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Vard Marine Inc.

SHIP ENERGY EFFICIENCY AND UNDERWATER RADIATED NOISE

Report 545-000-01

Rev 1

Prepared for
Transport Canada

by
Vard Marine Inc.

Date: 11 September 2023

NOTICES

This report reflects the views of the authors and not necessarily those of the Innovation Centre of Transport Canada or the Canadian government.

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

This report does not attempt to provide a comprehensive description of any aspect of energy efficiency, GHG reduction, or URN.

This current study does not focus on alternative fuels and combustion engines.

Many of the provided Energy Efficiency, Greenhouse Gas and Underwater Radiated Noise improvements as well as mentioned advantages/disadvantages of potential solutions are based on VARD's ship design experience.

The report is available in English only.

ACKNOWLEDGEMENTS

"to be written after receiving feedback and comments from the various parties"

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SUMMARY OF REVISIONS

Rev	Date	Description	Prepared by	Checked by
0	30 August 2023	Initial submission for comments	AMK, EMS	RTE
1	11 September 2023	Incorporation of TC comments	AMK, EMS	RTE

EXECUTIVE SUMMARY

This report has been developed by Vard Marine Inc (VARD) for Transport Canada, to provide a convenient reference source for technical and operational measures which can:

a) increase the energy efficiency (EE) and reduce greenhouse gas (GHG) emissions from ships, and/or
b) mitigate underwater radiated noise (URN) from ships, which can have damaging effects on marine animals of many types.

In some cases, measures may have desirable outcomes for both aspects, while in others they may conflict. The report highlights when each of these may apply.

The report text introduces some of the key issues related to EE, GHG and URN, and to the current initiatives at the International Maritime Organization (IMO) which relate to these. Factors which contribute to EE, GHG and URN, including ship resistance and propulsion, ship machinery systems, and operational approaches are outlined, with brief explanations of the underlying causes.

Energy efficiency and greenhouse gas reduction are often very closely linked, though this may not be the case for alternative fuels. The report does not aim to go into any depth on alternative (zero- and near-zero carbon) fuels, which will be essential to achieving longer-term net zero emission targets. It does, however, note areas in which their adoption may have significant URN implications due to the different machinery types which they may utilize.

Measures are consolidated in the matrix which forms Appendix A to the report. The matrix provides an overview of each measure, and a summary of its effectiveness for EE, GHG and URN. Other aspects of each measure are also outlined, the applicability to different ship types is summarized, and information on implementation costs is provided. Where possible, citations are provided which offer additional information. Any values provided in the report and matrix are indicative, and that results for a specific ship may well be quite different. Shipowners and their designers and builders need to undertake their own due diligence to select measures appropriate to their own vessels and operations.

The report provides a set of recommendations for future actions. Many of these relate to increased data collection and knowledge dissemination. For both EE/GHG and URN there is a lack of high-quality, measured data on the effectiveness of many of the methods that have been proposed. This increases risk and uncertainty for owners who wish to improve the performance of their ships, and will delay any improvement of the overall global fleet. IMO, and its member administrations, should take and encourage steps to improve this situation.

The report and matrix have been developed in draft form as inputs to the pending IMO Workshop on the Relationship between Energy Efficiency and Underwater Radiated Noise from Ships (September 2023), and will be updated based on feedback from attendees.

TABLE OF CONTENTS

LIST OF FIGURES

NOMENCLATURE

ABS	American Bureau of Shipping
AC	Alternating Current
CAPEX	CAPital EXpenditure
CII	Carbon Intensity Index
CLT	Contracted Loaded Tip
CPB	Costa Propulsion Bulb
CPP	Controllable Pitch Propeller
CRP	Contra-Rotating Propeller
dB	deciBel
DC	Direct Current
ECHO	Enhancing Cetacean Habitat and Observation
EE	Energy Efficiency
EEC	Electronic Engine Control
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency of eXisting ships Index
ESS	Energy Storage Systems
GHG	GreenHouse Gas
GPD	Gross Domestic Product
GT	Gross Tonnage
GWP	Global Warming Potential
HR	Heat Recovery
HVAC	Heating, Ventilation and Air Conditioning
IMO	International Maritime Organization
ISED	Innovation, Science and Economic Development Canada
LNG	Liquified Natural Gas
LT	Low Temperature
NASA	National Aeronautics and Space Administration
NE	North East
NOAA	National Oceanic and Atmospheric Administration
OPEX	OPerational EXpenditure

OPV	Offshore Patrol Vessel
PBCF	Propeller Boss Cap Fins
PCT	Propeller Cap Turbines
PEMS	Power/Energy Management System
PRAIRIE	PRopeller AIR-Induced Emission
PTI	Power Take-In
PTO	Power Take-Off
PV	PhotoVoltaic
rpm	Revolutions Per Minute
SG	Steam Generator
SW	Sea Water
TC	Transport Canada
TPK	Turns Per Knot
TRL	Technology Readiness Level
UN	United Nations
URN	Underwater Radiated Noise
US	United States
USD	United States Dollar
VARD	VARD Marine Inc.
VFD	Variable Frequency Drive
VVT	Variable Valve Timing
WASP	Wind ASisted Propulsion
µPa	microPascal

1 INTRODUCTION

This report presents the results of a combined review of means to:

a) increase the energy efficiency (EE) and reduce greenhouse gas (GHG) emissions from ships, and
b) mitigate underwater radiated noise (URN) from ships, which can have damaging effects on marine animals of many types.

Both GHG reduction and URN are important considerations for the International Maritime Organization, and for its member national administrations. The rationale for a joint review is that many of the measures that will improve one of these two characteristics will also impact the other — often positively but sometimes negatively. It is important for stakeholders to understand the options available to allow them to comply with mandatory and recommended standards now and in the future.

Vard Marine (VARD) has been engaged for this work by Transport Canada (TC). TC is the Federal Government department responsible for safe, secure, efficient and environmentally responsible transportation. TC is one of the lead departments delivering Canada's domestic Oceans Protection Plan, and represents Canada in a permanent mission at the International Maritime Organization. TC is working on the development of policies to improve the safety, security and environmental responsibility of the maritime sector, for example international measures aimed at promoting energy efficiency and protecting the marine environment. TC needs to acquire information on the technological measures that are currently implemented or that could be implemented which have the potential to impact either or both of these characteristics. VARD has undertaken prior consulting work for TC and other clients in these areas and is also a designer of ships which have incorporated many aspects of energy efficiency and URN reduction to meet client requirements.

VARD's analysis includes both technologies and operational measures. It considers their applicability to different ship types and to both existing and future ships. Other advantages and drawbacks are indicated, including space and weight demands, ship acquisition and running costs, crew and passenger comfort, and other factors. For potential measures not yet widely adopted, the technology readiness level (TRL) is estimated, based on published information. All of this is intended to assist TC and other stakeholders in making decisions ranging from regulations to ship refits.

The main work product is a matrix of options and aspects, presented as Appendix A to the report, which can be used as a stand-alone summary of energy efficiency improvement and GHG and URN reduction measures that can be used now and in the future. This matrix is linked to reference data to the source with a number in square brackets (see Appendix B) and internal (VARD) analyses that support each aspect of the assessments. The document will be used as a reference document for the IMO Expert Workshop on the relationship between Energy Efficiency and Underwater Radiated Noise in September 2023, and international experts will contribute to the final version.

This report does not attempt to provide a comprehensive description of any aspect of energy efficiency, GHG reduction, or URN, which are all vast and complex subjects. This study does not focus on alternative fuels and combustion engines. Where alternative fuels enable technologies (such as fuel cells), the implications are reviewed. This is an introductory treatment, supported where possible by reference, to more in-depth explorations of one or more aspects of the field. The report also does not aim to endorse or recommend any specific brand of manufacturer. The report provides recommendations and next steps to support the advancement or treatments to reduce GHG and URN. Where opinions and assumptions are included, they are those of VARD's project team, and should not be taken to represent any position or policy on the part of Transport Canada and the Canadian government.

2 SCOPE OF WORK AND REPORT LAYOUT

VARD’s scope of work for Transport Canada can be summarized as a recapitulation of the latest research and understanding of EE improvement measures and what is known about their relationship to URN reduction. The focus of this study is global. and does not intend to do a deep dive into every single technology. EE improvement methods are drawn from those being used as compliance approaches for the IMO’s Energy Efficiency of eXisting ships Index (EEXI), Energy Efficiency Design Index (EEDI), and Carbon Intensity Index (CII). Findings should be relevant to diverse ship types, taking into account their design and construction, modifications, and their operating conditions, in accordance with the application of the *Revised Guidelines for the reduction of underwater radiated noise from shipping to address adverse impacts on marine life* (MEPC.1/CIRC.906).

In addition to presenting EE effectiveness and URN effectiveness (sound level and frequency range), the work is to cover:

a) Advantages and benefits to the ship’s design and operations;
b) Disadvantages and challenges;
c) Technology readiness level;
d) Cost impacts for implementation and operation; and
e) Applicability to different ship types.

VARD has consolidated this information in the ‘Matrix of Technical and Operational Measures’ which is provided at Appendix A to this report and will be called ‘the matrix’ from now on in the report. The remainder of the report provides context for the work, and also explains how some of the assessments in the matrix have been derived.

3 ENERGY EFFICIENCY AND GHG REDUCTION – OVERVIEW

A ship exists to fulfil a purpose. This is often the transportation of goods or people. It may be to provide a service, such as wind farm installation, or to act as a stand-by offshore support ship. In other cases, it may undertake fishing or sub-sea mining. All of these require the expenditure of energy. Energy efficiency enhancements to design or operations are measures that reduce the energy demands per unit for output; in whatever way this output is defined, whether as tonnes/miles of cargo transported or wind turbines installed.

There are many potential sources of energy. The earliest boats were propelled by human muscles, using the energy stored in our bodies between meals. Later vessels used wind power for many millennia. Steamships used wood, coal, and subsequently liquid fossil fuels, as did their motor ship successors. Nuclear fission energy has a niche role in military vessels and a few others. In each era of shipping, during transitional periods (as the maritime industry is in at the moment) vessels have often used a mix of technologies such as sail and steam or the transition from coal to oil when fuel supply chains were uncertain, and the reliability of the newer technology incurred risks.

Energy efficiency is distinct from GHG reduction, though they are often closely correlated (see Appendix A). As an example, a dual-fuel engine capable of using both traditional fossil fuels (diesel or heavy fuel) may use a less thermodynamically efficient combustion cycle than a pure Diesel[1] cycle. However, if the alternative fuel has less carbon content, then the overall GHG emissions will be reduced. Similarly, the total efficiency of battery energy systems may be less than that of an internal combustion engine but, provided that the batteries are recharged using renewable electricity, their GHG impact will be reduced. Both energy efficiency and GHG reduction are addressed in this report, and the differences are highlighted where appropriate.

The International Maritime Organization (IMO) has wrestled somewhat with several of the concepts introduced above, including the appropriate metrics for energy efficiency, the clarification of how energy efficiency and GHG reduction should be considered together, and the question of how much of the energy supply chain needs to be taken into account when defining GHG reduction in particular. The trend is, increasingly, to account for emissions from "well to wake", i.e., to include the emissions required to produce and transport the fuel in addition to those created when it is used aboard the ship. All of these aspects are discussed in more detail later in the report.

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[1] "Diesel" has multiple meanings. It can be (a) a thermodynamic cycle, in which case it is capitalized in this report, or (b) a generic term for a family of internal combustion engines, or a range of refined fuel oils, in which case it is not. A diesel engine may or may not be burning diesel fuel or using a Diesel combustion cycle.

3.1 SHIP ENERGY DEMAND AND SUPPLY

3.1.1 SHIP ENERGY DEMAND

Most ships consume the most energy in moving, though other onboard power demands can be similar or greater for some ship types such as cruise ships and various offshore support vessels. Water provides resistance to movement, and this has to be overcome. Ship resistance is often expressed, analyzed, and mitigated by considering various components, including (but not limited to):

- Skin friction between the moving ship and the stationary water;
- Wave-making resistance as the ship pushes water out of its way;
- Form drag created by regions of high and low pressure around the hull; and
- Air drag, created by ship motion and wind.

All resistance components increase with speed, and wave-making in general increases the most rapidly, approximately as the cube of the speed, with other components increasing as roughly the square. Reducing speed reduces energy demands. It also normally reduces the amount of useful output of the ship, for example the volume of cargo that can be moved between two points in a given time. However, the output falls more slowly – approximately linearly – than the exponential reduction in energy requirements, so speed reduction can be a highly effective means of increasing energy efficiency and reducing GHGs, subject to some caveats that are discussed later. Other energy-efficiency measures that work to reduce resistance address one or more of the three components introduced above, for example:

- Smooth surfaces reduce skin friction;
- Finely tapered hull forms reduce wave-making and form drag;
- Bulbous bows create interfering wave patterns that can reduce the wave-making energy demand; and
- Various appendages at the stern can reduce form and wave-making drag and improve propeller performance.

References to these and other measures are provided at Appendix A.

While moving the ship is normally the largest component of energy consumption, other power demands can be significant. Heating, ventilation, and air conditioning (HVAC) are often major consumers, particularly for passenger ships and cruise ships. In addition, other “hotel” services, such as light, water, meal preparation, and waste management are required on these ships. Cargo operations can require energy, both in port and while at sea, and are often coupled to ballast water management demands for pumping ballast in and out of the ship and treating it to avoid transfer of invasive species. All of these power requirements are normally met using electricity, though some machines such as boilers may be fueled independently. In port, the ship can be connected to shore power supplies where installations exist, but at sea, all of the energy must be supplied by ship systems, normally electrical generators or energy storage systems such as batteries. Energy efficiency improvements can be made for any of the consumption systems and will contribute to the overall energy efficiency of the ship.

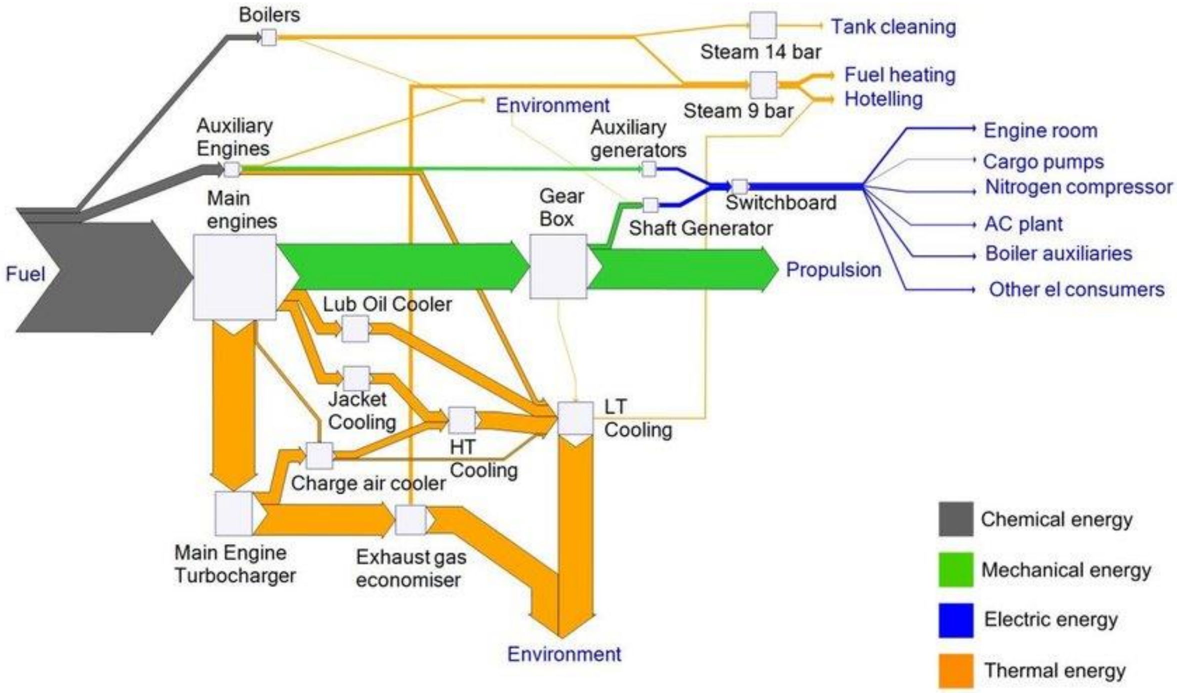
3.1.2 SHIP ENERGY SUPPLY

The energy needed to overcome a ship's resistance must be delivered using mechanisms that provide some type of propulsive thrust. With a paddle or oar this is achieved by pushing against the water. Water is accelerated in one direction, and an opposite thrust is transmitted to the ship through the paddler's body, rowlocks, and other fixtures. Wind power is created though lift and drag on the sail, or other device, and transmitted through the ship's rigging. Most commercial ships and pleasure craft use a marine propeller as their main propulsion thrust delivery system, each of whose blades generates lift and drag and a resulting thrust force in the direction of desired motion. The marine propeller is the most efficient class of propulsor for most ships under most circumstances, but still "wastes" about a third or more of the energy supplied to it within the wake wash left behind [31]. Much design effort, many energy efficiency devices, and considerable amounts of operational planning go into propeller improvements.

Energy is supplied to a propeller through a transmission system and from an energy source, which may be an engine of some form or an energy storage system. There are energy losses at every point in the system, though these vary considerably in magnitude. Typically, a heat engine, such as a diesel engine, may be around 50 % efficient, with only half or less of the energy content of the fuel providing useful work and much of the rest being lost to exhaust and cooling. Electric transmission systems may lose up to 10 % of the energy in various processes, while mechanical shafting systems have losses of 1-5 %, including reduction gear losses [116] (VARD calculation processes, see also Figure 1 below).

When looking for energy efficiency, every item is important, but a system designer will focus on the areas where the losses are greatest, and the largest potential exists for energy savings. This may be at the component level but is often at a higher system level. As noted above, losses in an electrical transmission system are higher than those in a mechanical shafting system. However, using an electrical system may allow the engines to be used much more efficiently. For some ship types and operational profiles, the engine efficiency gains can more than compensate for the transmission losses; this needs to be considered at the ship design stage to ensure that an appropriate approach is selected. Some of the heat lost to the engine cooling water and exhaust systems can be recovered in various ways at a cost to system complexity, size, and weight. Trade-off studies are needed to find the optimum approach, which will depend on the cost of energy and, increasingly, on regulatory requirements.

The complexity of energy supply and demand is sometimes shown by means of a Sankey diagram, which illustrates how the energy flows for the ship are distributed, and their relative magnitudes. The example in Figure 1 [121] is for a Chemical Tanker, which has a complex set of demands and uses relatively complex system configurations to meet these. Diagrams such as Figure 1 are unique to a ship and to the specific service(s) on which it operates.



Notes: HT –Low Temperature
LT – Low Temperature
Lub – Lubrication
AC – Air Conditioning
el – electrical

Figure 1:Chemical Tanker Sankey Diagram

3.2 ALTERNATIVE ENERGY SOURCES

3.2.1 ALTERNATIVE FUELS

The great majority of ships worldwide use fossil fuels as their energy source. Traditional marine fuels include:

- Heavy fuel oils, also known as residual fuels, which are by-products from refining crude oils;
- Intermediate fuel oils, which are blends of residual and refined fuels;
- Diesel fuels, which are refined products from crude oil; and
- Gasoline, for smaller ships.

All of these are complex mixtures of hydrocarbons.

The need to reduce GHGs has started a transition towards alternative fuels with lower carbon content. This includes:

- Natural gas, predominantly methane (CH_4), which has the lowest carbon content of any fossil fuel source;
- Biofuels, with similar properties to traditional fuels, produced from renewable sources including agriculture, wood wastes, algae, etc.;
- Methanol (CH_3OH), which is currently mainly generated from fossil fuels but has the potential for low net carbon content production;
- Ammonia (NH_3), which is currently mainly generated from fossil fuels but has the potential for low carbon production;
- Hydrogen (H_2), which is currently mainly generated from fossil fuels but has the potential for low carbon production; and
- Other liquid and solid fuels that can potentially act as carriers for hydrogen, such as metal hydrides or hydrogen peroxide.

Almost all of these fuels can be used in internal and external combustion engines similar to current units (diesels, turbines, etc). Compared to running on fossil fuels, using alternative fuels in this way hardly affects the energy efficiency [117] [118]. However, depending on the ignition method (spark or compression) the efficiency of alternative fueled engines could be less than diesel engines (which are compression ignited). Even if the efficiency of an alternative fueled engine is less, it can still have a dramatic effect in reducing GHG, depending on its source.

Some alternative fuels can be converted to usable energy in fuel cells, which is a very different process with both efficiency and URN impacts. This current study does not focus on alternative fuels and combustion engines. No publicly available data has been found about the impact of alternative fuels on the URN levels from engines. Where alternative fuels may enable alternative technologies such as fuel cells, the efficiency and URN implications are reviewed.

3.2.2 OTHER ENERGY SOURCES

In addition to alternative fuels, there has been a rapid uptake over the last 10 years of energy storage systems such as batteries and, to a lesser extent, supercapacitors. Similar to electric vehicles, these can be charged using external supply, and/or used to manage on-board energy use to maintain higher overall engine efficiency. This study considers such storage systems from efficiency, GHG, and URN perspectives.

Wind and solar power are also considered. Later vessels used wind power for many millennia. In this study, VARD has considered a range of wind-assist technologies as an auxiliary rather than a primary source of propulsion energy, which is in line with almost all current and proposed applications (as mentioned in the Appendix A). Solar power is another potential auxiliary source of power, in a much more limited way due to the small amounts of solar energy falling directly onto a ship’s topsides [75].

Nuclear power is used extensively in warships. Only a small handful of commercial ships have ever installed nuclear reactors essentially as technology demonstrators, but recently a number of proposals for new types of nuclear plants for shipping have gained attention as potentially cost-effective zero-GHG options. ; EE is not a particularly relevant metric for nuclear ships, as much of their overall energy use relates to construction and fueling. The level of URN from nuclear power will be determined by the type of heat engine and auxiliary machinery used to turn the fission energy into usable power on a ship.

4 UNDERWATER RADIATED NOISE – OVERVIEW

“Noise” is a term used for unwanted or unpleasant sound. Physically, acoustic sound is a phenomenon created by the transmission of waves by an emitter, through a medium, to a receiver such as the human ear or another suitable sensor. Sound is created in many ways; by natural phenomena such as wind and wave actions, ice interactions, landslides, and earthquakes; by animals using a multitude of techniques, and by humans (anthropogenic) either deliberately for music, exploratory investigations (seismic, echolocation, etc.), or as a by-product (machinery and process noise).

Sound waves, particularly in the frequency ranges usually considered acoustic travel with less attenuation (for longer distances) through water than through air. Anthropogenic sound waves in water are used extensively for exploratory purposes and are generated even more extensively as low frequency by-products through the operation of ships and other offshore systems. Seismic exploration, military sonars, commercial echo-sounders, and fish-finders are all significant sound and noise sources of concern in some areas but fall outside the scope of this project. The focus here is on underwater radiated noise (URN) generated by ships in their transiting operations, which can be categorized as shown in Figure 2 [60]:

a. flow noise
b. machinery noise
c. propeller (propulsor) noise, including cavitation

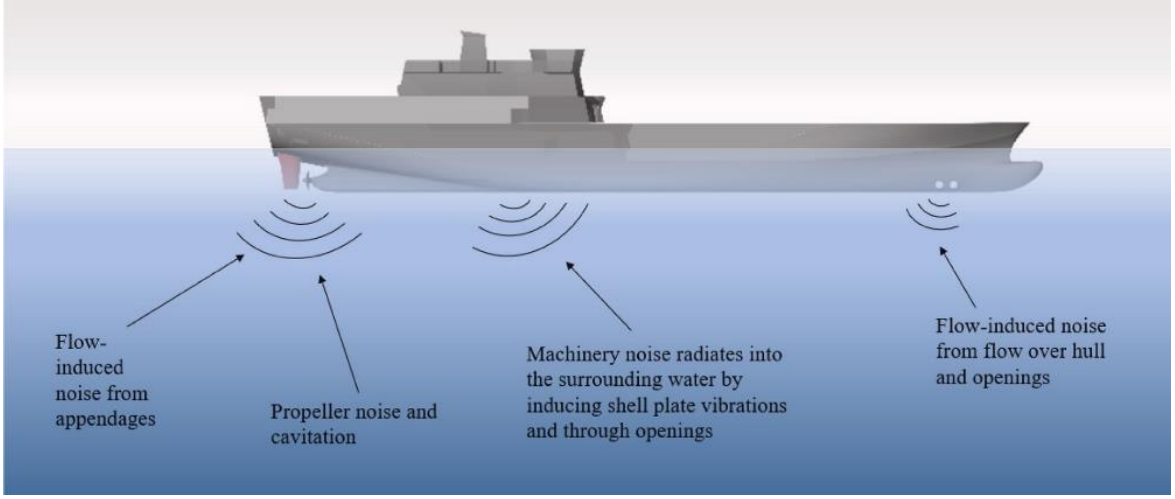


Figure 2: URN Sources

URN levels are largely not currently regulated at the international or national levels, though some shipowners require their ships to meet certain noise levels to meet operational requirements (research ships, etc.) or for reasons of social license and reputation. A few ports offer incentives to operators who implement noise reduction measures, such as speed reductions in port approaches.

Most classification societies will certify ships according to their rules for URN, at various levels of stringency. Additionally, owners and operators are encouraged to adopt best practices for URN reduction. The IMO has recently (July 2023) issued revised URN Guidelines [107], which:

- Include updated technical knowledge, including reference to international measurement standards, recommendations, and classification society rules.
- Provide sample templates to assist shipowners with the development of an underwater radiated noise management plan.
- Provide an overview of approaches applicable to designers, shipbuilders, and ship operators to reduce the underwater radiated noise of any given ship.

4.1 SHIP NOISE SOURCES

4.1.1 FLOW NOISE

The passage of a ship through the water creates pressure fields, that in turn are the source of waves of various types, including the visible ship wake spreading out from the hull and sound waves. In calm water and at low speeds, this flow noise is of low intensity. It increases as ship speeds increase, and when there is an increase in ship motion due to the wind-generated waves. However, flow noise is generally still of lower intensity than other noise sources. Another form of "passage" noise is icebreaking. Icebreaking is an energy-intensive process that creates considerable audible noise, both airborne and waterborne. Icebreaking noise is still generally at lower levels of intensity in the water than the machinery and propulsor noise required to accomplish icebreaking.

4.1.2 MACHINERY NOISE

Machinery noise arises from all rotating and reciprocating equipment operating on board a ship, and even from more static equipment such as electrical transformers and converters, heat exchangers, etc. Noise and vibration are forms of energy loss. A perfect machine, with zero energy losses, would be completely silent, but also impossible. Normally, only a very small amount of a machine's energy is lost as noise and vibration, typically much less than 1% (it is so limited that the energy loss is not even mentioned in Figure 1). In general, the more imbalance there is in a machine, the higher the intensity of the noise and vibrations it will generate for any power level. Rotating machines, such as turbines, are easier to balance than reciprocating machines, such as diesel engines. Gear noise is generated when gear teeth engage as shafts rotate. There are other sources, such as flow noise in pipes and air ducts which can also be an issue, but more for the crew as airborne noise emissions than as underwater noise sources.

Noise can be reduced at the source, by making the machines run more quietly. Improving balance, tightening tolerances, changing gear tooth profiles, and many other means are used for this.

Marine machinery benefits from advances in other vehicle and power generation technologies, where noise levels are being driven down by societal and competitive pressures.

There are many transmission paths for noise from any machine into the water, but they are most often characterized as airborne and structure-borne (Figure 3 [33]).The noise a human hears next to a machine is transmitted to the air to the hull, exciting vibrations of the hull structure that generate sound vibrations in the backing water (as named "2nd Structureborne Path" in Figure 2). In structure-borne noise, the vibrations transmitted by a machine into its foundations and connected systems excite the hull structure and generate underwater noise. All these noise paths can be treated. Machines can be surrounded by an acoustic enclosure to prevent transmission of the acoustic energy. Resilient mounts can impede the transmission of vibration from the machine to connected structures. Damping treatments can be applied to the structure to absorb energy. All of these options are discussed in Appendix A of this report.

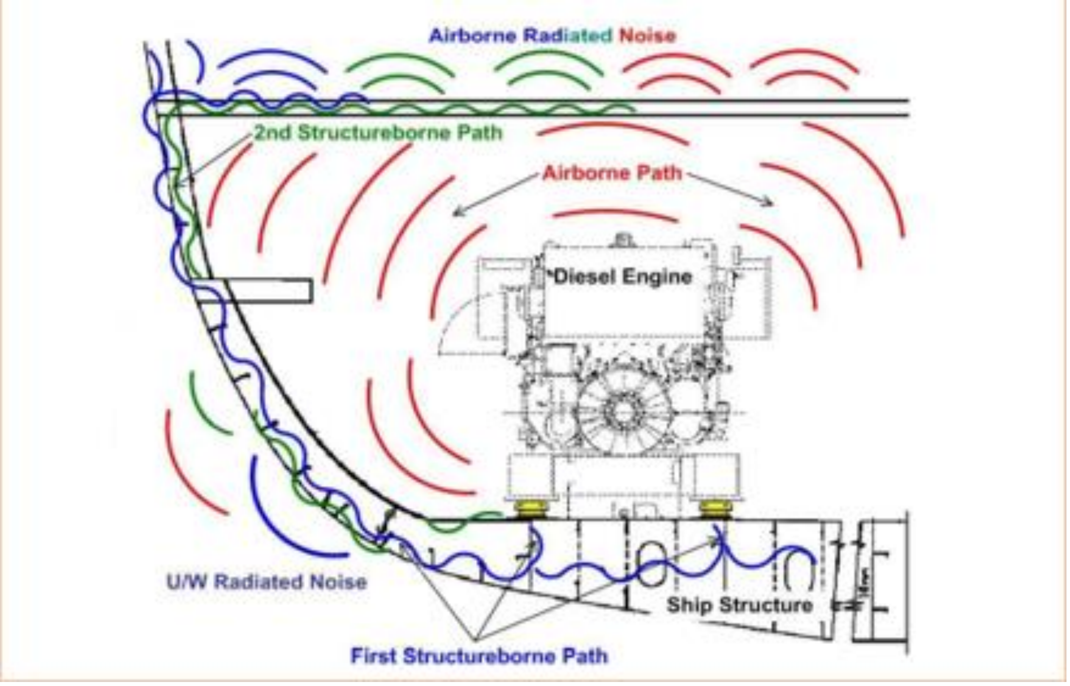


Figure 3: Machinery Noise Transmission Paths

4.1.3 PROPELLER NOISE

Propeller or propulsor noise is not completely unique to the marine industry but different phenomena in air and water make the problem different from that in the aviation industry (or wind energy). The passage of a propeller blade through the water creates flow noise, which is aggravated by the uneven wake field behind the ship. As each blade moves through a fluctuating pressure field, it sets up pulses of sound energy; this is similar to propellers and turbines in air. However, for ship propellers, the phenomenon of cavitation creates higher intensity noise. This occurs when low pressure is created over the propeller airfoil section, at blade tips, and at the hub. The pressure can become low enough that the water essentially “boils”. Cavitation bubbles form from the negative pressure, move into areas of higher pressure, and then collapse. The collapse is very rapid and creates high pressure pulses that could be intense enough to damage the propeller blades or the rudder often found behind them. This process also generates a great deal of noise. For most ships, there is a cavitation inception speed (CIS) above which cavitation becomes the dominant URN source for the ship as a whole. There are multiple types of cavitation on propellers, with different CIS and different noise characteristics. Similarly, there are many different mitigation measures, which are discussed at Appendix A.

4.2 NOISE CHARACTERISTICS

Different noise sources have different frequency characteristics. Much machinery noise has most of its energy at discrete frequencies, such as engine firing rate and its harmonics (multiples). If a diesel engine is run at varying speeds, these frequencies will change accordingly. For a generator designed to create current at 50 or 60 Hz (cycles per second), engine speeds will be aligned to this, using values such as 720, 900, or 1200 rpm (revolutions per minute) and appropriate gearing. Similarly, much equipment driven from the ship service electrical power will also generate noise at discrete frequencies related to the main alternating current frequency value. These noise sources are often referred to as narrowband, and are audible as discrete tones.

Flow and propeller noise, including cavitation, is more broadband, i.e., the energy is distributed across a wide range of frequencies. In audible terms, broadband noise is sometimes considered “white noise” as opposed to narrowband tonals. Propeller noise may be modulated at the shaft rotational speed (shaft rate) and by the passage of each blade (blade rate).

Auditory systems, including the human ear and analogues in marine life , react differently to narrow- and broadband noise. Broadband noise produces an overall ambient noise level, which can overwhelm the ability to pick out other narrowband signals such as communications (speech/vocalization) and echolocation (hunting, etc.). Noise sensors integrate the energy over a range of frequencies, often an octave or a 1/3 octave, where an octave defines a doubling of frequency.

The loudness, or power, of any sound is usually referred to in terms of decibels (dB). dB are expressed in logarithmic terms, related to some reference values. This means that if two adjacent noise sources each produce 100 dB – when both are operating – the total noise is 103 dB, not 200 dB. Similarly, reducing the noise energy by half will only reduce the dB value by 3. Sound power or pressure levels in air are by convention linked to different reference values to those in water; therefore 100 dB in airborne noise does not mean the same as 100 dB in water. The reference value for URN is typically 1 µPa (see ISO 18405, which defines terms and expressions used in the field of underwater acoustics), versus a reference level of 20 µPa for airborne sound. This should be appreciated when, for example, trying to relate the airborne noise in a ship’s engine room to the noise levels in the water outside the hull.

Noise treatment methods may be more, less, or equally effective against narrow- and broadband sources, and for different frequencies. Higher frequencies dissipate more rapidly and are predominantly considered a problem in proximity to the ship. Lower frequencies can be transmitted over very long distances. The depth of the water, the existence of thermal gradients, the characteristics of the sea floor, and many other factors affect noise transmission paths, which is a challenge for comparing noise levels and for establishing measurement and monitoring standards.

5 REQUIREMENTS FOR ENERGY EFFICIENCY AND GHG REDUCTION

Efforts towards reducing marine GHG emissions and increasing energy efficiency are part of the global effort to mitigate the impacts of climate change, under the overall auspices of the United Nations (UN). Sustainable Development Goal 14 from the UN is such an effort as it focuses on "Life Below Water" and addresses the need to conserve and sustainably use the oceans, seas, and marine resources for future development. The lead agency of the UN towards reducing marine GHG emissions and increasing energy efficiency is the International Maritime Organization (IMO). This section of the report provides a brief introduction to the IMO's approach, which in turn forms the basis for most nations' own requirements and regulations for their marine sectors.

5.1 IMO STRATEGY

IMO strategies for the reduction of GHG emissions have been underway since the late 1990s. In the first years, these were often presented partly in terms of EE improvement rather than GHG reduction, though a set of GHG studies in 2000, 2009, 2014 and 2020 focused on the GHG aspects of the issue. All of these studies can be found on the IMO website [108].

The initial IMO strategy for decarbonization was adopted in 2018 [109]. This established levels of ambition for:

- Carbon intensity of individual ships to decline through implementing increased stringency for energy efficiency design index values (see Section 5.2 below);
- Overall carbon intensity of international shipping to decline;
- Total GHG emissions from international shipping to peak as soon as possible and begin its decline.

More recently, this strategy has been updated through a revised GHG reduction strategy, adopted in mid-2023 [110]. This increases the levels of ambition in the areas listed above and adds some further considerations. The provisions can be summarized as:

1. **Carbon intensity of the ship to decline through further improvement of the energy efficiency for new ships:** to review with the aim of strengthening the energy efficiency design requirements for ships;
2. **Carbon intensity of international shipping to decline:** to reduce CO2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, compared to 2008;
3. **Uptake of zero or near-zero GHG emission technologies, fuels and/or energy sources to increase:** uptake of zero or near-zero GHG emission technologies, fuels and/or energy sources to represent at least 5%, striving for 10%, of the energy used by international shipping by 2030; and

4. **GHG emissions from international shipping to reach net zero:** to peak GHG emissions from international shipping as soon as possible and to reach net-zero GHG emissions by or around, i.e. close to 2050.

Indicative checkpoints to reach net-zero GHG emissions from international shipping are stated as follows:

1) to reduce the total annual GHG emissions from international shipping by at least 20%, striving for 30%, by 2030, compared to 2008; and
2) to reduce the total annual GHG emissions from international shipping by at least 70%, striving for 80%, by 2040, compared to 2008.

Figure 4 illustrates key aspects of the strategy. In addition, the IMO is considering a basket of candidate measures that will assist in achieving the goals, including both technical elements and economic elements, such as a GHG emissions pricing mechanism.

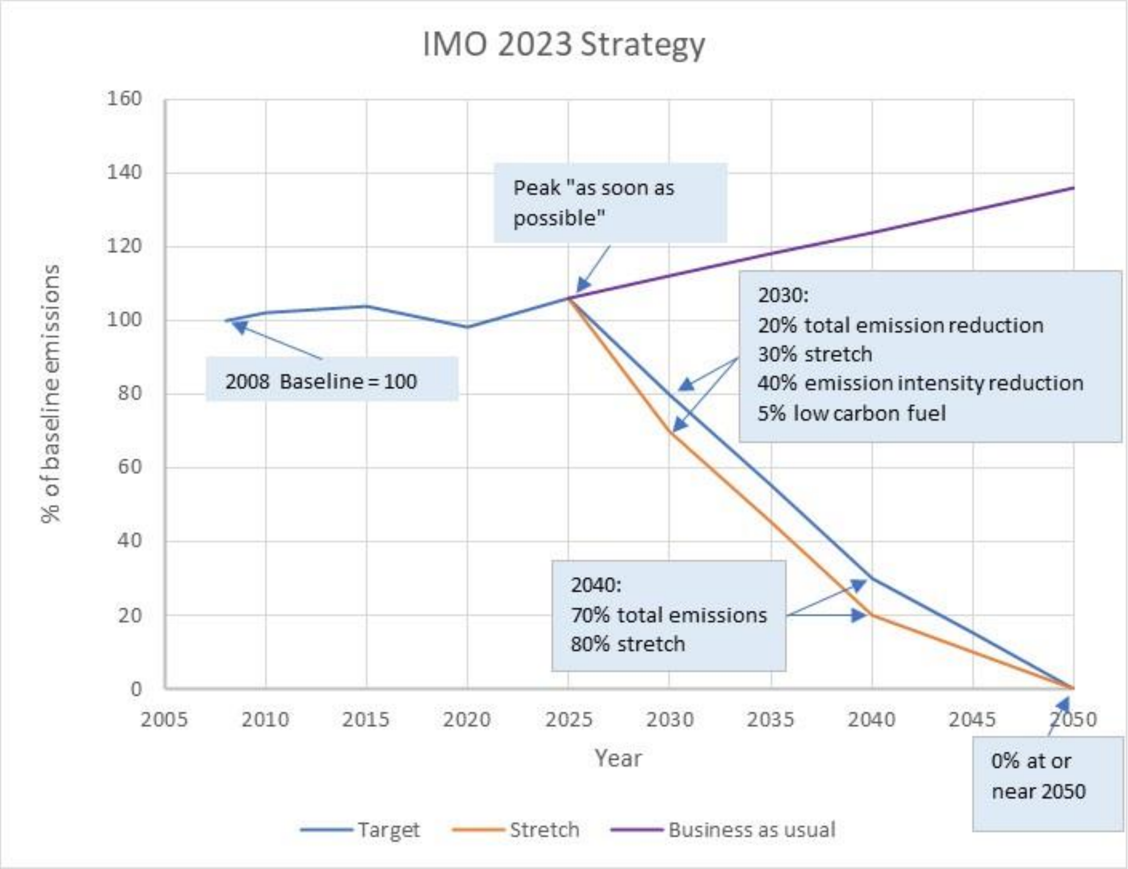


Figure 4: IMO Strategy Goals, 2023

5.2 IMPLEMENTATION INITIATIVES

The first substantive measure to improve the greenhouse gas emissions of ships, introduced by IMO, is the Energy Efficiency Design Index, EEDI, first adopted in 2011 as an amendment to MARPOL Annex VI [119]. This EEDI (which entered into force in 2013) applies energy efficiency (though effectively GHG emissions) standards to new ships. As shown in Figure 5 [120], acceptable performance has been stepped downwards in phases. Various ship types have different size cut-offs and (now) different EE/GHG targets; multiple elements of the design are considered and there are numerous correction factors for different ship types [119]. In the earlier phases, the carbon intensity of different traditional fuels was taken into account in the formulae, but only Natural Gas (principally LNG) was covered amongst developing fuel alternatives. New designs under EEDI have needed to become more energy efficient by the use of measures such as those captured in this report; but it should be understood that a design index does not directly determine the actual volumes of emissions, which are also dependent on how ships are operated.

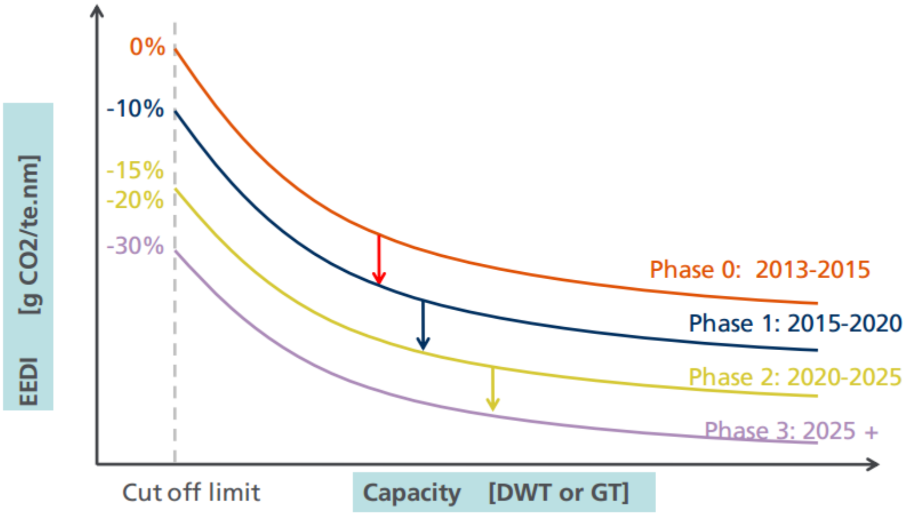


Figure 5: EEDI Standards

To limit the continued use of older (pre-2013) and less efficient ships, the second initiative this report delves into, EEXI, was introduced under the 2018 IMO strategy [110] and came into effect in 2023. EEXI applies similar efficiency (GHG emission) standards to EEDI, but recognizing the difficulty of retrofitting new systems, it allows for the use of shaft power limiters to reduce energy consumption. These limiters permanently or temporarily reduce available engine power and therefore speed (temporary limiters can be overridden in navigational emergencies, which must be reported and justified).

A third key component discussed in this report is the Carbon Intensity Indicator (CII). As of 2023 [110], all ships must report their CII value, based on actual annual fuel burnt and transportation work accomplished, through their Flag State administration to IMO The CII overall approach is shown in Figure 6 [123]. Values were derived for every ship of a given type, to create a reference line by data regression. Rating levels going forward were then set from this line, going from most efficient (A) to least (E). Ships must achieve a CII value in the “C” band; if they do not, they must provide the administration with an improvement plan.

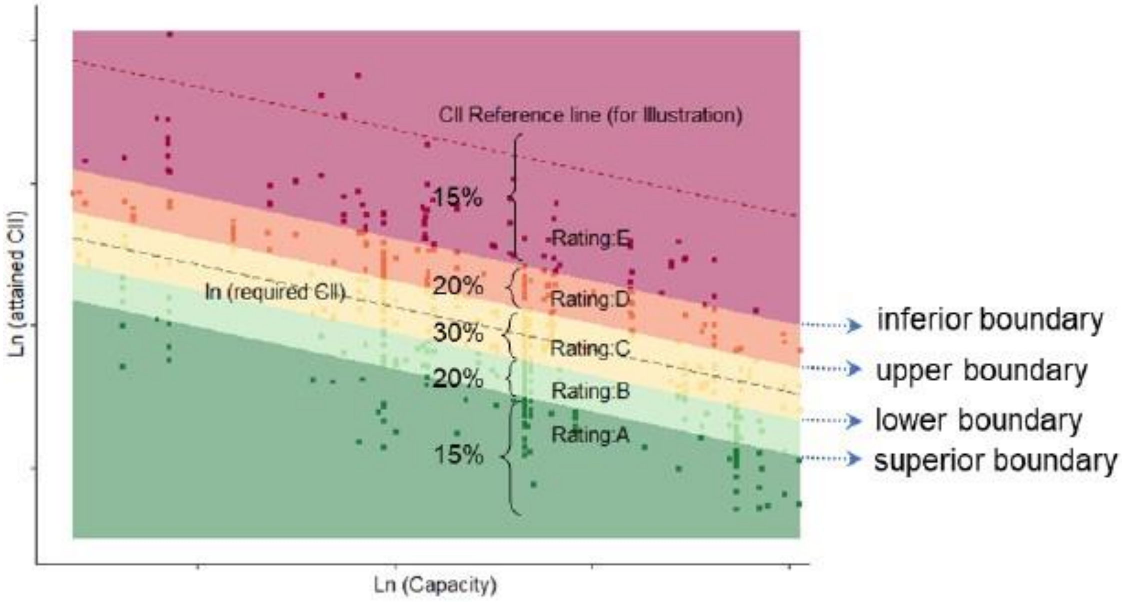


Figure 6: IMO CII Bands

The intention is that ships will reduce their CII values progressively as the upper and lower limits of each rating band themselves are reduced (see Figure 7 [111]), through measures that can include efficiency enhancement retrofits, changes to modes of operation, and fuel switching. CII is currently in an experience-building phase, and there are continuing questions as to how (for example) transportation work can be better defined, how enforcement mechanisms can be applied, and how rapidly the rating bands will be lowered by year. For the purposes of this study, it is sufficient to understand the underlying continuous improvement philosophy and how the measures being identified can contribute to this.

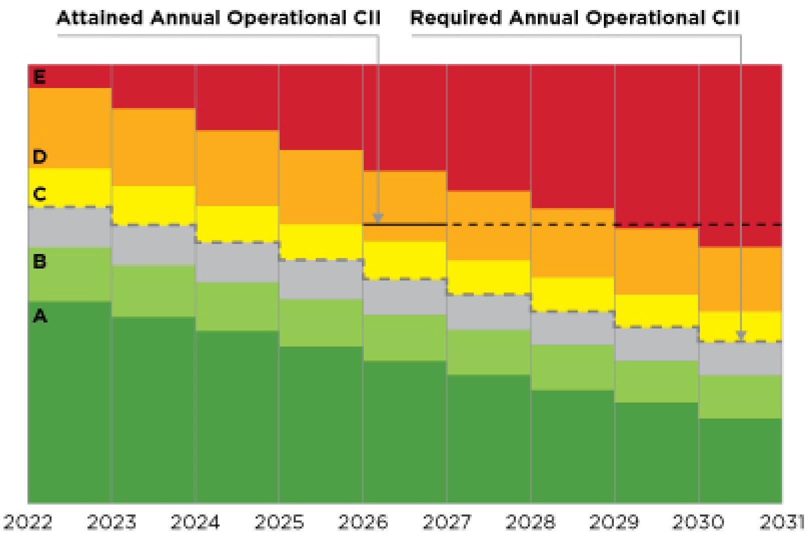


Figure 7: CII Approach

Another key element of the implementation approach is to ensure that carbon intensity values account for the full lifecycle emissions of all fuels – "well-to-wake" analysis. For traditional fossil fuels, there are some differences in extraction (e.g., oil sands versus wells) and refining intensity. For alternative fuels, different pathways can have far greater effects. For example, most ammonia is currently derived by liberating hydrogen from natural gas (often referred to as "grey" ammonia) and, on a well-to-wake basis, may create more emissions than traditional fuel oils due to its reliance on fossil fuels. Newer processes can capture the carbon from the natural gas used in production("blue" ammonia) or use hydrogen from sources such as electrolysis (”green" ammonia) to offer low or zero-carbon fuels by avoiding any use of fossil hydrocarbons….

There can be even more complexity in handling fuels that are carbon-based, such as methanol and a wide variety of biofuels. If the source of the carbon is a renewable process, such as growing crops or algae, then the fuel may attain or approach net-zero. However, agriculture can itself be carbon-intensive, and the contributions of cultivation, fertilization, transportation, and processing should all be taken into account. IMO currently accepts a number of international certification systems for the calculation of overall carbon intensity, and this remains a developing area globally.

The matrix at Appendix A presents estimates for EE and GHG impacts of various EE/GHG improving technologies that will not in all cases translate directly into EEDI/EEXI or CII values. The EEDI and EEXI approaches involve fairly complex calculations and, as noted, mix EE and GHG considerations in some parts of their formulae. CII is similar and involves a mix of design and operational decisions. As explained further in Section 7, each technical and operational measure with EE and GHG impacts identified in this report is considered as a stand-alone item and in terms of its direct impact on the metric under consideration.

6 REQUIREMENTS FOR URN REDUCTION

There are no international requirements for measures to reduce URN, though the IMO has developed voluntary guidelines [107]. A number of ship classification societies have developed voluntary notations that can be requested for ships under their class, and there are other international standards such as the International Council for the Exploration of the Sea developed for application mainly to research ships – these are all referenced in the latest IMO Guidelines. The increasing focus on this issue has come from a recognition of the deleterious effects that URN can have on a wide range of marine life, and an understanding that URN has becoming increasingly pervasive in many of the world's sea areas.

6.1 NOISE EFFECTS ON MARINE LIFE

Both the loudness and the frequency at which sounds are produced will determine the level of impact on marine species. The red box in Figure 8 [112] shows the frequency of shipping related noise that overlaps with the hearing frequency of many marine species.

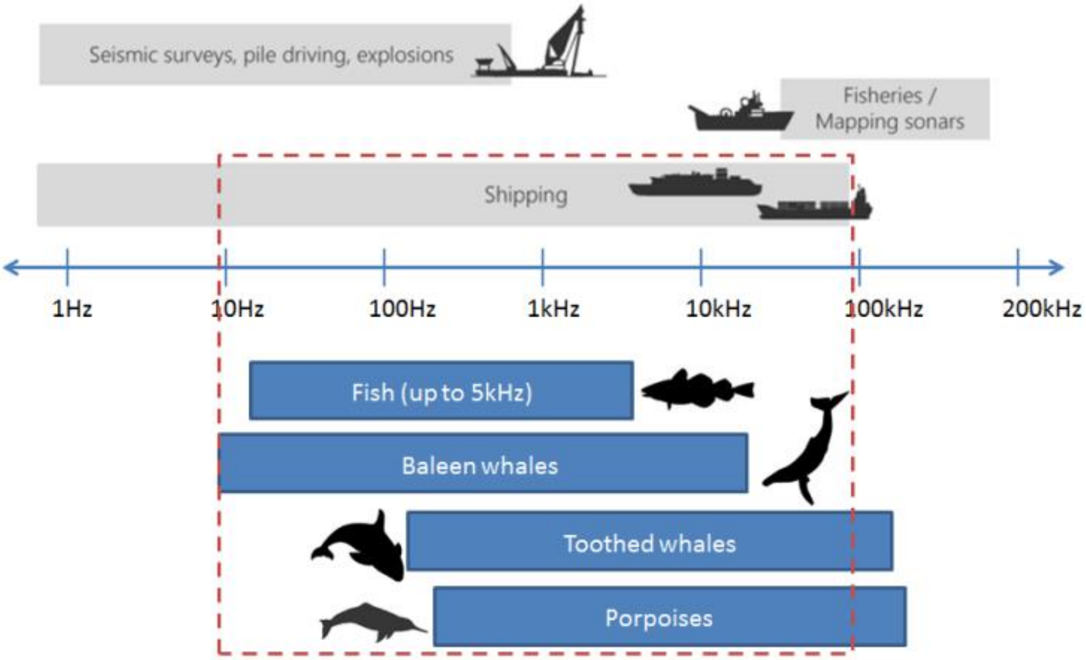


Figure 8: Overlap of Selected Emission and Hearing Frequencies

Many scientific studies have explored the effects of anthropogenic noise on marine life ranging from invertebrates to fish and marine mammals. These include:

- Physical damage, from loss of hearing to death;
- Masking communications, affecting mating and other interactions;
- Reduced foraging activity, particularly where animals use sound to locate prey;

- Increased stress levels, with overall adverse impacts on health, in a wide variety of species; and
- Behavioural modification, including avoidance of high noise areas that may also be preferred habitats.

These adverse impacts are particularly acute for populations that are already under threat from habitat loss, over-harvesting, and other stressors. While considerable work has been done in such areas, it remains challenging to quantify actual effects. More research would be particularly useful in sea areas where there are rapid changes in shipping patterns (number, type and season) and localized populations of species.

It is generally accepted that the world's seas and oceans are becoming noisier. Figure 9 [113] provides an example for the Northeast Pacific showing how the Gross Domestic Product (GDP), the world fleet Gross Tonnage (GT), and the ambient noise all exponentially increase over time (which corresponds to a linear rate of increase on a dB scale). The increase in shipping activity is hypothesized to increase its contribution to URN, leading to more than doubling (3dB) every decade. Few comparable data sets are available for other sea areas, are more would be very valuable to verify similar trends and to establish overall baselines – this is particularly true in unfrequented waters such as the Arctic, and in many sensitive sea areas.

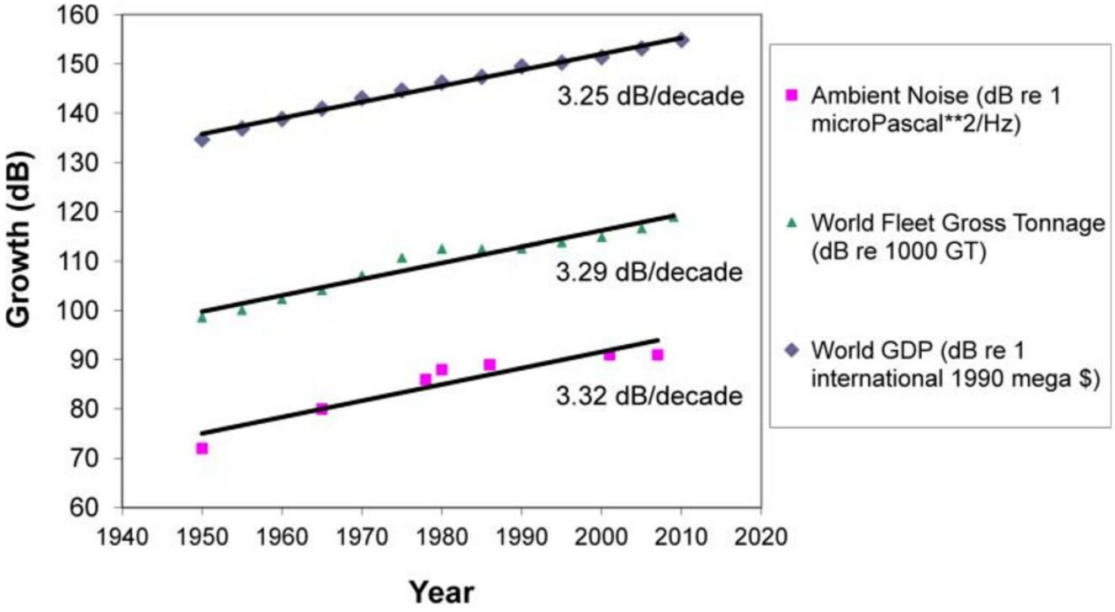


Figure 9: Increases in Ambient Noise, Gross Tonnage and GDP with Time

7 MATRIX

7.1 OVERVIEW

The matrix (see Appendix A) developed for this report is a further development of an approach first used in a report developed by the US National Oceanic and Atmospheric Administration (NOAA) in 2007 [14] and subsequently extended and adapted in several VARD reports on URN and energy efficiency [114] and [115].

The matrix itself is included as Appendix A to this report. It includes a summary of each measure that has been identified and, in most cases, references to information sources used in compiling the matrix. The following sub-sections of the report provide additional explanation of how the information has been organized and how the matrix should be interpreted.

Four types of measures potential combinations exist between EE/GHG and URN, and are mentioned in the matrix as with the corresponding below mentioned number:

1) Those which increase efficiency, reduce GHG and reduce URN;
2) Those which increase efficiency, reduce GHG but increase URN;
3) Those which reduce efficiency, increase GHG but reduce URN; and
4) Those which reduce efficiency, increase GHG and increase URN.

The last of these is not covered in the matrix, as such options would be working against the objectives of this project. However, such measures do exist and may be implemented for operational or cost reasons. For example, a cheap high-speed diesel with poor energy efficiency and poor GHG emissions and poor noise characteristics may be selected for low first cost. Further distinction between the three quantities can be found in Section 7.3.

In some areas, the assessments included in the matrix are those of VARD and are based on our engineering judgement and assessment. This has been done in good faith, and without any commercial interests being involved. However, we recognize that differences of opinion may arise in such cases unless, and until, actual physical data is gathered to validate and quantify performance claims. Also, the effectiveness of measures and their other benefits and costs will vary greatly across the very wide range of ship types and operations found in the global marine industry. We have aimed to indicate realistic assessments of potential effectiveness for efficiency gains and URN reductions for typical ships amongst the types of ships that could benefit from each measure. However, it needs to be recognized that in many cases the potential improvements will be much smaller. Individual stakeholders will need to undertake more detailed analysis of their specific applications.

7.2 MEASURES

7.2.1 GENERAL CATEGORIES (TECHNICAL AND OPERATIONAL)

Measures have been consolidated into a set of general categories that cover both technological and operational options for efficiency improvement and GHG and URN reduction. These build on various general principles introduced in Sections 3 and 4 of the report. Most measures will potentially have some impact on both efficiency and URN – positive or negative – but in some cases the impacts on one aspect may be quite minor.

As outlined earlier, alternative fuels are only included where they are enablers or requirements for other technologies for energy efficiency or for URN reduction. A low(-er) carbon fuel can be very effective for GHG reduction but does not, in most cases, give other efficiency and/or URN benefits.

In other cases, a technology may be an enabler of increased efficiency or noise reduction without necessarily leading directly to it. As an example, using electric transmission rather than direct drive from a prime mover (engine) through a shaft to a propeller does not necessarily reduce noise, and reduces peak efficiency in comparison to a mechanical transmission. It may however improve overall efficiency by allowing better load matching over a wide range of power demands, and by simplifying the use of energy storage systems to assist with this. It also simplifies noise reduction through various measures, including more efficient isolation mounts, removal of gear noise, relocation of noise sources away from the hull, etc.

7.2.2 DESCRIPTION

The first column in the matrix provides a summary of the mechanisms by which a mitigation measure operates. For example, does it improve efficiency by reducing demand or by improving equipment performance; and does it reduce noise at source or by treating the transmission path. This column also cites one or more reference documents that provide more detail on the method and/or provide examples of its use in the marine field. Other citations may be included in subsequent columns to clarify specific points.

7.3 EFFECTIVENESS

A total of four columns in the matrix address each measure's significance for energy efficiency and GHG and URN reduction, as described in the following sections.

Each measure is considered in isolation; except where one measure is a prerequisite for another, as outlined earlier. Where measures fall into different categories, their combined effect for energy efficiency may be more or less additive; for example, an improvement in hull form may be combined with an increase in machinery efficiency. This is much less likely if measures are in the same or similar categories. Applying one flow improvement measure is likely to make additional measures in flow improvement ineffective. This is even more broadly true for URN reduction, due to the logarithmic nature of the dB metric.

7.3.1 ENERGY EFFICIENCY AND GHG REDUCTION

These two impacts are often closely correlated, but can also differ considerably, particularly with respect to measures involving alternative energy sources and the technologies used to implement these. As noted above, using an alternative or supplementary energy source may not improve overall ship energy efficiency, but may have large GHG benefits.

Effectiveness is shown in the matrix in terms of percentage improvement – or degradation – with additional information where necessary and available. For example, some flow improvement measures may be much more effective in percentage terms for a high block coefficient hull form such as a tanker or bulk carrier than for a fine hull form such as a container ship or fast ferry. On the other hand, although the percentage improvements may be smaller for a fast ship than for a slow one, there may still be worthwhile benefits due to the larger overall power demand.

7.3.2 URN (INTENSITY, FREQUENCY RANGE)

Any effective URN mitigation measure will provide a reduction in radiated energy, which may cover a wide range of frequencies or a narrower band. Similarly, if an energy-related measure increases URN, it is important to understand both the intensity and frequency range to allow mitigation measures to be considered. Both intensity and frequency range are covered by the two matrix columns.

There is often some uncertainty, or a considerable range in effectiveness for many measures. “Ideal” values are often not fully achieved in real installations; for example, mounting systems or acoustic enclosures may lose effectiveness due to noise short-circuits through piping, exhaust systems, etc. Propeller treatments may be compromised by minor damage or by marine fouling. The matrix aims to present effectiveness bands that would be expected to be achieved in practice, using the terminology:

Amount of Expected Noise Reduction in Decibels (dB):

- Low (up to 5 dB)
- Medium (5-10 dB)
- High (> 10 dB)

The effectiveness values relate to the noise source being treated, and not necessarily to the overall noise signature of the ship. If propeller noise dominates the URN, then machinery noise reduction treatments will have little or no effect on the overall noise signature.

The frequency ranges treated are linked to the type of noise source and to the treatment approach. Resilient mounts, rafting systems, etc. are intended mainly to block the transmission of energy at the characteristic frequencies of the source, such as engine firing rate and harmonics. Cavitation noise reduction has broad spectrum benefits, and it will also address blade rate effects at lower frequencies.

Only a few of the methods listed in the matrix have been explored in sufficient detail to define their URN benefits in typical ship applications. There is an urgent need for more measurement campaigns to provide better definition in this area.

7.4 POTENTIAL ADVANTAGES AND BENEFITS

The advantages and benefits column within the ship impacts category indicates whether a measure has benefits beyond EE, GHG and URN. Obviously, many noise reduction measures will benefit not only the underwater signature but also the comfort of crew and other persons on board such as passengers, scientists, or offshore workers. Some new technologies may offer other performance benefits.

In this column of the matrix, a set of codes are used to identify common types of advantages and benefits. In some cases, additional notes are provided to clarify aspects of the potential use. The codes include:

C - Enhanced Crew/passenger Comfort
M - Reduced Maintenance
MA - Increased MAnoeuverability
S - Decreased Space Demand
W - Decrease in Weight

In a few cases, other potential advantages are described in the matrix text where these are unique to a single measure; for example, hull polishing removes biofouling, which is a transmission vector for invasive species.

7.5 POTENTIAL DISADVANTAGES AND CHALLENGES

Almost all energy efficiency improvement and noise reduction measures will have some form of disadvantage, often related to the cost of implementation and also in many cases to a reduction in the functionality of the ship by occupying space, consuming additional power, adding maintenance effort, and other factors. As with advantages, the matrix uses a set of codes to classify significant disadvantages of these and other types. Proponents are less likely to highlight disadvantages than advantages, and so many of the assessments in this area are based on VARD’s ship design experience.

The codes used in this column are in most cases the opposite of the advantages, and include:

D - Increased Design effort
M - Increased Maintenance
MA - Reduction in MAnoeuverability
P - Increased comPlexity
S - Increased Space demand
W - Increased Weight

For both disadvantages and advantages, an attempt has been made to consider the impact on the ship as a whole, though this is dependent on other factors such as its operational profile. Adding supplementary equipment will normally add weight and consume space and is likely to lead to more complexity in overall system design. This is not always the case, so separate factors are used for each. Somewhat similarly, complexity in total will almost always be increased by adding more items. For simplicity, in this matrix, the design effort is considered to be at ship level, where alternative technologies may actually simplify the process, even if the equipment/system design process is itself demanding. An example here is the use of podded propulsors, which can simplify some aspects of hull form design even if the propulsors themselves are very highly engineered devices. Somewhat similarly, energy storage systems (batteries, etc.) need to be very highly engineered by their suppliers in complex processes. To some degree, they can then be treated as “black boxes” by the ship designer, though their integration into the ship then still requires considerable effort in areas such as fire protection, control, and monitoring.

7.6 TECHNOLOGY READINESS

VARD has used the Technology Readiness Level (TRL) method to classify the maturity of each mitigation measure. TRL was developed by NASA and is increasingly used by organizations including Transport Canada to indicate the status of a wide range of technologies. The definitions used by Innovation, Science and Economic Development Canada (ISED) are shown below; most others are very similar. TRL 1 represents “blue sky” concepts while TRL 9 is mature and in widespread service.

> **TRL 1: Basic principles observed and reported:** Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.
>
> **TRL 2: Technology concept and/or application formulated:** Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions.
>
> **TRL 3: Analytical and experimental critical function and/or characteristic proof of concept:** Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology.
>
> **TRL 4: Product and/or process validation in laboratory environment:** Basic technological products and/or processes are tested to establish that they will work.
>
> **TRL 5: Product and/or process validation in relevant environment:** Reliability of product and/or process innovation increases significantly. The basic products and/or processes are integrated so they can be tested in a simulated environment.
>
> **TRL 6: Product and/or process prototype demonstration in a relevant environment:** Prototypes are tested in a relevant environment. Represents a major step up in a

technology's demonstrated readiness. Examples include testing a prototype in a simulated operational environment.

TRL 7: Product and/or process prototype demonstration in an operational environment: Prototype near or at planned operational system and requires demonstration of an actual prototype in an operational environment (e.g. in a vehicle).

TRL 8: Actual product and/or process completed and qualified through test and demonstration: Innovation has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development.

TRL 9: Actual product and/or process proven successful: Actual application of the product and/or process innovation in its final form or function.

VARD has assigned TRL to each method in the matrix, based on our own knowledge and research. As many measures at lower TRLs are kept quite confidential until ready for market, it is possible that some are more mature than indicated. Obviously, any promising concepts that have not yet been publicly revealed cannot be included in the matrix. The matrix is a snapshot in time that should be updated in the future.

While a number of measures have been classed as TRL 9, at this level, there can still be substantial differences in the level of application by the industry, and between ship types. Electric transmission systems, for example, are widely used in smaller ships and in a few larger types, such as cruise ships; but not in tankers, bulkers, or container ships. This is mainly due to different economic drivers. Often a new technology will see its first applications in specialized ships and then move gradually into other areas of commercial shipping.

7.7 COST IMPACT

Cost is a critical factor in the adoption of any measures. Where mandatory requirements must be met, owner/operators will tend to adopt the lowest cost (set of) measures that will achieve compliance. Where goals are voluntary, then there will normally be a much lower threshold for what owner/operators are prepared to incur.

Costs can include both installation costs and operating costs. The total installation cost includes the direct costs of all additional equipment items and supporting systems such as piping, cabling, tanks, etc. In certain cases, it may also include increases in capacity; for example, the size of the generators needed to provide overall electrical power. For some cases, the ensemble of additional requirements may increase the size of the ship (where this is possible) or reduce its cargo capacity.

VARD has tried to capture in various ways in order to convey information that may be of most use to operators and regulators. We have found that no single approach can accomplish this well. In a few areas, we refer to terms of percentages of a standard ship newbuilding in one or more of the types most suited to the technology, using bands as follows:

- Low – less than 1% of new ship cost
- Medium – 1 to 5% of new ship cost
- High – greater than 5% of new ship cost

Unfortunately, this is not very meaningful when a measure can be applied to a wide variety of ships, as factors such as the hull form or machinery plant represent a quite different percentage of the cost of (say) a tanker as compared to a cruise ship. We have therefore applied a set of other metrics, which aims to main consistency within each main category of measures to maintain like-with-like comparability.

Typically, it is much less expensive to introduce new systems for a newbuilding than for a retrofit; relative cost can be 3-10 times as high in refits, with the higher end cost associated with internal modifications. For many refit items the ship must be taken out of the water to implement the measure. This applies to all propeller and flow noise treatments, and many for machinery. The cost of dockings has not been considered as part of the cost impact, as it is assumed that the measures would be implemented alongside other scheduled work.

Operating costs can include the energy required to drive certain devices, other consumables, increased maintenance effort, and various other factors. For example, air injection and certain wind technologies require energy to drive them but normally provide greater overall savings. In this study technologies are considered on a net energy basis; i.e. if an approach consumes energy in one process in order to reduce it overall, the two are combined in VARD’s assessment. Certain technologies, such as batteries and fuel cells do not currently have life expectancies approaching those of the ships in which they are installed, and so an allowance should be made for replacement costs – these are “lumpy”, being needed at reasonably lengthy intervals rather than annually or more regularly. Maintenance costs are quite difficult to establish but are typically higher for early installations before devices are widely adopted. We have attempted to combine all of these factors where operating cost has been estimated.

For some measures, that also offer efficiency gains, the proponents often claim payback periods i.e., the time required for recovery of the investment in fuel cost savings. Where payback periods have been claimed, these values are cited. If no such estimates have been found, this is left blank.

All of these numbers should be considered very approximate. The differences between ships and ship types mean that the absolute values of cost will vary widely, as will the percentage of a ship’s value that any measure represents.

7.8 APPLICABILITY

In almost all cases, operational measures can be applied to both new and existing ships. Some technical measures may be applicable only to the building of new ships, while others may also be possible for retrofits or modernizations. A conversion to fuel cell propulsion, or a change from shafted to podded propulsors may not be technically feasible for most existing ships, for example. The changes required to internal configuration, hull form or other overall ship parameters may be impractical.

The codes used in this column are:

New Build - NB
Re-Fit - RF

A wide variety of ship types and sizes sail the world's oceans and coastal waters. Figure 10 shows some examples, categorized by size and speed as being selected as two key parameters. Many types do come in a wide range of shapes and sizes; for example, ferries can be large, small, slow or fast. The quadrants of the figure have been numbered for ease of referencing in the matrix. Not all ship types are shown – for others, the main characteristics should be considered when deciding where they should fit in a quadrant.

In general, most techniques will be broadly applicable. Exceptions come where ship characteristics make a technique infeasible. For example, ship types on short routes and fixed schedules such as many ferries are unlikely to use wind-assist technologies but are well-suited to battery and other energy storage systems (ESS). The opposite may be true for high endurance ships, where current ESS can only provide a small fraction of the stored energy requirements. In the matrix, quadrants 1, 2, 3 and 4 of Figure 10 are used to identify which methods are most applicable to which ship types. Where this is challenging for certain types, a note is added to explain why.

Other exceptions may exist due to specific design drivers. Ice class ships, for example, need to have strengthened propeller blades and high power. This can limit the use of noise reduction technologies focused on blade shape and loading distribution. Shallow draft ships will have restrictions on propeller diameter, leading to high loadings. In general, all ship designs balance conflicting drivers and constraints.

The second aspect of applicability considers the types of ships which could utilize the technology or methodology. Ships that operate for all or significant parts of their voyage profile at low speeds are most likely to benefit from machinery noise reduction. Those that operate mainly at higher speeds will benefit more from propeller noise reduction, e.g. by increasing the cavitation inception speed. Many ships have higher and lower speed operations over some part of their voyage profiles, so that both machinery and propeller noise reductions may be valuable.

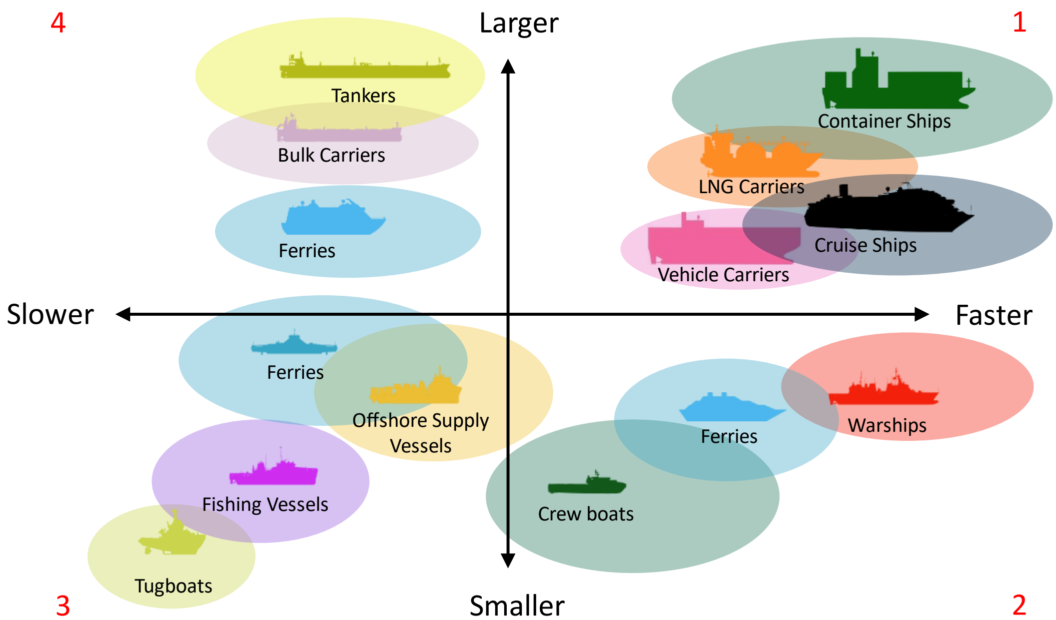


Figure 10: Ship Types

8 RECOMMENDATIONS

VARD's scope of work for the project includes providing recommendations for next steps, including research priorities and policy considerations to support the advancement/adoption of technologies or operational practices with positive effects on reducing both GHG and URN.

8.1 GHG AND EE

Requirements for the reduction of GHGs are now mandated by IMO, though with much remaining uncertainty as to how this will be enforced at the Flag State level. Shipowners and operators understand in general terms that they will need to implement new technical and operational measures in order to meet GHG and EE objectives. The need in many cases is to understand what the effectiveness of many measures will be in practice. While there are well-established standards (for example) for assessing the fuel efficiency of a marine diesel engine at various load levels, there are no such standards for defining the effectiveness of many of the technical measures identified in Appendix A, which is why many of the numbers provided are heavily caveated. Owners are left with the challenge of assessing the credibility of competing claims, and potentially with making unsound investment decisions which will then compromise the availability of funding for other measures.

IMO, and its members and observers could play useful roles

1. in setting standards or guidelines in this area, for example by promoting or requiring sea trials to validate the performance of EE/GHG technology retrofits;
2. using their ongoing data collection activities to provide longer-term validation of performance in real-world conditions.

This work can use toolsets already included in procedures for EEDI/EEXI and CII calculations. There is a need to ensure that results are made publicly available, rather than being kept proprietary, to ensure that information is disseminated and applied as rapidly as possible.

Costing data is also very useful, but is typically quite commercially confidential. Where possible, OEMs and operators should be encouraged to:

3. Provide verifiable information on payback periods for retrofit items.

8.2 URN

Data collection is also of vital importance for further progress on URN, both in terms of establishing the effectiveness of ship-level measures and also in monitoring progress towards overall objectives for ambient URN levels, as outlined in Section 6. There is also a continuing need for education of shipowners and operators, cargo owners, and other stakeholder groups on the benefits of URN mitigation for environmental protection. Recommendations in these areas include:

1. Projects such as the ECHO Program on Canada's West Coast should be expanded to cover other areas of the world's deep and shallow waters, and a wide range of ship types and operational practices. These should be used both to collect ship noise data, and also to establish baseline levels of ambient and ship-related URN to enable monitoring of the overall effectiveness of URN mitigation.
2. IMO should continue to encourage the collection and dissemination of ship-specific baseline data through noise ranging of new vessels and those retrofitted with URN reduction measures (like the impact of alternative fuels on the URN levels from engines).
3. IMO should assist in the development of more standardized approaches to measurement approaches and noise level characterization. The current IMO Guidelines reference the large number of alternatives that currently exist from standards bodies, classification societies and others. Consolidation of these would be a valuable initiative.
4. Incentivization measures are outlined in the IMO Guidelines. Examples should be collected and disseminated to encourage wider uptake. Incentivization should be linked to the sharing of performance information to assist in education and adoption.
5. IMO should continue to enable access to relevant information, though venues such as the Workshop on the Relationship between Energy Efficiency and Underwater Radiated Noise from Ships, the publication of associated documentation, and potentially through the development of model courses by the World Maritime University and other bodies.

9 CONCLUSIONS

Global agreements to mitigate climate change have led to a huge increase in the numbers and types of measures being introduced in the marine industry to increase EE and reduce GHG emissions. Many of these can have direct economic payback, while others may also be needed to meet new mandatory requirements. The effectiveness of measures is governed by many factors, and the best mix of measures for any ship needs to be considered on a case-by-case basis. While there has been some increase in the amount of scientific-quality information available for the benefits of some technologies, there is still very little published data on many of these. Additional data collection and knowledge dissemination will assist in ensuring that measures with proven effectiveness can be implemented with confidence.

On the URN front, reducing noise remains voluntary under the IMO Revised Guidelines, though there is an increasing appreciation of the desirability of protecting marine life by reducing noise levels. This has led to a considerable volume of work on potential technological and operational measures, though even more than is the case for EE/GHG measures there is still very little scientific-quality data on the effectiveness of many of these. Again, additional data collection and knowledge dissemination will assist in ensuring that measures with proven effectiveness can be implemented with confidence on a wide variety of ships.

In many cases, EE/GHG and URN measures can be complementary, i.e., benefits will be realized in both areas. However, there are cases in which the two can conflict. The matrix generated by this project aims to identify such cases, and the matrix itself and this report provide brief explanations of why such conflicts may exist. In very general terms, any measures that reduce the amount of mechanical energy needed to power a ship can both increase EE and reduce GG and URN. Improved hull designs, slow steaming, and the use of wind-assist in most cases fall into this category. Many types of propeller treatments and flow modifications can also be beneficial in both areas, but this is more dependent of the ship type. On-ship treatments for noise and in some cases for EE need to be considered on a case-by-case basis, considering overall ship impacts.

The main recommendations arising from this project are in the areas of data collection and analysis. Shipowners need to make changes to their ships and their operations, and they need assistance in ensuring that their decisions are appropriate.

Appendix A TECHNOLOGY MATRIX

Report 545-000-01

Rev 1

Prepared for
Transport Canada

by
Vard Marine Inc.

Date: 11 September 2023

TERMINOLOGY

Treatment/Description:

Provides a summary of the mechanisms by which a mitigation measure operates. References are cited (as may be in subsequent columns to clarify specific points).

Energy Efficiency:

% change (range). The change in energy required to transport a unit of cargo by a certain distance.

GHG Reduction:

% change (range). The change in $CO_{2equivalent}$ required to transport a unit of cargo by a certain distance.

URN:

dB Change - Expected Noise Reduction in Decibels (dB):

Low (up to 5 dB),

Medium (5-10 dB),

High (greater than 10 dB

Freq Rng - Frequency Range:

BroadBand/Narrowband; Expected Frequency Range Affected in Hertz (Hz)

T - Type:

1 - Increase EE, decrease GHG and reduce URN

2 - Increase EE, decrease GHG but increase URN

3 - Reduce EE, increase GHG but reduce URN

4 - Reduce EE, increase GHG and increase URN

N/A – not available

Ship Impacts:

A/B – Advantages/Benefits

C - Enhanced crew/passenger Comfort

M - Reduced Maintenance

MA - Increased MAnoeuvrability

S - Decreased Space Demand

W - Decrease in Weight

C/D – Challenges/Disadvantages

D - Increased Design effort

M - Increased Maintenance

MA - Reduction in MAnoeuvrability

P - Increased comPlexity

S - Increased Space demand

W - Increased Weight

(Impact on EE, GHG and URN is mentioned in the dedicated columns)

TRL – Technology Readiness Level:

TRL 1: Basic principles observed and reported.

TRL 2: Technology concept and/or application formulated.

TRL 3: Analytical and experimental critical function and/or characteristic proof of concept.

TRL 4: Product and/or process validation in laboratory environment.

TRL 5: Product and/or process validation in relevant environment.

TRL 6: Product and/or process prototype demonstration in a relevant environment.

TRL 7: Product and/or process prototype demonstration in an operational environment.

TRL 8: Actual product and/or process completed and qualified through test and demonstration.

TRL 9: Actual product and/or process proven successful.

Cost Estimation:

Range - Range of expected cost:

- Low – less than 1% of new ship cost
- Medium – 1 to 5% of new ship cost
- High – greater than 5% of new ship cost

Percentage - Percentage increase or decrease

Payback Period - Time in months/years to recover investment

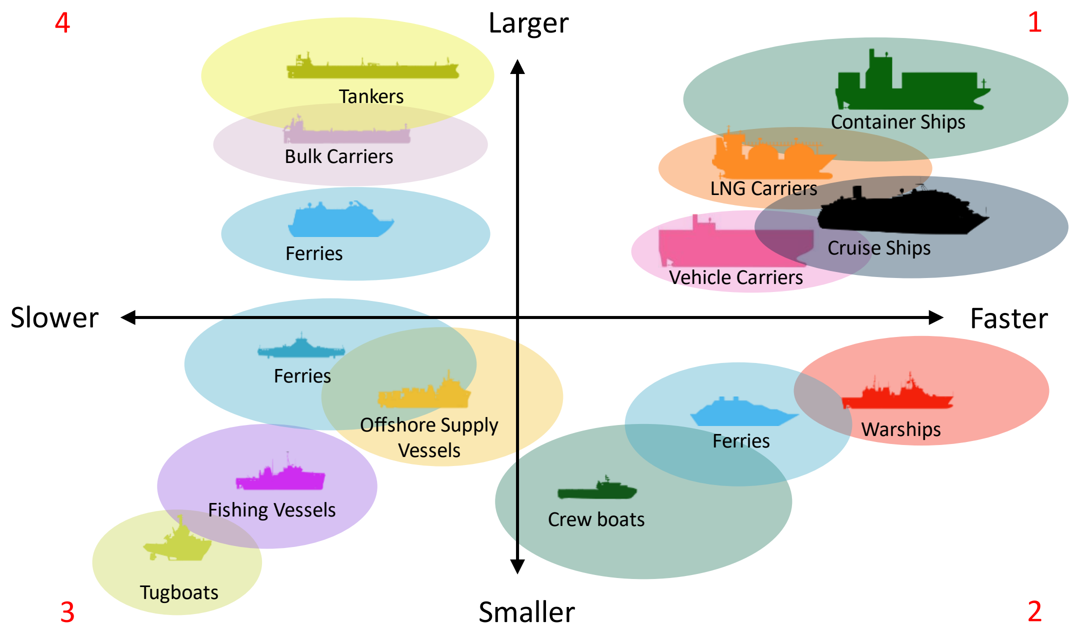
Shorthand - Whether to expect an increase or decrease

Applicability:

<u>R</u>e<u>F</u>it - RF

<u>N</u>ew <u>B</u>uild - NB

Ship Type - By quadrant from the below presented figure, except where indicated.



Comments:

Last column is reserved for remarks and statements that do not fit the earlier mentioned columns.

General Notes:

Many of the provided Energy Efficiency, Greenhouse Gas and Underwater Radiated Noise improvements as well as mentioned advantages/disadvantages of potential solutions are based on VARD's ship design experience.

VARD has aimed to provide realistic assessments of each treatment. Nonetheless, it needs to be recognized that in many cases, potential improvements will differ based on the ship type and operation. Individual stakeholders will need to undertake more detailed analysis of their specific applications.

The effectiveness values of the URN reduction relate to the noise source being treated, and not necessarily to the overall noise signature of the ship. The URN frequency ranges treated are linked to the type of noise source and to the treatment approach (and not to the URN frequency distribution of the ship as a system).

This matrix reflects the views of the authors and not necessarily those of the Innovation Centre of Transport Canada or the Canadian government.

The Innovation Centre of Transport Canada does not endorse products or manufacturers. Trade or manufacturers' names appear in this report only because they are essential to its objectives.

This matrix does not attempt to provide a comprehensive description of any aspect of energy efficiency, GHG reduction, or URN.

This current matrix does not focus on alternative fuels and combustion engines.

TECHNOLOGY MATRIX

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
1 HYDRODYNAMICS											
1.1 HULL APPENDAGE/DESIGN											
1.1.1 DESIGN FOR SERVICE Design energy-efficient and safe ships with good performances in realistic sea and operating conditions with actual sea states and an actual operational profile in mind. Design for service instead of for trial conditions. [99]	5-10 %	5-10 %	< 5 dB	All	1	C	D	9	low	NB All	EE, GHG and URN from VARD's assessments. 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 analyses.

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
1.1.2 EFFICIENT HULL FORMS Hydrodynamically (for calm water and waves) efficient hull forms will reduce power requirements and therefore both machinery and propulsor noise. Such hulls will also generally have good wake characteristics, increasing cavitation inception speeds. Can include selecting an optimal slenderness ratio, ship length, etc. [50]	5-10 %	5-10 %	< 5 dB	All	1	C	D	9	low	NB All	EE, GHG and URN from VARD's assessments over a range of ship types. Note that efficient hulls may lose carrying capacity. 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 analyses. Additional cost may incur due to more streamlined hull production, e.g. for plates with double curvatures, esp. in North America.
1.1.3 BULBOUS BOW Bulbous bow helps to reduce the ship's resistance by modifying the water flow around the hull and thus helps to save the fuel consumption. Bow increases the buoyancy in the front which helps in slightly reducing the pitch of the ship.	3 to 5 %	3 to 5 %	< 5 dB	All	1	C	D	9	low	RF / NB All	Bulbs are speed optimized. Ships adapted to lower sailing speeds may need to consider implementation of bulbs, or even change the current bulb geometry.

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
1.1.4 EFFICIENT ABOVE WATER FORMS Aerodynamically efficient forms will reduce air and wind resistance power requirements and therefore both machinery and propulsor noise. [79]	<1 %	<1 %	None	-	N/A	C	D	9	low	NB 1, 2	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 analyses. Additional cost may incur due to more streamlined hull production.
1.1.5 STERN FLAP/WEDGE Small extensions from the lower transom. Modifies the stern wave produced by the ship and reduces powering requirements, reducing hydrodynamic noise. [51] [52] [74]	Up to 10 %	Up to 10 %	< 5 dB	All	1	C	D	9	low	RF / NB 1, 2	EE is from VARD's assessments for relatively fast ships.

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
1.1.6 BOW FOILS (WAVEFOIL) They can generate net thrust when ship heaves and pitches while moving forward in waves. Reduces motions and thrust to propel the ship. [86] [87] [88] [104]	Up to 10 %	Up to 10 %	< 5 dB	All	1	C	D (P)	8	High. 6 % of CAPEX for small fishery vessels.	RF / NB 3	Can be effective for very specific ship types and operations. Retractable versions avoid extra fuel consumption when fins are not needed. Ship needs to move up and down in the waves to benefit from bow foils, hence ships will need to be relatively small. Foils will reduce ship motions as well.
1.1.7 STERN FOILS (HULL VANE) Reduces pitch motions and losses in stern wave system, provides crew comfort and forward thrust at speed. [89] [90] [105]	Up to 10 %	Up to 10 %	< 5 dB	All	1	C	D (P)	9	Payback period for OPV 3 years.	RF / NB 2	Can be effective for very specific ship types and operations. Energy efficiency and GHG reduction change is application dependent and applies to high-speed ships with immersed transom. At low speeds, additional losses may occur due to increased resistance and reduced foil performance.

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
1.1.8 RETRACTABLE (ACTIVE) STABILIZER FINS Effective in forward speeds, active fins more accurately counteract the effect of the waves in comparison to fixed fins. By also having the fins retractable it enables them to be stored when not in use to avoid adverse impact on hull resistance when they are not required. [95] [100]	Up to 5 %	Up to 5 %	< 5 dB	All	1	C	D M S W	9	Unknown	RF / NB 2	EE and GHG for calm water conditions for retractable fins in comparison with non-retractable fins.
1.2 FRICTIONAL RESISTANCE REDUCTION											
1.2.1 HULL COATING SELECTION Appropriate hull coating selection can reduce frictional resistance; should consider operational profile and maintenance philosophy	Up to 5 %	Up to 5 %	< 5 dB	All	1	C	M	9	low	NB All	All ships have coatings; however, there is potential to improve selection process.
1.2.2 UNDERWATER HULL SURFACE CLEANING AND MAINTENANCE Poor hull surface maintenance can lead to resistance increases. This can cause the machinery load and the URN to increase. Hull surface cleaning and maintenance must be completed regularly to avoid this. [49] [67] [75] [76]	Up to 5 %	4 to 10 %	< 5 dB	All	1	C	M	9	Hull polishing cost depends on ship size	RF All	Cleaning in drydock is more effective than by diver or robot in the water. Need to consider environmental impacts of polishing itself.
1.2.3 HULL COATING RENEWAL Fresh anti-fouling coating can improve fuel and GHG savings. [67] [76]	Up to 5 %	0.5 to 5 %	< 5 dB	All	1	C	M	9	Typically, similar or greater cost than initial application (see 1.2.1)	RF All	

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
1.2.4 AIR BUBBLER SYSTEM (MASKER) Air injection around the hull of the ship to reduce noise created by machinery, creates a blanket of air bubbles between the machinery noise and water, and uses tubing systems and an air compressor. Also has the effect of highly reducing marine growth on the hull, improving overall efficiency. Must be used while docked as well to reduce marine growth clogging tubing holes. Used by navies to reduce noise for detection stealth purposes. [22] [28] [56] [83] [61]	3 to 6 %	3 to 6 %	> 10 dB	20 to 80 Hz > 500 Hz	1	C	D M P S W	7	Payback Period: 3 to 5 years	RF / NB All	TRL is valid for commercial ships. EE valid for low sea states.
1.2.5 AIR LUBRICATION SYSTEMS (ALS) ALS that creates a (near) continuous air layer between the ship and the water flow. ALS have been introduced by several shipbuilders to reduce skin friction resistance for power savings. [57] [59] [61] [75] [76]	4 to 12 %	4 to 12 %	> 10 dB	20 to 80 Hz > 500 Hz	1	C	D M P S W	8	Similar to 1.2.4	RF / NB All	Similar effects to Masker systems on naval ships, but extended over more of the underwater hull. EE valid for low sea states.
1.2.6 PARTIAL CAVITY DRAG REDUCTION (PCDR) Air lubrication system that reduces frictional resistance by injecting air into a recess or cavity at the bottom of the hull to separate the lower part of the hull from water. Applicable for slow going (inland) ships. [61]	4 to 18 %	4 to 18 %	> 10 dB	20 to 80 Hz > 500 Hz	1	C	D M P S W	8	Similar to 1.2.4	NB 3, 4	Applicable for ships with a high block coefficient and sailing in sheltered area.

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
2 PROPULSOR											
2.1 PROPELLER/PROPULSOR DESIGN											
2.1.1 PROPELLER OPTIMIZATION Balancing the propeller design in such a way that maximum efficiency is fulfilled, and at the same time limiting the URN as far as practical. May include altering the blade number, pitch distribution, camber, rake, diameter, blade area ratio, clearance to hull and rudder, etc.	Up to 5 %	Up to 5 %	Depending on the original propeller design	-	1 or 2	-	D	9	10 to 15 % more over conventional	RF / NB 1 to 4	EE, GHG and URN from VARD's assessments. Retrofitting a propeller after operational speed reduction (see 5.1.1) can give similar EE improvements.
2.1.2 REDUCTION OF TURNS PER KNOT (TPK) Reducing the number of propellers turns per knot speed, thus, reducing the speed of the flow at the tips of the blades. This requires a larger diameter of propeller or a higher gearbox ratio and is applicable to both fixed and control pitched propellers. Reduces all forms of propeller cavitation (especially propeller tip cavitation) and increases Cavitation Inception Speed (CIS). [1]	Up to 5 %	Up to 5 %	< 5 dB	All	1	C	D MA S W	9	A 10% larger propeller costs approximately 7% more.	NB 1 to 4	Has consequences to on-board machinery as well (for instance: might need to change gearbox reduction and engine revolution rate).

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
2.1.3 CONTROLLABLE PITCH PROPELLER The propeller blades are attached to the boss and their pitch can be altered via a (hydraulic) system. The efficiency at design point is slightly lower, however off design point one can increase the efficiency, especially if an internal combustion engine is driving the propeller. Effect on URN can be highly variable. See also item 2.1.4 below.	-2 to 5 %	-2 to 5 %	Variable, positive or negative	-	1, 2, 3 or 4	C MA	D M S W	9	Unknown	RF / NB All (especially for ships with varying load profile)	Controllable pitch propellers simplifies reversing and most other manoeuvres. Noise levels at design point may increase, however off design point may reduce compared to a fixed pitch propeller. Thicker hub is likely to increase noise levels slightly more compared to fixed pitch propellers.
2.1.4 CPP COMBINATOR OPTIMIZATION Adjusting pitch and rpm settings for controllable pitch propellers can mitigate the early onset of cavitation on pressure and suction sides both at constant speeds and during acceleration. This may also improve propeller efficiency in these conditions. [55]	5 to 10 %	5 to 10 %	5 to 10 dB	All	1	C	D	9	Modest, requires software updates and potentially additional sensors	RF / NB 1 to 4	
2.1.5 SHROUDED PROPELLER Shrouded (also known as ducted or Kort nozzle) propellers are particularly effective for improving thrust at low speeds and highly loaded propellers. Nozzles serve to reduce propeller tip cavitation, and therefore underwater radiated noise. [64]	2 to 4 %	2 to 4 %	Unknown reduction	Unknown reduced vibration	1	C	D S W	9	Doubles the capital cost compared to a conventional propeller.	RF / NB 3,4	Ducts/shrouds will not improve efficiency at higher speeds, though they may still offer noise benefits. Can improve bollard pull performance by 40 %.

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
2.1.6 INCREASED PROPELLER IMMERSION The hydrostatic pressure put forth on the propeller can affect the amount of cavitation that occurs and the CIS. The greater distance the propeller is from the free surface of the sea, the less cavitation will occur and the higher the CIS. Practical design constraints may limit. [2]	Small	Small	< 5 dB	All	1	S	D P	9	No direct cost; but may drive other design decisions	NB 1, 2	May generate a cleaner inflow into the propeller with marginal Energy Efficiency and GHG benefits.
2.1.7 HIGHLY SKEWED PROPELLER Propeller with blades swept back substantially more than conventional propellers. This allows for the blade to pass through the varying wake field in a more gradual manner, improving the cavitation patterns. Load reduction on the tip of the propeller results in further reduction of propeller cavitation and increased CIS. [3] [4] [5] [72] [78]	None	None	5 to 10 dB (Depending on initial wake field)	40 to 300 Hz	N/A	C	D W	9	Typically skewed propeller no additional cost, for highly skewed propellers with greater than 25° skew, 10 to 15 % higher capital cost than conventional propellers	RF / NB 1, 2	The EE is not affected. Up to approximately 110 degrees skew.
2.1.8 CONTRACTED LOADED TIP PROPELLERS (CLT) Propellers designed with an end plate allowing for maximum load at the propeller tip, which reduces propeller tip cavitation and increases CIS. The end plate also promotes a higher value of thrust per area (higher speed with smaller optimum diameter) further reducing noise, vibrations and further increasing CIS. [5] [6] [7]	Up to 5 %	Up to 5 %	5 to 10 dB	40 to 300 Hz	1	C	D	9	20 % Higher capital cost than conventional propellers	RF / NB All	
2.1.9 CONTRA-ROTATING PROPELLERS (CRP) Co-axial propellers, one propeller rotating clockwise & the other rotating counterclockwise. Increases CIS due to reduction in blade loading resulting in lower blade surface cavitation. Also, optimized flow circulation results in lower tip vortex cavitation. [8] [9] [26]	Up to 6 %	Up to 6 %	5 to 10 dB	40 to 300 Hz	1	C	D M P W	9	Much higher capital cost than conventional propeller. Depending on the configuration.	RF / NB All	Can be used with both shafter and azimuthing propulsors.

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
2.1.10 KAPPEL PROPELLERS Propeller blades modified with tips curved towards the suction side. This reduces the strength of the tip vortex thus increasing efficiency, decreasing tip vortex cavitation, and increasing CIS. [10] [11] [72]	4 %	4 %	< 5 dB	40 to 300 Hz	1	C	D	9	20 % higher capital cost than conventional propellers [5]	RF / NB All	
2.1.11 PROPELLERS WITH TIP FINS RAKED BACKWARD Propeller modified in such a way the blades are curved towards the Pressure side (Opposite of Kappel Propellers), Studies have shown that there is an increase in efficiency and decrease in cavitation expected, however, there are few studies on the subject. [12]	3 %	3 %	Unknown (Improves wake flow)	Unknown	1 or 2	C	D	6	20 % higher capital cost than conventional propellers	RF / NB All	Cost estimation is based on Kappel Propeller information.
2.1.12 AZIMUTHING PROPULSORS Azimuthing propulsors have motors (electric or reciprocating machines) inside the hull with transmission gears in the gondola. Depending on technology may have gear noise or electric motor/converter noise to mitigate. Limited public domain information is available on the machinery noise characteristics of the podded (see 2.1.13) and azimuthing, both types claim good performance. [13] [14]	-6 to 0 % Ship and installation specific	-6 to 0 % Ship and installation specific.	Unknown	Unknown	3 or 4	C MA S	P W	9	Components more expensive than shafted system but installation costs can be reduced.	NB 1, 2, 3	Cost estimation is from VARD's internal assessments. EE and GHG compared to a shafted solution. URN during steering is relatively high. Manoeuvring is improved compared to shafted system.
2.1.13 PODDED PROPULSORS Variant of azimuthing propulsion with an integrated electrical motor in the gondola can achieve improved wake performance to the propeller reducing cavitation and CIS. However, the electric motor and magnetic noise effects can increase medium to high frequency noise; see also 3.1.1 (Enabled by Diesel electric design). [13] [14]	-5 % to 1 % Ship and installation specific.	-5 % to 1 % Ship and installation specific.	Unknown	Unknown	1, 2, 3 or 4	C MA S	P W	9	Components more expensive than shafted system but installation costs can be reduced.	NB 1, 2, 3	See 2.1.12.

Treatment/Description	**Energy Efficiency**	**GHG Reduction**	**URN**		**T**	**Ship Impacts**		**TRL**	**Cost Estimation**	**Applicability**	**Comments**
	% Change	**% Change**	**dB Change**	**Freq. Rng.**		**A/B**	**C/D**		**Percentage/Range/Pay-back Period/Shorthand**	**RF/NB** **Ship Types**	
2.1.14 WATER JETS Operate in ducting internal to the ship, with increased pressures at the jet. Noise reduction from higher cavitation inception speed and by isolating the propeller from the sea. [14] [15] [16]	Dependent on speed	Dependent on speed	> 10 dB	All	1 or 3	C MA	P S W	9	Higher than conventional propeller and shafting; higher installation cost	NB 2 Highest speeds and some specialty types	Can improve peak efficiency at highest speeds (normally above ~27 knots), reduce efficiency at lower speeds.
2.1.15 PUMP JETS Combine a full pre-swirl stator, propeller and duct. Normally used in ultra-quiet applications such as submarines. [17] [63]	Up to 5 %	Up to 5 %	> 10 dB	All	1	-	M P W	8	Higher cost than conventional prop	NB 2	TRL is for conventional civilian ships.
2.1.16 COMPOSITE PROPELLERS Use of advanced composites to allow for blade distortion under load to increase efficiency, delay cavitation onset and reduce blade vibration. [31] [80] [81] [82]	Up to 4 %	Up to 4 %	< 5 dB	All	1	C W	D	6	Unknown at this time	RF / NB 1 to 4	Mentioned TRL for smaller size applications. TRL for large propellers: 5.

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
2.1.17 VERTICAL AXIS PROPELLERS Trochoïdal, Kirsten-Boeing and Voith-Schneider type vertical axis/crossflow propellers that provide increased manouevring at the expense of energy efficiency with possible URN reduction. [31]	-10 % Ship and installation specific.	-10 % Ship and installation specific.	Unknown	Unknown	3 or 4	MA	P	9	Unknown	NB 3	Energy efficiency suffers when compared to conventional axial-flow propellers. When operational profile is considered for ships requiring station-keeping capabilities, GHG reduction is possible due to good directional control of thrust. Onboard vibrations are expected to be lower, but URN emissions are unknown. More expensive but removes the need for rudders.
2.2 WAKE FLOW MODIFICATION											
2.2.1 PRE-SWIRL STATORS Consists of stator blades located on the stern boss in front of the propeller, flow is redirected before entering the propeller, increasing over all flow performance, thus increasing EE and reducing cavitation and increases CIS. [17]	Up to 5 %	Up to 5 %	< 5 dB	All	1	C	D	9	Typical Payback Period: 24 months	RF / NB 4	

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
2.2.2 SCHNEEKLUTH DUCT An oval shaped duct located just forward of the upper half of the propeller, designed to improve the flow to the upper part of the propeller, this improves flow performance, increasing EE, lowering the formation of cavitation of propeller blade tips and increasing CIS. [18] [19]	4 %	4 %	< 5 dB	All	1	C	D	9	Typical Payback Period: 4 months	RF / NB 1, 4	
2.2.3 PROPELLER BOSS CAP FINS (PBCF) Small fins attached to the hub of the propeller, reducing hub vortex cavitation, thus, reducing noise and vibration and increasing CIS. The design also recovers lost rotational energy, increasing efficiency. Similar concepts include ECO-CAP. [19] [20] [21]	3 to 7 %	3 to 7 %	5 to 10 dB	< 1000 Hz	1	C	D	9	Typical Payback Period: 4 to 6 months	RF / NB 1, 4	
2.2.4 PROPELLER CAP TURBINES (PCT) Hydrofoil shaped blades integrated into the hub cap, similarly to PBCF reducing hub vortex cavitation, and increasing CIS. The design also recovers lost rotational energy, increasing efficiency. [19] [20] [22]	5 %	5 %	5 to 10 dB	< 1000 Hz	1	C	D	9	Typical Payback Period: 4 to 6 months	RF / NB 1, 2, 4	
2.2.5 GROTHUES SPOILERS A series of curved fins attached to the hull forward of the propeller, designed to improve flow to the propeller, reducing cavitation, increasing CIS and increasing fuel efficiency. [18]	3 %	3 %	< 5 dB	Unknown	1	C	D	9	Typical Payback period: Less than a year	RF / NB 1, 4	EE is from VARD's internal assessments
2.2.6 MEWIS DUCT A combination of a duct with pre-swirl stators integrated into the duct just forward of the propeller, thus having the benefits of both pre-swirl stators and Grothues spoiler. Similar concepts include Super Stream Duct. [5] [19]	3 to 8 %	3 to 8 %	< 5 dB	Unknown	1	C	D	9	Typical Payback Period: Less than a year	RF / NB 1, 4	

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
2.2.7 RUDDER THRUST FINS Horizontal fins that are attached directly to the rudder horn. Those fins capture energy and convert to thrust. [75]	< 2 %	< 2 %	None	-	N/A	C	D S W	9	Typical Payback Period: Less than 2 years	RF / NB 1, 4	
2.2.8 PROMAS Integration of the propeller, hubcap, rudder bulb, and rudder into one hydrodynamic efficient unit. Reduces propeller tip loading and limiting blade pressure pulses, thus, reducing cavitation and CIS. Similar concepts include Ultimate Rudder Bulb and SURF-BULB. [23] [65]	3 to 6 %	3 to 6 %	5 to 10 dB (Depending on initial flow)	Unknown	1	C	D	9	Typical Payback Period: less than 2 years	NB 1, 2	
2.2.9 COSTA PROPULSION BULB (CPB) Consists of two bulb halves that are welded to the rudder, in line with the propeller. Designed to recover energy losses aft of the propeller, by eliminating vortices caused by cavitation, ultimately reducing propeller vibrations and lowering URN. [19] [22] [24]	1 %	1 %	< 5 dB	Unknown	1	C	D	9	Payback Period: 4 to 15 years	RF / NB 1, 2	
2.2.10 TWISTED RUDDERS Rudder designed to twist in order to vary the angle of attack to match local water flow pattern. This reduces cavitation and increases CIS. Used on a variety of ships, including BC Ferries and U.S Navy Destroyers. [22] [25]	2 to 3 %	2 to 3 %	< 5 dB	Unknown	1	C M MA	D	9	Payback Period: 4 to 15 years	RF / NB 1, 2	

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
2.2.11 GATE RUDDER An asymmetric twin rudder system placed on either side of the propeller, mainly for single propeller ships for improved EE, GHG, URN characteristics and manouevring capability. Behaves similar like an accelerating duct and benefits from oblique flow angles in the stern. [69] [70] [73]	3 to 8 % depending on slenderness	3 to 8 % depending on slenderness	Unknown reduction	Unknown, reduced vibration	1	C MA	M	9	Payback Period: approx. 1 year	NB 1, 4	
2.2.12 ASYMMETRIC BODY FOR SINGLE SCREW SHIPS The purpose of designing an asymmetric after body is to account for the asymmetrical flow of a single screw propeller about the centerline. This will slightly increase CIS. [26] [3] [62]	Up to 6 %	Up to 6 %	< 5 dB	Unknown	1	C	D	9	Unknown	NB 1, 4	
2.3 SUPPLEMENTARY TREATMENTS											
2.3.1 IMPROVED MANUFACTURING PROCESSES Tighter tolerances on blade manufacture may reduce cavitation. [27] [66]	< 1 %	< 1 %	< 5 dB	Unknown	1	-	D	9	10 % more expensive than standard propeller	RF / NB 1 to 4	GHG is from VARD's assessments.
2.3.2 PROPELLER AIR-INDUCED EMISSION (PRAIRIE) Air injection through holes in the propeller blade tips or from a nozzle like apparatus upstream of the propellers, which fills the vacuum left as propellers rotate, allowing cavitation bubbles to contract more slowly as area that is under pressured is minimized, reducing cavitation and increasing CIS. Must be used while docked as well to reduce marine growth clogging holes. Used by navies to reduce noise for stealth purposes. [28] [83]	Unknown	Unknown	< 5 dB	20 to 80 Hz	1 or 3	C	D M S W	6	Unknown	NB 1, 2	TRL is valid for commercial applications.

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
2.3.3 PROPELLER MAINTENANCE Imperfections of a propeller blade can encourage cavitation. Polishing between dry docks can prevent this, reducing cavitation and increasing CIS. [29] [67] [76]	2 to 5 %	2 to 5 %	< 5 dB	All	1	C	M	9	2% of CAPEX of propeller, order of magnitude 10 k USD	RF 1 to 4	
2.3.4 PROPELLER COATING A coating applied to the surface of a propeller with the purpose of reducing propeller fouling. Research has been done regarding underwater noise with varying results. [22] [30]	Up to 4 %	Up to 4 %	< 5 dB	50 to 10 kHz	1	C M	-	9	Payback Period: 2 years	RF / NB 1 to 4	
2.3.5 APPLICATION OF ANTI-SINGING EDGE Modification to the propellers trailing edge, designed to alter naturally occurring vortex shedding phenomenon. [31] [32]	None	None	> 10 dB	10 Hz to 12 kHz	N/A	C	-	9	Minor increase in manufacture cost	RF / NB 1 to 4	URN reduction is only possible where propeller singing is a problem.

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
3 POWERING											
3.1 MACHINERY SELECTION											
PRIME MOVER SELECTION	The choice of prime mover (main engines) has a strong influence on the basic machinery noise characteristics of the ship and on the potential use of mitigation measures. Diesels are currently the default choice of prime mover for almost all commercial ships and so are assumed here except where otherwise indicated. See main report for additional discussion. Diesel engines are normally classed as slow speed (SS), medium speed (MS) and high speed (HS); with the first using two-stroke technology and the others four-stroke. Peak efficiency falls somewhat as engine speed increases. SS engines have low power-to-weight ratios (much larger for same power output) and are used in larger ships, usually with direct drive transmission. MS and HS use geared transmission systems (or electric, see below). Engine selection has major impacts on EE and URN, and on the treatments available.										
3.1.1 (DIESEL) ELECTRIC Using electric rather than mechanical transmission enables and/or facilitates many noise reduction approaches, from the use of mounts and enclosures to active noise cancellation. A wider range of propulsor selections are also available. Electrical transmission has worse peak efficiency than mechanical, and capital costs are higher, so use is generally in ships where other benefits outweigh these costs. [33] [75]	-10 to 10 %	-10 to 10 %	> 10 dB	All	1 or 3	C MA	D P S W	9	Highly variable	NB All	Most applicable to ships that have widely varying speeds in operational profile, and/or redundancy requirements for dynamic positioning, etc. EE & GHG reduction depends on application; Diesel-electric favours variable loads and is inefficient under constant load (greater losses than gains).
3.1.2 VARIABLE SPEED POWER GENERATION (DIESEL ELECTRIC) Generating power through variable speed generators can modify their generating speed to meet the changing electrical consumer demands. This allows them to run at more efficient point on their operating curve, thus improving efficiency and reducing fuel consumption.	Up to 5 %	Up to 5 %	< 5 dB	All	1	M	D	9	Minor increase	NB All	The EE, GHG and URN impacts are valid for the change from fixed speed generator to variable speed generator.

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
3.1.3 DC BUS SYSTEM (DIESEL ELECTRIC) A DC bus system decreases the maximum efficiency slightly. The arrangement of the system does introduce more electrical energy transformation components (AC to DC, and DC to AC) into the system and increases system complexity. DC gives high flexibility for variable engine speed to reduce fuel consumption (see 3.1.2) and to incorporate other energy sources (like fuel cells and batteries). [97]	Up to 5 %	Up to 5 %	< 5dB	All	1	M S W	-	9	Slightly more expensive than an AC system.	NB 1 to 4	
3.1.4 GAS/STEAM TURBINE Rotating turbines are generally quieter than diesels but have lower fuel efficiency and higher capital cost. Very few steam ships are now constructed (other than for nuclear ships) but many naval ships use gas turbines for high power density. [34]	-15 %	-15 %	> 10 dB	All	3	C S W	D P	9	Order of 2 times higher capital cost than Diesel	NB 1, 2	Air intakes and exhaust ducts larger than for Diesel engines. High frequency noise is less attenuated.
3.1.5 STIRLING ENGINE The external combustion Stirling engine produces lower noise then conventional internal combustion engines. Load following characteristics are relatively poor, so difficult to have rapid variations of power. Main uses are for submarines and naval ships to reduce radiated noise. [35] [77]	5 %	5 %	5 to 10 dB	Unknown	1	M	W S	6	High capital cost	NB 2, naval, submarine.	

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
3.1.6 PEM FUEL CELLS PEM (Proton-Exchange Membrane) Fuel Cells produce electricity through chemical reaction, this is done by converting hydrogen and oxygen to water. Significantly quieter than any combustion engine. [45] [46] [47]	Up to 10 %	Depending on the fuel source	> 10 dB	All	1	C W	D P S	7	High capital cost Increase in fuel cost	NB	Various fuel cell technologies exist, PEM currently most mature for marine applications. Most Marine Fuel Cells run on hydrogen. No large-scale installations to date. The type of EE, GHG and URN combination is solely based on EE and URN (GHG is not taken into account).
3.2 MACHINERY TREATMENTS TO NOISE											
3.2.1 RESILIENT MOUNTS (EQUIPMENT) Spring mounts impede the transmission of vibration energy from machinery, and the generation of energy into the water from the hull. Requires appropriate selection and installation of mounts. Generally, not practical for heavy 2-stroke Diesel engines. [36]	None	None	> 10 dB	All	N/A	C	S W	9	20 to 2000$ per mount	RF / NB 2, 3, 4	URN reduction is best at higher frequencies. Large engines require many more mounts, increasing installation cost.
3.2.2 FLOATING FLOOR (DECK) A floating/false deck is constructed and resiliently mounted to the deck, effectively isolating all machinery on the false deck; applicable to lighter equipment only. [36]	None	None	< 5 dB	All	N/A	C	S W	9	Unknown	RF / NB 2, 3, 4	Main benefit is reduction in internal noise while also reducing URN.

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
3.2.3 RAFT FOUNDATION (DOUBLE STAGE VIBRATION ISOLATION SYSTEM) One or several pieces of machinery are mounted on an upper layer of mounts supported by a raft (steel structure) which is further supported on the hull girder on a lower-level set of mounts. This reduces noise by creating an extra impedance barrier to the transmission of vibration energy. Often used for engine/gearbox or engine/generator; not applicable to 2-stroke diesels due to their high weight. [37]	None	None	> 10 dB	All	N/A	C	W D S	9	Adds significantly to installation cost; can be 10 %+ of cost of installed equipment	RF / NB 2, 3	Normally an even larger. URN reduction best at higher frequencies.
3.2.4 ACOUSTIC ENCLOSURES Structures designed to enclose a specific piece of machinery, absorbing airborne noise. This reduces the airborne transmission of energy to the hull and the generation of URN from the hull. [38].	None	None	> 10 dB	125 to 500 Hz	N/A	C	S D	9	Adds significantly to installation cost; can be > 10 % of cost of installed equipment	RF / NB 2, 3	Typically used only with smaller Diesels and gas turbines. Used on ships requiring very low noise signatures such as warships, research ships after treatment of other noise paths.
3.2.5 ACTIVE CANCELLATION Reduction of machinery excitation of the hull structure by means of secondary excitation to cancel the original excitation. Uses sensors for measuring excitation, a device to read the sensor and actuators to produce counter phase excitation. Capital cost is high. [39]	None	None	> 10 dB	see comments	N/A	C	S D	6	Highly variable	NB	URN is effective at discrete frequencies rather than overall noise levels. Effective at tuned frequencies.

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
3.2.6 SPUR/HELICAL GEAR NOISE REDUCTION Gear design can be used to optimize number of teeth & profile shift angle. This will optimize sound reduction due to teeth mashing lowering machinery noise. Also requires high quality manufacturing. [40] [41]	1 %	1 %	5 to 10 dB	see comments	1	M	D	9	Increase in manufacture cost, can double gear cost	NB	Effective mainly at gear meshing frequencies.
3.2.7 CONTROL OF FLOW EXHAUST GASES (ENABLED BY 2-STROKE DIESEL ENGINE) Exhaust flow component designed to reduce noise produced by sudden gas expansion during the combustion/exhaust stroke of a 2-stroke diesel engine. [42]	None	None	< 5 dB	Unknown	N/A	-	D	3	Unknown	NB 1, 4	
3.2.8 METALLIC FOAM A porous material designed to be used in the tanks of diesel or water ballast tanks, to reduce underwater radiated noise. The material has open enhanced acoustical properties when saturated by liquids. [43]	None	None	Unknown, claimed as > 10 dB	Unknown	N/A	C	W	6	Unknown	RF / NB	Reduces radiated noise from diesel or water tanks. Simulation based URN numbers. No field data.
3.2.9 STRUCTURAL (HULL/GIRDER/FLOOR THICKENING) The thickness of structural members is directly linked to URN mitigation. Rigid structure creates impedance mismatch and is particularly effective when used with resilient mounts; added weight is also useful for noise transmission reduction. [1]	None	None	< 5 dB	10 to 1000 Hz	N/A	C	D S W	9	Unknown	NB 2, 3	

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
3.2.10 STRUCTURAL DAMPING TILES The application of dampening tiles integrated into the structure of a ship, absorbing vibration energy, resulting in a reduction of URN. [1]	None	None	< 5 dB	100 to 1000 Hz	N/A	C	W D	9	\$50 to 150 per m^2	RF / NB 2, 3	URN is valid if treatment is extensive, covering external areas of noise sources such as hull sections around machinery room, etc. Best at higher frequencies.
3.2.11 ACOUSTIC DECOUPLING COATING Layer of rubber foam or polyethylene foam applied to the exterior of the ships hull, designed to decrease noise radiation from machinery vibration energy (most commonly applied to submarines). [44]	Unknown	Unknown	Unknown, claimed as > 10 dB for higher frequencies	> 800 Hz 100 to 800 Hz	1 or 3	-	M	7	\$250 to \$1000 per m^2 plus engineering design and installation costs	RF / NB 2, 3	Most commonly applied to submarines. Hard to control corrosion between coating and hull.
3.3 MACHINERY TREATMENTS TO ENERGY											
3.3.1 VARIABLE FREQUENCY DRIVE (VFD) FOR PROPULSION VFDs simplify electric propulsion control and eliminates the need of gearboxes and improve system efficiency and nearly instantaneous load demand matching. [64]	5 %	5 %	< 5 dB	< 1000 Hz	1	-	M P	9	US\$ 250 per kW	RF / NB 1 to 4	
3.3.2 VARIABLE VALVE TIMING (VVT) OR VARIABLE INJECTION TIMING (VIT) VVT modifies the timing of the inlet/exhaust valves over the range of engine loads to optimize efficiency and emissions. Similarly, VIT modifies the timing of the fuel injection valves over the range of engine loads to optimize efficiency and emissions. [93]	2 to 3 %	2 to 3 %	None	None	N/A	-	P	9	5 % higher cost of engine compared with mechanical system	RF / NB 1 to 4	EE and GHG are from VARD's assessments.

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
3.3.3 ELECTRONIC ENGINE CONTROL (EEC) Electronically controlled combustion engines have the camshaft functions replaced by an electronically controlled set of actuators. These actuators control the main components of the engine combustion system with far greater precision than camshaft-controlled engines, improving the engine efficiency. [93]	2 to 3 %	2 to 3 %	None	None	N/A	-	P	9	5 % higher cost of engine compared with mechanical system	RF / NB 1 to 4	
3.3.4 ENGINE CYLINDER DEACTIVATION/ SKIP FIRING Allows cylinders in multiple cylinder engine to be deactivated or cut off from fuel supply. When fewer cylinders are used to meet the load demand, these can function at higher load and combustion temperatures, resulting in higher efficiency as well as improved emission characteristics.	4 to 6 %	4 to 6 %	< 5 dB	All	1	-	-	9	Minor increase	RF / NB All	EE and GHG are VARD's own assessment.
3.3.5 WASTE ENERGY RECOVERY (HEAT) Heat from engine exhaust and jacket water cooling systems can be used to supply HVAC and other heating loads [75] [93] [97]	3 to 8 %	3 to 8 %	None	None	N/A	-	M P S	9	medium	RF / NB 1, 2, 4	Space intensive so mainly for larger ships.
3.3.6 WASTE ENERGY RECOVERY (ELECTRICITY) Waste heat can be used to drive power turbines and generate electricity for hotel loads. [75] [93] [97]	Up to 4 %	Up to 4 %	None	None	N/A	-	M P S	9	Unknown	RF / NB All	

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
3.3.7 MILLER CYCLE/TWO STAGE TURBO CHARGING The Miller cycle reduces the in-cylinder combustion temperature which reduces the NOx emission, however it results in reduced volumetric efficiency and engine power. Therefore, it should be used in conjunction with a two-stage turbocharger which counteracts the loss in power and increases the efficiency. [94]	6 to 7 %	6 to 7 %	None	None	N/A	-	-	9	> 10 % higher cost of engine	RF / NB 1 to 4	GHG is from VARD's assessments.
3.3.8 CARBON CAPTURE AND STORAGE Capture and store onboard the CO2 that is created by the power source. The stored CO2 will need to be offloaded and permanently stored (for instance underground). [122]	-10 %	Up to 90 %	None	None	N/A		D M P S W		Unknown	RF / NB 1 to 4	Exhaust gasses need to be extremely clean (even LNG still need to be cleaned before the CO_2 can be captured).
3.4 ALTERNATIVE FUEL SELECTION											
3.4.1 LIQUIFIED NATURAL GAS (LNG) Liquified Natural Gas (LNG) has become popular as an alternative fuel due to low cost and emission benefits. LNG has a marked improvement in emissions compared to diesel (25-30 %) provided that methane slip can be minimized; methane has a global warming potential (GWP) of 30.	This study does not focus on alternative fuels. Where alternative fuels enable technologies (such as fuel cells), the implications are reviewed. This matrix is an introductory treatment of means to increase energy efficiency and/or to reduce underwater radiated noise. A low(-er) carbon fuel can be very effective for GHG reduction but does not, in most cases (if used in an internal or external combustion engine), give other efficiency and/or URN benefits.										LNG is normally used in dual fuel ("diesel") engines which can also operate on fuel oils if required. Noise signatures similar to conventional diesels.

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
3.4.2 METHANOL Methanol is the simplest alcohol with the lowest carbon content and highest hydrogen content of any liquid fuel. Methanol combustion in an internal combustion engine reduces CO_2 emissions compared with fuel oils, however the amount of GHG reduction is dependent on the source of the methanol.	This study does not focus on alternative fuels. Where alternative fuels enable technologies (such as fuel cells), the implications are reviewed. This matrix is an introductory treatment of means to increase energy efficiency and/or to reduce underwater radiated noise. A low(-er) carbon fuel can be very effective for GHG reduction but does not, in most cases (if used in an internal or external combustion engine), give other efficiency and/or URN benefits.										Methanol is normally used in dual fuel ("diesel") engines which can also operate on fuel oils if required. Noise signatures similar to conventional diesels.
3.4.3 HYDROGEN Hydrogen is a carbon free fuel. Hydrogen is an indirect greenhouse gas with a global warming potential (GWP) of 5.8 over a 100-year time horizon. The source of the hydrogen determines the emission reduction compared with fuel oils.	This study does not focus on alternative fuels. Where alternative fuels enable technologies (such as fuel cells), the implications are reviewed. This matrix is an introductory treatment of means to increase energy efficiency and/or to reduce underwater radiated noise. A low(-er) carbon fuel can be very effective for GHG reduction but does not, in most cases (if used in an internal or external combustion engine), give other efficiency and/or URN benefits.										Hydrogen can be burnt in relatively conventional "diesel" engines or used in fuel cells.
3.4.4 AMMONIA Ammonia is a carbon free compound of nitrogen and hydrogen with a GWP of 0. As with other alternative fuels, the level of GHG reduction depends on the source.	This study does not focus on alternative fuels. Where alternative fuels enable technologies (such as fuel cells), the implications are reviewed. This matrix is an introductory treatment of means to increase energy efficiency and/or to reduce underwater radiated noise. A low(-er) carbon fuel can be very effective for GHG reduction but does not, in most cases (if used in an internal or external combustion engine), give other efficiency and/or URN benefits.										Ammonia can be used in dual fuel ("diesel") engines which can also operate on fuel oils if required. It can also be used as a hydrogen source for fuel cells.
3.4.5 BIOFUELS Biofuels such as "biodiesel" and "renewable diesel" are generated from conventional and novel agricultural sources. The level of GHG reduction depends on the source.	This study does not focus on alternative fuels. Where alternative fuels enable technologies (such as fuel cells), the implications are reviewed. This matrix is an introductory treatment of means to increase energy efficiency and/or to reduce underwater radiated noise. A low(-er) carbon fuel can be very effective for GHG reduction but does not, in most cases (if used in an internal or external combustion engine), give other efficiency and/or URN benefits.										Biofuels are generally "drop in" fuels that can be used directly by most modern diesels. Noise signatures are unaffected.

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
3.4.6 BATTERIES (STORED ELECTRICAL ENERGY) Draws on stored energy provided by shore power or from integrated electric power plant on ship. Batteries themselves are inherently silent removing all prime mover noise when in use. Low energy density means can only be used for short voyages, or for portions of longer voyages in (e.g.) noise-sensitive areas. [48]	5 to 10 %	5 to 10 %	> 10 dB	All	1	C	S W	9	High capital cost	RF / NB 2, 3, 4 Applicable to ships with short routes or highly varying speed profiles	Where batteries can provide full endurance, they can completely remove GHGs. Where used to improve the efficiency of an on-board plant will offer smaller gains. Battery operation is essentially silent for machinery noise.
3.4.7 SUPER/ULTRACAPACITORS Like batteries, supercapacitors are electrical storage devices, but unlike batteries they have low energy but high power densities. This makes them suitable for meeting sudden power demands such as during engine startup, dynamic positioning, manouevring and braking. [97] [102] [103]	5 to 10 %	5 to 10 %	> 10 dB	All	1	C	S W	8	High capital cost	RF / NB 2, 3	Currently only used to supplement rather than to replace conventional plants.
3.4.8 NUCLEAR Mature and feasible technology, it eliminates GHGs completely. Particularly suitable for long mission ships due to infrequent refueling requirements. The use relies heavily on public perception. [91] [92]	N/A	100 %	> 10 dB	All	1	C	D P	6	High	NB 1, 4	Increased operator skill/training required. Perceived (inherent) risks to the crew and public. The type of EE, GHG and URN combination is solely based on GHG and URN (EE is not taken into account).

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
3.5 HOTEL LOAD											
3.5.1 LOAD SCHEDULING Load scheduling by running machinery near or at their rated operating points to maximize efficiency. [84]	Dependent on number of machinery and specs.	Dependent on number of machinery and specs.	5 to 10 dB	Low	1 or 3	S	D M	9	No or small cost	RF / NB 1 to 4	Large improvement in EE and GHG is possible compared to equal load sharing. Noise signature tends to shift from low freq. to high due to operating at rated point (peak power, rpm). Cost is associated with load scheduling software and crew training.
3.5.2 REDUCED MANNING Minimizing the size of crew (or going for automation/autonomous operation) will result in a reduction of hotel load, energy consumption and emissions. [101]	Dependent on the number of crew members eliminated.	Dependent on the number of crew members eliminated.	< 5 dB	All	1 or 3	S W	P M	8	Depending on the level of automation/autonomy.	RF / NB 1 to 4	Maintenance costs may increase due to increased intervals for safe working of machinery. RF may be possible for some systems, only. Others may be cost prohibitive. Complete autonomy may be cost prohibitive, optimization of crew size is desirable.

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
3.5.3 VARIABLE FREQUENCY DRIVE (VFD) FOR AUXILIARY Variable frequency drive (VFD) can be applied to essentially any fluid handling system that is served by a pump or fan. As a result, almost all auxiliary systems on a ship have the potential to benefit from the use of VFDs to improve system efficiency and load demand matching. [93] [97]	Dependent on auxiliary system load	Dependent on auxiliary system load	< 5 dB	< 1000 Hz	1 or 3	E F	M P	9	US$250 per kW	RF / NB 1 to 4	
3.5.4 AUXILIARY BOILER Where feasible, using boilers rather than electric heaters will increase energy efficiency.	Up to 5 %	Up to 5 %	None	All	N/A	C M	D M S W	9		RF / NB 1 to 4	The EE and GHG benefits depend on level of heating loads on ship
3.5.5 POWER TAKE-OFF (PTO)/POWER TAKE-IN (PTI) In the PTO mode, additional power that is available on the main engine drives a generator connected to the PTO shaft to supply additional power to loads other than propulsion, eliminating the need for running additional gensets and keeping the engine near its peak power and its peak efficiency. In the PTI mode, gensets provide propulsion power at speeds at which the main engine efficiency is low, while supplying other loads as well, increasing overall efficiency. [96] [97]	Up to 10 %	Up to 10 %	< 5 dB	All	1	M	D P	9	Payback period: 5+ years (short)	NB 1 to 4	

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
4 OTHER MITIGATION TECHNOLOGIES											
4.1 WIND ASSISTED SHIP PROPULSION (WASP)											
4.1.1 CONVENTIONAL SAILS Reduce machinery power requirements by a sail with a single layer of fabric with a mast like system [22] [98] Noise benefits come from reduced propeller loading.	1 to 6 %	1 to 6 %	5 to 10 dB	All	1	C	D S P	9	Dependent on ship and installation	NB 3, 4 (not suited for short routes, e.g. smaller ships)	Peak performance and fuel reduction depend on the wind direction and intensity. URN reduction depends on speed reduction and primary propulsion source. Not suited to smaller ships or to operations on short routes and fixed schedules, e.g. smaller ferries.
4.1.2 KITE SAILS Kites attached to the bow creating supplementary thrust. [22] [53] [76] Noise benefits come from reduced propeller loading.	4 to 13 %	4 to 13 %	5 to 10 dB	All	1	C	D S P	8	Payback Period: 15+ years (medium)	RF / NB 1, 4	See 4.1.1.
4.1.3 FLETTNER/MAGNUS ROTORS Rotating cylinders use Magnus effect to generate supplementary thrust from wind. [22] [54] [71] [98] Noise benefits come from reduced propeller loading.	7 to 11 %	7 to 11 %	5 to 10 dB	All	1	C	D S P	8	Payback Period: 15+ years (medium)	RF / NB 1, 4	See 4.1.1.

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
4.1.4 RIGID AND SOFT WING SAILS Wing shaped sails (either rigid or soft) improve upwind performance. [22] [53] Noise benefits come from reduced propeller loading.	3 to 8 %	3 to 8 %	5 to 10 dB	All	1	C	D S P	7	Payback Period: 15+ years (medium)	RF / NB 1, 4	See 4.1.1.
4.1.5 SUCTION SAILS Suction sails reduce flow separation by suction induced boundary layer control, increasing the lift forces of the wing shaped sails. [22] [53] Noise benefits com from reduced propeller loading.	6 to 10 %	6 to 10 %	5 to 10 dB	All	1	C	D S P	7	Payback Period: 15+ years (medium)	RF / NB 1, 4	See 4.1.1.
4.2 OTHER ENERGY SOURCE											
4.2.1 COLD IRONING Provision of higher power shore supplies to large ships (cruise ships, containers ships) can allow these ships to turn off all generating equipment while in port, lowering URN while alongside. [58]	100 % in port	100 % in port	5 to 10 dB	< 1000 Hz	1	C M	S W	9	$1.5 m per berth, $400k per ship	RF / NB All	EE and GHG improvements are with respect to the ship's own operation. They do not consider EE or GHG of port facilities. Ship types include smaller ship with standard home ports.
4.2.2 SOLAR Marine grade solar panel array(s) or string(s) of photovoltaic (PV) panels used to produce power, normally in combination with an Energy Storage System (ESS). For the ships considered in this matrix, the PV panels will supplement the auxiliary power generation system. [75]	Up to 2 %	Up to 2 %	None	-	N/A	-	D M P S W	6	Minor to moderate $15.000/kW	RF / NB 1 to 4	Most ships do not have space for large solar arrays. EE reflects saved fuel for ship.

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
5 OPERATIONAL MEASURES											
Ship Energy Efficiency Management Plan (SEEMP)	The (mandatory) Ship Energy Efficiency Management Plan (SEEMP) is a ship specific document that requires the collection and analysis of information to enable energy efficiency improvement. It can incorporate any or all of the measures outlined below.										
5.1 OPERATIONAL PLANNING											
5.1.1 SPEED REDUCTION (SLOW STEAMING)/ENGINE POWER LIMITATION (EPL) The engine load is approximately proportional to the cube of speed, so reducing the speed of the ship will reduce its own fuel consumption. At the fleet level, more ships are required to transport the total cargo. This method has already been adopted and returned good results in terms of fuel economy/emissions reduction by many ship operators. To implement a good practice at the existing fleet level, an overridable engine power limitation can be imposed (mechanically or electronically). [68] [76] [93]	Approximately proportional to square of speed reduction.	Approximately proportional to square of speed reduction.	< 5 dB	All	1	M	-	9	Cost mainly from reduction in transport efficiency – slower ships will deliver less cargo over a given time period.	RF 1 to 4	Exposure duration increases for URN. EE change is taking into account the transportation reduction, and hence the required additional sailing if speed is reduced. Sufficient power and speed must be is maintained for safe navigation. Not suited to ships designed/customized for a specific route/mission profile e.g., icebreakers

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
5.1.2 WEATHER ROUTING AND SCHEDULING Planning the voyage and choosing the route to minimize the impact from current, waves and wind can reduce the powering requirement and save fuel. Weather/wind routing software helps to predict, plan and operationally adjust sailing routes to maximize the benefits from wind and minimize the disruption from adverse weather conditions.[76] [93]	0 to 5 %	0 to 5 %	< 5 dB	All	1	M	-	9	$15.000/ship for system. Assuming weather data is already received via other means.	RF 1, 4	EE and GHG depend on ship size and type; large intercontinental ships can benefit the most. Cost is associated with weather routing system upgrade.
5.1.3 VOYAGE EXECUTION (JUST-IN-TIME ARRIVAL PLANNING) Voyage planning and execution from one port to another, considering port availability, the economical speed, engine loading and use of autopilot can reduce the fuel consumption. [93]	1 to 10 %	1 to 10 %	< 5 dB	All	1	M	-	9	low	RF 1, 4	EE and GHG depend on ship size type and route;
5.1.4 TRIM/DRAFT OPTIMIZATION Active planning of cargo loading in such a way to optimize the trim/draft for each loading/voyage (to avoid unnecessary ballasting) to reduce the hull resistance and save fuel. [93]	Up to 2 %	Up to 2 %	< 5 dB	All	1	-	M	9	$25.000/ship for loading computer $100k/ship for supporting analyses of trim optimization	RF 1 to 4	Cost is associated with ship loading computer upgrade and crew training.
5.1.5 CARGO LOAD OPTIMIZATION Planning of cargo loading such that each voyage is executed with the ship at full (or close to full) loading capacity, thus saving fuel per each unit of cargo transported. [93]	Up to 10 %	Up to 10 %	< 5 dB	All	1	-	M	9	low	All cargo	EE and GHG impact (VARD's internal assessment) can be Up to 40 % for ships that trade half the time in ballast condition. Cost is associated with shore side management.

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
5.1.6 MARITIME SPATIAL PLANNING Planning to actively deviate from the optimal route to circumvent areas with sensitive marine species in order to reduce the URN in these areas. [85]	Negative, depending on route	Negative, depending on route	Positive, depending on route	All	3	-	M	9	Depending on route	1-4	As proposed by MEPC 80/16/3, in April 2023, for a new traffic separation scheme south of Sri Lanka.
5.2 SYSTEM MONTORING AND MANAGEMENT											
5.2.1 CONDITION MONITORING Embedded sensors provide data that can identify developing faults and performance shortfalls and enable predictive maintenance (see 5.2.4). This measure will not reduce URN or improve EE by itself, it needs to be followed up by Machinery Maintenance and/or speed reduction.	Indirect (mitigates degradation)	Indirect (mitigates degradation)	Indirect (mitigates degradation)		N/A	M		9	Dependent on analysis approaches		Most modern equipment comes with suitable sensor fit, analysis has to be considered/provided
5.2.2 CONTINUOUS URN MEASUREMENT Continuous URN measurements will give insight in the ability of the ship to reduce URN below a certain threshold (or to perform maintenance). This measure will not reduce URN or improve EE by itself, it needs to be followed up by Machinery Maintenance and/or speed reduction.	Indirect (mitigates degradation)	Indirect (mitigates degradation)	Indirect (mitigates degradation)	-	N/A	-	D S W	9	Unknown	RF / NB All	Most fits use airborne noise and structural vibration as indirect measurement tools; calibration is important.
5.2.3 CONTINUOUS FUEL AND EMISSION MEASUREMENT Continuous fuel consumption and emission measurements will give insight in the ability of the ship to improve its fuel consumption and emissions below a certain threshold (or to perform maintenance). This measure will not reduce URN or improve EE by itself, it needs to be followed up by Machinery Maintenance.	Indirect (mitigates degradation)	Indirect (mitigates degradation)	Indirect (mitigates degradation)	-	N/A	-	D S W	9	$100k for fuel measurement system; Maintaining moving parts of machinery and maintaining resilient mounts (see 3.2.1), helps to keep the vibrations and higher for direct measurement of emissions.	RF / NB All	

Treatment/Description	Energy Efficiency	GHG Reduction	URN		T	Ship Impacts		TRL	Cost Estimation	Applicability	Comments
	% Change	% Change	dB Change	Freq. Rng.		A/B	C/D		Percentage/Range/Pay-back Period/Shorthand	RF/NB Ship Types	
5.2.4 MACHINERY MAINTENANCE Maintaining moving parts of machinery and maintaining resilient mounts (see 3.2.1), helps to keep the vibration, noise and energy efficiency from degrading with time. Condition-based maintenance uses actual performance data to schedule work.	Indirect (mitigates degradation)	Indirect (mitigates degradation)	Indirect (mitigates degradation)		1	M				All	Condition-based maintenance generally more efficient than time-based or corrective.
5.3 SHIP ENERGY MANAGEMENT											
5.3.1 POWER/ENERGY MANAGEMENT SYSTEM (PEMS) Automated PEMS correlates the power plant generation with the ship's machinery configuration to ensure efficient operation of the engines. [75]	5 to 10 %	5 to 10 %	Negligible	All	1	-	D W P	9	15+ % higher capital cost	RF / NB 2, 3	

Appendix B CITATION INDEX

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