Vard Marine Inc.

TECHNOLOGY MATRIX

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TECHNOLOGY MATRIX

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Title:	TECHNOLOGY MATRIX
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SUMMARY OF REVISIONS

Rev	Date	Description	Prepared By	Checked By
0	31 Oct 23	Initial Issue, based on below mentioned reference 1 and minor manual additions.	RTE	EMS

REFERENCES

No.	Source
1	Vard Marine, "Ship Energy Efficiency and Underwater Radiated Noise", revision 3, report # 545-000-01, 20 October 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 (EE):
% 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 (Underwater Radiated Noise):
dB Change - Expected Noise Reduction in Decibels (dB) for the specific treatment, *and not (depending on the dominant noise source) necessarily the overall noise signature of the ship.*
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)

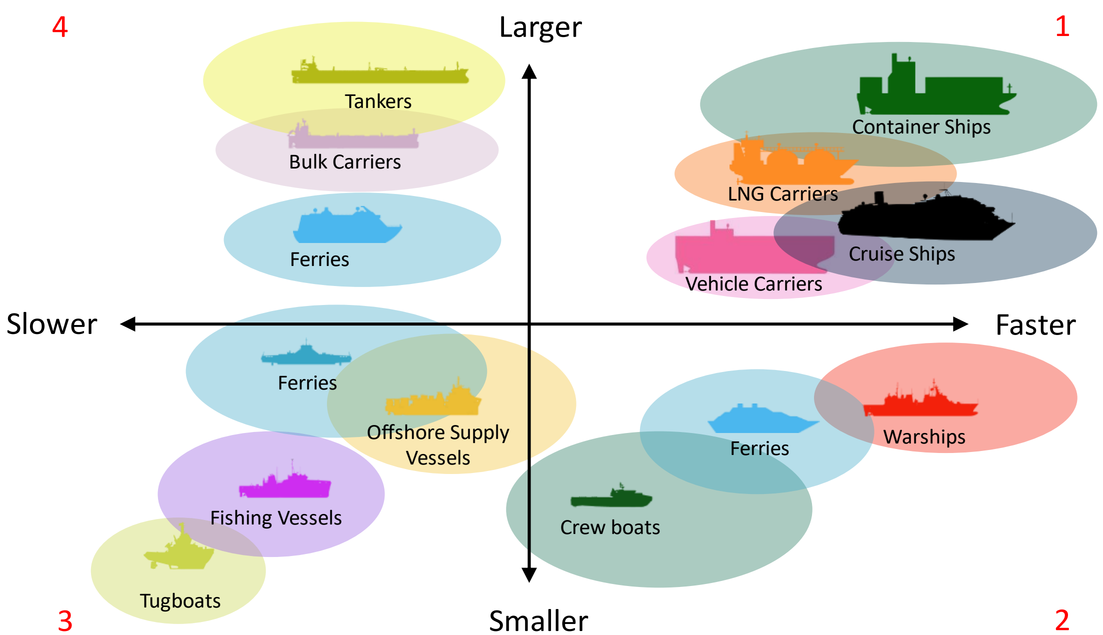
TRL – Technology Readiness Level:
TRL 1: Basic principles observed and reported.
TRL 2: Technology concept and/or application formulated.
TRL 3: Analytical and experimental critical function and/or characteristic proof of concept.
TRL 4: Product and/or process validation in laboratory environment.
TRL 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>Re</u><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.

<u>General Notes:</u>

- *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 (depending on the dominant noise source) 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.*
- *This matrix is a snapshot of the current treatments available, and it is linked to reference data to the source with a number in square brackets (see Appendix B of the reference mentioned in the revisions table)*

MATRIX

Category (-)	Sub-Category (-)	Treatment (-)	Description (-)	Energy Efficiency (% Change)	GHG Reduction (% Change)	URN (dB change)	URN (Freq. Rng)	Type (-)	Ship Impacts (Advantages/ Benefits)	Ship Impacts (Challenges/ Disadvantages)	TRL (-)	Cost Estimation (-)	Applicability (RF / NB)	Applicability (Ship Types)	Comments (-)
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. [117]	5 to 10 %	5 to 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.
1 HYDRODYNAMICS	1.1 HULL APPENDAGE/DESIGN	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. [70]	5 to 10 %	5 to 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 HYDRODYNAMICS	1.1 HULL APPENDAGE/DESIGN	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.
1 HYDRODYNAMICS	1.1 HULL APPENDAGE/DESIGN	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. [97]	< 1 %	< 1 %	None	-	N/A	C	D	9	Low	RF / 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 HYDRODYNAMICS	1.1 HULL APPENDAGE/DESIGN	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. [71] [72] [93]	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.
1 HYDRODYNAMICS	1.1 HULL APPENDAGE/DESIGN	1.1.6 BOW FOILS	They can generate net thrust when ship heaves and pitches while moving forward in waves. Reduces motions and thrust to propel the ship. Exemplar is Wavefoil. [104] [105] [106] [121]	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 HYDRODYNAMICS	1.1 HULL APPENDAGE/DESIGN	1.1.7 STERN FOILS	Reduces pitch motions and losses in stern wave system, provides crew comfort and forward thrust at speed. Exemplar is Hull Vane. [107] [108] [122]	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.
1 HYDRODYNAMICS	1.1 HULL APPENDAGE/DESIGN	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. [113] [118]	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 HYDRODYNAMICS	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 HYDRODYNAMICS	1.2 FRICTIONAL RESISTANCE REDUCTION	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. [69] [86] [6] [94]	Up to 5 %	Up to 5 %	< 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 HYDRODYNAMICS	1.2 FRICTIONAL RESISTANCE REDUCTION	1.2.3 HULL COATING RENEWAL	Fresh anti-fouling coating can improve fuel and GHG savings. [86] [94]	Up to 5 %	Up to 5 %	< 5 dB	All	1	C	M	9	Typically, similar or greater cost than initial application (see 1.2.1)	RF	All	
1 HYDRODYNAMICS	1.2 FRICTIONAL RESISTANCE REDUCTION	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. [44] [50] [76] [101] [80]	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 HYDRODYNAMICS	1.2 FRICTIONAL RESISTANCE REDUCTION	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. [77] [79] [80] [6] [94]	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 HYDRODYNAMICS	1.2 FRICTIONAL RESISTANCE REDUCTION	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. [80]	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.

2 PROPULSOR	2.1 PROPELLER/PROPULSOR DESIGN	2.1.1 PROPELLER OPTIMIZATION	Improving the propeller design to increase the efficiency. May include altering the blade number, pitch distribution, camber, rake, diameter, blade area ratio, clearance to hull and rudder, etc. Increasing the efficiency, may increase the URN for fully-optimized propellers.	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. Propeller design should match the hull form
2 PROPULSOR	2.1 PROPELLER/PROPULSOR DESIGN	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). [24]	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). Hull propeller clearance needs to be sufficient to avoid high pressure pulses.
2 PROPULSOR	2.1 PROPELLER/PROPULSOR DESIGN	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 propeller 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. Larger hub is likely to increase noise levels slightly more compared to fixed pitch propellers.
2 PROPULSOR	2.1 PROPELLER/PROPULSOR DESIGN	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. [75]	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	URN benefit is especially large if a constant propeller revolution rate is changed to a variable revolution rate.
2 PROPULSOR	2.1 PROPELLER/PROPULSOR DESIGN	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 shield propeller tip cavitation, and therefore underwater radiated noise. [83]	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 %.
2 PROPULSOR	2.1 PROPELLER/PROPULSOR DESIGN	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. [25]	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. Increasing the shaft angle normally leads to an increase in cavitation and should hence be avoided.
2 PROPULSOR	2.1 PROPELLER/PROPULSOR DESIGN	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. [26] [27] [28] [91] [96]	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 PROPULSOR	2.1 PROPELLER/PROPULSOR DESIGN	2.1.8 CYCLIC VARYING PITCH (CVP) PROPELLER	With the CVP propeller it is possible to control the pitch of the propeller blades individually. Having the possibility of making a cyclic variation to the blade pitch can yield performance improvements with respect to: efficiency, cavitation, vibrations, pressure pulses and noise. [130]	1 %	1 %	< 5 dB	Unknown	1	C	D M P S	5	More than for a CPP (see 2.1.3)	RF / NB	All (especially for ships with varying load profile)	Energy loss due to the pitching motion of the blades is unknown and not taken into account. Reliability (wear and fatigue) of the CVP needs to be further investigated.
2 PROPULSOR	2.1 PROPELLER/PROPULSOR DESIGN	2.1.9 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. [28] [29] [30]	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 PROPULSOR	2.1 PROPELLER/PROPULSOR DESIGN	2.1.10 TANDEM PROPELLER	Two co-rotating propellers, usually of the same diameter and the same number of blades, mounted on the same shaft or azimuthing unit with certain angular shift between them. Exemplar is TwinPropeller from Schottel. [131]	Up to 4 %	Up to 3 #	< 5 dB	Unknown	1	C	D M P W	9	Higher capital cost than conventional propeller. Depending on the configuration.	RF / NB	All	Can be used with both shafted and azimuthing propulsors.

2 PROPULSOR	2.1 PROPELLER/PROPULSOR DESIGN	2.1.11 CONTRA-ROTATING PROPELLERS (CRP)	Co-axial propellers, one propeller rotating clockwise and the other rotating counterclockwise. Increases CIS due to reduction in blade loading resulting in lower blade surface cavitation. [31] [32] [48]	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 shafted and azimuthing propulsors.
2 PROPULSOR	2.1 PROPELLER/PROPULSOR DESIGN	2.1.12 PROPELLERS WITH TIP RAKED FORWARD	Propeller blades modified with tips curved towards the suction side (like Kappel propellers). This reduces the strength of the tip vortex thus increasing efficiency, decreasing tip vortex cavitation, and increasing CIS. [33] [34] [91]	4 %	4 %	< 5 dB	40 to 300 Hz	1	C	D	9	20 % higher capital cost than conventional propellers [5]	RF / NB	All	
2 PROPULSOR	2.1 PROPELLER/PROPULSOR DESIGN	2.1.13 PROPELLERS WITH TIP 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. [35]	3 %	3 %	Unknown (Improves wake flow downstream of propeller)	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 PROPULSOR	2.1 PROPELLER/PROPULSOR DESIGN	2.1.14 PROPELLERS WITH HOLES NEAR THE TIP	By drilling small holes near the tip of the blade, tip vortex cavitation is significantly reduced and thereby also URN, with a slight EE reduction. [125] [126]	Up to -4 %	Up to -4 %	5 to 10 dB	Up to 1000 Hz	3	C	D M	6	Small increase in design and manufacturing cost	RF / NB	All	Could increase singing behavior of propellers (see 2.3.5)
2 PROPULSOR	2.1 PROPELLER/PROPULSOR DESIGN	2.1.15 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 2.1.16) and azimuthing, both types claim good performance. [36] [21]	-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. Manoeuvring is improved compared to shafted system. At higher speeds, flow asymmetry in manoeuvring may increase URN. At low speeds, use of directed thrust may be quieter than prop/rudder flow deflection.
2 PROPULSOR	2.1 PROPELLER/PROPULSOR DESIGN	2.1.16 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). [36] [21]	-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 2.1.15.
2 PROPULSOR	2.1 PROPELLER/PROPULSOR DESIGN	2.1.17 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. [21] [37] [38]	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 PROPULSOR	2.1 PROPELLER/PROPULSOR DESIGN	2.1.18 PUMP JETS	Combine a full pre-swirl stator, propeller and duct. Normally used in ultra-quiet applications such as submarines. Exemplar is Voith Linear Jet. [39] [82]	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 PROPULSOR	2.1 PROPELLER/PROPULSOR DESIGN	2.1.19 COMPOSITE PROPELLERS	Use of advanced composites to allow for blade distortion under load to increase efficiency, delay cavitation onset and reduce blade vibration. [1] [98] [99] [100]	Up to 4 %	Up to 4 %	< 5 dB	All	1	C W	D	6	Unknown	RF / NB	1 to 4	Mentioned TRL for smaller size applications. TRL for large propellers: 5.
2 PROPULSOR	2.1 PROPELLER/PROPULSOR DESIGN	2.1.20 VERTICAL AXIS PROPELLERS	Trochoïdal, Kirsten-Boeing and Voith-Schneider type vertical axis/crossflow propellers that provide increased manoeuvring at the expense of energy efficiency with possible URN reduction. [1]	-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 PROPULSOR	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. [39]	Up to 5 %	Up to 5 %	< 5 dB	All	1	C	D	9	Typical Payback Period: 24 months	RF / NB	4	
2 PROPULSOR	2.2 WAKE FLOW MODIFICATION	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. [40] [41]	4 %	4 %	< 5 dB	All	1	C	D	9	Typical Payback Period: 4 months	RF / NB	1, 4	
2 PROPULSOR	2.2 WAKE FLOW MODIFICATION	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. [41] [42] [43]	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	URN benefit valid in case hub vortex cavitation is the dominant noise source.

2 PROPULSOR	2.2 WAKE FLOW MODIFICATION	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. [41] [42] [44]	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 PROPULSOR	2.2 WAKE FLOW MODIFICATION	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. [40]	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 PROPULSOR	2.2 WAKE FLOW MODIFICATION	2.2.6 MEWIS DUCT	A combination of a duct with pre-swirl stators integrated into the duct just forward of the propeller. Reduces losses at the inflow to the propeller, reducing slipstream losses and reducing hub vortex losses. Similar concepts include Super Stream Duct. [28] [41]	3 to 8 %	3 to 8 %	< 5 dB	Unknown	1	C	D	9	Typical Payback Period: Less than a year	RF / NB	1, 4	
2 PROPULSOR	2.2 WAKE FLOW MODIFICATION	2.2.7 BECKER TWISTED FINS	Combination of a smaller Mewis Duct (see 2.2.6) with fins extended beyond the pre-duct structure. [128]	Up to 5%	Up to 5%	< 5 dB	Unknown	1	C	D	8	Typical Payback Period: Approx. 1 year	RF / NB	1	Specifically for faster vessels with finer hull forms.
2 PROPULSOR	2.2 WAKE FLOW MODIFICATION	2.2.8 RUDDER THRUST FINS	Horizontal fins that are attached directly to the rudder horn. Those fins capture energy and convert to thrust. [6]	Up to 2 %	Up to 2 %	None	-	N/A	C	D S W	9	Typical Payback Period: Less than 2 years	RF / NB	1, 4	
2 PROPULSOR	2.2 WAKE FLOW MODIFICATION	2.2.9 INTEGRATED PROPELLER-HUBCAP-RUDDER	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 PROMAS, Ultimate Rudder Bulb and SURF-BULB. [45] [84]	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 PROPULSOR	2.2 WAKE FLOW MODIFICATION	2.2.10 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. [41] [44] [46]	1 %	1 %	< 5 dB	Unknown	1	C	D	9	Payback Period: 4 to 15 years	RF / NB	1, 2	
2 PROPULSOR	2.2 WAKE FLOW MODIFICATION	2.2.11 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. [44] [47]	2 to 3 %	2 to 3 %	< 5 dB	Unknown	1	C M MA	D	9	Payback Period: less than 2 years	RF / NB	1, 2	
2 PROPULSOR	2.2 WAKE FLOW MODIFICATION	2.2.12 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 manoeuvring capability. Behaves similar like an accelerating duct and benefits from oblique flow angles in the stern. [88] [89] [92]	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. 5 years	RF / NB	1, 4	For optimum performance the propeller design needs to be adjusted.
2 PROPULSOR	2.2 WAKE FLOW MODIFICATION	2.2.13 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. [48] [26] [81]	Up to 6 %	Up to 6 %	< 5 dB	Unknown	1	C	D	9	Unknown	NB	1, 4	
2 PROPULSOR	2.3 SUPPLEMENTARY TREATMENTS	2.3.1 IMPROVED MANUFACTURING PROCESSES	Tighter tolerances on blade manufacture may reduce cavitation. [49] [85]	< 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 PROPULSOR	2.3 SUPPLEMENTARY TREATMENTS	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. [50] [101]	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.
2 PROPULSOR	2.3 SUPPLEMENTARY TREATMENTS	2.3.3 PROPELLER MAINTENANCE	Imperfections of a propeller blade can encourage cavitation. Repairing between dry docks can prevent this, reducing cavitation and increasing CIS. [51] [86] [94]	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 PROPULSOR	2.3 SUPPLEMENTARY TREATMENTS	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. [44] [52]	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 PROPULSOR	2.3 SUPPLEMENTARY TREATMENTS	2.3.5 APPLICATION OF ANTI-SINGING EDGE	Modification to the propellers trailing edge, designed to alter naturally occurring vortex shedding phenomenon. [1] [53]	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.
3 POWERING	3.1 MACHINERY SELECTION	3.1.0 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	-	-	-	-	-	-	-	-	-	-	-	

3 POWERING	3.1 MACHINERY SELECTION	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. [10] [6]	-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 POWERING	3.1 MACHINERY SELECTION	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.
3 POWERING	3.1 MACHINERY SELECTION	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). [115]	Up to 5 %	Up to 5 %	< 5 dB	All	1	M S W	-	9	Slightly more expensive than an AC system.	NB	1 to 4	
3 POWERING	3.1 MACHINERY SELECTION	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. [54]	-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 POWERING	3.1 MACHINERY SELECTION	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. [55] [95]	5 %	5 %	5 to 10 dB	Unknown	1	M	MA W S	6	High capital cost	NB	2, naval, submarine.	
3 POWERING	3.1 MACHINERY SELECTION	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. [65] [66] [67]	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	All	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 POWERING	3.2 MACHINERY TREATMENTS TO NOISE	3.2.1 RESILIENT MOUNTS (EQUIPMENT)	Flexible/spring/isolators/resilient 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/available for heavy, powerful, slow speed, 2-stroke engines. [56]	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 POWERING	3.2 MACHINERY TREATMENTS TO NOISE	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. [56]	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.
3 POWERING	3.2 MACHINERY TREATMENTS TO NOISE	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. [57]	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 POWERING	3.2 MACHINERY TREATMENTS TO NOISE	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. [58].	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 POWERING	3.2 MACHINERY TREATMENTS TO NOISE	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. [59]	None	None	> 10 dB	see comments	N/A	C	S D	6	Highly variable	NB	All	URN is effective at discrete frequencies rather than overall noise levels. Effective at tuned frequencies.
3 POWERING	3.2 MACHINERY TREATMENTS TO NOISE	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. [60] [61]	1 %	1 %	5 to 10 dB	see comments	1	M	D	9	Increase in manufacture cost, can double gear cost	NB	All (as long as the propulsion train is geared)	Effective mainly at gear meshing frequencies.
3 POWERING	3.2 MACHINERY TREATMENTS TO NOISE	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. [62]	None	None	< 5 dB	Unknown	N/A	-	D	3	Unknown	NB	1, 4	
3 POWERING	3.2 MACHINERY TREATMENTS TO NOISE	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. [63]	None	None	Unknown, claimed as > 10 dB	Unknown	N/A	C	W	6	Unknown	RF / NB	All	Reduces radiated noise from diesel or water tanks. Simulation based URN numbers. No field data.

3 POWERING	3.2 MACHINERY TREATMENTS TO NOISE	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. [24]	None	None	< 5 dB	10 to 1000 Hz	N/A	C	D S W	9	Unknown	NB	2, 3	
3 POWERING	3.2 MACHINERY TREATMENTS TO NOISE	3.2.10 STRUCTURAL DAMPING	The application of damping tiles or other compounds on the structure of a ship, absorbing vibration energy, resulting in a reduction of URN. [24]	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 POWERING	3.2 MACHINERY TREATMENTS TO NOISE	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). [64]	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 POWERING	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. [83]	5 %	5 %	< 5 dB	< 1000 Hz	1	-	M P	9	US\$ 250 per kW	RF / NB	1 to 4	
3 POWERING	3.3 MACHINERY TREATMENTS TO ENERGY	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. [111]	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.
3 POWERING	3.3 MACHINERY TREATMENTS TO ENERGY	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. [111]	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 POWERING	3.3 MACHINERY TREATMENTS TO ENERGY	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 POWERING	3.3 MACHINERY TREATMENTS TO ENERGY	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 [6] [111] [115]	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 POWERING	3.3 MACHINERY TREATMENTS TO ENERGY	3.3.6 WASTE ENERGY RECOVERY (ELECTRICITY)	Waste heat can be used to drive power turbines and generate electricity for hotel loads. [6] [111] [115]	Up to 4 %	Up to 4 %	None	None	N/A	-	M P S	9	Unknown	RF / NB	All	
3 POWERING	3.3 MACHINERY TREATMENTS TO ENERGY	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. [112]	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 POWERING	3.3 MACHINERY TREATMENTS TO ENERGY	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). [124]	-10 %	Up to 90 %	None	None	N/A	-	D M P S W	8	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 POWERING	3.4 ALTERNATIVE FUEL SELECTION	3.4.0 LOW CARBON FUELS	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	-	-	-	-	-	-	-	-	-	-	-	
3 POWERING	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.	-	-	-	-	-	-	-	-	-	-	-	LNG is normally used in dual fuel ("diesel") engines which can also operate on fuel oils if required. Noise signatures similar to conventional diesels.
3 POWERING	3.4 ALTERNATIVE FUEL SELECTION	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.	-	-	-	-	-	-	-	-	-	-	-	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 POWERING	3.4 ALTERNATIVE FUEL SELECTION	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.	-	-	-	-	-	-	-	-	-	-	-	Hydrogen can be burnt in relatively conventional "diesel" engines or used in fuel cells.
3 POWERING	3.4 ALTERNATIVE FUEL SELECTION	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.	-	-	-	-	-	-	-	-	-	-	-	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 POWERING	3.4 ALTERNATIVE FUEL SELECTION	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.	-	-	-	-	-	-	-	-	-	-	-	Biofuels are generally "drop in" fuels that can be used directly by most modern diesels. Noise signatures are unaffected.

3 POWERING	3.4 ALTERNATIVE FUEL SELECTION	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. [68]	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 POWERING	3.4 ALTERNATIVE FUEL SELECTION	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, manoeuvring and braking. [115] [16] [120]	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 POWERING	3.4 ALTERNATIVE FUEL SELECTION	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. [109] [110]	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).
3 POWERING	3.5 HOTEL LOAD	3.5.1 LOAD SCHEDULING	Load scheduling by running machinery near or at their rated operating points to maximize efficiency. [102]	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 POWERING	3.5 HOTEL LOAD	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. [119]	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.
3 POWERING	3.5 HOTEL LOAD	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. [111] [115]	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 POWERING	3.5 HOTEL LOAD	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 POWERING	3.5 HOTEL LOAD	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. [114] [115]	Up to 10 %	Up to 10 %	< 5 dB	All	1	M	D P	9	Payback period: 5+ years (short)	NB	1 to 4	
4 OTHER MITIGATION TECHNOLOGIES	4.1 WIND ASSISTED SHIP PROPULSION (WASP)	4.1.0 WASP TECHNOLOGIES	WASP technologies have a considerable range of configurations and complexity. In almost all cases, their EE/GHG benefits are higher if vessels can use weather routing to take advantage of favourable conditions for wind speed and direction. This and other factors will also affect payback periods. Certain wind propulsion studies, for niche markets, have shown EE and GHG change of up to 90%.	-	-	-	-	-	-	-	-	-	-	-	
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 [44] [116] 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)	URN reduction depends on speed reduction and primary propulsion source. EE could increase by a factor of 1.5 to 2 if weather routing could be applied.
4 OTHER MITIGATION TECHNOLOGIES	4.1 WIND ASSISTED SHIP PROPULSION (WASP)	4.1.2 KITE SAILS	Kites attached to the bow creating supplementary thrust. [44] [73] [94] Noise benefits come from reduced propeller loading.	4 to 13 %	4 to 13 %	5 to 10 dB	All	1	C	D S P	9	See 4.1.1	RF / NB	1, 4	See 4.1.1. Kites take limited deck space compared to other WASP technologies.
4 OTHER MITIGATION TECHNOLOGIES	4.1 WIND ASSISTED SHIP PROPULSION (WASP)	4.1.3 FLETTNER/MAGNUS ROTORS	Rotating cylinders use Magnus effect to generate supplementary thrust from wind. [44] [74] [90] [116] Noise benefits come from reduced propeller loading.	7 to 11 %	7 to 11 %	5 to 10 dB	All	1	C	D S P	9	Payback period of 6 years and up are mentioned. See 4.1.1	RF / NB	1, 4	See 4.1.1.
4 OTHER MITIGATION TECHNOLOGIES	4.1 WIND ASSISTED SHIP PROPULSION (WASP)	4.1.4 RIGID AND SOFT WING SAILS	Wing shaped sails (either rigid or soft) improve upwind performance. [44] [73] Noise benefits come from reduced propeller loading.	3 to 8 %	3 to 8 %	5 to 10 dB	All	1	C	D S P	9	See 4.1.1	RF / NB	1, 4	See 4.1.1.
4 OTHER MITIGATION TECHNOLOGIES	4.1 WIND ASSISTED SHIP PROPULSION (WASP)	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. [44] [73] Noise benefits com from reduced propeller loading.	6 to 10 %	6 to 10 %	5 to 10 dB	All	1	C	D S P	9	See 4.1.1	RF / NB	1, 4	See 4.1.1.

4 OTHER MITIGATION TECHNOLOGIES	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. [78]	100 % ship energy reduction in port	Up to 100 % in port (dependent on source of electricity)	5 to 10 dB in port	< 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 OTHER MITIGATION TECHNOLOGIES	4.2 OTHER ENERGY SOURCE	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. [6]	Up to 2 %	Up to 2 %	None	-	N/A	-	D M P S W	7	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.
5 OPERATIONAL MEASURES	5.1 OPERATIONAL PLANNING	5.1.1 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 OPERATIONAL MEASURES	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). [87] [94] [111] [132] [133]	Approximately proportional to square of speed reduction.	Approximately proportional to square of speed reduction.	~2 dB/knot (if propeller cavitation is dominant for cargo vessels)	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	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 maintained for safe navigation. Less suitable for ships designed/customized for a specific route/mission profile e.g., icebreakers (where a certain amount of power is required to maintain its operation). Slow steaming for URN can be used in marine sanctuaries or critical habitat areas rather than for complete voyages.
5 OPERATIONAL MEASURES	5.1 OPERATIONAL PLANNING	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.[94] [111]	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 OPERATIONAL MEASURES	5.1 OPERATIONAL PLANNING	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. [111]	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 OPERATIONAL MEASURES	5.1 OPERATIONAL PLANNING	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. [111]	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 OPERATIONAL MEASURES	5.1 OPERATIONAL PLANNING	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. [111] [127]	Up to 10 %	Up to 10 %	Unknown	All	1	-	M	9	Low	RF / NB	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.
5 OPERATIONAL MEASURES	5.1 OPERATIONAL PLANNING	5.1.6 MARITIME SPATIAL PLANNING	Planning to actively deviate from the initial route (re-routing) to circumvent areas with sensitive marine species in order to reduce the URN in these areas. [103]	Negative, depending on route	Negative, depending on route	Positive, depending on route	All	3	-	M	9	Depending on route	RF / NB	1 to 4	As proposed by MEPC 80/16/3, in April 2023, for a new traffic separation scheme south of Sri Lanka.
5 OPERATIONAL MEASURES	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	Indirect	Indirect	-	N/A	M	-	9	Dependent on analysis approaches	RF / NB	All	Most modern equipment comes with suitable sensors, analysis has to be considered/provided
5 OPERATIONAL MEASURES	5.2 SYSTEM MONTORING AND MANAGEMENT	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	Indirect	Indirect	-	N/A	-	D S W	9	Unknown	RF / NB	All	Most use airborne noise and structural vibration as indirect measurement tools; calibration is important.

5 OPERATIONAL MEASURES	5.2 SYSTEM MONTORING AND MANAGEMENT	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	Indirect	Indirect	-	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, noise and energy efficiency from degrading with time.	RF / NB	All	
5 OPERATIONAL MEASURES	5.2 SYSTEM MONTORING AND MANAGEMENT	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	Indirect	Indirect	-	1	M	-	9	-	RF / NB	All	Condition-based maintenance generally more efficient than time-based or corrective.
5 OPERATIONAL MEASURES	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. [6]	5 to 10 %	5 to 10 %	Negligible	All	1	-	D W P	9	15+ % higher capital cost	RF / NB	2, 3	