SHIP OPERATIONS COOPERATIVE PROGRAM

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Table of Contents

List of Tables

List of Figures

Revision History

Section	Rev	Description	Date	Approved
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References

1. *Second IMO GHG Study 2009*, International Maritime Organization, 2009
2. Regulation (EU) No 2015/757, European Parliament and the Council of the European Union, 29 April 2015
3. Resolution MEPC.203(62) Annex 19, MARPOL Annex VI, SOLAS, International Maritime Organization, 15 July 2011
4. *The Energy Efficiency Design index (EEDI) for new Ships,* Policy Update No. 15 of the International Council on Clean Transportation, 3 October 2011
5. Resolution MEPC.213(63) Annex 9, MARPOL Annex VI, SOLAS, International Maritime Organization, 2 March 2012
6. Johnsen, T.; "The Norwegian NO_x Fund – how does it work and results so far," Næringslivets NOx-fond, 11 April 2013
7. *Main events in IMO's work on limitation and reduction of greenhouse gas emissions from international shipping,* International Maritime Organization, October 2009
8. International Maritime Organization (IMO), http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Market-Based-Measures.aspx , February 2016.
9. World Shipping Council, http://www.worldshipping.org/industry-issues/environment/air-emissions/carbon-emissions , February 2016
10. *Prevention of Air Pollution From Ships – Emissions "Caps" and Reduction Targets,* World Shipping Council, 15 January 2010
11. Baltic and International Maritime Council (BIMCO), https://www.bimco.org/About/About_BIMCO.aspx , February 2016
12. Baltic and International Maritime Council (BIMCO), https://www.bimco.org/About/Viewpoint/04_Greenhouse_Gases_and%20Market_Based_Measures.aspx , February 2016
13. *Anti-fouling systems,* International Maritime Organization, Focus on IMO, 2002
14. Svensen, T., "Hull design boosts fuel economy of ultra large container ships," *SMM,* Hamburg*,* 5 September 2012.
15. *Airship of the Sea,* Surveyor, American Bureau of Shipping, Fall 2011
16. PBCF Energy Saving Device, MOL Techno-Trade, Ltd. http://www.pbcf.jp/english/characteristics/index.html , October 2015
17. *Cargill Reveals the World's Largest kite-Powered Vessel,* The Maritime Executive, 1 June, 2011
18. Gougoulidis, G. , "Energy Saving Basics for the Maritime Industry", Society of Naval Architects and Marine Engineers, 19 March 2015
19. Sailing Ships – Renewable Energy Research, http://www.bluebird-electric.net/sailing_ships.htm , October 2015
20. Suntory Mermaid II, Wikipedia, https://en.wikipedia.org/wiki/Suntory_Mermaid_II , February 2016

21. *Wave Augmented Foil Technology (WAFT) for Manned Vessels,* Rolls Royce, 7 November 2013
22. Tûranor PlanetSolar, Wikipedia, https://en.wikipedia.org/wiki/T%C3%BBranor_PlanetSolar , February 2016
23. Solar Sailor, Ocius, http://ocius.com.au/wp-content/uploads/2014/08/CaptainCookBack.pdf , February 2016
24. Solar Sailor, Ocius, http://ocius.com.au/solar-sailor-ferries/current-designs/ , February 2016
25. Solar Sailor, Ocius, http://ocius.com.au/wp-content/uploads/2014/08/100312-GA-HK-TOURIST-BOAT-generic-1.pdf , February 2016
26. *Auriga Leader Recognized as "Ship of the Year" at Lloyd's List 2009 Global Awards*, NYK Line, http://www.nyk.com/english/release/31/NE_090918.html
27. What is Peace Boat, Peace Boat, http://peaceboat.org/english/?menu=46 , February 2016
28. Ecoship, Peace Boat, http://ecoship-pb.com/ecoship/ , Febrary 2016
29. Wärtsilä-Sulzer RTA96-C, Wikipedia, https://en.wikipedia.org/wiki/W%C3%A4rtsil%C3%A4-Sulzer_RTA96-C , October 2015
30. The Marine Diesel Engine, Martins Marine Engineering Page, http://www.dieselduck.info/machine/01%20prime%20movers/diesel_engine/diesel_engine.01.htm , October 2015
31. Eos Aurora – Grid Scale Energy Storage, Eos Energy Storage Solutions, http://www.eosenergystorage.com/products/ , October 2015
32. Electric power transmission and distribution losses (% of output), The World Bank, http://data.worldbank.org/indicator/EG.ELC.LOSS.ZS , March 2016
33. Teo, A., "Battery Powered Ships – *Ampere*", *Ferries*, Seattle, 6 November 2015
34. Fuel Cells, DOE Hydrogen Program, https://www.hydrogen.energy.gov/pdfs/doe_fuelcell_factsheet.pdf , March 2016
35. *Hydrogen Production and Distribution,* International Energy Agency, IEA Energy Technology Essentials, ETE 05, April 2007
36. *Viking Lady Fuel Cells Trial Ends In Success,* gCaptain, http://gcaptain.com/viking-ladyfuel-cells-trial-ends-success/ , 5 September 2012
37. Carbon Dioxide Emissions Coefficients, US Energy Information Administration (EIA), https://www.eia.gov/environment/emissions/co2_vol_mass.cfm , March 2016.
38. *Where communities have banned fracking,* Boston Globe, https://www.bostonglobe.com/news/nation/2014/12/18/where-communities-have-banned-fracking/05bzzqiCxBY2L5bE6Ph5iK/story.html , 18 December 2014
39. *List of places that ban fracking keeps growing,* Houston Chronical, http://www.chron.com/business/article/List-of-places-than-ban-fracking-keeps-growing-6057266.php , 2 February 2015
40. *Waste Heat Recovery System (WHRS) for Reduction of Fuel Consumption, Emissions and EEDI*, MAN Diesel & Turbo
41. *Energy Efficiency for Diesel Power Plants,* Enertime, http://www.enertime.com/sites/default/files/documentation/enertime-diesel-en-july2015-web.pdf

42. Vlaskos, I. Feulner P., Michos, C, "Waste Heat Recovery in Marine Propulsion Systems", Society of Naval Architects and Marine Engineers, March 2014

43. Exhaust Energy Recovery Systems, GE Aviation, http://www.geaviation.com/marine/systems/exhaust-energy-recovery/docs/echogen-datasheet.pdf , March 2016

44. Wigforss, J.; "Benchmarks and measures for better fuel efficiency," *Master of Science Thesis in Nordic Master in Maritime Management*, Chalmers University of Technology, 2012

45. *Ship Energy Efficiency Measures – Status and Guidance*, American Bureau of Shipping (ABS), 2013

46. Takano S.,; Kawabuchi, M.; "CFD Predictions of Bubbly Flow around an Energy-saving Ship with Mitsubishi Air Lubrication System," *Mitsubishi Heavy Industries Technical Review*, Mitsubishi Heavy Industries (MHI), Vol. 48, No. 1, March 2011.

47. *MHI Completes Conceptual Design of MALS-14000CS ,* Mitsubishi Heavy Industries, Ltd., http://www.mhi-global.com/news/story/1010141379.html , 14 October 2010

48. *Silverstream Air Lubrication Technolgy Delivers Significant Energy Savings ,* Shell Global, http://www.shell.com/business-customers/trading-and-supply/shell-shipping-and-maritime/shell-shipping-news-and-media-releases/silverstream-air-lubrication-technology.html , 4 February 2015

49. *NCL Cruise vessel to feature air lubrication system,* Vessel Finder, https://www.vesselfinder.com/news/3044-NCL-Cruise-vessel-to-feature-air-lubrication-system , 10 March 2015

50. *What is the Silverstream System?,* Silverstream Technolgies, http://www.silverstream-tech.com/the-technology/ , March 2016

51. *Air Lubrication Advances,* The Motorship, http://www.motorship.com/news101/ships-equipment/air-lubrication-advances , 26 May, 2015

52. Terwisga, P., Damen Shipyards, "Air Lubrication as a means to reduce Cost and CO2 emissions in Inland Shipping"

53. Schnackenberg, T. "Vessel Propulsion Using Kites", HISWA Symposium, 2008

54. *Enercon E-Ship 1- A Wind-Hybrid Commercial Cargo Ship*, Enercon, *4th Conference on Ship Efficiency*, Hamburg, 23-24 September 2013

55. Thiiink Intelligent Industrial Design, http://www.thiiink.com/advantages-rfr-technology/ , March 2016

56. Technology, Oceanfoil®, http://oceanfoil.com/technology/ , October 2015

57. Windship Technology Ltd. http://www.windshiptechology.com/ October 2015

58. Rogers, S. (email) [Windship Technologies, Ltd.], "Inquiry from Seattle", 6 October 2015

59. Ocius Technology Ltd., http://ocius.com.au/wind-assisted-shipping/opening-flat-plate-sails/ , October 2015

60. *The Ecoliner Concept,* Dykstra Naval Architects, 29 January, 2013

61. Jeppesen Vessel and Voyage Optimization Solution, Jeppesen, http://ww1.jeppesen.com/marine/commercial/vvos/commercial-marine-product.jsp , October 2015

62. Vessel Fuel Management System, Krill Systems, http://www.krillsystems.com/products/vessel-total-management-software/ , March 2016

63. Installation Requirements, Norsepower™, http://www.norsepower.com/rotor-sail-solution/installation_requirements , March 2016

64. *Norsepower Rotor Sail's Fuel Efficiency Verification Spurs €3 million Investment, Commercial order*, World News, Ship & Bunker, http://shipandbunker.com/news/world/550337-norsepower-rotor-sails-fuel-efficiency-verification-spurs-3-million-investment-commercial-order , March 2016

65. *Norsepower and Bore Successfully Test Wind Power Technology for Ships,* Solutions for Design and Operation of Ships, NAPA Ltd., https://www.napa.fi/News/Press-Releases/Norsepower-and-Bore-Successfully-Test-Wind-Power-Technology-for-Ships , March 2016

66. Key Advantages, Norsepower ™, http://www.norsepower.com/rotor-sail-solution/key-advantages , March 2016.

67. *Windsail: energy saving solution?,* Green Port, http://www.greenport.com/news101/energy-and-technology/windsail-energy-saving-solution , March 2016

68. *The History of Wave Powered Boats,* http://www.wavepropulsion.com/ , March 2016.

69. *New Energy for Shipping,* SkySails GmbH, http://www.skysails.info/fileadmin/user_upload/Presselounge/Dokumente/englisch/EN_SkySails_Press_Kit.pdf , March 2016

70. *Flettner Freighter Factsheet,* Project SAIL, European Union, http://www.nsrsail.eu/wp-content/uploads/2015/11/SAIL_FinalReport_Engineering.pdf , October 2015

71. Innovative Ships, France Peche, http://www.francepechedurable.eu/en/innovative-ships/ , March 2016

72. Hybrid Marine Power, Ocius Technology Ltd., http://ocius.com.au/hybrid-marine-power/ , March 2016.

73. Norsepower Rotor Sail Solution on Bore's *M/V Estraden*, Norsepower, http://www.norsepower.com/rotor-sail-solution/Reference%20installation , March 2016.

Executive Summary

Improving energy efficiency on marine vessels represents a tangible and significant opportunity for reducing fuel consumption, operating costs, and CO_2 emissions. Historically, a willingness to invest in efficiency has directly correlated with energy costs. However, over the last two decades concerns over climate change have shifted energy efficiency from a fringe political issue to an integral component national and international maritime policies and regulations.

The Energy Efficiency Design Index (EEDI), part of MARPOL (International Convention for the Prevention of Pollution from Ships) Annex VI since 2013, requires a 30% improvement in efficiency for new-build ships by 2025, over an established baseline. Most types of new-build cargo vessels are bound by EEDI. EEDI is a performance-based regulation, which relies on industry to determine most cost effective means of compliance. Other national and international regulations are in effect for existing vessels in various jurisdictions. It is likely regulations will trend toward increased emphasis on increased efficiency. However, for many, if not most vessels, improving efficiency is still a voluntary measure that must ultimately be justifiable by cost savings.

Numerous opportunities for energy savings exist on a typical vessel from the propulsion system to the hull as seen in Figure 1. This report is a broad reaching survey of energy efficiency measures, including both technologies and operational strategies.

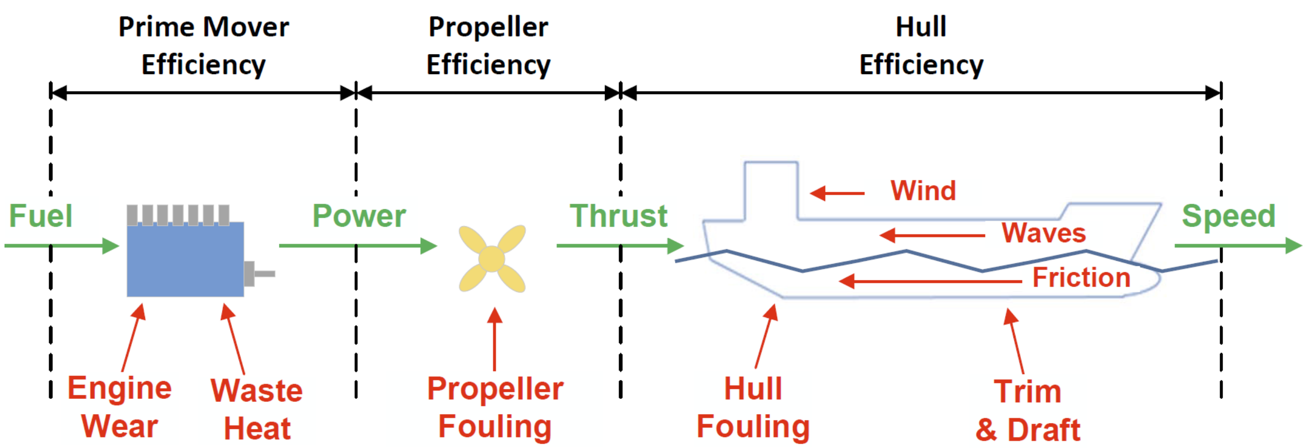


Figure 1 Typical energy losses on a large vessel

Each technology is described at a high level, so as to be easily understood and quickly digested. The paper can also serve as an evaluation tool, for operators to understand and compare the relative merits of various technologies. Stakeholders can leverage the information in the paper to launch a detailed cost analysis of their project once one or more technologies have been selected.

For each efficiency measure, various critical issues are discussed:

- What is the potential for fuel savings?
- How does it work?
- What is the applicability to various vessel types?
- Is it best for new-builds or retrofits?
- What is the level of the technology development?
- What is the relative lifecycle cost?

The presentation is organized into six sections:

Section 1: Introduction The section looks at where energy losses occur on a vessel and how this can translate to opportunities for savings. In addition, the regulations and market based measures driving efficiency technology adoption are considered. The end of the section presents the general methodology of the paper.

Section 2: Hull Non-operational methods for improving efficiency of the hull are presented and evaluated. These include design strategies, hull coatings, and technological solutions.

Section 3: Propellers and Appendages Information on efficiency improving devices related to the propeller and rudder are discussed. These include various types of propellers as well as devices placed upstream (pre-swirl), and downstream (post-swirl) of the propeller.

Section 4: Renewable Energy This section presents various forms of wind, wave, and solar assisted propulsion that could be deployed on new vessels as well as retrofitted on existing vessels.

Section 5: Mechanical and Electrical This section provides a comprehensive look at available technologies for improving the efficiency of the propulsion plant such as diesel and gas engines, electric vessel technology, battery and hybrid solutions, fuel cells, and many types of waste-heat recovery technologies.

Section 6: Operational Various operational strategies, and some technologies, that improve the efficiency of the vessel as well as the overall operation are presented and discussed.

Following the main body of the paper three appendices are included:

Appendix A: Technology Summary Table A summary of all the technologies and characteristics discussed in the report. This table is not intended as a standalone reference but rather is to be used and understood in the context of the report scope and methodology.

Appendix B: Air Lubrication Technology Developers Describes known commercial developers of the technology and the general state of development (prototype, commercial, etc.)

Appendix C: Wind Propulsion Technology Developers Describes known commercial developers of the technology and the general state of development (prototype, commercial, etc.)

Section 1 Introduction

Moving goods and people over the water on marine vessels, like any means of transportation, consumes energy. 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 (SFOC), which is the amount of fuel the vessel consumes at a given speed, draft, or engine power. The ***fleet manager*** may measure efficiency as fuel consumption per ton-mile per year. The ***international community*** may favor discussing efficiency in terms of carbon emissions per ton-mile. Each of these efficiency definitions are legitimate and appropriate for the application.

Generally, all methods are trying to determine 'how much *work I get out* for how much *fuel I put in*.' There are many opportunities to improve efficiency for vessels. This can happen by reducing energy wasted on the vessel propulsion, or it can happen by improving the efficiency of the overall operation so the minimum number of vessels or trips can do the required work, while consuming the least amount of fuel.

1.1 Energy Losses and Opportunities for Savings

The amount of propulsion power required is a function of the desired speed, hull efficiency, propeller efficiency, and prime mover efficiency. Numerous factors will affect the efficiency of each. Figure 2 illustrates an example of how energy losses for an example vessel are distributed based on 100 units of fuel [Ref. 1]. Engine efficiency limitations mean roughly 57 units of the fuel energy is lost as waste heat through the cooling water or out the exhaust. Consequently, only 43 of the starting 100 units of fuel energy are converted to mechanical work in the shaft. Propeller and transmission loses reduce those 43 units, leaving only 28 of the original 100 units of fuel energy (28%) to actually move the vessel.

Figure 2 also provides a helpful visual map for where *wasted* energy can provide opportunities for savings. In this example, hull friction is the largest contributor to propulsion energy. 16% of the bunker fuel goes to overcoming hull friction, and roughly 57% of the propellers energy goes to overcoming hull friction (i.e. $16/28 \approx 0.57$). Naturally, reducing hull friction is an enormous opportunity to improve efficiency. Such technologies as air lubrication and low friction coatings seek to do just this, as well as operational changes such as 'slow steaming'. Waste heat is another significant opportunity, accounting for a whopping 57% of the *overall* energy losses. Capturing waste energy or improving the efficiency of the engine are two ways to benefit from this. Even small losses around the propeller can be significant opportunities for cost savings. Moderate investments in energy saving devices at the propeller and other places on a vessel return savings over the entire life of the vessel and can have short payback times.

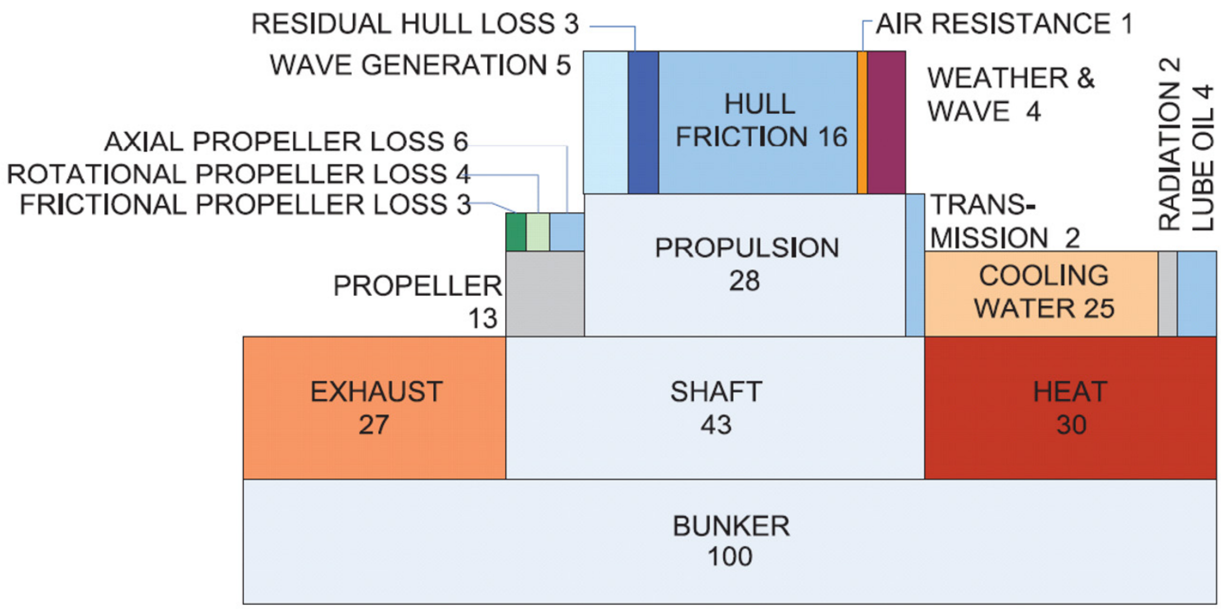


Figure 2 Energy breakdown for Use of propulsion energy onboard a small cargo ship, head sea, Beaufort 6. Source: [Ref. 1].

1.2 Regulations

Energy efficiency requirements for ships and marine vessels exist at the international level (i.e. for vessels engaged in international commerce) through international conventions as well as the regional level.

1.2.1 European Union MRV Regulation

On 29 April 2015, the EU adopted Regulation 2015/757 on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport. Known as the MRV regulation, it creates an EU-wide legal framework for collecting, and later publishing, annual data on CO_2 emissions and other relevant information from all ships over 5,000 gross tons calling at EU ports from January 1, 2018 regardless of where the ships are registered.

It requires that after January 1, 2018 companies assuming the responsibility for operating large ships would have to monitor and annually report the verified amount of CO_2 emitted on voyages to, from and between EU ports and also when in EU ports [Ref. 2]. Companies are also required to monitor certain parameters as distance, time at sea and cargo carried to determine the ships' average energy efficiency.

A document of compliance issued by an independent verifier and indicating the ship has satisfactorily complied with its MRV reporting obligations for the precedent year will have to be carried on board of ships when visiting EU ports. It is possible this could be subject to inspections by member state authorities.

1.2.2 International Maritime Organization (IMO)

In July 2011 mandatory technical and operational energy-efficiency measures were adopted by parties to MARPOL (the International Convention for the Prevention of Pollution from Ships) Annex VI entered into force on 1 January 2013[Ref. 3]. Per these regulations, the Energy Efficiency Design Index (EEDI) is mandatory for certain types of new ships, and the Ship Energy Efficiency Management Plan (SEEMP) is mandatory for all ships of 400 gross tons and above. These new regulations are considered the first to establish CO_2 standards across a global sector. However, under regulation 19, the Administration may waive the requirements for new ships up to a maximum of four years.

1.2.2.1 EEDI

EEDI requires most new ships to be 10% more efficient beginning 2015. This efficiency must improve 20% by 2020 and 30% by 2025 [Ref. 3]. The International Council on Clean Transportation (ICCT) projects that implementing this schedule will reduce CO_2 emissions by 263 million metric tons (Mt) annually by 2030 [Ref. 4]. According to ICCT, even if the EEDI will add capital and implementation costs for next-generation ship designs and technology, these costs are expected to be offset by projected savings up to $52 billion of fuel annually [Ref. 4].

The EEDI is a performance-based approach, by which industry may choose the best technology approach for a specific vessel design. As long as the required energy-efficiency level is attained, ship designers and builders may choose to use the most cost-efficient solutions for the ship to achieve the required efficiency improvements. The EEDI estimates vessel CO_2 emissions per ton-mile relative to a reference average index of similar ships. The categories of ships covered, which account for over 70% of new-build ship emissions, include tankers, gas carriers, bulk carriers, various cargo ships, and container vessels [Ref. 4].

The regulation does not currently apply to passenger and various mixed-use vessels such as cruise ships, Ro-Ro ships, car carriers, or other specialized vessels, or vessels below 400 Gross Tons. Other limitations include the inability to be applied to vessels such as diesel electric, since installed power cannot be predictably correlated to propulsion.

Flag State is ultimately responsible for verifying compliance. The process requires both design review and sea trial and culminates with the issuance of an International Energy Efficiency Certificate (IEEC). The verifying agency may be either the Maritime Administration or a Classification Society.

1.2.2.2 SEEMP

In addition to the EEDI, the new Chapter 4 of MARPOL Annex VI requires all ships or operating companies to develop a Ship Efficiency Management Plan (SEEMP) for vessels over 400 Gross Tons [Ref. 5]. The plan requires the vessel to be able to monitor and track efficiency performance over time. It also forces consideration of new technologies and procedures for optimizing performance. As envisioned, the plan should evolve over time as the vessel ages, new technologies are available, and market conditions change.

Currently it is enough for a vessel to merely *have* a plan. There are no requirements for the contents of the plan to be scrutinized, progress tracked, or formal reporting. Many responsible operators and those genuinely interested in improving and tracking efficiency were already developing and using similar approaches prior to 2013 so the SEEMP was not necessarily an onerous requirement. Additionally, class societies, industry groups, and private companies now offer services related to implementing and managing a vessel’s or a fleet’s SEEMP. Many of the ‘best practices’ laid out in the SEEMP are discussed in this paper.

1.3 Market Based Measures (MBMs)

Market Based Measures are policy instruments that incentivize polluters to reduce emissions using markets, price, and other economic mechanisms. For example, while there is international consensus that externalities such as climate change are directly correlated to greenhouse gas (GHGs) 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 are possible mechanisms in addition to mandatory or prescriptive regulations that can drive industrial or consumer choices to reduce emissions.

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 time 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 therefor the cost to society will be the lowest. Emissions trading has been implemented with varying degrees of success in many countries including the US, Japan, the European Union, South Korea and others. The Kyoto Protocol includes emissions trading as a possible mechanism for meeting carbon reduction limits.

Pollution taxes set levies on each ton, kg, etc. of a given pollutant. While cost of the taxes may incentivize polluters to reduce emissions, the cost of implementing the technology is often high. In many schemes, the taxes are collected in a fund that is reinvested to offset the cost reducing emissions. An example of this in the maritime industry is the Norwegian NO_x fund. The agreement was initiated in 2008 between 15 business organizations and the Ministry of the Environment. Since inception, it has generated approximately 80 million euros annually ($90 million) which has been reinvested into NO_x reducing measures for ships. The fund, which supports up to 80% of the cost of projects, has invested heavily in such technology as LNG for ship propulsion. In its first five years the fund had supported conversion or construction of over 50 LNG vessels bringing the total up from only 3 LNG vessels in 2008 [Ref. 6].

1.3.1 International Maritime Organization

Market Based Measures are described by the IMO's Marine Environmental Protection Committee (MEPC) as measures that:

"*…place a price on GHG emissions and serve two main purposes:*

1. *Providing an economic incentive for the maritime industry to reduce its fuel consumption by investing in more fuel efficient ships and technologies and to operate ships in a more energy efficient-manner (in-sector reductions); and*
2. *Offsetting in other sectors of growing ship emissions (out-of-sector reductions).*

In addition, MBMs can generate funds that could be used for different purposes such as adaptation and transfer of technology." [Ref. 7]

MBM's were actively discussed at IMO between 2006 and 2013 (MEPC 56 to MEPC 65). Many proposals were introduced by various countries between MEPC 60 and 61. During MEPC 63 it was agreed that an 'impact assessment' of any proposed MBMs should be undertaken to understand the impact on consumers and industries in developing countries and to further develop the criteria that the methodology should be based on. In MEPC 65, the committee agreed to *"suspend discussions on MBMs and related issues to a future session."* [Ref. 8]

It is not clear when *or if* the issue of MBM's will be brought back to the table for discussion within the MEPC even though in 2009 the committee *"recognized that technical and operational measures would not be sufficient to satisfactorily reduce the amount of greenhouse gas (GHG) emissions from international shipping in view of the growth projections of world trade."* [Ref. 8]

1.3.2 World Shipping Council (WSC)

The World Shipping Council is an industry group representing the international liner shipping industry, chiefly container shipping lines. The WSC members collectively represent 90 percent of global container shipments. They serve as a lobbying organization to world governments for such issues as regulations, security and environmental issues. According to the WSC website [Ref. 9]:

> *"Discussions at the IMO have led to a number of proposals for "market-based measures" or MBM, and how such measures might stimulate further advances and improvements in addressing CO_2 emissions. MBM proposals include establishing a carbon tax on marine fuels, creating an emission trading regime applicable to shipping, and efficiency-based systems and related proposals that involve a hybrid approach. In 2010, the WSC proposed to the IMO that mandatory energy efficiency design standards be created and applied to both new and existing vessels through the establishment of a global Vessel Efficiency System (VES). As part of on-going discussions on this issue and as a refinement of earlier proposals, WSC and Government of Japan jointly proposed in 2011 that the IMO create a global Vessel Efficiency Incentive Scheme (EIS).*
>
> *The WSC and its members have also argued that the most effective means to addressing carbon emissions from shipping is to improve the fuel efficiency and carbon footprint of ships themselves. Some proposals seek to generate large sums of money from shipping that would, in theory, purchase carbon "offsets" and fund other activities in other land-based sectors."*

In a letter to the IMO, the WSC stated [Ref. 10]:

> *"The World Shipping Council and its members fully support the establishment of an effective global regime addressing CO2 emissions from ships, and it believe that the IMO is the most appropriate forum for developing such an agreement. The IMO should move forward with development of a global agreement to improve the efficiency of the world's fleet with a consequent and significant reduction in emissions. Improving the efficiency of shipping will serve society well, will improve global environmental results, and will reduce resource consumption while continuing to foster trade and improved quality of life. Adoption of explicit carbon emission caps applicable only to maritime shipping would, in WSC's judgment, be inappropriate in the absence of a broader approach to regulating transportation emissions at the national and global level."*

1.3.3 Baltic and International maritime Council (BIMCO)

BIMCO is the world's largest international shipping association, with more than 2,200 members globally with core objectives *"to facilitate the commercial operations of our members by developing standard contracts and clauses, and providing quality information, advice and education."* [Ref. 11]. The organization actively promotes consensus based global regulations, fair business practices, free trade and open access to markets. They strongly advocate for harmonization and standardization of shipping related activity.

From the BIMCO website [Ref. 12]:

> *"BIMCO is of the view that Market Based Measures (MBMs) do not appear warranted at this particular time. In the event that MBMs are eventually introduced to shipping, these should apply globally and should completely address the nine IMO principles - effective;*

binding and equally applicable; cost-effective; limit distortion; not penalizing trade and growth; goal based; promote R&D; accommodating energy-efficient technology; practical, transparent, fraud-free and easy to administer. BIMCO supports regulations, which provide incentives for owners to invest in low-carbon technology. If ultimately it is found that technical and operational measures cannot wholly meet the agreed reduction targets, then any funds generated by means of a globally applied MBM for shipping must be controlled by the IMO and, in the large part, be disbursed to support further technological development focused on energy efficiency in shipping. Collection and distribution of such funds should be based on a simple, transparent, verifiable and auditable scheme, which minimizes any additional bureaucracy and financial burdens on shipping companies. Before finally deciding on an MBM for international shipping, a cost/benefit analysis should be completed paying particular attention to the impact on the industry, the global supply chain and developing countries. These are fundamental conditions, in line with BIMCO's objectives of promoting fair business practices and defending free trade as well as open access to markets."

1.4 Scope and Methodology

This paper presents a survey-level look at current ship energy efficiency methods. This includes strategies such as design, technology, devices, and operational practices. Individual efficiency measures, be it a technology, an operational practice, or something else, are summarized in five broad areas: Savings potential, Technology Stage, Lifecycle Cost, Retrofitable, and Compatibility. For each efficiency, measure a 'Technology Table' is presented that summarizes the characteristics. An example table is below in Table 1.

MECHANICAL/ELECTRICAL				**Waste Heat Recovery Exhaust Gas Turbine Generator (EGTG)**	
Savings Potential				**Compatability**	
Low	**Mean**	High		Vessel Category	Power Group
3%	**4%**	5%		A	All
				B	1,2
Technology Stage (1 to 3)			2	C	1,2
Lifecycle Cost (Low to High)			Med	D	2,3,4
Retrofitable (Yes or No)			Yes	E	None

Table 1 Example of a 'Technology Table'. Each efficiency measure is summarized with a similar table.

Savings Potential: This metric presents the anticipated fuel *savings,* as a percentage reduction from a baseline. The metric is presented as a *low,* meaning the minimum anticipated savings were the method adopted, a *high*, meaning the maximum anticipated savings, and a *mean*. The mean is a direct average of the high and low. The savings potential is a number that is considered 'typical' over all *applicable* vessel types. The applicability of a particular technology is considered below.

Technology Stage: This metric varies from 1 to 3 and denotes the state of development of the technology or practice.

1. *Prototype or early implementation stage*: It may have reached a higher maturity level outside of the marine industry and is just making inroads to the marine sector. Few installations on operating vessels. The risk of implementation may be high and should be carefully evaluated by the owner.

2. *Early commercial stage:* The technology has been installed on vessels but operational history is limited and sample sizes are small. The overall risk of implementation is medium.

3. *Mature practice or technology*: The technology has been applied on many vessels and is commercially available or available through service providers. The overall risk of implementation is low. Information on cost, maintenance, installation, and reliability should be readily available.

Lifecycle Cost: Since there is *so* much variation in vessel types, operations, sizes, propulsion systems, etc. this metric should be considered only as a gage for the *relative* capital and operational costs, as a *percentage,* compared to the existing propulsion engine(s). A universal cost metric (e.g. $/horsepower or $/kilowatt) is virtually impossible with so many different types of technologies and methods.

- Low – less than 25%
- Medium – 25% to 75%
- High – 75% to greater than 100%

Retrofitable: Distinguishes between technologies that can only be installed on new vessels (No) and technologies that can be retrofitted to existing vessels (Yes).

Compatibility: This category describes the specific types of vessels to which the technology or strategy can be applied (see Table 2). There are five 'Vessel Categories' (A – E) and each category has a 'Vessel Power Group'.

The Vessel Categories and Vessel Power Groups have been established to facilitate pairing specific efficiency strategies with the broad range of marine vessel types. Once strategies are paired with a vessel group, they can be directly compared with other strategies applicable to that group. This grouping effort recognizes that there hundreds of unique vessel configurations. However, in each of these configurations it is recognized that only a few considerations will affect which efficiency strategies are applicable.

1. *Footprint and Weight Tolerance:* How tolerant is the vessel of weight and footprint? Is the vessel like a car carrier, which has significant space for the location of large equipment? Is the vessel like a harbor tug, where added weight can compromise stability and added volume will compromise maneuverability?
2. *Power Plant Size:* What is the power plant size? Is the plant small like in a crew boat, where modified bus hybrid technology might be applicable? Is the plant large like an ocean going container ship, where modified industrial efficiency technology might be applicable?
3. *Engine Speed:* Is it a large, slow-speed diesel classified by IMO based on its particular rotations per minute and therefore have higher thermal efficiency?
4. *Duty Cycle:* What is the vessel duty cycle? Is it continuous like an ocean going crude carrier, where long transits allow equipment to reach steady state operation? Is it intermittent like a short haul ferry, supply vessel, or escort tug, which rarely reaches steady-state operation?

Further to this, not all permutations of these criteria will specifically match a vessel. A broad listing of vessel types was compared to these considerations and all were found to fall within eight unique combinations, or 'Group Numbers'. Table 2 identifies these groups, and provides some examples of vessels within each of these.

VESSEL CATEGORY		Example Vessel Types	Vessel Power Group (see definition below)
Letter	**Description**		
A	**Ocean Going Cargo Vessels**	Container	1
		General Cargo	1
		Dry Bulk	1
		Crude Oil Tanker	1
		General Cargo	
		General Cargo Liner	1
		Reefer (w/(out) Container)	1
		Roll-on/Roll-off (Various)	1
		Chemical Tanker	1, 2
		Petroleum Product Tanker	1, 2
		Natural Gas Carrier	1, 2
B	**Passenger**	Ferry (Long Haul)	1, 2
		Cruise/Tour (Long Haul)	2
		Ferry (Short Haul)	6, 7, 8
		Cruise/Tour (Short Haul)	6, 7, 8
		High Speed Ferry	6, 7, 8
		Crew Transport	8
C	**Other Cargo Vessels**	Heavy Lift	1
		Lake Freighter	2
		River Transport	6, 7
D	**Work/Service/Misc**	Oceangoing Science/Research	2
		Drill Ships	3
		Offshore Platforms	3
		Cable Layer	3
		Ice Breakers	3
		Platform Supply	4
		Anchor Handling Tug Supply	4
		Ocean Tug/Tow	5
		Coastal/Harbor Tug/Tow	7
		Fireboat	7
		Construction/Crane	8
		Near Shore Science/Research	6, 7, 8
E	**Fishing**	Ocean Going	5
		Processing	5
		Near Shore	8

VESSEL POWER GROUP DEFINITION

Group Number	*Footprint & Weight Tolerance*	*Power Plant Size* MW = Megawatts 1MW = 1,340 hp	*IMO Speed Rating*	*Duty Cycle*
1	*Large*	*Greater Than 10 MW*	*Slow*	*Continuous*
2	*Large*	*Greater Than 10 MW*	*Medium*	*Continuous*
3	*Large*	*Greater Than 10 MW*	*Medium*	*Intermittent*
4	*Large*	*1 MW to 10 MW*	*Medium*	*Intermittent*
5	*Small*	*1 MW to 10 MW*	*Medium*	*Continuous*
6	*Small*	*1 MW to 10 MW*	*Medium*	*Intermittent*
7	*Small*	*1 MW to 10 MW*	*High*	*Intermittent*
8	*Small*	*Less Than 1 MW*	*High*	*Intermittent*

Table 2 Vessel Compatibility Matrix

Section 2 Hull

In order to minimize the propulsion losses due to the hull, one must reduce the overall hull resistance. For most commercial vessels, the vast majority of that resistance comes from viscous effects between the hull and the water. As speeds increase, the effects of wave making become more significant. Figure 3 shows the resistance curve for a typical large commercial vessel. The vessel designer must consider all effects on resistance. However, the design flexibility will depend on many factors and must be balanced against the vessels primary mission requirements. Because viscosity effects are dominant, the majority of methods for reducing resistance focus on reducing skin friction.

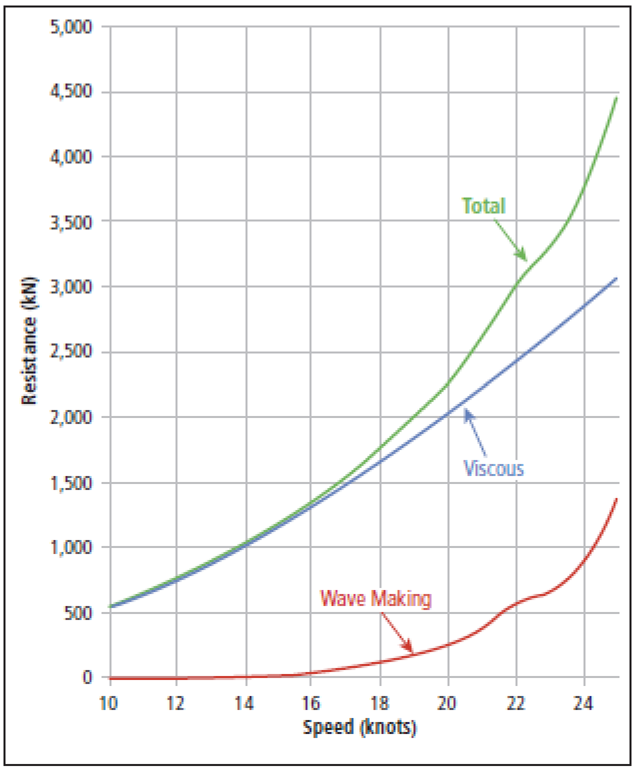


Figure 3 Typical resistance curve for a large commercial vessel. Source: [Ref. 45].

2.1 Advanced Hull Coatings

HULL				Advanced Hull Coatings	
Savings Potential				Compatability	
Low	**Mean**	High		Vessel Category	Power Group
1%	**3%**	4%		A	All
				B	1,2
Technology Stage (1 to 3)			3	C	1,2
Lifecycle Cost (Low to High)			Low/Med	D	2,3,4
Retrofitable (Yes or No)			Yes	E	5

Table 3 Characteristics of Advanced Hull Coatings for fuel savings

Surface roughness has a significant effect on frictional resistance for a ship's hull. Roughness can be described on both the macro and the micro level. The surface roughness can be caused by both physical imperfections and the accumulation of biological growth (Table 4). 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 significantly reduce the fuel efficiency of the vessel.

ROUGHNESS			
Micro		Macro	
Physical	Biological	Physical	Biological
minor corrosion	Slime	Welds	barnacles
steel profile		Corrosion	mussels
coating profile		Plate wavines	weeds
		Plate overlaps	
		Mechanical damage	

Table 4 Types of surface roughness affecting hull friction

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. Another purpose is to inhibit the growth of marine organisms on the exterior of the hull (anti-fouling). Historically, tributyltin (TBT) was added to marine paints to inhibit the growth of organisms on the ship's hull. While effective, TBT is also damaging to the marine environment. The use of TBT has now been banned by many countries and IMO [Ref. 13]. Many suppliers have agreed to stop selling antifouling coatings containing TBT. However, the use of biocides to inhibit hull fouling is only one strategy.

Another strategy is the foul-release hull coating. Using advanced materials, modern foul-release coatings are designed to prevent organisms from getting a good hold on the hull. When the ship is sitting still the organisms can attach themselves to the hull of a ship, but when the ship gets above threshold velocity, the hydrodynamic forces strip the growth away. In this sense, the hulls are 'self-cleaning' and do not poison the organism.

After application of a new coating system the performance will diminish over time. Inevitably, some organisms will find a way to attach to imperfections or damaged areas of the coating. Coatings are usually applied on the dry-docking schedule which is typically 60 months for most cargo vessels and even shorter for some passenger vessels. For optimal performance, the owner must continually maintain the integrity of the hull coating at periodic intervals and commensurate with the coating's condition.

Advantages

The benefits of a clean hull are reduced drag and fuel savings. 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 docking cycle. Biocidal coatings are more prone to mechanical damage and roughening.

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 the higher level leading to greater improvements to vessel efficiency. For some operators, the reduced friction from advanced hull coatings can also result in higher speed without an added fuel penalty. Depending on the operation, the added speed may be more of an economic benefit that lower fuel consumption.

Foul release coatings will require less paint to be added at future dockings, following the first application. This can potentially reduce time needed in drydock, as well as costs for paint and labor.

Disadvantages

Foul release coatings have a higher first cost than traditional coatings. This is driven by the material costs as well as the labor required. The quality of the application is very important to lifecycle performance. Additionally, dedicated equipment is required for installing foul-release paints, as they are not compatible with other paint types. New spray lines and cleaned (or new) pumps are required. More frequent cleanings may also be required, though the cleaning process is significantly less labor due to the nature of the coating. An experienced contractor is recommended for application of foul-release paints to maximize the benefits though this is generally no longer an issue since the market has heartily embraced the product over the last decade.

2.2 Hull Form Optimization

HULL				Hull Form Optimization	
Savings Potential				Compatability	
Low	**Mean**	High		Vessel Category	Power Group
2%	**11%**	20%		A	All
				B	All
Technology Stage (1 to 3)			3	C	All
Lifecycle Cost (Low to High)			Low	D	All
Retrofitable (Yes or No)			No	E	All

Table 5 Characteristics of Hull Form Optimization for fuel savings

Many vessel hull forms are designed to meet a complex and conflicting set of requirements. They need to provide enough buoyancy to support the weight of the vessel while providing enough space for the interior arrangements and cargo. Each must have enough stability and good seakeeping for all weather conditions that the vessel will encounter. A well-designed vessel should do all of the above while having the least possible resistance for maximum speed at minimum power.

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.

The optimization process takes a starting hull as a baseline 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 perhaps 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. 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 chin is 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 4, right). Alternatively, a design may require a low resistance hull form that also minimizes underwater-radiated noise leading to a different hull form (Figure 4, left). In this way, the process is leveraged to consider multiple competing design requirements while minimizing resistance.

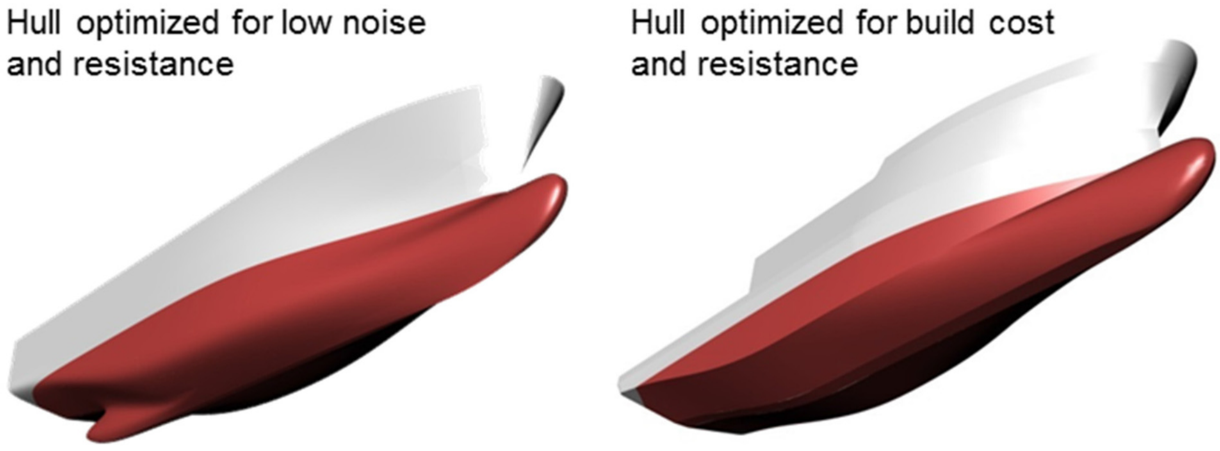


Figure 4 Comparison of two research vessel hull forms optimized to minimize resistance: Low noise (Left) vs. build cost (Right). Source: Glosten, Inc.

The formal optimization process described above should not be confused with a vessel designer using advanced tools such as CFD to evaluate several variations of hull shape. Formal hull form optimization is a significant departure from the days when naval architects used 'gut instinct' and experience to improve hull forms. In some ways, the optimization process requires the architect to let go of the feeling of ownership that can come with designing, or improving 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 10-20% over the initial hull form are not atypical.

Advantages

The formal hull form optimization is primarily done to save fuel. If done properly and early enough in the design process, reductions in resistance of up to 20% can be expected [Ref. 14]. The best results will be seen for commercial vessels operating at above 10 knots where resistance effects are more significant.

Disadvantages

The optimization process takes time and must be accounted for in the schedule. The process may take 6-8 weeks, even if properly managed. The designer must account for this in the design process, which can sometimes be difficult. If the process is initiated too late in the schedule, there is much less flexibility to vary the hull form without affecting arrangements. The process will add additional cost to the design a new vessel. For most vessels, the payback time will be very rapid, even under a year, and continue to benefit the owner for the life of the vessel.

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.

Hull form optimization is a highly effective tool for reducing fuel consumption on new vessels if implemented early in the design process. In practical terms, it cannot be used to improve existing hull forms.

2.3 Air Lubrication

HULL				Air Lubrication	
Savings Potential				Compatability*	
Low	**Mean**	High		Vessel Category	Power Group
5%	**15%**	25%		A	All
				B	All
Technology Stage (1 to 3)			1 - 2	C	All
Lifecycle Cost (Low to High)			Med/High	D	All
Retrofitable (Yes or No)			Yes	E	All
*Compatable with flat bottomed displacement hulls					

Table 6 Characteristics of Air Lubrication for fuel savings

Air lubrication is a method whereby air is injected to the underside of a vessel's hull for reducing skin friction. It has been discussed in literature and studied for many years. Recently a number of companies have developed air lubrication products that are in the early stages of commercialization. Information on commercial installations and developers of air lubrication systems can be found in (Appendix B).

There are two primary methods of air lubrication: Micro bubbles and Air Cavities

2.3.1 Micro-Bubbles and Air Carpets

This technique injects compressed air to produce micro-bubbles underneath a flat-bottomed vessel (Figure 5). Under the right conditions, the bubbles merge and form a single large 'air carpet' which effectively reduces the wetted surface area. Much work is going on in various institutions to understand the physics of the system. The size of the bubbles and the speed of the water stream is very important to the effectiveness and the stability. To be commercially viable the system must work in various sea states and conditions and the net energy savings must be significantly lower than the energy required to compress or blow the air.

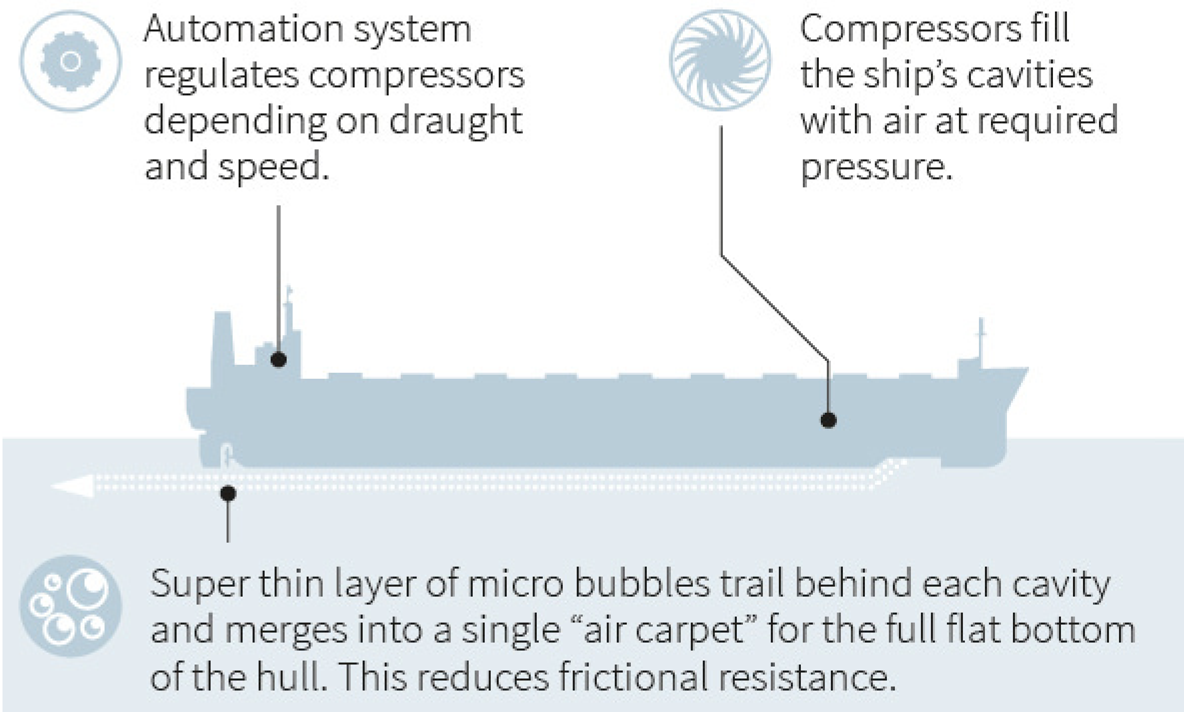


Figure 5 Micro-bubbles are injected on the ships bottom and merge into a large 'air carpet' to reduce friction and save fuel. Source: [Ref. 50].

2.3.2 Air Cavities

When large volumes of bubbles are injected along a flat plate, they can merge to form a layer of air. Though unstable, this layer effectively reduces the wetted surface of the vessel and significantly reduces overall resistance. If the bottom of the vessel is modified with a cavity or cavities to contain the air, the air layer can be made stable, even in weather. This is the technique behind several systems that are being developed.

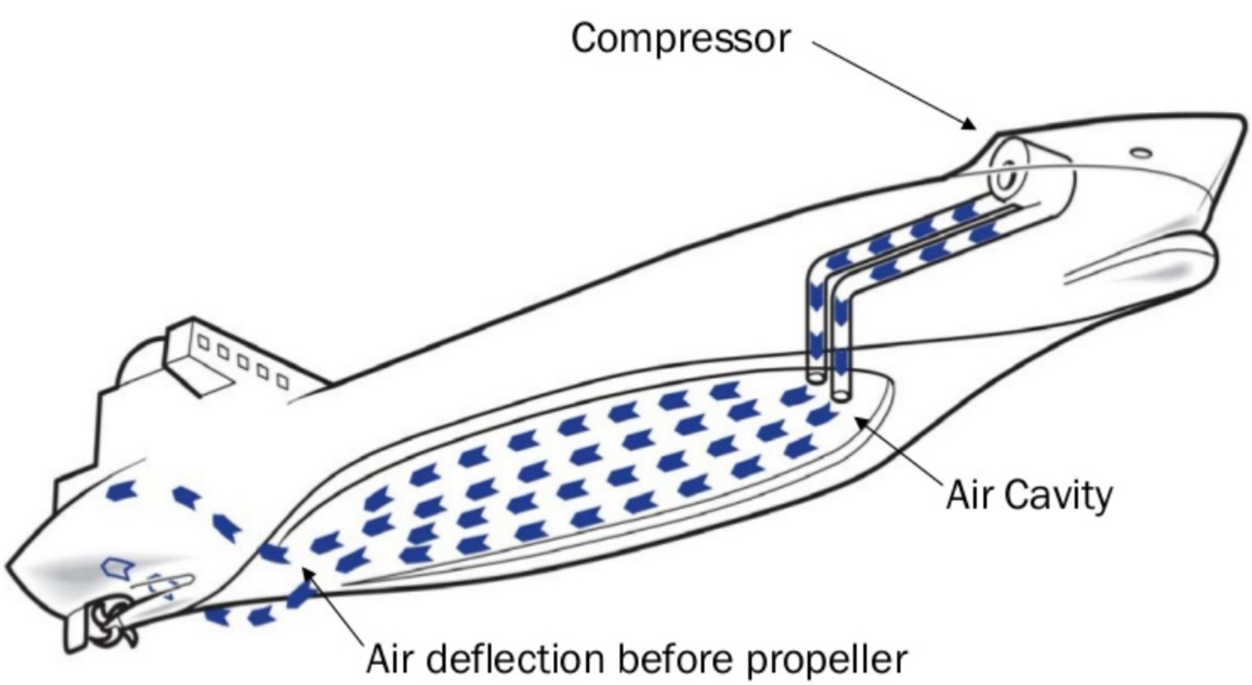


Figure 6 An Air Cavity System injects air into a shallow cavity, or cavities, installed on the underside of a ship's hull to reduce frictional resistance. (Source: DK Group)

Advantages

There are very few technologies with the potential benefits of air-lubrication. In particular, air-cavity technology has been shown to reduce hull resistance by 25% or even greater in particular conditions [Ref. 15]. For this reason, the technology continues to generate a huge amount of excitement within the industry.

The technology can be applied to displacement hulls with flat bottoms, travelling at moderate speeds. Most developers are claiming that the system can be retrofitted to existing vessels. However, it is clear that the savings can be maximized for new vessels, in which the hull design can be optimized for the use of air bubbles or air cavities.

Disadvantages

The technology only applies to flat-bottomed displacement hulls. However, there are a huge number of vessels, including the thousands of barges used in trade that could benefit.

For micro-bubbles, the physics are not well understood. There are conflicting studies of how the micro-bubbles interact with propellers. Some studies show that the bubbles do not interact with the propellers as they mostly cling to the hull surface. However, some studies show a beneficial effect which reduces propeller vibration (a particular advantage for passenger vessels) while others claim that the vibration is exacerbated.

Running compressors or blowers can take a significant amount of energy. For some vessel types, the generator may not be adequate which could either increase the cost of retrofit or make it infeasible.

Section 3 Propellers and Appendages

Increasing propulsor efficiency is a viable means of energy savings. There are many factors that contribute to the overall efficiency of the propulsors, such as wake characteristics and quality, interaction between the hull and the propeller, propeller type and characteristics, and interactions with the propeller flow field and the rudder or other downstream appendages. Most of these factors can and should be considered in the vessel design. However, optimizing efficiency will not always be possible in the design process due to design budget and schedule, construction capital cost, vessel characters and mission, capabilities of the designer, and a myriad of other possible reasons.

Additionally, as ship design and technology have advanced so have the number of opportunities to improve the efficiency of the vessel propulsion system. Some of these opportunities are limited once the vessel has been constructed and some are definite retrofit options that can save an owner significant fuel costs. As always, there must be careful consideration given to implementation cost vs. return on investment.

3.1 Propellers

PROPELLERS AND APPENDAGES				**Efficient Propellers**	
Savings Potential				**Compatability**	
Low	**Mean**	High		Vessel Category	Power Group
3%	**7%**	10%		A	All
				B	1,2
Technology Stage (1 to 3)			3	C	All
Lifecycle Cost (Low to High)			Low/Med	D	2,4,5,6,7
Retrofitable (Yes or No)			Mixed	E	5

Table 7 Characteristics of efficient Propellers for fuel savings

Propellers represent a very broad range of devices that can vary significantly depending on the vessel needs. Several types of propellers are discussed below.

3.1.1 Large Diameter, Low Speed

Generally, larger and slower propellers with fewer blades will have greater efficiency. The size, speed and design of the propeller will obviously need to be balanced by other practical design factors such as hull geometry, reasonable clearances, engine speed, drive type (e.g. direct, geared, mechanical, electrical), draft, and other factors.

3.1.2 Ducted Propellers (Kort Nozzle)

By fitting a propeller with a nozzle, or cylindrical duct, the efficiency of the propeller can be increased at speeds less than 10 knots. Nozzles are widely used on vessels with heavily loaded, smaller diameter propellers such as tugs, where maximizing the thrust to size ratio is critical and low speeds are typical.

The cross section of the duct is foil shaped so the flow is accelerated, causing lift which increases the thrust (Figure 7). This effect loses out to the additional drag created above about 10 knots. The propeller should be optimized for operate within the flow created by the duct. The ducts are sometimes used in lieu of rudders for steering a vessel.

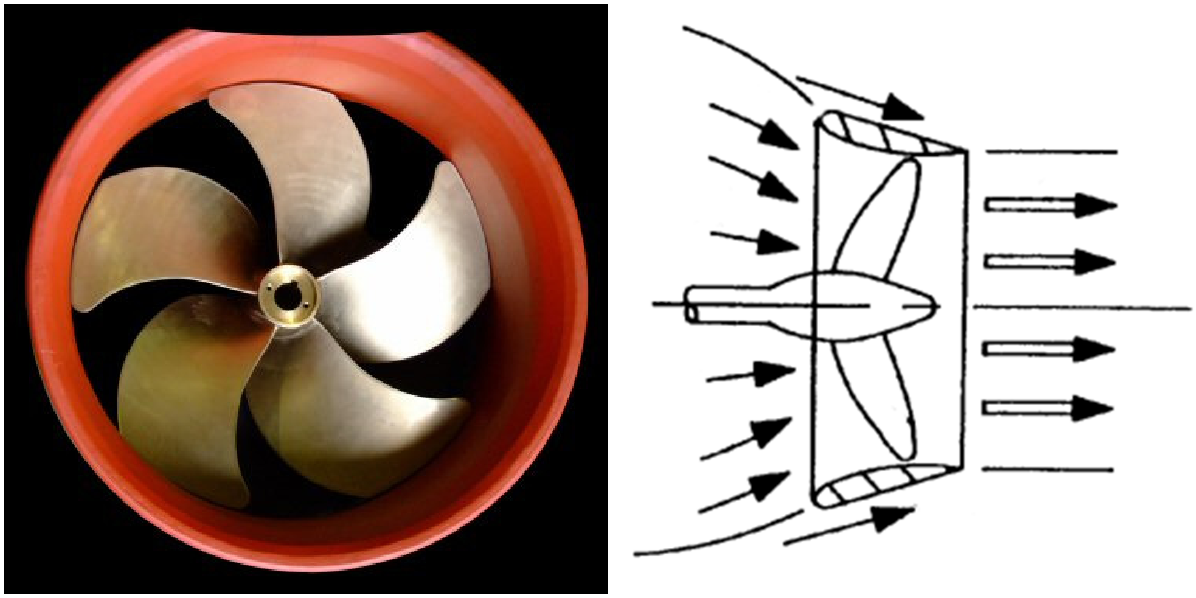


Figure 7 A ducted propellers (Kort Nozzle) can increase propeller efficiency at lower speeds. (Source: Maritime Professional).

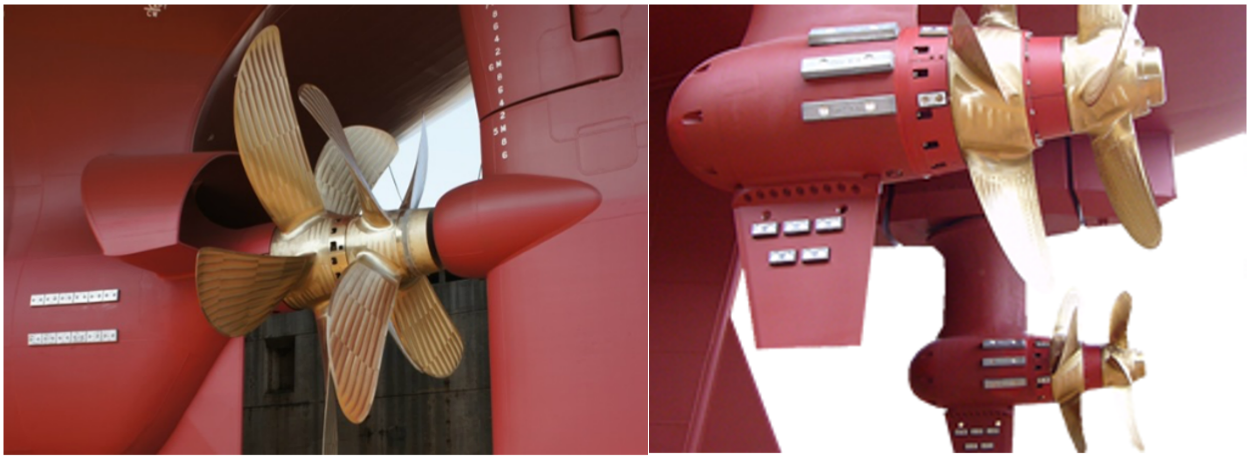
3.1.3 Controllable Pitch

A Controllable Pitch Propellers (CPP) operates by rotating each propeller blade, usually hydraulically, to vary the pitch of the blade for varying operating conditions. A CPP will be *less* efficient than a fixed pitch propeller (FPP) at it's design condition. However, CPPs can significantly improve 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. Peak efficiency of a CPP will not compare to an FPP for a given speed-power combination but CPPs are much more efficient for vessels that will have multiple operating points.

CPPs offer other operational advantages such as the ability to reverse thrust without changing rotational sense of the shaft and fine control. Disadvantages are higher first cost and higher maintenance cost.

3.1.4 Contra-rotating

Contra-rotating propellers, have two propellers rotating in opposite directions on a common shaft. They have the potential to significantly increase the propulsion efficiency by exploiting the rotating flow field of the upstream propeller to condition the wake of the downstream propeller. This is not unlike the use of a pre-swirl device (below). They are applied commercially where the added efficiency gains are great enough to make up for the added complexity and expense of the system (Figure 8). They are commonly employed on podded propulsors (below).



Source: Japan Maritime United *Source: Nakashima Propeller Co. Ltd.*

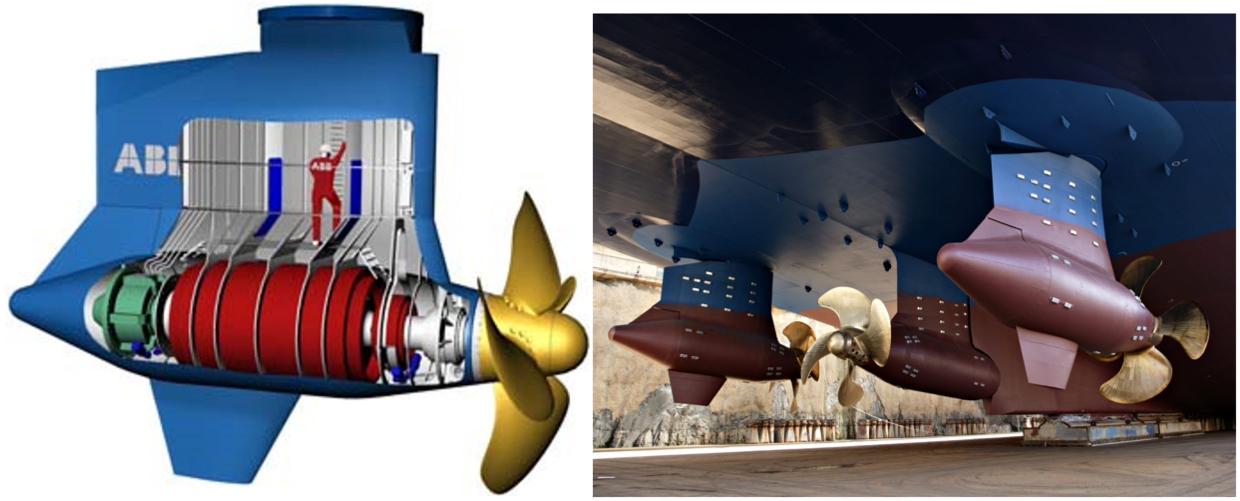
Figure 8 Contra-rotating propeller on a conventional propeller (left) and a podded propeller (right).

3.1.5 Podded and Azimuthing Propellers

Podded and azimuthing propellers are by far the most complex types of propellers. The concept combines the functions of propulsion and steering into a single device and can potentially enhance both functions. The propeller can operate either as a pushing propeller (conventional), or as a pulling propeller. Podded or azimuthing propellers can sometimes be configured to get outside of the vessel wake, where the flow is cleaner, and efficiency can be improved. The ability to get clean inflow is one particular reason the podded propellers, which are often pulling, are so efficient.

Functionally, podded propellers and azimuthing propellers are very similar. Typically, podded propellers have the motor inside a pod, which directly drives the propeller. The motor must be protected from ingress of seawater. In azimuthing propellers (aka Z-drives) the shaft is driven from a motor or an engine and the forces are transmitted by shafts and gears down to the propeller. Due to the complexity, the early versions of both types of devices saw some significant reliability issues.

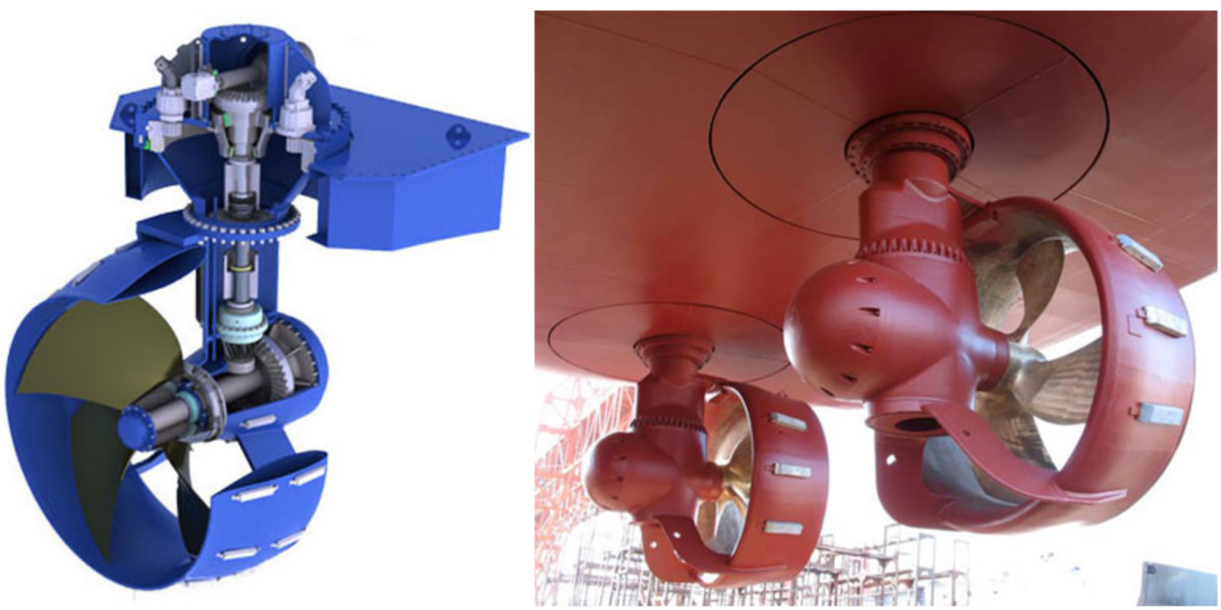
Podded propellers are widely used on very large passenger vessels. They offer many advantages in these niche applications such as high efficiency, low in-vessel noise, very high maneuverability, and significant space savings since the propulsion motor is not taking space inside the vessel. They are particularly well suited to passenger vessels, which are often diesel electric due to their large hotel loads.



Source: ABB Group

Figure 9 Podded, azimuthing propellers

Azimuthing propellers such as z-drives are very common for harbor tugs, and many offshore vessels that require dynamic positioning (DP) capability. For tugs and offshore platforms, they are often provided with a nozzle, which increases their bollard pull (zero speed thrust) capacity.



Source: Thrustmaster *Source: Pacific Marine and Industrial*

Figure 10 Azimuthing Z-drives

3.2 Pre-Swirl Devices

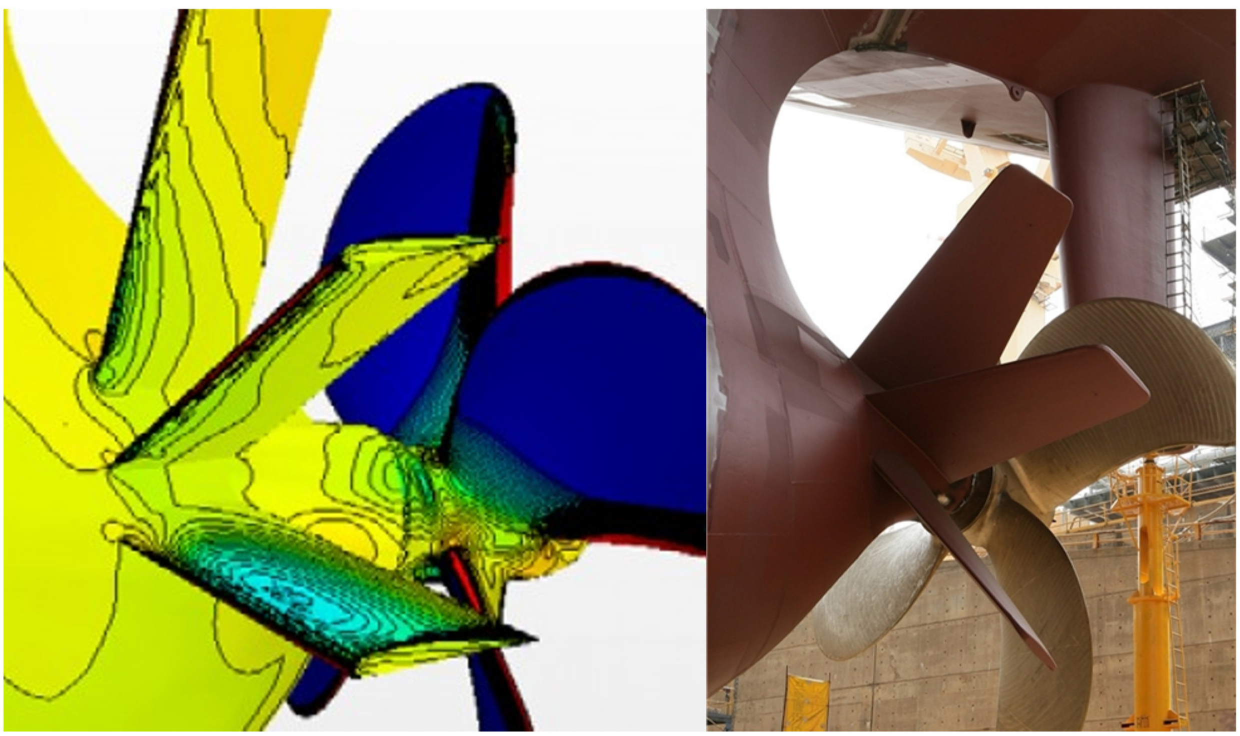
PROPELLERS AND APPENDAGES				Pre-Swirl Devices	
Savings Potential				Compatability	
Low	**Mean**	High		Vessel Category	Power Group
2%	**4%**	6%		A	All
				B	N/A
Technology Stage (1 to 3)			3	C	1,2
Lifecycle Cost (Low to High)			Low/Med	D	N/A
Retrofitable (Yes or No)			Yes	E	N/A

Table 8 Characteristics of pre-swirl devices for fuel savings

Pre-swirl devices will condition the flow coming into the propeller to improve the loading and efficiency of the propeller, as well as reducing the momentum lost to downstream twist induced by the propeller.

3.2.1 Stators

A pre-swirl stator is a set of fins installed on the propeller boss ahead of the propeller disc area (Figure 3). By itself, it does not improve efficiency and in fact, adds resistance. However, it interacts with the propeller by adding a twist to the flow in the opposite direction of the propeller rotation, which increases the angle of attack on the propeller blades and increases propulsion efficiency. The rotational flow of the pre-swirl stator can also counteract the rotational flow induced by the propeller so that the water leaving the propeller disc has less momentum in the circumferential direction. Normally the twist in the flow downstream of the propeller results in lost propulsion efficiency.



Source: CD Adapco *Source: American Bureau of Shipping (ABS)*

Figure 11 Pre-swirl stator fins

These devices are best suited for faster vessels with highly loaded propellers, such as container ships. Ideally, the propeller is optimized to work behind the stator because it will become more highly loaded as a result of the stator induced twisted flow. The devices have been designed for new vessels (best) but also retrofitted onto existing vessels.

3.2.2 Pre-swirl stator-ducts

For some vessel types with very full hull forms, such as tankers and bulkers, the pre-swirl fins are combined with an accelerating duct. The effect is similar to the pre-swirl stators but they are more suited to slower flows.

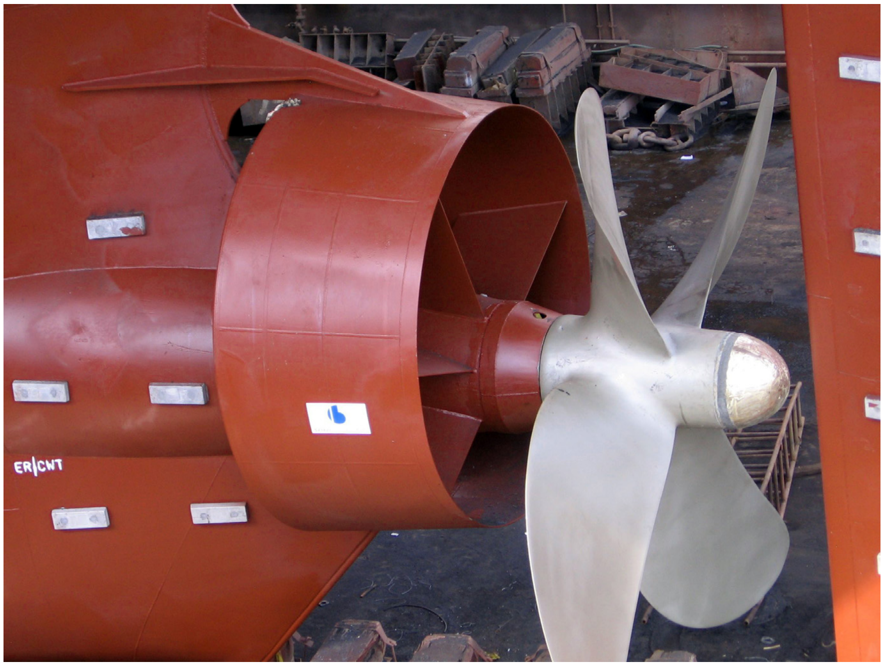


Figure 12 Becker-Mewis Duct® installed on a chemical tanker (Source: Becker Marine Systems)

3.3 Post-Swirl Devices

PROPELLERS AND APPENDAGES				Post-Swirl Devices	
Savings Potential				Compatability	
Low	**Mean**	High		Vessel Category	Power Group
2%	**4%**	6%		A	All
				B	1,2
Technology Stage (1 to 3)			3	C	1,2
Lifecycle Cost (Low to High)			Low/Med	D	2
Retrofitable (Yes or No)			Yes	E	5

Table 9 Characteristics of post-swirl devices for fuel savings

Post-swirl devices typically aim to capture some of the rotational energy that remains downstream of the propeller into thrust. They are also installed to correct detrimental flow effects such as hub vortices, or to improve rudder lift and maneuvering. Often, the devices will provide an overlap of multiple benefits since all downstream appendages are so closely interlinked. Depending on the device, they can be provided as retrofits or for new builds.

3.3.1 Rudder Thrust Fins

Rudder thrust fins are foils mounted directly to the rudder that convert a component of the rotational outflow from the propeller into useful thrust (Figure 13). The fins should not be attached to the pivoting rudder blade or the flow cannot be optimized and structural problems could ensue. Consequently, rudder fins are not suited for all rudder types. Rudder fins should be ideally attached to the rudder horn (fixed surface at the leading edge), as in Figure 13.

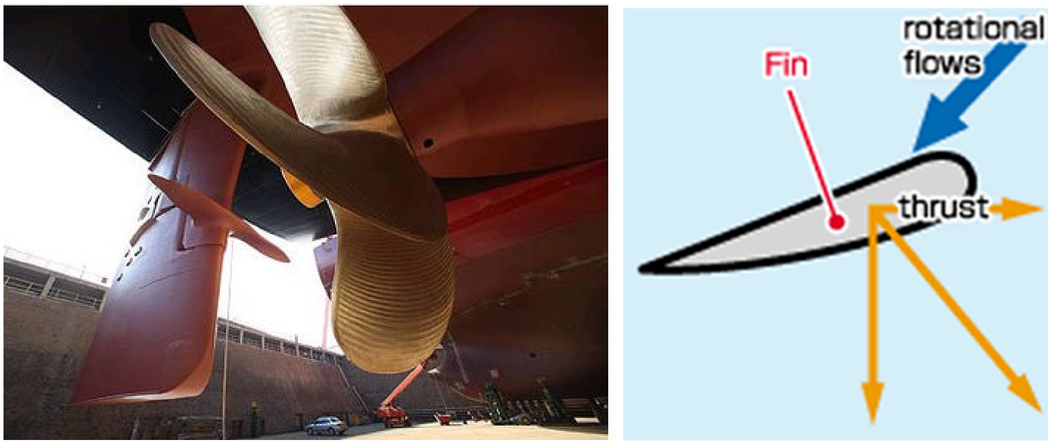


Figure 13 Hyundai (HHI) thrust fins attached to a ships rudder

3.3.2 Asymmetric Rudders

Asymmetric rudders have a twisted leading edge profile to take advantage of the fact that the flow coming off the propeller has angular momentum. The design can be combined with a Costa bulb (Figure 14) and with a modified propeller cap to improve the overall thrust and propulsion efficiency. However, the improved attack angle increase the rudder efficiency and maneuverability. They are suitable for retrofit under some circumstances.

Source: Becker Marine Systems *Source: Van der Velden® Marine Systems*

Figure 14 Asymmetric rudder (left) and asymmetric rudder with Costa bulb (right)

3.3.3 Costa Bulbs

Costa bulbs (Figure 14, right) are bulbs that extend along the line of the propeller hub to help condition the radial distribution of the flow behind the hub, where there is often a lot or rotation and vortices. A side effect is that they help accelerate the flow past the rudder, which improves its efficiency as well. A boss cap, Costa bulb, and twisted rudder can be completely integrated for even greater efficiency gains, improved maneuverability, and reduced vibration (Figure 15)

Figure 15 Rolls Royce Promas rudder (left) and Wärtsilä Energopac rudder (right) integrates a Costa bulb, rudder cap, and twisted rudder into a single device

3.3.4 Propeller Boss Cap Fin (PCBF)

Propeller Boss Cap Fins have been installed on around 3,000 vessels are a well-proven method of energy savings [Ref. 16]. They are suitable for retrofits and new builds alike and due to their simplicity, they have a very fast payback time. The difference in flow velocity between the top and bottom of the propeller blade, especially at the root, results in a strong vortex being formed behind the propeller boss cap (Figure 16, left). By adding small fins to the boss cap, the flow is redirected, converting some of the rotational energy into thrust and eliminating the hub vortex. (Figure 16, right). An installed PCBF is seen in both a new installation and a retrofit (Figure 17).

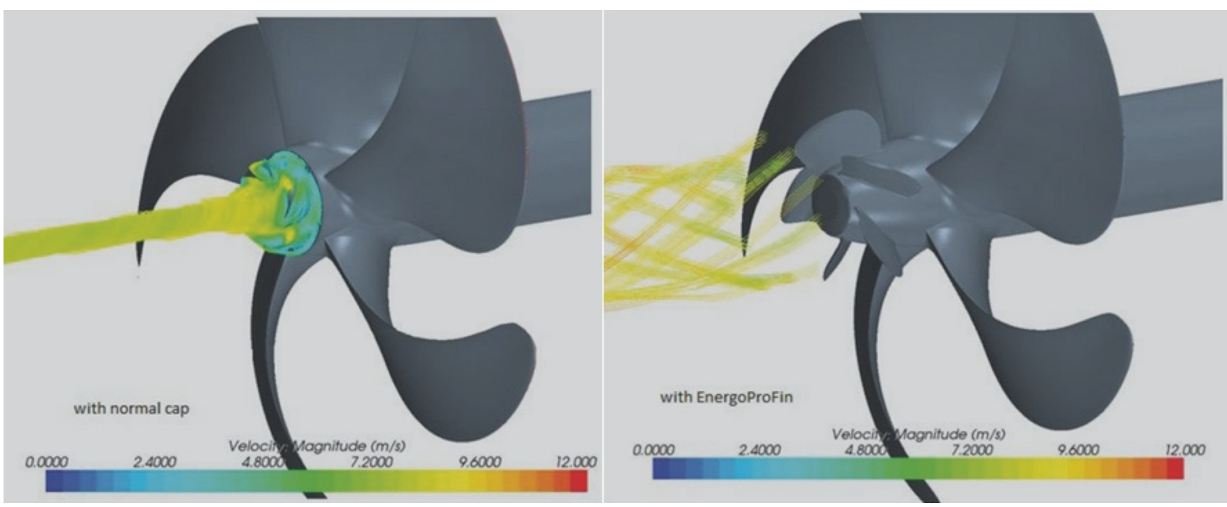


Figure 16 Hub vortex behind a boss cap (left) and with a PBCF there is no vortex (right). (Source: Marine Propulsion)

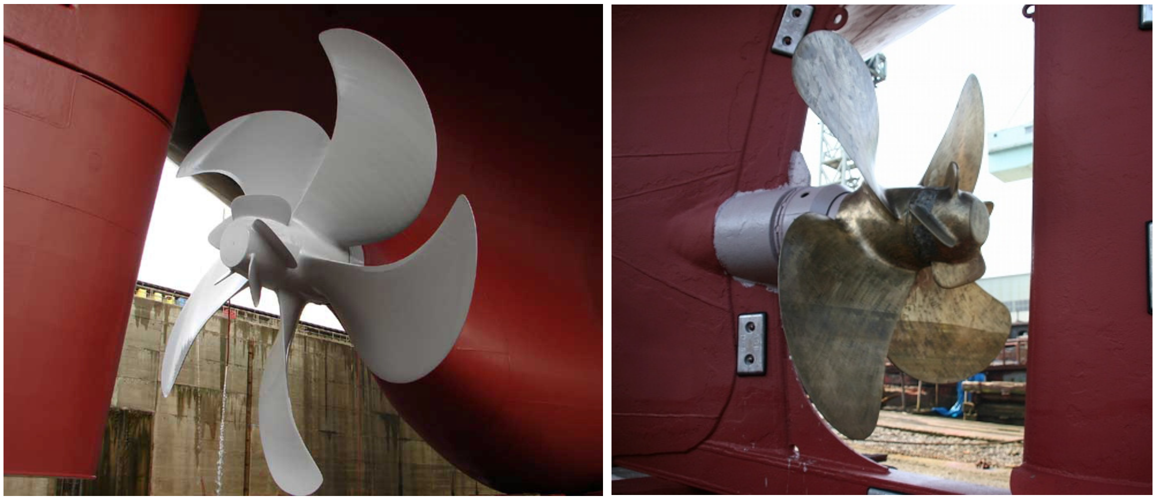


Figure 17 PCBF installations on new vessel (left) and retrofit (right). (Source: GCaptain.com)

Section 4 Renewable Energy Technologies

4.1 Wind Assisted Propulsion

RENEWABLE ENERGY				Wind	
Savings Potential				Compatability	
Low	**Mean**	High		Vessel Category	Power Group
5%	**20%**	35%		A	All
				B	1,2
Technology Stage (1 to 3)			1 - 2	C	1,2
Lifecycle Cost (Low to High)			Low/Med	D	2,4,5,7
Retrofitable (Yes or No)			Yes	E	5

Table 10 Characteristics of Wind Assisted Propulsion for fuel savings

Wind power is perhaps the most 'pure' form of maritime renewable energy and the one with the richest history. In the yacht and racing sectors, sail technology has advanced continuously, propelled by a tremendous number of innovations over the last century. However, since the end of the age of sails in the early part of the 20th century, the role of wind propulsion in commercial commerce has been minimal. With new environmental pressures, and the rising cost of fuel over the last decade, wind may be poised for a comeback.

Fully wind propelled vessels are technically as viable as ever. However, modern commercial trade requires a vessel's sailing schedule to be as reliable as clockwork. Consequently, virtually all wind propulsion concepts being considered today are to assist the diesel propulsion plant.

The last decade has seen an explosion of innovation and investment in wind assist technologies. Most devices, in principle, can be installed on new vessels or on existing vessels. However, retrofitting an existing vessel with a wind assist device will depend on numerous factors including vessel type, design, compatibility with cargo handling operations, crewing needs, etc.

Most commercial wind assist solutions fall into one of four categories: Wingsails, Kites, Flettner Rotors, and Cloth Sails. Each sail type has advantages and disadvantages based on many factors. Table 11 is a comparison of various characteristics of sail types and how these could have an impact on operation, performance, flexibility, installation, investment risk, etc.

Sail Type Comparison *(1=Least Favorable, 3=Most Favorable)*									
Sail Type	**Can it be scaled?**	**Cargo Ops Impact**	**Effective Wind Area**	**Deck Impact**	**Can it be reefed?**	**Thrust vs. Heel**	**Can it be Retrofit?**	**Technology Maturity**	**Total Score**
Kites	3	3	2	3	3	3	3	3	23
Flettner Rotor	3	2	1	2	2	2	3	3	18
Rigid Wingsail	3	1	3	1	1	1	2	2	14
Cloth Sails									
Dynarig	2	1	3	1	2	1	2	2	14
Jibs	1	1	3	1	2	1	1	3	13

Table 11 Comparison of different types of commercially scalable sails

Eight factors are compared in Table 11. Each factor is rated on a scale of one (1) to three (3). For each type of sail, the numbers are totaled so the largest overall number would tend to the most favorable for integration on a ship. It should be noted that this analysis is looking at *typical* characteristics and is also highly subjective. For example, for a specific vessel, or vessel type, a more detailed analysis could easily show that a rigid wingsail is the most favorable and/or cost effective solution. Also, it could be that certain characteristics are not relevant, or important for specific applications (e.g. retrofitable is not relevant to a new vessel, or scalability isn't relevant if a commercial vendor's solution *fits* an application). Table 11 is presented as a tool for owners to assist in understanding the many characteristic that must be considered for a sail to be installed on a vessel.

Scalability – Scaling sails to large commercial vessels, especially existing vessels, can have significant challenges. Mast size, weight and sail area can all be susceptible to scaling challenges that can significantly affect the practical adaptation needed for commercial shipping.

Cargo Operations Impact – Different sail types can have varying impacts to in-port cargo operations. The less a device influences the in-port infrastructure, or cargo loading and unloading operations the better.

Effective Wind Area – All sails produce thrust based on a ratio of lift and drag. The effectiveness or ability to create meaningful thrust in a wide variety of wind headings depends greatly on the sail type.

Deck Impact – The lower the impact on the deck area the better. For some vessel types, such as container ships that use essentially all available deck space for container stowage, there is no available deck space for sails. Some vessel types (e.g. tankers or bulkers) can tolerate some impact to deck area.

Reefable – Reefing, the ability to reduce sail area, is very important for safety, stability, and port operations. Different sail types vary in their ability to be reefed. Some can be 'virtually reefed' such as feathering a rigid wingsail so it does not produce lift. However, unless a sail can be stowed away, it can adversely affect performance in foul weather, limit cargo operations, and increase air-draft.

Thrust vs. Heel – The direction and force of thrust that a sail imparts on a vessel is rarely aligned exactly with the direction of travel. Furthermore, with most sails that force is imparted high on a mast, which acts as a lever to heel the vessel over. A vessel's tolerance for heeling depends on factors such as stability, crew comfort, and operations. Some sail types will result in much higher heeling angles on a vessel for a given amount of thrust.

Retrofitable – Some sail types or designs are poor candidates for retrofitting on existing vessels and some are excellent for all vessel types.

Technology Maturity – While sail technology is very old, new concepts still abound. Additionally new materials and technology have breathed new life into older concepts. Some sail concepts being marketed have matured enough to be implemented at scale, on commercial ocean-going vessel. Some are still in the concept phase, and have come to life only in computer models and renderings.

4.1.1 Kite Sails

Kite sails are one of the most interesting types of wind assist devices. The kite operates by the same principle of all sails and wings in which lift is generated as air passes over a 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 forces are transferred to the vessel through tension in the towing line, which is attached to the bow of the vessel.

Unlike other sail types the kite is not fixed in a single position for a given wind direction. To maximize the lifting forces, the kite flies itself in a figure eight pattern in around a central position. In doing so relative wind speed is significantly increased, resulting in much higher towing forces than if the kite were fixed. The only known manufacturer of kite sails for large commercial vessels, SkySails GmbH, claims their kites generate up to 25 times higher forces than conventional sails for the same sail area.

Advantages

Kites have advantages over other sail technologies in almost every way. They are arguably the most efficient in that they generate the highest lift per a given sail area. One reason, discussed above is that the kite can fly itself to create higher apparent wind speeds. Another reason is that the kites typically operate at much higher elevations (100 – 400 meters) where the wind speeds are normally much greater (Figure 18).

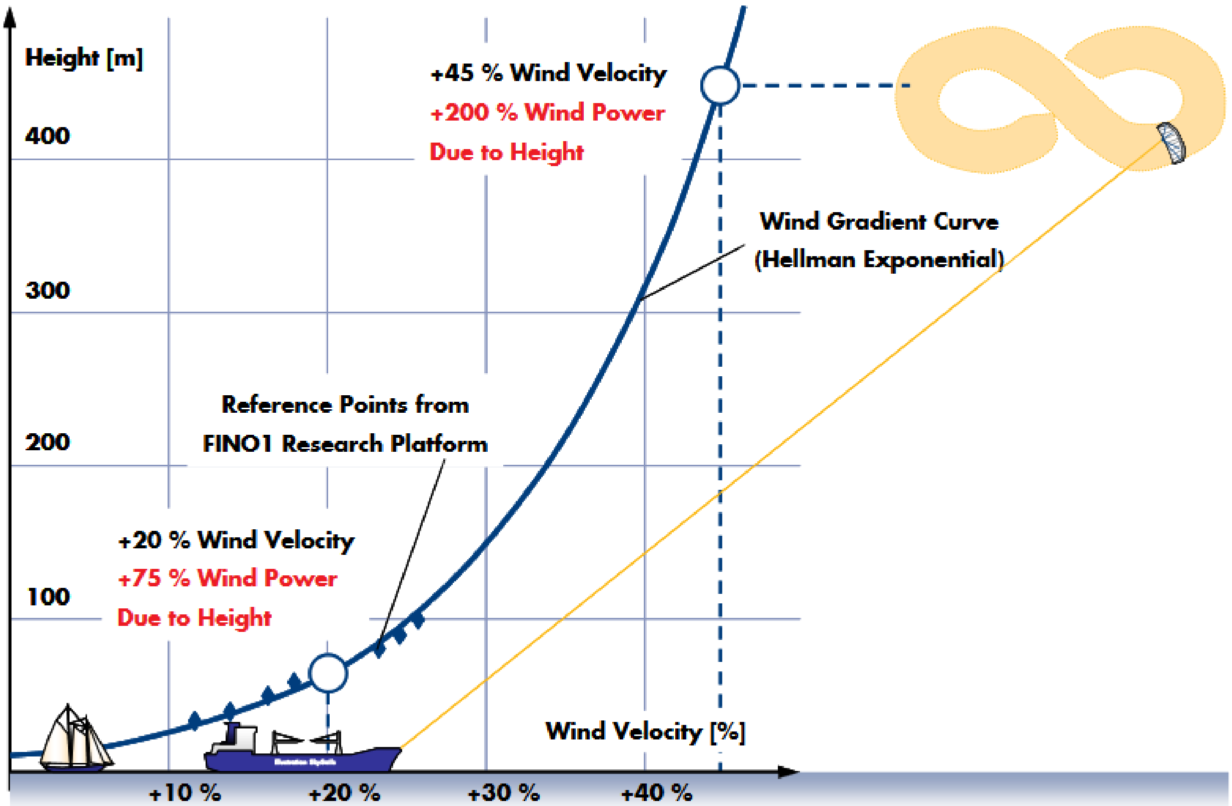


Figure 18 Wind power and velocity relative to elevation. Source: [Ref. 69].

Another key advantage of kites is that they take up almost no deck space at all and are therefore useable on essentially any vessel type. They are likely the only sail technology that can be used on container vessels, without significantly impacting operations. There is a small footprint needed for the launch and recovery mechanism and for kite stowage. The entire device can be installed as a single unit on a suitable deck foundation, only needing power and communications. When not in use, or in heavy weather, the kites can be stowed away and create no drag on the vessel.

Of all of the sail types, kites produce the smallest amount of heeling force on the vessel. Since the rope that tows the vessel is pulling up at an angle, part of the force is pulling forward, and part of the force is pulling to the side. However, because the rope is attached at the deck level, there is only a small lever-arm acting on the vessel to heel it over. In fact, this force may help to stabilize the vessel, resulting in a smoother ride with less rolling (Figure 19).

Information on commercial installations and developers of kite sails can be found in (Appendix C).

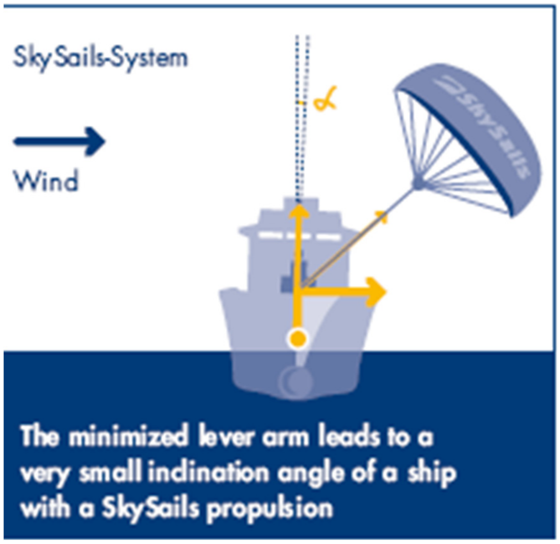


Figure 19 The low acting towing force minimizes vessel heel (Source: SkySails GmbH)

Disadvantages

Kites are less effective sailing upwind (into a headwind) than most other types of wind-assist technologies. Sailing at less than 40º from a headwind is not possible (Figure 20). Another potential disadvantage is the relative mechanical complexity of the kite compared to other sailing systems. While it may be simple compared to a vessel's main propulsion, operating the kite requires a launch and recovery system as well as a 'steering' system that is flown with the kite. These complex controls will all require maintenance. Theoretically, scaling the kite for very large vessels should be possible. However, the largest vessel currently installing a kite is a 28,000 DWT bulk carrier [Ref. 17]. Manufacturing and handling of a kite for a 300,000 DWT VLCC would present additional challenges. Kite sails are best suited for sailing in large expanses of open water, either on coastal or ocean routes, or perhaps on the Great Lakes. However, due to the length, height, and dynamic nature of the towline, kites are not suited for inland waterways, rivers, bays, lakes or sounds. These areas will have too many potential collision or entanglement hazards such as low flying aircraft, bridges, buildings, or other vessels.

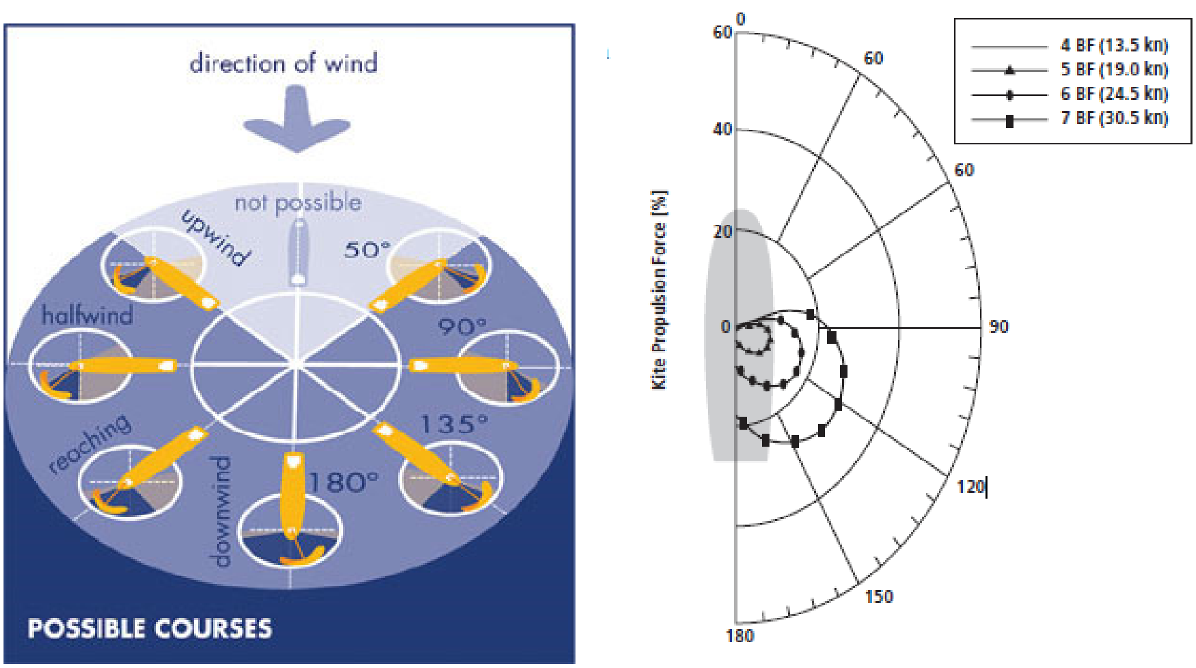


Figure 20 Possible sailing courses for kites relative to wind direction and strength (Source: Skysails, GmbH)

4.1.2 Flettner Rotors

A Flettner Rotor is a vertically aligned spinning cylinder attached to the deck of a ship to make a kind of 'virtual sail' (Figure 21). Flettner Rotors are one of the most promising, but least intuitive means of wind-assisted propulsion. Their operation is based on the 'Magnus' effect (Figure 22), caused by air passing over a spinning cylinder or sphere. When the spinning motion is in the same direction as the air movement, there is an acceleration of the fluid, which results in a lower pressure region on one side. The lower pressure region will cause the object to experience a *suction* force. The effect is similar to Bernoulli's principle, which describes lift forces created by motion of air over a wing (Figure 23). Comparing Figure 22 and Figure 23, it is evident that the motion of the air around each surface is similar. However, the turbulent wake behind the spinning cylinder results in a significant drag force that must be overcome, and results in a loss of efficiency.

Figure 21 Enercon E-ship1 utilizing four Flettner Rotors. Source: [Ref. 54]

The lift produced by a Flettner rotor is directly proportional to both the wind speed and the rotational speed (rpm) of the rotor. The lift also increases with the *square* of the cylinder diameter. In practice however, the rotor diameter of the rotors on a ship will be limited by drag, available deck space, and possibly weight and stability. Typically, rotor diameters are between 3 and 4 meters on large vessels. However, if implemented on *very* large vessels, the diameter of the rotor required may need to be even larger to achieve similar results.

Information on commercial installations and developers of Flettner rotors can be found in (Appendix C).

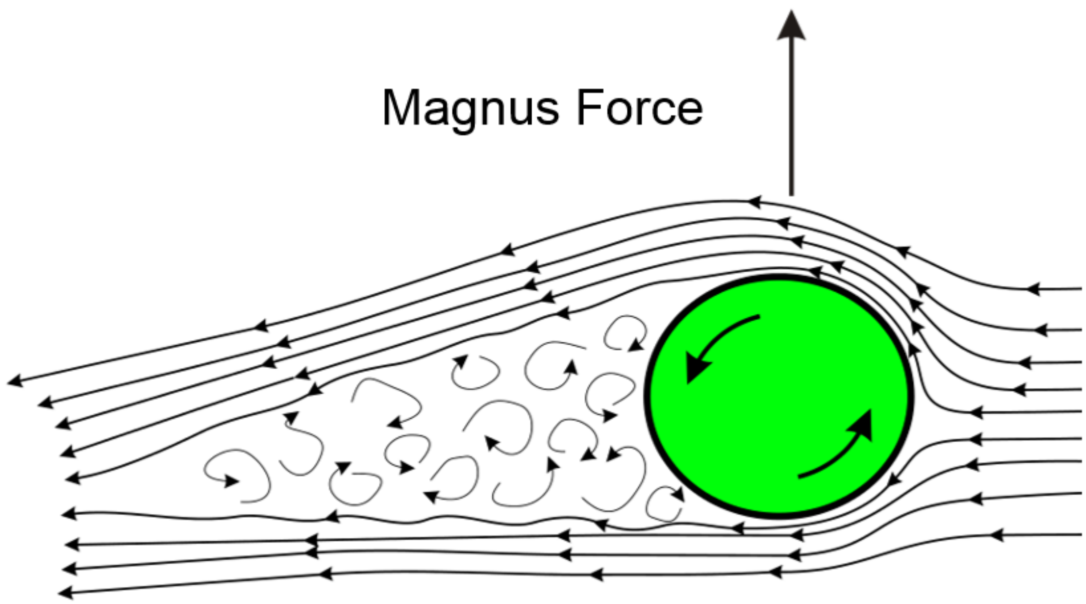


Figure 22 Magnus effect, caused by air passing over a spinning sphere of cylinder (Source: Wikipedia)

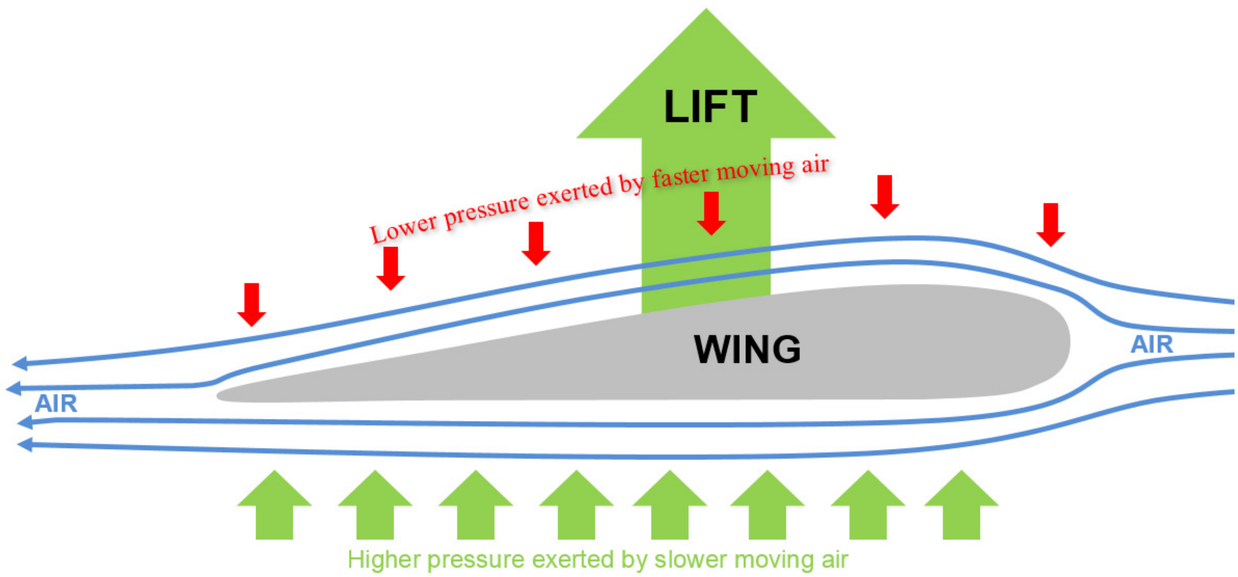


Figure 23 Lift over a wing which is described by Bernoulli's principle

Advantages

Flettner rotors may look awkward, but they can produce 8-10 times higher forces when compared to conventional sails or wingsails of similar area [Ref. 18]. This is a big advantage on a commercial vessel where free deck space can be scarce. Additionally, systems that take up a lot of area, can make cargo operations (loading/unloading) difficult or impossible. The lifting efficiency of Flettner rotors also allows them to be shorter than conventional sails, which reduces heeling moments induced on the vessel.

Compared to other sail types Flettner rotor are very simple. The only mechanical system needed in the rotation motor and brake. Since the rotor is cylindrical, it is self-adjusting as the wind changes direction along the beam of the vessel. If the wind heading changes from one side of the vessel to the other, the cylinder rotational direction is changed. The amount of thrust can be adjusted by changing the speed of rotation.

The concept is so simple that it is easily scalable to practically any size, and more retrofitable compared to any other type of sail, except kites.

In heavy weather, the rotor spin can be stopped so the rotor only produces drag. Because the rotors to not have a large area compared to other types of sails, the drag is *relatively* low, but still needs to be considered in stability calculations. Some companies are working on retractable rotors that can be stowed on or below deck. For some operators, the added complexity and expense may well be worth the convenience of stowage.

Disadvantages

Flettner rotors require continuous power to operate as a sail. While the *power consumed* is small relative to the *thrust generated* in good wind conditions, available generator power needs to be evaluated on a case-by-case basis for retrofits.

Flettner rotors cannot produce forward thrust in a headwind or a tailwind. The limit for a Flettner rotor depends on wind speed but is generally no greater than 30 degrees from ahead or astern (Figure 24). They are most effective between 80 and 100 degrees from the true wind heading.

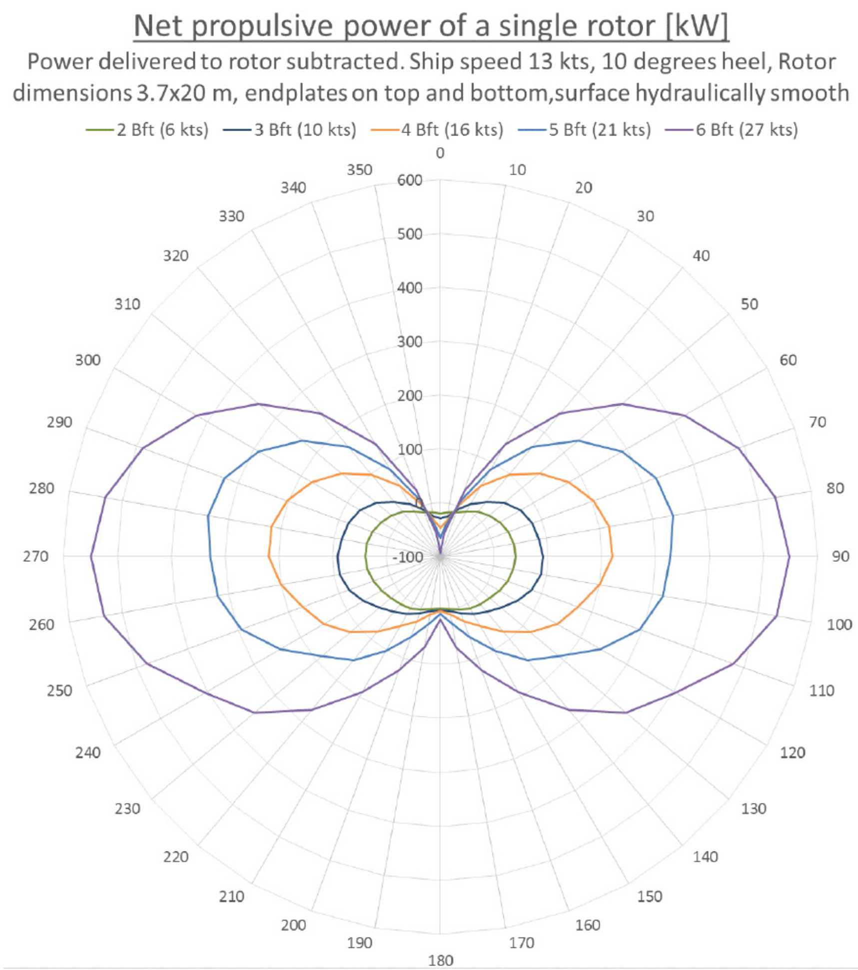


Figure 24 Net propulsive power vs. wind speed and heading for single rotor. Source: [Ref. 70].

4.1.3 Rigid Wingsails

Rigid wingsails are similar to an airplane wing attached to a vertical mast, though often with a symmetrical cross section (Figure 25). A rigid wingsail adjusts camber by rotation of a trailing edge flap rotating about a fixed vertical mast. The sail shape and direction relative to the wind (angle of attack) will determine the direction and magnitude of thrust imparted on the vessel. If wind conditions allow, the sail can provide forward or reverse thrust (Figure 26).

Both the angle of attack (angle of the leading edge relative to the wind direction) and the camber (curvature of the wing) are adjusted to maximize lift, minimize drag, and provide the most thrust for a given heading and wind speed. If the angle of attack cannot be optimized by rotation of the wing, the vessels heading can be changed to allow meaningful thrust, by tacking or jibing. Along with a thrust force, propelling the vessel forward, there is also lateral force that will heel the vessel to one side or another. The amount of heeling angle tolerated for commercial vessels will be far less than for recreational sailing yachts, and ultimately will minimize the amount of thrust that can be achieved.

Wingsails are being commercialized of for large steel vessels by several companies. Figure 27 shows a concept of how rigid wingsails could be installed on a VLCC (Very Large Crude Carrier).

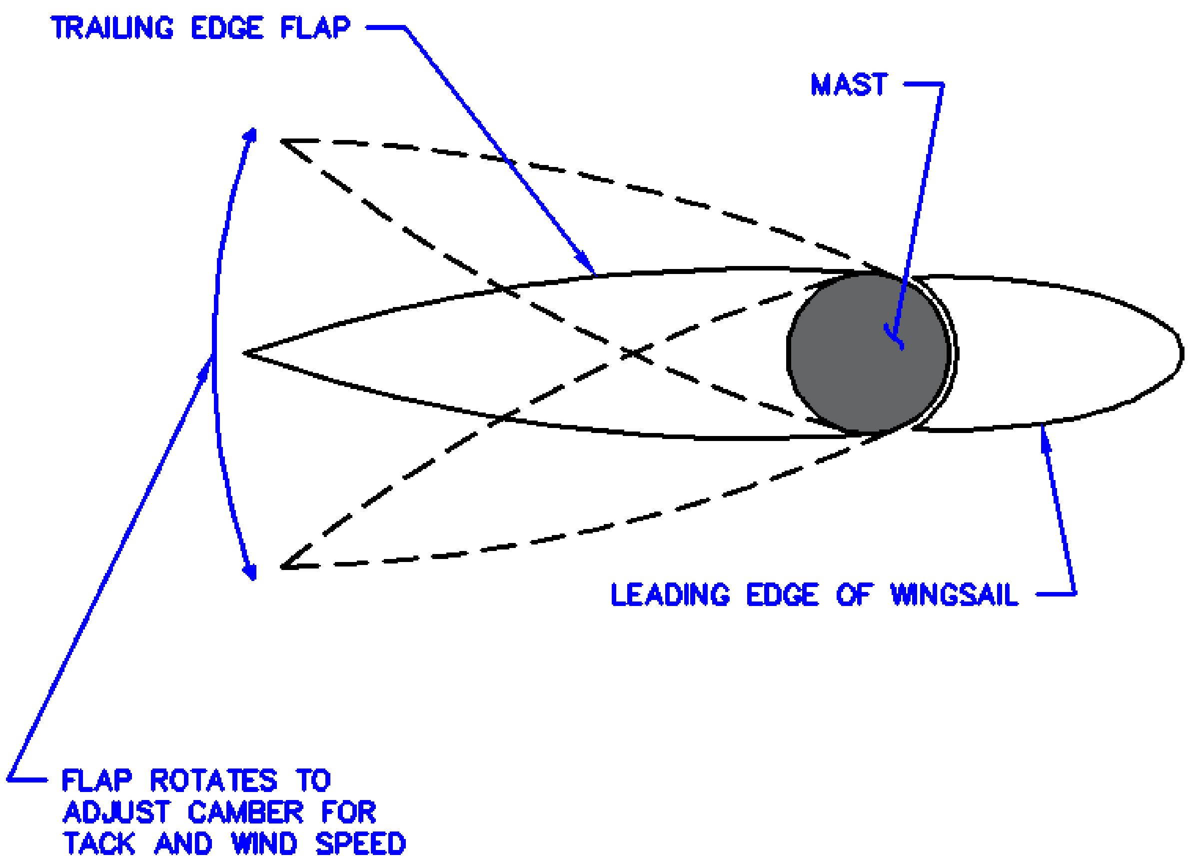


Figure 25 Typical anatomy of a rigid wingsail

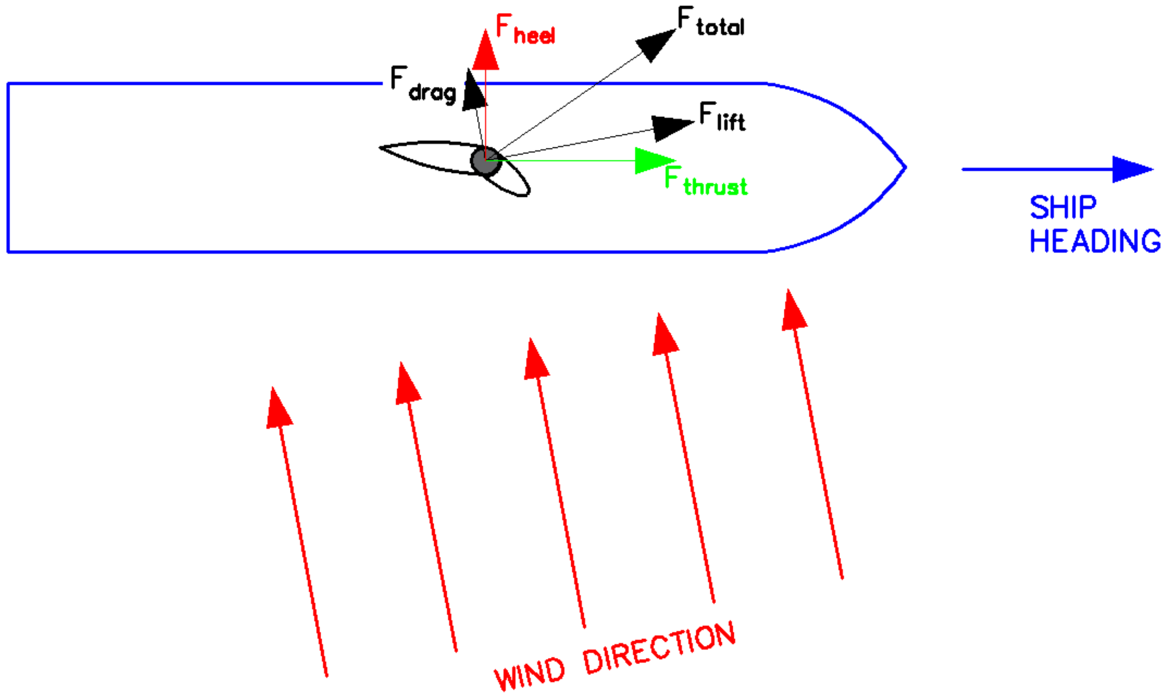


Figure 26 How wind is resolved to thrust forces on a sailing vessel

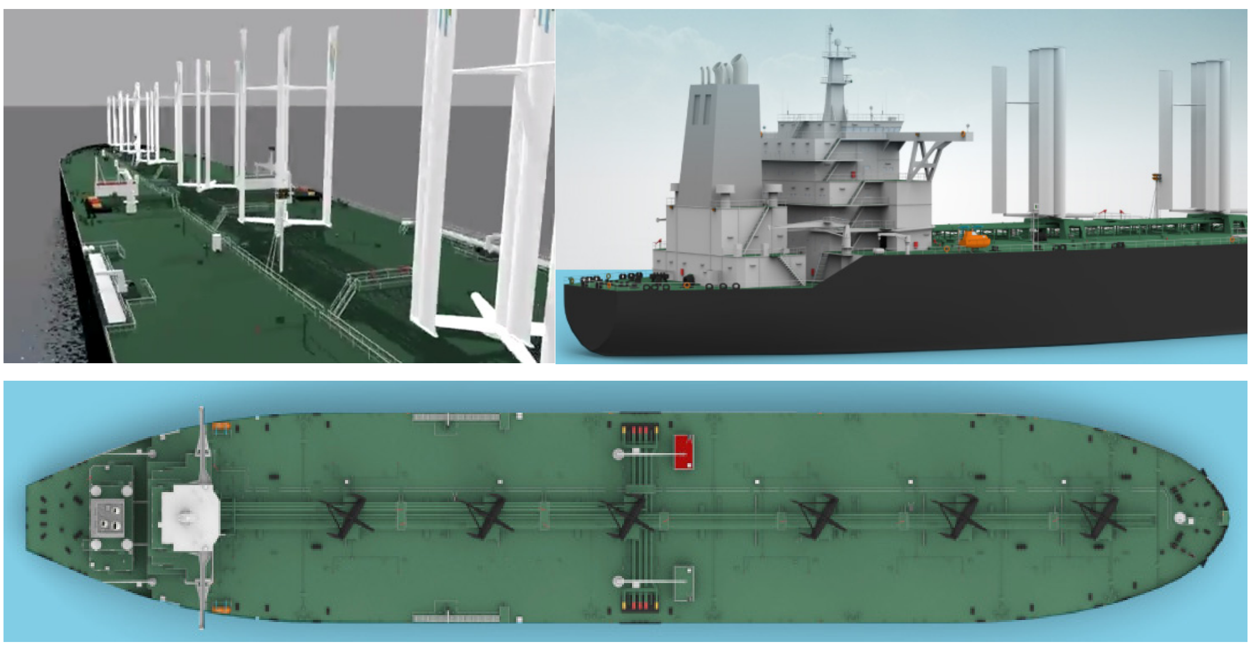


Figure 27 300,000 DWT VLCC Concept with Six Oceanfoil® Sails (Source: Oceanfoil®)

Advantages

Rigid wingsails have the potential to be very efficient and easy to operate. They can produce good thrust in most wind headings with reasonable availability (amount of time in a voyage that the wind conditions will allow use of the sails). The technology is scalable for commercial applications and for the right vessel type, feasible to retrofit. The technology is mature at the smaller scale but immature at commercial scales. However, the technology itself is not exotic and science is well understood. At the time of writing, there were no commercial installations though several companies are actively pursuing the technology (Appendix C)

Disadvantages

Rigid wingsails are not appropriate for all vessel types. Deck cargo vessels (not container vessels) may be able to implement wingsails depending on the design. Bulkers could be candidates though the sails may interfere with cargo handling. Tankers or similar vessels are ideal since the deck space for piping can be shared and the mast structure can be integrated with tank bulkheads. Another concern is how the sails will tolerate heavy weather since they cannot be fully reefed, as with a cloth sail. In heavy weather, the sails would be feathered into the wind. However, as wind directions can change somewhat rapidly it is not clear how effective this would be, especially when the vessel was stationary such as tied up at the dock for cargo operations.

4.1.4 Cloth Sails

Since the early days of sailing, the most common sail material has been cloth. Conventional rigging (masts, yards, sails, lines, and tackle) is still the most common method of sailing, even though it is the lowest technology. There are many reasons conventional sails are preferred:

- Light weight but robust
- Easy to repair with simple tools
- Work in most wind headings and conditions
- Reasonable efficiency
- Well understood
- Reefable

However, scaling these up for larger vessels presents many challenges. Retrofitting conventional sails on existing vessels is probably not possible in most cases. There are some concepts being investigated that could provide options for larger vessels but are mostly appropriate for new builds.

For sails to be appropriate for a modern commercial vessel, particularly as wind-assisted propulsion, they will need to be fully automated. Sailors are expensive and the trend is towards smaller crews and increasing automation. Conventional rigging does not generally lend itself to ‘pushbutton’ automation. Additionally, having many lines for rigging will not suit modern vessel operations. Successful concepts must be simple to operate and not be a cost or time burden on the crew.

4.1.4.1 DynaRig Sails

The DynaRig was conceived in the last 1960’s by German hydraulics engineer Wilhelm Prölss. During the 1970’s oil crisis, Prölss proposed the DynaSchiff, a 160 meter bulk carrier. The concept looks similar to conventional square rigs, but testing proved it twice as efficient. Unfortunately, the technology of the day was not sufficient and realization did not happen until the 88m yacht *Maltese Falcon* was built in 2006. The company that designed the *Maltese Falcon*, Dykstra Naval Architects, has designed an 8200 DWT cargo vessel using four DynaRig sails.

The DynaRig operates on the same principles of lift and drag as all other sails. Each mast has a number of yardarms similar to a square rig sailboat. A separate sheet can be unfurled between each pair of horizontal members (Figure 29). The yardarms are curved to help the tensioned sheet to have an optimal shape in the wind. The mast and the yardarms rotate as needed to maximize the lift. In practice, the rig is somewhat similar to a wingsail, though the camber is not adjustable (Figure 28). The sheet is stowed in the mast, and through multiple complex mechanisms is automatically extended out and tensioned.

Advantages

The DynaRig is fairly scalable and it can be reefed for heavy weather. The design also allows for pushbutton deployment of the sails (uncommon for cloth rigging), which is critical for reducing crew. The materials make this a very light sail design with a high thrust to weight ratio compared with other types for commercial vessels.

Disadvantages

The system is very complex and expensive. The designer claims the *Maltese Falcon* sails have had excellent reliability, though the cost of the DynaRig has been reported at $80 million [Ref. 19]. Even if mass-produced, it is unlikely the DynaRig could compete commercially against other, more scalable concepts. Relative to other modern sail designs, which are rapidly evolving, it is unclear that this design has many advantages. The large amount of sail area will also likely induce large heeling angles on the vessel. This is normal for a sailing yacht, but not for commercial cargo vessels. However, the aesthetic appeal and ability to automate may lead to continued development within the yacht business.

Figure 28 Dykstra Ecoliner concept drawing with DynaRig sails. Source: [Ref. 60].

Figure 29 *Maltese Falcon* with sails partially reefed (Source: BYM News)

4.2 Wave Assisted Propulsion

RENEWABLE ENERGY				**Wave**	
Savings Potential				**Compatability**	
Low	**Mean**	High		Vessel Category	Power Group
Unknown	**Unknown**	Unknown		A	All
				B	1,2
Technology Stage (1 to 3)			1	C	1,2,8
Lifecycle Cost (Low to High)			Unknown	D	4,5
Retrofitable (Yes or No)			Yes	E	5

Table 12 Characteristics of Wave Assisted Propulsion for fuel savings

Concepts for using wave energy to propel ships have been around for more than a century. The designs typically make use of horizontal hydrofoils (underwater wings) which convert the movement of water over the surface of the foil into meaningful thrust (Figure 30).

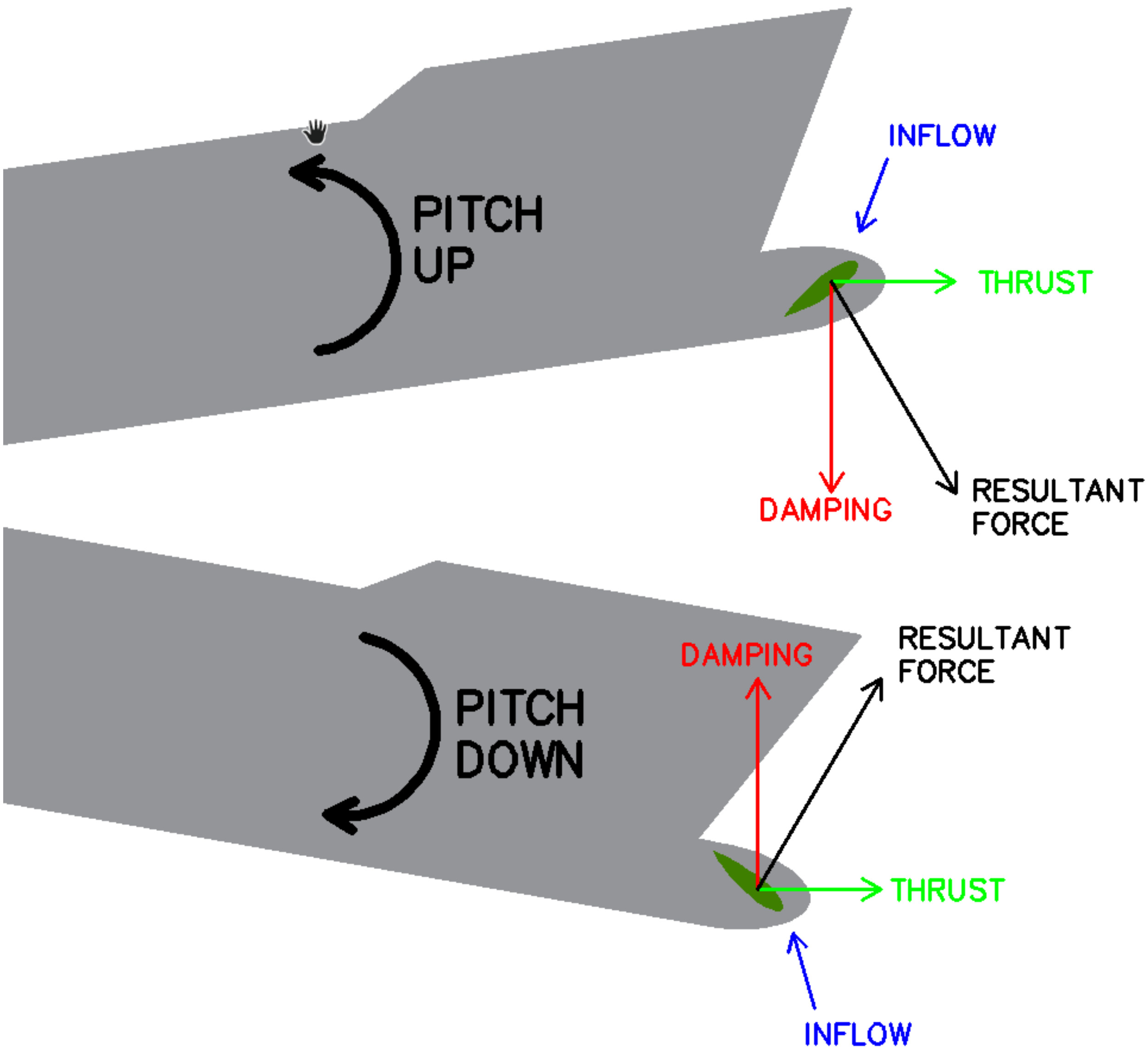


Figure 30 Specially designed hydrofoils convert vessel pitching motion from waves to meaningful thrust. Damping forces, which reduce vessel motions in a seaway, are an ancillary benefit.

On a small scale, the technology has been used to propel a vessel over thousands of miles of ocean, though at very low speeds (Figure 31). The Suntory Mermaid II is a small catamaran yacht that is propelled by wave power. In 2008, the vessel sailed from Honolulu, HI to Wakayama, Japan. The nonstop journey took 110 days at an average speed of approximately 1.5 knots, covering a distance of 3,780 nautical miles. The 31 foot, 3-ton yacht is powered by two foils at the bow [Ref. 20].

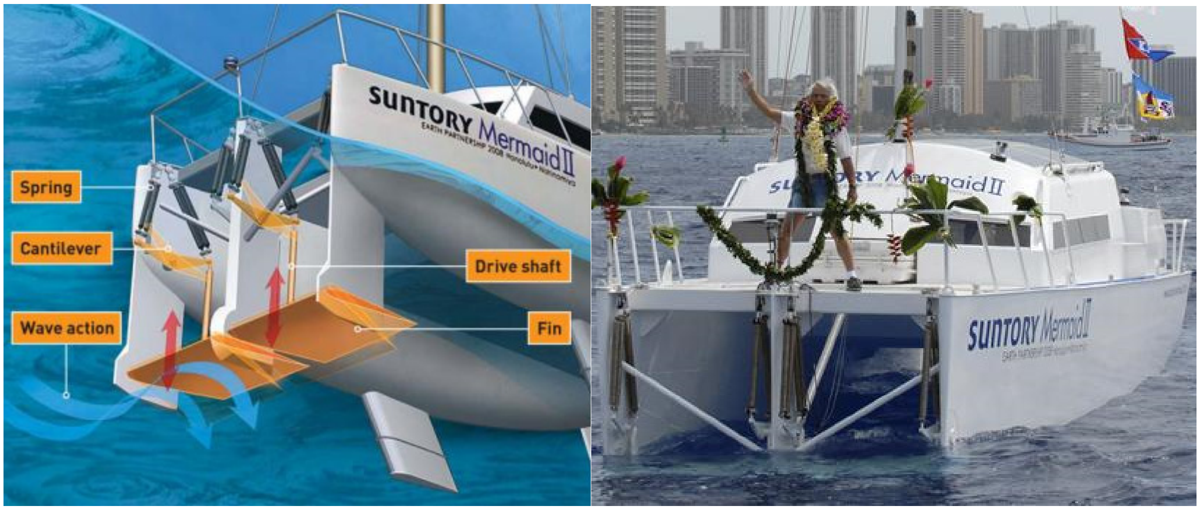


Figure 31 In 2008, the wave-powered Suntory Mermaid II sailed from Hawaii to Japan. Source: [Ref. 20]

A number of prototype wave-power systems have been tested over the years, primarily in Japan and Scandinavia. Results showed that under the right conditions, propulsion effects were significant.

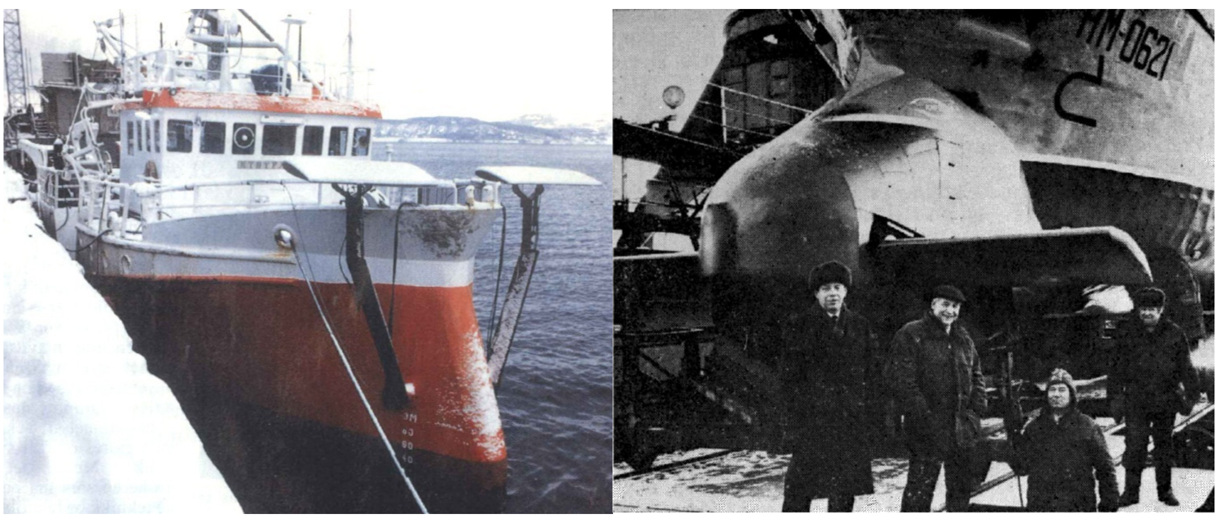


Figure 32 Prototype wave propulsion on a Norwegian fisheries vessel (left) and a Russian trawler (right). Source: [Ref. 68].

More recently, companies such as Rolls Royce have undertaken research programs with an eye towards commercialization (Figure 33). The Wave Augmented Foil Technology project (WAFT) ran from November 2013 to July 2015 and sought to reduce fuel burn by at least 10% [Ref. 21].

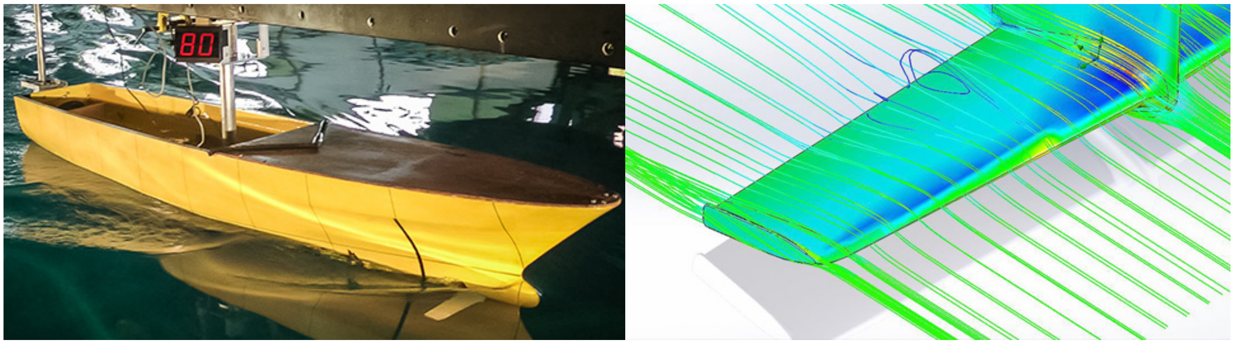


Figure 33 The WAFT (Wave Augmented Foil Technology) program led by Rolls Royce sought to mature the technology with increased R&D rigor and scalable solutions. (Source: Rolls Royce)

With fuel prices reaching historic lows in 2015 and 2016, the future of programs such as WAFT are unclear. However, concepts for future vessels running entirely on renewable energy technology and energy storage continue to be developed to spark interest in the possibilities (Figure 34).

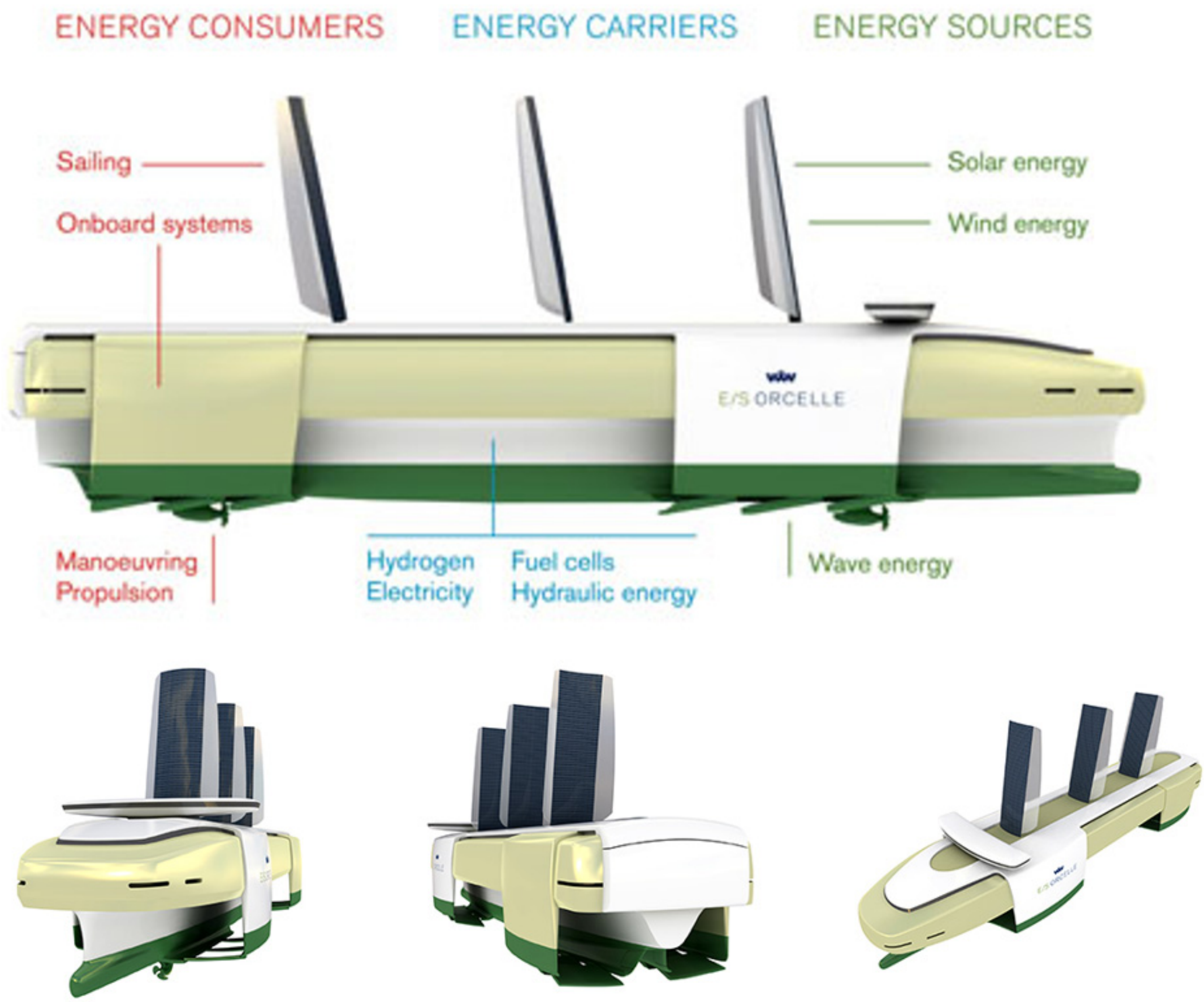


Figure 34 The E/S Orcelle is a concept for a future car carrier utilizing 100% renewable energy. Propulsion comes from solar, wind, and wave power and utilizes energy storage. (Source: Wallenius Wilhelmsen)

After more than a hundred years of investigation, interest in wave-powered vessels has not waned though the technology has still not moved beyond the prototype stage. Though it is unclear what is holding the development back, wave power is not ready for commercial adoption even if it continues to hold some allure to designers and researchers.

Advantages

- Damping. The wave foils produce significant damping forces, which reduce the pitching motions in a seaway. The amount of damping is proportional to the amount of thrust.
- Compact. Due to the density of water, the foils do not have to be large in order to produce a significant amount of thrust.
- Potentially retrofitable. The foils can theoretically be retrofitted to most vessel types.

Disadvantages

- Not commercially available. The technology has been experimental for years but has not reached the commercial stage.
- Underwater obstruction. For some vessel types, the foils will potentially be an obstruction.

4.3 Solar Assisted Propulsion

RENEWABLE ENERGY				**Solar**	
Savings Potential				**Compatability**	
Low	**Mean**	High		Vessel Category	Power Group
0%	**0.5%**	1%		A	All
				B	1,2
Technology Stage (1 to 3)			1 - 2	C	1,2
Lifecycle Cost (Low to High)			Med/High	D	None
Retrofitable (Yes or No)			Yes	E	None

Table 13 Characteristics for Solar Assisted Propulsion for fuel savings

Directly harnessing solar energy onboard a ship for propulsion power has been demonstrated on a number of vessels. However, the incident solar radiation is generally not adequate for propulsion of large commercial vessels. While pure solar vessels have been demonstrated, most applications of solar energy on marine vessels are to supplement or compliment other forms of energy capture such as wind. Most solar vessels are in fact *hybrid vessels* (See section 5.5.2).

The *MS Tûranor PlanetSolar* (Figure 35), launched in 2010 has sailed around the world on solar power *alone* and broken the solar powered speed record for crossing the Atlantic in 22 days [Ref. 22]. The owner, PlanetSolar SA, started the project in 2008 with a mission to demonstrate that "Mankind has the resources, expertise, and technologies required to completely eliminate the use of fossil fuels". While the *MS Tûranor PlanetSolar* has been wildly successful as a demonstrator to generate publicity, industry has not yet widely embraced solar powered vessels.

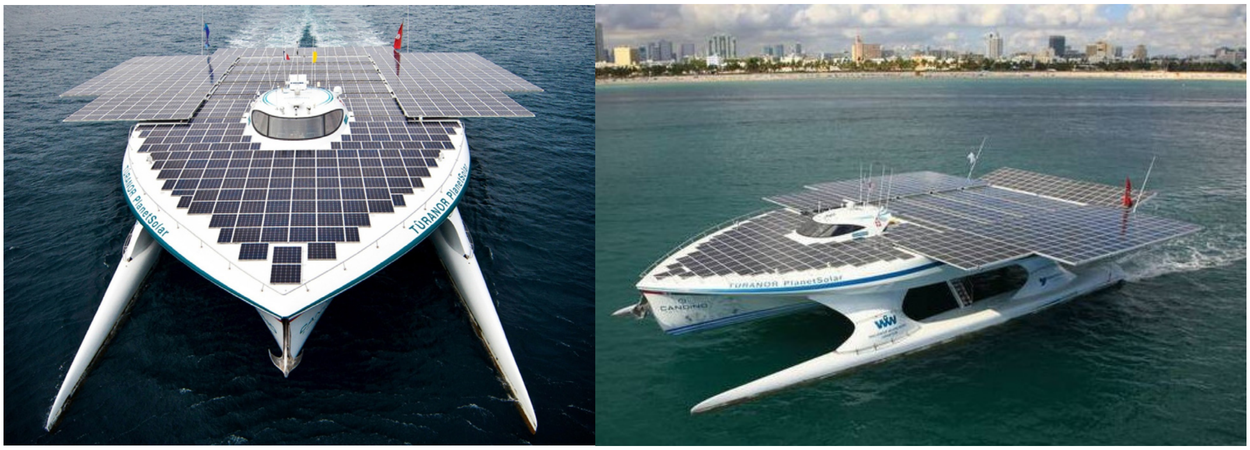


Figure 35 ***MS Tûranor PlanetSolar*** **has set a number of world records for circumnavigating the globe on solar power and speed records for crossing the Atlantic on solar power. (Source: PlanetSolar SA)**

Ocius®, formerly Solar Sailor Holdings Ltd., has developed at least six solar powered ferries and tour vessels. The best known of these, *Solar Sailor* (Figure 36), is an electric tour vessel operating on wind and solar power. Rigid wingsails with solar panels provide wind propulsion and electric power for the propeller. The system operates as a series hybrid (see Section 5.5.2.1) with batteries storing energy from the solar and a propane-fueled generator, which acts as a backup power source. The vessel can make 6 knots on solar alone via its 16 kW solar array, and 3-6 knots on wind alone (batteries allow the vessel to sail at 5 knots for 2 hours) [Ref. 23].

Figure 36 ***Solar Sailor*** **operated as a passenger tour vessel in Sydney harbor for over ten years. (Source: Ocius®)**

Ocius® has also developed four ferries in Hong Kong, and one in Singapore. The *Solar Albatross* (Figure 37) is an electric hybrid with solar wingsails and solar panels installed atop the vessel. It has a service speed of 9 knots and is rated for 76 passengers [Ref. 24]. The two wingsails can fold down when the vessel in port or when not needed. The vessel relies on solar, wind, batteries, and has two small diesel generators for backup power. As the solar array is only 4kW and the vessels peak propulsion needs are 90 kW, the solar power must be stored in battery banks to provide power when needed [Ref. 25].

Figure 37 The *Solar Albatross* uses two retractable wingsails and solar arrays for propulsion. (Source: Ocius®)

Large commercial operators such as NYK and Nissan (Figure 38) have demonstrated solar projects by retrofitting vessels with solar arrays and connecting them to their electrical grid. The relative savings from such efforts are small, accounting for less than 1% of the propulsion needs of the vessel [Ref. 26]. Little data on the overall costs (installation, operation, maintenance, ROI) are available.

Figure 38 NYK (left) and Nissan (right) have both retrofitted large car carriers with solar panels

A far more ambitious effort, still in the planning stages, is the Ecoship project (Figure 39). Ecoship is being managed by Peace Boat, a Japanese based NGO (non-governmental organization) that "*seeks to create awareness and action based on effecting positive social and political change in the world…Peace Boat carries out its main activities through a chartered passenger ship that travels the world on peace voyages.*" [Ref. 27]. The Ecoship claims to reduce fuel consumptions by 40% over conventional vessels through a combination of sails, solar panels, low friction hull technologies, waste heat recovery, and other efficiency technologies [Ref. 28]. Ecoship is a hybrid vessel with a significant contribution from solar power. Peace Boat hopes to have the vessel sailing by 2020.

Figure 39 The Ecoship is a hybrid cruise ship concept utilizing unprecedented levels of solar, wind, and biofuel for vessel operations. Source: [Ref. 28].

Installation of solar panels on commercial vessels will likely remain a niche application since not all vessel types are suited for having solar panels installed on deck. Also, the relative large area needed compared to the return in electricity makes solar unlikely to become a significant contributor to energy needs on large commercial vessels. However, when fuel prices are high, and solar costs are sufficiently low, there will likely be interest in solar for specific applications to offset onboard power usage.

Advantages

- Flexible. Solar cells can be installed on many different types of surfaces and locations but access is required maintenance.
- Quiet. Solar cells are solid state and emit no noise or vibration making them good for passenger vessels.
- Lower maintenance. Other than routing cleaning (rinsing) solar cells should be low maintenance.

Disadvantages

- Low power density. The amount of energy that can be captured compared to typical vessel power requirements is very small.
- Large footprint. Due to the low power density, solar cells require a large amount of deck space.
- Cleaning. In a salty environment, the surface of the solar cells will require regular cleaning to minimize corrosion and obstruction from salt buildup.
- High cost. For the amount of power returned, the cost of solar is high. However, the costs are falling rapidly.

Section 5 Mechanical and Electrical Systems

5.1 Prime Movers

MECHANICAL/ELECTRICAL				Prime mover	
Savings Potential				Compatability	
Low	**Mean**	High		Vessel Category	Power Group
5%	**13%**	20%		A	All
				B	All
Technology Stage (1 to 3)			3	C	All
Lifecycle Cost (Low to High)			Varies	D	All
Retrofitable (Yes or No)			Mixed	E	All

Table 14 Characteristics of Prime Mover selection in fuel savings

There are many different types of prime movers powering commercial marine vessels such as diesel engines, gas engines, gas turbines (both gas and diesel fueled), and steam turbines. Selection of the right prime mover for a particular application is a complicated affair based on factors such as size, torque, weight, speed, specific fuel consumption (fuel efficiency), and many others. Various drivers will favor different types of prime movers. However, the thermal efficiency of any prime mover will always be compared to diesel. Modern, slow-speed diesel engines can reach efficiencies well over 50% (Table 15). The *savings potential* in Table 14 reflects the *range* of efficiency variation that is seen between the various types of prime movers.

Machine Type	Small 2 MW (~2,700 HP)	Medium 10 MW (~13,500 HP)	Large 30 MW (~40,000 HP)
Low-speed diesel	~47%	~50%	~53%
Medium-speed diesel	~43%	~47%	~50%
Gas turbine	-	~32%	~35%
Gas turbine combined cycle	-	-	~40%
Steam turbine	-	-	~32%

Table 15 Peak thermal efficiencies of various marine prime movers

In the last several years, gas engines have been developed as alternatives to nearly every type of diesel engine including slow speed, medium speed, and even high speed. They can also be used for both direct drive and electrical generation. Thermal efficiencies of internal combustion gas engines will vary, but are generally comparable to diesel and in some cases slightly better. The situation can be somewhat clouded as there are numerous competing gas engine technologies and many, if not most, are burning a mixture of gas and diesel.

5.2 Direct Drive Propulsion

MECHANICAL/ELECTRICAL				Direct Drive	
Savings Potential				Compatability	
Low	**Mean**	High		Vessel Category	Power Group
N/A	N/A	N/A		A	All
				B	All
Technology Stage (1 to 3)			3	C	All
Lifecycle Cost (Low to High)			Low	D	All
Retrofitable (Yes or No)			No	E	All

Table 16 Characteristics of Direct Drive Propulsion for fuel savings

Direct drive propulsion couples the diesel or gas engine directly to the shaft that is moving the propeller. In some cases, the speed of the propeller will turn at the same rate as the engine, and in some cases, the speed of the shaft will be reduced by use of a gearbox. Generally, any mechanical device that is used between the engine output and the propeller shaft will reduce efficiency. These include shaft bearings, torsional couplings, clutches, and particularly reduction gears. In many, or most cases, these devices are necessary for the practical transmission of energy or for the safe operation of the vessel. However, when looking to save energy, the designer must consider all avenues for increasing efficiency. Transmission losses between the engine and the propeller will be 1-5% and vary somewhat based on speed [Ref. 1]. The *savings potential* in Table 16, N/A (not applicable), reflects the fact that Direct Drive Propulsion is *the standard* type of propulsion, against which other types are compared. There is certainly much variation in efficiency between various types of direct drive systems, depending on the efficiency of the prime mover, or the transmission losses. It is included here for completeness and for the purposes of discussion.

5.2.1 Slow speed engines

Slow speed diesel engines are the most efficient and generally the simplest. These large engines are available up to ~85MW (~113,000 bhp) [Ref. 29]. They are the typical prime movers for a majority of the large tonnage commercial fleet. The engines turn at the same speed as the propellers, reducing transmission losses to a minimum. These engines typically run on heavy fuel, though some manufacturers are making dual fuel or multi-fuel versions available for operation on distillate fuel and LNG. They are best suited for continuous operation with little load variation, with speeds up to around 300 rpm [Ref. 30].

5.2.2 Medium or high speed engines

Medium speed engines operate in the speed range of 300 – 1000 rpm [Ref. 30] and are available from approximate sizes between 1 – 20MW (1,340 – 27,000 bhp). They can burn light or heavy diesel, as well as LNG. They offer good load response and are therefore used for both direct drive propulsion as well as power generation. Medium speed engines typically require a reduction gear if used for directly driving a propeller.

High-speed engines operate in speed ranges above 1,000 rpm [Ref. 30]. They are used for both direct driving propellers (via a reduction gear) and power generation. Their primary advantage is light weight and low cost. They are very common on many small to medium sized vessels.

5.3 Diesel Electric Propulsion (DEP)

MECHANICAL/ELECTRICAL				Diesel Electric	
Savings Potential				Compatability	
Low	**Mean**	High		Vessel Category	Power Group
5%	**8%**	10%		A	All
				B	All
Technology Stage (1 to 3)			3	C	1
Lifecycle Cost (Low to High)			Low/Med	D	2,3,4,6,7,8
Retrofitable (Yes or No)			No	E	5

Table 17 Characteristics of Diesel Electric Propulsion for fuel savings

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 will typically have a best efficiency in the higher power ranges between 70-90% of maximum continuous rating (MCR). To maximize the efficiency, the diesel engine should spend as much time as possible operating at or near its' best efficiency point.

A vessel operating on a fixed route and schedule will have a clearly defined point for which to optimize the diesel engine. However, a vessel may operate on multiple routes or the routes may change with each contract. Consequently, the load profile (which defines the demand for power as a function of annual operating hours) may have no obviously dominant operating point. It is also common in sizing an engine for there to be a conflict between maximum power and best efficiency. For example, a vessel may have a contractual requirement to operate as 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 power demands for services other than forward propulsion. For example, large passenger vessels (e.g. cruise ships and ferries) can have very large hotel loads with a high level of variability. This also applies to many work vessels that have high auxiliary loads for special equipment or station keeping (i.e. dynamic positioning).

A diesel electric power plant is well suited in cases with highly variable loads and high auxiliary loads. Diesel electric plants use multiple electric generators to produce power, which can then be distributed for both auxiliary and propulsion demands (Figure 40). The number and size of the generators can be optimized to meet all anticipated power demands. Modern power management systems can optimize fuel consumption for each load demand case. The *savings potential* in Table 17 is compared to a direct drive propulsion system *plus* auxiliary power (total fuel consumption) for *applications that are appropriate* (e.g. variable load and high auxiliary power, etc.). Diesel electric propulsion is not suitable for all vessel types.

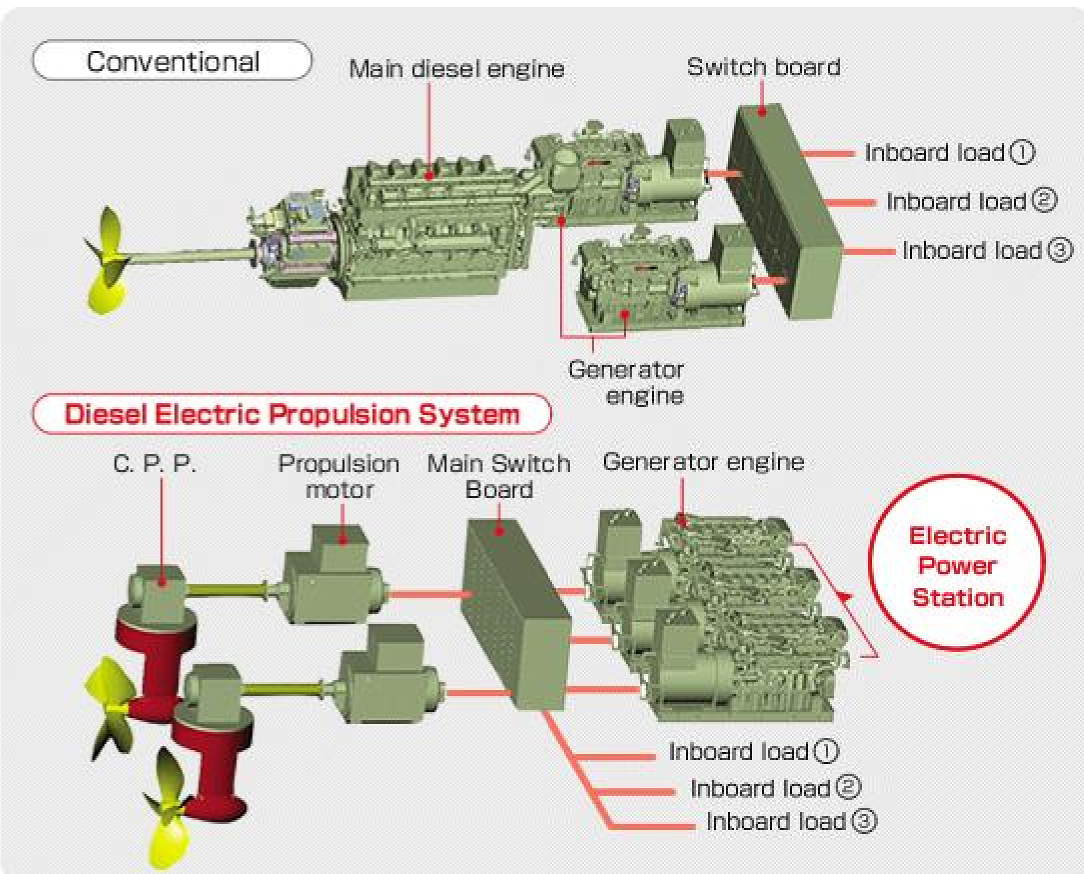


Figure 40 Conventional direct drive propulsion (top) vs. diesel electric propulsion (bottom). Source: [Ref. 71].

Advantages

- High efficiency (for the specific vessel mission)
- High reliability due to multiple engine redundancy
- Higher flexibility of arrangements (the engines location is not limited by the shaftline)
- Higher operational flexibility (one engine can drive multiple different devices or multiple engines can drive one device)
- High power density
- Lower noise and vibrations
- High torque due to electric propulsion motors (can be an advantage for certain operations)
- Only match for certain propulsors (e.g. podded propulsors)

Disadvantages

Even if diesel electric propulsion is the best choice for a certain vessel, the designer must be aware of its limitations or challenges, which go along with the great advantages that it brings.

Below is a list of disadvantages of diesel electric systems:

- High electric conversion losses (typically ~10%) between engine and shaft (Figure 41)

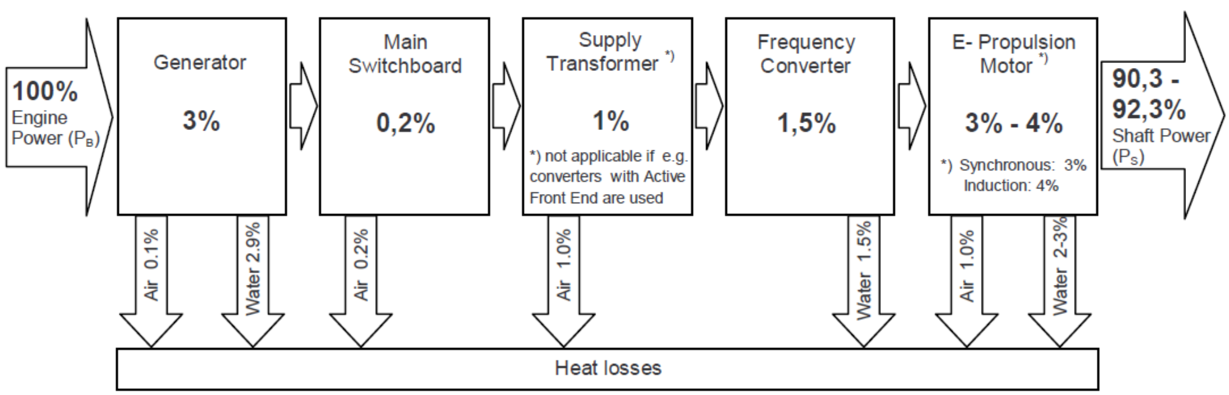


Figure 41 Typical diesel electric propulsion conversion losses between engine and shaft (Source: MAN)

- High capital cost. A DEP system may have a higher upfront cost than separating propulsion engines and auxiliary generators.
- High complexity. Depending on the capabilities of the crew and shoreside engineering staff, a diesel electric system may be considered complicated for some operations.
- Power quality risks. A poorly designed DEP system can cause power quality issues due to harmonics from the propulsion drives affecting the other electrical systems. Correcting power quality issues, even at the design stage, can add considerable cost to the overall project.
- Maintenance challenges. Although diesel electric systems are generally very reliable, their inherent complexity can create maintenance issues. A breakdown in a foreign port can sometimes mean costly delays for flying in specialized technicians or waiting for parts. It should be noted that these events are rare, but not outside of the norm.

- Component obsolescence. Complex controls and electronics can become hard or impossible to get, in some cases within 7-10 years after construction. The operator should plan components and software upgrades into lifecycle cost projections.
- Lower efficiency at lower loads. When diesel generators operate at low loads, the fuel efficiency is significantly lower. This is usually mitigated by having multiple engines and sometimes various engine sizes within a plant available to be combined to match a given load demand. However, sometimes operating at sub-optimal loads cannot be avoided which results in lower efficiency.

5.4 Variable Speed Generators (VSG's)

MECHANICAL/ELECTRICAL				**Variable speed generators**	
Savings Potential				**Compatability**	
Low	**Mean**	High		Vessel Category	Power Group
3%	**7%**	10%		A	All
				B	All
Technology Stage (1 to 3)			2	C	1
Lifecycle Cost (Low to High)			Med	D	2,3,4,6,7,8
Retrofitable (Yes or No)			Yes	E	5

Table 18 Characteristics of Variable Speed Generators for fuel savings

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

New electrical architectures entering the market in the last several years allow operation of DEP systems at varying diesel engine speeds to match power demands. This offers an added level of flexibility and efficiency over conventional DEP systems and addresses some of the primary weaknesses. VSG's can still achieve near optimal levels of fuel efficiency at low engine loads (Figure 42).

When comparing the efficiency to a standard DEP system the gains 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 VSG's. However, most DEP plants have unpredictable loads and should see some benefit from VSG's. As can be seen in Figure 42 , the fuel savings between fixed-speed and variable-speed generators increases significantly at lower loads. Therefore, an evaluation of the load profile of the vessel should be done prior to selection of VSG's. With increased volume of installations, the cost of VSG systems will likely approach the cost of standard 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.

The *savings potential* in Table 18 is compared to a conventional DEP system. In applications where DEP is preferred, owners are advised to consider the potential advantages of VSG's.

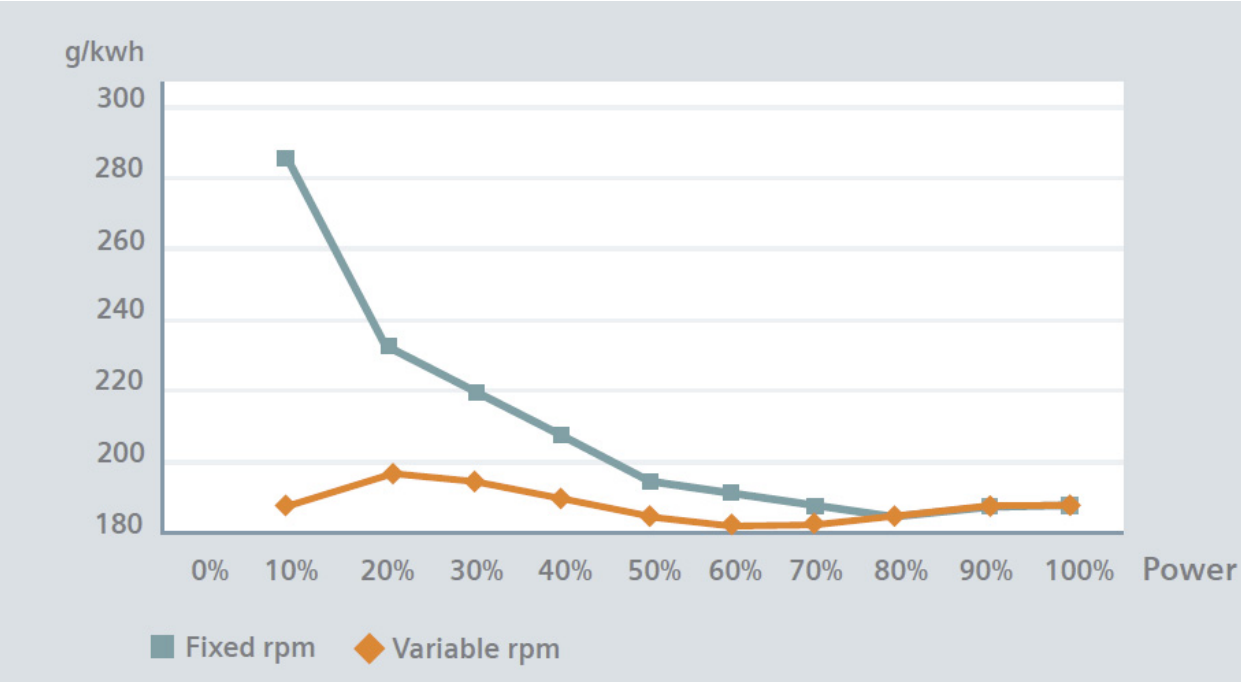


Figure 42 Specific fuel consumption for variable speed vs. synchronous speed diesel generators (Source: Siemens)

Advantages

- Reduced fuel consumption over conventional DEP for some vessel load profiles
- Reduced maintenance
- Less equipment (volume and weight)
- Potentially fewer diesel generators.
- No paralleling due to DC bus
- Simpler integration with batteries for energy storage
- Retrofitable in some cases

Disadvantages

- Higher capital cost than standard DEP
- Short operational history in the industry

5.5 Hybrid and Battery Electric

5.5.1 Energy Storage

Energy storage is an extremely important *enabler* technology in that in allows many other efficiency solutions to be possible. Hybrid power technology utilizes energy storage to maximize the efficiency of the prime movers. Energy storage also allows a marine vessel to take advantage of many other sources for power such as solar, wind, regeneration or grid power.

There has been tremendous investment and technological progress in energy storage technology over the last decade. This has been driven by multiple factors including electric vehicles, power grid stabilization and frequency regulation, renewable energy, and portable electronics.

Renewable energy such as solar and wind are highly intermittent and have been increasingly integrated into the power grid. Because they are not dispatchable, an energy industry term meaning 'on-demand,' they can sometimes stress the grid, especially as they make up a higher percentage of the overall energy mix. Energy storage is increasingly in demand for grid storage to allow greater quantities of renewables on the grid.

Costs of batteries have been falling precipitously while their overall capabilities have been improving steadily. The marine industry stands to benefit from these improvements.

5.5.1.1 Solid State Batteries

A multitude of battery chemistries are vying for a place in the rapidly growing energy storage market. Some of the key factors that one must consider with batteries are noted below.

Energy density – The amount of energy (kWh or MWh) that can be stored for a given weight (gravimetric energy density) or volume (volumetric energy density). This is very important in transportation.

Power density – The amount of peak power (kW or MW) that is available from a battery for a given weight or volume.

Efficiency – This is sometimes called 'round trip efficiency' and is the amount of 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 is 90% *efficient*. The energy put in is usually lost to internal resistance and comes out as heat. The efficiency of batteries will also vary depending on many circumstances including how quickly it is charged or discharged.

Capacity – The amount of energy that a battery can deliver in a single discharge. This is usually expressed in amp-hours, kilowatt-hours, or megawatt-hours (for very large batteries).

Cycle life – The number of full charge-discharge cycles a battery can endure before its' capacity has been reduced to 80% of its' rated capacity. Most battery chemistries will degrade in a predictable manner, depending on how hard they are cycled. The cycle life will usually be much higher if the battery is not charged or discharged as 'deeply'.

Cost – Usually noted as $/kWh. This is a key factor for consideration for any project. 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.

Safety – 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. It is important in selecting a particular type of battery, 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. One cannot simply rely on regulations as a means of ensuring safe design and operation of batteries.

Numerous types of batteries are commercially available, and the science is rapidly progressing. While energy storage is a volatile and dynamic industry, the promise of low cost energy storage will likely keep innovation at a high level for years to come. A few of types of solid-state batteries are discussed below.

5.5.1.1.1. Lead-acid

Lead acid are typically used on marine vessel for UPS's (uninterrupted power supply) and for on-board voltage supplies for various types of equipment. There are many different types but they are all generally characterized by low energy and power density, low cycle life, and low cost. They are a good choice for a UPS but a poor choice for auxiliary or propulsion power.

5.5.1.1.2. Lithium Ion

Lithium Ion batteries have become ubiquitous in the portable electronics industry. They are also ideal for transportation as they have a high energy and power density, and have a relatively high cycle life. In the past, these batteries have been quite expensive, but economies of scale brought on from the electronics and automotive industries are rapidly driving the cost of these down.

Not all lithium ion battery-types are inherently safe. For many, the safety is managed by sophisticated control and monitoring systems that constantly look at battery conditions and can shut them down if anomalies occur. Integrating them on a marine vessel needs to be done with an understanding of the inherent risks and failure modes of the particular battery chemistry. Battery storage compartments may require fire monitoring and suppression systems and should be designed in cooperation with regulatory bodies.

For small-scale battery installations on most small to medium sized marine vessels, lithium ion batteries will be the preferred solution. An increasing number of suppliers have developed systems specifically for the marine market. Lithium ion batteries are becoming increasingly accepted for on-board energy storage on a variety of vessels including workboats, ferries, fishing vessels, construction vessels, and others.

5.5.1.1.3. Sodium Sulfur

On their face, these batteries seem quite attractive for large-scale storage on a ship. They are widely used for very large grid-scale storage projects (multi-MWh). They have a high 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.

5.5.1.1.4. Zinc hybrid cathode (Znyth™)

This early stage battery technology (Eos Energy Storage, LLC) has what they claim to be a very low cost, long cycle life, high energy and power density, high efficiency, and inherently safe battery technology. Their initial product, available in early 2016, is a 4MWh battery system that is housed in a 40' ISO container intended for the enormous grid-storage market [Ref. 31]. The technology has tremendous promise, and seems very well suited for medium to large-scale marine storage applications but is still unproven. This is a technology to watch for in the future since it seems to have all of the hallmarks of a great marine battery. Also, the volatility of technology startups makes investing in novel battery types risky to owners.

5.5.1.2 Flow Batteries

Flow batteries are similar to fuel cells but reversible and closed cycle. 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 alone make them intriguing for marine applications.

They are characterized by moderate efficiency, moderate power density, moderate energy density, and low cost. An interesting possibility would be for the fluids to be charged on-shore and bunkered to tanks on the vessel similar to a fuel. This would allow the possibility for zero emission vessels of very large size.

5.5.2 Hybrid Mechanical/Electrical systems

MECHANICAL/ELECTRICAL				**Battery Hybrid**	
Savings Potential				**Compatability**	
Low	**Mean**	High		Vessel Category	Power Group
5%	**13%**	20%		A	None
				B	6,7,8
Technology Stage (1 to 3)			2	C	6,7
Lifecycle Cost (Low to High)			Med/High	D	All
Retrofitable (Yes or No)			Yes	E	All

Table 19 Characteristics of Battery Hybrid for fuel savings

There are many types of so-called hybrid systems. Usually, in the marine world, hybrid propulsion refers to a propulsion system that combines both mechanical and electrical elements, and sometimes energy storage (i.e. batteries) to optimize efficiency. Hybrid propulsion systems are often categorized as either 'Series Hybrid' or 'Parallel Hybrid' depending on the system architecture. There are advantages and disadvantages to both types of systems. Either type may be more appropriate for a given application, and highly dependent on the project goals. The *savings potential* in Table 19 is for both Series Hybrid (5.5.2.1) and Parallel Hybrid (5.5.2.2) and is relative to a *non-hybrid* vessel, either diesel-electric or direct drive.

5.5.2.1 Series Hybrid

A series hybrid is like a diesel-electric propulsion (DEP) plant with energy storage (Figure 43). The propellers are driven entirely by electric motors and the diesel engines are used to provide propulsion power and auxiliary power. The battery bank(s) is charged by the diesel generators or shore power, and/or other sources (solar, wind, regenerative power from propellers, etc.). The batteries are charged during times of low power demand and discharged during times of high power demand. Therefore, the diesel engines can operate more often near their best efficiency point rather than spending time following the load changes in real time.

The added efficiency comes from the more efficient operation of the diesel engines. Fuel savings can also come from charging the battery bank from shore, either during the night or while the vessel is idle at the dock. In addition, if other sources of power are available, such as wind or solar, these can trickle charge the battery while the vessel is underway to offset fuel consumption.

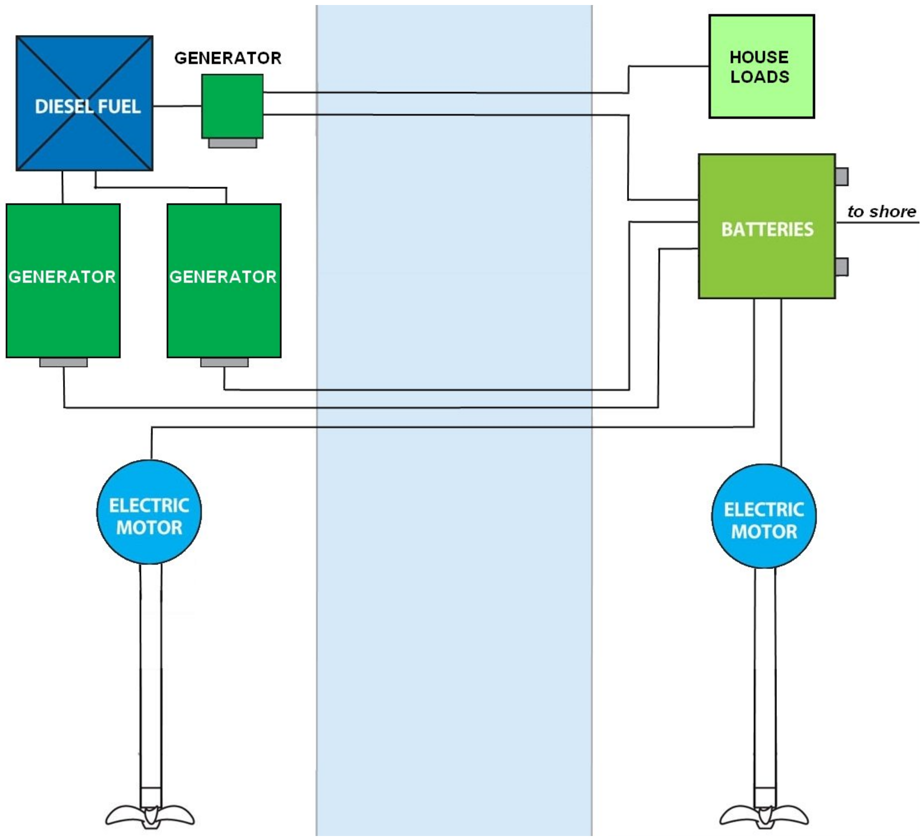


Figure 43 Series Hybrid Electric Plant. Source: [Ref. 72].

Advantages

- Relatively easy conversion from standard DEP plant.
- Potential to have smaller sized diesel engines since they do not have to handle peak loads.
- Potential for lower maintenance by reducing hours on the diesel engines.
- Potential to operate without diesel engines at low speeds providing zero emissions and/or low noise operation near port or at the dock. This is only limited by the power and energy storage limits of the batteries.
- Easy to integrate alternative sources of power (wind, solar, fuel cells, etc.)
- If used with high torque motors (e.g. permanent magnet) the gearbox can be eliminated saving weight and fuel.
- Potential to capture regenerative power either from propellers or from onboard auxiliary machinery like winches (the motors must also be configured as generators). For certain vessel types this can provide significant energy savings.
- Potential regulatory futureproofing. As battery or fuel cell technology advances, with higher capacity and lower cost, these can be easily integrated into the existing platform. In this way, the vessel can potentially get significantly cleaner over time as upgrades are integrated.

Disadvantages

- Potentially higher cost due to larger battery and larger motors
- Potentially high weight due to large battery bank

- High volume since large engines, motors, switchgear, batteries are all needed.

5.5.2.2 Parallel Hybrid

A parallel hybrid system is more similar to a conventional propulsion system but blended with a small diesel electric system (Figure 44). They are well suited when the vessel load profile has competing demands for both high and low power.

This is easily understood with harbor assist or escort tugs which need to have very high power available for arresting or moving a large oceangoing vessel. This requires installing very large diesel engines driving very large propellers. However, the high power is only needed for maybe 5-15% of the vessel's operating time. The remainder of the time the vessel may be transiting at very low power or loitering (often at idle). A parallel hybrid 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 high power is needed, the main engines and the motors can work in parallel providing an added boost of power. Potentially this can allow the main engines to be slightly downsized.

Efficiency can potentially be gained by operating all of the engines at their best efficiency. Additional fuel can be saved by charging the batteries from shore or by using power regeneration, in some cases.

The parallel hybrid concept is sometimes used without the energy storage option, to lower cost. This can still be very attractive from an emissions and energy savings point of view and still has the potential for future retrofits with batteries. As battery costs come down, they will be increasingly included in power plants for efficiency optimization.

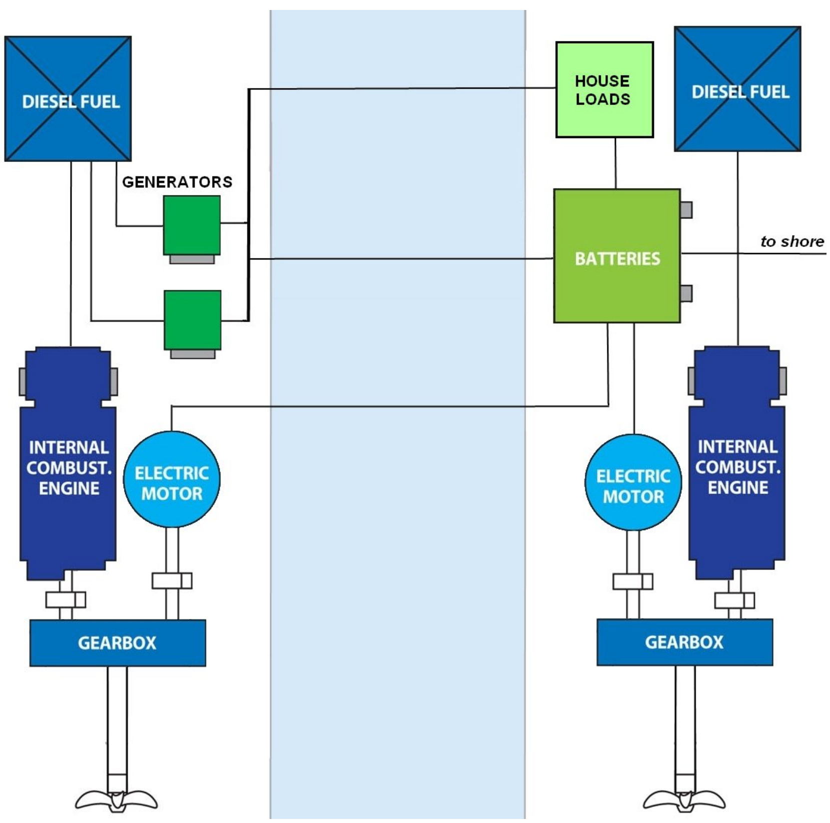


Figure 44 Parallel Hybrid Electric Plant. Source: [Ref. 72].

Advantages

- Potentially higher efficiency than DEP (in some operating modes) since the engines are allowed to drive the propellers directly without electrical losses.
- Potential to have smaller sized diesel engines since they do not have to handle peak loads.
- Potential to lower maintenance by reducing hours on the large diesel engines.
- Potential to operate without diesel engines at low speeds providing zero emissions and/or low noise operation near port or at the dock. This is only limited by the power and energy storage limits of the batteries.

Disadvantages

- Not easily converted from conventional or DEP plant
- Potentially higher cost due to batteries and motors
- Potentially higher weight

5.5.3 Battery-Electric

MECHANICAL/ELECTRICAL				**Battery Electric**	
Savings Potential				**Compatability**	
Low	**Mean**	High		Vessel Category	Power Group
100%	**100%**	100%		A	None
				B	7,8
Technology Stage (1 to 3)			1 - 2	C	None
Lifecycle Cost (Low to High)			Med/High	D	7,8
Retrofitable (Yes or No)			Mixed	E	None

Table 20 Characteristics of Battery-Electric for fuel savings

For niche applications, a zero-emission vessel is possible today by use of a battery electric system. Batteries must provide adequate energy storage for at least one trip or several round trips. The stored energy can be used for both propulsion and auxiliary power. Charging from shore can happen when the vessel is at the dock. The charging infrastructure must be carefully considered to fit the vessels' operational needs. The *savings potential* in Table 20 reflect the assumption of fully displacing combustion devices with stored energy (i.e. no fuel is burned onboard).

Even if the vessel emits no pollution, if the vessel is charging its' batteries from the grid, there may be a question as to whether this is more efficient *or cleaner* than having a diesel powered vessel. There are a number of ways energy can be lost between power plant and the ships propeller.

- Average electricity generation efficiency for thermal conversion plants in the US: 33% – 41% (Best ~ 60%) – Figure 45;
- Average transmission efficiency in the US: 94% (i.e. 6% transmission loss) [Ref. 32];
- Assumed round trip efficiency for charge/discharge cycle, including losses for inverters, chargers, and internal battery resistance: ~90% (will vary depending on battery type, charge rate, equipment efficiency, etc.);
- Assumed efficiency between battery and shaft output: 90-95% (5-10% losses in drives, shaft and gears).

Summing these losses it is reasonable to expect 20-25% losses between the power plant and the shaft input to the propeller, not including the thermal efficiency of the power generation. The US energy grid is about 1/3 renewables and nuclear (Figure 46) which are carbon neutral and this fraction is rising steadily as renewables are increasingly adopted. So *over time* the electricity grid is getting cleaner and more efficient.

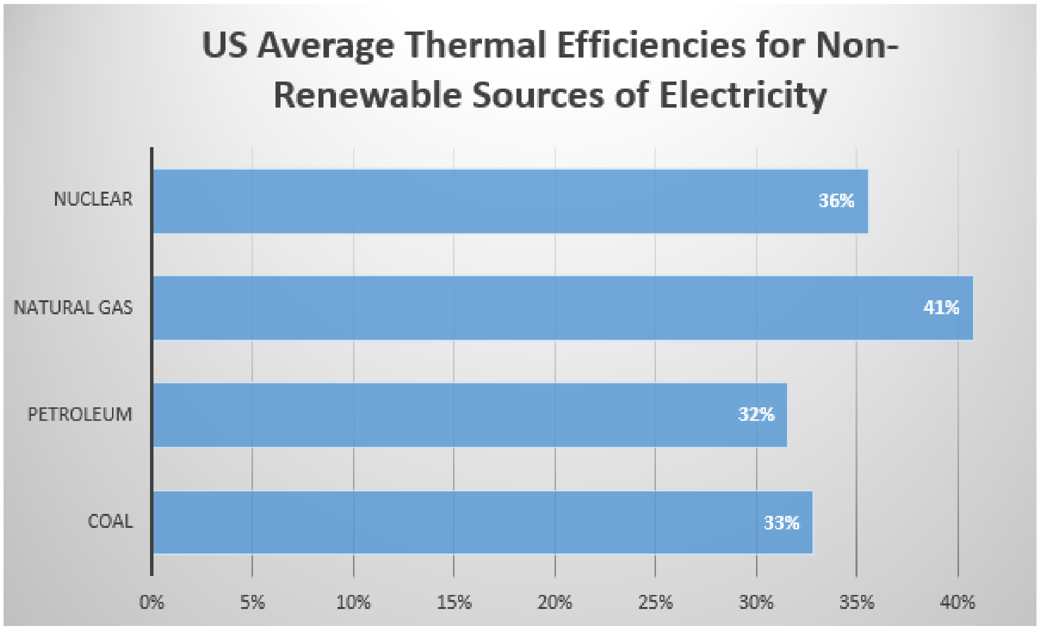


Figure 45 Ten-Year Average Thermal Efficiencies of Non-Renewable US Electricity (Source: Energy Information Administration (EIA))

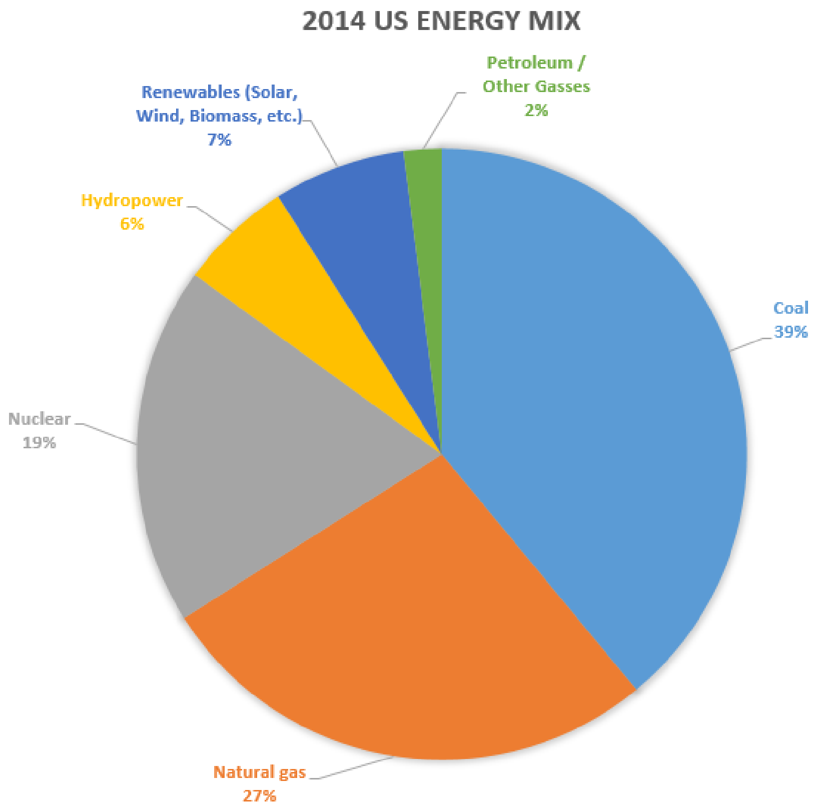


Figure 46 US Electricity Generation Energy Mix (Source: EIA)

On the other hand, if one knows their electricity is coming from a dirty or inefficient source it may be more efficient to generate electricity on-board with a diesel or gas generator operating at optimal load. Energy storage via an efficient battery can greatly improve the efficiency of the electricity generation as can variable speed operation. One cannot make a broad statement that battery-electric ferry will be *more efficient* than a diesel fueled ferry as there are so many factors affecting this. However, over the life of a vessel it is very likely that the grid will become much cleaner as an energy source than a diesel fueled vessel.

Advantages

Pure battery powered vessels have many potential advantages. At the present capacity and cost of batteries, they will only be practical on short routes in niche applications. Charging frequency and operations will need to be carefully considered, as will the realities of backup generators in the event of equipment failures.

- Zero on-vessel emissions
- Extremely responsive propulsion (instantaneous torque)
- Very low noise and vibration
- Potentially very low lifecycle cost. Costs depend on battery cost, battery cycle life, on shore infrastructure costs, and power costs. The maintenance costs are very low compared to diesel systems and there is no fuel to purchase. However, the batteries will need replacement. Lifecycle cost assumptions should include cost reductions over time for batteries.
- Battery costs are rapidly declining and capacities are steadily improving.

Disadvantages

Pure battery powered vessels will likely be niche applications for the near future until battery costs and capacity improve significantly.

- High capital cost (somewhat offset by the elimination of many complex mechanical systems)
- Shore infrastructure will likely require upgrades due to the high current requirements for rapid charging.
- Rapid charging, often required for battery-powered vessels, shortens the battery life. Overnight slow charging is preferred if possible.
- Careful risk analysis surrounding the battery safety should be undertaken, especially for passenger vessels.
- Bleeding edge technology usually requires additional regulatory work in the planning and construction phases.

Battery electric technology has been demonstrated on a medium sized ferry in Norway. The Norwegian ferry operator Noreled AS operates the *Ampere* between Lavik and Oppedal Norway (Figure 48, left). The 80 meter (262 feet) vessel carries 120 cars and 360 passengers on the 6 km (9 mile) route, which it transits 34 times per day. The vessel has two 520 kWh battery backs on board and each shore station has a 410kWh battery pack (Figure 47) [Ref. 33]. The vessel plugs in on each end of the route and gets a quick charge using a large plug (Figure 48, right) which is handled by an automated system.

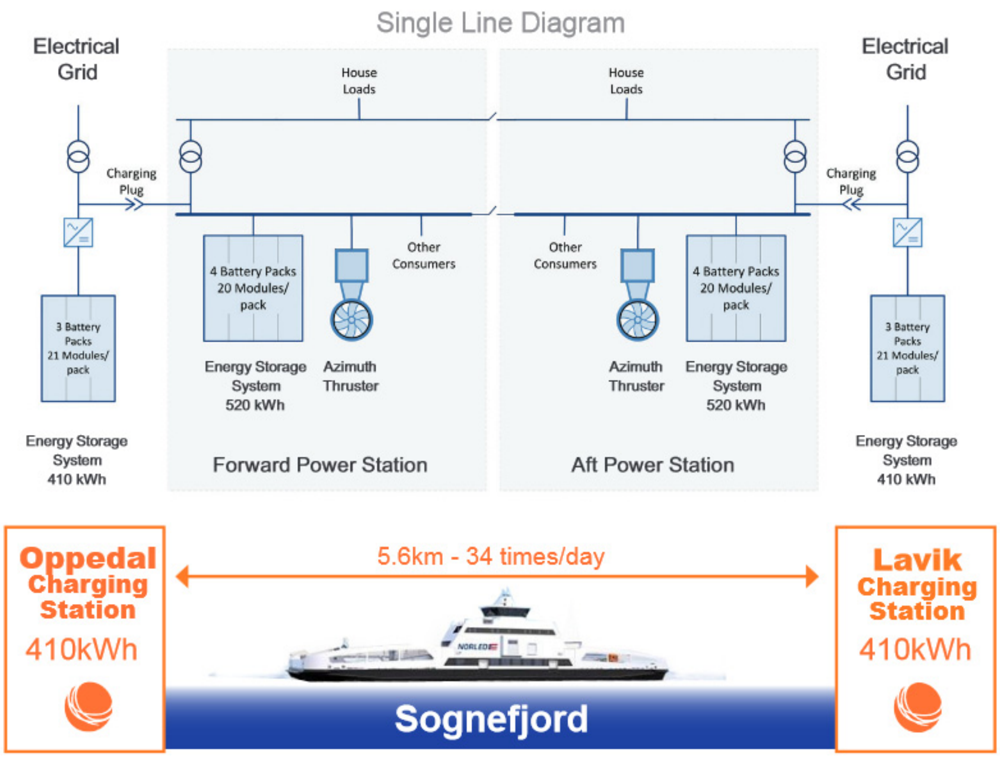


Figure 47 Electrical schematic for the *Ampere* battery ferry (Source: Corvus, LLC)

Figure 48 Ampere ferry (left) and shore charging plug (right). Source: Siemens

5.6 Fuel Cells

MECHANICAL/ELECTRICAL				**Fuel Cells**	
Savings Potential				**Compatability**	
Low	**Mean**	High		Vessel Category	Power Group
Unknown				A	None
				B	None
Technology Stage (1 to 3)			1 - 2	C	None
Lifecycle Cost (Low to High)			High	D	7,8
Retrofitable (Yes or No)			Mixed	E	8

Table 21 Characteristics of Fuel Cells for fuel savings

A fuel cell is a device that electrochemically converts the energy of a 'fuel' such as hydrogen or methane to direct current (DC power). The conversion is very clean and efficient (50-70% efficiency in converting fuel to DC power), with the only by-products being water vapor (if the fuel is hydrogen) and CO2 (if the fuel is a hydrocarbon like methane) [Ref. 34]. The process does not produce particulates or NO_x, which makes it very attractive.

Different kinds of fuel cells operate at different temperatures. Some operate as low as 80ºC and some operate as high as 1000ºC [Ref. 34]. High temperature fuel cells can be very efficient but are very slow to start up and slow to respond to load changes. They are best suited to steady state operation, such as on-shore power generation. Low temperature fuel cells are used for vehicles such as cars and busses, because they are quick to start up and can respond to load changes more quickly. Low temperature fuel cells, which are most well suited for transportation, typically operate on pure hydrogen.

The hydrogen must be stored in tanks at a high pressure. The tanks are very robust and generally tested to withstand impacts for the automotive industry. However, there is always concern when using hydrogen due to its' high flammability, and storing gas under pressure. Though these issues can be overcome, there are significant regulatory and design risks that come with using hydrogen fuel on a marine vessel.

While fuel cells *are* efficient at converting hydrogen to electricity, it must be considered where the hydrogen comes from. The vast majority of hydrogen (~96%) is produced by conversion from fossil fuels such as steam reforming of methane (SMR) [Ref. 35]. Consequently SMR hydrogen costs at least two times the cost of natural gas per unit of energy produced [Ref. 35]. Hydrogen can also be produced by electrolyzing water, but the efficiency is very low, and the cost very high compared to SMR. There is significant research underway to invent new and more efficient ways of producing hydrogen from renewable sources such as sunlight but these are not close to commercialization. Considering the conversion losses to manufacture hydrogen and *then* to convert the hydrogen to electricity, it is *much* more efficient to use the natural gas or electricity directly.

Fuel cells that convert methane to DC power have been around for many years and are a very mature technology. Methane fuel cells have been developed for use on ships and demonstrated on several vessels for small sizes (~330kW) [Ref. 36]. Using methane fuel cells on LNG fueled ships could be a very efficient and clean way to produce power. It could be more efficient than using gas engines, especially if the power were used for auxiliary power.

5.7 Bunker Fuels

5.7.1 Diesel

The marine industry is primarily powered by various grades of diesel fuel. The nomenclature for diesel fuels varies somewhat and can be confusing, even to an insider. A thorough discussion of fuel grades is beyond the scope of this paper. Marine diesel fuels consist of various blends of heavy (residual) fuel oil and light distillates.

5.7.1.1 Heavy Fuel Oil

Most larger ocean going vessels, especially cargo vessels, use heavy fuel oil blends such as IFO180 or IFO380, and are sometimes just called HFO. These high viscosity fuels can only be pumped when heated. Vessels using these fuels will often utilize waste heat from exhaust for fuel heating but require an auxiliary boiler, operating on lighter diesel, for start-up and port operations. Due to the complication of operating with heavy fuels, their use is best suited to a large vessel with a fairly steady load profile (i.e. not requiring frequent load changes). These fuels have become attractive for marine operators because they are the least expensive type of fuel. These fuels also have a somewhat higher caloric content than distillate fuels which is an added benefit to the operator.

These fuels are notoriously dirty. They typically contain a large percentage of sulfur, as well as heavy metals. When combusted, they produce significant amount of particulate matter and release other poisons into the environment. Emissions Control Areas (ECA's) only allow operators to use these fuels if they are outfitted with sulfur scrubbers, and for new engines, they must have aftertreatment to reduce NOx.

5.7.1.2 Distillate Fuels

Most smaller coastal commercial and passenger vessels use distillate blends such as MGO (Marine Gas Oil) or MDO (Marine Distillate Oil or Marine Diesel Oil). These are lighter fuels that do not require heating or special handling except in extremely hot or cold conditions. They are preferred for medium and smaller commercial vessels that operate medium and high-speed diesel engines. They are generally cleaner burning, but have also been heavily regulated to reduce emissions. Large commercial vessels are allowed to burn these fuels within ECA's as an alternative to using sulfur scrubbers. Distillate fuels come with a significant cost premium over heavy fuels, which is why they are only used for niche operations requiring lower emissions or highly variable load profiles.

5.7.2 Liquefied Natural Gas (LNG)

LNG is getting a great deal of attention in the marine community due the fact that it burns very cleanly, and in some cases has a relatively low cost differential when compared to distillate fuel or even heavy fuel. LNG's primary advantages to the operator are low cost and clean combustion. However, the adoption of the fuel is being hindered by numerous factors. Combustion of LNG produces 25-30% lower CO2 levels [Ref. 37] due to the lower carbon content of the methane molecule compared with other hydrocarbons. However, combustion of LNG is not more *efficient* than combustion of diesel (on average), and the greenhouse gas impacts can be overstated.

Considerable energy is involved in the liquefaction and transportation of LNG fuel, which is often not accounted for when discussing LNG combustion. Additionally, methane gas (which is the primary component of natural gas) is a potent greenhouse gas and is inadvertently released throughout the supply chain and even the combustion process. Therefore, while LNG has an important role to play in reducing the environmental impact of the marine industry, it is not necessarily more *efficient*.

International regulations for design of LNG fueled vessels (SOLAS) have not yet been enacted, though a draft code has been developed. Class societies are leading in the development of regulations with most major societies now having rules for design of LNG fueled vessels. The USCG has developed several NVIC's (Navigation and Vessel Inspection Circulars) to assist the industry in getting plans approved and vessels constructed. Construction costs for LNG vessels are higher and additional training is required for crew. However, for some owners the advantages are still outweighing the challenges. Retrofitting vessels to LNG is highly dependent on vessel design, but is definitely possible for some vessels.

The largest challenge facing the industry for adoption of LNG fueled vessels is the availability of LNG fuel. Natural gas, which is widely available in the US and many places in the world, is not practical as a marine fuel due to its low energy density. Compressed Natural Gas (CNG) has been proposed, but only partially solves the density issue and presents numerous safety and regulatory challenges. To solve the issue, the gas must be liquefied, for storage and transport.

Natural gas liquefies at around -162ºC (-260ºF). The liquefaction process takes energy and special equipment. Additionally in many countries, including the USA, siting and operating an LNG plant is highly regulated. To be available for marine use, the liquefaction plant must either be sited where the vessels need the fuel, or special vessels must be used to move and transfer the fuel from the liquefaction facility to the vessel. Eventually these issues will be resolved and a wider adoption of the fuel is certainly possible, but the process can be frustratingly slow.

An additional challenge facing the oil and gas industry is the increasing public and environmental scrutiny it is facing over hydraulic fracturing (a.k.a. 'hydrofracking', or 'fracking'). The US 'fracking revolution' is the primary driver for the increased domestic production of natural gas but the widespread enthusiasm of the late 2000's has given way to caution today. Fracking has now been completely banned in several US states, with moratoriums in several others [Ref. 38]. It has also been banned in several European countries [Ref. 39] over safety and pollution concerns. Others have opted for increased regulation.

5.8 Waste Heat Recovery (WHR)

MECHANICAL/ELECTRICAL				**Waste Heat Recovery**	
Savings Potential				**Compatability**	
Low	**Mean**	High		Vessel Category	Power Group
3%	**8%**	13%		A	All
				B	All
Technology Stage (1 to 3)			2 - 3	C	All
Lifecycle Cost (Low to High)			Med/High	D	All
Retrofitable (Yes or No)			Mixed	E	5

Table 22 Characteristics of Waste Heat Recovery for fuel savings

While modern diesel engines are extremely efficient, especially so with slow speed engines, there is still a significant amount of good quality heat that is ejected. The most efficient large, slow speed diesel engines today reject half of the fuel energy as waste heat. The waste heat rejection is even greater for smaller engines. Approximately half of the waste rejection is from exhaust gas and the rest to cooling water with a small amount as radiation. Capturing some of the energy of waste heat can significantly increase a ships overall efficiency, reducing operational costs and emissions.

The savings potential in Table 22, as well as the following tables for specific WHR technologies (Tables 24-28), are relative to conventional direct-drive propulsion plants *including* diesel generators *or* conventional DEP plants. In all cases the savings assume there is no significant waste heat recovery system already being implemented on board. The savings potential is not potential *fuel savings* in this case, but recoverable electrical power noted as a percent of the engine rating (MCR). For example if an exhaust turbine generator if hooked up to the exhaust of a diesel generator which is rated for 1000kW, it would be expected to generate 30-50kW of electrical energy (3-5% of the rated power). The electrical energy can be used to offset grid power for hotel services, or for larger generators, can be used to power a shaft motor for propulsion.

Depending on the needs of a particular vessel, waste heat may be captured for heating purposes. Waste heat, for heating, has been commonly practiced for decades and can be an excellent means of increasing overall plant efficiency. Heat can be captured from either exhaust, as steam, or hot water from jacket water and charge air-cooling. The heat can be used for heating fuel, domestic heating (domestic hot water, water-making from evaporation, space heating, etc.), and cargo heating. For a cold weather vessel, these loads can be very significant and using waste heat can significantly extend range or save in operating costs. These systems are much simpler compared to systems for generator power and are retrofitable.

There are several methods of power recovery from engine waste heat (Table 23). The methods discussed here all involve conversion of thermal energy to mechanical energy using a thermodynamic power cycle. The methods discussed here are methods actually being applied to marine vessels. Some are very mature technologies (steam generators) and some are innovative, but based on common processes (supercritical CO_2 and Organic Rankine Cycle). Other methods certainly exist but are left out because they are either too speculative, or are not considered appropriate for marine applications.

Waste Heat Recovery Technology	Max Electrical Recovery (% MCR)	Engine Size Applicability	Recovery Source	Notes
EGTG - *Exhaust Turbine Generator*	3% - 5%	< 15,000kW (~20,000HP)	Exhaust Gas	Above 40% MCR
STG - *Steam Turbine Generator*	4% - 8%	< 25,000kW (~33,500HP)	Exhaust Gas	Above 30% MCR
EGTG + STG	8% - 11%	> 25,000kW (~33,500HP)	Exhaust Gas	Above 30% MCR
ORC - *Organic Rankine Cycle*	5% - 15%	> 250kW (~335HP)	Exh. Gas or Clg. Wtr.	Min. 75 - 90ºC (167 - 194ºF)
SCO_2 - *Supercritical CO_2*	8% - 11%	> 5,000kW (~6,700HP)	Exhaust Gas	No operating restrictions

Table 23 Characteristics of WHR methods for power generation. Compiled from multiple sources including: [Refs. 40, 41,42, 43]

A number of considerations for application on a vessel should be considered. All of the technologies discussed will require some additional systems to be installed, which come with an upfront cost and an upkeep cost. The operator must consider how appropriate each technology would be for their particular operation.

Many factors should be considered by the operator regarding use of a WHR system.

- *Waste Heat Availability* – All types 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 power is generated, 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 will be best (e.g. transoceanic 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. refrigerated container vessels) there may be a relatively high under way power demand, which can be supplemented or supplanted 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 motor for propulsion. Augmenting propulsion can be used either for speed boost or to reduce the load on the main engines.

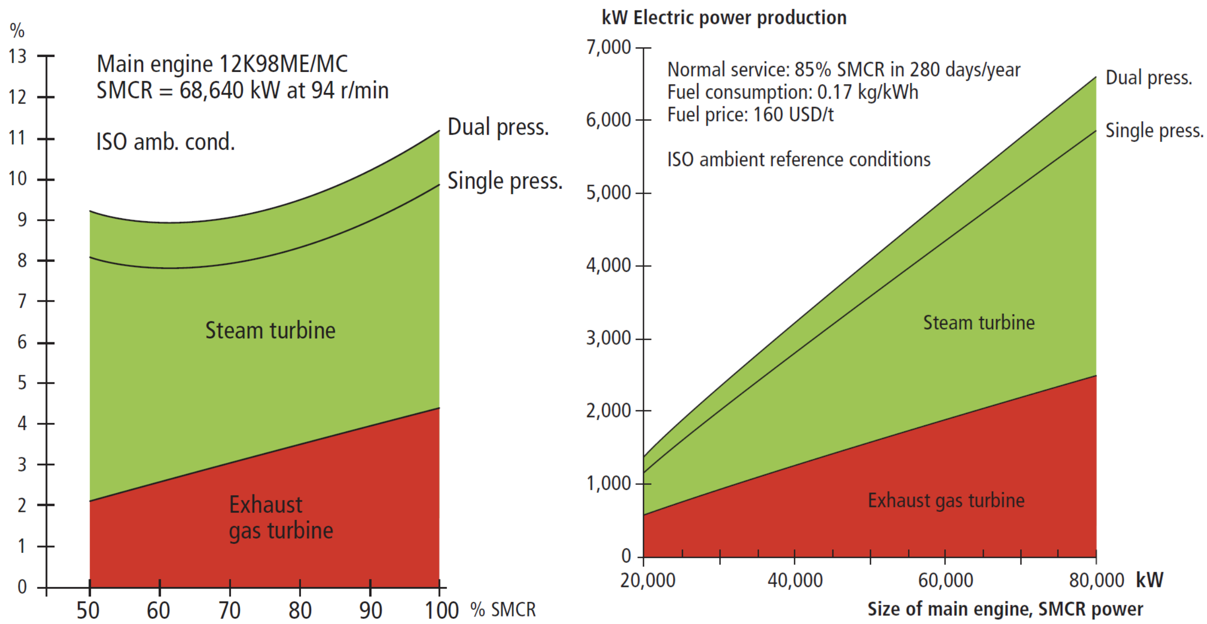


Figure 49 Available power as percentage of MCR (left) and engine size (right) for several WHR systems. Source: [Ref. 40]

5.8.1 Exhaust Gas Turbine Generator (EGTG)

MECHANICAL/ELECTRICAL				**Waste Heat Recovery Exhaust Gas Turbine Generator (EGTG)**	
Savings Potential				**Compatability**	
Low	**Mean**	High		Vessel Category	Power Group
3%	**4%**	5%		A	All
				B	1,2
Technology Stage (1 to 3)			2	C	1,2
Lifecycle Cost (Low to High)			Med	D	2,3,4
Retrofitable (Yes or No)			Yes	E	None

Table 24 Characteristics of Exhaust Gas Turbine Generators for fuel savings

One of the simplest and least expensive WHR methods are Exhaust Gas Turbine Generators. EGTG's utilize bypassed exhaust gas above approximately 40% of Maximum Continuous Rating (MCR) to drive a turbine generator (Figure 50) [Ref. 40]. Typically, the EGTG would be connected in parallel with the Ship Service Diesel Generators (SSDG's). If the vessel cannot utilize the additional auxiliary power underway, then the system is often used to augment shaft power via an electric propulsion motor. EGTG's can be retrofitted or (more typically) installed as part of a new vessel. Compared to larger, more complex steam systems the EGTG is relatively simple and compact (Figure 51).

It will require 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 150ºC (~300ºF) in order to prevent the condensing of gases and the formation of sulfuric acid in the system, which can be very corrosive [Ref. 40]. This will depend somewhat on the sulfur content of the fuel.

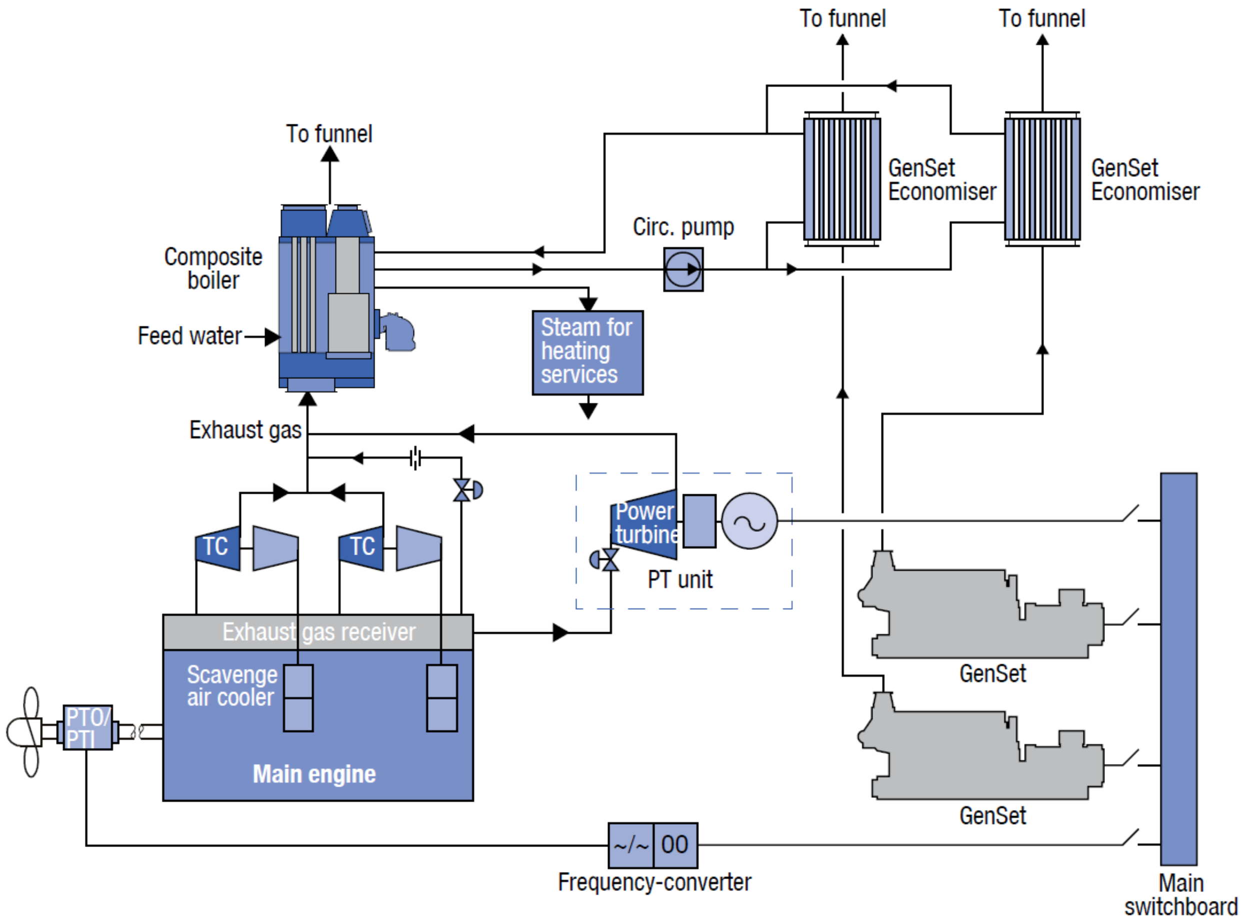


Figure 50 Conceptual schematic of EGTG system for waste heat recovery of electrical energy. Source: [Ref. 40]

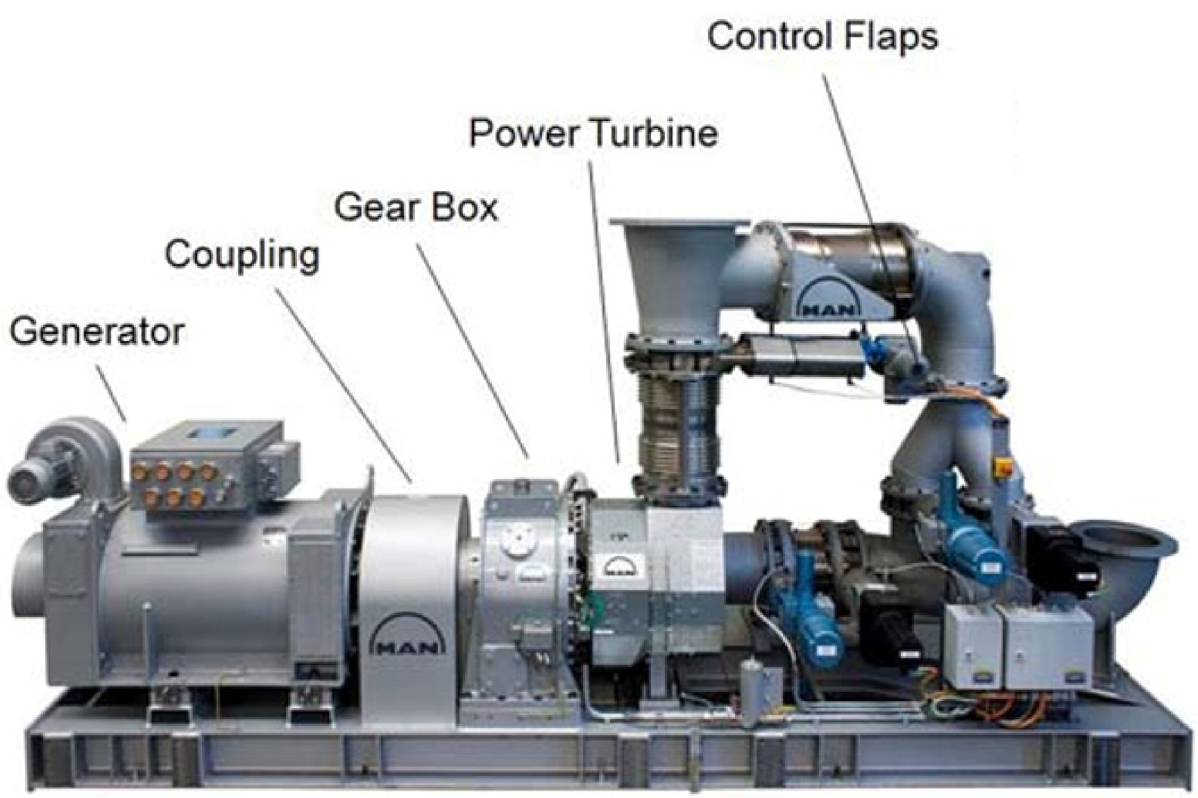


Figure 51 Skid mounted EGTG system. Source: [Ref. 40]

Advantages

- Efficient. 3 – 5% of MCR equivalent in electrical energy can be recovered [Ref. 40]
- Compact. No steam piping, condenser, WHR boiler required
- Potentially retrofitable. Still requires engine and exhaust system integration for bypass valve installation but much less equipment than steam systems.
- Available up to almost 3MWe for underway power production [Ref. 40]
- Lower maintenance and much simpler than a steam system.
- Available for engine loads above 40% MCR

Disadvantages

- Limited power production for vessels with large demands

5.8.2 Steam Turbine Generator (STG)

MECHANICAL/ELECTRICAL				Waste Heat Recovery Steam Turbine Generator (STG)	
Savings Potential				Compatability	
Low	**Mean**	High		Vessel Category	Power Group
4%	**6%**	8%		A	All
				B	1,2
Technology Stage (1 to 3)			3	C	1,2
Lifecycle Cost (Low to High)			Med/High	D	2,3,4
Retrofitable (Yes or No)			Mixed	E	None

Table 25 Characteristics of Steam Turbine Generators for fuel savings

Many large vessels with slow speed engines have exhaust gas boilers for providing fuel or cargo heating. The steam can also be used for driving a turbine generator for auxiliary and/or propulsion power. The application is similar to the EGTG with the steam turbine providing power in parallel to the auxiliary generators or it can be stand alone. There is typically enough steam at loads greater than 30-35% of MCR though the efficiencies are greater at peak loads [Ref. 40]. The steam turbines will be mounted on a compact skid. If there are other waste heat requirements such as fuel or cargo heating, these will need to be considered during design to ensure that power production will not interfere with heating needs.

5.8.2.1 Single Pressure

The simplest and most compact steam cycle will use only the exhaust gas heat to generate steam for power. Typically, the boiler will have a preheater, evaporator, and super-heater section in the stack and the turbine will have a single stage (Figure 52). The steam turbine, gear, and generator will be located on a skid in a machinery room with the condenser and hot well located below the turbine. The boiler is bypassed around 30% of MCR [Ref. 40].

Single pressure systems recover a potential equivalent to 4-7% of MCR as electrical power [Ref. 40].

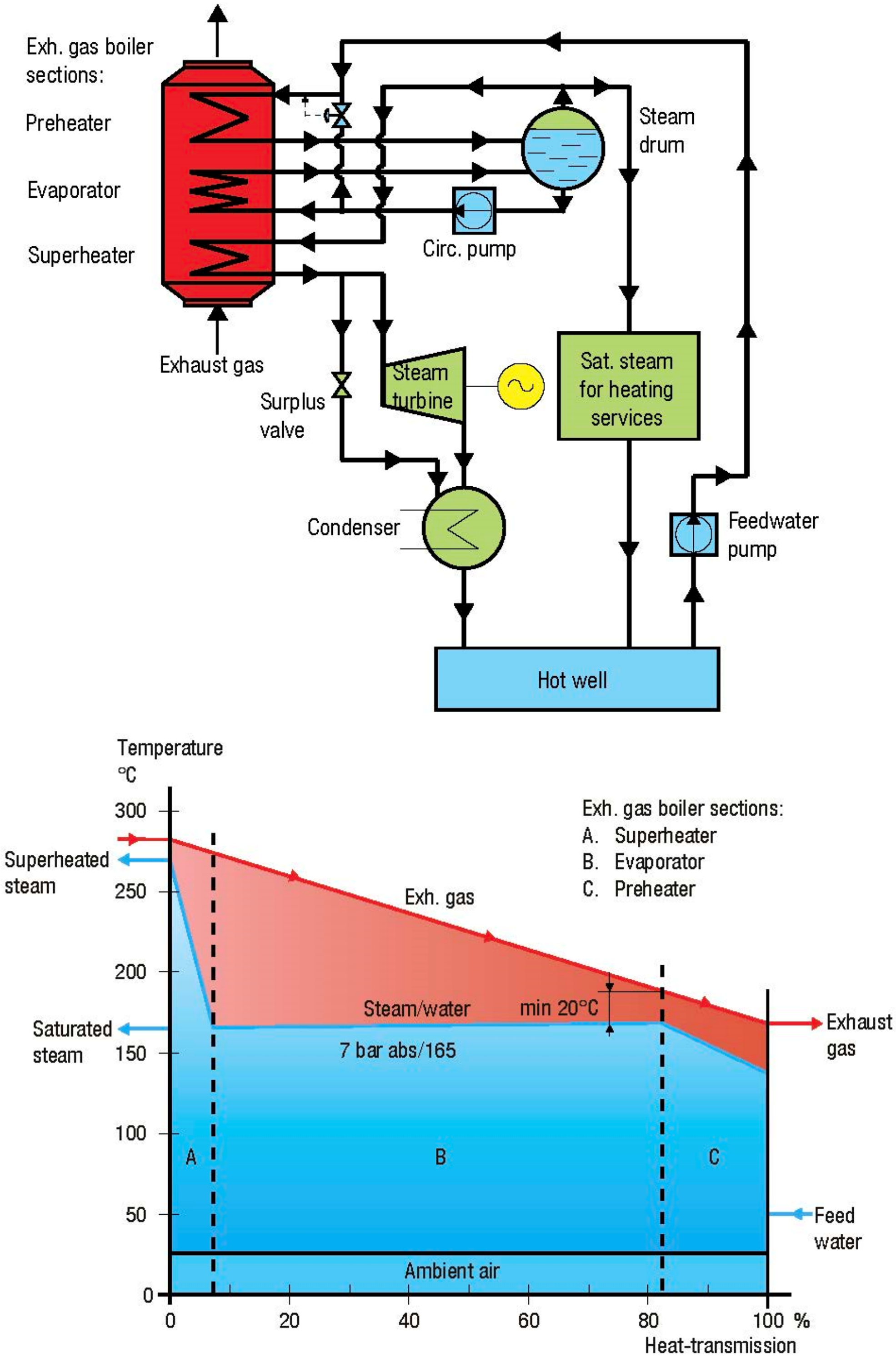


Figure 52 A simpler Single pressure steam power system. Source: [Ref. 40]

Advantages

- Efficient. Up to 7% of MCR equivalent in electrical energy can be recovered. Significantly more recovery potential than EGTG alone.
- Available for engine loads above 30% MCR.

Disadvantages

- Steam systems can require significant operation and maintenance resources to keep running.
- High volume. Steam systems require a lot of volume for large condensers, steam drums, large and complex boilers, etc.
- Not easily retrofitable for existing vessels.

5.8.2.2 Dual Pressure

Additional efficiency can be gained by adding a second pressure stage to the turbine and the WHR boiler (Figure 53). This will usually require using an additional source of waste heat for preheating the feedwater coming out of the hot well. Using exhaust gas to preheat the feedwater would risk cooling the exhaust to the point that corrosive condensation occurs, which could damage the piping. Waste heat from jacket water or scavenge air can be used as a preheating source, if available. If other waste heat is not available, it *is* possible to preheat the feed water using some of the low-pressure steam, though this will come at the expense of reducing overall steam production by around 15% [Ref. 40].

Assuming service steam is still required for various auxiliary heating services, this would be taken from the saturated steam coming off the high-pressure steam drum. Therefore, this amount must be deducted when determining how much superheated high-pressure steam is available for power production. The boiler is bypassed below around 30% of MCR [Ref. 40].

Dual pressure steam systems recover a potential equivalent to 5-8% of MCR as electrical power. These systems are the norm on new container ships using WHR [Ref. 40].

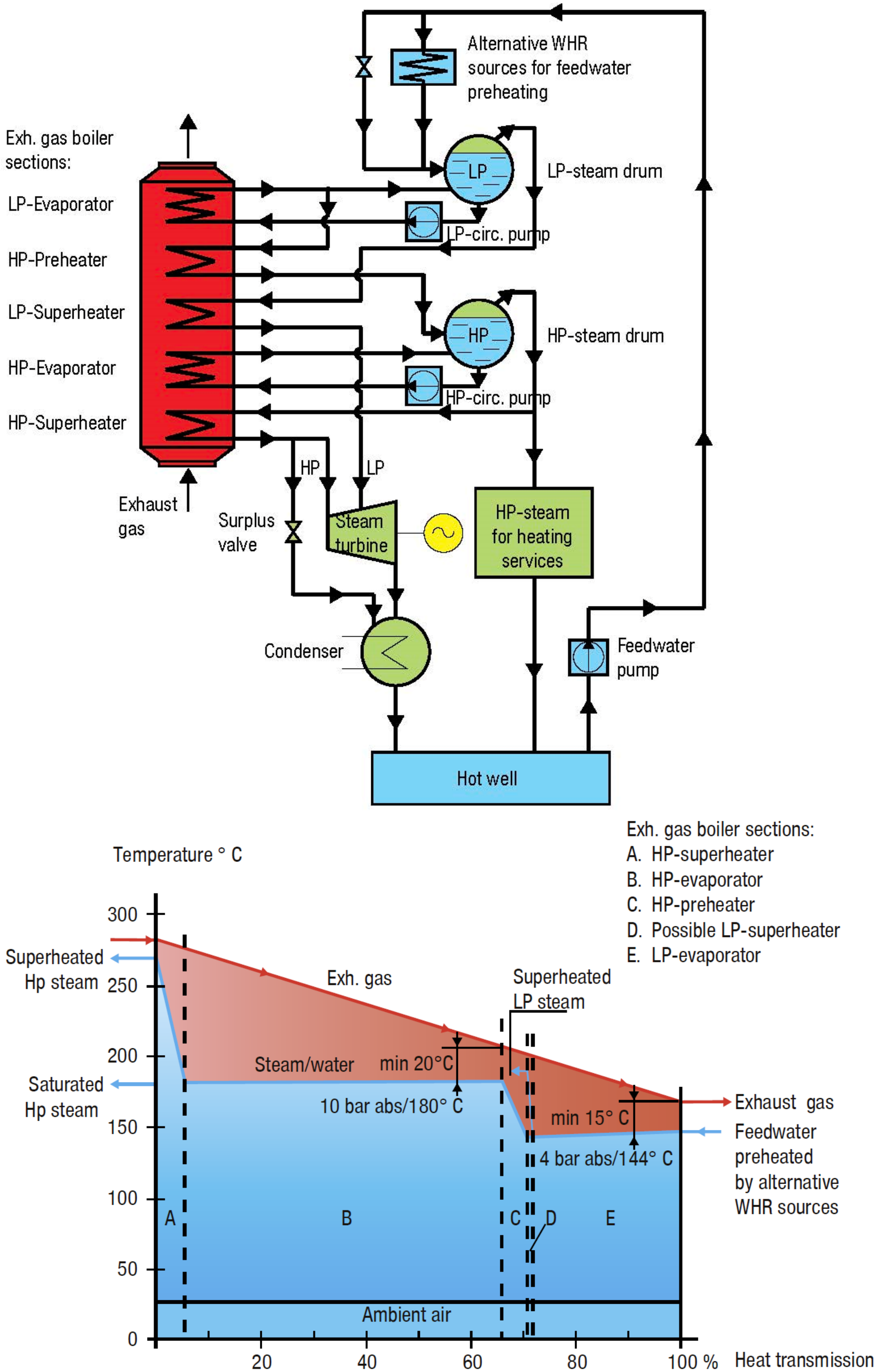


Figure 53 Dual pressure steam power system. Source: [Ref. 40].

Advantages

- Efficient. Up to 8% of MCR equivalent in electrical energy can be recovered. Significantly more recovery potential than EGTG alone.
- Available at engine loads above 30% MCR.

Disadvantages

- Only a little more potential energy recovery than single pressure systems.
- Steam systems can require significant operation and maintenance resources to keep running.
- High volume. Steam systems require a lot of volume for large condensers, steam drums, large and complex boilers, etc.
- Not easily retrofitable for existing vessels

5.8.3 Combined Systems (EGTG + STG)

MECHANICAL/ELECTRICAL				Waste Heat Recovery Combined (EGTG + STG)	
Savings Potential				Compatability	
Low	**Mean**	High		Vessel Category	Power Group
8%	**10%**	11%		A	All
				B	1,2
Technology Stage (1 to 3)			2	C	1,2
Lifecycle Cost (Low to High)			Med/High	D	2,3
Retrofitable (Yes or No)			Mixed	E	None

Table 26 Characteristics of Combined EGTG + STG systems for fuel savings

For vessels with very high electrical power demands (e.g. a container vessel with a lot of refrigerated cargo), it is possible to combine an EGTG with a STG in order to maximize the amount of recovered energy. The turbines are typically integrated on a single skid and drive a common generator (Figure 55). If the vessel does not need this much power, these systems are still an option if a shaft motor is added for augmenting propulsion (Figure 54).

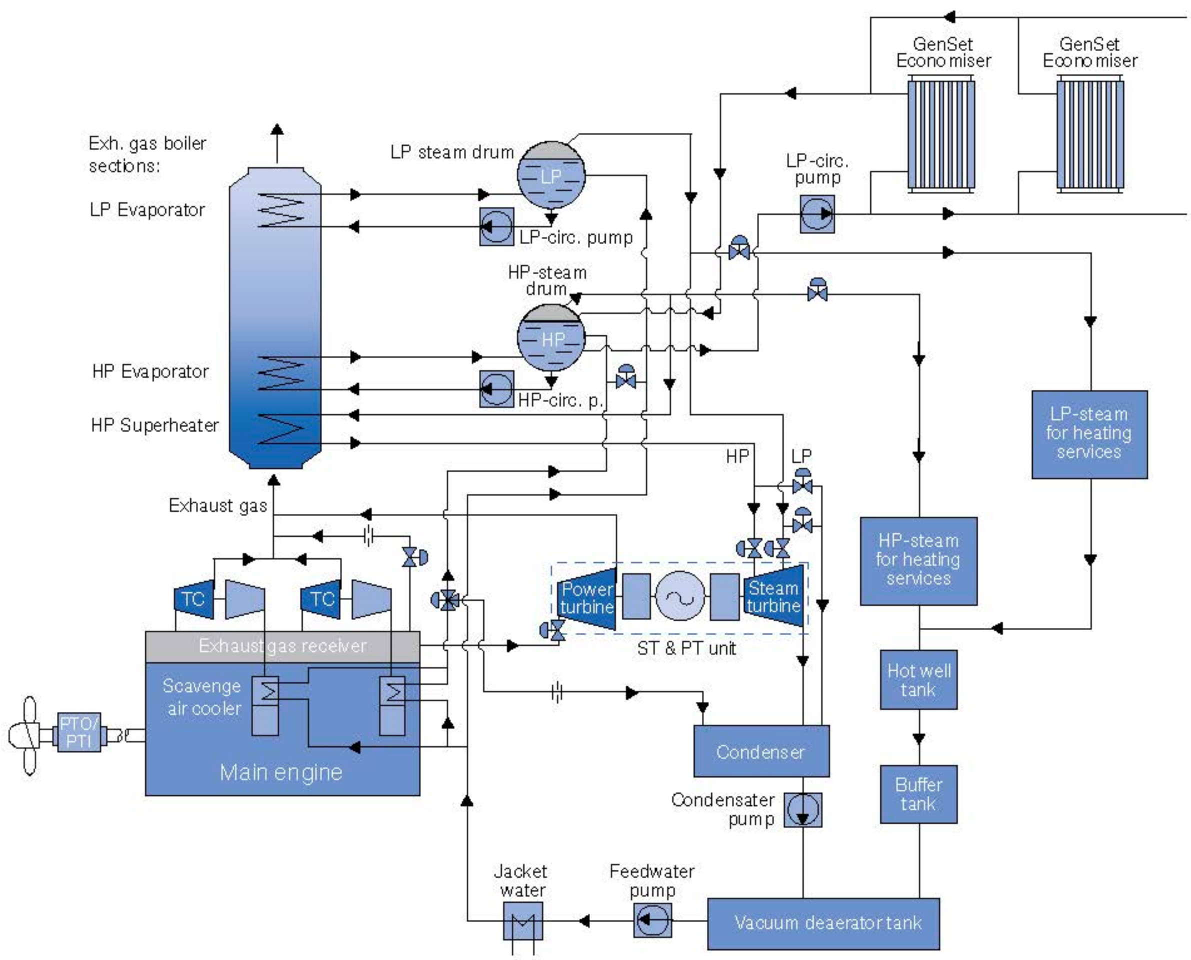


Figure 54 Conceptual schematic of a WHR system combining EGTG and STG. Source: [Ref. 40].

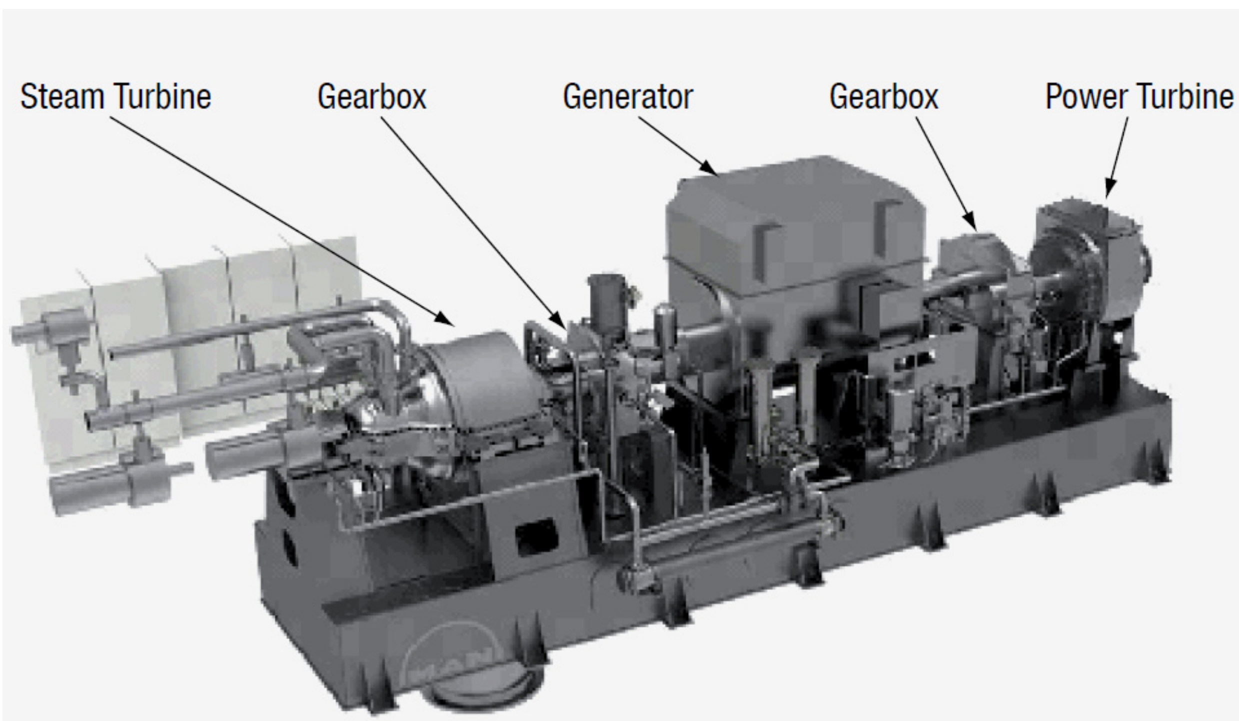


Figure 55 Compact skid mounted Steam Turbine Generator. Source: [Ref. 40].

Advantages

- Very Efficient. Up to 11% of MCR equivalent in electrical energy can be recovered [Ref. 40]. Significantly more recovery potential than EGTG or STG alone.
- Enough power to significantly boost propulsion or completely offset auxiliary power needs while underway.
- Available at engine loads above 30% MCR [Ref. 40].

Disadvantages

- Steam systems can require significant operation and maintenance resources to keep running.
- High volume. Steam systems require a lot of volume for large condensers, steam drums, large and complex boilers, etc.
- Probably only appropriate for new vessels due to significant space and integration requirements.

5.8.4 Organic Rankine Cycle (ORC)

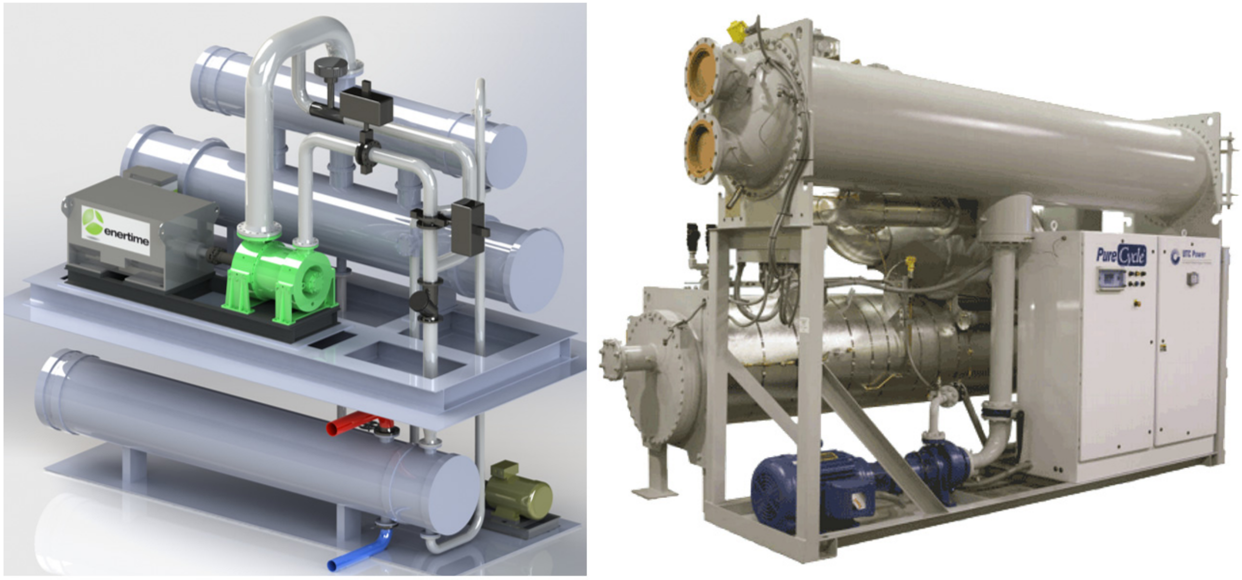
MECHANICAL/ELECTRICAL				Waste Heat Recovery Organic Rankine Cycle (ORC)	
Savings Potential				**Compatability**	
Low	**Mean**	High		Vessel Category	Power Group
5%	**10%**	15%		A	All
				B	All
Technology Stage (1 to 3)			2	C	All
Lifecycle Cost (Low to High)			Med/High	D	2,3,4,5,6,7
Retrofitable (Yes or No)			Yes	E	5

Table 27 Characteristics of Organic Rankine Cycle (ORC) systems for fuel savings

An Organic Rankine Cycle (ORC) works on the same principle as the steam cycle only the working fluid is an organic substance with different thermodynamic properties. 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 water and charge air-cooling loops.

If the system is capturing exhaust waste heat then integration will require an exhaust bypass similar to the STG and EGTG systems above. An exhaust economizer will need to be installed to capture heat for the ORC. The footprint will be significantly smaller for an ORC system and the installation should be less expensive due to less piping and equipment. Most of the system piping is integrated on the equipment skid. Up to 15% efficiency gains are possible with this type of system [Ref. 41]. The higher efficiencies are partly because the ORC can operate at very low engine loads and still generate substantial power. Additionally, the conversion efficiencies are very high (within 90% of peak) down to 50% load [Ref. 42].

If the system is capturing lower temperature waste heat from jacket water or charge air cooling water then heat exchangers will need to be installed on the respective loops. The ORC skid will capture heat from these heat exchangers and generate power. Efficiency gains of 5-6% are possible from low quality heat sources [Ref. 42].



Source: Enertime *Source: Turboden, Pratt & Whitney*

Figure 56 Organic Rankine Cycle Generators for shipboard use

<u>Advantages</u>

- Much lower volume than STG systems
- Higher efficiency than EGTG systems (more power capture)
- Able to generate power at low engine loads
- Multiple commercial developers competing in the marine market
- Able to generate significant power from very low quality heat sources

<u>Disadvantages</u>

- High capital cost (should decrease with higher volume of installations)
- Operator needs to be aware of chemicals used in system. Some chemicals have high global warming potential (GWP) and could be subject to future regulatory bans.

5.8.5 Supercritical CO_2 (SCO_2)

MECHANICAL/ELECTRICAL				Waste Heat Recovery Supercritical CO2 (SCO2)	
Savings Potential				Compatability	
Low	**Mean**	High		Vessel Category	Power Group
8%	**10%**	11%		A	All
				B	All
Technology Stage (1 to 3)			2	C	All
Lifecycle Cost (Low to High)			Med/High	D	2,3,4
Retrofitable (Yes or No)			Mixed	E	None

Table 28 Characteristics of Supercritical CO_2 (SCO_2) systems for fuel savings

Supercritical CO_2 systems are a closed cycle energy-recovery system that occupies a much smaller footprint than a steam system. While the installed cost is similar to steam, the operational and maintenance costs are purported to be lower. They have many of the same benefits as ORC systems, and are available for both smaller plants and very large plants. They operate on higher temperature waste heat than ORC systems, 240-600ºC (464-1112ºF), or well within the realm of diesel engine exhaust temperatures [Ref. 43].

Installation is very similar to other WHR systems, with a heat exchanger installed in the exhaust system. The relative simplicity and size compared to steam systems should make SCO_2 systems retrofitable.

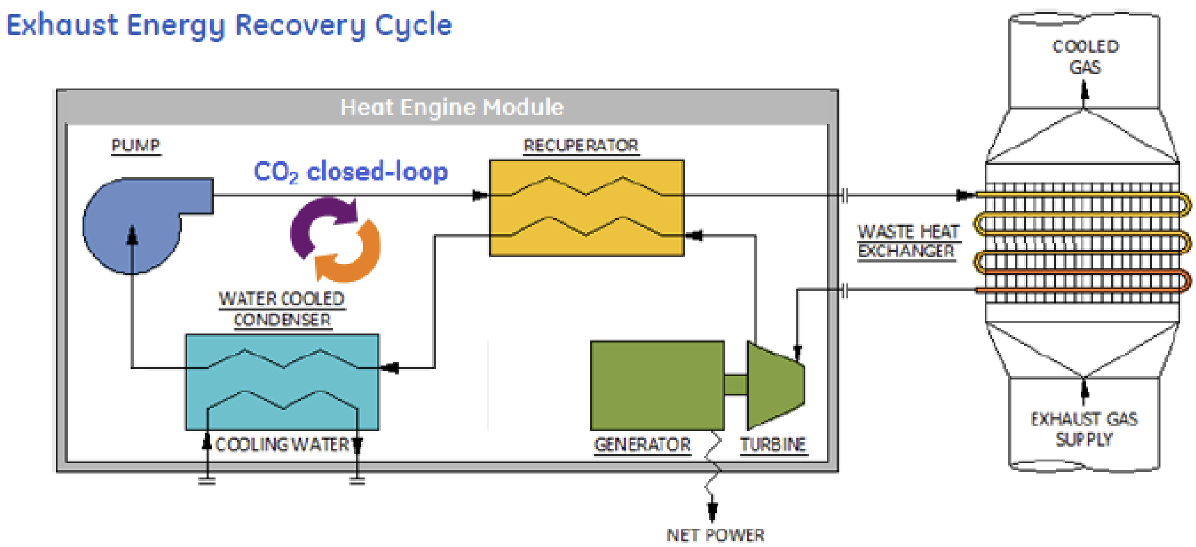


Figure 57 A supercritical CO_2 WHR system. Source: [Ref. 43].

Section 6 Operational Practices

6.1 Fuel Consumption Monitoring

OPERATIONAL				Fuel Consumption Monitoring	
Savings Potential				Compatability	
Low	**Mean**	High		Vessel Category	Power Group
2%	**6.0%**	10%		A	All
				B	All
Technology Stage (1 to 3)			3	C	All
Lifecycle Cost (Low to High)			Low	D	All
Retrofitable (Yes or No)			Yes	E	All

Table 29 Characteristics of Fuel Consumption Monitoring for fuel savings

Operational efficiency gains are increasingly afforded with the gathering, processing, and dissemination of data. This data can provide critical insights at both the fleet and vessel levels and lead to better decision-making. Owners and fleet managers are turning to data analytics to reduce downtime, maintenance expenses, environmental fines, and fuel consumption. Reducing fuel use is a major challenge as fuel costs have surpassed labor for many operations, in particular when fuel costs are high.

Vessel and fleet owners have always tracked fuel to some degree. Even when costs were low, operators needed to know how much range they could get with available fuel, or when they needed the fuel truck at the dock. Tracking gross consumption over a period of days or weeks is helpful, but lacks the fidelity and impact of real time monitoring.

Real time Fuel Consumption Monitoring (FCM) is typically accomplished by installing flow meters on the fuel supply and return piping for each engine (Figure 58). The meters can be ‘mass flow’ type or ‘volume flow’ type with temperature correction. The data is collected, processed, and transmitted to the crew in units such as gallons or liters per hour. Significant value can be realized when the fuel data is logged, tracked, and processed with other key data such as speed through the water, towline pull, engine rpm, shaftline torque, etc. Collecting and processing fuel consumption data with other key data types provides synergies that transcend simple fuel monitoring.

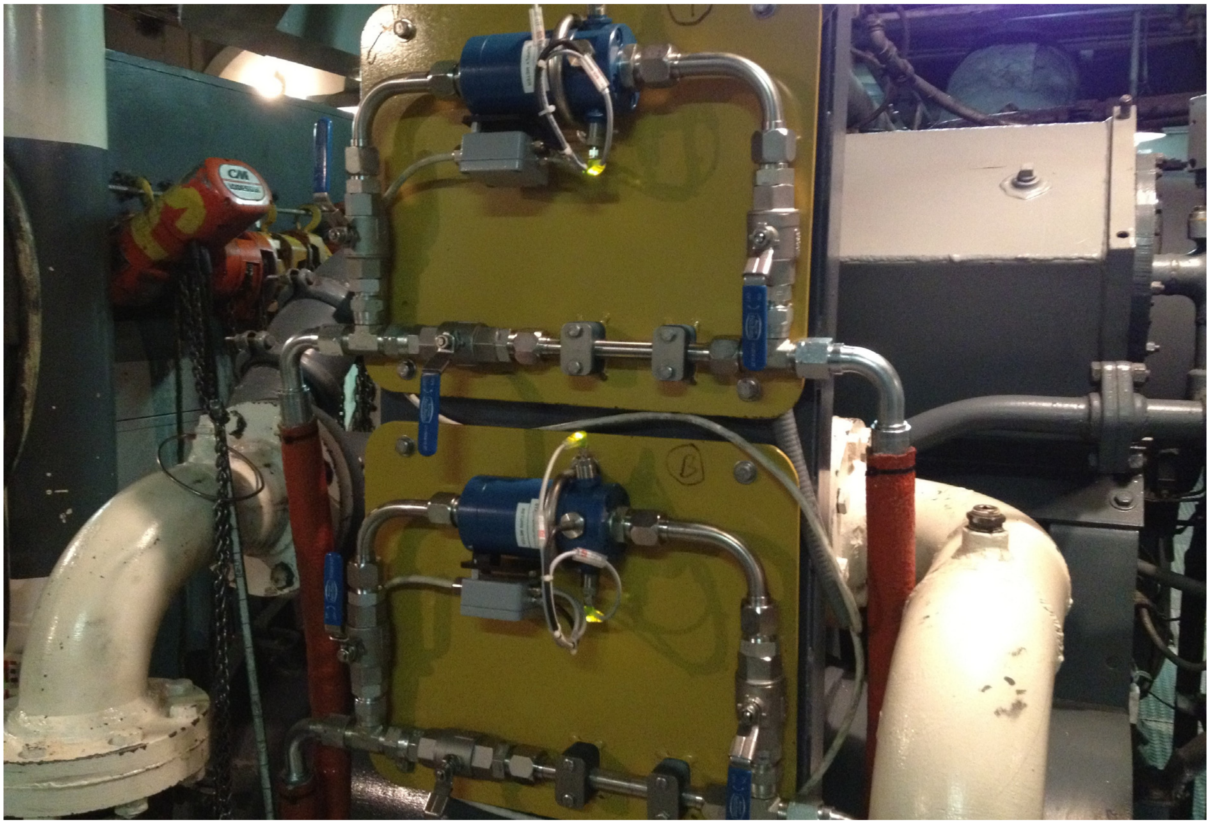


Figure 58 Typical installation of FCM system on an engine. (Source: Krill Systems)

FCM reduces fuel use in two key ways: By influencing throttle controls and by benchmarking efficiency measures. However, once an FCM system is installed, it can form the basis for a program with many ancillary benefits. Fuel data can be combined with data from the GPS, engines, weather, or other sources creating synergies that would not otherwise be possible.

The system informs the crew how changes in throttle settings affect consumption. The nature of a vessel's speed-power relationship can mean that small changes in speed require large changes in power. In general, fuel consumption increases by the cube (third power) of vessel speed so the effect is most pronounced at higher speeds. Real time FCM lets the operator see this effect and make adjustments. Even a difference of one-half knot can have significant effects on fuel consumption due to the exponential relationship between speed and power.

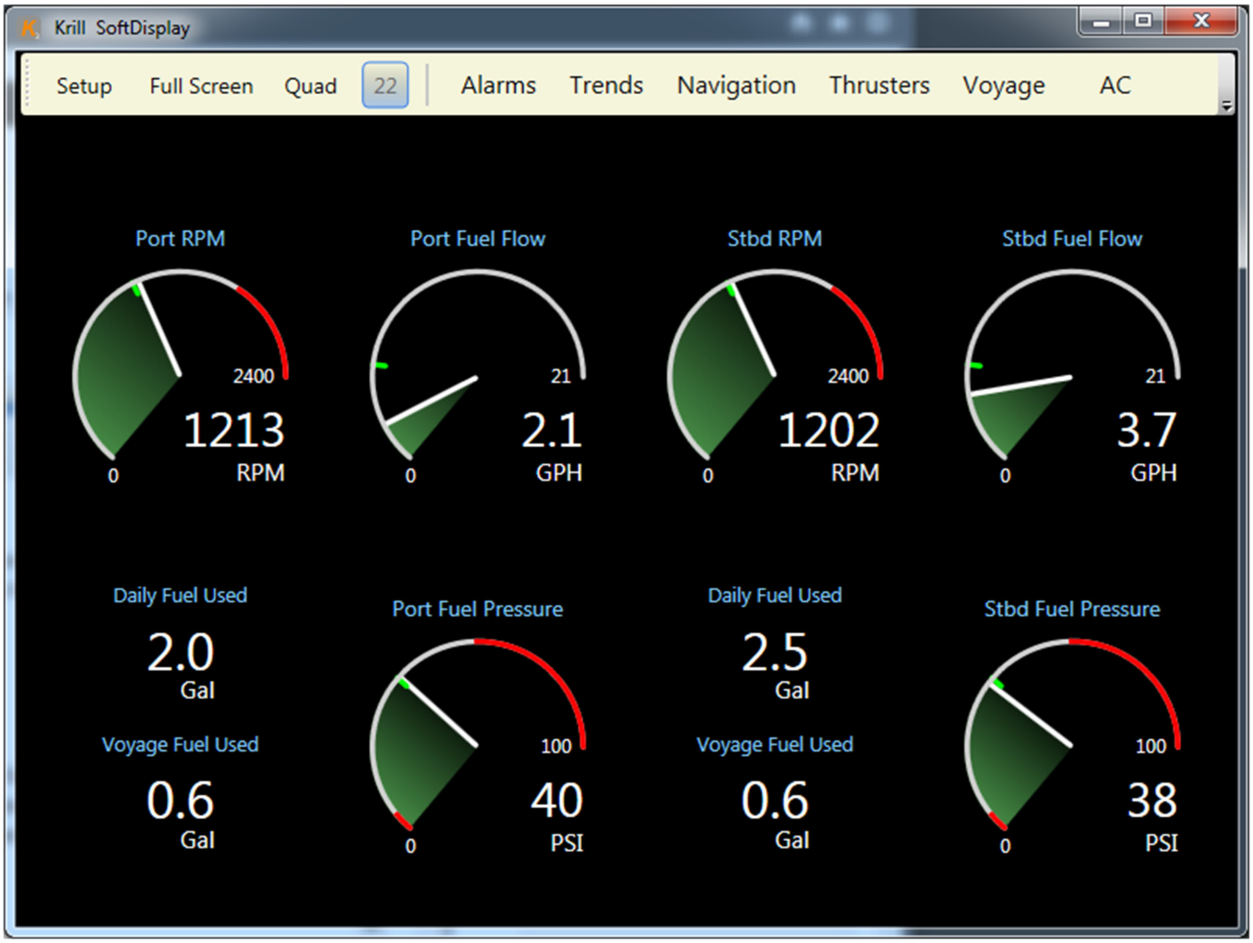


Figure 59 Typical pilothouse display of FCM system for a tug. Source: [Ref. 62]

There are times when maximizing speed is necessary to make schedule. It may also be that going one-half to one-full knot slower will be acceptable while burning significantly less fuel. Real time FCM empowers the operator to make better choices.

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.
- 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, horsepower 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. In short, a corporate culture, which values efficiency, will realize the most savings.

6.2 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 (draft, trim, etc.), 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 modern navigation tools such as Electronic Chart Display and Information Systems (ECDIS) and ARPA (Automatic Radar Plotting Aid) enabled radar systems, both of which may be integrated with real-time AIS (Automatic Identification System) and GPS (Global Positioning System) data. Fuel consumption monitoring systems may also be integrated. For larger, oceangoing vessels, active weather routing services and associated software programs are now standard and in cases where internet connectivity is available, meteorology data and other tools can be integrated and accessed.

At the administrative level, voyage planning is often about strategic, business, and logistics planning. Modern tools for this purpose include:

- Shore-based active weather routing services and their associated suite of software tools (similar to above);
- Proprietary spreadsheet/modeling tools;
- Proprietary software programs;
- Voyage/fuel optimization services and software;
- Systematic processes for data collection and continuous performance improvement.

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, and Just-in-Time Routing are all interrelated components of the overall Voyage Optimization program. A comprehensive approach to Voyage Optimization will save the operator fuel while improving the safety and efficiency of the overall operation.

6.2.1 Speed Optimization

OPERATIONAL				**Speed Optimization**	
Savings Potential				**Compatability**	
Low	**Mean**	High		Vessel Category	Power Group
0%	**10%**	20%		A	All
				B	All
Technology Stage (1 to 3)			3	C	All
Lifecycle Cost (Low to High)			Low	D	All
Retrofitable (Yes or No)			N/A	E	All

Table 30 Characteristics of Speed Optimization for fuel savings

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 percent speed reduction will decrease fuel consumption by over 20 percent, and a 20 percent speed reduction will use 45 percent less fuel. These significant savings have led to substantial interest in speed reduction (i.e. 'slow-steaming'), especially when fuel prices are high. The corresponding reduction in total fuel consumption is somewhat offset by increased voyage times and must be accounted for in the planning process. Figure 60 shows a typical speed power relationship for an ocean-going vessel.

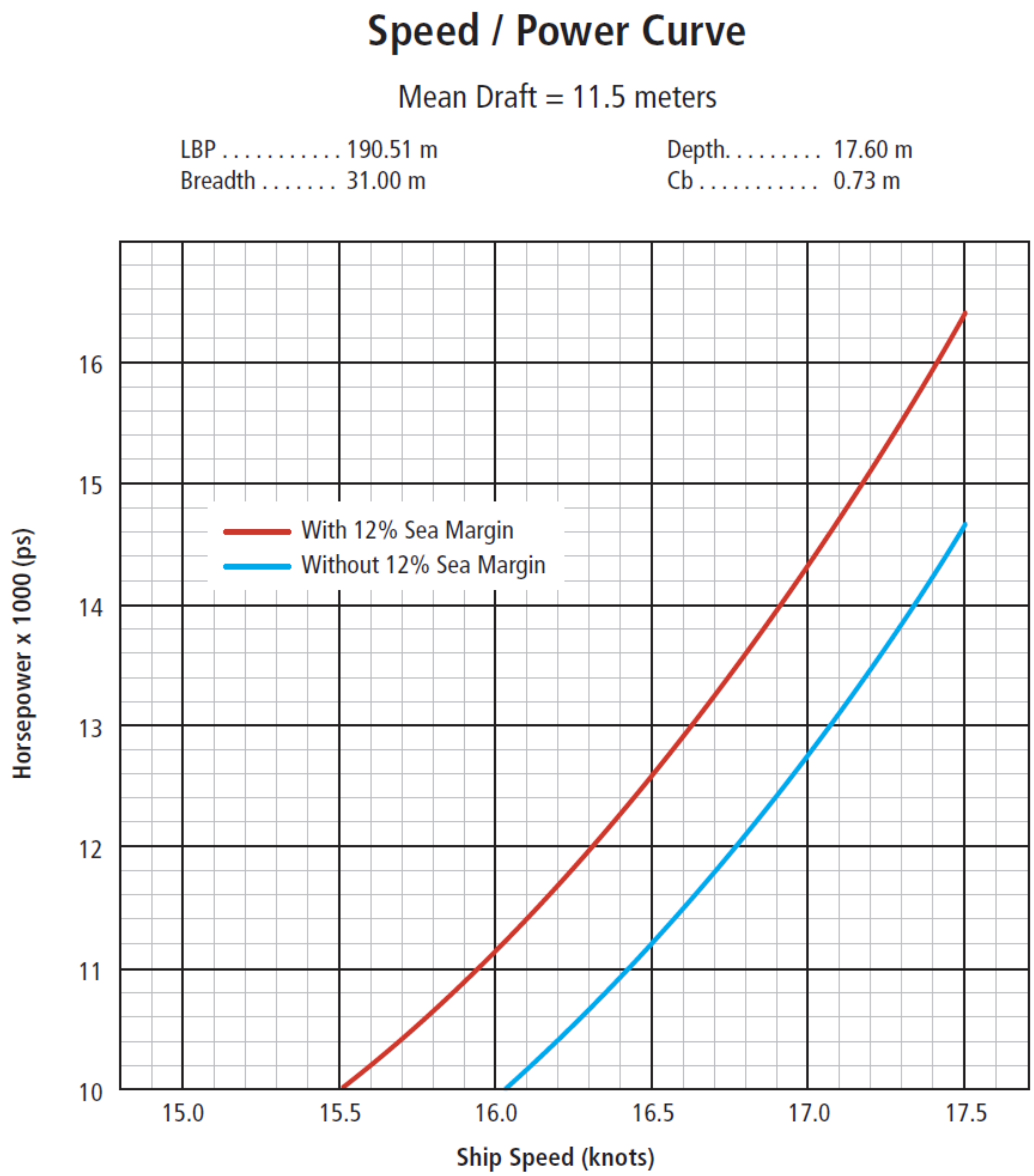


Figure 60 Typical Speed-Power curve for an ocean-going vessel. Source: [Ref. 45]

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, fleet size can be affected if speeds are reduced too much, etc. 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:

- 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

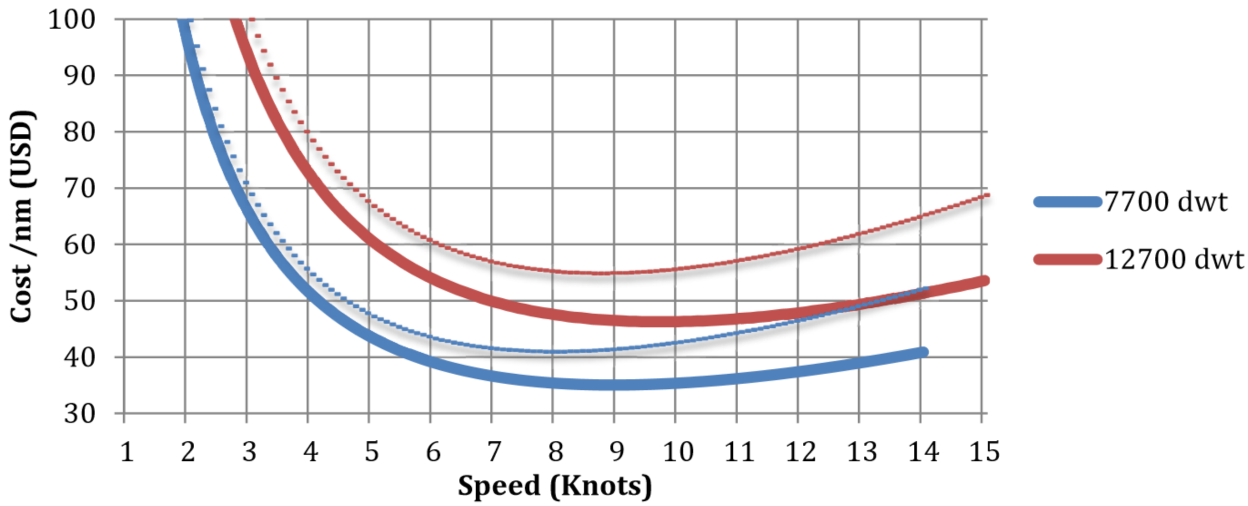


Figure 61 Example of a speed optimization curve for two vessels and two fuels (HFO – thick / MGO – thin). Source: [Ref. 44]

6.2.2 Weather Routing

OPERATIONAL				**Weather Routing**	
Savings Potential				**Compatability**	
Low	**Mean**	High		Vessel Category	Power Group
2%	**3%**	4%		A	All
				B	All
Technology Stage (1 to 3)			3	C	1,2
Lifecycle Cost (Low to High)			Low	D	All
Retrofitable (Yes or No)			N/A	E	All

Table 31 Characteristics of Weather Routing for fuel savings

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 taking into account 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 shoreside 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 62). The ability to customize these software packages varies from very little, to significant. With on-board satellite communications, it is even possible to get daily updates to the routes that continually monitor changes to conditions in real-time, and adjust and optimize routes on the fly.

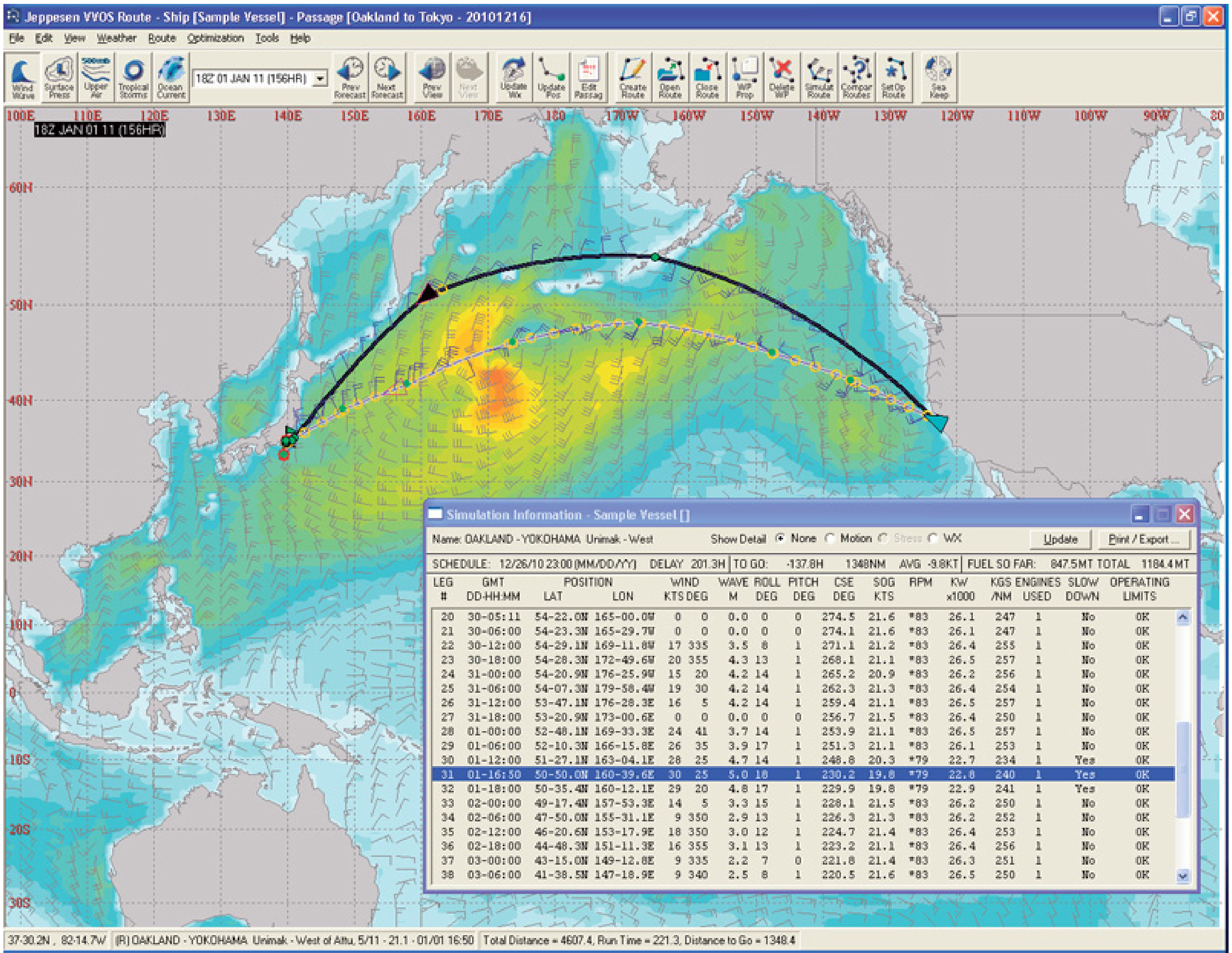


Figure 62 Screenshot example from a commercial weather routing system. Source: [Ref. 61]

Weather routing is typically used for longer voyages (>1,500 NM) and where navigation routes are not too restrictive. For example, some inland routes or on rivers do not have enough alternative routes for there to be an advantage to weather routing. Higher speed liner services where weather conditions will have a greater effect on speed will likely benefit more than slower speed operations. Additionally higher speed services stand to benefit more from speed changes.

6.2.3 Just in Time Arrival

OPERATIONAL				**Just in Time Routing**	
Savings Potential				**Compatability**	
Low	**Mean**	High		Vessel Category	Power Group
1%	**3%**	5%		A	All
				B	All
Technology Stage (1 to 3)			3	C	1,2
Lifecycle Cost (Low to High)			Low	D	All
Retrofitable (Yes or No)			N/A	E	All

Table 32 Characteristics of Just in Time Routing for fuel savings

Just-in-time arrival offers the vessel charterer, or owner, to minimize time spent loitering in port, and possibly minimize voyage speed for fuel savings. If operating at constant shaft RPM, or speed over the course of a voyage, a vessel may arrive early in port where berthing may not be available, only to spend time in anchorage. Voyage optimization software as well as good voyage management practices, allow continuous communication with ports or terminal operators to ensure that the vessel arrival coincides with an available, and appropriate berth.

The factors affecting berth availability can vary for different ports around the world. If charterers and owners have good communication with ports and terminals and understand the dynamics driving berth availability, they can adjust their schedule to minimize wasted time. For example, in US ports if a vessel arrives in the middle of a work shift, they may not be able to berth until a shift change. In other ports, the factors could be availability of night pilots.

Just-in-time arrival practices are often integrated with and factored into weather routing and speed optimization features in commercial voyage management services.

6.3 Trim/Draft Optimization

OPERATIONAL				**Trim/Draft Optimization**	
Savings Potential				**Compatability**	
Low	**Mean**	High		Vessel Category	Power Group
1%	**1.5%**	2%		A	All
				B	1,2
Technology Stage (1 to 3)			3	C	1,2
Lifecycle Cost (Low to High)			Low	D	2,3,4
Retrofitable (Yes or No)			N/A	E	5

Table 33 Characteristics of Trim and draft optimization for fuel savings

Vessel design is often optimized for a limited number of drafts (one or two) and zero trim. Small trim changes can cause significant differences in fuel consumption and resistance. Even lighter drafts can have a higher resistance than design if the trim is not even.

In real operations, it may be common to sail at outside design drafts and with non-zero trims. This may be due to cargo dynamics, ballast conditions, and even normal changes to consumables such as fuel and water. While new ship designs are optimizing around a greater number of draft cases, operations outside of design conditions are inevitable.

Achieving best fuel consumption requires giving the vessel crew the information and tools needed to optimize trim and draft for a given voyage to achieve the lowest fuel consumption. Commercial tools are available to provide crew and cargo planners a means of optimizing trim and draft. However, there are various methods for calculating the optimum trim and draft. In general, the methods are either based on theoretical calculations/testing or in-service measurements.

Theoretical/testing methods use either model test data or computational fluid dynamics (CFD) programs to establish a continuum of trim-draft combinations and corresponding resistance data to inform the software programs about the conditions utilized by the actual operators. These programs, especially model test programs, are more expensive if done after the vessel has been built. Extrapolating model tests results to the actual vessel is not an exact science. Likewise, CFD can be used in concert with or in place of model tests but results are *theoretical* and must be taken as such.

The other method is a full-scale test program with the actual vessel to test various draft/trim combinations and record the corresponding resistance data to generate optimum trim tables for use with loading programs. However, a myriad of real-world effects that can change resistance while underway are difficult to isolate from trim/draft changes.

Both methods have variations and will have advantages and disadvantages. Each vessel owner/operator will have to choose what makes sense for each situation. In the grand scheme however, the costs are fairly minimal for the potential payoff in fuel savings.

6.4 Hull Cleaning and Maintenance

HULL				Hull Cleaning	
Savings Potential				Compatability	
Low	**Mean**	High		Vessel Category	Power Group
1%	**3%**	5%		A	All
				B	All
Technology Stage (1 to 3)			N/A	C	All
Lifecycle Cost (Low to High)			Low	D	All
Retrofitable (Yes or No)			N/A	E	All

Table 34 Characteristics of Hull Cleaning for fuel savings

Marine growth on a hull, (i.e. biofouling, or hull fouling) greatly increases the friction between the hull and the water. In certain climates hull fouling can occur very rapidly, especially when the vessel is in port and not in motion. The roughness of the marine growth impedes the flow of water over the vessel surface, resulting in increased resistance. Severe fouling can dramatically increase resistance.

Hull cleaning should be done as part of routine maintenance practices for the vessel. The frequency will depend on many factors but generally, any time the vessel is laid up the bottom should be inspected. When the vessel is in drydock, the bottom should be thoroughly cleaned and the undercoating maintained as needed.

Condition-based maintenance is knowing when to perform maintenance by measuring the condition against a known baseline. For hull maintenance, this can be done in several ways:

1. Direct observation by divers in port
2. Observed degradation vs. time by fuel consumption monitoring

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 counter the contractor's self-interest in getting the job.

A better method is to use fuel consumption monitoring equipment and software to track normal degradation over time starting from the baseline of a clean hull. This method works best when the vessel 'normal' fuel consumption can be correlated to a known set of conditions. For some vessel types, such as ocean going cargo vessels, this may be easier than with smaller working vessels that do not necessarily transit routine routes and speeds. However, having accurate fuel tracking equipment, combined with the ability to log the data over time, will likely be the most accurate, especially if combined with direct observation.

Advantages

Hull cleaning and maintenance are widely practiced in the industry and the benefits well understood. Cleaning a hull that is severely fouled can decrease resistance by more than 10% [Ref. 45]. However, typically routine cleaning of moderate fouling will reduce resistance in the range of 1 – 5% [Ref. 45]. The cost to benefit ratio is extremely low assuming the vessel is already out of service.

Disadvantages

Hull cleaning must be done in accordance with local environmental regulations and laws whether the vessel is in the water or out of the water. To the owner, there are really no disadvantages to cleaning the hull on a reasonable schedule.

Appendix A Technology Summary Table

Table 35, *Technology Summary Table*, is a summary of all the technologies and characteristics discussed in each section of the report. This table is not intended as a standalone reference but rather is to be used and understood in the context of the report scope and methodology (Section 1.4). The table is intended as a convenient reference for comparing the various technologies discussed.

Efficiency Approach	Retrofitable (Yes/No)	Technology Maturity (1-3)	Fuel Savings (%) Low	Fuel Savings (%) High	Lifecycle Cost (Low - High)
HULL					
Advanced Hull Coatings	Yes	3	1%	4%	Low/Med
Hull Form Optimization	No	3	2%	20%	Low
Air Lubrication	Yes	1 - 2	5%	25%	Med/High
PROPELLERS AND APPENDAGES					
Efficient Propellers	Mixed	3	3%	10%	Low/Med
Large Diameter/Low Speed	No				
Ducted Propellers (Kort Nozzles)	Yes				
Controllable Pitch	Yes				
Contra-Rotating	No				
Podded and Azimuthing	No				
Pre-Swirl Devices	Yes	3	2%	6%	Low/Med
Stators	Yes				
Pre-swirl stator ducts	Yes				
Post-Swirl Devices	Yes	3	2%	6%	Low/Med
Rudder Thrust Fins	Yes				
Asymmentric Rudders	Yes				
Costa Bulbs	Yes				
Propeller Boss Cap Fins (PBCF)	Yes				
RENEWABLE ENERGY					
Wind	Yes	1 - 2	5%	35%	Low/Med
Kite Sails	Yes	2			
Fletner Rotors	Yes	2			
Rigid Sails	Yes	1 - 2			
Cloth Sails	Mixed	3			
Wave	Yes	1	Unknown		Unknown
Solar	Yes	1 - 2	0%	1%	Med/High
MECHANICAL/ELECTRICAL					
Prime mover	Mixed	3	5%	20%	Varies
Direct Drive	No	3	N/A		Low
Diesel Electric	No	3	5%	10%	Low/Med
Variable speed generators	Yes	2	3%	10%	Med
Battery Hybrid	Yes	2	5%	20%	Med/High
Battery Electric	Mixed	1 - 2	100%		Med/High
Fuel Cells	Mixed	1 - 2	Unknown		High
Waste Heat Recovery	Mixed	2 - 3	3%	15%	Med/High
*Exhaust Gas Turbine Generator (**EGTG**)*	Yes	2	3%	5%	Med
*Steam Turbine Generator (**STG**)*	Mixed	3	4%	8%	Med/High
*Combined (**EGTG + STG**)*	Mixed	2	8%	11%	Med/High
*Organic Rankine Cycle (**ORC**)*	Yes	2	7%	13%	Med/High
Supercritical CO2 (SCO2)	Mixed	2	8%	11%	Med/High
OPERATIONAL					
Fuel Consumption Monitoring	Yes	3	2%	10%	Low
Voyage Optimization	N/A	3	0%	20%	Low
Speed Optimization	N/A	3	0%	20%	Low
Weather Routing	N/A	3	2%	4%	Low
Just in Time Routing	N/A	3	1%	5%	Low
Trim/Draft Optimization	N/A	3	1%	2%	Low
Hull Cleaning	N/A	N/A	1%	5%	Low

Table 35 Summary of Energy Efficiency Technology Characteristics. Estimates obtained from various sources including: [Ref. 14, 15, 26, 40, 41,42, 43, 45, 68]

Appendix B Air Lubrication Technology Developers

Air Lubrication Technology Developers

Mitsubishi Heavy Industries (MHI)

Mitsubishi has developed an air lubrication system to the commercial level known as the Mitsubishi Air Lubrication System (MALS). The MALS (Figure 63) system blows fine bubbles (micro-bubbles) from several openings near the forward area of the vessel and allow them to run along the bottom of the vessel to reduce skin friction.

The system has been installed on three large grain carriers, two container vessels (YAMATAI and YAMATO operated by NYK), and a ferry (NAMINOUE operated by Japan's A-line Ferry Co.). The company says the system has been proven to save 5-10% average fuel consumption [Ref. 46].

The system has mostly been implemented as a retrofit for existing vessels. However, MHI has completed the conceptual design for a new 14,000 TEU Panamax container vessel where, along with other energy saving technologies they expect to reduce overall CO_2 emissions by 35% [Ref. 47].

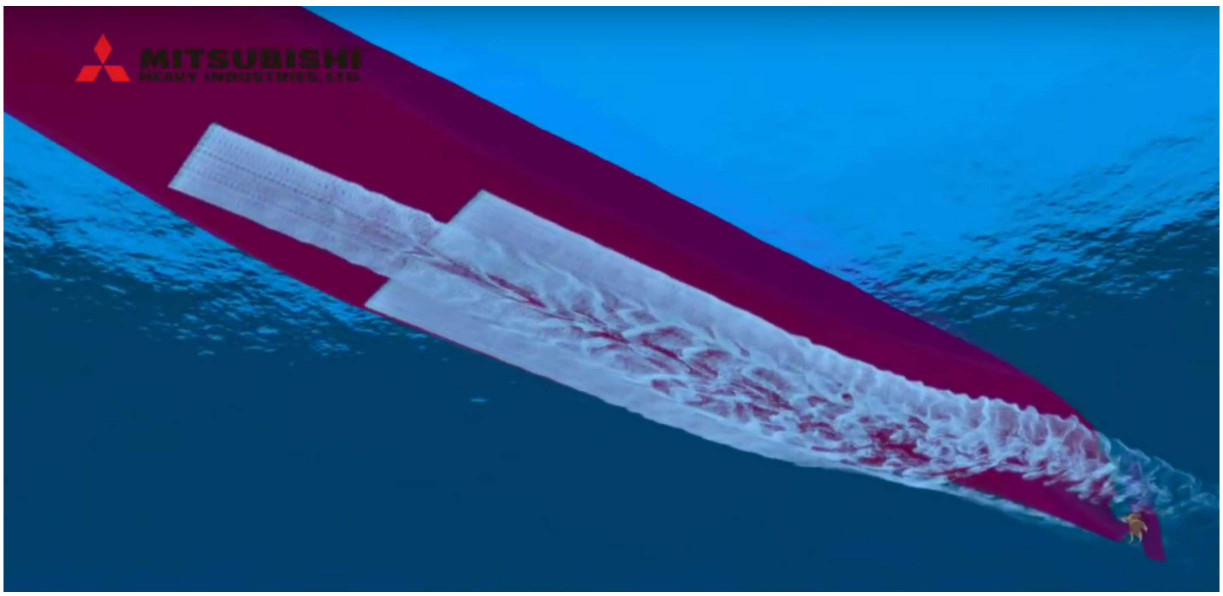


Figure 63 Mitsubishi Air Lubrication System (MALS) shown on the underside of a large commercial vessel (Source: Mitsubishi Heavy Industries)

Silverstream Technologies Ltd.

Silverstream Technologies is a company that has been set up to commercialize the air lubrication technology developed by DK group, with development going back at least 12 years. The system operates by injecting micro-bubbles from air cavities installed on the underside of the vessel, near the bow of the vessel.

Silverstream has retrofitted a small product tank (40,000 DWT) with the system [Ref. 48]. The retrofit took approximately 14 days. A large, 143,000 GT, cruise ship under construction at Mayer Werft (*MV Norwegian Bliss*) will be outfitted with the system which the company says is in high demand [Ref 49]. The company claims it can reduce fuel consumption by up to 10% [Ref. 50]. The reduction on the product tanker has been verified at 4-5% energy savings [Ref. 48].

Figure 64 The Silverstream system injects micro-bubbles from air cavities installed near the bow of the ship (Source: Silverstream Technologies Ltd.)

Foreship Oy

Foreship has designed an air lubrication system, which has been installed on the RCCL *Quantum of the Seas*. The system is self-contained in a box installed to the underside of the hull. The system does not produce a drag penalty when not turned on, according to Foreship. When operating the system the ship saves 7-8% on fuel [Ref. 51]. Additionally the system is said to reduce excitation from the propellers, which cuts noise and vibration levels down inside the vessel. The system will soon be installed on a second RCCL new build according to the company. The company believes their system is suitable for retrofit as well. Unlike others in the industry, Foreship does not build the system, but rather provides clients with design and build specifications for the shipyard or others to construct. They are targeting payback times of under two years. The company believes the optimal speed range is between 12-18 knots for their system, based on CFD calculations [Ref. 51].

Damen

Damen has developed an Air Cavity Energy Saving (ACES) system suitable for retrofit or new build. The system was developed with the Maritime Research Institute Netherlands (MARIN) as part of a multi-year research program to study air lubrication. The system was first retrofitted on a small self-propelled river barge. It is comprised of an array of narrow air cavities installed on the flat under bottom of a vessel (Figure 65). In tests of the retrofitted vessel, the savings were as high as 25% with average fuel savings of 15% under all sail conditions [Ref. 52]. The first commercial system was also installed on the recently launched EcoLiner. The EcoLiner is an LNG fueled tanker designed for river service. The savings are so significant that the company intends to integrate the product into a number of other vessel designs.

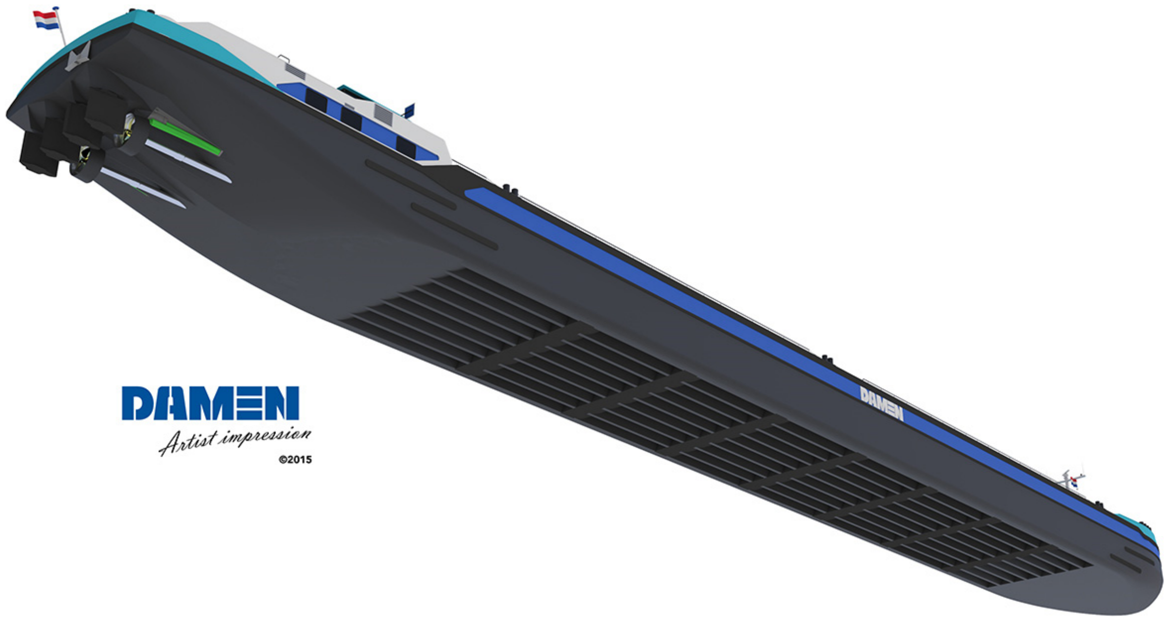


Figure 65 The Damen ACES system is a series of air filled cavities installed on flat hull bottom (Source: Damen)

Stena Bulk

Stena Bulk is one of the world's leading tanker operators. They have been developing an air cavity system for integration into a new class of tankers, along with several other energy savings technologies. The company built a 1/12 scale model which it is testing in actual waterways during the sailing season. The system is called the AirMAX and consists of a flat-bottomed hull with an air-filled cavity underneath. Currently the company is not looking to market the technology for vessels other than Stena vessels. The company believes the system will save approximately 25% on fuel [Ref. 15].

Figure 66 The Stena AirMAX developed by Stena Bulk is an air-filled cavity under the vessel. Source: [Ref. 15].

Appendix C Wind Energy Technology Developers

Kite Technology Developers

SkySails GmbH

The company was founded in 2001 and launched their first kite on a marine vessel in 2007. They have four installations in operation (Figure 67 and Figure 68) and one under development. The company claims savings between 10 – 35% annually, depending on route conditions [Ref. 53].

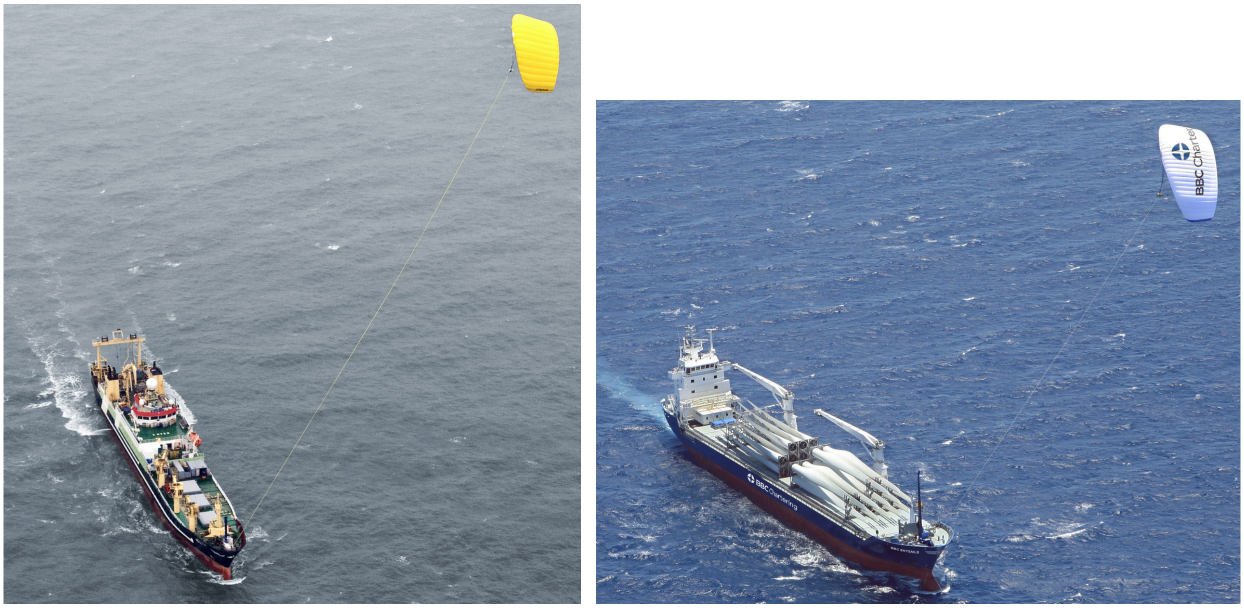


Figure 67 MV Maartje Theadora (left) and the MV BBC Skysails (right). Source: Skysails GmbH

Figure 68 MV Michael A (left) and MV Theseus (right). Source: Skysails GmbH

Irish Navy

The Irish Navy has been developing kite sails in collaboration with multiple Irish university partners. The project, AEOLUS (named from the ruler of the winds in Greek mythology), will allow naval vessels to save significant energy. However, of particular interest to the Navy is the potential of the kites to enhance the reach of sensor technology due to the great heights that they reach. Normal radar reach is 12-15 NM to the horizon. However, mounted 100m above the vessel on a kite, the radar can see 50 MM to the horizon (an obvious advantage for a warship). If successfully, the Irish hope to sell the technology to other navies around the world.

The Irish Navy is equally interested, or perhaps more interested, in developing shipboard generators with kites. They are collaborating with SkySails, which just opened an office in Cork.

Flettner Rotor Technology Developers

Norsepower Oy Ltd.

Norsepower has developed the Rotor Sail, which is an automated Flettner rotor for merchant vessels. The product comes in 18, 24, and 30 meter lengths with a 3 meter diameter [Ref. 63]. The first installation was retrofitted onto the M/V *Estraden* (Figure 69) in December of 2014 for testing at sea. In June 2015, the company announced fuel savings of 2.6% with a single rotor (18m long x 3m diameter) for a route in the North Sea [Ref. 64]. With that single test rotor, the payback period is expected to be 4 years [Ref. 65]. On the success of the installation of a single rotor, the owner of the *Estraden*, (Bore Ltd.) opted to install a second rotor on the vessel in November of 2015 [Ref. 64]. Norsepower forecasts savings up 30% for vessels with multiple, large rotors travelling in favorable wind routes [Ref. 66].

Figure 69 Norsepower Rotor Sail installation on the M/V *Estraden*. The left image shows the first installation from 2014, and the right image shows the second installation from 2015. Source: [Ref. 73].

Enercon GmbH

The Enercon E-Ship 1, utilized four Enercon designed and constructed Flettner Rotors for wind-assisted propulsion (Figure 70). Enercon is a developer of wind turbines and decided to use wind-assist on their flagship transport vessel E-Ship 1. The vessel entered service in 2010 and has been sailing around the world delivering the company's wind turbine components ever since with over 170,000 sea miles as of 2013 [Ref 54].

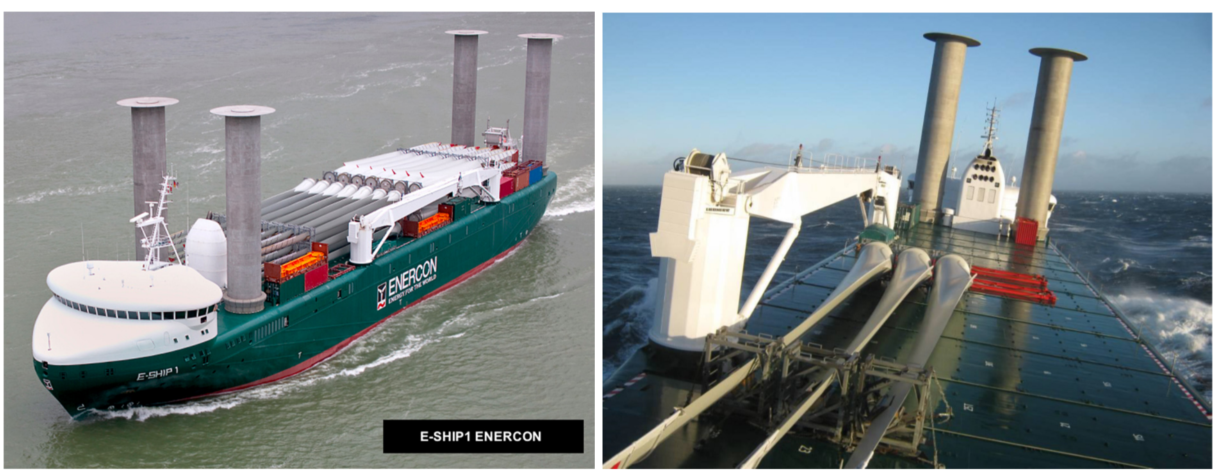


Figure 70 Enercon E-ship1 utilizing four Flettner Rotors. Source: [Ref. 54]

Calculated savings are shown below (Figure 71). The model has been validated based on the vessel's actual operational experience, in which the vessel has achieved 25% fuel savings after several hundred thousand miles at sea [Ref 54]. While only shown at 24 kt wind speed and 16 kt service speed, projected savings are very significant and mimic projections by other manufacturers [Ref. 54].

For now, it does not seem that Enercon is attempting to market their system for other vessel owners. However, their willingness to push the boundaries of technology still serves the Flettner rotor industry well by demonstrating the effectiveness of their system under real world conditions.

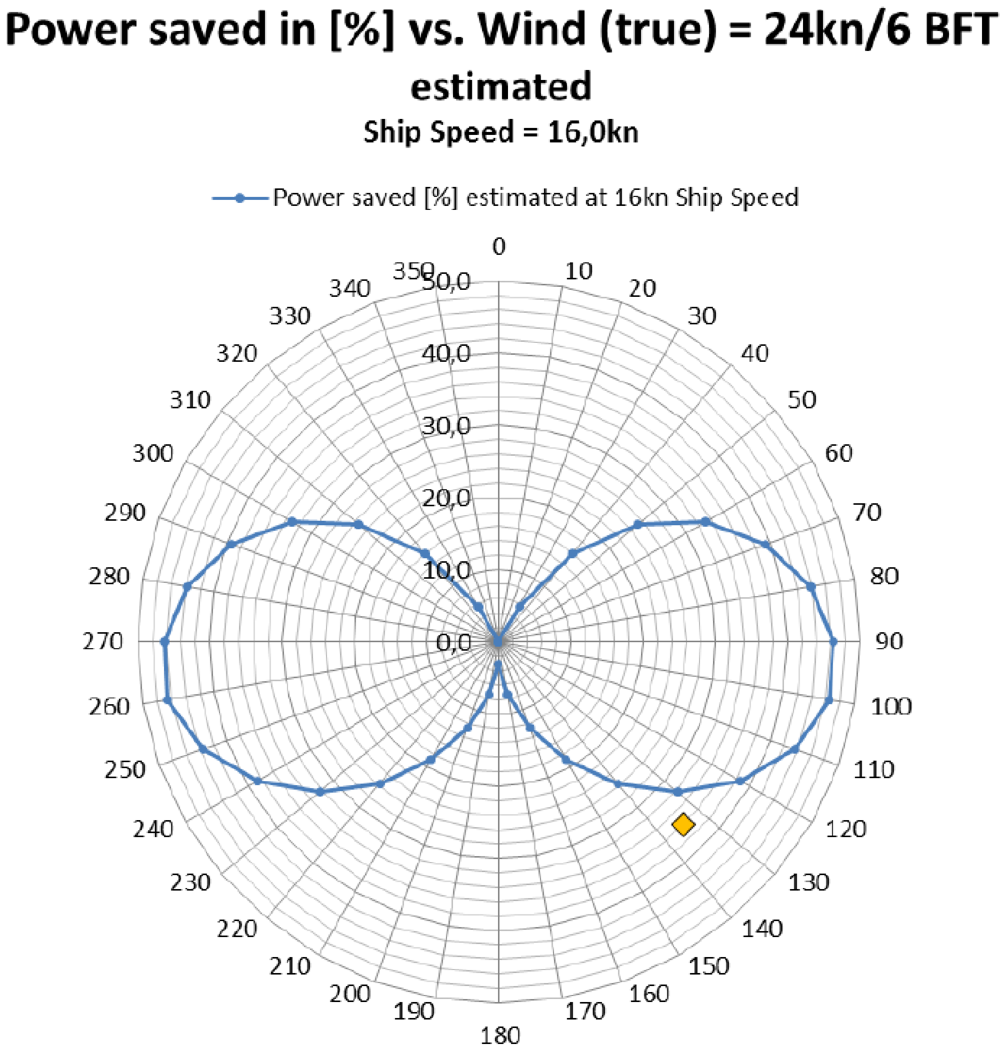


Figure 71 Percent of power saved in 24 kt wind for E-Ship 1. Source: [Ref. 54]

<u>Magnuss Ltd.</u>

Magnuss Ltd. has developed a retractable Flettner Rotor system for large vessels called the Vertically-Variable Ocean Sailing System (VOSS™). Each VOSS™ has the ability to 'reef' vertically in order to maximize the benefit at sea, while improving safety in foul weather and staying out of the way for port operations (Figure 72). Essentially the system has addressed most of the main weaknesses of Flettner Rotor technology. They claim that the technology is ready for deployment, but does not seem to have been tested at sea. It is not clear whether the added complexity of the VOSS system is cost effective as compared to a standard Flettner Rotor. However, it is likely to be attractive to some owners as a standard rotor may not be workable for a variety of reasons.

Figure 72 Magnuss VOSS™ rotors depicted on a large bulk carrier. (Source: Magnuss Ltd.)

Thiiink Holding Switzerland AG

Thiiink has developed an improved version of the Flettner rotor called a Rotor Wing (Figure 73). By installing a sail flap on the rotor, the drag that is normally caused by the turbulent wake of the rotor is greatly reduced. Since the effective propulsive force is the combination lift and the drag, the efficiency is greatly improved, particularly in upwind conditions.

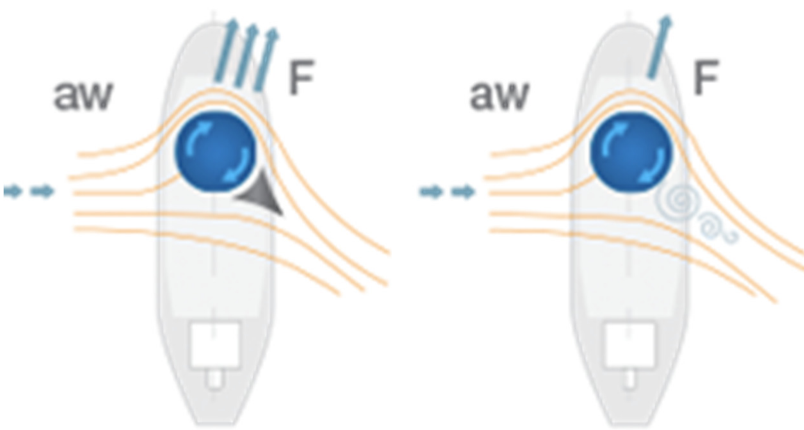


Figure 73 Thiiink Flettner Rotor Wing (Source: Thiiink Holding Switzerland AG)

In addition to improving the rotor performance, Thiiink has designed a retractable system that can be stowed for heavy weather, or during port operations (Figure 74). These improvements address many of the concerns with Flettner Rotors and should improve the economics. The company claims that their system improves performance by 50% and Internal Rate of Return (IRR) up to 55% compared to standard rotors [Ref. 55]. The also claim an improved upwind performance from 40º to 25º [Ref. 55]. The company has not announced any prototype installations yet.

Figure 74 Thiiink Retractable Flettner Rotor Wing (Source: Thiiink Holding Switzerland AG)

Rigid Wingsail Technology Developers

<u>Oceanfoil® Ltd.</u>

Oceanfoil® Ltd. has developed a propulsion assist wingsail with a steering rudder, or tail fin. Each sail has a set of three wingsails that rotate about a common axis (Figure 75). Each wingsail has an independently controlled flap to adjust camber for optimal efficiency. By combining three on each mast, the overall height required to return a given thrust is reduced, as is the height of the heeling force. When not used, or in heavy weather, the system will automatically feather to the wind, creating minimal drag.

The system is best suited to tankers (Figure 76) but may work for some bulk carriers though the size of the wingsails would make unloading difficult. Any vessel with available deck space would be a potential candidate. All controls are automated from the bridge and require no crew interaction once activated.

The company claims up to 20% fuel savings in computational models and model testing [Ref 56]. A prototype of the system was tested on a the bulk carrier *M/V Ashington* in 1986/7, and delivered a 10% reduction in fuel savings (Figure 77) [Ref. 56].

No information on upfront cost or maintenance is available, though the company claims the system should have a payback time of 15-18 months [Ref 56].

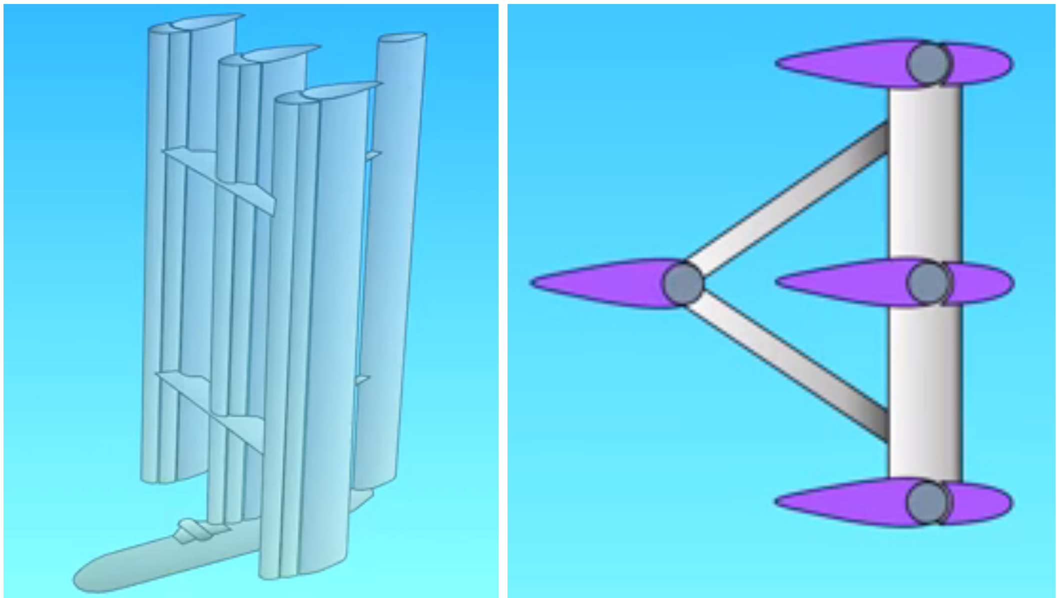


Figure 75 Oceanfoil® wingsail design with tail rudder (Source: Oceanfoil® Ltd.)

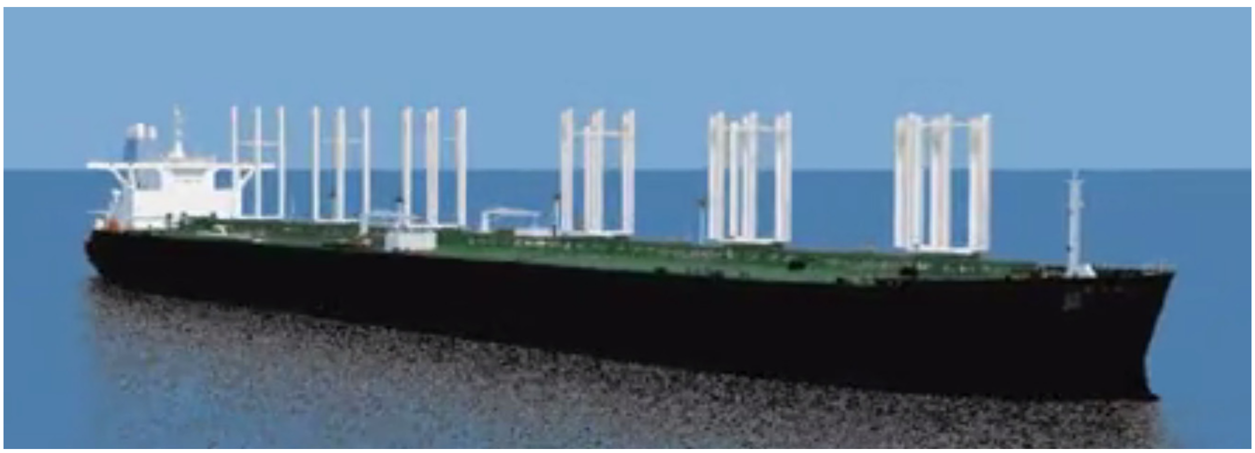


Figure 76 300,000 DWT VLCC Concept with Six Oceanfoil® Sails (Source: Oceanfoil® Ltd.)

Figure 77 6,570 DWT bulk carrier *MV Ashington* Ca. 1987. Source: [Ref. 67].

WindShip Technology Ltd.

WindShip has developed a wingsail system with three airfoils on a single mast (Figure 78). As the mast rotates, the three leading edges rotate around the center of the mast as a unit, while the trailing edges hinge off the leading wings independently. The company claims the system will produce up to 30% fuel savings for a typical bulk carrier, Handy, or Panamax size ($2.5 - $3MM/year) [Ref. 57]. Cost is $6 million for three rigs generation 200kN of towing force over an average trading year [Ref. 58].

The company has spent several years optimizing the design and is scheduled to start the prototype construction in the 1st quarter of 2016. The first installation will be on a 74,000 DWT vessel in late 2016 and operate commercially for one year [Ref. 58].

Each wingsail weighs approximately 400MT [Ref. 57]. On the prototype installation, the system is expected to induce a maximum of 5º of heel in a 40 kt wind [Ref. 58]. If 50 kts of wind, the additional air drag on the vessel is expected to be approximately 3% of the total air drag [Ref. 58]. In heavy weather (greater than 50 kts wind), the system is designed to automatically weather cock (feather into the wind) which will minimize impacts to the vessel [Ref. 58].

Interestingly, they anticipate a vessel will tack and jibe to optimize weather routing solutions. Comparing two identical vessels, leaving and arriving from the same ports, at the same times, a vessel outfitted with their sails would travel farther (due to tacking and jibing) but save at least 30% on fuel, according to company claims [Ref. 58]. They are basing their estimate on weather data collected over 10 years based on over 10,000 routes sailed [Ref. 58].

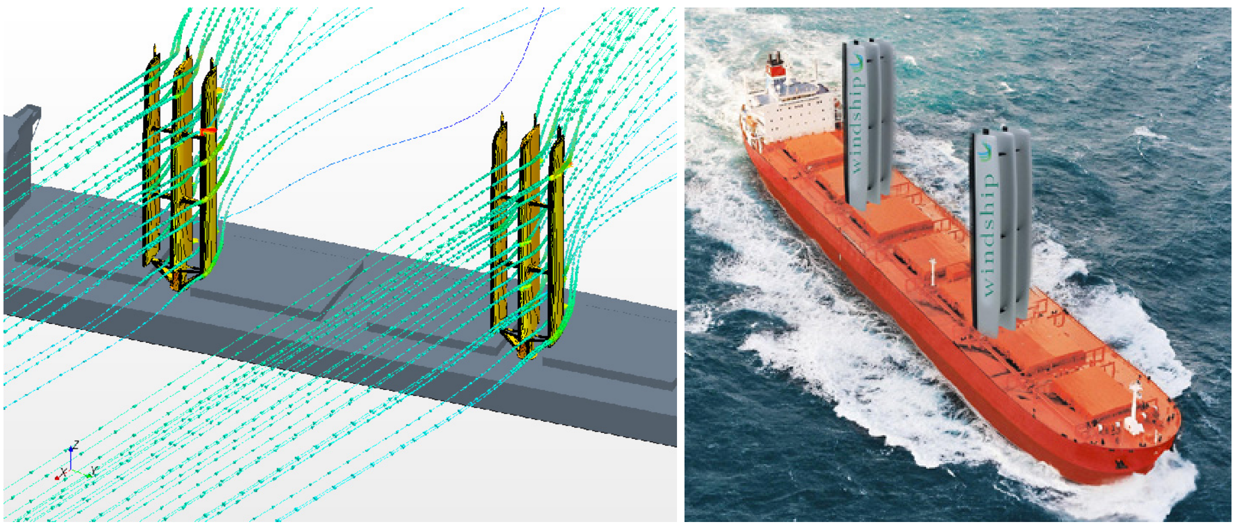


Figure 78 Windhip Ltd. wingsail concept on a bulk freighter (Source: Windship, Ltd.)

Ocius Technology Ltd.

Ocius has developed a design called a Rigid Opening Sail (ROS), which unlike other wingsail designs, has the ability to be completely stowed away, or reefed. The sail folds in two, so that it takes up only half the area in the stowed position (Figure 79). According to the company, it is well suited to the layout and conditions on board a bulk carrier. The company claims $0.5 million cost per sail resulting in a two year return on investment [Ref. 59].

The design solves the issue of reefing in poor weather, and interference for cargo loading/unloading. The CEO of Ocius, Dr. Robert Dane, was also the developer of the 'Solar Sailor', which has plied Sydney harbor for many years.

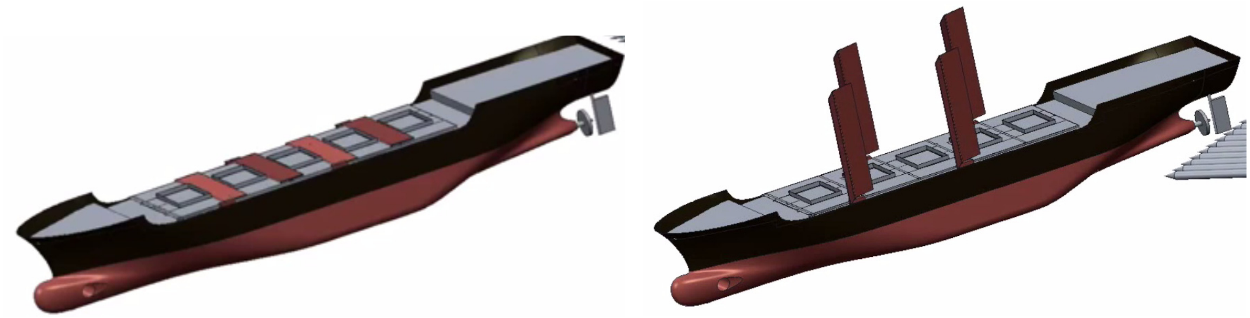


Figure 79 Ocius ROS foldable, stowable wingsails. (Source: Ocius Technology Ltd.)

DynaRig Sails Technology Developers

Ecoliner

Insensys Ltd. (acquired by Moog, Inc.) builds the DynaRig but the *Maltese Falcon* was built by Perini Navi shipyard group in Italy. The patent rights were bought by Tom Perkins, the American venture capitalist and first owner of the *Maltese Falcon,* from the German government. Perini Navi, has continued to develop the concept and just built a 333' superyacht with a 'new and improved' DynaRig.

Commercial cargo vessel concepts like the Dykstra Ecoliner have continued to be promoted advocates of sustainable ship solutions. The Ecoliner project was initiated by Fairtransport BV, Dykstra Naval Architects, and developed further by the Trans-European partnership SAIL. SAIL has 18 maritime partners from seven countries, which have all contributed to the development of the Ecoliner concept. At this point, the project seems to be held up by lack of an investment partner.

The vessel is designed to sail 12 kts under engine power and 18 kts under sail [Ref. 60]. Routing of the vessel would be optimized for the best wind. The expectation is that even traversing a longer route, the vessel would save fuel and make the same time as an engine only vessel.