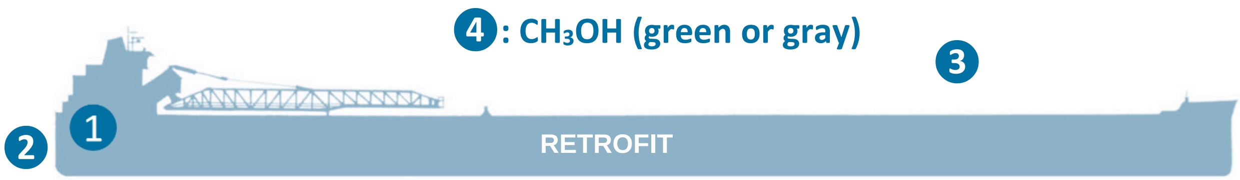
Table 108: Escort tug estimated CapEx

Category	Technology	CapEx (% of vessel cost)	CapEx Impact
Battery (All-Electric)	Electric with batteries and fuel cells	40-80%	Significant Cost
Total		*40% - 80%*	*Significant Cost*

OpEx

By switching from MGO to green hydrogen, the relative price of each fuel will impact the change in OpEx for the vessel. The expected cost of green hydrogen is not presently understood, but it can be assumed to be more expensive than MGO by a factor of 5 to 10 initially, on a mass basis. Therefore, the annual OpEx of the vessel would initially increase significantly over the MGO baseline, but may decrease as green hydrogen production matures and becomes more widely available. The replacement cost of battery and fuel cell systems must also be considered, which are expected to be much higher than typical OpEx for diesel engine maintenance.

Case Study 5: Bulk Carrier (Great Lakes)



Source: Interlake Steamship Company

1. Pre-Swirl Device
2. Post-Swirl Device
3. Rotor Sails
4. Methanol ICE

Overview

The vessel selected for Bulk Carrier in the Great Lakes is a 305-meter self-unloading ore carrier as a retrofit. Self-propelled bulkers represent 40% of vessels operating on the US Great Lakes.

The vessel's operating region is the US Great Lakes, primarily between ore loading locations on Lake Superior and offloading locations on Lake Michigan.

A summary of the vessel's decarbonization results compared to the vessel baseline is provided in Table 109 and Table 110. Table 109 assumes the implementation of dual fuel ICEs burning methanol in gas mode, with 100% green methanol as an available fuel source. Table 110 assumes gray methanol is the only available fuel source. Where a composite fuel is sourced that is a mixture of green and gray (or blue) fuel pathways, composite emission factors EF_f can be determined, as discussed in the section on Composite Fuels. No decarbonization technologies were implemented to improve vessel electrical performance. As such, electrical decarbonization was not evaluated and is grayed out in Table 109 and Table 110.

The selected efficiency technologies with green methanol resulted in an estimated 75% reduction in WtW GHG intensity for the propulsion plant. No technologies were implemented for reducing electrical load, so a 0% reduction in WtW GHG intensity for the electrical plant is estimated.

Table 109: Bulk carrier (Great Lakes) results summary using green methanol (WtW)

Parameter	Unit	Propulsion		Electrical	
		Baseline	Decarbonized Result	Baseline	Decarbonized Result
Fuel	-	MGO	CH_3OH	MGO	
CO_2 Emission Factor EF_f,	MT/MT	3.78	0.63	3.78	
CO_2e Emission Factor EF_f,	MT/MT	4.21	0.69	4.21	
Reduction Factor RF_e	-	1.00	0.88	1.00	
CO_2 Performance Value CPV	MT/MT	3.78	0.96	3.78	N/A
CO_2e Performance Value CePV	MT/MT	4.21	1.05	4.21	
Annual Fuel Consumption	MT	6,609	10,151	616	
CO_2 Emissions	MT	24,982	6,345	2,328	
CO_2e Emissions	MT	27,824	6,939	2,593	
Total Emissions		**Baseline**		**Decarbonized Result**	
CO_2	MT	27,311		8,673	
CO_2e	MT	30,417		9,533	
GHG Intensity % Change		**Propulsion**		**Electrical**	
CO_2	%	-75%		N/A	
CO_2e	%	-75%			

Improved performance in green

The selected efficiency technologies with gray methanol resulted in an estimated 25% / 26% (CO_2 / CO_2e) reduction in WtW carbon intensity for the propulsion plant. No technologies were implemented for reducing electrical load, so a 0% reduction in WtW carbon intensity for the electrical plant is estimated.

Table 110: Bulk carrier (Great Lakes) results summary using gray methanol

Parameter	Unit	Propulsion		Electrical	
		Baseline	Decarbonized Result	Baseline	Decarbonized Result
Fuel	-	MGO	CH_3OH	MGO	N/A
CO_2 Emission Factor EF_f,	MT/MT	3.78	1.84	3.78	
CO_2e Emission Factor EF_f,	MT/MT	4.21	2.03	4.21	
Reduction Factor RF_e	-	1.00	0.88	1.00	
CO_2 Performance Value CPV	MT/MT	3.78	2.83	3.78	
CO_2e Performance Value CePV	MT/MT	4.21	3.11	4.21	
Annual Fuel Consumption	MT	6,609	10,151	616	
CO_2 Emissions	MT	24,982	18,703	2,328	
CO_2e Emissions	MT	27,824	20,554	2,593	
Total Emissions		**Baseline**		**Decarbonized Result**	
CO_2	MT	27,311		21,032	
CO_2e	MT	30,417		23,147	
GHG Intensity % Reduction		**Propulsion**		**Electrical**	
CO_2	%	-25%		N/A	
CO_2e	%	-26%			

Improvements indicated in green

Vessel Particulars

The ore bulk carrier vessel particulars are provided in Table 111. This case study assumes the vessel is being retrofitted.

Table 111: Bulk carrier (Great Lakes) particulars

Particular	Value	Notes
Capacity (DWT)	93,645 MT	
Length Overall	305 m	
Beam	105 m	
Draft (Load Line)	28 m	
Service Speed	14 knots	
Propulsion Plant		
Type	Diesel-mechanical	
Power	4 x 2,685 kW MCR	4 x two-stroke, medium speed diesel
Fuel	MGO	
SFC (g/kWh)	200	Average value for all engine loads, from Fourth IMO GHG Study (pre-1983)

Particular	Value	Notes
Electrical Plant		
Type	Diesel-generators	AC switchboard
Power	2 x 600 kWe	2 x four-stroke, high speed diesel-generators
Fuel	MGO	
SFC (g/kWh)	210	Average value for all engine loads, from Fourth IMO GHG Study (pre-1983)

Operating Profile

Operating Modes

The vessel's operating profile consists of three modes:

- SERVICE mode. Transporting iron ore between Two Harbors, MN and Indiana Harbor, IL.
- IDLE mode. Extended idle, at anchor or dock, operating on diesel-generators.
- LAYUP mode. Winter lay-up at dock, operating at minimal load (30%) on one diesel-generator.

These operating modes are summarized in Table 112.

Table 112: Bulk carrier (Great Lakes) operating modes overview

Mode	Description	Hours Per Cycle	Cycles Per Year	Equivalent Days Per Year
SERVICE	Two Harbors/Indiana Harbor ore trade	162	40	270
IDLE	Extended Idle, running on generators	30	3	3.75
LAYUP	Winter layup, minimal generator loads	2,190	1	91.25

Operating modes are detailed in Table 113 through Table 115, including all details necessary to estimate annual fuel consumption for the vessel.

Table 113: Service mode details: Two Harbors/Indiana Harbor ore trade

Location	Condition	Speed (kts)	Distance (nm)	Duration (hr)	Propulsion Load (bkW)	Electrical Load (bkW)
Two Harbors, MN	Maneuver in	5	10	2	1,074	450
	Idle/anchor	0	0	4	0	300
	Cargo ops	0	0	16	0	350
	Maneuver out	5	10	2	1,095	450
Laden voyage	Transit	14	672	48	9,129	500
	Maneuver locks	5	45	9	1,074	450
Indiana Harbor, IL	Maneuver in	5	10	2	1,095	500
	Idle/anchor	0	0	4	0	300
	Cargo ops	0	0	16	0	400
	Maneuver out	5	10	2	1,095	450

Location	Condition	Speed (kts)	Distance (nm)	Duration (hr)	Propulsion Load (bkW)	Electrical Load (bkW)
Ballast voyage	Full steam	14	672	48	7,518	400
	Maneuver locks	5	45	9	859	450
Total				162		

Table 114: Idle mode details: extended idle running on diesel-generators, at anchorage or dock

Location	Condition	Speed (kts)	Distance (nm)	Duration (hr)	Propulsion Load (bkW)	Electrical Load (bkW)
Anchorage	Idle/anchor	0	0	30	0	300
Total				120		

Table 115: Layup mode details: extended idle running on diesel-generators at minimal load

Location	Condition	Speed (kts)	Distance (nm)	Duration (hr)	Propulsion Load (bkW)	Electrical Load (bkW)
Ohio	Layup	0	0	2,190	0	150
Total				2,190		

Baseline Fuel Consumption, CO_2/CO_2e Performance Values, and Annual Emissions

Fuel Consumption

The estimated fuel consumption for each operating mode is calculated and provided in Table 116. The fuel per cycle and per year are both provided, based on the operating mode summary in Table 112.

These estimates are simplified, and apply the base SFC for each engine type across all operating modes. Actual fuel consumption will vary based on specific engine fuel curves and the engine loading at each operating condition.

Table 116: Bulk carrier (Great Lakes) fuel consumption by mode

Mode	Description	Propulsion - MGO (MT)		Electrical - MGO (MT)	
		per cycle	per year	per cycle	per year
SERVICE	TH/IH ore trade	165	6,609	13.5	542
IDLE	Extended idle	0	0	1.9	5.7
LAYUP	Winter layup	0	0	69	69
	Annual Total	*Tons MGO*	*6,609*	*Tons MGO*	*616*

Baseline CPV and Annual CO_2 Emissions

The resulting CPV and tons CO_2 are summarized in Table 117. For calculating TtW emissions only, the value EF_f can be replaced with its TtW components: 3.21 for MGO.

Table 117: Bulk carrier (Great Lakes) annual CO_2 emissions, baseline

Fuel	LHV (MJ/kg)	EF_f, WtW (MT CO_2/ MT fuel)	RF_e	SFC_{FT}/ SFC_{FO}	CPV (MT CO_2/ MT fuel)	Annual Fuel (MT)	WtW CO_2 (MT)
MGO (propulsion)	42.7	3.78	1	1	3.78	6,609	24,982
MGO (electrical)	42.7	3.78	1	1	3.78	616	2,328
						Total Tons CO_2	*27,311*

Baseline CePV and Annual CO_2e Emissions

The resulting CePV and tons CO_2e are summarized in Table 55. For calculating TtW emissions only, the value EF_f can be replaced with its TtW component: 3.49 for MGO.

Table 118: Bulk carrier (Great Lakes) annual CO_2e emissions, baseline

Fuel	LHV (MJ/kg)	EF_f, WtW (MT CO_2e/ MT fuel)	RF_e	SFC_{FT}/ SFC_{FO}	CePV (MT CO_2e/ MT fuel)	Annual Fuel (MT)	WtW CO_2e (MT)
MGO (propulsion)	42.7	4.21	1	1	4.21	6,609	27,824
MGO (electrical)	42.7	4.21	1	1	4.21	543	2,593
						Total Tons CO_2e	*30,417*

Technology Implementation

The baseline ore bulk carrier is assumed to already have the following efficiency technologies included in its design:

- Antifouling coating on hull.
- Routine hull cleaning & maintenance.
- Controllable pitch propellers.

The following efficiency technologies were selected for implementation on the vessel:

1. Pre-swirl device: Schneekluth wake equalizing duct.
2. Post-swirl device: Kongsberg Promas bulb.
3. Rotor Sails: Anemoi rotors.

The efficiency technologies and their reduction factor RF_e characteristics for the vessel are provided in Table 119.

Table 119: Bulk carrier (Great Lakes) reduction factors RF_e

Technology	Energy Category	Operating Conditions	Propulsion % Reduction Base	Propulsion % Reduction Weighted*	Electrical % Reduction Base	Electrical % Reduction Weighted*
Pre-Swirl Device	Propulsion/ HFO	Maneuver	0.0%	0.0%	-	-
		Transit	-3.0%	-2.9%	-	-
Post-Swirl Device	Propulsion/ HFO	Maneuver	0.0%	0.0%	-	-
		Transit	-2.1%	-2.0%	-	-
Rotor Sails	Propulsion/ HFO	Transit	-8.0%	-7.7%	-	-
			% Reduction by Operating Condition		% Reduction by Operating Condition	
		Maneuver	0%		0%	
		Idle/anchor	0%		0%	
		Cargo ops	0%		0%	
		Transit	-12.2%		0%	
		Total % Reduction (∑)	**-12.2%**		**0.0%**	
		Total RF_e	**0.878**		**1.000**	

*Weighted % reduction is scaled based on the fraction of energy that is consumed for a given operating condition

Dual fuel ICEs burning methanol in gas mode was selected as a fuel technology for the propulsion engines. Green and gray methanol emission factors EF_f and specific fuel consumption SFC, assuming use in medium speed diesel (MSD) propulsion engines, are provided in Table 120. Pilot fuel is still required for combustion, so 5% of propulsion fuel consumption (by energy) remains as MGO, with the remaining 95% of propulsion fuel consumption being methanol. The values for EF_f in Table 120 account for this 95/5 ratio, represented as a composite value accordingly.

Table 120: Bulk carrier (Great Lakes) emission factors EF_f for green and gray methanol

Fuel	CO_2 EF_f, WtW[a] ($MT\ CO_2/MT$ fuel)	CO_2e EF_f, WtW* ($MT\ CO_2e/MT$ fuel)	SFC (g/kWh)	% of vessel consumption
Green CH_3OH (propulsion)	0.63	0.69	350	91
Gray CH_3OH (propulsion)	1.84	2.03	350	91

*EF_f values are a composite representing a 95/5 fuel ratio of CH_3OH to MGO.

Pre-Swirl Device

A Schneekluth wake equalizing duct (WED) was selected based on its significant uptake in bulk carriers of many sizes over the past 50 years. Ducts are readily retrofitted as they attached to the hull exterior, and bulk carriers on the Great Lakes are under less commercial pressure during drydock periods due to the annual winter shutdown of lake commerce. While up to 12% savings has been indicated by Schneekluth, MAN estimates WEDs to reduce propulsion energy required by 3 to 8%. In the case of a retrofit, the hull, propeller, and rudder interactions will not be optimized for installation, so savings will not be at a maximum.

- Energy category: propulsion, affecting prime mover consumption.
- Operating conditions: maneuvering and transit.
- Percent reduction: 0% while maneuvering, 3% while transiting at service speed of 14 kts.
    - Assumed percent reduction is reduced from Schneekluth's claim of 12% [B15].
    - Assumed negligible effect while maneuvering.

Post-Swirl Device

A Kongsberg Promas bulb was selected based on its suitability for deep draft vessels operating at speeds of 14 knots and up.

- Energy category: propulsion, affecting prime mover consumption.
- Operating conditions: maneuvering and transit.
- Percent reduction: 0% while maneuvering, 2.1% while transiting at service speed of 14 kts.
    - Assumed negligible effect while maneuvering.
    - Assumed percent reduction is based on Kongsberg data for a deep draft vessel with high block coefficient [B18].

Rotor Sails

Anemoi rotor sails were selected based on Anemoi's focus on bulk carriers, as well as the vessel's consistent trade route that sees reasonable wind speeds throughout the trade months. Four rotor sails were assumed, based on their being at least five holds with interstitial space. Anemoi's folding units make them suitable for installation on a bulker between cargo hatches. The rotor sails would possibly need to be located forward of the offloading conveyor truss to not interfere with cargo operations.

- Energy category: propulsion, affecting prime mover consumption.
- Operating conditions: transit.
- Percent reduction: 8% while transiting at service speed of 14 kts.
    - Assumed percent reduction is based on similar size vessel case study by Anemoi, reduced due to environmental conditions expected in Great Lakes [A141].

Dual Fuel ICE – Methanol in Gas Mode

Methanol fuel was selected as an alternative fuel for the 305-meter ore bulk carrier. At approximately 165 MT of MGO consumed per roundtrip by the propulsion engine in service mode, the equivalent mass of methanol would be 354 MT, or 404 m^3 of volume. This is well within the hull fuel tankage of the vessel. As discussed in the section on Methanol, 5% pilot fuel injection is assumed for both green and gray methanol combustion.

Methanol conversion may be reasonable for a bulk carrier on the Great Lakes in the next few years, either as a replacement for old propulsion engines, or retrofit for newer propulsion engines. The supply chain for methanol in the Great Lakes is not a certainty, but plants are located in Oregon, Ohio (Alpont) and Institute, Kentucky (Liberty One), the latter of which is expected to begin production in 2022. Both production facilities are focused on gray methanol sourced from natural gas. Plans for renewable, green methanol in the region are farther out, so a vessel would likely rely on gray methanol initially and may need to cycle with diesel while production scales up.

For the selected vessel, the four medium speed diesel, 2-stroke propulsion engines would be replaced with medium speed diesel, 4-stroke dual fuel engines burning methanol in gas mode. This is a more practical arrangement than switching to larger, modern 2-stroke engines.

The ship service diesel-generators are assumed to be high speed diesel, 4-stroke engines. With marine engine manufacturers not focusing on HSD engines, the vessel's diesel-generators would not convert to methanol, continuing to run on MGO. As such the emission factors achieved by switching to methanol only apply to propulsion fuel consumption, not electrical fuel consumption.

Improved Vessel Fuel Consumption, CO_2/CO_2e Performance Values, and Annual Emissions

The total reduction factors RF_e from Table 119 and the emission factors EF_f from Table 120 are applied to calculate improved vessel CPV and CePV values from implementing these measures on the vessel. CPV/CePV values are then used to calculate the annual tons CO_2 and CO_2e emitted after technology implementation. The results are provided in Table 121 and Table 122.

Improved Vessel CPV and Annual CO_2 Emissions

Table 121: Bulk carrier (Great Lakes) CPV and CO2 emissions, improved vessel

Fuel	LHV (MJ/kg)	EF_f, WtW* (MT CO_2/ MT fuel)	RF_e	SFC_{FT}/ SFC_{FO}	CPV (MT CO_2/ MT fuel)	Baseline Annual Fuel (MT)	WtW CO_2 (MT)
Green CH_3OH (propulsion)	19.9	0.63	0.878	1.75	0.96	6,609 (MGO)	6,345
Gray CH_3OH (propulsion)	19.9	1.84	0.878	1.75	2.83	6,609 (MGO)	18,703
MGO (electrical)	42.7	3.78	1.000	1.00	3.78	543 (MGO)	2,328
Total Tons CO_2 (using green CH_3OH)							*8,673*
Total Tons CO_2 (using gray CH_3OH)							*21,032*

*EF_f values for methanol are a composite representing a 95/5 fuel ratio of CH_3OH to MGO.

Improved Vessel CePV and Annual CO_2e Emissions

Table 122: Bulk carrier (Great Lakes) CePV and CO_2e emissions, improved vessel

Fuel	LHV (MJ/kg)	EF_f, WtW* (MT CO_2e/ MT fuel)	RF_e	SFC_{FT}/ SFC_{FO}	CePV (MT CO_2e/ MT fuel)	Baseline Annual Fuel (MT)	WtW CO_2e (MT)
Green CH_3OH (propulsion)	19.9	0.69	0.878	1.75	1.05	6,609 (MGO)	6,939
Gray CH_3OH (propulsion)	19.9	2.03	0.878	1.75	3.11	6,609 (MGO)	20,554
MGO (electrical)	42.7	3.78	1.00	1.00	4.21	543 (MGO)	2,593
Total Tons CO_2e (green CH_3OH for propulsion)							*9,533*
Total Tons CO_2e (gray CH_3OH for propulsion)							*23,147*

*EF_f values for methanol are a composite representing a 95/5 fuel ratio of CH_3OH to MGO.

GHG Intensity Reduction

The GHG intensity percent reductions by fuel and demand (propulsion green methanol and gray methanol, electrical MGO) and emission (CO_2 and CO_2e) for the 305-meter ore bulk carrier are provided in Table 123. The GHG intensity is reduced (indicated by a green negative value) for both green and gray CH_3OH propulsion, where the GHG intensity for electrical is unchanged, as the fuel type did not change.

Table 123: Bulk carrier (Great Lakes) GHG intensity percent reduction

Fuel (Demand)	Baseline CO_2 EF_f	Baseline CO_2e EF_f	Improved Vessel CPV	Improved Vessel CePV	CO_2 % Change	CO_2e % Change
Green CH_3OH (propulsion)	3.78	4.21	0.96	1.05	-75%	-75%
Gray CH_3OH (propulsion)	3.78	4.21	2.83	3.11	-25%	-26%
MGO (electrical)	3.78	4.21	3.78	4.21	0%	0%

Capital Expenditure (CapEx) and Operational Expenditure (OpEx)

CapEx

The selected efficiency and fuel technologies could have combined retrofit CapEx of approximately 25 to 42% of the original vessel cost. The repower of main propulsion engines with dual fuel ICE burning methanol, including replacement of fuel systems, exhaust modifications, safety systems, and tank coating for methanol protection, are all expected to be significant expenditures that would drive the overall cost of the vessel. The estimated CapEx impacts are provided in Table 124.

Table 124: Bulk carrier (Great Lakes) estimated CapEx

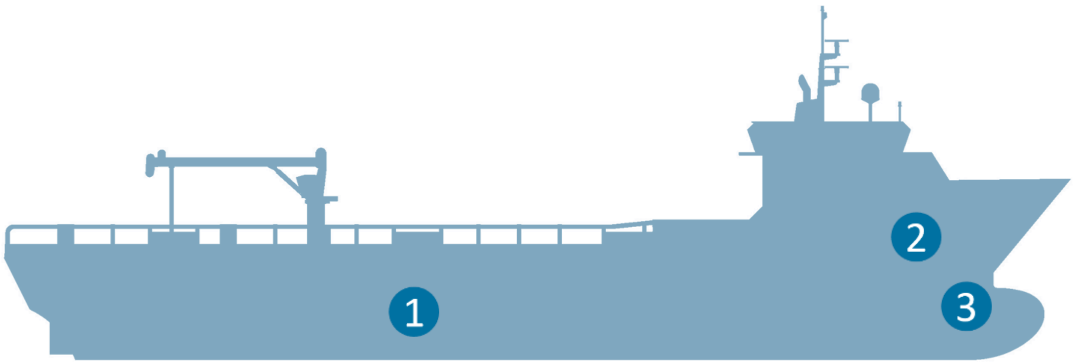
Category	Technology	CapEx (% of vessel cost)	CapEx Impact
Pre-swirl device	Wake equalizing duct	< 1%	Minor
Post-swirl device	Promas bulb	< 1%	Minor
Wind power	Rotor sails (4)	3-10%	Moderate/Significant
Methanol	Methanol ICE propulsion	20-30%	Significant
Total		*25% - 42%*	*Significant Cost*

OpEx

By switching from MGO to green or gray methanol for the propulsion engines, the relative price of each fuel will impact the change in OpEx for the vessel. The expected cost of methanol from any pathway will depend on the region of operation and broader industry and market factors at the time of implementation. Based on current pricing estimates, gray methanol may decrease or increase the operational cost ($0.010 to $0.020 per MJ, compared to $0.014 per MJ for MGO), whereas green methanol would certainly increase the operational cost ($0.035 to $0.081 per MJ). See the methanol sub-section on Integration & Cost for more fuel cost details.

The rotor sails will reduce the overall power required for propulsion, and therefore fuel, but will require additional maintenance as new, powered equipment that is located in the weather. Dual fuel ICE burning methanol, and their associated fuel systems are also expected to increase the OpEx of a vessel over the baseline diesel equipment.

Case Study 6: Offshore Supply Vessel



1 **Nanocoatings**

2 **Diesel-Electric Propulsion (DEP) with Variable Speed Generators (VSG)**

3 **Wave-Assisted Propulsion (Bow Foil)**

Overview

The vessel selected for Offshore Supply Vessel (OSV) is a 96-meter refueling vessel as a newbuild. OSVs and other offshore vessels represent 17% of US commercial self-propelled vessels. The vessel's operating region is the US Gulf Coast.

A summary of the vessel's decarbonization results compared to the vessel baseline is provided in Table 125. The selected efficiency technologies did not change the propulsion WtW GHG intensity, and increased the electrical WtW GHG intensity by 4.9%.

This case study demonstrates the importance of matching the technologies with the appropriate vessel type as well as operating profile. This OSV spends most of its time and fuel in transit. As a result, its GHG emissions performance does not benefit from a diesel-electric configuration using variable speed generators (VSG) in lieu of a conventional diesel-mechanical propulsion plant. A diesel-mechanical plant can be sized to operate at an optimal load for most transit conditions, without incurring electrical losses that come with an electrified VSG plant. If the VSGs weren't implemented, the combined energy reductions by nanocoating and bow foil technologies would have reduced the vessel's propulsion and overall WtW GHG intensity.

OSVs benefit from diesel-electric propulsion in several aspects apart from emissions reductions. Diesel-electric is more compatible with thrusters required for high levels of dynamic positioning performance. OSVs often have motorized deck handling equipment with large, intermittent loads. With a diesel-electric plant that has more generating power available in standby, intermittent thruster and deck equipment loads do not over-burden the electrical plant or require constant management to avoid ship service blackouts. Further, diesel-electric offers a high level of prime mover redundancy, increasing the reliability of OSVs operating offshore and enabling continued operations or safe return to port in the event of a one or multiple generator engines going offline.

Table 125: OSV results summary (WtW)

Parameter	Unit	Propulsion		Electrical	
		Baseline	Decarbonized Result	Baseline	Decarbonized Result
Fuel	-	MGO	MGO	MGO	MGO
CO_2 Emission Factor EF_f,	MT/MT	3.78	3.78	3.78	3.78
CO_2e Emission Factor EF_f,	MT/MT	4.21	4.21	4.21	4.21
Reduction Factor RF_e	-	1.00	1.00	1.00	1.05
CO_2 Performance Value CPV	MT/MT	3.78	3.78	3.78	3.97
CO_2e Performance Value CePV	MT/MT	4.21	4.21	4.21	4.42
Annual Fuel Consumption	MT	2,635	2,635	429	450

Parameter	Unit	Propulsion		Electrical	
		Baseline	Decarbonized Result	Baseline	Decarbonized Result
CO_2 Emissions	MT	9,960	9,960	1,622	1,703
CO_2e Emissions	MT	11,093	11,093	1,806	1,896
Total Emissions		**Baseline**		**Result**	
CO_2	MT	11,582		11,663	
CO_2e	MT	12,899		12,990	
GHG Intensity % Change		**Propulsion**		**Electrical**	
CO_2	%	0.0%		4.9%	
CO_2e	%	0.0%		5.0%	

Improved performance in green
Degraded performance in red

Vessel Particulars

The OSV particulars are provided in Table 126. This case study assumes the OSV is a newbuild construction.

Table 126: OSV particulars

Particular	Value	Notes
Capacity (GT)	4,900	
Length Overall	96 m	
Beam	20 m	
Draft (Load Line)	9 m	
Service Speed	13 knots	
Propulsion Plant		
Type	Diesel-mechanical	
Power	2 x 2,750 kW MCR	2 x four-stroke, high speed diesel
Fuel	MGO	
SFC (g/kWh)	185	Average value for all engine loads, from Fourth IMO GHG Study
Electrical Plant		
Type	Diesel-generators	AC switchboard
Power	2 x 900 kWe	2 x four-stroke, high speed diesel-generators
Fuel	MGO	
SFC (g/kWh)	185	Average value for all engine loads, from Fourth IMO GHG Study

Operating Profile

Operating Modes

The vessel's operating profile consists of two modes:

- SERVICE mode. Transporting supplies from New Orleans, LA multiple offshore sites in the Gulf of Mexico.

- IDLE mode. Extended idle, at dock, operating on shore power.

These operating modes are summarized in Table 127. Operating modes are detailed in Table 128 and Table 129, including all details necessary to estimate annual fuel consumption for the vessel.

Table 127: OSV operating modes overview

Mode	Description	Hours Per Cycle	Cycles Per Year	Equivalent Days Per Year
SERVICE	Gulf of Mexico offshore supply	144	50	300
IDLE	Extended idle, running on shore power (no fuel consumption onboard)	120	13	65

Table 128: Service mode details: Gulf of Mexico offshore supply

Location	Condition	Speed (kts)	Distance (nm)	Duration (hr)	Propulsion Load (bkW)	Electrical Load (bkW)
New Orleans, LA	Maneuver	4	2	0.5	550	450
	Canal transit	11	100	10	2,750	360
Gulf of Mexico	Gulf transit	13	550	42	3,850	405
	Maneuver	4	24	6	550	450
	On-station	0	0	12	550	1,080
	Gulf transit	13	200	15	3,850	405
New Orleans, LA	Canal transit	11	100	10	2,750	360
	Maneuver	4	2	0.5	550	450
	Dock	0	0	48	0	0
Total				144		

Table 129: Idle mode details: extended idle running on shore power, at dock

Location	Condition	Speed (kts)	Distance (nm)	Duration (hr)	Propulsion Load (bkW)	Electrical Load (bkW)
New Orleans, LA	Dock	0	0	120	0	0
Total				120		

Baseline Fuel Consumption, CO_2/CO_2e Performance Values, and Annual Emissions

Fuel Consumption

The estimated fuel consumption for each operating mode is calculated and provided in Table 130. The fuel per cycle and per year are both provided, based on the operating mode summary in Table 127.

These estimates are simplified, and apply the base SFC for each engine type across all operating modes. Actual fuel consumption will vary based on specific engine fuel curves and the engine loading at each operating condition.

Table 130: OSV fuel consumption by modes

Mode	Description	Propulsion - MGO (MT)		Electrical - MGO (MT)	
		per cycle	per year	per cycle	per year
SERVICE	NOLA/LB trade	52.7	2,635	8.6	429
IDLE	Extended idle	0	0	0	0
	Annual Total			*Tons MGO*	*3,064*

Baseline CPV and Annual CO_2 Emissions

The resulting CPV and tons CO_2 are summarized in Table 131. For calculating TtW emissions only, the value EF_f can be replaced with its TtW component: 3.21 for MGO.

Table 131: OSV annual CO_2 emissions, baseline

Fuel	LHV (MJ/kg)	EF_f, WtW (MT CO_2/ MT fuel)	RF_e	SFC_{FT}/ SFC_{FO}	CPV (MT CO_2/ MT fuel)	Annual Fuel (MT)	WtW CO_2 (MT)
MGO (propulsion)	42.7	3.78	1	1	3.78	2,635	9,960
MGO (electrical)	42.7	3.78	1	1	3.78	429	1,622
						Total Tons CO_2	*11,582*

Baseline CePV and Annual CO_2e Emissions

The resulting CePV and tons CO_2e are summarized in Table 132. For calculating TtW emissions only, the values EF_f can be replaced with its TtW component: 3.49 for MGO.

Table 132: OSV annual CO_2e emissions, baseline

Fuel	LHV (MJ/kg)	EF_f, WtW (MT CO_2e/ MT fuel)	RF_e	SFC_{FT}/ SFC_{FO}	CePV (MT CO_2e/ MT fuel)	Annual Fuel (MT)	WtW CO_2e (MT)
MGO (propulsion)	42.7	4.21	1	1	4.21	2,635	11,093
MGO (electrical)	42.7	4.21	1	1	4.21	429	1,806
						Total Tons CO_2e	*12,899*

Technology Implementation

The baseline OSV is assumed to already have the following efficiency technologies included in its design:

- Antifouling coating on hull.
- Routine hull cleaning & maintenance.
- Hull form optimization.
- CPP propellers.

The following efficiency technologies were selected for implementation on the vessel:

1. Nanocoatings: Nippon FASTAR coating.
2. Diesel-electric propulsion (DEP) coupled with variable speed generators (VSG), in place of diesel-mechanical propulsion: three 2,500 kW diesel-generators.
3. Wave-assisted propulsion: Wavefoil bow foil.

The efficiency technologies and their reduction factor RF_e characteristics for the vessel are provided in Table 133.

Table 133: OSV reduction factors RFe

Technology	Energy Category	Operating Conditions	Propulsion % Reduction Base	Propulsion % Reduction Weighted*	Electrical % Reduction Base	Electrical % Reduction Weighted*
Nanocoatings	Propulsion	Maneuver	0.0%	0.0%	-	-
		Canal transit	-4.0%	-0.8%	-	-
		Gulf transit	-5.0%	-3.9%	-	-
VSG	Propulsion & Electrical	Maneuver	+4.8%	+0.1%	-3.0%	0.0%
		Canal transit	+9.1%	+1.7%	+1.0%	+0.2%
		Gulf transit	+14.6%	+11.2%	+6.1%	+4.7%
		On-station	+10.0%	+0.2%	+1.9%	0.0%
Bow Foil	Propulsion	Gulf transit	-10.0%	-7.7%	-	-
			% Reduction by Operating Condition		**% Reduction by Operating Condition**	
		Maneuver	+0.1%		0.0%	
		Canal transit	1.0%		+0.2%	
		Gulf transit	-1.3%		+4.7%	
		On-station	+0.2%		0.0%	
		Total % Reduction (∑)	**0.0%**		**4.9%**	
		Total RF_e	**1.000**		**1.049**	

*Weighted % reduction is scaled based on the fraction of energy that is consumed for a given operating condition

As shown Table 133, VSG implementation actually results in positive values for percent reduction in some operating conditions, representing an increase in energy. For propulsion, this is offset by the nanocoatings and bow foil technologies. For electrical, VSG implementation results in a RF_e value over 1. Percent reduction and RF_e values for VSG power are determined based on the following assumptions and calculations:

- Two diesel propulsion engines and two diesel fixed-speed generators are replaced by three 2,500 kW diesel-generators configured for variable speed operation (VSG).
    - Relative specific fuel consumption (SFC) for VSG compared to fixed speed is determined based on the plot in Figure 39 on page 60.
    - New combined load for each operating condition, including propulsion and electrical, and resulting relative SFC due to speed matching with VSG:

Operating Condition	Total Load (kW)	VSG Generators Online	Capacity Online (kW)	VSG Relative SFC
Maneuver	1,000	1	2,500	91.5%
Canal transit	3,110	2	5,000	95.2%
Gulf transit	4,255	2	5,000	100%
On-station	1,630	1	2,500	96%

- All operating conditions: assumed that electricity for propulsion has increased losses over diesel-mechanical due to additional electronics required for diesel-electric operation, and electricity for the electrical plant also has increased losses due to conversions for VSG power.
    - Electrical losses (series) and resulting reduction factors:

ID	Component	Efficiency	
		Propulsion	Electrical
A	Alternator (VSG)	96.8%	
B	Switchboard rectifier (DC/AC)	98.0%	
C	Propulsion inverter (DC/AC)	96.3%	
D	VFD for propulsion (AC)	98.0%	
E	Propulsion motor – permanent magnet (AC)	97.5%	-
H	Ship service inverter (DC/AC)	-	95.3%
I	Ship service transformer (AC)	-	98.9%
$RF_e = 1/(A×B×C×D×E) =$		1.146	-
$RF_e = 1/(H×I) =$		-	1.061

- Relative SFC values for each operating condition are multiplied by RF_e values for VSG electrical losses (minus 1) to determine base percent reduction for each operating condition:

Propulsion Base % Reduction:

Operating Condition	VSG Relative SFC		Propulsion Losses RF_e		Base % Reduction
Maneuver	91.5%	×	1.146	-1 =	+4.8%
Canal transit	95.2%	×	1.146	-1 =	+9.1%
Gulf transit	100%	×	1.146	-1 =	+14.6%
On-station	96.0%	×	1.146	-1 =	+10.0%

Electrical Base % Reduction:

Operating Condition	VSG Relative SFC		Electrical Losses RF_e		Base % Reduction
maneuver	91.5%	×	1.061	-1 =	-3.0%
canal transit	95.2%	×	1.061	-1 =	+1.0%
gulf transit	100%	×	1.061	-1 =	+6.1%
on-station	96.0%	×	1.061	-1 =	+1.9%

No fuel technologies were selected for the OSV. Propulsion ICEs using methanol as fuel could be considered. However, methanol HSD (>900 rpm) engines are not as developed as MSD (300-900 rpm) and SSD (<300 rpm) engines in this vessel's power range, so methanol as an alternative fuel coupled with diesel-mechanical or diesel-electric propulsion is not a practical approach in the near-term.

Nanocoatings

Nanocoatings were selected based on their suitability for vessels that operate over long distances at consistent speeds. While the OSV is not continuously underway, 94% of its fuel consumption is at transit speeds of 11 to 13 knots. Nanocoatings are best-suited for newbuilds where they can be applied in tandem with an antifouling coating.

- Energy category: propulsion, affecting MGO consumption.
- Operating conditions: maneuvering and transit.

- Percent increase: 0% while maneuvering, 4% while transiting in canal, 5% while transiting in gulf.
  - Assumed percent reduction is reduced from Nippon Paint Holdings' claim of 8% [B4].
  - Assumed negligible effect while maneuvering.

Variable Speed Generators (VSG)

Three 2,500 kW VSGs were selected to replace the OSV's two main propulsion engines and two fixed-speed diesel-generators, including a DC bus and switchboard to enable integration of variable-speed generators. A change to the design's drive train was based on VSG's general compatibility with ocean/offshore service vessels. However, the operating profile of the OSV is not variable enough to gain appreciable benefits from VSG operation, and is penalized by the additional electrical losses required for DEP as well as VSG. This OSV consumes 94% of its fuel in continuous load transit, so the opportunity for matching generator rpm to combined propulsion and electrical load is limited.

- Energy category: propulsion and electrical, affecting MGO consumption.
- Operating conditions: all operating conditions were not connected to shore power.
- Percent increase (see assumptions and calculations in previous section):
  - +4.8% while maneuvering.
  - +9.1% while in canal transit.
  - +14.6% while in gulf transit.
  - +10.0% while on-station.

Wave-Assisted Propulsion (Bow Foil)

A Wavefoil, a type of bow foil, was selected based on the vessel's operation in the Gulf of Mexico, where it may see reasonable pitching motion. At 96 meters, the OSV is an appropriate length for the Wavefoil technology.

- Energy category: propulsion, affecting MGO consumption.
- Operating conditions: gulf transit only. Assumed bow foils are retracted in all other operating conditions.
- Percent reduction:
  - 10% while in gulf transit.

Improved Vessel Fuel Consumption, CO_2/CO_2e Performance Values, and Annual Emissions

The total reduction factors RF_e from Table 133 are applied to calculate improved vessel CPV and CePV values from implementing efficiency technologies on the vessel. CPV/CePV values are then used to calculate the annual tons CO_2 and CO_2e emitted after technology implementation. The results are provided in Table 134 and Table 135.

Due to a reduction factor value over 1, the tons CO_2 and tons CO_2e increased for the modified vessel design.

Improved Vessel CPV and Annual CO_2 Emissions

Table 134: OSV CPV and CO2 emissions, improved vessel

Fuel	LHV (MJ/kg)	EF_f, WtW (MT CO_2/ MT fuel)	RF_e	SFC_{FT}/ SFC_{FO}	CPV (MT CO_2/ MT fuel)	Baseline Annual Fuel (MT)	WtW CO_2 (MT)
MGO (propulsion)	42.7	3.78	1.000	1	3.78	2,635	9,960
MGO (electrical)	42.7	3.78	1.049	1	3.97	429	1,703
						Total Tons CO_2	*11,663*

Link to Guide Navigator

Improved Vessel CePV and Annual CO_2e Emissions

Table 135: OSV CePV and CO_2e emissions, improved vessel

Fuel	LHV (MJ/kg)	EF_f, WtW (MT CO_2e/ MT fuel)	RF_e	SFC_{FT}/ SFC_{FO}	CePV (MT CO_2e/ MT fuel)	Baseline Annual Fuel (MT)	WtW CO_2e (MT)
MGO (propulsion)	42.7	4.21	1.000	1	4.21	2,635	11,093
MGO (electrical)	42.7	4.21	1.049	1	4.42	429	1,896
						Total Tons CO_2e	*12,990*

GHG Intensity Reduction

The GHG intensity percent reductions by energy demand (propulsion and electrical) and emission (CO_2 and CO_2e) for the OSV are provided in Table 136. The GHG intensity did not change for propulsion energy, whereas the GHG intensity increased for electrical energy (indicated by a red positive value). The energy penalty of incorporating VSG power outweighed the efficiencies gained by optimal engine loading, as well as nanocoating and bow foil technologies.

Table 136: OSV GHG intensity reduction, WtW

Demand	Baseline CO_2 EF_f	Baseline CO_2e EF_f	Improved Vessel CPV	Improved Vessel CePV	CO_2 % Change	CO_2e % Change
Propulsion	3.78	4.21	3.78	4.21	0%	0%
Electrical	3.78	4.21	3.97	4.42	4.9%	5.0%

Capital Expenditure (CapEx) and Operational Expenditure (OpEx)

CapEx

The selected efficiency technologies could have combined CapEx of approximately 22% to 36% of the original vessel cost. The estimated CapEx impacts are provided in Table 137.

Table 137: OSV estimated CapEx

Category	Technology	CapEx (% of vessel cost)	CapEx Impact
Hull coating	Nanocoating	< 1%	Minor
Propulsion	DEP with VSG	20-30%	Significant
Wave power	Bow foil	1-5%	Moderate
Total		*22% - 36%*	*Significant Cost*

OpEx

The selected efficiency technologies are estimated to increase fuel by 0.7% annually, having a minor increase on OpEx. The estimated fuel change is provided in Table 138. This is due to the added energy penalty of electrical losses in the diesel-electric/variable speed propulsion system, offsetting savings from nanocoatings and bow foil implementation.

Table 138: OSV estimated OpEx impact

Annual Fuel Baseline (MT)	Annual Fuel Improved Vessel (MT)	Fuel Expense Change	OpEx Impact
3,064	3,084	+0.7%	Minor Added Cost

Concluding Remarks

Maritime energy efficiency technologies and decarbonization solutions comprise a dynamic landscape. This guide provides both a snapshot of that landscape, as well a forward view of what energy efficiency and decarbonization solutions will reach maturity and gain adoption in near- and mid-term timelines. However, the evolving landscape will prove some technologies to become obsolete, while others that are not broadly known today may see rapid development and uptake in that same near- and mid-term timeline.

The developers of this guide seek to maintain a record of technology developers and vessel deployments, and periodically update this guide every three to five years to reflect new and upcoming advancements across the marine industry.

Corrections, suggestions for additional content, and owner/operator insight on implemented technologies may be provided by email to decarbonizationguide@glosten.com, and will be considered for future updates.

Appendices

Appendix A: References

[Link to Online List with Hyperlinks]

Appendix B: Technologies

[Link to Online List with Hyperlinks]

Appendix C: Deployments

[Link to Online List with Hyperlinks]

Appendix A: References (hyperlinks available online)

#	Name	Organization	Author(s)	Document #	Version/Date	Online Location
1	Prevention of Air Pollution from Ships	IMO				Webpage
2	Denmark, U.S. and 12 other nations back tougher climate goal for shipping	Reuters	Abnett, K., Saul, J., Filks, I.		2 November 2021	Webpage
3	2018 Guidelines on the Method of Calculation of the Attained Energy Efficiency Design Index (EEDI) for New Ships	IMO		MEPC.308(73)	26 October 2018	Sharefile Doc
4	Amendments to the 2018 Guidelines on the Method of Calculation of the Attained Energy Efficiency Design Index (EEDI) for New Ships	IMO		MEPC.322(74)	17 May 2019	Sharefile Doc
5	Amendments to the 2018 Guidelines on the Method of Calculation of the Attained Energy Efficiency Design Index (EEDI) for New Ships	IMO		MEPC.332(76)	17 June 2021	Sharefile Doc
6	2021 Revised MARPOL Annex VI	IMO		MEPC.328(76)	17 June 2021	Sharefile Doc
7	Amendments to the Annex of the Protocol of 1997 to Amend the International Convention for the Prevention of Pollution from Ships, 1973, as Modified by the Protocol of 1978 Relating Thereto	IMO		MEPC.203(62)	15 July 2011	Sharefile Doc
8	Report of the Marine Environmental Protection Committee on its Seventy-Eighth Session	IMO		MEPC 78/17	1 July 2022	Sharefile Doc
9	2021 Guidelines on the Operational Carbon Intensity Reduction Factors Relative to Reference Lines (CII Reduction Factors Guidelines, G3)	IMO		MEPC.338(76)	17 June 2021	Sharefile Doc
10	EU Emissions Trading System (EU ETS): Revision for phase 4 (2021-2030)	European Commission				Webpage
11	International Shipping: The Norwegian NOx Fund	Environmental Defense Fund (EDF)	Bektas, C., Hubatova, M., O'Leary, A.			Sharefile Doc
12	Emission reductions through the Norwegian NOx Fund	The Norwegian NOx Fund	Johnsen, T.			Sharefile Doc

#	Name	Organization	Author(s)	Document #	Version/Date	Online Location
13	ICS Renews Decarbonization Debate Supporting Carbon Tax on Shipping	The Maritime Executive			6 September 2021	Webpage
14	Is a Global Maritime Carbon Levy on the Horizon? Why Companies Should be Paying Attention to the IMO Proposals and Preparing for Potential Supply Chain Disruption	Steptoe Global Trade Policy Blog	Schachter, C., Weiss, J.		24 September 2021	Webpage
15	Poseidon Principles Signatories	Poseidon Principles			accessed October 2022	Webpage
16	Global shipping fleet value hits all time high of $1.2 trillion	Seatrade Maritime News	Glass, D.		27 August 2021	Webpage
17	Sea Cargo Charter Signatories	Sea Cargo Charter			accessed October 2022	Webpage
18	Fourth IMO Greenhouse Gas Study 2020	IMO			2021	Sharefile Doc
19	Technology Readiness Assessment Guide	US Government Accountability Office (GAO)		GAO-20-48G	January 2020	Sharefile Doc
20	Neste Renewable Diesel Handbook	Neste			October 2020	Sharefile Doc
21	Initial IMO Strategy on Reduction of GHG Emissions from Ships	IMO		MEPC.304(72)	13 April 2018	Sharefile Doc
22	Anti-fouling systems	IMO			accessed October 2022	Webpage
23	Hull Coating	Global Maritime Energy Efficiency Partnerships (GloMEEP)			accessed October 2022	Webpage
24	Effects of coating roughness and biofouling on ship resistance and powering	Biofouling: The Journal of Bioadhesion and Biofilm Research	Schultz, M.		23(5), 2007	Sharefile Doc
25	This underwater robot cleans ships to cut emissions and protect marine ecosystems	World Economic Forum	Broom, D.		14 January 2021	Webpage

#	Name	Organization	Author(s)	Document #	Version/Date	Online Location
26	The energy efficiency effects of periodic ship hull cleaning	Journal of Cleaner Production	Cariou, P., Jia, H., Wolff, F.C.		March 2018	Sharefile Doc
27	Hull Design Boosts Fuel Economy of Ultra Large Container Ships	The Maritime Executive			5 September 2012	Webpage
28	Eco Valencia saves 5.1 pct in fuel with Silverstream's air lubrication	Offshore Energy	Mandra, J.		25 March 2021	Webpage
29	Silverstream Air Lubrication Technology Delivers Significant Energy Savings	Lloyd's Register, Shell			4 February 2021	Sharefile Doc
30	Air Lubrication Technology	ABS			1 April 2019	Sharefile Doc
31	Fuel and financial savings for operators of small fishing vessels	FAO Fisheries Technical Paper	Wilson, J.D.K.	no. 383	1999	Sharefile Doc
32	Wärtsilä propeller solutions enable energy savings through slow steaming	Wartsila			9 December 2020	Webpage
33	Propulsion Efficiency Upgrade with a High Performance Nozzle	Wartsila			2015	Sharefile Doc
34	Power Pods: Thrusters maximize fuel efficiency	National Fisherman	Molyneaux, P.		22 December 2021	Webpage
35	Propeller and Aft Ship solutions	MAN Energy Solutions				Sharefile Doc
36	A New Energy Saving Twin Rudder System - Gate Rudder	Newcastle University	Turkmen, S., Carchen, A., Sasaki, N., Atlar, M.		November 2016	Sharefile Doc
37	Promas	Kongsberg			9 October 2015	Sharefile Doc
38	Contributions to Global Environmental Conservation: The PBCF	Mitsui O.S.K. Lines			3 March 2021	Webpage
39	PBCF Frequently Asked Questions	PBCF			accessed October 2022	Webpage
40	Improved Fuel-Use Efficiency in Diesel—Electric Tugboats With an Asynchronous Power Generating Unit	IEEE Transactions on Transportation Electrification	Kumar, B., Selvaraj, R., Chelliah, T., Ramesh, U.S.	Vol. 5, No. 2	2 June 2019	Sharefile Doc

#	Name	Organization	Author(s)	Document #	Version/Date	Online Location
41	Shaft generators for low speed main engines	MAN Energy Solutions				Sharefile Doc
42	Wartsila HY TUG propulsion system	Wartsila	Waage, R., Myhre, R., Eijnatten, J., Nones, C.		2018	Sharefile Doc
43	Motor Project Final Report	ECM PCB Stator Technology			14 June 2019	Sharefile Doc
44	Guide for Hybrid Electric Power Systems for Marine and Offshore Applications	ABS			February 2022	Sharefile Doc
45	Practical Considerations for Hybrid Electric Power Systems Onboard Vessels	ABS			April 2022	Sharefile Doc
46	Electric power transmission and distribution losses (% of output)	The World Bank			accessed October 2022	Webpage
47	Electricity Data Browser	U.S. Energy Information Administration			accessed October 2022	Webpage
48	Batteries on board ocean-going vessels	MAN Energy Solutions				Sharefile Doc
49	A guide to use of batteries in shipping	DNV				Sharefile Doc
50	Guide for Lithium-ion Batteries in the Marine and Offshore Industries	ABS			January 2022	Sharefile Doc
51	Design Guidance for Lithium-Ion Battery Installations Onboard Commercial Vessels	USCG CG-ENG		Policy Letter No. 02-19	2 October 2019	Sharefile Doc
52	Quick-Reference Guide for Development of Shore-Side Electricity/Ops in Maritime Ports	EMSA				Sharefile Doc
53	ABS Advisory on Hybrid Electric Power Systems	ABS			2017	Sharefile Doc
54	Superconducting magnetic energy storage (SMES)	UN Climate Technology Centre & Network			accessed October 2022	Webpage

#	Name	Organization	Author(s)	Document #	Version/Date	Online Location
55	Waste Heat Recovery System (WHRS)	MAN Diesel & Turbo				Sharefile Doc
56	A review of the use of organic Rankine cycle power systems for maritime applications	Renewable and Sustainable Energy Reviews	Mondejar, M.E., Andreasen, J.G., Pierobon, L., Larsen, U., Thern, M., Haglind, F.	Volume 91	August 2018	Sharefile Doc
57	Climeon Introduces Next-Gen WHR Technology: HeatPower 300 Marine	gCaptain			8 May 2022	Webpage
58	Waste Heat Recovery on the Training Ship Golden Bear	Naval Postgraduate School	Hahn, E.		2020	Webpage
59	Energy efficiency guide: the other alternative fuel	ABB				Sharefile Doc
60	HVAC&R | Cruise Ships	Heinen & Hopman			accessed October 2022	Webpage
61	Demonstration of an innovative wind propulsion technology for cargo vessels	European Commission, WINTECC			accessed October 2022	Webpage
62	First Automated Kite Sail Installed to Begin Ship Trials in 2022	The Maritime Executive			14 December 2021	Webpage
63	Seawing kite system approved by ClassNK	Offshore Energy	Mandra, J.		19 August 2020	Webpage
64	Timberwolf (ex Maersk Pelican)	Norsepower			accessed October 2022	Webpage
65	DNV GL issues Norsepower first-ever design type approval for onboard wind propulsion system	Norsepower			5 March 2018	Webpage
66	DSME and DNV Partner to Develop and Promote Wind Rotor	The Maritime Executive			6 September 2022	Webpage
67	Wind Propulsion for Dry Bulk Carriers	Oldendorff			26 January 2021	Webpage
68	Norsepower Rotor Sail technology	Norsepower				Sharefile Doc
69	Ventifoil Retrofit	Econowind				Sharefile Doc
70	Wavefoil and IP Huse to co-operate in bow foil manufacturer	ShipInsight			17 August 2021	Webpage

#	Name	Organization	Author(s)	Document #	Version/Date	Online Location
71	Comparison of Alternative Marine Fuels	DNV			5 July 2019	Sharefile Doc
72	The climate implications of using LNG as a marine fuel	International Council on Clean Transportation (ICCT)	Pavlenko, N., Comer, B., Zhou, Y., Clark, N.		January 2020	Sharefile Doc
73	Hydrocarbon gas liquids explained	U.S. Energy Information Administration			accessed October 2022	Webpage
74	Ammonia as a marine fuel, Risks and perspectives	Oeko-Institu e.V.	Cames, M., Wissner, N., Sutter, J.		June 2021	Sharefile Doc
75	Hydrogen Tracking Report	International Energy Agency (IEA)	Bermudez, J., Evangelopoulou, S., Pavan, F.		September 2022	Webpage
76	Sustainability Whitepaper: Hydrogen as Marine Fuel	ABS			June 2021	Sharefile Doc
77	Carbon capture, utilisation and storage	International Energy Agency (IEA)			accessed October 2022	Webpage
78	IGF Code	IMO			1 January 2017	Sharefile Doc
79	Life Cycle Assessment of LNG Fueled Vessel in Domestic Services	Journal of Marine Science and Engineering	Hwang, S., Jeong, B., Jung, K., Kim, M., Zhou, P.		10 October 2019	Sharefile Doc
80	Fuel Cell	Air Liquide			accessed October 2022	Webpage
81	Update: Accounting for well-to-wake carbon dioxide equivalent emissions in maritime transportation climate policies	International Council on Clean Transportation (ICCT)	Comer, B., Osipova, L.		August 2021	Sharefile Doc
82	Guidelines for the Approval of Alternatives and Equivalents as Provided for in Various IMO Instruments	IMO			24 June 2013	Sharefile Doc
83	IPCEI Green Hydrogen @ Blue Danube	Hydrogenious LOHC			accessed October 2022	Webpage

#	Name	Organization	Author(s)	Document #	Version/Date	Online Location
84	Hydrogen Shot	U.S. DOE, Hydrogen and Fuel Cell Technologies Office			accessed October 2022	Webpage
85	Global Hydrogen Review	International Energy Agency (IEA)			November 2021	Sharefile Doc
86	Hydrogen Webpage	International Energy Agency (IEA)			accessed October 2022	Webpage
87	Handbook for Hydrogen-Fuelled Vessels	DNV			June 2021	Sharefile Doc
88	Sustainability White Paper: Ammonia as a Marine Fuel	ABS			October 2020	Sharefile Doc
89	Ammonia: zero-carbon fertiliser, fuel, and energy storage: policy briefing	The Royal Society			2020	Sharefile Doc
90	Guide for Ammonia Fueled Vessels	ABS			September 2021	Sharefile Doc
91	Setting the Course to Low Carbon Shipping II: Pathways to Sustainable Shipping	ABS				Sharefile Doc
92	Setting the Course to Low Carbon Shipping III: View of the Value Chain	ABS				Sharefile Doc
93	Wartsila and Eidesvik Offshore to cooperate in world's first ammonia conversion project	Wartsila			8 October 2021	Webpage
94	Demonstration Project Begins for Commercialization of Vessels Equipped with Domestically Produced Ammonia-Fueled Engine	NYK Line			26 October 2021	Webpage
95	Ammonia as a Marine Fuel	DNV			2020	Sharefile Doc
96	Greenhouse Gases, Regulated Emissions, and Energy use in Technologies (GREET) Model	Argonne National Laboratory			accessed October 2022	Webpage

#	Name	Organization	Author(s)	Document #	Version/Date	Online Location
97	The potential of liquid biofuels in reducing ship emissions	International Council on Clean Transportation (ICCT)	Zhou, Y., Pavlenko, N., Rutherford, D., Osipova, L., Comer, B.		September 2020	Sharefile Doc
98	Sustainability Whitepaper: Biofuels as Marine Fuel	ABS			May 2021	Sharefile Doc
99	Corn and soybean production up in 2021, USDA Reports...	USDA National Agricultural Statistics Service			12 January 2022	Webpage
100	Transforming Corn Stover to Useful Transport Fuel Blends in Resource-Limited Settings	Makerere University	Munu, N., Banadda, N., Kiggundu, N., Zziwa, A., Kabenge, I.		22 January 2021	Sharefile Doc
101	Fischer-Tropsch Diesel and Biofuels Exergy and Energy Analysis for Low Emissions Vehicles	MDPI: applied sciences	Torres, F., Doustdar, O., Herreros, J., Li, R., Poku, R., Tsolakis, A., Martins, J., Vieira de Melo, S.		26 June 2021	Sharefile Doc
102	Advanced Biofuels - Potential for Cost Reduction	IEA Technology Collaboration Programme	Brown, A., Waldheim, L., Landalv, I., Saddler, J., Ebadian, M., McMillan, J., Bonomi, A., Bruno, K.		January 2020	Sharefile Doc
103	Sustainability Whitepaper: Methanol as Marine Fuel	ABS			February 2021	Sharefile Doc
104	Immediately Dangerous to Life or Health (IDLH) Values: Methyl alcohol	The National Institute for Occupational Safety and Health (NIOSH)			May 1994	Sharefile Doc
105	The Methanol-fuelled MAN B&W LGIM	MAN Energy Solution				Sharefile Doc
106	Innovation Outlook: Renewable Methanol	International Renewable Energy Agency			2021	Sharefile Doc
107	Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel	IMO		MSC.1/CIrc.16 21	7 December 2020	Sharefile Doc

#	Name	Organization	Author(s)	Document #	Version/Date	Online Location
108	Compatibility of Metals & Alloys in Neat Methanol Service	Methanol Institute				Sharefile Doc
109	Guide for Methanol and Ethanol Fueled Vessels	ABS			January 2020	Sharefile Doc
110	WasteFuel and Maersk Announce Landmark Agreement Accelerating Shipping Industry Decarbonisation	Business Wire			10 March 2022	Webpage
111	eMethanol for the masses	The Royal Institute of Naval Architechts			May/June 2021	Webpage
112	Additional Resources on Methanol as a Marine Fuel	Methanol Institute			accessed October 2022	Webpage
113	Methane Number	Clark Energy			accessed October 2022	Webpage
114	Hydrogen Use in Internal Combustion Engines	College of the Desert		Module 3	Revision 0, December 2001	Sharefile Doc
115	A Review on Combustion Characteristics of Ammonia as a Carbon-Free Fuel	Frontiers in Energy Research	Li, J., Lai, S., Chen, D., Wu, R., Kobayashi, N., Deng, L., Huang, H.		6 October 2021	Webpage
116	Fuel Cell Fact Sheet	U.S. DOE, Fuel Cell Technologies Program				Sharefile Doc
117	Types of Fuel Cells	U.S. DOE, Hydrogen and Fuel Cell Technologies Office			accessed October 2022	Webpage
118	Fuel Cell Power Systems for Maritime Applications: Progress and Perspective	MDPI: sustainability	Xing, H., Stuart, C., Spence, S., Chen, H.		24 January 2021	Sharefile Doc
119	Guide for Fuel Cell Power Systems for Marine and Offshore Applications	ABS			November 2021	Sharefile Doc
120	Rules for Classification, Part 6 Additional class notations	DNV			October 2019	Sharefile Doc
121	Interim Guidelines for the Safety of Ships Using Fuel Cell Power Installations	IMO		MSC.1/Circ.1647	15 June 2022	Sharefile Doc

#	Name	Organization	Author(s)	Document #	Version/Date	Online Location
122	Fuel Cell Handbook	EG&G Technical Services, Inc.			Seventh Edition, November 2004	Sharefile Doc
123	Study on the Use of Fuel Cells in Shipping	DNV/EMSA			Version 0.1	Sharefile Doc
124	Guide for Gas and Other Low-Flashpoint Fuel Ready Vessels	ABS			March 2022	Sharefile Doc
125	Cryogenic Carbon Capture Development	Sustainable Energy Solutions and NETL	Baxter, L.	NETL FE-0028697	August 2017	Webpage
126	Is Carbon Capture on Ships Feasible?	Oil and Gas Climate Initiative			November 2021	Sharefile Doc
127	Evaluation of the Marine Application of Advanced Carbon Capture Technology	PMW Technology		Version v1.1	8 July 2020	Sharefile Doc
128	Review of amine emissions from carbon capture systems	Scottish Environment Protection Agency		Version 2.01	August 2015	Sharefile Doc
129	Overview of "CC-Ocean" project	Mitsubishi Heavy Industries			July 2021	Sharefile Doc
130	Cryogenic Carbon Capture (CCC) Status Report	Sustainable Energy Solutions	Baxter, L.		March 2021	Sharefile Doc
131	Carbon Capture, Utilization and Storage	ABS			August 2021	Sharefile Doc
132	A review of large-scale CO2 shipping and marine emissions management for carbon capture, utilisation and storage	Elsevier Applied Energy	Al Baroudi, H., Awoyomi, A., Patchigolla, K., Jonnalagadda, K., Anthony, E.J.	Applied Energy 287	2021	Sharefile Doc
133	How Low Can They Go?	Power Engineering	Hansen, T.		1 August 2008	Webpage
134	TerraPower's Molten Chloride Fast Reactor (MCFR)	TerraPower	Latkowski, J.		22 February 2021	Sharefile Doc
135	Rules and regulations	Core Power			accessed October 2022	Webpage
136	National Transportation Statistics 50th Anniversary Edition: 2021	U.S. Department of Transportation			30 November 2021	Sharefile Doc

#	Name	Organization	Author(s)	Document #	Version/Date	Online Location
137	National Transportation Statistics 50th Anniversary Edition: 2021, Chapter 1	U.S. Department of Transportation			30 November 2021	Sharefile Doc
138	Great Lakes-St. Lawrence Seaway ship emissions inventory, 2019	International Council on Clean Transportation (ICCT)	Meng, Z., Comer, B.		March 2022	Sharefile Doc
139	Fuel Savings	Schneekluth Hydrodynamik			accessed October 2022	Webpage
140	Hornblower Received $8M Grant to Develop Hydrogen Fueling Station	The Maritime Executive			5 May 2022	Webpage
141	Rotor Sails for Bulk Carrier	Anemoi			accessed October 2022	Webpage

Appendix B: Technologies (hyperlinks available online)

#	Name	EE or FT	Technology	Notes	Online Location
1	Selektope	Energy Efficiency (EE)	Antifouling Coatings	Selective biocide	Webpage
2	Selektope (testimonials)	Energy Efficiency (EE)	Antifouling Coatings	selective biocide	Webpage
3	Nano-Clear Coatings	Energy Efficiency (EE)	Nanocoatings		Webpage
4	Nippon FASTAR	Energy Efficiency (EE)	Nanocoatings		Webpage
5	Fleet Cleaner	Energy Efficiency (EE)	Hull Cleaning and Maintenance	Robotic hull cleaner	Webpage
6	HullWiper	Energy Efficiency (EE)	Hull Cleaning and Maintenance	Robotic hull cleaner	Webpage
7	Silverstream Technologies	Energy Efficiency (EE)	Air Lubrication		Webpage
8	SES-X Technologies	Energy Efficiency (EE)	Air Lubrication	Air cushion, electric boats	Webpage
9	MAITA Propeller (Oshima Shipbuilding)	Energy Efficiency (EE)	Propellers	large diameter/low speed	Webpage
10	ABB Azipod	Energy Efficiency (EE)	Propellers	Podded propulsor	Webpage
11	Wartsila EnergoFlow	Energy Efficiency (EE)	Pre-Swirl Devices	Pre-swirl stator	Webpage
12	Becker Mewis Duct	Energy Efficiency (EE)	Pre-Swirl Devices	Pre-swirl duct	Webpage
13	Kawasaki SDS-F	Energy Efficiency (EE)	Pre-Swirl Devices	Semi-duct with contra fins	Webpage
14	Sanoyas Tandem Fin (STF)	Energy Efficiency (EE)	Pre-Swirl Devices	Pre-swirl stator	Webpage
15	Schneekluth Hydrodynamik	Energy Efficiency (EE)	Pre-Swirl Devices	Wake equalizing duct	Webpage
16	Van der Velden Asymmetric Rudder Technology (ART)	Energy Efficiency (EE)	Post-Swirl Devices	Asymmetric rudder	Webpage
17	Kamome Gate Rudder System	Energy Efficiency (EE)	Post-Swirl Devices	Gate rudder	Webpage
18	Kongsberg Promas Propulsion	Energy Efficiency (EE)	Post-Swirl Devices	Costa bulb	Webpage
19	Brunvoll Integrated Costa Propulsion	Energy Efficiency (EE)	Post-Swirl Devices	Costa bulb	Webpage
20	PBCF	Energy Efficiency (EE)	Post-Swirl Devices	Propeller boss cap fin (PBCF)	Webpage

#	Name	EE or FT	Technology	Notes	Online Location
21	Damen Silent Bulb	Energy Efficiency (EE)	Post-Swirl Devices	Costa bulb	Webpage
22	Ingeteam Complete Integrated Marine Solutions	Energy Efficiency (EE)	Diesel-Electric Propulsion Variable Speed Generator PTO/PTI	Propulsion and power generation solutions	Sharefile Doc
23	SeaGreen PTO/PTI	Energy Efficiency (EE)	PTO/PTI		Webpage
24	Cat Hybrid Propulsion System	Energy Efficiency (EE)	PTO/PTI	Booster motor PTI	Webpage
25	Wartsila Shaft Generators	Energy Efficiency (EE)	PTO/PTI		Webpage
26	Wartsila Shaft Generators (infograph)	Energy Efficiency (EE)	PTO/PTI		Webpage
27	Magnomatics Magnetically Geared Thrusters	Energy Efficiency (EE)	Magnetic Gearing		Webpage
28	Magnomatic Industry Solutions	Energy Efficiency (EE)	Magnetic Gearing		Webpage
29	ECM PCB Stator Technology	Energy Efficiency (EE)	PCB Stator Motor		Webpage
30	Maersk Stillstrom	Energy Efficiency (EE)	Electrical Energy Storage		Webpage
31	Twin Disc Hybrid Solutions	Energy Efficiency (EE)	Hybrid Mechanical/Electrical		Webpage
32	Praxis Automation Technology Green Battery	Energy Efficiency (EE)	Battery (All-Electric)	LFP, DNV type approved	Webpage
33	Eos Znyth battery system	Energy Efficiency (EE)	Battery (All-Electric)	zync hybrid cathode	Webpage
34	PortLiner battery system	Energy Efficiency (EE)	Battery (All-Electric)	Vanadium redox flow	Webpage
35	Corvus Energy	Energy Efficiency (EE)	Battery (All-Electric)	Li-ion, DNV type approved	Webpage
36	Leclanche Energy Storage Solutions	Energy Efficiency (EE)	Battery (All-Electric)	Li-ion, DNV type approved	Webpage
37	Spear Power Systems	Energy Efficiency (EE)	Battery (All-Electric)	Li-ion, DNV type approved	Webpage
38	Becker Marine Systems Cobra Compact Battery Rack	Energy Efficiency (EE)	Battery (All-Electric)	LFP, DNV type approved	Webpage
39	Cavotec Shore Power	Energy Efficiency (EE)	Shore Power		Webpage
40	Alfa Laval E-PowerPack	Energy Efficiency (EE)	Waste Heat Recovery	Organic Rankine Cycle	Sharefile Doc

#	Name	EE or FT	Technology	Notes	Online Location
41	Climeon HeatPower 300	Energy Efficiency (EE)	Waste Heat Recovery	Organic Rankine Cycle	Webpage
42	Echogen Power Systems	Energy Efficiency (EE)	Waste Heat Recovery	Supercritical CO2 system	Webpage
43	MHI Waste Heat Recovery Systems	Energy Efficiency (EE)	Waste Heat Recovery		Webpage
44	DRI Heat Recovery Wheel	Energy Efficiency (EE)	HVAC Optimization	Enthalpy wheel	Sharefile Doc
45	Desiccant Rotors	Energy Efficiency (EE)	HVAC Optimization	Enthalpy wheel	Webpage
46	HVACON TimeSchedule and Energy Saving System programs	Energy Efficiency (EE)	HVAC Optimization	Smart HVAC control	Webpage
47	Black Sun Heating	Energy Efficiency (EE)	HVAC Optimization	Infrared heating	Webpage
48	SkySails	Energy Efficiency (EE)	Kite Sail		Webpage
49	Airseas Seawing	Energy Efficiency (EE)	Kite Sail		Webpage
50	Norsepower	Energy Efficiency (EE)	Rotor Sail	DNV type approval	Webpage
51	Anemoi	Energy Efficiency (EE)	Rotor Sail	RINA AiP	Webpage
52	DSME rotor sail system	Energy Efficiency (EE)	Rotor Sail	DNV AiP	Webpage
53	Eco Marine Power Aquarius MRE	Energy Efficiency (EE)	Rigid Wingsail		Webpage
54	Wallenius Wilhelmsen Orcelle Wind	Energy Efficiency (EE)	Rigid Wingsail	Coupled with RoRo concept	Webpage
55	Wallenius Wilhelmsen Ocean Bird	Energy Efficiency (EE)	Rigid Wingsail	Coupled with cargo ship concept	Webpage
56	Windship	Energy Efficiency (EE)	Rigid Wingsail		Webpage
57	Econowind Ventifoil	Energy Efficiency (EE)	Rigid Wingsail	Foldable technology	Webpage
58	MOL "Wind Challenger"	Energy Efficiency (EE)	Rigid Wingsail	ClassNK AiP	Webpage
59	Neoline/Michelin Neoliner	Energy Efficiency (EE)	Flexible Sail		Webpage
60	Dykstra WASP	Energy Efficiency (EE)	Flexible Sail		Webpage

#	Name	EE or FT	Technology	Notes	Online Location
61	Michelin WISAMO	Energy Efficiency (EE)	Inflatable Sail		Webpage
62	Inflated Wing Sails	Energy Efficiency (EE)	Inflatable Sail		Webpage
63	Wavefoil	Energy Efficiency (EE)	Wave-Assisted Propulsion		Webpage
64	Ocius Solar Sail	Energy Efficiency (EE)	Solar Power		Webpage
65	NYK Super Eco Ship 2050	Energy Efficiency (EE)	Solar Power		Sharefile Doc
66	BeHydro Hydrogen Marine Engines	Fuel Technology (FT)	Hydrogen ICE		Webpage
67	MAN B&W LGIM methanol-fuelled 2-stroke engine	Fuel Technology (FT)	Methanol ICE		Sharefile Doc
68	Wartsila Future Fuels Conversion Platform	Fuel Technology (FT)	Methanol ICE		Webpage
69	J-ENG Ammonia-fueled engine, Hydrogen-fueled engine	Fuel Technology (FT)	Hydrogen Ammonia ICE		Webpage
70	MAN ES hydrogen-fueled engine developments	Fuel Technology (FT)	Hydrogen ICE		Webpage
71	Wartsila hydrogen-fueled engine developments	Fuel Technology (FT)	Hydrogen ICE		Webpage
72	Wartsila hydrogen and ammonia test program	Fuel Technology (FT)	Hydrogen Ammonia ICE		Webpage
73	MAN B&W two-stroke engine operating on ammonia	Fuel Technology (FT)	Ammonia ICE		Sharefile Doc
74	WinGD X-DF2.0 ammonia-ready engines	Fuel Technology (FT)	Ammonia ICE		Webpage
75	MAN ES/DNV ammonia-fueled ME-LGI engine	Fuel Technology (FT)	Ammonia ICE		Webpage
76	Wartsila 32 Methanol	Fuel Technology (FT)	Methanol ICE		Sharefile Doc
77	WinGD methanol and ammonia engines	Fuel Technology (FT)	Ammonia Methanol ICE		Webpage
78	ScandiNAOS 150-450 kW, 4-stroke high speed engines	Fuel Technology (FT)	Methanol ICE		Webpage
79	Caterpillar 3500E-series dual fuel methanol engines	Fuel Technology (FT)	Methanol ICE		Webpage
80	Ballard 200 kW FCwave fuel cell	Fuel Technology (FT)	Hydrogen Fuel Cell	DNV type approved	Webpage
81	Cummins 360 kW HyPM fuel cell	Fuel Technology (FT)	Hydrogen Fuel Cell		Webpage

#	Name	EE or FT	Technology	Notes	Online Location
82	PowerCellution Marine System 200 fuel cell	Fuel Technology (FT)	Hydrogen Fuel Cell		Sharefile Doc
83	TECO2030 Marine Fuel Cell	Fuel Technology (FT)	Hydrogen Fuel Cell	DNV AiP	Sharefile Doc
84	Bloom Energy SOFC fuel cells	Fuel Technology (FT)	Hydrogen Fuel Cell	DNV AiP, SOFC fuel cells	Webpage
85	Ship FC project Multi MW SOFC with Prototech technology	Fuel Technology (FT)	Ammonia Fuel Cell		Sharefile Doc
86	Ammonia-Fuel Ready LNG Vessel Concept (NYK and Elomatic Oy)	Fuel Technology (FT)	Ammonia Fuel Cell Fuel-Ready		Webpage
87	Conoship International Projects (CIP) 3600 TDW sea river cargo concept	Fuel Technology (FT)	ICE Fuel-Ready Rigid Wingsail	Concept for future conversion of diesel-electric plant.	Webpage
88	MHI KS-21 solvent for absorption carbon capture	Fuel Technology (FT)	oCCS	Absorption	Webpage
89	Alfa Laval modified PureSOx for carbon capture	Fuel Technology (FT)	oCCS	SOx-modified	Webpage
90	MHI KM CDR Process	Fuel Technology (FT)	oCCS	Absorption testing on Corona Utility	Webpage
91	EverLoNG arbon capture project	Fuel Technology (FT)	oCCS	Absorption	Webpage
92	Sustainable Energy Solutions (SES) carbon capture	Fuel Technology (FT)	oCCS	Cryogenic	Webpage
93	PMW Technology A3C process	Fuel Technology (FT)	oCCS	Cryogenic	Webpage
94	Seaborg Compact Molten Salt Reactor	Fuel Technology (FT)	Marine Nuclear Power	power barge concept	Webpage
95	Core Power nuclear electric ships	Fuel Technology (FT)	Marine Nuclear Power		Webpage

Appendix C: Deployments (hyperlinks available online)

#	Name	EE or FT	Technology	Install Type	Notes	Online Location
1	E-Flexer class (Stena Line)	Energy Efficiency (EE)	Advanced Hull Coatings	Newbuild	Selektope anti-fouling coating	Webpage
2	COSCO Shipping VLCCs using FASTAR	Energy Efficiency (EE)	Nanocoatings	Retrofit	VLCC coating replacement planned	Webpage
3	Iskenderun Panamax Bulkers using FASTAR	Energy Efficiency (EE)	Nanocoatings	Retrofit	Five vessels planned	Webpage
4	EcoLiner (Damen Group)	Energy Efficiency (EE)	Air Lubrication	Newbuild	Single demonstration vessel	Webpage
5	AiriEL (BB Green)	Energy Efficiency (EE)	Air Lubrication	Newbuild	Air cushion, SES-X technology	Webpage
6	CWind Pioneer (CWind)	Energy Efficiency (EE)	Air Lubrication Hybrid Mechanical/Electrical	Newbuild	Air cushion	Sharefile Doc
7	Eco Valencia (Grimaldi Group)	Energy Efficiency (EE)	Air Lubrication	Newbuild	Silverstream Technologies ALS	Webpage
8	Quantum class (Royal Caribbean)	Energy Efficiency (EE)	Air Lubrication	Newbuild	Foreship ALS	Webpage
9	YM Mobility (Yang Ming Lines)	Energy Efficiency (EE)	Propellers	Retrofit	Wartsila FPP and EnergoProFin	Webpage
10	Schneekluth References	Energy Efficiency (EE)	Pre-Swirl Devices	Various	Wake equalizing ducts	Webpage
11	MV Shigenobu	Energy Efficiency (EE)	Post-Swirl Devices	Retrofit	Gate rudder	Webpage
12	Washington State Ferries Electrification	Energy Efficiency (EE)	Hybrid Mechanical/Electrical	Retrofit	16 ferry conversion program	Sharefile Doc
13	Stena Jutlandica (Stena Line)	Energy Efficiency (EE)	Hybrid Mechanical/Electrical	Retrofit	Phased battery conversion	Webpage
14	Vision of the Fjords (The Fjords)	Energy Efficiency (EE)	Hybrid Mechanical/Electrical	Newbuild	DNV classed vessel	Webpage
15	Maurel (aquaculture support vessel)	Energy Efficiency (EE)	Hybrid Mechanical/Electrical Battery (All-Electric)	Newbuild	LFP battery system by Praxis Automation	Webpage
16	Stena Elektra (Stena Line)	Energy Efficiency (EE)	Battery (All-Electric)	Newbuild	215-m RoPax vessel	Webpage

#	Name	EE or FT	Technology	Install Type	Notes	Online Location
17	MF Ampere (Norled)	Energy Efficiency (EE)	Battery (All-Electric)	Newbuild	80-m car ferry	Webpage
18	Asahi (Asahi Tanker)	Energy Efficiency (EE)	Battery (All-Electric)	Newbuild	61-m bunker tanker	Webpage
19	Glory (Viking Line)	Energy Efficiency (EE)	Waste Heat Recovery	Retrofit	Climeon HeatPower ORC	Webpage
20	Scarlet Lady (Virgin Voyages)	Energy Efficiency (EE)	Waste Heat Recovery	Newbuild	Climeon HeatPower ORC	Webpage
21	Valiant Lady (Virgin Voyages)	Energy Efficiency (EE)	Waste Heat Recovery	Newbuild	Climeon HeatPower ORC	Webpage
22	Ville de Bordeaux (Fret/CETAM)	Energy Efficiency (EE)	Kite Sail	Retrofit	Airseas Seawing	Webpage
23	MS Beluga (heavy lift carrier)	Energy Efficiency (EE)	Kite Sail	Newbuild	SkySails	Webpage
24	K Line LNG-powered bulker	Energy Efficiency (EE)	Kite Sail	Newbuild	Airseas Seawing	Webpage
25	E-Ship 1 (Enercon)	Energy Efficiency (EE)	Rotor Sail	Newbuild	Enercon technology	Sharefile Doc
26	M/V Estraden (Bore Ltd.)	Energy Efficiency (EE)	Rotor Sail	Retrofit	Norsepower rotor sails	Webpage
27	m/v Afros (Blue Planet Shipping)	Energy Efficiency (EE)	Rotor Sail	Newbuild	Anemoi rotor sails	Webpage
28	SC Connector (SEA CARGO)	Energy Efficiency (EE)	Rotor Sail	Retrofit	Norsepower rotor sails	Webpage
29	MV Ankie (Van Dam Shipping)	Energy Efficiency (EE)	Rigid Wingsail	Retrofit	Ventifoil folding installation	Webpage
30	New Aden (China Merchants Group)	Energy Efficiency (EE)	Rigid Wingsail	Newbuild		Webpage
31	MN Pelican (Compagnie Maritime Nantaise)	Energy Efficiency (EE)	Inflatable Sail	Retrofit	Small-scale prototype	Webpage
32	MF Teistin	Energy Efficiency (EE)	Wave-Assisted Propulsion	Retrofit	Case study provided	Sharefile Doc
33	Aditya	Energy Efficiency (EE)	Solar Power	Newbuild		Webpage
34	Auriga Leader (NYK Line)	Energy Efficiency (EE)	Solar Power	Newbuild		Webpage
35	BW Gemini (BW LPG)	Fuel Technology (FT)	Petroleum Gas	Retrofit		Webpage
36	INEOS INTREPID (Evergas)	Fuel Technology (FT)	Ethane Gas	Newbuild		Webpage

#	Name	EE or FT	Technology	Install Type	Notes	Online Location
37	MF Hydra (Norled)	Fuel Technology (FT)	Hydrogen Fuel Cell	Newbuild	First classed ferry powered by hydrogen. Delivered summer 2021, not yet operating on hydrogen.	Webpage
38	Sea Change (Hornblower)	Fuel Technology (FT)	Hydrogen Fuel Cell	Newbuild	First commercial vessel powered by 100% hydrogen. Launched, awaiting final approvals before entering service.	Webpage
39	HydroTug (Port of Antwerp)	Fuel Technology (FT)	Hydrogen ICE	Newbuild	Harbor tug under design, to be powered by hydrogen dual fuel engines supplied by BeHydro, a JV between CMB Tech and ABC Engines.	Webpage
40	Viking Energy (Eidesvik)	Fuel Technology (FT)	Ammonia Fuel Cell	Retrofit	2 MW fuel cell installation	Webpage
41	Stena Germanica (Stena Line)	Fuel Technology (FT)	Methanol ICE	Retrofit	4x Wartsila Sultzer8ZA40S engines, not as readily commercialized	Webpage
42	Capilano Sun (MOL)	Fuel Technology (FT)	Methanol ICE	Newbuild	part of 4 methanol tanker series	Webpage
43	Stena Pro Marine (Proman Stena Bulk)	Fuel Technology (FT)	Methanol ICE	Newbuild	2nd of 6 methanol tankers	Webpage
44	17,000-TEU containership series (Maersk)	Fuel Technology (FT)	Methanol ICE	Newbuild	MAN B&W LGIM engines	Webpage
45	A-Tug (NYK Line)	Fuel Technology (FT)	Ammonia ICE	Newbuild	4-stroke ammonia engine demonstration	Webpage
46	Ammonia-fueled ammonia gas carrier (NYK Line)	Fuel Technology (FT)	Ammonia ICE	Newbuild	2-stroke ammonia propulsion engine with 4-stroke auxiliary engines	Webpage
47	Ammonia-ready 14,000-TEU containerships (PIL)	Fuel Technology (FT)	Ammonia ICE	Newbuild	Series of 4 vessels with WinGD X-DF2.0 engines	Webpage
48	Wind Installation Jack-Up (Van Oord)	Fuel Technology (FT)	Methanol ICE	Newbuild	5x Wartsila 32 engines	Webpage

#	Name	EE or FT	Technology	Install Type	Notes	Online Location
49	Methanol-fueled methanol tankers (Waterfront Shipping)	Fuel Technology (FT)	Methanol ICE	Newbuild	11 in service, 8 additional ordered	Webpage
50	MV Shapinsay (Orkney Ferries)	Fuel Technology (FT)	Hydrogen Fuel Cell	Retrofit	Demonstration	Webpage
51	HySeas III Ferry (CMAL Ltd.)	Fuel Technology (FT)	Hydrogen Fuel Cell	Newbuild	Demonstration	Webpage
52	Wartsila Future Future conversion (MSC)	Fuel Technology (FT)	ICE LNG	Retrofit	Demonstration	Webpage
53	Kriti Future (Avin International)	Fuel Technology (FT)	ICE Ammonia	Newbuild	Ammonia-ready design	Webpage
54	Corona Utility (K Line)	Fuel Technology (FT)	oCCS	Retrofit	Demonstration	Webpage
55	Sleipnir (Heerema)	Fuel Technology (FT)	oCCS	Retrofit	Demonstration	Webpage
56	Akademik Lomonosov (Rosatom)	Fuel Technology (FT)	Marine Nuclear Power	Newbuild	First floating nuclear plant	Webpage
57	Containership air lubrication testing (Maersk)	Energy Efficiency (EE)	Air Lubrication	Retrofit	Demonstratio	Webpage