



Short-Term Greenhouse Gas Emission Reduction in the Maritime Sector: The Role of Energy Efficiency Measures.

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Executive summary

The harmful effects of greenhouse gas emissions (GHGs) on climate change, air pollution, human health and ecosystems are becoming increasingly evident. The maritime sector significantly contributes to these emissions globally, nationally and locally. In 2018 shipping was responsible for 2.89% of global anthropogenic emissions, increasing from 2.76% in 2012 [1]. Consequently, there is a pressing need for measures to reduce emissions from shipping and ports to ensure the sector contributes to achieving environmental objectives. This will require action by all stakeholders, with national and international governance and regulations.

Domestically, in 2019 the UK government's Department for Transport published Maritime 2050, which set out a strategic vision for the future of the maritime sector in the UK and pledged several policy commitments. The strategic vision is to proactively drive the transition to zero emissions shipping in UK waters, be a global role model, move faster than other countries and faster than international standards, whilst capturing significant economic, environmental and health benefits.

Internationally, the United Nations International Maritime Organization (IMO) has committed to reach net-zero GHG emissions from international shipping by or around, i.e. close to, 2050. This commitment encourages an uptake of alternative zero and near-zero GHG technologies, fuels and/or energy sources by 2030. The IMO have specified indicative emissions reduction checkpoints over the period to achieving the 2050 goal. This is to reduce the total annual GHG emissions from international shipping by at least 20%, but striving for 30%, by 2030, and by at least 70%, striving for 80%, by 2040 (compared to 2008). The 2023 IMO GHG Strategy also envisages a reduction in the carbon intensity of international shipping (to reduce CO₂ emissions per transport work), as an average across international shipping, by at least 40% by 2030 (compared to 2008).

To drive this sector change, the IMO has implemented measures to increase the energy efficiency of ships both new and old. For existing vessels these are the Carbon Intensity Indicator (CII) and Energy Efficiency Existing Ship Index (EEXI) regulations, which vessels must comply with. The IMO is committed to reviewing the implementation of the CII and EEXI requirements by 1 January 2026. Similarly new ships are the subject of the Energy Efficiency Design Index (EEDI) which aims to reduce the GHG emissions of ships being built today and in the future. All ships (over 400 gross tonnage) need to have a Ship Energy Efficiency Management Plan (SEEMP). These are ship specific and designed to continuously improve energy efficiency. IMO collects SEEMP data on an annual basis to report on emissions reduction progress.

The implementation of various measures, including the SEEMP, will improve the energy efficiency of ships and reduce their carbon emissions to achieve compliance with Carbon Intensity Indicator (CII) and Energy Efficiency Existing Ship Index (EEXI) regulations. There are

a number of actions ship owners and operators can take to achieve CII and EEXI compliance: Implement energy efficiency measures; Invest in retrofitting and upgrades; Optimise voyage planning and operations; Use of alternative fuels and technologies; Regular maintenance and performance monitoring; Crew training and awareness; Compliance monitoring and reporting. The actions are not only applicable to existing short-term application but also future longer-term implementation and new vessel designs meaning compliance with the EEDI.

This report provides an independent assessment of the methods and technologies with the potential to reduce emissions in the maritime sector, focusing particularly on solutions for improvements in energy efficiency. Energy efficiency should always be prioritised and is a critical pathway for reducing emissions in the near term while more advanced decarbonisation technologies continue to mature.

The report consolidates peer reviewed and grey literature to assess the current state of the art and uptake of GHG abatement options for the maritime sector. Firstly, the report outlines the opportunities, options and the key barriers to maritime decarbonisation. Secondly, the report examines the IMO regulations which aim to incentivize the implementation of energy efficiency measures and technologies to improve energy efficiency of ships. Thirdly, the report explores energy efficiency technologies and practices in detail, introducing each technology, the energy saving potential of the technology, the maturity of the technology and the current deployment of the technology.

The 1st section provides an overview of the decarbonisation of the maritime sector and summarises the numerous opportunities for reducing emissions and improving the energy efficiency. The shift towards more sustainable practices in maritime operations is essential for mitigating climate change, reducing pollution and improving global health. The role of energy efficiency reduces the amount of energy required to propel or power the systems of a vessel or operate a port which ultimately services the vessel. Reducing the energy used will reduce emissions, such as carbon dioxide, methane, sulfur or particulate matter, among others. This drive for energy efficiency creates significant opportunities for technological advancement and economic growth, as well as economic benefits due to using less fuel there are wider economic benefits such as economic and investment growth of innovative companies and investments. Furthermore, the maritime sector relies heavily on other sectors such as other transport modes, agriculture, energy and forestry, sectors which will all have a role to play in the wider sustainable decarbonisation efforts.

The EEDI and EEXI require the implementation of sustainable energy efficient technologies on vessels. Broadly technological efficiency measures include vessel propulsion, vessel auxiliary power, waste heat recovery, improved hull design, antifouling and low drag coatings, and propeller and rudder devices. Operational measures such as the optimisation of routing, slow steaming, weather routing and just-in-time arrival while ensuring proper ballast and draft of the vessel can all significantly improve energy efficiency and therefore lower fuel usage. Port

efficiency savings can be achieved through efficient operations and the implementation of improved infrastructure, for example a 5G private network. Digitisation and smart shipping, using data, analytics, automation, and smart energy management systems will play significant roles in improving energy efficiency.

Electrification of both vessels and ports will allow for the elimination of local emissions and upstream emissions using renewable energy. These technologies are discussed in section three of the report, also hybrid systems using a combination of electrical systems with fossil fuel power sources can provide a transition to improved efficiency and reduced emissions.

The decarbonisation of the maritime sector cannot be achieved through energy efficiency alone, this will require the switching from traditional fuels, such as heavy fuel oil or LNG to alternative fuels like hydrogen, ammonia, methanol and biofuels. Furthermore, carbon capture and storage will play a role in capturing CO₂ but this faces obstacles such as space, cost, energy demand and storage; these obstacles are not unique to the maritime sector. These measures are not discussed in detail within this report since they are not directly energy efficiency measures.

The evidence collected indicates that a combination of operational measures, technological implementation and alternative fuels can achieve significant short-term GHG reductions in the shipping industry for existing and new vessels. The effectiveness of these measures varies significantly by vessel type and operations, for example a cruise liner is very different to a bulk carrier and so improving its energy efficiency will be significantly different in application. Wide adoption will require local policies to ensure compliance with the IMO framework and further incentives for ports to decarbonise too.

There is a vast amount of international literature available, including academic papers, reports, articles, sales brochures and policy document, such as those made available by governments or the IMO. Real world peer reviewed data of efficiency improvements are largely lacking and so this report attempts to establish an efficiency range and a consensus from various sources. Uptake data is also hard to establish for many of the technologies, often relying on press releases and company websites, this alongside costings are almost always commercially sensitive, nevertheless, this report has attempted to draw conclusions about each technology. It should be noted that multiple technologies or operational measures are often applied together and so they are unlikely to exist in isolation and so the actual efficiency improvement achieved will be a complex union.

The 2nd section of this report explores the IMO regulatory framework (CII, EEXI EEDI, and the SEEMP) and discusses the issues reported within the literature. The CII is primarily concerned with optimising operational measures for efficiency. Some shipping companies are actively making smart decisions to ensure they do not arrive at port too early and so spend significant amount of time at anchor. Through just-in-time arrival, weather routing and speed optimisation, significant fuel savings can be made. Not all shipping agreements, between the

owners and charterers or customers allow for this due to the nature of maritime contracts, historically choosing the 'best speed' and wait mentality. Bulk carriers for instance may not have sold the cargo before they embark on a voyage, so instead may sail fast to the region and then wait at anchor to sell their goods when the price is right. For this reason, a single 'one size fits all' approach is not able to provide the right incentives for all vessel types to optimise for energy efficiency and companies can simply factor in the additional costs of sailing fast and pass it onto the customer.

The CII aims to reflect the operational profile of a vessel, but its calculation method has drawn significant criticism within the maritime industry. One key issue is that the CII penalises vessels with irregular operational patterns, operating outside of the normal envelope, such as those that spend extended periods in port or at anchor due to their operational nature — like bulk carriers, tankers, and ferries — making it challenging for them to meet targets. By applying the CII uniformly across all ship types and regions, the calculation overlooks the unique challenges faced by different sectors, leading to a commercially unfair environment. Since the CII is strongly tied to a vessel's operational profile, it may not incentivise the adoption of sustainable technologies. In fact, even highly advanced, low-emission vessels could receive a non-compliant CII rating, and identical ship types could have vastly different CII scores purely based on their operational patterns. Additionally, the CII formula does not always accurately reflect actual emissions, particularly under varying factors such as weather, loading, or ballast condition. The calculation assumes ideal conditions, penalising vessels operating in less favourable loading conditions and sea states. A more detailed analysis of the literature on CII, EEXI, and EEDI is presented in Section 2.

This report collates extensive information to provide an overview of maritime decarbonisation including a review of IMO's initiatives and an analysis of measures to improving energy efficiency in the maritime sector. The report includes over 200 references, with thousands of sources reviewed and processed. Overall, the CII, EEXI and EEDI are key drivers of change, aimed at reducing GHG emissions and pollution from vessels and ports. To support these goals, a wide range of technologies and operational measures are available which have the potential to make significant energy savings.

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Our Partnerships. Funded by the Engineering and Physical Science Research Council, the Department for Transport, collaborating universities and industry, the UK National Clean Maritime Research Hub (UK-MaRes Hub) is a consortium of 13 universities, led by Durham University in collaboration with the universities of Aston, Birmingham, Brighton, City, Cranfield, Liverpool, Newcastle, Nottingham, Sheffield, Solent Southampton, St Andrews and Ulster.

We are also supported in this endeavour by over 70 industrial, civic and international partners.

Our Vision is to go beyond conventional marine engineering and naval architecture to create a pioneering research hub, providing technically, environmentally, socially and economically informed pathways to decarbonise the maritime sector.

Our Research is focused on 5 key themes:

- Marine fuel scale-up and safety
- Power and propulsion systems
- Port and vessel support infrastructure
- Vessel design and efficiency
- Digitalisation, maritime operations and finance

Contents

1	Maritime decarbonisation	14
1.1	Economic opportunities	14
1.2	Decarbonisation Options.....	15
1.3	Collaboration.....	19
1.4	Key barriers to increasing energy efficiency	20
2	IMO regulations	22
2.1	Strategies.....	22
2.2	The Energy Efficiency Design Index.....	23
2.3	Energy Efficiency Existing Ship index	23
2.4	Carbon Intensity Indicator.....	23
2.5	The Ship Energy Efficiency Management Plan.....	24
2.6	EEDI/EEXI/CII/SEEMP observations.....	24
2.6.1	The way forwards.....	25
3	GHG abatement measures that can improve energy efficiency in the maritime sector	28
4	Vessel propulsion and power measures.....	32
4.1	Propulsion technology - Wind Assisted Propulsion Systems	32
4.1.1	Explanation of measure	33
4.1.2	GHG emission reduction potential	34
4.1.3	Status of technology	34
4.1.4	Technology application - Size of vessel, type of vessel and profile.....	35
4.1.5	Status of deployment and barriers to deployment	35
4.2	Propulsion and power technology - Battery electric propulsion	36
4.2.1	GHG emission reduction potential	37
4.2.2	Status of technology	37
4.2.3	Technology application - Size of vessel, type of vessel and profile.....	37
4.2.4	Status of deployment and barriers to deployment	38
4.3	Propulsion and power technology – Hybrid propulsion and energy storage systems	39
4.3.1	GHG emission reduction potential	40
4.3.2	Status of technology	40

4.3.3	Technology application - Size of vessel, type of vessel and profile	40
4.3.4	Status of deployment and barriers to deployment	41
4.4	Propulsion and Power technology - Fuel cell.....	42
4.4.1	Explanation of measure	42
4.4.2	GHG emission reduction potential	43
4.4.3	Technology application - Size of vessel, type of vessel and profile.....	44
4.4.4	Status of technology	44
4.4.5	Status of deployment and barriers to deployment	45
4.5	Power technology - Solar power onboard shipping.....	47
4.5.1	Explanation of measure	47
4.5.2	GHG emission reduction potential	48
4.5.3	Technology application - Size of vessel, type of vessel and profile.....	49
4.5.4	Status of technology	49
4.5.5	Status of deployment and barriers to deployment	49
5	Waste heat recovery.....	50
5.1	Waste heat recovery - Organic Rankine Cycle waste heat recovery	50
5.1.1	Explanation of measure	50
5.1.2	GHG emission reduction potential	51
5.1.3	Technology application - Size of vessel, type of vessel and profile.....	51
5.1.4	Status of technology	51
5.1.5	Status of deployment and barriers to deployment	51
5.2	Waste heat recovery - Steam waste heat recovery	54
5.2.1	Explanation of Measure	54
5.2.2	GHG reduction potential.....	54
5.2.3	Status of Technology.....	55
5.2.4	Technology application - Size of vessel, type of vessel and profile.....	55
5.2.5	Status of deployment and barriers to deployment	55
6	Ship hull measures	55
6.1	Ship hull - Block coefficient reduction	55
6.1.1	Explanation of measure	55
6.1.2	GHG emission reduction potential	56
6.1.3	Technology application - Size of vessel, type of vessel and profile.....	56

6.1.4	Status of technology	56
6.1.5	Status of deployment and barriers to deployment	56
6.2	Ship hull - Hull management of coatings	57
6.2.1	Explanation of measure	57
6.2.2	GHG emission reduction potential	59
6.2.3	Technology application - Size of vessel, type of vessel and profile	60
6.2.4	Status of technology	60
6.2.5	Status of deployment and barriers to deployment	61
6.3	Ship hull - Air lubrication system (ALS)	61
6.3.1	Explanation of Measure	61
6.3.2	GHG emission reduction potential	62
6.3.3	Technology application - Size of vessel, type of vessel and profile	62
6.3.4	Status of technology	63
6.3.5	Status of deployment and barriers to deployment	63
7	Propeller and rudder flow conditioning devices	63
7.1	Propeller technology – Pre-swirl propeller ducts	63
7.1.1	Explanation of measure	63
7.1.2	GHG emission reduction potential	63
7.1.3	Technology application - Size of vessel, type of vessel and profile	64
7.1.4	Status of technology	64
7.1.5	Status of deployment and barriers to deployment	64
7.2	Propeller technology – Contra rotating propellers	64
7.2.1	Explanation of measure	64
7.2.2	GHG emission reduction potential	64
7.2.3	Technology application - Size of vessel, type of vessel and profile	64
7.2.4	Status of technology	64
7.2.5	Status of deployment and barriers to deployment	65
7.3	Propeller technology – Vane wheels	65
7.3.1	Explanation of measure	65
7.3.2	GHG emission reduction potential	65
7.3.3	Technology application - Size of vessel, type of vessel and profile	65
7.3.4	Status of technology	65

7.3.5	Status of deployment and barriers to deployment	65
7.4	Propeller technology - Boss cap fin	65
7.4.1	Explanation of measure	65
7.4.2	GHG emission reduction potential	66
7.4.3	Technology application - Size of vessel, type of vessel and profile	66
7.4.4	Status of technology	66
7.4.5	Status of deployment and barriers to deployment	66
7.5	Propeller and rudder technology - Rudder bulb	66
7.5.1	Explanation of measure	66
7.5.2	GHG emission reduction potential	66
7.5.3	Technology application - Size of vessel, type of vessel and profile	67
7.5.4	Status of technology	67
7.5.5	Status of deployment and barriers to deployment	67
7.6	Rudder technology - Twisted rudders	67
7.6.1	Explanation of measure	67
7.6.2	GHG emission reduction potential	67
7.6.3	Technology application - Size of vessel, type of vessel and profile	67
7.6.4	Status of technology	67
7.6.5	Status of deployment and barriers to deployment	68
8	Operational measures	68
8.1	Operational - Speed optimisation	68
8.1.1	Explanation of measure	68
8.1.2	GHG emission reduction potential	69
8.1.3	Technology application - Size of vessel, type of vessel and profile	69
8.1.4	Status of technology	69
8.1.5	Status of deployment and barriers to deployment	70
8.2	Operational - Weather routing and voyage optimisation	70
8.2.1	GHG emission reduction potential	71
8.2.2	Status of technology	71
8.2.3	Technology application - Size of vessel, type of vessel and profile	71
8.2.4	Status of deployment and barriers to deployment	72
8.3	Operational - Derating of main propulsion engines	72

8.3.1	Explanation of measure	72
8.3.2	GHG emission reduction potential	73
8.3.3	Technology application - Size of vessel, type of vessel and profile	73
8.3.4	Status of technology	73
8.3.5	Status of deployment and barriers to deployment	73
8.4	Operational - Ship ballast - Trim optimisation	74
8.4.1	Explanation of measure	74
8.4.2	GHG emission reduction potential	74
8.4.3	Technology application - Size of vessel, type of vessel and profile	75
8.4.4	Status of technology	75
8.4.5	Status of deployment and barriers to deployment	75
9	GHG abatement measures whilst vessels are in port.....	75
9.1	Port - Hull management (hull cleaning and propellor polishing).....	75
9.1.1	Explanation of measure	75
9.1.2	GHG emission reduction potential	76
9.1.3	Status of technology	76
9.1.4	Technology application - Size of vessel, type of vessel and profile	77
9.1.5	Status of deployment and barriers to deployment	78
9.2	Port - Shore-to-ship power or cold ironing (CI).....	79
9.2.1	Explanation of measure	79
9.2.2	GHG emission reduction potential	79
9.2.3	Technology application - Size of vessel, type of vessel and profile	80
9.2.4	Status of technology	81
9.2.5	Status of deployment and barriers to deployment	81
10	Conclusions	82
11	References	84

List of Abbreviations

AALS	Air lubrication systems
AER	Annual efficiency ratio
AFC	Alkaline fuel cell
ALDR	Air layer drag reduction
ALS	Air lubrication systems
AUV	Autonomous underwater vehicle
BCF	Boss cap fin
BDR	Bubble drag reduction
BEP	Battery electric propulsion
BESS	Battery energy storage system
Bi ₂ WO ₆	Bismuth Tungstate
BWTS	Ballast water treatment systems
CapEx	Capital expenditure
CCS	Carbon capture and storage
CDP	Copolymer depletion paint
CI	Cold ironing
CII	Carbon Intensity Indicator
CO ₂	Carbon dioxide
CO ₂ e	Carbon dioxide equivalent
CPC	Copolymer coating
CRL	Commercial readiness level
DWT	Deadweight tonnage
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Index
EEXI	Energy Efficiency Existing Ship Index
EGCS	Exhaust gas cleaning system
EGR	Exhaust gas recirculation
ESS	Energy storage system
EU	European Union
EU ETS	European Union Emissions Trading Scheme
FRC	Fouling-release coatings
FREMM	European multi-purpose frigate
GHG	Greenhouse gases
GT	Gross tonnage
H ₂	Hydrogen
H ₂ O	Water
HES	Hybrid-electric systems
HRSG	Heat recovery steam generator
IC	Internal combustion
IHO	International Hydrographic Organisation

IMO	International Maritime Organization
JITA	Just-in-time arrivals
LNG	Liquid natural gas
MCFC	Molten carbonate fuel cell
MEPC	Marine Environment Protection Committee
CH ₄	Methane
N ₂	Nitrogen
NCR	Normal continuous rating
NG	Natural gas
NO _x	Nitrogen oxides
ORC	Organic Rankine cycle
PAFC	Phosphoric acid fuel cell
PAHS	Polycyclic aromatic hydrocarbons
Pax	Passenger vessels
PCDR	Partial cavity drag reduction
PEMFC	Proton exchange membrane fuel cell
PM	particulate matter (PM).
PTH	Power-take-home
PTI	Power-take-in
PTO	Power take-off
PV	Solar photovoltaic
Ro-Pax	Roll-on/roll-off passenger
Ro-Ro	Roll-on/roll-off
ROV	Remotely operated vehicle
RTA	Requested time of arrival
S2SP	Shore-to-ship power
SCR	Selective catalytic reduction
SEEMP	Ship Energy Efficiency Management Plan
SLIPS	Slippery liquid-infused porous surface
SOFC	Solid oxide fuel cell
SO _x	Sulfur oxides
SPC	Self-polishing coatings
SRC	Steam Rankine cycle
TiO ₂	Titanium dioxide
TRL	Technology readiness level
UK	United Kingdom
UK-MaRes Hub	UK National Clean Maritime Research Hub
USA	United States of America
WAPS	Wind assisted propulsion systems
WHR	Waste heat recovery

1 Maritime decarbonisation

The transition towards more sustainable practices in maritime operations is critical to mitigating climate change, reducing pollution and promoting global health. Additionally, this shift presents substantial opportunities for technological innovation and economic growth. As such there is a large volume of worldwide research activity into improving the energy efficiency of ships and associated industries [2], ports, energy and supply chains, amongst others, which all need decarbonising [3-5]. Clean air, clean water and economic development are the ultimate goals.

Emissions - Maritime transport is a significant source of CO₂ emissions, contributing to global warming. Vessels also emit sulfur oxides (SOx), nitrogen oxides (NOx) and particulate matter (PM), which contribute to local air pollution and have adverse effects on the environment and human health [1, 6-14]. Detailed estimates of maritime emissions were published by the IMO in 2020, which stated that in 2018 shipping was responsible for 2.89% of global anthropogenic emissions [1]. In 2022, Transport and Environment (T&E) estimated that cruise ships emitted 4.4 times more SOx than all the cars in Europe [15].

Marine ecosystems - Sustainable shipping practices help protect marine biodiversity by reducing oil spills, ballast water discharge and underwater noise pollution, which are harmful to marine life. Measures such as hull cleaning or ballast water treatment systems (BWTS) are key to reduce the spread of invasive species which could otherwise devastate the local marine environment. Regulations, such as the IMO Ballast Water Management Convention, and others, aim to prevent damage to ecosystems.

Air quality and toxins - Reducing emissions from vessels improves air quality and reduced environmental toxins, particularly in port cities and coastal regions, leading to lower rates of associated diseases. [6, 16-20].

1.1 Economic opportunities

Along with the environmental benefits, clean air and clean water, there are economic opportunities as well [21-23].

Energy-efficient technologies can lead to significant savings on fuel costs over time. For example, wind-assisted propulsion [24], solar panels and advanced hull designs are contributing to reduced fuel consumption [25].

Innovation and technology - The push for decarbonisation is driving innovation in vessel technologies and adoption of existing technologies from other sectors. This can position companies and countries at the forefront of maritime technology, creating new business opportunities and high-tech jobs. [21, 26-28]

Commercial and investment growth. The maritime industry's transition will open new business, markets and investment opportunities. Companies that pioneer green technologies will capitalise on their expertise through new revenue opportunities [21].

Societal benefits: The long-term sustainability of the global supply chain relies on the decarbonisation of the maritime sector, for long-term availability of goods and resources. Furthermore, there is increasingly consumer and other stakeholder demand for companies to enhance their reputation through decarbonisation [29].

Wider stakeholders. Alongside the direct port and maritime operations, there are wider sector coupling opportunities, other transport modes, agriculture, energy industry, supply and forestry all have a role to play [30].

Achieving the IMO level of maritime decarbonisation required by 2030 necessitates urgent action that involves deploying multiple technologies and implementing operational changes. No single technology can meet the IMO's 2030 goal on its own, thus, a combination of strategies is essential [31]. Improving energy efficiency of existing assets alone will not be enough to reach the IMO's goals; commercially viable zero or near-zero GHG emission vessels must be available well before 2050 [5, 32, 33]. There are currently insufficient incentives to stimulate investment in vessels with higher energy efficiency [34]

The economic and business models of the maritime industry can be complex and so sharing the responsibility of decarbonising can also be complex. Typically voyages will be chartered by a charter company from a ship owner. There is a complex relationship between owners and charter companies and there are different kinds of charter also. Time charter is where the company leases the vessel for a period and can undertake multiple voyages within that timeframe, or voyage charter where a company leases the vessel for a specific voyage. The CII regulation binds shipowners to maintain efficient operations and comply with emission standards [35]. Although the ship owner is responsible for the IMO compliance the operation may be governed by the charter party agreement and so ultimately, they must balance their contractual requirements with regulatory requirements. Ports also have a role to play since inefficient port operations and long stop overs can reduce the CII of a vessel outside of the owner's control.

1.2 Decarbonisation Options

There are several key decarbonisation options which are being considered, these should not be seen as independent but instead there are typically interdependencies between technologies, value chains and users. As such, all decarbonisation options should be looked at holistically [25, 36-40, 41, 42-46].

The following is a high-level grouping of decarbonising options:

Fuel switching - Alternative Fuels - zero or near-zero GHG emission fuels such as hydrogen, ammonia, methanol and biofuels can significantly reduce GHG emissions.

However, the infrastructure is not yet at the appropriate scale for widespread deployment [47-49]. According to T&E [50], 4% of European shipping could run on e-fuels by 2030, but this is at risk because fuel suppliers fear a lack of demand. The take up of e-fuels requires a clear signal of demand to provide certainty for commercialisation at scale [32, 51]. Going forwards clarity is required on a number of sustainable aspects of the regulatory frameworks, both from the IMO and governments, such as which pollutants will be regulated, whether tank-to-wake (TtW) and well-to-tank (WtT) will be accounted for, how the sustainability of the feedstocks of the fuel will be assessed, how e-fuel carbon will be accounted for, how CCS will be accounted for and what will be the incentives there are to switch; these are uncertainties which need addressing. Ultimately e-fuels are expected to be more expensive than existing fuels and so there needs to be incentives to switch, in the short-term increased costs and uncertainty are barriers but over the longer term with clear demand then the increased costs can be planned for.

When switching to different fuels care should be taken not to increase emissions indirectly, for example through methane slip [52]. It has been reported that switching to LNG, which is primarily methane, may actually increase global warming when considering emissions over the full life cycle [15, 53]. This is because methane is a potent greenhouse gas and current engine technology used on ships suffer from methane slip which effectively releases methane into the atmosphere through the exhaust [53, 54]. LNG emits approximately 25% less CO₂ than conventional marine fuels in providing the same amount of propulsive power [53]. However, it has been estimated that over a 20-year period LNG engines emit 4% more GHG emissions than using marine gas oil when considering the full life-cycle. This is because over a 20-year period the released CH₄ traps 86 times more heat in the atmosphere than the same amount of CO₂ over the same 20-year period, and so overall depending on the engine technology the burning of LNG may not have any climate benefit [53]. The Intergovernmental Panel on Climate Change (IPCC) [55] provide standards for the global warming potential of different GHG's over two time frames, the 100-year global warming potential of CH₄ is 36 times that of CO₂ and the 20-year period is 86 times that of CO₂. As an aside, the cruise ship MS Iona was calculated by T&E to emitted as much methane as 10,500 cows over a year [15]. This report is primarily aimed at energy efficiency measures and so fuel switching is not covered in detail.

Carbon capture and storage (CCS) – Similar to other sectors, CCS is an emerging set of technologies that have the potential to play a significant role in maritime decarbonisation. It involves post-combustion capturing CO₂ emissions from the power system exhaust and onboard storing the captured CO₂. Challenges include the space and weight restriction, energy demand, economic viability, storage capacity, leakage risks, regulatory support and the infrastructure to permanently store the captured CO₂ [56]. Research is exploring the use of molten carbonate fuel cell technology in an

integrated power and CO₂ capture system. This report is primarily aimed at energy efficiency measures and so CCS is not covered in detail within this report.

Energy efficiency measures and devices – The drive to reduce energy demand is not only applicable to new vessels but also to retrofitting and upgrading existing vessels [46]. Such measures include:

- **Propulsion systems** - Upgrading to more efficient propulsion systems, such as engine modifications or the additional use of wind-assisted technologies, such as Flettner rotors, sails or kites [24, 57].
- **Hull** – Reducing drag has a direct correlation with fuel efficiency. This could be achieved through improved hull design, coatings and cleaning. However, it should be noted that hull design innovation has been ongoing for many decades. The scope for significant improvements may therefore be limited. Existing vessels can be retrofitted with features such as modified bulbous bows or stern flaps, and advanced hull coatings reduce friction and biofouling, leading to lower fuel consumption. The hull should in any case be frequently maintained through inspection and cleaning, possibly using in-water robotic systems, to maintain minimum levels of drag [58-60].
- **Propeller enhancements** - Secondary devices, such as vane wheels, fins or ducts around the propeller can improve hydrodynamic performance and enhance propulsion efficiency.
- **Thermal energy recovery and utilisation** – Low temperature heat is wasted energy from all power systems. Implementing systems that can capture waste heat and use it will improve overall efficiency. This may be by using the heat for another purpose such as heating, converting the heat to a more useful temperature, or conversion to a different form of energy. Waste heat recovery is only useful in a situation where the energy can be usefully and economically used, for example in refrigeration and air conditioning, heating, power production, or desalination [61].

Alternative energy integration – The integration of solar photovoltaic cells, heat pumps, solar thermal or wind driven systems are suitable for hotel-load applications [24, 62].

Operational optimisation – Efficiency measures are not just technological, changes to the operation of the vessel can also have a significant effect on fuel consumption [63]. This optimisation is very dependent on the type of vessel and voyage [64]. For example, large container ships can travel long distances between ports, whereas Ro-Ro ferries have much shorter duration journeys [65]. Operational optimisation and decision making for freight movement is a complex problem of vessel planning, port scheduling, costing, routing, weather, terms of charter party and many more elements [66].

- **Voyage planning** - Voyage optimisation involves continuously updating the optimal route based on weather forecasts, tides and other external factors, such as shipping lanes. Sometimes the shortest route is not always the most energy efficient.
- **Speed management** - Slow steaming means operating ships at lower speed to save fuel. For example, a 13% speed reduction could yield almost a 40% daily fuel saving. This reduces emissions but increases voyage time which may have some operational challenges and a reduction in cargo throughput [31, 35].

Port infrastructure and operations

- **Just-in-time arrival** – Reducing waiting times in ports or at anchor through coordinating arrival times mean a reduction of unnecessary fuel consumption [67].
- **Port operations** - Efficient ports are essential for achieving maritime decarbonization goals. Ports can significantly reduce their environmental footprint through technical and operational measures [3, 68-72]. An efficient port is one which maximises its capacity, minimises delays, and reduces costs while ensuring safety and environmental compliance.
- **Efficient port management** – Similarly to just-in-time arrival [67], efficient port management optimises operations to reduce freight movements and the amount of time a vessel is in port.
- **Reducing Congestion and Idle Ships** – Ships waiting in port for port services still require some power to operate. Meaning ships which are waiting release GHG emissions which could be avoided through planning.
- **Onshore power supply** – A vessel alongside in port still requires on board power for systems other than propulsion. Ships generally use onboard engines to provide this power which increases GHG emissions and contribute to significant local air pollution. Cold ironing allows ships to connect to a shore-based cleaner electrical supply and for the engines to be shut down. Cost of infrastructure is a major factor, and electricity capacity is a significant challenge to supply the necessary power without impacting on local grids.
- **Energy efficiency** – Electrification of equipment, energy management systems, infrastructure investments, renewable energy (e.g. wind and solar) energy storage systems and reducing building energy demand are all important initiatives.
- **Incentives** – The incentives for ports to adopt energy efficiency measures is driven by local governance. Incentives are needed for ports to act, especially since many of the actions are likely to increase port fees [28, 72, 73].

Digitalisation and smart shipping – These technologies leverage data, automation and advanced analytics, to enable optimised operations and improved energy efficiency through

better decision making [3].. As these technologies evolve, they will play an increasingly significant part using:

- Data analytics and machine learning
- Automation and autonomous vessels
- Energy management systems
- Digital twins
- Efficient supply chain and logistics

When retrofitting solutions, the choice of which energy saving technologies and operational measures to implement requires careful data driven decision making [74]. There is a vast amount of literature which analyses these technologies and the potential benefits they have on efficiency [6, 16, 22, 23, 25, 31, 43, 46, 73-77].

1.3 Collaboration

The rapid decarbonisation of the maritime industry will require a collaborative approach involving regulators, industry, researchers, financial institutions and the community at large.

Technology - Technological Innovation and rollout will require collaboration across stakeholders. Including collaborative R&D efforts between maritime companies and research institutions. Sharing of best practice and tackling common challenges together.

Regulatory frameworks and policies - Regulations via the IMO play a crucial role in setting global standards. Collaboration among nations to shape the regulations, adhere to and implement these standards is crucial. Furthermore, standardised reporting and monitoring of emissions will ensure transparency and accountability across the maritime sector, as well as monitoring of progress towards the IMO decarbonisation goals. National policies of individual countries or regions need to develop and align their policies with international regulations, and to support innovation or projects leading to large scale development [78, 79].

European Union policy - FuelEU Maritime regulation will be implemented from 2025 and sets requirements for the well-to-wake GHG emissions of fuels used on board ships over 5,000 GT. The EU has adopted FuelEU Maritime to increase the share of renewable and low-carbon fuels in maritime transport and to adopt green technologies. There is also a requirement to connect to onshore power supplies at major EU ports from 2030, when at berth for more than two hours, and this will be extended to all ports from 2035.

Trading Schemes – Emissions trading schemes aim to limit the emissions of specific pollutants over an area and allows companies to trade emissions rights within that area. In the EU this is called the European Union Emissions Trading Scheme (EU ETS)

and it was extended to the maritime sector in 2024. It is the main tool to control GHG emissions used by the EU.

Infrastructure - Upgrading and investment in facilities is required to support new technologies. For example, upgrading port infrastructure for electrification, low carbon fuel and shore power, will require coordinated efforts between port authorities, shipping companies and government bodies. The availability of alternative fuels involves collaboration across the entire supply chain, from fuel producers to end users, with government support to de-risk these activities. Investing into new technologies and infrastructure projects requires a supportive environment for innovation and investment while minimising risk for stakeholders, for example reducing uncertainty can minimise the financial, regulatory and operational risk associated with a project in a rapidly changing environment such as the decarbonisation of a sector.

Financial investment - Funding mechanisms, incentives, market-based measures [80] and subsidies are all required to support green initiatives. Financial incentives for companies investing in sustainable technologies and practices can drive faster adoption [78, 81].

Training and awareness - Skill development for new technologies and sustainable practices will enable them to be implemented. In addition, collaboration and engagement with local communities and stakeholders to address the social and environmental impacts of maritime activities will be beneficial. This includes awareness campaigns on the importance, regulatory requirements and benefits of decarbonisation within the maritime sector.

Green shipping corridors - A green shipping corridor is a designated shipping route between two or more ports where stakeholders collaborate to reduce GHG emissions and promote sustainable shipping practices. These corridors aim to showcase and implement innovative technologies, fuels and operational strategies that contribute to lower emissions and enhanced environmental performance, therefore they are an important near-term strategy. Green shipping corridors represent a significant step towards sustainable maritime operations but come with added costs that need to be managed collaboratively by various stakeholders, including shipowners, port authorities, governments and international organisations. It is also noted that they can potentially negatively impact international trade competitiveness, especially between developed and developing countries [82].

1.4 Key barriers to increasing energy efficiency

The barriers to implementing technological solutions within the maritime sector are reflected by other industrial sectors. In addition, the maritime sector is very much global in nature and

so requires an international regulatory effort by the IMO and certificating bodies. Understanding these barriers is crucial in the development of strategies to overcome them.

Conflicting interests - In the chartering market, a key issue arises where the main beneficiary of the savings associated with low-carbon technologies (the charterer, who hires the vessel), is often not the party that has invested in these technologies. This creates a disconnect between the costs and benefits of implementing energy-efficient solutions, complicating efforts to reduce emissions and improve operational efficiency [83]. Therefore, operational measures like slow steaming are the most frequently implemented measure because it is directly under the control of the charter company.

Commercial decisions – There may be commercial decisions made which prioritise profit over energy efficiency. Which agency makes the decisions varies between sectors but in general agency for energy efficiency is highly networked between contrasting requirements and shipping departments [84]. Achieving significant energy efficiency will require sociotechnical change affecting all stakeholders of the shipping sector [85].

Long asset lifespan - Ships have long operational lifespans (25 to 30 years), making a slow transition to new vessels while older vessels remain in service. For this reason, in the near-term retrofitting of existing ships is extremely important. However, retrofitting existing vessels with new technologies may be less feasible, less effective, or more expensive than implementing them in newly designed and built vessels.

Regulatory and policy – In a global sector, inconsistent regulation and standards are unhelpful. Variations in standards and regulation cause uncertainty, extra work and complicate compliance. Delays or gaps in policy measures can slow down the adoption of decarbonisation technologies through uncertainty of the requirements.

High capital costs and economic competitiveness – Substantial capital investment is required for new emerging technologies. These technologies will become cheaper in the long term as the technology matures. Shipping companies often operate on small margins, making it difficult to justify the upfront costs without clear incentives. Financing decarbonisation projects may be seen as a risk or the payback periods may be too long so shipping companies, especially smaller ones, may struggle to secure the necessary finance. Concern over economic competitiveness may prevent companies from adopting new measures, especially if competitors do not adopt similar measures; all companies need to move together. There are studies that have been undertaken which show efficiency measures to be profitable [86].

Technological maturity and scalability - Many decarbonisation technologies are still in the early stages of development and not yet commercially viable at scale. Scaling

up new technologies to be used at the global scale presents significant infrastructure, technical and logistical challenges.

Infrastructure - There is a lack of established supply chains for many of the technologies, especially low carbon marine fuels. Alongside the supply chain, port infrastructure will need to be equipped to support new technologies, such as fuel bunkering facilities and shore power capacity.

Operation and safety - Technologies must meet and demonstrate safety and reliability standards. These can be difficult to demonstrate for insurance and achieve in the harsh maritime environment. Furthermore, the safety of the work force, the public and the environment must be paramount.

Integration with existing systems - Retrofitting of new technology on vessels can have technical challenges as vessels often have unique complex systems.

2 IMO regulations

The IMO vision to reduce greenhouse gas emissions was first introduced in MEPC 40 through resolution 8 in 1997. 12 years later in 2009, technical and operational measures were proposed to assess the energy efficiency of ships, including the Energy Efficiency Design Index (EEDI) [87], the Ship Energy Efficiency Management Plan (SEEMP) [88] and the Energy Efficiency Operational Index (EEOI) [89].

2.1 Strategies

Between 2012 and 2018, there was a 9.6% increase in GHG emissions from shipping, mostly due to an increase in total trade, increasing the need for significant improvements in maritime energy efficiency [1]. The IMO set ambitious targets in 2020 to achieve a reduction in carbon intensity by at least 40% by 2030 and a 50% reduction in total GHG emissions by 2050, compared to 2008.

In 2023 the IMO further strengthened these targets, including agreeing to reach net-zero GHG emissions from international shipping by or around, i.e. close to, 2050, a commitment to ensure an uptake of alternative zero and near-zero GHG technologies, fuels and/or energy sources by 2030, as well as indicative checkpoints to reduce the total annual GHG emissions from international shipping by at least 20%, but striving for 30%, by 2030, and by at least 70%, striving for 80%, by 2040 (compared to 2008). The 2023 IMO GHG Strategy also envisages a reduction in carbon intensity of international shipping (to reduce CO₂ emissions per transport work), as an average across international shipping, by at least 40% by 2030 (compared to 2008).

The 2030 ambition means that the bulk of energy efficiency measures must rely on existing fleet technologies which are immediately scalable. Longer term options applicable to new vessels or not yet scalable technologies such as fuel switching to hydrogen, ammonia or methanol are longer term prospects beyond 2030. For this reason, the Ship SEEMP, Energy Efficiency Existing Ship Index (EEXI) and the annual operational Carbon Intensity Indicator (CII) are designed to improve the operational energy efficiency of existing ships.

At MEPC 80, the committee agreed on a plan for reviewing the calculation of the short-term GHG reduction measures, the CII and EEXI. There is a data-gathering phase until MEPC 82 in autumn 2024, the data will be analysed, and any amendments to the measures will be ready by MEPC 83 in summer 2025.

It should be noted that without switching to low carbon fuels, meeting the IMO short term emissions reduction target will be extremely challenging [40].

2.2 The Energy Efficiency Design Index

The Energy Efficiency Design Index (EEDI) is applicable to newbuilds and came into effect on January 1, 2013. It requires new ship designs to meet or exceed a specified EEDI value to ensure energy efficiency and reduced associated CO₂ emissions. The required EEDI value varies by ship type/size and is based on historical data, reflecting the average efficiency of ships built between 1999 and 2009. These EEDI reference lines are regularly reviewed and updated to incorporate advancements in technology and to push for greater reductions in emissions. They are crucial for evaluating the energy efficiency of ships, ensuring that new designs continue to improve in terms of fuel efficiency and emission reductions. The guidelines for calculating and verifying the attained EEDI, including the reference lines, are detailed in [90].

2.3 Energy Efficiency Existing Ship index

The Energy Efficiency Existing Ship index (EEXI) is an IMO regulation to improve the energy efficiency of existing ships. The goal is to ensure that older vessels also contribute to the reduction of GHG emissions through improvements and investment in onboard technologies. It complements the EEDI, which applies to new ships. The EEXI is required to be calculated for ships of more than 400 gross tonnage.

2.4 Carbon Intensity Indicator

At the same time as the EEXI, an annual operational Carbon Intensity Indicator (CII) aims to improve the energy efficiency of the ships during operations. It is a dynamic rating which operators can significantly improve through voyage optimisation. The CII is applied to ships with more than 5,000 gross tonnage and came into force on the 1st of January 2023. The CII gives a rating from 'A' to 'E', 'A' being the best. 'D' or 'E' ratings require improvement, in this case the SEEMP must be considered to re-evaluate the ship's performance and to provide the retrofit solutions to improve the CII rating. A ship which is rated 'D' for 3 consecutive years,

or 'E' for one year, is required to submit a corrective action plan but the incentive to act is left to administrations other than the IMO. Stakeholders, such as governments or port authorities, are urged to provide incentives for ships to have a CII compliance of 'A' or 'B' [91-94]. For example, there may be commercial implications if ships have a low CII and are unable to attract charterers, therefore incentivizing ships to upgrade their CII rating.

2.5 The Ship Energy Efficiency Management Plan

All ships of 400 gross tonnage and above, which engage in international voyages must develop and maintain a SEEMP on board. The SEEMP is a tool, which entered into force on the 1st January 2013, to help shipowners manage, and improve, the environmental performance of their ships in a cost-effective manner. The IMO provides guidelines and templates for the completion of the SEEMP and suggests suitable technologies. The SEEMP consists of 3 parts:

- Part I: Ship management plan to improve energy efficiency
- Part II: Ship fuel oil consumption data collection plan
- Part III: Ship operational carbon intensity plan

2.6 EEDI/EEXI/CII/SEEMP observations

There are many observations and proposed amendments to the EEDI, EEXI, CII and SEEMP in the public domain. This section summarises these. The observations have not been validated but the sources are all peer reviewed work.

- EEDI/EEXI thresholds are based on calm idealistic water conditions. It is suggested that IMO's EEDI/EEXI should in some way account for real sea conditions [95].
- The EEDI/EEXI does not consider speed, only the power of the engine(s). One observation is that this may lead ship designers to under power ships to be compliant with EEDI. The effect of this may be that the ship is less safe in bad weather and in their attempt to maintain course the ships engine(s) will need to operate at levels above optimum, and so this could lead to a real-world increase in GHG emissions [96].
- Underpowering the engine(s) and reducing the design speed, to be EEDI/EEXI compliant, may be an easy option and could shift the focus away from other energy efficient measures such as hull, engine, or propeller upgrades [96, 97].
- Compliant CII may be possible through operational initiatives only and so limiting the uptake of fuel-efficient technological initiatives. Energy Efficiency retrofits are capital expenditure (CapEx) intensive and often require dry docking, for this reason it is expected that owners will seek to improve CII through operational efficiency changes first. This may be undertaken on a fleet basis targeting an average of a 'C' grade. Operational changes include speed reduction, fuel reduction for non-propulsion energy needs, route optimisation and omitting certain ports, or swapping vessels between routes. Biofuels are also an attractive pathway as this means limited onboard changes [32].

- There is currently no incentive to obtain a CII higher than a grade 'C'.
- A good CII does not guarantee that a vessel is energy efficient [97].
 - The CII is based on deadweight and so does not directly reflect the vessel's efficiency in transporting cargo. Two vessels with similar deadweight, dimensions and installed equipment could have the same CII rating and Annual Efficiency Ratio (AER) but differ significantly in the amount of cargo they transport annually.
 - The current CII rating system can unintentionally encourage vessel operators to choose longer routes to avoid port waiting times, resulting in higher CO₂ emissions but lower CII values.
 - The current CII framework's uniform treatment of different CO₂ emission sources can lead to operational strategies that reduce idle emissions but increase overall CO₂ output.
 - The CII ratings are influenced by external factors such as port stays and weather conditions, which are beyond the direct control of vessel owners and operators, and so introduce uncertainty for the ship owner/operator.
- The CII is based on both operation and technology. Different types of vessels exhibit varying levels of operational efficiency, largely influenced by their cargo types, operational patterns and contractual obligations. Understanding these differences is crucial in identifying areas that require improvement and for maintaining competitiveness in the shipping market. Cargo vessels such as tankers, general cargo ships, gas carriers, LNG carriers, dry bulk carriers, and refrigerated cargo carriers can achieve higher CII levels through operating efficiency compared to other ship types. Vessels such as cruise ships, container ships, Ro-Ro ferries may have a weak operational efficiency due to the frequency of entering and leaving ports [65].
- Currently the regulations are focused on CO₂ emissions [37]. There is a case to extend the framework to include other emissions such as SO_x and NO_x.

2.6.1 The way forwards

The IMO frameworks have guided the global maritime industry to reduced GHG emissions. However, the short time scales are challenging and every opportunity must be taken to improve the framework to meet these ambitious targets [98]. Here are a number of summarised considerations from several peer reviewed sources:

- Adaptive strategies and technological investments will be essential to navigate the evolving regulatory landscape and ensure that efforts to comply with CII ratings lead to genuine environmental benefits [97].
- Data sharing. At the MEPC 80 meeting the IMO agreed to enhance data collection. This decision is widely welcomed as it paves the way for better regulatory development. Improvements can be made by increasing the granularity and the availability of the data and efforts in this direction should be prioritised. Fostering

transparency and collaboration will support the development of more effective and targeted regulations, benefiting the entire maritime sector and the environment [97].

- Ports and canals have a significant impact on vessel efficiency but are not currently regulated by the IMO.
- Current regulations must be met by the owner/operator only, meaning little incentive for the charterers, port or other stake holders to improve for CII compliance. New regulations could share responsibilities for emissions among different stakeholders, rather than solely penalising the vessel owner/operators [97].
- There is a case to shift focus from CO₂ emissions to energy consumption [97]. It is suggested the existing framework for energy efficiency measures could be aligned to the goals of reducing overall energy consumption rather than CO₂ emissions.
- Market-based measures to regulate emissions on a well-to-wake basis have been proposed which would encapsulate the wider energy efficiency. Well-to-wake means accounting for the emissions of the full life-cycle of the fuel, including the production, delivery, use on board power production. This would allow the industry to put more focus on reducing the energy demand of the fleet rather than a specific emission and encourage a transition to new fuels [97].
- The EEDI could be strengthened by enlarging the scope of emission types covered by the EEDI. This would help to increase GHG reduction rates [97].
- Monitoring of the CII. Monitoring and analysis of the implementation of the CII across the sector would allow for monitoring of any unintended consequences to overall CO₂ emissions. One notable example is that reducing speed will also reduce the cargo tonnage of the whole sector, prompting the introduction of additional vessels to meet demand, which could ultimately increase absolute emissions from the fleet. Also, until those new vessels are built, the reduced effective supply of the fleet can elevate freight rates. By carefully designing and regularly reviewing regulations, the maritime industry can avoid counterproductive outcomes and achieve its environmental goals more effectively [97].
- The exclusions and correction factors that have been agreed upon by IMO for calculation of the CII should be reviewed. This review should aim to determine whether these factors are necessary and if they might be influencing the mechanism's effectiveness [31, 97].
- Transparency and cooperation are important. All stakeholders should increase transparency and cooperation to optimise the CII equation. The equation can only be improved through industrially relevant data. This will likely require a regulatory push from the IMO [97].
- Strengthening of the SEEMP Part III. This part of the SEEMP, which outlines the measures vessels must undertake to comply with the CII, currently relies on vague and subjective requirements. It is suggested that these requirements should be clearer and more specific [97].

- Clarification of SEEMP and CII auditing. Clarification of the role of the audit, who and what skills are required to undertake the audit is not clear and should be clarified.
- Decarbonisation of the maritime sector cannot fully be achieved without including all areas of the industry. Fishing is one aspect of the industry that is not included even though some fishing vessels are large and significant contributors to emissions [99]. For example, one study found a fishing vessel to have an EEDI up to 3.78 times that of a ferry. The IMO should consider adding more sectors to the framework, which would require new CII calculation factors due to the operational differences [100].
- It is reported that the EEDI is currently insufficient for vessels with unconventional propulsion systems [101]. Extension of the index to cover more vessel types and propulsion systems, such as electric propulsion whilst considering the alternative methods of energy storage.
- Common port incentive scheme. One study proposes a common port incentive scheme focused on GHG emissions reduction to facilitate the implementation of IMO regulations and increase participation [72]. Furthermore, a harmonised and collaborative approach among ports is suggested to create a level playing field and maximize environmental and economic benefits.

To summarise the SEEMP, CII, EEDI and EEXI are important tools for managing the carbon emissions from ships. However, to improve their effectiveness and address some of the current limitations, several amendments can be considered. Suggested changes to the **CII are:**

- Set differentiated CII targets for various ship types based on their operational characteristics and cargo types.
- Adjust the CII formula to account for cargo carried, ensuring that the efficiency of transporting cargo, not just the vessel's deadweight. This would incentivize the carrying of cargo rather than ballast. Furthermore, cargo volume rather than cargo density should be considered.
- Differentiate between various types of fuels and their respective GHG emissions, including a detailed breakdown of propulsion and non-propulsion emissions. This would allow the CII to more accurately reflect the true carbon footprint of shipping activities.
- Adjust for external factors outside the control of the ship owner or operator, such as adverse weather conditions, to provide a fairer assessment of a vessel's operational efficiency.
- Conduct a thorough review of the current exclusions and correction factors to evaluate their impact on the CII mechanism.
- Strengthen the SEEMP Part III by defining clear and specific requirements for measures to be undertaken by vessels to comply with CII.
- Shift focus from CO₂ to energy efficiency and/or include other GHG emissions in the metrics.

- Provide clear guidelines for mechanisms to ensure enforcement of compliance.

These measures would enable the CII to become a more robust and fairer measure.

Suggested **EEDI** and **EEXI** amendments are the same as for the **CII**, in addition, the following could be applied:

- Establish differentiated EEDI/EEXI targets for different ship types, sizes and operational characteristics.
- Include operational profiles into the EEDI/EEXI calculation, including average speeds, voyage distances and load factors, providing a more realistic measure of a ship's energy efficiency.
- Provide incentives for innovative ship designs and energy-efficient technologies, including R&D spend.
- Provide incentives to speed-up the adoption and innovation of energy-efficient technologies.

Finally, it would be valuable to align the GHG emission targets with other environmental regulations and in doing so aligning targets to other sectors, especially those facing similar decarbonisation challenges such as switching to low carbon fuels.

3 GHG abatement measures that can improve energy efficiency in the maritime sector

This report now examines individual energy efficiency technologies and measures for GHG abatement of the maritime sector, that are available to ship owners to improve the EEXI, EEDI and CII ratings. Table 1, is a list of GHG abatement measures and technologies that have been identified within this evidence review and grouped into suitable categories. Each measure or technology is discussed in turn. First an explanation of the measure is provided, then an assessment of the evidence is made of the GHG emission reduction potential, commercial status, deployment status and any barriers to deployment.

Table 1, List of GHG abatement measures and technologies

Vessel propulsion and power measures	
Measure / technology	Description
Wind Assisted Propulsion Systems	<ul style="list-style-type: none"> • Captures the wind to provide additional propulsion in addition to the main engines. The amount of propulsion is dependent on the weather. • There are several technologies available: soft Sails, rigid sails, suction sails, kite sails, flettner rotors. • Reduces the amount of fuel used and so reduces emissions.
Battery electric propulsion	<ul style="list-style-type: none"> • Provides propulsion from electric motors using battery storage. • Motors are a more efficient energy conversion than an engine. The full life-cycle savings are dependent on the source of electrical energy. • Removes onboard emissions assuming batteries are charged through shore-to-ship power.
Hybrid propulsion and energy storage systems	<ul style="list-style-type: none"> • Provides propulsion from a combination of an engine and an electrical motor. • Includes hybrid, plug-in hybrid, hybrid-electric and battery energy storage. • Usually increases energy/efficiency conversion and so reduces emissions.
Turbo-compounding in series	<ul style="list-style-type: none"> • Turbine is used to recover energy from the exhaust gasses and provide additional power to the propeller shaft. • Increases fuel energy conversion/efficiency and so reduces emissions.
Optimised shaft power	<ul style="list-style-type: none"> • Constant rotational speed so to operate engine at an efficient speed without changes. • Increases fuel energy conversion/efficiency and so reduces emissions.
Fuel cell for aux systems or/and propulsion	<ul style="list-style-type: none"> • Power the auxiliary systems, or propulsion of small vessels, from a fuel such as hydrogen without emissions. • Reduces emissions.
Solar power onboard shipping	<ul style="list-style-type: none"> • Powers the auxiliary systems from renewable energy. • Reduces the amount of fuel used and so reduces emissions.
Energy efficient auxiliary systems	<ul style="list-style-type: none"> • LED lighting, variable frequency drives, heat recovery form auxiliary systems. Air conditioning, refrigeration, etc. • Reduces the amount of fuel used and so reduces emissions.
Smart energy management	<ul style="list-style-type: none"> • Installation of a smart energy management systems to monitor and optimise energy consumption on board. • Reduces the amount of fuel used and so reduces emissions.
Waste heat recovery	

Organic Rankine waste heat recovery	<ul style="list-style-type: none"> • Converts low temperature waste heat into useful energy, typically electricity. Heat sources are the engines and other onboard systems. • Increases fuel energy conversion/efficiency and so reducing fuel usage and emissions.
Steam waste heat recovery	<ul style="list-style-type: none"> • Converts higher temperature waste heat to steam and then into useful energy such as for heating, propulsion or electrical power generation. • Increases fuel energy conversion/efficiency and so reducing fuel usage and emissions.
Ship hull GHG reduction measures	
Block coefficient reduction	<ul style="list-style-type: none"> • Block coefficient is the ratio of the ship's submerged volume to the volume of a rectangular block with the same length, breadth, and draft. Reducing the block coefficient of a ship's hull minimises water resistance and so: • Increases fuel energy conversion/efficiency and so reducing fuel usage and emissions.
Hull management of coatings	<ul style="list-style-type: none"> • Specialised coatings to a ship's hull to reduce biofouling, minimise drag, and enhance fuel efficiency. • Increasing fuel energy conversion/efficiency.
Air lubrication system (ALS)	<ul style="list-style-type: none"> • Air lubrication releases air bubbles beneath from the hull to reduce skin friction between the hull's surface and the water, which reduces drag. • Methods include bubble drag reduction, air layer drag reduction and partial cavity drag reduction. • Increases fuel energy conversion/efficiency and so reducing fuel usage and emissions.
Propeller and rudder flow conditioning devices	
Pre-swirl propeller ducts	<ul style="list-style-type: none"> • Positioned ahead of the propeller to guide the incoming water onto the propeller to reduce flow separation and cavitation. • Increases fuel energy conversion/efficiency and so reducing fuel usage and emissions. Also reduces noise.
Contra rotating propellers	<ul style="list-style-type: none"> • Two propellers on the same axis rotating in opposite directions to recover swirl energy, increase thrust, resist cavitation, and reduce wear and noise. • Increases fuel energy conversion/efficiency and so reducing fuel usage and emissions. Also reduces noise.
Vane wheels	<ul style="list-style-type: none"> • A vane wheel is a device placed immediately behind a ship's propeller that helps convert the swirling, low-thrust flow in the wake into more efficient, higher-thrust water flow aligned with the ship's axis. • Increases fuel energy conversion/efficiency and so reducing fuel usage and emissions.

Boss cap fin	<ul style="list-style-type: none"> • A boss cap fin is fitted to the hub, or "boss," of a ship's propeller, consisting of small fins around the cap. Its primary function is to reduce the swirling water flow behind the propeller, and so improving the overall efficiency of the propulsion system. • Increases fuel energy conversion/efficiency and so reducing fuel usage and emissions.
Rudder bulb	<ul style="list-style-type: none"> • A rudder bulb is a hydrodynamic device attached to the leading edge of the rudder that fills the low-pressure gap between the propeller and rudder, streamlining water flow, reducing turbulence and drag, mitigating cavitation, and enhancing overall efficiency and improving steering. • Increases fuel energy conversion/efficiency and so reducing fuel usage and emissions.
Twisted rudders	<ul style="list-style-type: none"> • Twisted rudders are designed to align water flow with the propeller's wake by twisting the rudder along the vertical axis, which equalises pressure distribution, reduces drag, increases propulsion efficiency and enhances vessel control. • Increases fuel energy conversion/efficiency and so reducing fuel usage and emissions.
Operational measures	
Speed optimisation	<ul style="list-style-type: none"> • The drag of a vessel increases to the square of speed, hence the power increase cubically with speed. • Optimum speed refers to operating at the most efficient speed profile for a voyage, considering factors such as fuel type, engine technology, routing and environmental conditions like wind and sea state, rather than merely slowing down. • Increases fuel energy conversion/efficiency and so reducing fuel usage and emissions.
Just-in-time arrival	<ul style="list-style-type: none"> • Involves precisely timing a vessel's arrival at port to minimise fuel consumption by reducing waiting times and optimising sailing speeds according to real-time data on berth availability and environmental conditions. • Increases fuel energy conversion/efficiency and so reducing fuel usage and emissions.
Weather routing	<ul style="list-style-type: none"> • Uses modelling and real-time meteorological data to optimise navigation and sailing speeds, to minimise exposure to adverse weather conditions that significantly increase the required propulsion. • Increases fuel energy conversion/efficiency and so reducing fuel usage and emissions.
Voyage optimisation	<ul style="list-style-type: none"> • Voyage optimization involves using advanced algorithms and real-time data to plan the most efficient routes for vessels. This process takes into account factors like weather conditions, sea currents, ship performance, speed optimisation and just-in-time arrival to improve overall operational efficiency. • Increases fuel energy conversion/efficiency and so reducing fuel usage and emissions.

Derating of main propulsion engines	<ul style="list-style-type: none"> • Engine modification to reduce an engine's power output, creating a shallower efficiency curve and increased efficiency overall at lower propeller shaft speeds. A measure implemented when a vessel has an engine larger than required. • Increases fuel energy conversion/efficiency and so reducing fuel usage and emissions.
Ship ballast, draft and trim optimisation	<ul style="list-style-type: none"> • Optimising the ballast draft and trim to minimise drag, dependent on loading and sea state. • Increases fuel energy conversion/efficiency and so reducing fuel usage and emissions.
GHG abatement measures whilst vessels are in port	
Port - Hull management (hull cleaning and propeller polishing)	<ul style="list-style-type: none"> • To maintain vessel performance, regular hull and propeller cleaning by divers or robots is used between costly dry-dock periods. Removing fouling reduces the drag which would otherwise accumulate on the coatings. • Maintains fuel energy conversion/efficiency and so reducing fuel usage and emissions which would otherwise increase.
Port - Shore-to-ship power or cold ironing (CI)	<ul style="list-style-type: none"> • Supplies electricity to vessels in port from shore-based sources, reducing emissions from onboard generators and cutting CO₂, NO_x, SO_x, and PM emissions while at berth. • Particularly beneficial for vessels with longer port stays. • Required to chart battery for plug-in hybrid or battery propulsion vessels. • Removes emissions within the port leading to cleaner local air.

4 Vessel propulsion and power measures

Maritime vessels have a high energy demand for their marine engines and auxiliary services. These are historically powered by conventional fuel oils and so are major contributors to GHG emissions. To drastically reduce GHG emissions future vessels will need to be powered by zero or near-zero GHG emission technologies, fuels, or energy sources, complemented by improved energy efficiency measures. This section discusses technologies which reduce fuel consumption, of both propulsion and auxiliary systems.

4.1 Propulsion technology - Wind Assisted Propulsion Systems

With the drive to reduce GHG emissions and cleaner shipping, the return to wind assisted power has increasingly been proposed for shipping beyond purposely built sailing vessels. Wind assisted propulsion systems (WAPS) harnesses the wind to reduce engine load while maintaining the same or increased sailing speed, and thus reducing fuel consumption.

4.1.1 Explanation of measure

According to IRENA, WAPS technology adopted by large vessels can reduce onboard energy by between 5% and 20%, when retrofitted [33]. Wind assisted sailing therefore offers substantial opportunity to reduce fuel consumption for many types of vessels. Five forms of WAPS are: [102-105].

- **Soft Sails** have been used for a very long time. They use a fabric to harness the wind to generate propulsion thrust. The vessel requires a mast and rigging to raise, lower and orient the sails. Modern soft sails utilise modern materials, complex shapes and advanced features to enhance performance in all wind conditions. Soft sails are a relatively low-cost solution.
- **Rigid Sails**, are a progression on the soft sail. They use advanced materials and are more efficient than soft sails. They can be precisely positioned to optimise thrust and so reducing fuel propulsion power demands.
- **Suction Sails** are rigid wing sails which have a thick foil-shape. They are positioned vertically and are typically between 10 and 36m high. They use a mechanical air suction mechanism to control the fluid flow boundary layer and may have a movable tail flap to maximise thrust. Suction sails can assist propulsion when the wind is coming from any angle, with the potential to produce a 3-4 times improvement in propulsion efficiency.
- **Kite sails** are an alternative to conventional sails. Using a parasail on a long cable, flying high above the deck of the vessel (100-300 m) to capture higher wind speeds at altitude to pull the vessel forward. Kite sails can either be static or dynamic. A static kite flies directly above the bow of a ship, aiding propulsion when the wind is directly behind the ship. Dynamic kites are mobile, flying in a figure of eight, using the winds at wider angles to the ship, improving performance and fuel saving capabilities. Kites require minimal structural changes to the vessel and have no reduction in cargo deck space, therefore they are ideal for retrofitting. Kites benefit from higher wind speeds than onboard sails but have not been widely adopted by the maritime industry due to the limited operational wind angles and lower impact on power savings.
- **Flettner Rotors** are a vertical rotating cylinder on the deck of a ship which develops lift and propulsive thrust due to the Magnus effect when wind blows across them. The direction of the thrust generated is dependent on the direction and speed of rotation and wind direction. The amount of propulsive thrust is dependent on the number, height and diameter of the rotors.

In addition to WAPS technologies, the power of the wind can be used to generate electrical power for non-propulsive systems. By installing wind turbines onboard a vessel, electrical power can be generated, reducing the power need from diesel generators. It is reported that wind turbines can reduce fuel consumption by 1-2% and GHG emissions by an equivalent amount [62].

4.1.2 GHG emission reduction potential

WAPS technologies can reduce a new build vessel fuel consumption by 5-47% depending on the type of technology and operational region in the world, due to the nature and strength of the wind encountered by the vessel. For retrofitted vessels the fuel reduction could be 5-20%, as the design may not be optimised for the vessel [106].

The vessel size, and type, will have an impact on the number and sizing of installations to ensure the aerodynamic interaction between the devices is minimised. In all cases the number and size of the installed WAPS system will affect fuel consumption with the general rule of thumb being *more and larger* installations produce greater savings.

Examples of typical WAPS systems and the specific fuel consumption savings are provided in Table 2 [62].

Table 2: Fuel Saving of Installed WAPS Systems [62]

WAPS Technology	No. WAPS	Dimensions	Fuel Saving
Flettner	1	H = 35m; D = 5m	2-21%
Flettner	1	H = 18m; D = 3m	1-6.6%
Flettner	2	H = 22m; D = 3m	5-7%
Flettner	2	H = 48m; D = 6m	17-23%
Flettner	3	H = 48m; D = 6m	9-13%
Flettner	4	H = 27m; D = 4m	8-47%
Kite Sail	1	A = 400m ² ; L = 350m	1-15%
Kite Sail	1	A = 500m ² ; L = 350m	1-32%
Kite Sail	1	A = 640m ² ; L = 600m	40%
Rigid Sails	1	H = 50m; W = 20m	6.1%
Rigid Sails	3	H = 25-27m; W = 17-18m	5-8%
Rigid Sails	5	H = 50m; W = 17-18m	9-24%
Rigid Sails	9	H = 50m; W = 20m	20-30%
Soft Sails	1	A = 1,000m ²	4.2-35%

Note: Height (H); Diameter (D); Area (A); Line Length (L); Width (W)

4.1.3 Status of technology

WAPS technology has rapidly developed over recent years with new materials, design/modelling and manufacturing techniques. It can be assumed that the technologies have matured to TRL/CRL9 and Flettner rotors, rigid sails and kites are expected to reach CRL10 by 2025 [106].

TRL, or technology readiness levels, are a standard measurement of the maturity of a particular technology. 1 being at a basic research level and 9 being at product launch. The Commercial readiness level (CRL) is a measure of how ready a technology is to be

commercially available, 1 is a belief that the technology can become commercially viable, to 9 where a technology has been introduced to the market.

4.1.4 Technology application - Size of vessel, type of vessel and profile

WAPS technology has been adopted on virtually all types of ship, except container vessels. They are preferred on medium/large ships with a large deck area not needed for cargo or where a greater number of WAPS units can be installed, increasing the potential propulsion thrust and so increasing the reductions in fuel consumption and GHG emissions. WAPS systems can be retrofitted to in service vessels, as well as new build vessels where the design can be optimised to best suit the technology implemented.

Table 3 shows the types of vessels, size of installed WAPS system and claimed/reported fuel consumption savings made after the installation [62].

Table 3: WAPS Technology Adoptions by 2022 [62]

Name of Ship	Ship Type	DWT (tons)	Technology Specifics	Build/Retrofitted Year	Claimed GHG Emissions Reductions
Flettner Rotors			Number/Diameter (m)/Height (m)		
E-Ship 1	General Cargo/Ro-Ro	10,020	4/4/27	2010	30-40%
Estraden	Ro-Ro	9,700	2/3/18	1999/2014	5.2%
Viking Grace	Passenger	6,107	1/4/24	2013/2018	20%
Fehn Pollux	General Cargo	4,250	1/3/18	1997/2018	10%
Maersk Pelican	Tanker	109,647	2/5/30	2008/2018	8.2%
Afros	Bulk Carrier	64,000	4/2/16	2018	12.5%
Copenhagen	Ferry	5,088	1/5/30	2012/2020	4-5%
Annika Braren	General Cargo	5,100	1/3/18	2020	10%
SC Connector	Ro-Ro	8,842	2/5/35	1997/2020	25%
Kite Sails			Kite Size (m²)		
Michael A.	General Cargo	4,884	160	1994/2008	10% *
BBC Skysails	General Cargo	9,832	320	2008	14%
Theseus	General Cargo	3,667	160	2009	10% *
Aghia Marina	Bulk Carrier	28,522	320	1994/2012	15% *
Ville de Bordeaux	Ro-Ro	5,200	500	2004/2020	30% *
Suction Sails			Number/Height (m)		
Ankie	General Cargo	3,600	2/10	2007/2020	8-10%
Frisian Sea	General Cargo	6,477	2/-	2013/2020	10%
Rigid/Wing Sails			Number/Height (m)/Width (m)		
MV Tharsis	General Cargo	2,364	2/9/3	2012/2021	No Info.
New Vitality	VLCC	306,751	2/32/15	2018	No. Info.
Soft Sails			Number/size (m²)		
Canopée	Ariane 6 Rocket Transport Ship	10,669	4/3	2022	15%

* Calculated estimates based on available information

4.1.5 Status of deployment and barriers to deployment

Since 2010, WAPS technology has been slowly adopted by the marine industry, but the demand for WAPS is increase year-on-year. New ship designs show an increasing number of

vessels with WAPS technologies, including bulk carriers and tankers and there are some proposed new container vessel designs without compromising box carrying capacity. According to the International Windship Association (IWA), in 2022 there were 51 installations of WAPS onboard 25 large commercial and in 2023 this had increased to 105 installations on 49 vessels [107]. The majority of WAPS installations occurred on bulk carriers, RoRos and general cargo ships, with 19 and 42 vessels in the respective years [107]. If the trends continue, by 2030 it is predicted between 3,700-10,700 installations would be onboard around 1,500 tankers and bulk carriers. A study predicted that by 2050 around 37,000 – 40,000 vessels, representing 40-45% of the worlds fleet, will have some form of WAPS system installed [108].

The main barriers of adoption of WAPS technologies are:

- **Cost of Installation:** Currently, the cost of installation can be prohibitive due to a lack of scale-up of the technology and the need to structurally change the vessel (strengthening deck plating and internal superstructure struts for the forces being applied). Costs will be reduced if WAPS technology scales up, and if implemented in the design of new vessels rather than retrofitting older vessels.
- **Pay-back period:** The payback period is around 3-5 years depending on the technology utilised and operational profile. Retrofitting ships in the last third of their working life is probably not viable. However, implementation of the technology in the early stages of new vessel design could reduce cost of implementing WAPS by around 60% and hence significantly reduce payback times.
- **Reduced cargo capacity:** On ships where cargo is not carried on deck, the impact of installation is seen as minimal. Ships where deck space is directly related to cargo capacity, such as container ships, retrofitting opportunities are limited but proposed designs for new vessel and kites can offer solutions.
- **Wind conditions:** All WAPS technologies are dependent on fair wind conditions to generate sufficient propulsion. Better global wind models, weather forecasting and weather routing can aid in their adoption of WAPS technologies in certain regions and improve their operational efficiency.
- **Safety:** Ship stability must not be compromised when using WAPS technology. Classification societies have developed guidelines for the safe design and installation of WAPS technologies in accordance with safety of life at sea (SOLAS) legislation. Consideration must be made of bridge visibility, radar blind spots, navigation light arrangements, air draft, safety of the crew during operation and therefore suitable training made available.

4.2 Propulsion and power technology - Battery electric propulsion

Battery electric propulsion (BEP) utilises electric motors powered by an onboard battery energy storage system (BESS). Early vessels used lead-acid or nickel-cadmium batteries, but lithium-ion batteries have surpassed this technology. New battery chemistry, materials and

designs are emerging at pace which may replace current commercially available technology for marine applications. The electrical architecture of BEP installations can vary widely, dependent on the overall power needs of the vessel, main propulsors employed (Shaft-electric Motor or Azimuth pods) and operational profile. BEP shipping has the potential for up to 100% reductions of GHG and other harmful emissions if the source of power used to charge the batteries is GHG free [106, 109].

Batteries are charged using onboard generators and/or a port charging system. Alternatively, a battery swap system can be used, where depleted batteries are replaced in port by fully charged ones. Either method, in most cases, needs to be simple and quick to perform in order not to affect normal sailing operations.

BEP has volumetric and gravimetric energy density limitations which determines the total power that can be installed. Therefore, this limits its application for small to medium sized vessels with relatively short-haul routes. BEP system operational costs are determined by the price of electricity and maintenance costs, maintenance costs can be 20-25% lower than a conventional power and propulsion system [110].

4.2.1 GHG emission reduction potential

BEP can produce zero GHG emissions and air pollution as the combustion of fossil fuels is eliminated for power and propulsion. However, emissions may occur upstream from the vessel depending on the source of electrical power used for charging the batteries, so called well-to-wake. For 2023, the mix of power generation per capita in the UK is about 40% from fossil fuels (coal, gas and oil) and 5% bioenergy, from burning wood chippings, organic waste materials, etc. contributing to overall UK GHG and other emissions. The remaining energy, 55%, is generated from renewables (wind, solar, hydro) and nuclear. Charging in a UK port would therefore release GHG emissions upstream of the vessel. In comparison, Iceland and Norway, who generate nearly 100% of their energy from renewables (mostly geothermal and hydroelectric) will have near zero emissions for charging BEP vessels [111, 112].

4.2.2 Status of technology

Currently there are 88 vessels with BESS as the only power source, and there are 26 newbuilds on order in 2023, with many more being considered for retrofitting [110]. It can be said that BEP is currently at TRL/CRL10 as the technology has not fully penetrated the market, but to consider the technology fully, each individual element needs to be considered, as shown in Table 4 [106].

4.2.3 Technology application - Size of vessel, type of vessel and profile

The application of the all-electric ship is limited to small-medium size, short-sea shipping vessels (typically <30 nautical miles), deep-sea shipping on the other hand may use BESS in conjunction with diesel-electric hybrid-technology to provide assisted power and/or propulsion to facilitate peak shaving. In certain areas of the world the uptake of BEP is

growing, these tend to be for short range ferries where the infrastructure is in place (ship-to-shore power supply) [110, 112].

Table 4: Technology Readiness of BEP [106]

Technology	TRL/CRL
Battery Storage	CRL10
Onshore fixed charging	CRL10
Swappable Battery Recharging	TRL9 & CRL9-10
Electric propulsion motors	CRL11 up to 44 MW
Electric propulsion pods	CRL11 up to 22 MW
Electric drive systems	CRL11 up to 50 MW/system

As of 2023, there were over 750 vessels with BESS installed or waiting for installation, of which 15% are BEP vessels. Most of the vessels with BEP in operation are passenger/car ferries and leisure vessels, but others include offshore support vessels, tugs, Ro-Ro cargo carriers, Ro-Pax and short-haul cargo ships such as those used for inland or coastal transportation [106]. These typically travel less than 30 nautical miles and require short charge times of 15 minutes. The E-Ferry project, funded by the EU Horizon 2020 programme designed and built the demonstration vessel “Ellen”, an all-electric ferry that came into service in 2022. This vessel can travel 50 nautical miles on a single charge but tends to sail 22 nautical miles and charges for 15-40 minutes between trips [110].

The uptake of all-electric BEP technology has stalled due to the lack of infrastructure around the world. To charge batteries there needs to be a power supply, either a shore-based power supply or power from an alternative energy source onboard the ship (such as solar, wind or nuclear) is required. The infrastructure necessary for shore-to-ship power (S2SP) requires extensive capital investment to implement, but before this investment is made there needs to be a demand from shipping. Similarly, for a ship owner to convert their vessel to BEP, the infrastructure needs to be in place to ensure charging can be carried out. For this reason, BEP is only seen as viable if port authorities and ship owners work in close cooperation. Legislation and subsidies to incentivize implementation could be used by governments to encourage the shift to BEP in the short sea shipping sector.

4.2.4 Status of deployment and barriers to deployment

With the current state of battery technology, BEP installations are limited to short-sea shipping (up to 50 nautical miles on one charge). In addition, the deployment of BEP can be affected on a regional basis by the infrastructure of visited ports. The ability to rapidly charge is essential since the ship does not generate onboard electrical power. Charging must be performed in port and requires a shore-to-ship power supply. At a regional level this is dependent on investment and grid supply.

Although BEP has the potential to reduce emissions for short-sea shipping, its use on large deep-sea vessels is impractical given the current state of the technology, instead hybrid systems can be appropriate, which use liquid fuels and electrical power together. There are numerous hybrid system types, all of which require some form of electrical power storage.

4.3 Propulsion and power technology – Hybrid propulsion and energy storage systems

Hybridisation of the maritime transportation sector is seen as a pathway towards the electrification of many ships. According to Clarksons, 80% of all new build designs have an energy storage system (ESS) incorporated [113].

ESS can be used to store excess power from onboard generators or engines when there is extra power being generated than required, such as at slow sailing speeds. Engines are optimised for higher efficiency at their normal operating points, under load at normal sailing speed, and so at low load conditions the efficiency will not be as high. The energy storage can be charged while provide load to the engine allowing it to run at a higher efficiency operating point.

There are several hybrid configurations that use ESS. The first example is the hybrid-electric system (HES) which decouples the engine from the vessels propulsion propeller and instead uses the main engines to generate electrical power. The electrical power then powers the propulsion motor/s, other systems and at the same time charging the ESS batteries. This enhances vessel safety, because of redundancy in generator/propulsion systems, and allows optimal running of the onboard generators, saving fuel and reducing emissions. Diesel-electric hybrid systems with BESS represent 85% of all vessels having some form of HES onboard [114].

The second example hybrid system operates alongside the main propulsion engine. Typically, the electric machine is connected, through a gear box to the main propellor drive shaft. At times, the electric machine operates as a motor, providing additional propulsion power to the propellor shaft. At other times, the electrical machine acts as a generator, taking excess drive shaft power and provides electrical power for auxiliary systems and charges the battery. When this combination works as a generator it is operating in power-take-off (PTO) mode. When it contributes to propulsion it is operating in power-take-in (PTI) mode. When the electric motor solely powers the vessel to a safe harbour, it is operating in power-take-home (PTH) mode. In all cases, depending on technology employed and the configuration, HEP saves fuel and reduces GHG emissions.

Plug-in hybrid allows for the vessels battery to be charges while at port. In this case, the ship can connect to a shore-based power supply, as well as having an onboard HES, to charge batteries and provide electrical power for the vessel while in port.

BESS can be directly integrated with onboard systems to provide power for dedicated onboard services (hotel load, loading/unloading equipment, mooring systems, lighting, etc.) or during specific operational modes (operating thrusters during manoeuvring, providing power in port and providing power at low speeds). In addition, BESS systems can be used with alternative low emission energy conversion technology, such as fuel cells and solar power systems, to charge batteries or extend operational performance, especially in the case of all-electric shipping. By using BESS with additional energy saving devices, greater fuel efficiencies can be achieved, nearly doubling GHG emission reductions [110, 115-117].

4.3.1 GHG emission reduction potential

Hybrid configurations with ESS make it possible to operate diesel engines at high-efficiency operating points. This will inevitably lead to fuel savings and reduced GHG emissions, depending on the drive configuration and operational profile. For short-sea Ro-Ro ferries this has been found to be in the range of 2.9-7.5% in fuel consumption [118]. A study of a deep-sea bulk carrier showed a 2-3% reduction in fuel consumption and CO₂, with 5-7% reduction in other emissions (NO_x) [119, 120]. In another study, an Italian Navy FREMM frigate with an ESS and hybrid-electric configuration showed a 10% reduction in fuel consumption, where the main engine was a gas turbine used to provide the electrical power [121].

4.3.2 Status of technology

Significant improvement in battery and electric machine technologies has led to the marine industry adopting increasingly larger ESS and electric propulsion systems.

Onboard battery storage is considered a mature technology, due to developments in recent years with CRL10 for pure electric vessels up to 11,000 GT. Hybrid-electric vessels with battery storage is considered CRL11 and plug-in hybrid propulsion is CRL10 [106].

Other elements of electric propulsion to be considered are the main electric devices, i.e. motor/generators, thruster pods and drives. All of which are considered mature with a CRL11 rating [106].

4.3.3 Technology application - Size of vessel, type of vessel and profile

In July 2023 there were 800 vessels with battery storage installed, with another 295 on order [122]. The vast majority being ferries, yachts, research vessels, offshore support vessels and tugs. However, in recent years this has included container ships, bulk carriers, oil/chemical tankers, crude oil carriers and general cargo ships. Whilst all-electric ship technology with battery ESS is limited to small/medium sized vessels and short-sea shipping, hybrid systems can be installed on all vessels of any size. This is because the electric component is not the main propulsion system but rather can operate as a secondary system which works in tandem to the main engines.

In 2022, 85% of all ships with installed ESS were either hybrid-electric or plug-in hybrid systems, the rest (15%) were for all electric vessels [106]. In 2022, the global uptake of ships with ESS systems was concentrated within Europe with a 71% share of all global installations. Norway alone accounted for 46% of the global installations in operation. Asia, a rapidly growing market for Hybrid ESS systems, operated 14%, the USA 8% and the rest of the world accounted for 6% [106].

4.3.4 Status of deployment and barriers to deployment

Within the maritime industry there are several trends driving the adoption of battery storage technology onboard ships [106].

- Batteries are seen as an enabler to net zero emissions.
- Battery technology is maturing, and increasingly seeing a variety of applications in shipping.
- Size of the world fleet is growing to meet increasing demand for shipping.
- Ships are demanding larger battery storage systems.
- Increased number of maritime battery manufacturers and suppliers (1 in 2010; 31 in 2023).

This has led to more ships requiring some form of ESS alongside hybrid propulsion systems. To date the largest ESS installation is 10 MWh as part of a hybrid-electric drive onboard a 126,000 GT retrofitted cruise ship, the AIDAprima. The MS Colour Hybrid is a 27,000 GT new build cruise ship, is the largest with a plug-in hybrid system at 6.5 MWh onboard. The Yara Birkeland, a 3,000 GT container vessel, has the largest BESS installed onboard an all-electric vessel at 6.7 MW [106].

Although, the installation of ESS onboard hybrid powered ships is increasing year-on-year, doubling every 3-4 years, there are still several barriers preventing more rapid growth [106, 109].

- **Cost of ESS:** Costing around 1,090 US\$/kW for maritime batteries as opposed to 436 US\$/kW for automotive batteries. However, as the technology becomes more mainstream and the number of manufacturers/suppliers increases then the costs will reduce, as seen in the automotive sector.
- **Availability of batteries:** With a limited number of manufacturers of maritime batteries compared to other industries, the production volumes are relatively low with long lead times for delivery. The availability is increasing with more manufacturers entering the market to meet demand.
- **High complexity requires standardised design:** Different possible configurations of battery systems and drives increases the flexibility but also the complexity of the system. Standardised designs reduce risk and cost.

- **Safety concerns:** There is a requirement for the battery management systems to prevent thermal runaway. Developments in monitoring and energy storage management will reduce risks associated with thermal runaway.
- **Safety systems:** Flooding, drenching, venting, cooling and containment need to be considered.
- **Limited size of installation:** ESS are limited in power due to the power density of each cell and the space they occupy. However, since 2012, when the average ESS installation capacity was 180 kWh, the average capacity has increased dramatically to 3 MWh, with the largest installation being 10 MWh.
- **Infrastructure limitations:** Plug-in hybrids and all-electric vessels need port side power supply to recharge batteries. This is limited around the world due to the high infrastructure costs and limited local power supply, which both have long lead times to implement. Although, investment in shore-to-ship power supplies is taking place, this will take time to have enough to guarantee recharging in all ports around the world. An alternative is to adopt a battery swap system, which can remove used batteries and install fully charged one quickly.

4.4 Propulsion and Power technology - Fuel cell

4.4.1 Explanation of measure

The auxiliary systems or propulsion of small vessels on existing and new ships can be powered by fuel cell technology. Fuel cells convert a fuel such as hydrogen into electrical power. Their use has been shown, through modelling, to power the auxiliary systems for small to medium applications, at various scales and operational distances, including vessels such as tankers and cargo freighters [123], commercial vessels [124] and others [125-127]. There are different types of fuel cells with different capabilities, the attribute of each type is provided in Table 5.

Table 5: Types of fuel cells and their attributes [124-128]

Fuel Cell Type	Fuel Options	Emissions	Overall efficiency	Operating Temperature	Lifetime (hours)	Cost (\$/kW)	Maximum power output (kW)
Alkaline Fuel Cell (AFC)	H ₂	Water	50-60 %	60-200 °C	5,000–8,000	1,000	500
Phosphoric Acid Fuel Cell (PAFC)	Methanol, Natural Gas, H ₂	Water + CO ₂ if carbon included fuel is used.	80 %	140-200°C	40,000–60,000	200-3,000	400
Molten Carbonate Fuel Cell (MCFC)	Natural Gas, H ₂ , methanol	Water + CO ₂ if carbon included fuel is used.	80 % (29-54% for diesel), (40-55% for NG)	650-800 °C	15,000-30,000	1250	10,000
Proton Exchange Membrane Fuel Cell (PEMFC)	H ₂	Water	40-60 % (30-40% for diesel), (35-45% for NG) and (40-60% for H ₂)	60-80 °C for low temperature and 110-180 °C for high temperature	>25,000	50-2,000	500
Solid Oxide Fuel Cell (SOFC)	Methanol, Natural Gas, H ₂	Water + CO ₂ if carbon included fuel is used.	85 % (45-55% for diesel), (45-60% for NG) and (42-67% for H ₂)	500–1,000 °C	20,000-80,000	1,500	10,000

4.4.2 GHG emission reduction potential

The GHG reduction potential of this technology mainly depends on the origin of the fuel, the type of fuel cell and size of application. Fuel cells can be used to provide auxiliary electrical service on a large vessel or provide electric power and propulsion for small vessels, producing low to no emissions depending on the type of fuel used [127]. Typically, large ships have high auxiliary services energy demand. High temperature fuel cells, for example solid oxide fuel cells (SOFC) and molten carbonate fuel cells (MCFC), can potentially replace conventional maritime diesel generators [129]. A typical diesel engine-based vessel's auxiliary services fuel consumption is 15% of the total fuel consumption, and the GHG reduction potential mainly depends on whether these services and/or the main propulsion can be fully/partly provided by fuel cell technology [130]. The fuel used for the fuel cell, such as hydrogen, needs to be from renewable sources to maximise the GHG reduction potential when considering the well-to-tank emissions.

The auxiliary engine power to main engine power ratio has been calculated for various vessel types: bulk carrier 22.2%, container ship 22.0%, cruise ship 27.8%, general cargo 19.1%, tanker 21.1% and reefer (refrigerated) ship 40.6% [131]. An analysis of short sea shipping and the use of SOFC and proton exchange membrane fuel cells (PEMFC) showed a 73–86% GHG reduction using blue hydrogen and green ammonia [132].

4.4.3 Technology application - Size of vessel, type of vessel and profile

Fuel cell technology has already been tested and demonstrated on vessels for power supply. However, the application size has several challenges due to the sustainable supply of fuel (H₂ or other renewable hydrocarbon fuel) and capacity of fuel cells especially for slow speed large ships with long voyages and high energy demand.

4.4.4 Status of technology

There is currently a lack of long-term testing of fuel cells for maritime applications, but the technology is well understood from applications in other transport sectors. Recent research projects, as shown in Table 6, have shown viable application of fuel cells in the maritime sector. New build vessels will have better options for deployment of this technology, as retrofitting to existing ships may face challenges with space and weight restrictions and the additional fuel storage space and safety requirements associated with hydrogen or other sustainable hydrogen carrier fuels.

Table 6: Fuel cell based international research projects for maritime applications [127]

Project Name	Period	Country	Fuel Cell Power	Type of fuel cell	Logistic Fuel	Application	Ship Name
FLAGSHIPS	2019–2023	The Netherlands, France, Norway	1,200 kW/400 kW/600 kW	PEMFC	Hydrogen	Container cargo ship/self-propelled barge/Passenger and car ferry	FPS Waal/Zulu/M F Hidle
H2PORTS	2019–2023	Spain, Valencia	70 kW	PEMFC	Hydrogen	Reach Stacker and Yard Tractor	-
HFC MARINE	2018–2020	Denmark	200 kW	PEMFC	Hydrogen	Ferry	-
SHIPPINGLAB	2020–2024	Denmark	N/A	PEMFC	Hydrogen	Dredger	-
HYSEAS III	2018–2022	Scotland	600 kW	PEMFC	Hydrogen	RoPax ferry	-
FellowSHIP	2003–2018	Norway and Germany	320 kW	MCFC	LNG	Offshore supply	Viking Lady
SchIBZ	2009–2018	Germany	100 kW	SOFC	Diesel	General cargo ship, yachts	MS Forester
Nemo H2	2008-present	Netherlands	65 kW	PEMFC	Hydrogen	Passenger boat	Nemo H2
PaXell 2	2019–2022	Germany	N/A	PEMFC	MeOH	Cruise ship	AIDAnova
RiverCell	2015–2022	Germany	90 kW	PEMFC	MeOH	Inland passenger ship	-
ELEKTRA	2017–2019	Germany	300 kW	PEMFC	Hydrogen	Canal tug	Elektra
DESIRE	2001–2004	Germany, The Netherlands, UK and Turkey	25 kW	PEMFC	Diesel	Naval ship	-
TecBIA	2018–2022	Italy	140 kW	PEMFC	Hydrogen	Research vessel	ZEUS
HI-SEA	2017–2022	Italy	250 kW	PEMFC	Hydrogen	Experimental plant	-
HIMET	2021–2022	United Kingdom	500 kW	PEMFC	Hydrogen	Ferries	MV Shapinsay

ShipFC	2020–2024	Norway	2 MW	SOFC	Ammonia	Offshore vessel	Viking Energy
Nautilus	2020–2024	European Union	60 kW	SOFC	LNG	Cruise ship	-
Maranda	2017–2022	European Union	165 kW	PEMFC	Hydrogen	Arctic research ship	Aranda
Energy Observer	2017–present	France	60 kW	PEMFC	Hydrogen	Experimental vessel	Energy observer
MF Hydra	2020–present	Norway	400 kW	PEMFC	Hydrogen	Ro-Pax ferry	MF Hydra
HyShip	2021–2024	Norway	3 MW	PEMFC	Hydrogen	Coastal goods-carrying RoRo	Topeka
NAVIBUS	2018–2019	France	10 kW	PEMFC	Hydrogen	River boat	Jules Verne 2
FC-PROMATE	2019–2022	Italy & Netherlands	35 kW	PEMFC	Hydrogen	Protocols for testing PEMFC for maritime applications	-
Sea Change	2016–2022	USA	360 kW	PEMFC	Hydrogen	Passenger ferry	Sea Change
Hydrogenia	2019–2021	South Korea	100 kW	PEMFC	Hydrogen	Small boat	Hydrogenia
sHYpS	2023–present	Europe	6 MW (sub module testing 300 kW)	PEMFC	Hydrogen	New build based on LH2 storage tank	-

4.4.5 Status of deployment and barriers to deployment

Fuel cells have been demonstrated in different types of maritime vessels as provided in Table 7. However, serious challenges remain maritime applications:

- Limited power capacity for large ships.
- Reliability of fuel cells to ensure trouble free operation in maritime vessels, with lack of long-term testing in maritime operation.
- Fuel availability.
- Fuel storage and safety.
- High capital and high operational expenditure lead to long payback periods.
- Lack of experienced crew and engineers.
- Lack of training and certification.

Table 7: Fuel cell deployment on vessels [127]

Ship Name	Ship Type	Type of Fuel Cell	Specification	Power System	Power Output	Fuel
German-based MTU Friedrichshafen	Yacht	PEMFC	12-m-long—range 225 km at a speed of 8 knots	4 × 1.2 kW + 9 lead-gel batteries	20 kW	Hydrogen
Ross Barlow	Canal boat	PEMFC	-	5 kW PEMFC module + lead-acid battery	5 kW	Hydrogen
Hydrogenesis	Small boat	PEMFC	Max operating time 10 h at max speed of 7 knots	12 kW PEMFC module	12 kW	Hydrogen

FCS Alsterwasser	Passenger ship	PEMFC	25 m long—100 passengers—maximum speed of 8 knots.	2 × 48 kW PEMFC, 7 lead-gel battery packs 234 kWh, 100 kW propulsion electric motor and a 20-kW bow thruster	96 kW	Hydrogen
Nemo H2	Passenger ship	PEMFC	22 m long—88 passengers—maximum speed of 8.6 knots	2 × 30 kW PEMFC, 55 lead-acid battery packs 70 kWh, a 75-kW propulsion electric motor and 11-kW bow thruster	60 kW PEMFC with 30–50 kW battery	Hydrogen
SF-BREEZE	Passenger ferry	PEMFC	150 passengers—maximum speed of 35 knots	41 × 120 kW PEMFC, each rack 4 × 30 kW PEMFC stacks.	120 kW	Hydrogen
Cobalt 233 Zet	Tourist Boat	PEMFC	20-m-long, light weight of 20 tons—50 passengers	2 × 28 kW PEMFC, 3 × 15.7 kWh Li-ion battery packs	50 kW	Hydrogen
MS Mariella	Passenger ship	PEMFC	2,500 Pax	2 × 30 kW PEMFC, each comprised 6 × 5 kW modules.	60 kW	Methanol
MF Vågen	Small passenger ship	PEMFC	-	-	12 kW	Hydrogen
Viking Lady	Offshore supply vessel	MCFC	Length 92.2—breadth 21 m—draft 7.6 m—deadweight 5,900 ton	320 kW MCFC as APU, internal reforming unit and WHR system	320 kW	LNG
MV Undine	Car carrier	SOFC	-	20 kW SOFC	20 kW	Methanol
MS Forester	General cargo ship	SOFC	-	50 kW SOFC with Li-ion battery packs developed for APU	50 kW	Low-sulfur diesel
Hornblower Hybrid	Passenger ferry	PEMFC	Length × Breadth: 20 × 10 m	Hybrid ferry with diesel generator, batteries, PV, wind and fuel cell	32 kW	Hydrogen + Diesel
Class 212A/214 Submarines	Submarines	PEMFC	-	Hybrid propulsion using a fuel cell and diesel ICE	306 kW	Hydrogen
ZEUS	Experimental research vessel	PEMFC	Length = 25.6 m Tonnage = 100 ton autonomy of approx. 8 h at 7.5 knots	2 × 150 kW diesel generators and 2 electric propulsion motors- 2 × 70 kW Fuel Cell plant and Battery	130 kW (FC) and 160 kWh (Battery)	Hydrogen
MF Hydra	Ro-Pax ferry	PEMFC	Length 82.4 m, 292 passengers and up to 80 cars—speed of 9 knots	2 × 200 kW PEMFC and 1.36 MWh Batteries and 2 × 440 kW diesel generators.	400 kW (FC), 880 kW (ICE), 1.36 MWh (Batteries)	Hydrogen + Diesel
Jules Verne 2	River boat	PEMFC	12 passengers and 6 bicycles	2 × 5 kW PEMFC + Batteries	10 kW	Hydrogen
FJORDS	Cruise ship	PEMFC	-	3.2 MW fuel cell + battery	3.2 MW	Hydrogen
MV Shapinsay	Ro-Ro Ferry	PEMFC	Length 26.6 m, Beam 8.8 m, Draft 1.45 m, Capacity 91 passengers + 12 cars	Hydrogen fuel cell for auxiliary power system	-	-

S80 class	Submarines	PEMFC	80.8m long	300 kW FC stacks	-	Hydrogen
MF Hidle	Passenger and car ferry	PEMFC	199 passengers, 60 cars & 6 trucks.— Daily operation: 260 km, 19 h	3 × 200 kW PEMFC modules—Battery capacity 500 kWh—Biodiesel generator back-up power	600 kW	Hydrogen
Topeka	Coastal goods-carrying RoRo	PEMFC	-	3 MW PEMFC + 1 MWh batteries	3 MW	Hydrogen
Hynova	Yacht	PEMFC	Autonomy 8 h	80 kW FC + 2 battery stacks + 2 electric motor of 300 kW	80 kW	Hydrogen
FPS Maas	Inland container vessel	PEMFC	Length × breadth = 110 × 11.45 m	825 kW PEMFC + 504 kWh lithium-ion battery pack	825 kW	Hydrogen
Ulstein SX190	Offshore construction vessel	PEMFC	Length × breadth × Draught = 99 × 23.4 × 6 m	2 MW PEMFC	2 MW	Hydrogen
Zero-V	Coastal research vessel	PEMFC	Trimaran Hull, Length × breadth × Draught = 52 × 17 × 3,7 m, Range: 2,400 nm, Cruise Speed: 10 knots,	10 × 180 kW PEMFC racks	1.8 MW	Hydrogen
Sea Change	Passenger ferry	PEMFC	Length × breadth = 22 × 7.5 m, 78 passengers, Max speed = 20 knots	3 × 120 Kw PEMFC + 2 × 50 Kw battery + 2 × 300 kW electric motor	360 kW	Hydrogen
EX38A	Experimental boat	PEMFC	Length × breadth = 12.4 × 3.4 m, Navigation speed = 22 knots, capacity = 10 passengers	2 × 92 kW PEMFC + 32 kWh battery + propulsion motor 250 kW	184 kW	Hydrogen
Xianhu 1	passenger cruise ship	PEMFC	Length × breadth = 12 × 4 m, Navigation speed = 22 knots, capacity = 20–30 passengers	30 kW PEMFC + Battery	30 kW	Hydrogen

4.5 Power technology - Solar power onboard shipping

4.5.1 Explanation of measure

Solar photovoltaic (PV) panels can be used to provide electrical power to onboard auxiliary systems and to charge the BES. These panels are now mature technology and are widely installed throughout the world onshore. In the maritime environment PV needs further development for the harsh marine environment, particularly regarding salt deposit build up on surfaces. The energy production depends on the sun which varies geographically, over the year, time of day and with the weather.

Rigid PV panels are the most common form of solar power, for example a 2 m² mono-crystal panel mounted on a flat surface will generate up to 400 W of power. Rigid PV has limited onboard applications because they require large flat uncluttered areas. Most maritime

systems have been deployed on small inland vessels, leisure craft and river ferries or taxis. Installations on car carriers and some passenger/car ferries have been 40-50 kW in size, which is about 5-10% of the total ship power requirements [133]. The efficiency of any PV installation can be improved by connecting to an onboard battery energy storage system providing a buffer between the energy source and energy load. Excess PV energy production can be used to charge batteries, which can then be used at night or for peak shaving when there is high demand or a reduction in production, for example due to weather conditions.

Flexible PV can be attached to curved surfaces, offering a wider range of installation opportunities onboard a vessel. They produce less energy than the flat panel, a 1.5 m² panel will generate 200-300 W, but they can be fitted to larger surfaces of the vessel that are not suitable for flat plates. Flexible PV mounted on rigid sails are being developed by a few companies and offer the benefits of renewable power generation alongside wind propulsion. There are more elaborate concepts of PV panel architecture installations. A study of 17 passenger ferries in Bengal, India, suggested a flower arrangement of PV panels, placed on towers and tracking the motion of the sun to optimise generation [134].

4.5.2 GHG emission reduction potential

The potential of PV is dependent on several factors including the size, configuration, type of PV and orientation towards the sun of the installation. As well as these installation factors, the time of day, season, region of operation, operational mode and the weather conditions are important. The global location of the vessel and the time of year affects the number of daylight hours and so the amount of electricity which can be produced. However, even if it is light the amount of energy produced can vary from 10% to about 90% because of cloud cover and shading. Most basic emissions models exploring the application of PV assume an average of 50% sunshine during daylight hours. Depending on the vessel operational mode (sailing, manoeuvring or harbour) determines how much power can be saved using PV and therefore the fuel saving. To this end, it is difficult to accurately predict the average annual savings that can be made from the installation of PV onboard a given vessel, without understanding the vessels movements.

Within the literature there are several application examples:

- In one, a cruise ship sailing in China uses a solar-sail-hybrid system, it is stated that emissions were reduced by 30%, but it is unclear what percentage of saving is down to PV cells or other energy saving system [133].
- While another study of a 12,000 kW PV installation with BESS, found an 8.2% power reduction under normal sailing and a 31-45% energy saving in harbour, depending on the operational mode [135].
- A study of The Blue Star Delos found that combining a 2.3 kW PV system with low voltage lighting required 20% of the energy needed compared to an equivalent higher voltage AC lighting system [136].

- 17 passenger vessels in the Bay of Bengal explored the potential of PV onboard and showed that installations of PV could save 325.6 tons of CO₂ each year [134].
- A study of PV onboard five different vessels, was found to improve a vessels compliance with EEXI and CII and in doing so extending the vessel CII compliance by up two years longer than equivalent conventionally powered vessels [137].
- A study of a Ro-Ro ship, sailing in the Adriatic, established an annual fuel consumption reduction of 7.38% through the installation of solar PV [137].

In conclusion, there are clear indications that PV installations onboard ships can reduce fuel consumption and GHG emissions. However, these studies have largely explored PV systems integrated with other technologies or in limited conditions on a limited number of vessels and therefore the benefits of PV installations in isolation are unclear. What is clear is that the adoption of solar PV onboard ships can produce enough power to provide useful electrical energy and prolong compliance with existing EEXI and CII, especially for short-sea shipping.

4.5.3 Technology application - Size of vessel, type of vessel and profile

It is common to see inland waterway pleasure craft and oceangoing sailing yachts with some form of PV installation; it is less common onboard larger commercial vessels with greater power needs. Examples of the application of PV systems onboard ships is currently limited. Ideally, the installation of PV with battery storage should be considered on vessels with enough area for installation.

4.5.4 Status of technology

Solar PV panels are mature technology, and their efficiency has increased. Manufacturing costs have reduced to a point where they are commonly seen on houses, industrial buildings and in large solar farms. Flexible PV is less mature, with lower efficiency but potentially even cheaper to manufacture. For the maritime environment, solar PV will need to operate under more challenging conditions. PV panels has been demonstrated in operation on several vessels around the world and the technology can be considered as mature at TRL9, but their application within the maritime industry has been limited.

4.5.5 Status of deployment and barriers to deployment

The application of solar PV is limited to a few case studies on vessels with large canopies and vessels with large deck areas which are not used for cargo. This includes installation on Ro-Ro, ferries, cruise ships and car carriers. Furthermore, most applications have been in conjunction with other energy saving technologies, such as WAPS, BESS and fuel cells, or to power specific systems onboard a vessel, such as lighting, mooring and emergency systems.

There are concerns over cost, lifespan and space requirements for installation. Installations operating within geographical locations where the solar radiance is more predictable are preferred especially since they require high capital expenditure and a long payback period (up to 11 years [137]).

5 Waste heat recovery

Waste heat recovery involves capturing and reusing the surplus heat generated by a process which would otherwise be lost to the environment. This recovery of thermal energy can significantly improve overall energy efficiency. The recovered heat can be used for a range of applications including space heating, electrical power production or desalination.

The largest source of waste heat on a ship is the engine system where typically 50% of the fuel energy is released as low-grade heat [138]. Waste heat recovery (WHR), from an internal combustion (IC) engine and other sources, can therefore significantly improve the overall thermal efficiency of the vessel. But this is only if the energy can be used directly or converted to a useful form of energy. The possibility to retrofit power and thermal cycles or other utilisation technology is dependent on the vessel's size and available space, as well as its economic viability.

Two waste heat recovery technologies are discussed in greater detail within this report, these are the organic Rankine cycle (ORC) and steam Rankine cycle (SRC). There are other emerging thermodynamic and thermo-chemical systems which could make an impact in the future. ORCs can utilise low-grade heat to produce electrical power useful for other onboard systems. SRC can utilise higher grade heat to provide propulsive power or electricity. It has been observed that an ORC based WHR system is suitable when the delivered propulsion power of the ship is ≤ 15 MW, and a conventional SRC is recommended for higher power vessels due to the possibility of generating superheated steam [79].

Most of the studies and demonstrated projects for maritime vessels focused on the main engine-based waste heat recovery, however there are other sources of waste heat which can be utilised, such as auxiliary machinery and equipment. These tend to be lower temperature energy sources suitable for ORCs.

5.1 Waste heat recovery - Organic Rankine Cycle waste heat recovery

5.1.1 Explanation of measure

The ORC in maritime applications is a technology used to convert low-temperature waste heat from ship engines and other onboard systems into useful energy, typically in the form of electricity. This process improves the overall energy efficiency of ships by utilising heat that would otherwise be lost to the environment.

The basic components of an ORC are the generator, expander, evaporator, pump and condenser. Recovered low-grade heat is used to evaporate a working fluid, to a high-pressure vapour, which then passes through an expander which in-turn powers an electrical generator. An ORC system uses the same thermodynamic cycle as an SRC system but replaces water with an organic fluid that has a low boiling point and a high vapour pressure, and therefore able to

utilize lower grade heat [139]. Organic compounds of hydrocarbons, hydrofluorocarbons, siloxanes, ethers, or blends of organic fluids are commonly used for maritime applications.

5.1.2 GHG emission reduction potential

ORC system integration and installation are possible both for retrofitting of existing vessels and for new builds. Each type of vessel will have a specific ORC selection criterion, matching the heat energy and engine technology with the load. The conversion efficiency is highly dependent on the ship's engine, recent studies claim a conversion efficiency range from <20%, increasing to ≈36% for LNG carriers, to ≈58% using a combined ORC cycle system [140]. Based on published results and demonstrated projects, shown in Table 8, fuel savings are estimated to be between 4-6% [140]. Consequently, a short payback period (2-4 years) has made it attractive for energy intensive cargo ships and oil tankers. However, for other vessels and retrofitting, the space required could be the main challenge for its deployment.

5.1.3 Technology application - Size of vessel, type of vessel and profile

Currently, ORC systems have been demonstrated on several different vessel types, such as Ro-Ro ferries, container ships, bulk carriers, passenger ferries and product tankers. Thus, implementation of ORC is not limited to any vessel size or type. However, the use of ORC systems for medium to low scale power ranges (≤ 15 MW) are advantageous over SRC due to the ability to operate at lower temperatures and the smaller footprint of the systems compared to steam systems [140].

5.1.4 Status of technology

ORC technology is a technical and commercially mature technology with a long history of onshore applications. However its installation on existing ships is more challenging, because of the barriers mentioned below. Currently, the maritime industry remains relatively slow in adopting ORC systems, but considering the widespread projects and potential benefits, it can undoubtedly play a key role to achieve short term GHG reduction due to the possibility of retrofitting and relatively short payback period.

5.1.5 Status of deployment and barriers to deployment

Despite the technical maturity of ORC systems, there are several challenges for large scale adoption for maritime applications:

- Investment cost to retrofit an existing ship. Several studies have reported a short payback period for an installed ORC system, but high initial capital cost is the main challenge for ship owners and investors [140].
- A change in engine load will vary the temperature of the WHR system, causing an unstable operation of the ORC. A thermal energy storage and a control system capable of maintaining the appropriate operational temperature is required.

- Working fluid selection is complex. Since IMO and SOLAS have restricted the use of hydrocarbons with a flash point less than 60 °C, most of the potential candidates with high thermodynamic performance are no longer viable.
- Direct utilisation of exhaust gases may cause problems for an ORC system because of sulfur impurities which can form sulfuric acid at low temperature and damage the heat exchanger and other parts of the WHR system. This problem can be avoided by scrubbing the exhaust gases prior to heat recovery. However, this additional equipment increases system complexity and will reduce the temperature of the low-grade heat.
- The additional weight and the volume of the ORC system can be an insurmountable problem. This may be an unsurmountable barrier for ORC retrofitting for vessels where the engine room has very limited available space.

Table 8: Projects demonstrated/delivered for ORC implementation specific to maritime applications [140].

Vessel	Year	Vessel type	Cargo capacity	ORC capacity	Provider	Fuel savings (%)	Payback period	References
Figaro	2012	Ro-Ro	31,143 DWT	500 kW	Opcon	4–6	3 years	Opcon Marine
Viking Grace	2015	Cruise Ferry	57,565 GT	150 kW	Marine Climeon	Up to 5	-	Viking Line
Arnold Maersk	2016	Container	109,000 DWT	125 kW	Calnetix & MHI	10–15	5 years	Haglund et al. [141]; Sellers [142]
Asahi Maru	2017	Bulk Carrier	85,009 DWT	125 kW	Kobe Steel	3	-	Kobelco
Orizzonte	2017	Fishing Vessel	-	20 kW	Enogia	5	-	Motorship
Veerle	2018	Pusher Boat	250 GT	3 efficiency PACKs	Orcan Energy	5	2-4 years	Orcan Energy AG
Maranta	2019	Pusher Barge	5,000 DWT	1 efficiency PACK	Orcan Energy	5	2–4 years	Orcan Energy AG
Scarlet Lady	2020	Cruise Ferry	110,000 GT	900 kW	Climeon	Up to 5%	-	Climeon
Shunzan Kaiun KK	2020	Bulk Carrier	215,000 DWT	100 kW	Kobe Steel	3	-	Kobelco; MOL
Willem Barentsz	2020	Passenger Ferry	3,744 GT	154 kW	Orcan Energy	6–9	2–4 years	Orcan Energy AG
Willem de Vlamingh	2020	Passenger ferry	3,744 GT	154 kW	Orcan Energy	6–9	2–4 years	Orcan Energy AG
Pacifico	2021	Product tanker	22,000 DWT	80 kW	Orcan Energy	6–9%	2–4 years	Orcan Energy AG
Prospero	2021	Product Tanker	22,000 DWT	80 kW	Orcan Energy	6–9%	2–4 years	Orcan Energy AG
Maas	2021	Dredger	204 DWT	100 kW	Orcan Energy	4–5%	2–4 years	Orcan Energy AG
Mersey	2021	Dredger	204 DWT	100 kW	Orcan Energy	4–5%	2–4 years	Orcan Energy AG
Viking Glory	2021	Cruise Ferry	63,813 GT	Up to 40% of passenger functions	Climeon	Up to 5%	-	Viking Line
Havila Capella	2021	Cruise Ferry	15,471 GT	-	Climeon	Up to 5%	-	Havila
Havila Castor	2022	Cruise Ferry	15,471 GT	-	Climeon	Up to 5%	-	Havila
Valiant Lady	2022	Cruise Ferry	110,000 GT	900 kW	Climeon	Up to 5%	-	Climeon
Resilient Lady	2022	Cruise Ferry	110,000 GT	900 kW	Climeon	Up to 5%	-	Climeon
Havila Polaris	2022	Cruise Ferry	15,471 GT	-	Climeon	Up to 5%	-	Havila
Havila Pollux	2022	Cruise Ferry	15,471 GT	-	Climeon	Up to 5%	-	Havila
Green Jade	2022	Offshore Installation		500 kW	Orcan energy		-	Orcan Energy AG
Unnamed	2023	Cruise Ferry	110,000 GT	900 kW	Climeon	-	-	Climeon

5.2 Waste heat recovery - Steam waste heat recovery

5.2.1 Explanation of Measure

Waste heat recovery (WHR) technologies (Table 9), such as exhaust gas boilers and economisers can be used for steam production either for power generation or for other services such as running auxiliary machinery, freshwater production, air conditioning, heating services etc. Air recuperators can be used to improve engine efficiency. These are mature technologies and generally fitted to all large vessels to reduce fuel consumption by improving the overall efficiency of the power and propulsion system.

Table 9: Waste heat recovery technologies for maritime applications [143, 144].

Technology	Heat recovery range	Potential benefits and applications on ship
Economiser	Low to medium temperature	Waste heat recovery to preheat/heat the fluids for a range of low to medium heat
Waste heat boiler	Medium to high temperature	Heat recovery to produce steam
Recuperators	Low to high temperature	Heat recovery to preheat inlet air
Regenerators	Medium to high temperature	Waste heat recovery for high-temperature applications (suitable for gas-to-gas thermal storage)
Heat recovery steam generator (HRSG)	High temperature	Heat recovery to produce steam generation

5.2.2 GHG reduction potential

Considering the recent developments, WHR systems are estimated to reduce fuel consumption by 3% to 8% depending on the type of technology deployed.

Waste heat recovery is not a new concept, and many vessels already have some form of waste heat recovery system. Examples include for space heating, and most small vessels using heavy fuel oil employ economizers to heat fuel tanks and therefore avoid using oil fired boilers for this purpose.

A case study was performed on an oil carrier/tanker, with a vessel speed of 14.5 to 15.5 knots to investigate steam WHR options [145]. The study showed that a simple, single pressure system, could achieve a fuel saving of 6.5–8.1% at engine full load. Single pressure recovery systems can be advantageous in terms of cost and fuel efficiency for medium to large size vessels. Dual pressure systems can achieve higher efficiencies but require more capital investment due to system complexity and this would negate their implementation for small vessels due to high payback periods.

Another study explored a preheating and steam waste heat recovery system which was realised by introducing a heat pump for different ship classes and sizes (Bulk carrier, container, general cargo, tankers, cruise and ferry-RoPax) [146]. Such systems gave fuel savings of 0.5–0.8% (preheat) and 0.6–2.7% (steam generation) for small to large ships with

payback periods of 2–6 years and a 60% reduction in emissions from an auxiliary boiler was observed.

5.2.3 Status of Technology

WHR for steam generation is a mature technology and has been used for many decades for vessel applications. Installation costs of WHR systems depend on the technology deployed and the size of vessel. Retrofitting existing ships can help achieve short term GHG reduction targets. However, the ship's layout may require significant alteration due to additional infrastructure and space requirements which will increase costs and payback periods.

5.2.4 Technology application - Size of vessel, type of vessel and profile

Application of steam WHR systems is equally important for all types of the vessels. However, their deployment for large ships, operating on long-distance routes is a viable option to reduce fuel consumption. Steam WHR technology can be retrofitted but it is best suited for new vessels where better options for its installation can consider the space and cost as part of an integrated design.

5.2.5 Status of deployment and barriers to deployment

Steam WHR is a mature technology (high TRL/CLR) and is already installed on many vessels. However, despite higher efficiency, the complexity of such systems may have several barriers, which includes installation cost and available space.

6 Ship hull measures

This section includes technological measures to improve the hulls hydrodynamics. First the block coefficient, which is a measure of how streamlined a vessel design. Then coatings which prevent the growth of organisms or are suitable for regular cleaning, maintaining low friction levels through anti-fouling. Finally, air lubrication systems help to reduce hull friction and so drag and therefore reducing the amount of power needed to propel the vessel.

6.1 Ship hull - Block coefficient reduction

6.1.1 Explanation of measure

The block coefficient of a vessel compares the actual hull volume of a vessel to that of a rectangular block with the same length, breadth and draft. It is a dimensionless number from 0 to 1, which provides insight into the fullness of the ship's form and therefore how streamline the hull is:

- As the block coefficient increases towards 1 then this indicates a box type shape. Increasing drag, increasing fuel durn and therefore reducing fuel efficiency. Typical for tankers or bulk carriers.

- As the block coefficient decrease this indicates a more streamline vessel shape. Reducing drag, reducing fuel burn and therefore increasing fuel efficiency. Common for faster vessels like container ships, cruise liners or naval vessels.

The block coefficient is an important parameter in ship design and helps to determine the appropriate hull form. Designs balance the block coefficient with cargo capacity and fuel efficiency. Bulk carriers and tankers, which benefit from a fuller form (higher block coefficient), may need to employ other energy saving technologies to improve their efficiency without compromising cargo volume.

6.1.2 GHG emission reduction potential

The block coefficient of a vessel significantly influences their efficiency through the water. For example, historical trends show that on average vessels can improve their hydrodynamic efficiency by 5-15% just by using 1990s designs compared to those of the 2000's [83, 147, 148]. A study showed that emission reductions by up to 22% was possible by implementing more slender designs [149].

6.1.3 Technology application - Size of vessel, type of vessel and profile

All vessels can benefit from a reduction in block coefficient. However, it may not be possible for some designs due to competing interests such as maximising the cargo capacity, or stability requirements.

6.1.4 Status of technology

This is a mature technology and well understood. The choice is driven by market requirements.

6.1.5 Status of deployment and barriers to deployment

This measure is suitable for new vessels or existing ships undergoing significant modification. Vessel design has historically reflected market conditions such as fuel costs or freight rates and so the block coefficient has mirrored these changes [150]. In general, fuel-efficient hull designs are more expensive to build so the additional cost only makes economic sense when fuel costs are high. Ship design involves a combination of complex competing variables, such as port and canal restrictions, cargo capacity and speed.

Fuel prices are not the only relevant factor, when freight rates are high, new ships are in high demand so shipyards may make designs which are quick to deliver and low risk to the shipyard. Higher block coefficient, fuller form vessels, tend to be cheaper to build, so when steel prices and wages are high and fuel is cheap, these less efficient ships become more attractive. Conversely when freight rates are low, shipyards compete for clients and may be willing to build more efficient designs.

6.2 Ship hull - Hull management of coatings

Hull fouling, biomass growing below the waterline of all vessels, is a problem that increases hydrodynamic resistance of vessels through the water, reducing voyage efficiency and significantly increasing fuel consumption. It is estimated that microbial fouling, microfouling (formation of biofilm or slime) increases fuel consumption onboard a ferry by up to 20% after a year [151], and that macrofouling, attachment of organisms such as barnacles, soft corals and seaweed, can significantly increase CO₂ emissions for worlds shipping by an estimated 1 billion tonnes annually [152]. For operators, the benefits of having an effective strategy against hull fouling will significantly reduce fuel and therefore costs, saving the world fleet an estimated \$720 million USD using foul control coatings [153].

6.2.1 Explanation of measure

The most common method of preventing hull fouling and to protect the vessel from corrosion, is to apply a suitable coating to the surface of the hull. Commonly there are three main types of coatings used by the maritime industry, either biocide, fouling release and hard coatings [151].

Since the 1990s, coatings using copper-based biocide agents have been used after the banning of tin-based biocides because of their negative effect on the maritime environment. Biocidal coatings are the lowest cost, most available and easiest to apply anti-fouling solution, they come in two main forms, copolymer depletion paint (CDP) or self-polishing coatings (SPC), known collectively as copolymer coatings (CPC). Both leach a biocidal agent into the water, killing the fouling organisms before or shortly after attaching. CDP is a permanent substrate layer that becomes less effective over time (up to 60 months active life), as the biocide agent retreats from the surface. SPC allows the depleted surface layer to be removed through hydrodynamic shear as the vessel moves through the water, extending the working life of a coating by 12 months. Although biocide-based coating is the most effective method of preventing fouling and the most widely used, concerns remain over their use due to their effect on the wider maritime environment. Their use may undergo tighter restrictions and potentially be banned completely [154, 155].

Another type of low friction coatings are fouling-release coatings (FRC) and hard coatings. These offer a more environmentally friendly method of controlling fouling than biocide-based coatings. Silicone or fluoropolymer compound coatings (FRCs) have a low shear friction, making it difficult for marine organisms to become firmly attach to the surfaces. They rely on the hydrodynamic forces as the vessel moves through the water at speeds of 10-20 knots [154, 156, 157]. They are not 100% effective and a microfouling layer can still form on the hull in the boundary layer and low flow regions.

An alternative to FRC is the use of epoxy or polysiloxane-based hard coatings, these coatings do not significantly inhibit marine growth but are instead suitable for regular mechanical cleaning in the water without the coating being degraded. The anti-fouling performance is

poor compared with the alternative coatings, but a well-maintained hard coating, cleaned every 2-3 months, could still have a lower fuel consumption [156, 158] over a more conventional coating.

Since the 1990s, a new series of coatings have been developed and demonstrated on a small scale. These are conductive coatings, slippery liquid-infused porous surface (SLIPS), and photocatalytic coatings. These draw on the natural aversions of marine organisms to certain stimulus [155].

- **Conductive Coatings:** It was discovered that most marine micro-organisms have a slight negative charge. The concept of conductive coatings allows an electric current on the surface for the electrolysis of seawater to produce hypochlorite ions to repel fouling organisms. Early forms of this coating used copper, aluminium and molybdenum as the paint's conductive material. In recent years, carbon nanotubes and graphene have been used, along with polymer polyaniline and zinc oxide suspended in an epoxy-based paint. The later combination was found to maintain a PH of 4-5 and produce hydrogen peroxide from the zinc oxide (ZnO) at the hull surface, further adding to the coating's anti-fouling capabilities. In laboratory testing, it was found that using conductive coatings could repel 99.5% of all bacterial and microbial fouling [155].
- **Slippery Liquid-Infused Porous Surface (SLIPS):** SLIPS coatings use microstructures to hold lubricating liquids on the surface of the coating creating a smooth liquid film, preventing fouling from occurring. In laboratory tests, it is estimated that using SLIPS can save approximately 27 million tons of fuel and can cut CO₂ emissions by 107 million tonnes. However, when vessels are heavily fouled with mature organisms, such as muscles, this coating is less effective and requires cleaning, making it unsuitable for vessels with long periods between dry-docking. The US Navy has been undertaking long term testing of commercial SLIPS coatings at four heavily fouling geographical locations, to explore their long-term potential [155].
- **Photocatalytic Coatings:** Titanium dioxide (TiO₂) is a naturally occurring compound that when exposed to UV light decomposes at the surface to form a strong oxidant layer, which can break down any attached organic matter. Thought to be environmentally friendly, TiO₂ occurs naturally in seaweed and the oxidant layer is short lived and breaks down after a short period of time into harmless elements. Tests have shown that 80% of all micro-fouling are killed after 24 hours, and after 48 hours the remaining microorganisms did not develop into viable larvae. Improvement in the coating by adding Bismuth Tungstate (Bi₂WO₆) have demonstrated improved anti-fouling properties through the production of hydrogen peroxide as the oxidant at the surface. Although the anti-fouling properties have been proven and commercial coatings are available, it is only effective when the hull is exposed to sufficient intensity of light for the oxidant to form [155].

An interesting area of research is bionic or biomimetic coatings which emulate natural phenomenon, for example the structure of shark skin or the underside of a lotus leave. Using a combination of physical or chemical deterrents a new generation of coatings aim to discourage biofouling where micro textures of nano particle/fibres prevent or weaken the adhesion and/or chemical secretions to disrupt protein adhesion [159].

- **Physical biomimetic coatings:** nano particles or filaments suspended in a coating substrate are arranged to mimic the properties of shark skin, whale skin, dolphin, the underside of a lotus leave, dragonfly wings or crab shells to prevent fouling. These surfaces prevent or weaken adhesion of the organism to the surface, which are then removed by hydrodynamic shear. In addition, these coatings can be hydrophobic, trapping a thin air layer on the hull surface that not only prevent adhesion, but reduce hydrodynamic resistance through the water. The application of these types of coatings shows promising result in the laboratory but they are a long way from large scale commercial use, as the application currently can be complicated, inefficient and expensive [160 , 161, 162] .
- **Chemical secretion biometric coatings:** the use of peptides, glycoproteins, zwitterionic and poly-ethylene glycol, work by preventing the attachment to the surface (fouling-resistant), reduces adhesion of foulant to the hull surface (fouling-releasing) and/or killing micro-organisms (fouling-degrading). This shows great promise in laboratory testing but there are several issues to overcome before commercial application can be realised. These include large scale extraction and synthesis of the compounds requiring significant investment; compounds applicable to a single or many micro-organisms; environment degradation leading to limited lifespan; coating bonding agents and large-scale application of compounds need to be addressed [161].

6.2.2 GHG emission reduction potential

A typical coating costs around US\$30,000-\$500,000,

Estimates state that a ship with a freshly applied biocide coating can have a hull roughness of 2%. With a slime layer this hull roughness can increase to around 11-20%. As the fouling matures this will increase up to 80% [158]. As roughness increases, the engine will have to deliver more power to maintain the same sailing speed and therefore fuel efficiency will decrease, increasing GHG emissions. It is estimated that the fuel reduction achievable using FRC, such as Nippon Paint Holdings coating Aquaterras, is around 10% more than SPC coatings.

depending on the size of the vessel [163]. The GreenVoyage2050 project reported that light-medium fouling of the hull and propeller can lead to a 10-20% increase in fuel consumption, a 20-45% increase for heavy fouling and a 45-55% increase for very heavy fouling [164].

Even without fouling, it is important to note that there will be an increase in surface roughness of the coating in operation. Townsin's rule of thumb states that 10 µm roughness increases fuel consumption by 1% and thus GHG emissions [165]. According to HEMPEL, for their FRC hull roughness increases by 5 µm per year. After five years of service the coating roughness will be 25µm, increasing fuel consumption and CO₂ emissions by 2.5%, with a mean reduction in speed of 0.8%. Similarly, a ship with a newly applied SPC will increase hull roughness by 20 µm, after 5 years the increase in fuel consumption and CO₂ emissions would be 10% with a 3.3% loss in sailing speed [158].

6.2.3 Technology application - Size of vessel, type of vessel and profile

CPC and hard coatings are applicable to any type and size of vessel, with CPC being applied to around 80% of commercial vessels in 2019. While FRC are applicable to most vessels, they require a vessel to sail in open water at between 10-20 knots. This is due to the need to create sufficient hydrodynamic shear to remove fouling which occurs at speeds above 10 knots and so the coating is not damaged by too high hydrodynamic forces which will occur at speeds higher than 20 knots. Furthermore, their higher cost compared to biocide coatings has limited their application [154-156].

Conductive paint coatings. Examples of coatings using active elements is limited to small vessels, such as tugs, yachts, pleasure craft and fishing boats. Conductive coatings require the installation of additional systems to provide the electrical current for activation. In smaller vessels, with a small hull surface area, this charge is relatively low and can be easily accommodated by the onboard power systems. The power required for large commercial ships can be significant and therefore currently not an attractive option.

Photocatalytic coatings require UV light to activate the coating. On small vessels this is possible because of their shallow draft and their slender hull form. These coatings are less suitable for large commercial vessels because their deep draft and full hull form means that the surface area of the hull exposed to sufficient light is limited.

Slippery liquid-infused porous surface (SLIPS). SLIPS coating is difficult to mass produce in large enough quantities currently for larger maritime vessels [155].

The biometric coatings, although showing great potential as an anti-foulant, have not been tested outside of laboratory conditions and only been produced in small quantities.

6.2.4 Status of technology

CDP, SPC, hard coatings and FRC are mature technologies, TRL9 and CRL11, widely used in the maritime sector, with virtually all vessels using one of these types of coatings. However, wider marine environmental concerns with the use of biocides and limitations on the use of FCR, have led to research being carried-out in a range of new coatings.

Active coatings, such as conductive coatings, SLIPS and photocatalytic coatings, have been demonstrated in the maritime sector on a small scale with good results, but scaling up to

medium and larger commercial vessels is problematic. Limits on their active surfaces (Ultraviolet light), additional equipment requirements (electrical systems) and long-term impacts and performance remain unclear. These technologies are at TRL5-7 and CRL7 stages of technical and commercial development.

Biometric coatings have the potential to be more efficient and environmentally friendly coatings. However, they are yet to be demonstrated on a vessel and are not commercially available. Therefore, the technology is at TRL4 and CRL4, having only been tested under laboratory conditions.

6.2.5 Status of deployment and barriers to deployment

Hull coatings are applied to all ships, primarily to protect the vessel hull from corrosion, but also to reduce drag in the water through minimising friction and preventing biomass fouling. Reduced ship activity leads to quicker hull fouling, for example due to congestion or slow steaming. Biocide coatings (CDP and SPC) are the most used, protecting around 80% of all vessels, due to their low cost, effectiveness, availability and toughness. FRC are the next most commonly used, but restrictions over their effective operating conditions, weak shear strength, inability to deal with slime fouling at slow speeds and cost have hampered their use. Hard coatings, allow for regular cleaning of the hull without degradation of the surface, rather than providing anti-fouling. Active coatings have limited use beyond small vessels. Biometric coatings are in the early stages of development and have mainly undergone testing in laboratory conditions and will not be commercially available until at least 2040.

6.3 Ship hull - Air lubrication system (ALS)

Regardless of the vessel size and weight, hydrodynamic resistance of the hull directly affects the fuel consumption. Air Lubrication Systems (ALS) have been tested and installed on various ship types to reduce hydrodynamic resistance or drag. The application of ALS has been considered for a wide range of vessels, including LNG carriers, bulk carriers, tankers, container ships, Ro-Ro ferries and cruise ships [166].

6.3.1 Explanation of Measure

ALS uses compressors/blowers to eject air from the underside of the ship's hull which in turn reduces the hydrodynamic resistance and improves fuel efficiency [167]. There are different ALS technologies which have been introduced to the market. The different systems include, bubble drag reduction (BDR), air layer drag reduction (ALDR) and partial cavity drag reduction (PCDR) [167]. However, all these technologies are fundamentally similar but differ in terms of the distribution and formation of the air bubbles.

- BDR technology reduces the Reynolds number by the injection of microbubbles to reduce the local density of the water within the boundary layer of the ship hull. The Reynolds number is a dimensionless quantity which helps to predict the ratio between the inertial and viscous forces and hence the flow regime, high Reynolds number flows

are turbulent and low Reynolds numbers are laminar which has a direct impact on the drag of the vessel. As a result of the low density, the viscosity is also reduced and the skin friction of the vessel is reduced [168].

- ALDR forms a continuous layer of air between the water and hull surface to reduce the hydrodynamic frictional effects [169, 170].
- PCDR injects air into a recess at the bottom of the hull to create an air cavity which is an effective complementary technology that significantly reduce the hydrodynamic friction for high-speed vessels [171].

Kim and Steen [167] analysed the potential energy saving opportunities through the implementation of different ALS techniques based on experimental results. The net power savings for BDR, ALDR and PCDR were recorded as 2–5%, 8–14% and 16–22%, respectively under calm water conditions.

In addition to the fuel savings, hull lubrication has other advantages, first in reducing underwater noise due to the reduction of vibration and engine noise transmitted to the water, and secondly there is evidence that the bubbles help to prevent the accumulated of aquatic organisms (fouling).

6.3.2 GHG emission reduction potential

ALS technologies have gained significant attention due to their high potential to reduce fuel consumption and improve ship speed. The companies providing ALS technology quote 15%–40% drag reduction with up to 15% main engine fuel reduction [60, 77]. Other sources state the reduction potential for crude/product tankers and bulk vessels to be 7%–10%, while for other more streamlined ships types a 3% to 5% main engine fuel reduction is quoted [172].

6.3.3 Technology application - Size of vessel, type of vessel and profile

Mitsubishi Co.- Mitsubishi Air Lubrication System, Silver-stream-Silverstream System, R&D Engineering - Winged Air Induction Pipe System, Samsung Heavy Industries-SAVER System, Alfa Laval – Fluidic air lubrication system, Foreship-Foreship Air Lubrication System (Foreship ALS) have all developed ALS technology with basic to advanced modifications to BDR, ALDR, PCDR designs which increase the propulsion efficiency with reduction in fuel consumption of up to 10% and power requirement by 12% [167, 170, 173].

The following are examples of company reports on their installed units:

1. Damen reports fuel savings of 7–12% for seagoing vessels and 8–15% for inland waterway vessels. [174]
2. Silverstream have installed system on 38 container ships, 15 gas carriers, 14 Ro-Ro ferries, 8 cruise ships and 4 bulk carrier and tankers, reducing fuel use by 5–10% [175].
3. Alfa Laval OceanGlide successfully installed their system to coaster M/V Tharsis in a week reducing fuel consumption by 10% [173].

6.3.4 Status of technology

There is a growing body of evidence of significant fuel savings and other advantages by adopting ALS technologies. Vessel retrofit is generally straightforward and cost effective. The technology has rapidly matured to reach TRL of 9 and CRL 10 [176]. It may take between a week and several months to retrofit ALS technology for existing vessels, depending on its size and type. The literature and available information on retrofitted vessels, suggests that ALS is more effective for large slow speed vessels. The installation cost is in the range of 2% to 3% of the new build cost for a vessel.

6.3.5 Status of deployment and barriers to deployment

This technology is attractive because it is easy to retrofit and has a very short payback period. A limited number of barriers have been identified:

- For small vessels, and where remaining life is short, capital investment and operating costs for this technology may not be economically viable.
- Weather can affect the optimum operation of ALS, it works better in calm conditions.
- Regular maintenance is required for smooth operation in the marine environment.
- Power is required to produce the compressed air.

7 Propeller and rudder flow conditioning devices

Propeller and rudder flow conditioning devices are used to reduce hydrodynamic loss by optimising fluid flow. There are no major technical barriers to installation, and they are suitable for new vessels or retrofitting onto a vessel in a dry dock.

7.1 Propeller technology – Pre-swirl propeller ducts

7.1.1 Explanation of measure

A pre-swirl duct is positioned upstream of the propeller and guides the incoming water onto the propeller blades. They consist of a set of stationary vanes or ducts positioned before the propeller and they produce a rotational motion (pre-swirl) to the water flow, which aligns the water flow onto the propeller blades. This reduces flow separation and cavitation, increasing the propulsive force and decreasing energy losses. The design of the duct must be optimised to prevent adversely increasing drag. There are numerous design ideas and variations of this technology in the literature [177-183].

7.1.2 GHG emission reduction potential

Pre-swirl ducts reduce hydrodynamic losses and so increase the thrust for a given amount of fuel. To achieve the same ship speed, potentially a power reduction of 3 to 9% can be achieved, dependent on the specific design and the propeller loading [101, 178-180, 183].

Additionally, increased thrust and reduced propeller cavitation and wear will reduce operating costs, prolong propeller life and reduce vessel underwater noise.

7.1.3 Technology application - Size of vessel, type of vessel and profile

The energy saving of such devices can be achieved on most vessel types. They may not be suitable at higher speed where the device may incur extra hydrodynamic drag which outweighs the propulsion savings.

7.1.4 Status of technology

Pre-swirl ducts are a mature technology and are suitable for new and existing vessels.

7.1.5 Status of deployment and barriers to deployment

It has not been possible to determine the number of ships using some form of pre-swirl technology. It should be noted that designs can be complex and unique to the design of the vessel. For this reason, retrofitting will require complex simulation techniques to achieve a design that provides the desired performance improvements without causing adverse effects elsewhere.

7.2 Propeller technology – Contra rotating propellers

7.2.1 Explanation of measure

Contra-rotating propellers consist of two propellers on the same axis but rotating in opposite directions. This configuration recovers the swirl energy from the first propeller and so increasing the thrust overall, it allows for an increase in power without the need to increase the propeller diameter [184]. They are common in large speed boats. A contra-rotating propeller is more resistant to cavitation as the load is shared between the propellers, mitigating component wear and noise.

7.2.2 GHG emission reduction potential

A contra-rotating propeller has been reported to provide a 6.2% improvement in fuel efficiency when compared to a single fixed pitch propeller. The implementation of other devices in conjunction can enhance the efficiency further, such as using a combination of a contra-rotating, cupped and modified high lift trailing edge was shown to achieve an efficiency saving of 11.7% [185]

7.2.3 Technology application - Size of vessel, type of vessel and profile

Contra-rotating propellers could be used on most vessels. Retrofitting is likely to be challenging and requires significant modifications.

7.2.4 Status of technology

Contra rotating propellers are a mature technology and already installed on some vessels.

7.2.5 Status of deployment and barriers to deployment

Installation of contra-rotating propellers is mostly reserved for new build vessels. The installation of a new shafts and gearbox or an external secondary drive system (pod) is a significant change and therefore unlikely to be undertaken on existing vessels. The barriers appear to be due to the mechanical complexity, high capital cost and increased operational maintenance costs.

7.3 Propeller technology – Vane wheels

7.3.1 Explanation of measure

The main function of the vane wheel is to convert low thrust but high swirl flow from the middle of the propeller wake into higher thrust water aligned with the axis of the ship. The vane wheel is positioned immediately behind the propeller, it is located on the same shaft as the propeller but is freely rotating. The vane wheel blades have a turbine profile in the inner radius and a propeller profile at the outer radius. In the turbine section, kinetic energy is taken from the propeller wake which makes the vane wheel rotate. The rotational energy is then transformed within the outer propeller section to provide additional thrust.

7.3.2 GHG emission reduction potential

The vane wheel is reported to reduce the required power of a vessel by 5 to 10 % [186]. In 2020 the Siem Curie, operated by SIEM Ship Management, was fitted with a Grim Vane Wheel and reported a 5-10% improvement in power.

7.3.3 Technology application - Size of vessel, type of vessel and profile

Vane wheels are suitable for many types of vessels.

7.3.4 Status of technology

The Grim Vane Wheel was developed in the 1970s, has been installed on numerous ships and as such is a mature technology. However, there is little literature in the public domain and no information could be found on how many are in operation today.

7.3.5 Status of deployment and barriers to deployment

It is reported that in 1987 the Grim vane wheels fitted to the QE2 structurally failed, and due to the vessels high-profile this resulted in the technology losing industry traction.

7.4 Propeller technology - Boss cap fin

7.4.1 Explanation of measure

The boss cap fin (BCF) is an energy saving device installed just downstream of the propeller blades on the propeller boss. It is a stator with blades which recovers swirl energy and produces additional axial thrust. The elimination of the propeller hub vortex also results in reduced stern vibrations, lower propeller noise and reduced rudder erosion.

7.4.2 GHG emission reduction potential

Propulsion improvements of 4%-5% are claimed [45, 187]. Reported gains must be considered with caution as the rudder significantly reduces the hub vortex and hence the gain in propeller efficiency. The effectiveness of a BCF can vary depending on the type of vessel, operating conditions and specific propeller characteristics. Detailed performance evaluations are necessary to predict the benefits accurately.

7.4.3 Technology application - Size of vessel, type of vessel and profile

Boss cap fins are installed on many propeller designs.

7.4.4 Status of technology

Boss cap fins are a mature technology. It is reported that over 3,400 propeller boss cap fins have been sold between 1987 and 2022. [45]

7.4.5 Status of deployment and barriers to deployment

Boss cap fins can be retrofitted to existing propellers without requiring major modifications, making them a cost-effective technology. It should be noted that they must be tailored to the specific propeller and vessel to maximize efficiency gains, requiring precise engineering and design.

7.5 Propeller and rudder technology - Rudder bulb

7.5.1 Explanation of measure

A rudder bulb is an advanced hydrodynamic device attached to the leading edge of the rudder, downstream of the propeller. It fills the space, which would otherwise hold a vacuum, between the propeller and the rudder. This bulb streamlines the flow of water around the rudder, reducing turbulence and drag, thereby enhancing the rudder's efficiency. Furthermore, the device reduces the swirl of the flow impinging on the rudder. The reduction in drag, reduction in swirl and improved manoeuvrability contribute to the overall efficiency gain. Furthermore, by filling the low-pressure gap between the propeller and the rudder, the rudder bulb mitigates cavitation, protecting both the propeller and rudder from cavitation damage and extending their lifespan. Overall, the rudder bulb is a significant enhancement for ship efficiency and durability, offering both performance benefits and long-term economic advantages. It is suitable for both retrofitting on existing vessels and incorporation into new build vessels. Other advantages include reduced vibration and noise.

7.5.2 GHG emission reduction potential

The exact percentage of efficiency improvement will vary based on several factors, including the size and type of the vessel, its operating conditions and the design specifics of the rudder bulb. However, studies and industry reports suggest that improvements in hydrodynamic efficiency can lead to fuel savings in the range of 1-6% [32, 188-191].

There is a wide range of efficiency values within the grey and peer reviewed literature and no verified data has been found for ship installations, the publicly available data is mostly peer review computational modelling or laboratory testing. The actual efficiency saving for a particular application will be highly dependent on the overall vessel design and operation. It should also be noted that rudder bulbs are not always applied in isolation and can be part of several other propeller and rudder hydrodynamic devices and so the efficiency gain will be a combination of all those changes.

7.5.3 Technology application - Size of vessel, type of vessel and profile

Becker Marine Systems give efficiencies saving up to 4% compared to conventional rudder designs for a container vessel, Ro-Ro ferry, LNG carrier and Ro-Pax ferry [192].

7.5.4 Status of technology

Rudder bulbs are a mature technology suitable for new build and retrofitting. [32, 183, 190-192].

7.5.5 Status of deployment and barriers to deployment

It is not envisaged that there are any technical or operational barriers to deployment of advanced hydrodynamic propeller and rudder modifications.

7.6 Rudder technology - Twisted rudders

7.6.1 Explanation of measure

Twisted rudders aim to align the flow of water with the wake generated by the propeller. In practice the rudder is twisted in the vertical axis. This improved alignment equalises pressure distribution on the rudder surface, and so reduces turbulence, increases the propulsion efficiency, reduces cavitation and allows the rudder to generate more lift and less drag compared to conventional rudders. It therefore improves the efficiency and control of the vessel. There are many advanced design shapes proposed which could further the potential of this technology.

7.6.2 GHG emission reduction potential

Details of efficiency improvements are not readily available in the literature. One study predicted an increase of 2.95% in propulsive efficiency [193].

7.6.3 Technology application - Size of vessel, type of vessel and profile

Twisted rudders are applicable to a wide variety of applications.

7.6.4 Status of technology

Twisted rudders are a mature technology.

7.6.5 Status of deployment and barriers to deployment

Twisted rudders are suitable for both new vessels and retrofitting. Retrofitting will require significant changes to the rudder and/or steering gear. As with the other propeller and rudder modifications, the design will be vessel dependent requiring customised engineering and design to optimise performance.

8 Operational measures

8.1 Operational - Speed optimisation

8.1.1 Explanation of measure

In the maritime industry, the mind set of *“Sail fast and wait”* is one of the biggest barriers to operational efficiency, with ships wasting fuel sailing faster than necessary and whilst waiting outside the harbour for a berth to become available. Optimising the voyage for *“just-in-time”* arrivals (JITA) has two effects on a shipping’s fuel consumption [194].

- The ship uses the least amount of fuel in getting from port A to port B, arriving just-in-time to berth and unload without burning additional fuel while waiting.
- A ship will sail at the optimal speed for the journey to arrive just-in-time. This will be nominally slower, saving fuel as the engine will use less energy for equivalent sailing distances, leading to cost savings and reduced emissions, with a 10% drop in power, leading to a 10-20% reduction in fuel consumption [195].

Optimum speed means operating at the most efficient speed profile for the voyage, not just slowing down. This is a complex interaction between the type of fuel, engine technology and the routing of the voyage. LNG vessels for example need to consider the pressure of the tank and so may sail faster at the start of the voyage to reduce the cost of LNG storage. Weather such as wind speed/direction and sea state also influence the most energy efficient speed.

One study estimated that optimising the sailing for JITA operation would reduce GHG by about 15% [194]. The IMO states just-in-time arrival as *“a ship that sailed to a port with the least amount of bunker fuel consumed, but still arriving in time”*. A key aspect of the JITA is to have up to date reliable and accurate data, primarily regarding the availability of a berth, the pilot, tugs and entry/exit approach. Also, weather, sea-state, tides and traffic, at certain junctures during the voyage, all affect the sailing speed of a vessel for JITA. Sharable information needs to be timely, relevant and standardised for real-time informed decision-making onboard the vessel and in port, especially in determining optimal sailing speed for JITA. To this end, the International Hydrographic Organisation (IHO) has developed the S-100 framework to standardise, collate and communicate data between all stakeholders [33, 195, 196].

AI development will play a role in the future of JITA, being able to handle large data sets to create informed optimised sailing options. Empirical methods of handling large data sets use only about 10% of available data, while AI can utilise around 90% creating a better understanding of the options available. This will enable additional scenarios to be explored simultaneously, and routes planned, such as to deliver weather routing and cargo optimisation, to optimise voyages [70].

8.1.2 GHG emission reduction potential

Studies in optimised speed steaming have shown that a ship reducing its power by 10% could reduce fuel consumption by 10-20% depending on the journey and type of vessel [195]. A study of 50 vessels showed a reducing speed to achieve JITA could lead to 4-14% saving in fuel depending on advanced notice of pilot boarding time by between 12 and 24 hours [196, 197].

In 2018 an IMO report, in association with TNO, examining the port of Rotterdam concluded that ships spent 5-10% of their time at anchor, waiting to enter port. It showed, that if the requested time of arrival (RTA) to the pilot was known 12 hours prior to the ship approaching the port, then emissions would be reduced by 4%. This could be significantly greater if the requested time of arrival RTA was known more than 12 hours in advance. In fact, it is predicted that JITA, given adequate, timely and up to date information in advance, could see emissions reduce by 12-15% as the vessel adjusted speed to suit arrival time [195].

8.1.3 Technology application - Size of vessel, type of vessel and profile

Optimised voyage planning to determine sailing speeds for JITA is not suitable for some vessels, such as Ro-Ro and passenger ferries, as these vessels run to a tight schedule and dock at regular berths within ports. It will also not apply to small working vessels, such as tugs, fishing and offshore support vessels, who can transit in and out of port without disruption.

JITA could be applied to container ships, bulk carriers, general cargo ships, LNG/LPG carriers and tankers - 80% of the world fleet.

8.1.4 Status of technology

Optimised speed steaming is an operational concept and relies on the reliable, timely collection and collation of data and communication of up-to-date information to enable optimisation for JITA. Satellite tracking of vessels provides accurate position, speed and heading information. Shipping hubs can then make smart decisions based on the available data, for example the progress of a ship, weather and port status, to advise on the optimal sailing speed for best arrival time. This technology is considered mature at TRL9 and CRL11.

The implementation of AI and automated ships is relatively new to shipping with a few demonstrations of the technology undertaken. Currently, AI and automated shipping is being research and developed and can be considered at TRL6 and CRL7.

8.1.5 Status of deployment and barriers to deployment

Some of the main barriers for the implementation of JITA are [195, 198]:

- **Relevant and timely information:** Sailing to a given port for a pre-arranged arrival date without up-to-date information on availability, typically would mean arrival a day before a berth was available and waiting near the harbour entrance for a berth to become available. However, with better communication and up-to-date information, sailing speeds can be optimised to arrive at the time the vessel can be docked.
- **Notice of Readiness:** The charter party terms regarding tendering of notice of arrival, if this could be done remotely, not at the pilot station, ships could slow down to conserve fuel. Currently the notice of readiness needs to be an arrived vessel which means that the ship vessel must have arrived and be at the immediate disposal of the charterer before it can enter port. Meaning there may be a wait outside the port before there is a berth at port available.
- **Industry mindset:** The maritime industry is conservative and slow to change without clear evidence of the benefits and lack of legislation. Over the last decade the evidence of the fuel saving from optimised sailing speeds for JITA is growing.
- **Timeliness of arrival:** One risk in adopting optimised speed sailing and JITA is that if there is a delay on route then the vessel may miss its slot at berth. For example, adverse weather, adverse sea conditions or a breakdown such as engine problems could cause a delay. Improved information gathering and communication between the port and the vessel would minimise this risk and allow for appropriate actions to take place.

8.2 Operational - Weather routing and voyage optimisation

The weather plays an important role in planning shipping routes. State of the art systems are now capable of monitoring the weather in real time and provide reasonably accurate weather forecasting up to two weeks in advance. This enables global shipping to plan and optimise their routes between ports, to avoid adverse weather systems, optimise sailing speeds and to provide the most fuel-efficient route. Combining this data with other route optimisation requirements can provide significant efficiency savings. Weather routing is especially effective with WAPS technology and additionally is important to prevent risk of damage or harm to the vessel, crew and cargo. The shortest journey may not always be the optimal route and longer journeys may offer greater flexibility and efficiency [114, 199-201].

Voyage optimisation is the planning of a ships voyage from port A to port B, to navigate the route as efficiently as possible in a safe and compliant manner. It uses sophisticated models and algorithms to make informed decisions and aims to provide the optimal route for the ship to sail at the optimal speed, promoting fuel efficiency and reducing GHG emissions. The combination of just-in-time arrivals, speed optimisation, weather routing and improved operational practises can realise high fuel efficiency. [114, 199-205].

Furthermore, weather routing can significantly reduce vessel damage and reduce cargo claims due to avoiding harmful ocean conditions.

8.2.1 GHG emission reduction potential

Weather routing. By improving weather modelling and predictions, more certainty can be given to weather conditions and sea states around the globe, allowing for the avoidance of adverse weather conditions detrimental to sailing, and better optimisation of route planning, heading and speed. It is estimated that through effective weather routing 0-5% fuel consumption savings can be made, depending on the size and type of vessel. It is also estimated that the EEOI and CII will be similarly affected by the implementation of weather routing [114, 205].

Voyage optimisation is a low-cost operational measure which can have significant fuel efficiency savings. Combining weather routing, just-in-time arrivals and speed optimisation, a fuel reduction of 1-10% can be achieved, depending on the size and type of vessel [114].

8.2.2 Status of technology

Weather monitoring and forecasting is a mature technology. The technology to monitor the earth weather has improved with more sensitive and accurate sensors in more locations giving real-time up to the minute data. Computational weather predictions are constantly improving in accuracy providing valuable weather forecast up to 14 days in advance. It can be said that weather routing is at TRL9 and CRL11

Voyage optimisation depends on reliable, up-to-date data from the ship and shore, as well as the latest weather and sea state predictions. This requires the collation and interpretation of large data sets. AI and advanced models of the sea, weather and vessels are helping interpret the data, using it to determine the best sailing route and speed for the ship. Self-learning AI uses historical data to plan more accurate and improved efficient sailing options. This requires a lot of computing power to handle the vast data sets and develop optimised voyage routes. Dedicated maritime hubs have been developed, in different locations around the world, providing a route/voyage planning service to meet the needs of the ship owners/operators. Currently AI is in its infancy, but development is rapidly increasing (TRL8 and CRL8), while the actual computing technology is mature TRL/CRL11.

8.2.3 Technology application - Size of vessel, type of vessel and profile

All ship types can implement weather routing anywhere in the world, irrespective of size and purpose. An installation of a dedicated weather routing interface and an annual subscription to a weather routing service will allow optimised sailing for weather conditions [114].

Voyage optimisation is best suited to vessels operating on long voyage routes, allowing greater flexibility in the choice of heading and speed. For this reason, it is particularly applicable to very large container shipping, bulk carriers and transoceanic tankers. Voyage optimisation is not suitable for short-sea shipping or shipping that operate to a tight schedule.

The system requires the installation of hardware and software onboard the ship to relay route information. In 2016, the estimated CapEx for equipment, software and training for the crew was estimated to be \$10,000 US, with an annual OpEx of \$5,000 US/year for software upgrades and annual training [114].

8.2.4 Status of deployment and barriers to deployment

Globally, in all major maritime centres, there are many maritime logistic hubs offering a range of services, including weather routing and voyage optimisation, tracking in real-time the global shipping fleet (updating every 5-15 minutes). Ships are utilising these services to improve efficiency and optimise route planning to reduce fuel consumption to meet the emissions targets of the IMO. The installation of equipment and software, for better systems monitoring and relay information to the hub for optimised sailing and operational planning, is increasing with new build ships and the retrofitting of existing ships.

Compared to other efficiency technologies, the CapEx costs of the initial installation is relatively low, but since the owner/operator is buying a service the OpEx can run into several hundreds of thousands of dollars over the lifetime of the vessel.

Voyage optimisation uses virtual ship models and AI to collate and interpret real-time sailing and onboard systems operational data is improving reliability and accuracy of planned routes. This is further improved by self-learning AI algorithms, which use historical data to improve parameters for optimisation and, thus voyage routes.

8.3 Operational - Derating of main propulsion engines

8.3.1 Explanation of measure

Derating is a method of reducing the power output of an engine from its nominal operational condition. Derating moves the nominal efficient operating point, nominally at 85% of maximum loading, and creating a shallower engine efficiency curve leading to better fuel efficiencies at slower sailing speeds.

There are several parameters that determine an engines normal continuous rating (NCR) and optimised around 85% of its maximum working load. Derating involves tuning or modification of the engine to reduce the engine power, creating a new engine efficiency profile for lower engine loads. This provides the opportunity for slower sailing speeds and therefore reduced fuel consumption and GHG emissions. Some changes to engine operation could include modify the fuel injection timing, changing the intake/exhaust valve timing, omitting a cylinder or modifications to the piston which would be relatively inexpensive.

Although, derating of the engine reduces fuel consumption, there are problems that can occur from continuous running of the engine at low loads, including reduced turbocharger efficiency, cold corrosion with lower combustion temperatures and increase exhaust manifold deposits.

8.3.2 GHG emission reduction potential

Slow-speed steaming at times of high fuel price, has commonly been used to reduce fuel consumption and operational costs for shipping. At slower vessel speeds the propulsion engine(s) are required to produce less power and so can be derated, further improving the efficiency of the vessel. It is estimated that derating the main engine could save 2-10% of fuel depending on the size of the main engine(s) and extent of the derating undertaken [206]. However, it can increase NO_x emissions due to impact on combustion and turbocharger efficiency.

8.3.3 Technology application - Size of vessel, type of vessel and profile

This measure has been applied to most commercial vessels, for example tankers, general cargo ships, bulk carriers, and container ships. Ships that operate to tight time schedules and/or need to sail at high speeds cannot generally operate at slow speeds and thus cannot derate their engines. This includes refrigerated vessels, passenger ferries, LNG/LPG ships, cruise ships and Ro-Ro ferries.

8.3.4 Status of technology

The derating of an engine is a mature technique, at TRL9/CRL11.

8.3.5 Status of deployment and barriers to deployment

Most engine manufacturers can derate their engines. However, there are still a few concerns about the practice.

- **Cost of derating:** Although cost can be very low, \$60,000 US, for a simple derating service, where the engine timings are tuned or cylinder deactivated, a full derating service can cost as much as \$3,000,000 US. In the latter case this would involve making physical changes to the engine, for example reduce piston stroke length and/or replacing the propellor to match new engine loads.
- **Time to implement derate:** Depending on the derating package implemented (simple tuning or full overhaul), will take time. If a simple package is implemented, where the engine is tuned this can be carried out while the ship is in the water and will take around 3 days. However, engine and turbocharger modifications and a propellor change can take up to 30 days in drydock.
- **NO_x emissions:** Derated engines can increased NO_x production, and so additional mitigation measures need to be implemented.
- **Engine wear:** Increased acidic deposit formation and engine fouling at very low loads can occur, increasing wear and reducing efficiency. Additives to the fuel and special formulated lubricating oils can be used to neutralise any acidity with the engine, reducing the risk of wear.
- **Exhaust deposits:** Build-up of exhaust gas deposits of un-burnt fuel and lubricating oil at low loads can happen in the exhaust manifold and turbocharger(s). Periodic running

of the engine at higher loads, above 80% MCR, for one hour to burn off accumulated carbon deposits and regular blowing of the economiser can mitigate against deposits build-up, reducing the risk of exhaust fires.

8.4 Operational - Ship ballast - Trim optimisation

8.4.1 Explanation of measure

The draft of a vessel is the vertical distance from the surface of the water to the deepest part of the keel.

The draft of the vessel changes due to the weight that the vessel is carrying including the cargo, ballast, fuel etc. Increasing the cargo load or amount of ballast lowers the vessel in the water and so increases the draft. Vessels with a deeper draft can carry larger loads, however increasing the draft reduces manoeuvrability and turning radius and prevents the vessel from entering shallow waters. Increasing the draft increases the wetted area of the vessel and therefore increases the drag of the vessel, which increases the fuel used. Load or plimsoll lines are markings on the side of the vessel which indicate the draft in a quick and accurate way. Vessels, such as cruise liners, may have a real time measurement of the draft for operational purposes.

The draft is not always the same at the bow to stern. When a vessel inclines from port to starboard is called heeling/listing and balancing the load ensures that the vessel is upright in the water. The trim of a vessel is a change in draft from the bow to stern. When the draft is higher at the bow, compared to the stern, the vessel has a trim by head. The trim is set before the voyage by positioning cargo, ballast water and fuel, and during the voyage by water ballast and fuel positioning alone. Under certain weather or sea-states the vessel may be trimmed by the bow, i.e., a deeper draft at the bow. However, trim by bow may not be possible on some vessels due to the need to keep the propeller properly submerged.

The hydrodynamic mechanisms which account for trim optimisation are the flow around the bow, stern and the propeller, the frictional resistance changes due to trim is a secondary effect [207]. Trim by the stern can cause transom submergence which then increases resistance due to the consequent complex flow regimes behind the transom. Bulbous bows are optimised for a specific narrow operational condition and therefore can lead to undesirable wave patterns and increased resistance when the vessel is in an incorrect trimmed state. Trim optimisation is setting the best trim at a given time. It is determined by considering the speed, draft, loading, vessel hydrodynamics, amongst other parameters.

8.4.2 GHG emission reduction potential

Efficiency savings are widely reported to be up to 6% [32, 33, 35, 101, 208-210]. There is the potential for slightly higher efficiency savings, through advanced operational trim optimisation which predicted a reduced total ship power consumption by up to 7.64% [211].

8.4.3 Technology application - Size of vessel, type of vessel and profile

Trim optimisation is applicable to all vessel types, but the implementation may be less flexible on some types of vessels, for example cruise vessels are designed to ensure passenger comfort as well as efficiency and there is the need for distributed ballast tanks to control the trim.

8.4.4 Status of technology

This is a mature technology.

8.4.5 Status of deployment and barriers to deployment

The loading of a vessel cargo, fuel and its ballast condition determines the relationship between the metacentre and centre of gravity. This in turn determines the vessel stability and danger of capsizing. Stability needs to be calculated when transferring fuel and water to change its trim. More reliable information on the savings through trim optimisation is necessary to maximise benefits.

9 GHG abatement measures whilst vessels are in port

9.1 Port - Hull management (hull cleaning and propeller polishing)

The latest hull coatings can reduce biomass fouling of a ship's hull, however there are limitations and challenges to their effectiveness and implementation. This includes reduced coating life, ease of damage and reduced robustness, and only effective under certain operational conditions. To supplement coatings effectiveness, regular hull cleaning with divers using scrubbers or underwater cleaning robots is the most cost-effective solution to maintain the vessels hydrodynamic performance. An alternative to underwater cleaning, is cleaning when the vessel is in dry-dock. Dry-docking is extremely expensive, and a ship is only expected to dry-dock every 3-5 years for regular maintenance and survey. It is estimated that regular hull cleaning 3-4 times a year can reduce GHG by 4-12% annually [58, 152, 212-214].

In addition to hull cleaning, propellers suffer from fouling, reducing their performance, which reduces vessel speed for a given power rating. During dry-dock periods, propeller polishing is an important operation often conducted. However, in the time between dry-docking the ship's propeller becomes fouled, and propulsion efficiency reduced. It is, therefore, common practise to use divers with hand operated polishing tools for underwater cleaning between dry-dock periods.

9.1.1 Explanation of measure

In-water hull cleaning usually involves a diver using a scrubbing device, with abrasive brushes or powerful waterjets to physically remove the biofouling. This work is performed in port, during periods of inactivity of the vessel. Underwater hull cleaning can take a few days to complete, depending on the size of vessel, specific system being used, number of divers

employed and operational conditions, e.g., heavy, or light harbour traffic, sea conditions and weather. The work is hazardous, time consuming and seen as aiding the forced migration of invasive non-indigenous marine species (i.e. zebra mussels from the Black Sea to Cardiff Bay) [212]. This is why some countries require collection/destruction of biomass waste, have severe restrictions or even ban hull cleaning in the ports and coastal regions.

Since the early 2000s, an alternative to using divers for underwater cleaning is to utilise robotic hull cleaners, either remotely operated vehicle (ROV) or autonomous underwater vehicle (AUV). The advantages of underwater robotic hull cleaners are they are less hazardous, reduced costs, operate in nearly all conditions and reduced time of cleaning, as a robot can work continuously for prolonged periods. Another advantage of underwater robotic hull cleaners, if designed correctly, is that they can collect all fouling waste and can operate during load/unload of the ship, not disrupting the ships normal operations in port. Underwater robotic hull cleaning systems have been developed in the USA, Australia, Hong Kong, Korea, Norway, Denmark, France and Netherlands, however worldwide their availability is very limited. [58].

The main problems encountered with underwater robotic hull cleaning systems are fouling detection and in-water visibility, hull attachment and cleaning systems preventing coating damage, effective biomass collection and destruction, and hull navigation and control systems. Many of these problems have receded over the years with improving technologies and design, for example localised ultra-high frequency sonar systems and improved high-definition cameras for improved fouling detection and tracking. It is expected that over the next decade, the use of robotic systems will increase as result of lower costs compared to other forms of cleaning, improved safety, versatility and the possibility to significantly reduce fuel and GHG emissions.

9.1.2 GHG emission reduction potential

Hull fouling can dramatically increase a vessel's hydrodynamic drag, with microfouling up to 0.5 mm high increasing drag by 20-25% and up to 55% for macrofouling [164]. This in turn increases workload on the engine to maintain specific sailing speeds, and thus, fuel consumption. It is estimated that fuel consumption of ferries increases by 20% after 1 year of service of a freshly applied coating [151]. Regular hull cleaning 3-4 times a year would reduce fuel consumptions by around 8-12% and thus emissions.

9.1.3 Status of technology

Underwater diver and drydock cleaning services are already mature and well established. They are commercially available around the world in many ports, CRL11. Underwater robotic hull cleaning for commercial shipping is still a maturing market with TRL9 and CRL8/9. Underwater robotic hull cleaning systems can offer a cost effective, rapid, versatile and safer method of cleaning without affecting the normal port operations of a vessel. Autonomous

systems could offer even greater advantages. Also, the effective biomass waste collection and disposal needs to meet regional, national and local environmental regulations which vary.

9.1.4 Technology application - Size of vessel, type of vessel and profile

Underwater cleaning either be conducted by divers or use underwater robotic systems are applicable to a wide range of sizes and types of vessels depending on availability of services within the port area. The nature of the hull coating and extent of fouling will influence the decision if underwater hull cleaning is feasible. Some coatings are soft and easily damaged, so harsh abrasive cleaning may not be possible. With the rising use of these types of coatings, less harsh cleaning methods have been developed using low pressure water jets, steam and soft-bristle brush heads.

While dry-docks and underwater cleaning with divers are widely available in nearly all locations around the world, only sixteen robotic systems (Table 10) are currently fully developed and commercially available, with room in the market for innovative robotic systems and global growth.

Table 10: Hull cleaning robotic systems

Robot	Country of Origin	Company	Operation	Cleaning Process	Website
CleanHull	Norway	Ecosubsea	ROV	Soft Water Jets	https://www.ecosubsea.com/home/sustainable-hull-cleaning
Fleet Cleaner	Netherlands	Fleet Cleaner	Semi-Autonomous ROV	High Pressure Water Jets	https://www.fleetcleaner.com/
EverClean	USA	Armach	Autonomous	Ultrasonic Action Brushes	https://greenseaiq.com/solutions/everclean/
Hull Surface Treatment (HST)	Australia	CDS (Commercial Diving Company)	ROV	Thermal Shock (Steam)	https://commercialdiving.com.au/ship-hull-cleaning-hst/
Hullbot	Australia	Hullbot	Autonomous	Brushes	https://www.hullbot.com/robot
HullBUG	USA	Sea Robotics	Semi-Autonomous ROV	Brushes & Jets	https://www.searobotics.com/products/hull-and-tank-cleaning
HullWiper	Dubai	HullWiper Ltd.	ROV	Pumped Seawater Driven Cleaning Disc	https://www.hullwiper.co/why-hullwiper
M6 Sub Sea Cleaning Tool	Unknown	AWE	ROV	Water Jets on Swinging Arm	
Magnetic Hull Crawler	France	Cybernetix	ROV	Cavitation Water Jets	https://www.cybernetix.fr/our-solutions/hull-inspection-and-cleaning-robotics
RovingBAT	France	ECA Group	Semi-Autonomous ROV	Cavitation Technology	https://www.ecagroup.com/en/solutions/rovingbat-hybrid-rov
LF ROV Hullcleaner	China	Langfeng Tech. Company	ROV	Cavitation Jets	https://www.shipcleaner.com/copy-of-lf-rov01
HullSkater	Norway	Jutman	ROV	Brushes	https://www.iotun.com/no-en/industries/solutions-and-brands/hull-skating-solutions/resources/meet-the-hullskater
fCHIRO	South Korea	SLM	ROV	Brushes	
Neptune ROV Hull Cleaner	Hong Kong	NEPTUNE Robotics	ROV	Cavitation Jets	https://neptune-robotics.com/technology/

ITCH (in-transit cleaning of hulls)	Demark	Shipshave	Semi-Autonomous	Soft Brushes	https://shipshave.no/itch/
RoverClean 3.0	USA	Alicia Bots Inc.	Autonomous		https://aliciabots.com/industries

Early development of underwater robotic hull cleaning systems has been led by Europe and USA, with most mature systems being in these regions. However, China is investing heavily in this growing market with a few commercialised systems currently available and several more under development. Coupled with renewed interest in the rest of the world, it is expected that regular underwater robotic hull cleaning will be more viable. By 2030 it is expected that at least 20 different systems will be available, and by 2050 it is expected that most ports and regions around the world will have some form of commercial underwater robotic hull cleaning system available.

9.1.5 Status of deployment and barriers to deployment

Hull cleaning is an accepted method of maintaining a vessels efficiency through the water. Underwater and drydock cleaning are available in most regions around the world, with many ports offering either or both services. Underwater robotic cleaning services are available in a few ports, seen as a safer and lower cost option to both underwater cleaning with divers and drydock cleaning services. Although limited in availability, new robotic systems are being developed, and existing systems are looking to expand beyond their home ports. The barriers to hull cleaning are:

- **Cost of operation:** Drydocking a ship is expensive, with a vessel only being drydocked, when necessary. This is usually every 3-5 years, depending on certification or when safety critical maintenance needs to be performed. Underwater cleaning can be carried out at a far less cost and whilst loading/unloading the vessel.
- **Time taken for cleaning:** Depending on the type of cleaning being undertaken this can mean the ship is laid-up for some time. Drydocking a ship will take the longest time but is generally only performed every 3-5 years. Underwater cleaning with divers can be carried out much more frequently and take several days, requiring the ship to be non-operational and the conditions in harbour waters to be viable (weather and harbour traffic), to ensure the safety of divers. Underwater cleaning with robots can be undertaken in any conditions and while the ship is loading/unloading cargo, thus reducing the time a ship may be non-operational.
- **Marine environmental impact:** Around the world there are concerns over the forced migration of non-indigenous marine species being transported on a ship's hull as biofouling. Underwater hull cleaning is seen to exasperate this by releasing these marine creatures in the harbour waters if the scrubbed biomass is not collected. To reduce the risk of problem, all the biomass waste can be collected during the cleaning operation, or all the marine species can be killed before entering the water, i.e. using

steam cleaning. Even so, underwater cleaning of hulls is prohibited in the territorial waters of Australia and New Zealand.

- **Balancing competing impacts:** As discussed, hull cleaning is required to prevent increased GHG emissions through increased hull drag, but this cleaning may have an impact on the marine environment.

9.2 Port - Shore-to-ship power or cold ironing (CI)

9.2.1 Explanation of measure

Shore-to-ship power or cold ironing (CI) is the process of reducing emissions by supplying power to vessels in port from shore-based generation. With vessel emissions in port negatively impacting health and the environment, eliminating the need for a ship to use onboard auxiliary generated power reduces CO₂, SO_x, NO_x and PM emissions.

It is estimated that CI can reduce overall ship emissions by up to 16% of CO₂, 13% of NO_x and 11% of PMs while at berth [215]. CI offers a method of reducing emissions for virtually all vessel types and would have greater impact on those that have high hotel and in-port power demands, especially with longer than 2-hour port stays, for example cruise ships, and dry bulk cargo ships. The true national and regional reductions will be dependent on the up-stream emission from the electrical power generation.

The implementation of CI has several drivers:

- **Reduction of GHG emissions:** The need to reduce GHG emissions to meet international agreements and regional/national legislation.
- **Reduction of environmentally harmful emissions (NO_x, SO_x & PMs):** The need to reduce NO_x and SO_x to protect the environment from acid rain and water acidification to meet international agreements and regional/national legislation. Protecting public health by reducing PMs preventing respiratory and cancerogenic diseases, which accounts for an estimated 60,000 death a year in coastal regions [216, 217].
- **Drive for electrification of shipping:** As the world fleet increases its demand for hybrid and fully electric propulsion, there will be increased demand for shore power required to charge the battery systems.
- **Reduced noise:** especially for ports close to urban conurbations.
- **Reduced cost and facilitating onboard maintenance:** Vital work can be conducted on shutdown systems maintaining high efficiency.

9.2.2 GHG emission reduction potential

On average a ship produces 16% of its annual CO₂ emissions while at berth, therefore this is the CO₂ saving which can be achieved from the adoption of CI. To achieve the full saving then the electrical power should be from renewable sources with near zero emissions [215]. The extent of upstream emission is dependent on the mix of electrical generation and so some indirect upstream emissions may be attributed to the ship while at berth, from the source of

the electric power supplied to the vessel. CI also importantly prevents other emissions harmful to human health from vessels in ports, for example particulate matter. vessels

The GHG reduction potential depends on the source of electricity. For example, in 2023 Norway, a strong advocate for CI because of increasing electrification of its short-sea shipping fleet, generates nearly all its electric power from renewable resources. Therefore, a ship with a shore connection point will have near zero emissions while in port and minimal emissions in and around harbour waters. In contrast, the UK in the same year generated around 55% of its electrical power from renewable and nuclear sources, reducing overall GHG emissions by around 9% while at berth. While China produces 65% of its generated power from fossil fuels and 35% from renewables and nuclear, GHG emissions saving from a vessel moored with a S2SP connection would be around 6.4%, depending on the exact mix of generation [111, 112].

9.2.3 Technology application - Size of vessel, type of vessel and profile

It is stated that any ship which spends longer than two hours in port should have CI capability. In fact, operators using ports in California at berth for longer than 2 hours, need 80% of their fleet CI capable. Currently, around 1,500 vessels are equipped with a CI connection, approximately 1.4% of the world's commercial fleet. Over half of these are container ships (809 vessels), around 15% of all container vessels. By far the largest sector that have embraced CI is for cruise ships with 27% of the current fleet, with 55 vessels having installed systems. Most ship types have had CI connections either retrofitted or incorporated in the design of new build vessels. However, certain sectors have been slow to adopt CI, such as bulk carriers (0.7% of all vessels) and gas/oil tankers (0.2% of all vessels), largely due to stricter safety guidelines and risk of fire/explosion [215].

The vessel is only one part to the CI equation. Ports must have the infrastructure in place to enable ships to connect to a power source. To drive port installation of CI, legislation (EU Directive 2014/94/EU– all EU ports must have some form of CI in place by 2025; California Air Resource Board) have encouraged regions and nations to implement infrastructure or alternative clean power sources [218]. In addition, EU legislation (Regulation (EU) 2023/1805 – *“On the use of renewable and low-carbon fuels in the maritime sector”*) is in place with legislation for compulsory installation of CI onboard container ships and passenger ships (ferries and cruise ships) by 2030 [219].

One of the main barriers to ports implementing CI is the cost of installing the infrastructure in port and onboard ship. Many countries, such as Germany, Norway, Netherlands, offer up to 80% of the funding to cover the cost of installation of CI infrastructure. In 2019, there were 9 ports in the USA with CI installed, the EU had 19 installations and 10 across Asia [215]. The rest of the world had 5 installations and the UK had 1 for tugs in Milford Haven. Since then, the number of ports in the UK with CI installations have increased by 2 (Southampton and Orkney) [218, 220]. Across the rest of Europe there are between 90-100 ports with some form of CI installed or planned, Norway is leading the way with 41 installations [221].

9.2.4 Status of technology

The port of Juneau (USA) was one of the first ports to provide CI connection in 2002, and it is still in operation today. Since then, the technology has matured with more ports offering CI connections and more ships have installed the technological systems. The technology can be considered as TRL9 and CRL10.

9.2.5 Status of deployment and barriers to deployment

The uptake of CI has been slow due to the associated costs, lack of onboard connectivity and complexity of supply. Standardisation of supply and connection is important. However, CI is seen as one of the technologies that can aid in reducing GHG emissions and also the drive to install BESS onboard ships, requiring to be charged in port.

There are still several barriers and concerns that need to be addressed before widespread implementation of this technology [215, 222].

- **Lack of Demand:** Both ships and ports need the technological infrastructure for CI. Currently the number of ships with shore-based power supply connectivity is relatively small compared to the size of the global shipping fleet, about 1.4% (1,500 vessels). This number is increasing as older ships are decommissioned and newer ones are built. On the other hand, port installations are required otherwise vessels which do install the systems may find a lack of port infrastructure which means that onboard CI systems are redundant.
 - **Capital Costs of Installation:** Capital costs for the port to install the necessary infrastructure and for localised distribution network can be high. Costs can vary dramatically depending on location in the world, ranging from 122 US\$/kW (40 MW, Genoa Italy) to 7,088 US\$/kW (8 MW, Oakland USA) [215]. In addition to these costs the ship owner/operators need to provide the connection technology to enable safe power transfer. Retrofitting an older ship is considerably more expensive than installing a system on new build.
 - **Cost of Electricity:** Another challenge can be that the cost of grid power needs to be cheaper than running the onboard engines, otherwise there needs to be another incentive for CI. The price of electricity is seen by most ship owners/operators as a major barrier to CI.
 - **Lack of Power Network Capacity:** In a busy commercial port, where large ships with high power demands are berthed the power grid may not have capacity to supply all the needs of the local area and shipping. In these cases, additional capacity will have to be installed in the form of micro-grid generation, which would increase capital costs for the port authorities.
- CI Standardisation:** The problem with CI is that individual ships will have their own power grids operating at 380-460 V or 6.6-11 kV with a frequency of 50 or 60 Hz. This causes problems for the shore supply as it needs to cater for all vessels. If ships have

a regular berth, i.e. ferries, cruise ships and tugs, it is not a problem ensuring the right supply of power to the vessel. However, most ships in the world fleet are container ships, bulk carriers, tankers and general cargo ships. To ensure adequate power supply to these vessels, CI needs to be standardised. To this end the IEC, ISO and IEEE work collaboratively to develop a comprehensive set of standards to aid the integration of CI onboard ship and in any port in the world [223].

10 Conclusions

The purpose of this report is to explore GHG reduction in the maritime sector from improvements in energy efficiency, to provide an assessment of the available information on potential relevant short-term GHG reduction methods and the implementation of the CII and EEXI. It relies on peer-reviewed and grey literature to evaluate the current state of relevant GHG reduction options and barriers to their implementation. The report includes an overall assessment and detailed discussions of each measure.

Overall, the evidence suggests that a combination of operational measures, technological advancements, alternative fuels and supportive policies can achieve significant short-term GHG reductions in the shipping industry. However, the effectiveness of these measures will depend on the scale of implementation and industry-wide adoption. This requires a regulatory drive, with the framework provided by the IMO, but governing bodies must ensure compliance.

In the future, fuel switching will play a major role in the decarbonisation of the maritime sector but in the short term there are other energy efficiency measures which should be prioritised. Fuel switching to LNG and biofuels is an attractive short-term solution; however, using LNG does not provide a zero GHG emission solution and there are concerns about methane slip. The biofuel supply chain is limited and long-term resource availability is a major concern. Switching to low carbon hydrogen and hydrogen carriers, such as methanol or ammonia will require massive scale up and will not significantly reduce GHG emissions in the short-term.

Energy efficiency should be the foremost method of GHG reduction to prevent energy waste. No single technical or operational measure can achieve the required GHG emissions reductions alone, so a combination of options will be necessary.

Operational changes are being implemented first. Vessel speed, weather routing and optimising voyages are tools which can achieve significant efficiency gains and provide CII compliance. The report includes specific proposals to modify the CII to further reduce GHG emissions, such as coordinating port and ship operations to minimise speed and prevent long waits at anchor or at berth.

Several hull, propeller and rudder modifications have been discussed in the report. While no single modification can achieve the 40% fuel savings required by the IMO, their combined effect is likely to be worth implementing. However, the combined impact of multiple technologies is not well understood due to the complex and highly specific nature of each vessel.

Advanced propulsion technologies, such as hybrid electric propulsion and wind-assisted propulsion, offer significant potential for fuel savings and should be explored where possible. These technologies are likely to be implemented primarily on new ships or on existing ships that are unable to meet IMO's CII standards through other means. Waste heat recovery systems will help to reduce fuel wastage, but it is not clear how the CII provides an incentive to install such systems.

Overall, the evidence suggests that a combination of operational measures, technological implementation, alternative fuels and supportive policies can achieve significant short-term GHG reductions in the shipping industry. However, the effectiveness of these measures will depend on the scale of implementation and industry-wide adoption which will require local and international policies to ensure compliance of the IMO framework and further incentives on ports to decarbonise too.

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