Energy Efficiency and Underwater Radiated Noise Technologies

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ABS does not endorse products or manufacturers. Trade or manufacturers' names appear in this report only because they are essential to its objectives.

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INTRODUCTION

Decarbonization, cost pressures and increasingly stringent environmental regulations are driving rapid innovation across the marine sector. Two closely related priorities, improving energy efficiency and reducing underwater radiated noise (URN), are now central to vessel design, operation and retrofit strategies. Energy-efficient technologies reduce fuel consumption and greenhouse gas emissions while also lowering operating costs; at the same time, quieter operations can mitigate adverse effects on marine life and help improve a vessel's social license to operate. This report brings these priorities together to provide a coherent view of technologies, practices and trade-offs that owners, designers and operators can apply to achieve both energy and acoustic performance goals.

This report surveys current and emerging technologies that affect shipboard energy use and underwater noise generation and assesses how they interact. The technologies covered include hull and propulsion optimization, energy management and auxiliary-system efficiency, hybrid and electric powertrains, propeller and wake-control measures, and active/passive noise mitigation technologies. Each category is summarized with the typical performance benefits, implementation considerations and cost estimates.

This is important as a combination of regulatory drivers (national and international emissions and environmental protections), stakeholder expectations (charterers, insurers, financiers and coastal communities) and advances in digital monitoring and propulsion technology means that investment in energy-efficient and low-noise solutions can deliver measurable environmental and commercial returns. Integrating acoustic considerations into early-stage design and into operational energy management helps avoid costly retrofits and reduces the risk of non-compliance or reputational harm. Moreover, better measurement and verification techniques can enable data-driven optimization that can deliver simultaneous reductions in fuel use and radiated noise.

This report is designed for shipowners and operators, naval architects and marine engineers, shipyards, offshore project managers, and environmental compliance teams seeking practical guidance for reducing fuel use and underwater noise through technology selection, design integration and operational practice.

By linking the technical, operational and regulatory aspects, this report aims to help stakeholders make informed, cost-effective decisions that help advance both energy efficiency and marine-environment stewardship.

ABBREVIATIONS

AFC - Alkaline Fuel Cell
ALS - Air Lubrication Systems
ALDR - Air Layer Drag Reduction
APUs - Auxiliary Power Units
BDR - Bubble Drag Reduction
BSP - Bionic Skin Propeller
Capex - Capital Expenditure
CFD - Computational Fluid Dynamics
CPP - Controllable Pitch Propeller
CRL - Commercial Readiness Level
CRP - Contra-Rotating Propellers
dB - Decibels
DEP - Diesel Electric Propulsion
DWT - Deadweight
ECU - Electronic Control Units (ECUs)
EE - Energy Efficiency
EEC - Electronic Engine Control
EETs - Energy Efficiency Technologies
ESS - Energy Storage System
FPP - Fixed-Pitch Propellers
GVU - Gas Valve Unit
GWP - Global Warming Potential
HVAC - Heating, Ventilation and Air-Conditioning (HVAC) Systems
IMO - International Maritime Organization
LCA - Life Cycle Assessment
LNG - Liquefied Natural Gas
LPG - Liquefied Petroleum Gas
MCFC - Molten Carbonate Fuel Cell
MCR - Maximum Continuous Rating
N/A - Not Applicable
OCCS - Onboard Carbon Capture System
Opex - Operational Expenditure
ORC - Organic Rankine Cycle
PAFC - Phosphoric Acid Fuel Cell
PALS - Passive Air Lubrication System
PBCF - Propeller Boss Cap Fin
PCDR - Partial Cavity Drag Reduction
PEM FC - Proton-Exchange Membrane Fuel Cell
PTG - Power Turbine Generator
PTI - Power Take-In
PTO - Power Take-Off
PV - Photovoltaic
RPM - Revolutions Per Minute
SFOC - Specific Fuel Oil Consumption
SOFC - Solid Oxide Fuel Cell
STG - Steam Turbine Generators
TRL - Technology Readiness Level
VFD - Variable Frequency Drive
VIT - Variable Injection Timing
VSG - Variable Speed Generators
VVT - Variable Valve Timing
WASP - Wind-assisted Ship Propulsion
WED - Wake Equalizing Duct
WHR - Waste Heat Recovery

ABS

1. Hull Appendage Design

Treatment/Description	Improvements from Technology		Energy Efficiency (EE) Reference	Ship Level of Intervention	Technology Readiness Level (TRL) (Scale of 1-9)	TRL Comments	Commercial Readiness Level (CRL) (Scale of 1-9)	CRL Comments	Estimated Time of Installation	Drydock Needed	Maintenance Needed	Maintenance Cost Estimation	Installation Cost Estimation	Applicability	Comments	List of Possible Suppliers	Compatibility	Regulation	Image Reference	In-text Citations
	Energy (%)	Underwater Radiated Noise (URN) (Decibels (dB))	Literature/ Vendors							Yes/No	Yes/No		Percentage/Range/Payback Period	Retrofit/Newbuild						
1.1 DESIGN FOR SERVICE Designing a vessel to meet its specific operational requirements and functions, while considering energy efficiency to optimize its performance, for the anticipated operating profile.	5-10%	< 5 dB	Literature	Improved crew/passengers comfort and increased design effort.	9	-	9	-	-	Yes	-	There is no additional maintenance cost specifically for this technology.	Less than 1% of the new ship's cost (for larger ships). Multi-pass model test and computational fluid dynamics (CFD) programs typically cost $150,000 to $500,000 USD [3].	Newbuild	For smaller ships, the engineering costs can be quite significant relative to the overall cost of the ship, especially depending on the complexity of the analyses required.	Shipyards	Compatible with other energy efficiency technologies (EETs).	Statutory-related requirements: International Code on Intact Stability, 2008, as amended · Load Lines 1966 and Protocol of 1988, as amended · SOLAS Consolidated Edition 2020, as amended · MARPOL Consolidated Edition 2017, as amended. Class-related requirements: The requirements for hull structural strength are included in the ABS *Rules for Building and Classing Marine Vessels, 2024*.	N/A, consists of many small design implementations and is mostly the result of advanced modeling. There is not a specific image to identify this technolgy with.	**Overarching Citations** VARD Marine Inc., "Ship Energy Efficiency and Underwater Radiated Noise," Transport Canada, Ottawa, 2023. A. Orthmann, S. Fitzgerald, J. Gerlach, A. McKee and K. Reynolds, "Energy Efficiency and Decarbonization Technical Guide," U.S. Department of Transportation Maritime Administration, Washington, 2022. **Direct Citations** 1. H. Scheekluth and V. Bertram, Ship Design for Efficiency and Economy, 2nd Ed., Oxford, U.K.: Butterworth-Heinemann, 1998. 2. G. Gougoulidis, N. Vasileiadis, "An overview of hydrodynamic energy efficiency improvement measures", 2015. 3. D. Cumming, R. Pallard, E. Thornhill, D. Hally and M. Dervin, "Hydrodynamic design of a stern flap appendage for the HALI AX class frigates," Mari-Tech Conf., 2006. 4. Y. Kummar and R. Vijayakumar, "Development of an Energy Stern Flap for Improved EEDI of a Typical High-speed Displacement Vessel", India, 2020. 5. American Bureau of Shipping. (2013). ABS Advisory on Ship Energy Efficiency Measures. https://ww2.eagle.org/content/dam/eagle/advisories-and-debriefs/ABS_Energy_Efficiency_Advisory.pdf 6. E. Bouman, E. Lindstad, A. Rialland, A. Hammer, "State-of-the-art technologies, measures, and potential for reducing GHG emissions from ships" Norway, 2017. 7. Global Maritime Energy Efficiency Partnerships. (n.d.). GloMEEP. Glomeep.imo.org; International Maritime Organization. Retrieved November 27, 2024, from https://glomeep.imo.org/ 8. Wallenius Wilhelmsen. (2023, October 12). A step forward: The new bulbous bow arrives. WalleniusWilhelmsen.com. https://www.walleniuswilhelmsen.com/news/a-step-forward-the-new-bulbous-bow-arrives
1.2 EFFICIENT HULL FORMS Hydrodynamically (for calm water and waves) efficient hull forms will reduce power requirements. Such hulls will also generally have good wake characteristics.	5-10%	< 5 dB	Literature The EE will depend on the vessel size, vessel segment and design speed.	Enhanced crew/passenger comfort and increased design effort.	9	-	9	Several CFD software packages exist and support hull shape development by assessing hydrodynamic performance.	-	Yes	Yes, the maintenance needed would be the periodic hull cleaning.	There is no additonal maintenance cost specifically for this technology.	Less than 1% of the new ship's cost. Multi-pass model test and CFD programs typically cost $150,000 to $500,000 [3].	Newbuild	Efficient hulls may lose carrying capacity. Cost is for larger ships. For smaller ships, engineering costs may be significant relative to the cost of the ship,depending on the complexity of analyses. Additional cost may be incurred due to more streamlined hull production, e.g., for plates with double curvatures. Cost generally scales with the complexity/constraints of optimization, not vessel size. The payback period is therefore longer for small vessels that often idle, given lower annual fuel costs.	Shipyards	Compatible with other EETs.	Statutory-related requirements: International Code on Intact Stability, 2008, as amended · Load Lines 1966 and Protocol of 1988, as amended · SOLAS Consolidated Edition 2020, as amended · MARPOL Consolidated Edition 2017, as amended. Class-related requirements: The requirements for hull structural strength are included in ABS *Rules for Building and Classing Marine Vessels, 2024*.	N/A, consists of many small hull and vessel line changes and is mostly the result of advanced modeling. There is not a specific image to identify this technolgy with.	
1.3 BULBOUS BOW The bulbous bow is a distinctive protrusion at the forward end of a ship's hull, located below the waterline. The bulbous bow's purpose is to reduce the ship's resistance by modifying the water flow around the hull. This reduces the required propulsion power.	3-6%	< 5 dB	Literature The EE will depend on the vessel size, vessel segment and design speed. The roll on/roll off vessel *Aniara* (deadweight (DWT) 30,089) has achieved a 6% fuel saving after installing a bulbous bow [8].	Improved crew/passengers comfort and increased design effort.	9	-	9	Several vessels have installed/retrofitted this technology.	Approximately 14 days.	Yes	Yes, the maintenance needed would be the periodic hull cleaning.	There is no additional maintenance cost specifically for this technology.	Estimated installation cost ranges from $100,000 to $800,000. With 5% fuel efficiency, the payback period is around one year.	Retrofit and newbuild	Bulbs are speed optimized. Ships adapted to lower sailing speeds may need to consider implementation of bulbs, or even change the current bulb geometry. Bulbous bow should be built tailored to meet the vessel operation profile, such as operation draught and speed.	Shipyards	Compatible with other EETs.	Statutory-related requirements: International Code on Intact Stability, 2008, as amended · Load Lines 1966 and Protocol of 1988, as amended · SOLAS Consolidated Edition 2020, as amended · MARPOL Consolidated Edition 2017, as amended. Class-related requirements: The requirements for hull structural strength are included in ABS *Rules for Building and Classing Marine Vessels, 2024*.	Ba Naga, M. H., & Nuramalia, Z. (2023). Comparative Analysis of Faired-In Bulb and Bulbous Bow Ram Bow's Bulbous Bow Shape On Total Ship Resistance. Maritime Park: Journal of Maritime Technology and Society, 2(1), 28–30. https://doi.org/10.62012/mp.v2i1.32649	
1.4 EFFICIENT ABOVE WATER FORMS Aerodynamically efficient forms will reduce air and wind resistance power requirements.	Up to 1%	None	Literature	Improved crew/passengers comfort and increased design effort.	9	-	9	-	-	Yes	Yes, the maintenance needed would be the periodic cleaning/painting maintenance.	There is no additional maintenance cost specifically for this technology.	Less than 1% of the new ship cost.	Newbuild	May warrant more consideration for smaller and faster ships. Cost is for larger ships. For smaller ships, engineering cost may be significant relative to the cost of the ship, depending on the complexity of the analyses. Additional cost may be incurred due to more streamlined hull production.	Shipyards	Compatible with other EETs.	Statutory-related requirements: International Code on Intact Stability, 2008, as amended · Load Lines 1966 and Protocol of 1988, as amended · SOLAS Consolidated Edition 2020, as amended · MARPOL Consolidated Edition 2017, as amended. Class-related requirements: The requirements for hull structural strength are included in ABS *Rules for Building and Classing Marine Vessels, 2024*.	D. S. Cusanelli and G. Karafiath, "Hydrodynamic Energy Saving Enhancement for DDG 51 Class Ships," Naval Surface Warfare Center, Bethesda, 2012. ADA582048.pdfADA582048.pdf	
1.5 STERN FLAP/WEDGE Small extensions from the lower transom. It modifies the stern wave produced by the ship and reduces powering requirements.	Up to 10%	< 5 dB	Literature	Improved crew/passengers comfort and increased design effort.	9	-	8	Technology usually adopted by the navy vessels and coast guard vessels.	From several hours to a few days.	Yes	Yes, the maintenance needed would be the periodic hull cleaning.	There is no additional maintenance cost specifically for this technology.	Less than 1% of the new ship cost.	Retrofit and newbuild	The technology has shown better effects on high-speed vessels.	Shipyards	Compatible with other EETs.	Statutory-related requirements: International Code on Intact Stability, 2008, as amended · Load Lines 1966 and Protocol of 1988, as amended · SOLAS Consolidated Edition 2020, as amended · MARPOL Consolidated Edition 2017, as amended. Class-related requirements: The requirements for hull structural strength are included in ABS *Rules for Building and Classing Marine Vessels, 2024*.	Creative Commons: Sourced From: Zero-emission cruise ship is powered by solar sails | FMT	

2. Frictional Resistance Reduction

Treatment/Description	Improvements from Technology		EE Reference	Ship Level of Intervention	TRL	TRL Comments	CRL	CRL Comments	Estimated Time of Installation	Drydock Needed	Maintenance Needed	Maintenance Cost Estimation	Installation Cost Estimation	Applicability	Comments	List of Possible Suppliers	Compatibility	Regulation	Image Reference	In-text Citations
	Energy (%)	URN (dB)	Literature/ Vendors							Yes/No	Yes/No		Percentage/Range/Payback Period	Retrofit/newbuild						
2.1 ANTIFOULING COATING Appropriate hull coating selection can reduce frictional resistance and power requirements. The vessel´s operational profile and coating maintenance should be considered. The material used to coat the hull of a ship below the waterline serves several purposes. The primary purpose is to prevent corrosion of the steel hull. A secondary purpose is to inhibit the growth of marine organisms on the exterior of the hull by means of antifouling.	Fuel saving from 1-7%. The ship's resistance decreases by up to 8%.	< 5 dB	Literature/Vendors International Coatings Co. states that the results indicate a fuel saving of more than 10% (tanker sizes included in that study: 19,885 DWT and 157,048 DWT) [8].	Enhanced crew/passenger comfort and increased maintenance.	9	-	9	Antifouling coatings are available from several paint companies and widely adopted across vessel types and trades. According to the International Coatings Study, antifouling paint was applied on more than 700 vessels [8].	From three to seven days.	Yes	Yes, it is considered a three to five-year drydock period to reapply coating, as the effect of the coating reduces over time [4].	A full blast to remove surface roughness and application of primer, anticorrosive and high-quality antifouling can cost $10/m2 (varying between $6 and $17 in the Far East, for instance) [3]. The estimated maintenance costs refer to the drydock periodic paint maintenance every fifth year, and it ranges from $100,000 to $500,000.	Low ($30,000 to $700,00). Payback period is usually less than a year. Payback period is less than nine months.	Newbuild	The performance of any coating system, including foul-release, will diminish over time. Organisms will find a way to attach to imperfections or damaged areas of the coating, increasing hull resistance. Coatings are usually renewed on the drydocking schedule, typically 60 months for most cargo vessels and more frequently for many passenger vessels. Suitable for all vessels, seawater and freshwater alike. Particularly beneficial in warm and seawater environments where marine growth advances aggressively. Savings are maximized for vessels that are frequently in transit, while also experiencing idle or low-speed periods when marine growth can accumulate. The cost of foul-release coatings is higher than that of traditional coatings for first-time applications. This is driven by both material costs and the skilled labor required.	Hempel Chugoku CMP PPG Jotun IP (International Paint) KCC Selektope	Dedicated equipment is required for installing foul-release coatings, as they are not compatible with other paint types. New spray lines and cleaned (or new) pumps are required. Nanocoating integrated into an antifouling product may be applied over an existing coating, but it is recommended by manufacturers to be applied over a blasted surface.	International Maritime Organization (IMO) – AFS Convention (International Convention on the Control of Harmful Antifouling Systems in Ships) IMO MEPC.378(80) resolution on Guidelines for the Control and Management of Ships' Biofouling to Minimize the Transfer of Invasive Aquatic Species asks for a bio-fouling management plan and a bio-fouling record book to be on board. This may limit the locational scope for cleaning of the hull. IMO MARPOL 73/78 NORMAM 20	"Choosing the Right Antifouling Coating: A Shipowner's Guide - Indonesia Trusted Ship Agency," Indonesia Trusted Ship Agency, 15 Feb. 2024. balancia.co.id/choosing-the-right-antifouling-coating-a-shipowners-guide/.	**Overarching Citations** VARD Marine Inc., "Ship Energy Efficiency and Underwater Radiated Noise," Transport Canada, Ottawa, 2023. A. Orthmann, S. Fitzgerald, J. Gerlach, A. McKee and K. Reynolds, "Energy Efficiency and Decarbonization Technical Guide," U.S. Department of Transportation Maritime Administration, Washington, 2022. **Direct Citations** 1. Air Lubrication Technology. (2019). https://ww2.eagle.org/content/dam/eagle/advisories-and-debriefs/Air%20Lubrication%20Technology.pdf 2. American Bureau of Shipping. (2022). Requirements for Air Lubrication System Installation. https://ww2.eagle.org/content/dam/eagle/rules-and-guides/current/other/301-requirements-for-air-lubrication-system-installation/301-air-lubrication-reqts-july22.pdf 3. American Bureau of Shipping. (2013). ABS Advisory on Ship Energy Efficiency Measures. https://ww2.eagle.org/content/dam/eagle/advisories-and-debriefs/ABS_Energy_Efficiency_Advisory.pdf 4. International Maritime Organization. (2015). Safe, secure and efficient shipping on clean oceans. 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International-Marine.com; AkzoNobel. https://www.international-marine.com/content/dam/akzonobel-coatings/international-marine/gl/document/CaseStudy-Intersleek-BulkCarrier.pdf generate over 10% fuel savings" 9. Yamamoto, Y. (2021, January 21). Nippon Paint Marine Launches FASTAR Next-Generation Industry-First Nanotechnology-Based Hydrolysis Antifouling Paint. NIPPON PAINT HOLDINGS CO.,LTD. https://www.nipponpaint-holdings.com/en/news_release/2021012201/ 10. Kapil Kajal. (2024, July 17). Dolphin skin propeller to help cargo ship cut emissions by 900 tons. Interesting Engineering. https://interestingengineering.com/transportation/china-dolphin-skin-propeller. 11. American Bureau of Shipping. (2013). ABS Advisory on Ship Energy Efficiency Measures. https://ww2.eagle.org/content/dam/eagle/advisories-and-debriefs/ABS_Energy_Efficiency_Advisory.pdf 12. American Bureau of Shipping. (2021). ABS Sustainability Trends Tankers. In Eagle.org. American Bureau of Shipping. https://absinfo.eagle.org/acton/attachment/16130/f-b7a88450-58da-410b-987a-16b1c48017d4/1/-/-/-/-/tankers-sustainability-trends-whitepaper-21118.pdf
2.2 NANOCOATING SELECTION While nanocoating itself is not a biocide or self-polishing material, it does reduce chemical elution (or the washing-away) of biocide agents in antifouling coatings, extending the functional life of coatings that rely on those biocides. Nanocoatings reduce the propulsion power requirement.	Up to 8%	< 5 dB	Literature/Vendor Nippon Fastar Paint estimates a fuel saving of approximately 8% when applying their antifouling coating [9].	Enhanced crew/passenger comfort and increased maintenance.	7	-	8	Nanocoating systems have been ordered and applied on commercial vessels.	From four to eight days.	Yes	Yes, it is considered a three- to five-year drydock period to reapply the coating as the effect of the coating reduces over time.	Likely higher than antifouling system.	Likely higher than antifouling coating.	Newbuild	Actual cost data of nanocoating-based systems has not been collected. As an emerging technology, the material cost is likely higher than other antifouling coatings. This may be offset by reduced coating thickness for some applications. The application is not supposed to require any specialized equipment or training. Nanocoating is generally associated with biocidal antifouling coatings, and its compatibility with foul-release (self-polishing) coatings was not examined. Although its use has been more centered on propellers, recently, hull applications have been performed.	Nano-Clear NCI Coatings Nippon Fastar GIT Coatings	For replacing traditional coatings with a foul-release coating on an existing vessel, more surface preparation may be required due to compatibility issues. Nanocoating integrated into an antifouling product may be applied over an existing coating, but it is recommended by manufacturers to be applied over a blasted surface.	IMO – AFS Convention (International Convention on the Control of Harmful Antifouling Systems in Ships) IMO MEPC.378(80) resolution on Guidelines for the Control and Management of Ships' Biofouling to Minimize the Transfer of Invasive Aquatic Species asks for a bio-fouling Management Plan and a Bio-fouling Record Book to be onboard. This may limit the locational scope for cleaning of the hull. IMO MARPOL 73/78 NORMAM 20	Nanovere Technologies, LLC., Sample Application of the Nano-Clear Industrial Coating, Brighton: Materials Performance, 2020. Hybrid Nanocoating Extends Life of Industrial Coating Systems	
2.3 PROPELLER POLISHING/COATING Aiming to minimize fouling from the propeller, the propeller should be treated with polishing and proper painting.	Up to 6% of the main engine's fuel consumption [11].	Unknown	Literature	Enhanced crew/passenger comfort.	9	-	9	Propeller polishing/coating is widely adopted in the industry.	1.5 to 12 hours	It depends on the method used. By using robots, it does not require shipyards, but most robots cannot clean underneath the vessels. Mechanical cleaning requires shipyards.	Yes, periodic propeller inspection and cleaning.	Estimated diving costs to perform a periodic propeller polishing range from $4,000 to $8,000, depending on the vessel size and the complexity of the propeller. Divers can clean a 10-meter diameter per five-blade propeller in about three to four hours for $3,000 in the Far East [3].	N/A	Retrofit and newbuild	-	GIT Coatings (X-GIT Prop)	Compatible with other technologies.	IMO – AFS Convention (International Convention on the Control of Harmful Antifouling Systems in Ships) IMO resolution MEPC.378(80): Guidelines for the Control and Management of Ships' Biofouling to Minimize the Transfer of Invasive Aquatic Species. IMO MARPOL 73/78 NORMAM 20	Atlantis Marine Services LLC, "Propeller Polishing," 2024. [Online]. Available: https://www.amssub.com/media/k2/items/cache/00e7056ec788d5b42162a6c13dbba43c_XL.jpg. [Accessed 20 November 2024]. Atlantis Marine Services - Propeller Polishing	
2.4 BIONIC (DOLPHIN) PROPELLER COATING It is a bionic skin propeller inspired by dolphins´ skin, aiming to enhance the ship´s efficiency. Bionic skin propeller is composed of liquid-like dynamic interfacial materials and flexible materials with a microstructure between 0.1 and 0.2 millimeters (mm). When placed on the propeller's surface, the bionic skin can reduce the shear force with the water, counteract the work of the reverse thrust on the water, improve the propeller efficiency and reduce energy consumption.	~2%	Unknown	Researchers at the Ningbo Institute of Materials Technology and Engineering claim that the bionic skin on the propeller led to a 2% reduction in the crude carrier's fuel consumption [10].	Enhanced crew/passenger comfort and increased design effort.	6	-	7	Although it is not commercialized yet, some projects have shown great progress: Fraunhofer IFAM has shown a drag reduction of around 6%. A research study from a collaboration between [illegible]	A few days to a week.	Yes	Yes, it is considered a three- to five-year drydock period to clean the propeller.	The maintenance cost is related to the periodic propeller cleaning.	In China, researchers at the Ningbo Institute of Materials Technology and Engineering estimate an installation cost of approximately $20,000. The payback period is less than a year [7].	Retrofit and newbuild	This technology is still in the testing and early adoption phase, but shows promising results in improving the fuel efficiency and emissions of large cargo ships by reducing drag on the propellers. Bionic skin propeller complies with the International Convention for the Control of Harmful Antifouling Systems on Ships. Further studies regarding static fouling are required.	-	N/A	IMO – AFS Convention (International Convention on the Control of Harmful Antifouling Systems in Ships) IMO MARPOL 73/78 NORMAM 20	Xinhua News Agency, "Across China: Bionic Dolphin Skin Saves Fuel for Large Crude Carrier," 16 July 2024. [Online]. Available: https://english.news.cn/20240716/c6adddcd7fd14655a472151f7462870b/c.html. [Accessed 25 November 2024]. Across China: Bionic dolphin skin saves fuel for large crude carrier-Xinhua	

APPENDIX

Technology Readiness Level (TRL)[1]	
Level	Description
1	Basic principles observed and reported.
2	Technology concept and/or application formulated.
3	Analytical and experimental critical function and/or characteristic proof of concept.
4	Product and/or process validation in laboratory environment.
5	Product and/or process validation in relevant environment.
6	Product and/or process prototype demonstration in a relevant environment.
7	Product and/or process prototype demonstration in an operational environment.
8	Actual product and/or process completed and qualified through test and demonstration.
9	Actual product and/or process have proven successful.

Commercial Readiness Level (CRL) [2]	
Level	Description
1	Basic hypothesis that the technology could be commercially viable, but there is no commercial proposition yet.
2	Basic market awareness demonstrated through research and initial stakeholder discussions. A conceptual proposition has been formulated.
3	Potential application for commercial ships has been identified, and commercial strategy has been formulated.
4	The commercial strategy is tested and validated in the market. Technology is in the late stages of deployment.
5	The technology has been demonstrated on a commercial scale but is not yet ready for the market.
6	The technology prototype has been built and tested. Market assumptions updated.
7	Demonstration as a partial system, with vessel specific approval.
8	Demonstration as a full system, with vessel specific approval.
9	Technology has been introduced in the marine industry, with type approval.

[1] Technology Readiness Levels based on the NASA TRL and NOAA Readiness Levels. Technology Readiness Levels - NASA, Readiness Levels – Office of Research Transition and Application

[2] Commercial Readiness Levels based on the scale from the British Institute of Non-Destructive Testing. CRL

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