MEDITERRANEAN ACTION PLAN (MAP)
REGIONAL MARINE POLLUTION EMERGENCY RESPONSE CENTRE FOR THE MEDITERRANEAN SEA (REMPEC)

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Agenda Item 8: Reduction of GHG emissions from ships

Study Analysing the Impact of Biofouling on the Energy Efficiency of Ships and the GHG Abatement Potential of Biofouling Management Measures in the Mediterranean Sea region

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REMPEC
Malta, 2025

Note by the Secretariat

This document presents the Study Analysing the Impact of Biofouling on the Energy Efficiency of Ships and the GHG Abatement Potential of Biofouling Management Measures in the Mediterranean Sea region.

Background

1 Biofouling is the accumulation of marine organisms on ship hulls and other surfaces that can significantly affect vessel efficiency by increasing hydrodynamic drag, leading to higher fuel consumption and GHG emissions. Given that shipping accounts for approximately 80% of global trade, and has seen a 20% increase in related GHG emissions over the past decade, enhanced biofouling management presents a significant opportunity for improved energy efficiency, whilst reducing the associated environmental impact. Efforts have been, and are being, made to reduce GHG emissions from shipping, but “a clean biofouling free hull” may enable further reductions with appropriate methods and cooperation The Study is set against the backdrop of increasing global attention on shipping emissions, and the growing need and awareness for sustainable practices in maritime operations. This includes the Mediterranean Sea, which is a key global shipping route. The ship-port interface is defined as the area of coverage of a ship’s operation from the time the pilot boards the vessel at the pilot station to help it berth. The coverage extends to the time the pilot leaves the vessel at the pilot station when the vessel departs from the port and includes the time the vessel is at the port. During this period, the vessel is involved in cargo operation, crew change, provision, bunker, ship surveys and repair, etc. Emissions happen during ship-port interface in berthing process, cargo operations and various other reasons.

2 In this context, the Secretariat commissioned AQASS Limited, to prepare a Study Analysing the Impact of Biofouling on the Energy Efficiency of Ships and the GHG Abatement Potential of Biofouling Management Measures in the Mediterranean Sea region, hereinafter referred to as the Study, in order to support any possible future regulatory or policy action by the Contracting Parties to the Barcelona Convention, in their efforts to mobilise and implement innovative solutions to reduce GHG emissions from ships in selected ports, including through energy efficiency and decarbonisation and in considering sustainable shipping in the region, focused on future possible options of biofouling management. It presents available information relating the impact of biofouling on ship energy efficiency and the relationship between GHG emissions released and subsequent reduction through biofouling management practice.

3 The Study evaluates current international practices, the effectiveness of biofouling management technologies, and develops possible future policy recommendations to enhance GHG emissions reduction efforts by biofouling management within the Mediterranean Sea context. It also evaluates various biofouling management practices, including antifouling coatings, in-water cleaning (IWC) technologies, and policy frameworks. The research draws from a range of academic sources, industry reports, and international guidelines, particularly from the International Maritime Organization (IMO) and its Global Environment Facility (GEF)-United Nations Development Programme (UNDP)-IMO GloFouling Partnerships Project.

4 The Study was carried out, pursuant to the Programme of Work and Budget for 2024-2025 of the Mediterranean Action Plan (MAP) of the United Nations Environment Programme (UNEP), adopted by the Twenty-third Ordinary Meeting of the Contracting Parties to the Barcelona Convention and its Protocols (Portorož, Slovenia, 5-8 December 2023).

5 This activity was financed by the voluntary contribution from the French Ministry for Europe and Foreign Affairs.

6 The Study is presented in the **Appendix** to the present document.

Action requested by the Meeting

7 **The Meeting is invited to take note** of the information provided in the present document.

Appendix

Study Analysing the Impact of Biofouling on the Energy Efficiency of Ships and the GHG Abatement Potential of Biofouling Management Measures in the Mediterranean Sea region

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Study analysing the impact of biofouling on the energy efficiency of ships and the GHG abatement potential of biofouling management measures in the Mediterranean Sea region

Final report

AQASS Ltd
12/12/2024

Disclaimer and acknowledgements

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The views expressed in this document are those of the Consultant and are not attributed in any way to the United Nations (UN), the Mediterranean Action Plan (MAP) of the United Nations Environment Programme (UNEP), IMO or REMPEC.

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Executive Summary

The Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea (REMPEC) commissioned a Study analysing the impact of biofouling on the energy efficiency of ships and the greenhouse gas (GHG) abatement potential of biofouling management measures in the Mediterranean Sea region (“the Study”). The Study aims to assist nations that are Contracting Parties (CPs) to the Barcelona Convention in considering sustainable shipping in the region, focused on future possible options of biofouling management. It presents available information relating the impact of biofouling on ship energy efficiency and the relationship between GHG emissions released and subsequent reduction through biofouling management practice. The Study evaluates current international practices, the effectiveness of biofouling management technologies, and develops possible future policy recommendations to enhance GHG emissions reduction efforts by biofouling management within the Mediterranean Sea context.

In the context of the Study, biofouling is the accumulation of marine organisms on ship hulls and other surfaces that can significantly affect vessel efficiency by increasing hydrodynamic drag, leading to higher fuel consumption and GHG emissions. Given that shipping accounts for approximately 80% of global trade, and has seen a 20% increase in related GHG emissions over the past decade, enhanced biofouling management presents a significant opportunity for improved energy efficiency, whilst reducing the associated environmental impact. Efforts have been, and are being, made to reduce GHG emissions from shipping, but “a clean biofouling free hull” may enable further reductions with appropriate methods and cooperation The Study is set against the backdrop of increasing global attention on shipping emissions, and the growing need and awareness for sustainable practices in maritime operations. This includes the Mediterranean Sea, which is a key global shipping route.

The Study includes a review of global biofouling regulations, shipping efficiency and GHG emissions related to biofouling. It also evaluates various biofouling management practices, including antifouling coatings, in-water cleaning (IWC) technologies, and policy frameworks. The research draws from a range of academic sources, industry reports, and international guidelines, particularly from the International Maritime Organization (IMO) and its Global Environment Facility (GEF)-United Nations Development Programme (UNDP)-IMO GloFouling Partnerships Project.

The key findings are as follows:

Global Policy Context:

Biofouling management is regulated through various international and national frameworks. The IMO’s 2023 Guidelines for the control and management of ships’ biofouling to minimise the transfer of invasive aquatic species (the “IMO Biofouling Guidelines”) serves as a primary reference. The IMO Biofouling Guidelines were primarily developed to minimise the transfer of invasive non-indigenous marine species (NIMS) through biofouling, the associated benefit of reducing GHG emissions is acknowledged within the Guidelines. However, the guidelines are not mandatory, leading to inconsistency when implemented by different countries and across different regions. Countries such as Australia and New Zealand have enacted biofouling regulations, while others are still developing their approaches. Further to this, the GEF-UNDP-IMO GloFouling Partnerships Project is focused on greater awareness of the impact potential of biofouling management for both NIMS and GHGs, as well as the subsequent benefits, financial, social and ecological, of such management. The need for coordinated global policies that align invasive species management with GHG emission reduction objectives is emphasised. Global approaches towards GHG management in shipping are being driven by the IMO. Aimed at 50% GHG emissions reduction by 2050, the IMO has introduced metrics towards measuring and reducing CO_2 using a Carbon Intensity Indicator (CII) assessment. Amongst the measures identified for modification of management, biofouling is a targeted area.

Impact on Shipping Efficiency:

Shipping is the most energy efficient method of global goods transport. Conversely, biofouling is long recognised as an impediment to efficient hull speed and fuel consumption, reflected in the search for, and adoption of, antifouling measures by mariners that date back to centuries BC Biofouling management is a significant opportunity to reduce GHG emissions from shipping. Macrofouling (barnacles, seaweed, etc.) is the recognisable face of biofouling. However, even the slime layer, formed by bacteria, microalgae, and other microorganisms, can increase the hydrodynamic resistance of ships and increase energy use and GHG emissions. Even a slime layer 0.5 mm thick, covering 50% of a given hull, can significantly increase resistance. Heavy calcareous fouling, such as barnacles, can require up to 86% more power for vessel propulsion. Effective biofouling management can therefore yield substantial energy savings and emission reduction. The Mediterranean Sea region, with its busy transitory and short shipping routes, could particularly benefit from proactive biofouling management. However, the role of biofouling in GHG emissions is a data driven requirement, influenced by multiple varying factors, and the effects have therefore not been clearly quantified. The paucity of data, and the consequent lack of a clearly quantifiable relationship between biofouling levels and energy efficiency, makes translation into actionable outcomes difficult.

Biofouling Management

The Study explores historical and current methods for biofouling management. In the history of biofouling controls, many methods have been tried to prevent or inhibit the macrofouling development on vessel hulls. The application of antifouling coatings has been the most common approach, and mostly using biocidal coatings that slowly release an antifouling biocide through the coating surface. More recent developments include foul release (FRC) and hard coatings. For biocidal antifouling coating effectiveness, a zenith was reached in the latter 20th century with tributyltin (TBT) self-polishing copolymer (SPC) coatings. However, the unexpected toxicity of this compound resulted in its global ban through the IMO's AFS Convention. Concerns about environmental impacts of replacement biocides continue necessitating the careful consideration of trade-offs between efficacy and environmental impact. Innovative biofouling management approaches are highlighted, including the use of nanoparticles and hydrogel layers, which aim to improve coating performance and sustainability. The necessity of tailoring management practices to specific vessel types, regions, and routes are also highlighted and this reiterates the difficulty of applying a general model of GHG emissions reduction value through biofouling control.

The Study shows that there are limited data on the effect of biocidal coatings and hull roughness on GHG release due to hydrodynamic resistance. Some researchers are suggesting a gradual move from biocidal paints towards FRCs, and possibly hard coatings, will develop in combination with hull management practices such as in-water grooming or cleaning. The majority of data on hull speed and efficiency discuss FRCs and hull smoothness and suggest that, with appropriate management, a smooth hull can achieve up to 10% fuel saving. There are no readily available data on hull roughness of hard coatings, their main advantage being long-life, but research is needed to establish hull efficiency with cleaning / grooming undertaken.

In the Study, practical biofouling management by IMO Member States and ports is considered. Some authorities have imposed restrictions on, or banning of, in-water cleaning (IWC) and others require a permit that considers prior biofouling management before IWC is allowed. Several companies are able to capture biological waste and contaminants (e.g. metals, biocides, microplastics) from IWC. Hull cleaning and grooming are promoted as options to control biofouling. Cleaning in this context is reactive, to remove established macrofouling, and, in some scenarios, may be required to permit entry into national waters. Proactive cleaning, or hull grooming, is regular tailored cleaning at the slime layer stage to minimise hydrodynamic resistance and inhibit the development of macrofouling. As an example, the Port of Bremen

(Germany) highlights that it only allows cleaning of hard coatings and that macrofouling cleaning is also not permitted. This promotes proactive grooming and a move towards the “clean before you leave / arrive” policy. This is the optimal approach to achieve hull smoothness and enhanced GHG management prior to passage.

Whilst recommendations for uptake of hull cleaning options may be laudable, the limitations of current infrastructure in supporting regular biofouling maintenance are also highlighted. The need for a balance between effective biofouling management and the associated costs is emphasised, especially for long-distance shipping. There is growth in the in-water hull cleaning industry, thus auditing of these in the Mediterranean region is suggested. Some points are raised on appropriate regulation of this industry in regard to safety and biological and chemical contamination of the environment and the need for waste capture. Guidelines have been proposed by the shipping industry (e.g. BIMCO) and regulators, as possible models to be followed for the effective management of operations.

GHG Reduction Potential:

Most available research indicates that, if biofouling is managed effectively, levels of GHG emissions from shipping may be reduced by around 10%. However, one study considered that, globally, the figure may be up to 19%, equivalent to 198 million tons of carbon dioxide (CO_2) annually. This highlights the critical role that biofouling management can play in broader efforts to decarbonise the shipping industry. It underscores the importance of integrating biofouling management into broader GHG emissions reduction strategies and improving the energy efficiency of vessels through proactive biofouling control.

The Mediterranean Sea, via the Suez Canal, is the primary shipping route between Asia and Europe, and is also the principle short sea shipping area in Europe. Shipping has been identified as a significant contributor to reduced air quality, even from offshore shipping routes so, by extension, shipping will contribute to regional GHG levels. CO2 levels have significantly increased over time, notably off Sicily, at the end of the Suez Canal in the Straits of Gibraltar, and the Bosporus.

Whilst fouling rates in the Mediterranean are described as relatively slow, a GEF-UNDP-IMO study based on a Mediterranean scenario, amongst others, identified that hull cleaning in the region had significant potential to reduce hydrodynamic resistance and thus CO2 levels. In this study, proactive cleaning is identified as the most efficient method to control biofouling. “Clean before you leave” is highlighted as a favourable option. However, policy changes would be required before this became the norm. There are limited practical data on the direct effects of hull cleaning in a Mediterranean context. One study on a ferry, cleaned every May prior to summer seasonal work, found over three years of data (2015-2017) a significant saving in fuel, and consequent decrease in CO2, for a three month period (June-August) following the cleaning. Calculations suggested a foul free hull saved “about 15 kg of fuel per mile”.

In addition to biofouling management, other GHG emission reduction measures have been considered for in conjunction use. Options include on board carbon capture, slow steaming of transitory traffic in the Mediterranean, alternate fuels, weather based route planning, and electric power plants. The latter is considered an option for the Mediterranean Sea as the region is the most significant in terms of short shipping routes.

A multiple criteria analysis indicates that “clean before you leave” (proactive) for FRCs and hard coatings (the latter requires more research on smoothness) is optimal in managing biofouling for the reduction of GHG levels from shipping.

Recommendations

The Study recommends a more coordinated international approach to biofouling management, including the need for:

- Contracting parties to the Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean Sea (the “Barcelona Convention”) to align with the IMO Biofouling Guidelines ensuring biofouling management consistency across the Mediterranean Sea region;
- Enhanced data collection on the impact of biofouling on shipping efficiency and GHG emissions to guide future policies;
- Alignment with biofouling management practices such as proactive IWC that balances efficiency gains with environmental protection.

For the Mediterranean Sea, specific collaborative study and guidance development, possibly leading to regional approaches, should be tailored to the unique environmental and operational challenges of the area. The Mediterranean Sea is susceptible to the introduction of NIMS and the impacts of those introductions. While there is substantial data on the movement of NIMS, less attention has been paid to the association between biofouling and GHG emissions in the Mediterranean Sea region and elsewhere.

CPs need to discuss future policy approaches in the Mediterranean region. Recommendations are for CPs to collaborate in developing biofouling management and hull cleaning approaches based on the IMO Biofouling Guidelines and IWC standards, such as that of BIMCO. Consideration should also be given to port control on arriving ships, such as developed by the USA EPA, and other synergistic approaches toward GHG reduction, e.g. slow steaming to reduce fuel use and to reduce waiting periods in arrival ports when the vessel could be prone to biofouling.

A roadmap and action plan are provided which suggests actions that may assist CPs finding agreement on an approach to regional biofouling management that would reduce GHG emissions from shipping in the Mediterranean Sea region.

Abbreviations / Acronyms

ABP – Associated British Ports

AFS – Control of Harmful Anti-fouling Systems on Ships - AFS Convention

Ag – Silver

AHR – Average Hull Roughness

ANZECC – Australian and New Zealand Environment and Conservation Council

BIMCO – Baltic and International Maritime Council

BWM – Ballast Water Management

CI – Carbon Intensity

CII – Carbon Intensity Indicator

CPs – Contracting Parties

CO – Carbon Monoxide

CO_2 – Carbon Dioxide

CoA – Commonwealth of Australia

CRMS – Craft Risk Management Standard [New Zealand]

Cu – Copper

Cu_2O – Copper I Oxide

DAFF – [Australian] Department of Agriculture, Fisheries and Forestry

DBT – Dibutyltin

ECAs – Emissions Control Areas

EDGAR – Emissions Database for Global Atmospheric Research

EEDI – Energy Efficiency Design Index

EEXI – Energy Efficiency Existing ship Index

EGSC – Exhaust Gas Cleaning System

EPA – Environmental Protection Agency

ESG – Environmental, Social and Governance

EU – European Union

EU ETS – EU Emissions Trading System

FOC – Fuel Oil Consumption

FRC – Foul Release Coating

GCPI – General Company for the Ports of Iraq

GEF – Global Environment Facility

GHG – Greenhouse Gases

HFO – Heavy Fuel Oil

IMO – International Maritime Organization

IMS – Invasive Marine Species

IPCC – Intergovernmental Panel on Climate Change

IWC – In Water Cleaning

LCA – Life Cycle Assessment

LCCA – Life-Cycle Cost Assessment

LNG – Liquefied Natural Gas

LPG – Liquefied Petroleum Gas

MGO – Marine Gas Oil

MPI – [NZ] Ministry for Primary Industries

NIMS – Non-Indigenous Marine Species

NIWA – National Institute of Water & Atmospheric Research Ltd [NZ]

NO_X – Oxides of Nitrogen

NSTM – Naval Ships' Technical Manual

NZ – New Zealand

PDMS – Polydimethylsiloxane

REMPEC – Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea

SO_X – Oxides of Sulphur

SPC – Self-Polishing Co-polymer

SEEMP – Ship Energy Efficiency Management Plan

SFE – Surface Free Energy

TBT – Tributyltin

TiO_2 – Titanium Oxide

UK – United Kingdom of Great Britain and Northern Ireland

UNFCCC – United Nations Framework Convention on Climate Change

UNDP – United Nations Development Programme

USA – United States of America

USCG – U.S. Coast Guard

VGP – Vessel General Permit

VIDA – Vessel Incidental Discharge Act

Zn – Zinc

ZnO – Zinc Oxide

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1. INTRODUCTION

1.1 Study Rationale

1.1.1 The Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea (REMPEC) administered by the International Maritime Organization (IMO), in cooperation with the Mediterranean Action Plan (MAP) of the United Nations Environment Programme (UNEP), has sought assistance with a study analysing the impact of biofouling on the energy efficiency of ships and the greenhouse gas (GHG) abatement potential of biofouling management measures in the Mediterranean region (the "Study").

1.1.2 REMPEC's work focuses upon the prevention of, preparedness, and response to marine pollution from ships within the Mediterranean Sea region. Under this, REMPEC's mandate is to assist the Contracting Parties (CPs) regarding Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean Sea (the "Barcelona Convention") pertaining to sustainable shipping practice within the Mediterranean Sea region. In addition, REMPEC's role is to provide assistance and mobilisation in the event of regional emergency situations pertaining to shipping / pollution incidents within the framework of the Protocol concerning Cooperation in Preventing Pollution from Ships and, in Cases of Emergency, Combating Pollution of the Mediterranean Sea (the "2002 Prevention and Emergency Protocol") to the Barcelona Convention.

1.2 Issue Overview

1.2.1 It is widely recognised that biofouling on vessel hulls and in submerged niche areas (e.g. intake pipes, sea chests) can facilitate the transport of Non-Indigenous Marine Species (NIMS), some of which may become Invasive Marine Species (IMS). The definition of an IMS is one that has ecological, sociological and / or economic impacts (e.g. see Henry *et al*., 2023) although, in the Study, these are not considered further. The transport of NIMS has been the subject of considerable and ongoing research globally (Vilizzi *et al*., 2021), including studies within the Mediterranean Sea (e.g. see Zenetos *et al*. (2020); Bédry *et al*. (2021)), and related management efforts (e.g. Tamburri *et al*. (2021[a]).

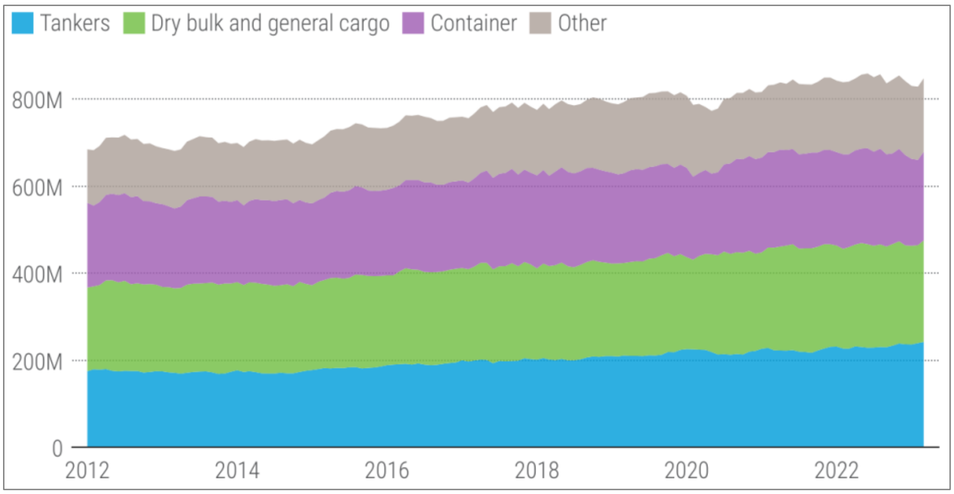

Figure 1.1 Growth in shipping emissions 2012-2023[1]
Modified from UNCTAD (2023)

1.2.2 Regarding NIMS transfer as biofouling, global policy and guidance instruments are led by the IMO's 2023 Guidelines for the Control and Management of Ships' Biofouling to minimise

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[1] The group "other" includes vehicles and roll-on / roll-off ships, passenger ships, offshore ships and service and miscellaneous ships.

the transfer of invasive aquatic species (the "IMO Biofouling Guidelines"), an update of the 2011 version (also see GEF-UNDP-IMO (2022[a])). There are also regional approaches (e.g. REMPEC, 2019) and national efforts such as Australia's National Biofouling Management Guidelines for Commercial Vessels (CoA, 2008[a]) and the Anti-Fouling and In-Water Cleaning Guidelines (DAFF, 2024[a]), which, with New Zealand in 1997, were the first to be introduced in the world (ANZECC, 1997). There has subsequently been a growing focus on the impact of biofouling on GHG emissions from commercial shipping and efforts to reduce the associated atmospheric carbon impact (Joung *et al*., 2020; Aakko-Saksa *et al*., 2023).

1.2.3 Considering GHG emissions, commercial shipping is the carrier of around 80% of global trade (UNCTAD, 2023), thus the potential for significant improvement and reduction in carbon emissions. Against this, the United Nations (UN) commented that "the [shipping] sector, whose greenhouse gas emissions have risen 20% over the last decade [Figure 1.1], operates an ageing fleet that runs almost exclusively on fossil fuels" (UNCTAD, 2023, IMO, 2023[a]).

1.2.4 In the context of the Study and, against the background of growing shipping GHG emissions (Figure 1.1) and management efforts directed at propulsion and fuel types, biofouling and shipping efficiency is receiving increased attention. For example, recent work has assessed the role of antifouling coatings in biofouling management and the consequent effects on shipping efficiency and fuel savings (e.g. Farkas *et al*., 2021). UNCLAD (2023), quoting Wärtsilä (2022), stated that "a clean biofouling-free hull can be around 10–15 per cent more fuel efficient than a fouled hull, but this is often overlooked, as it is challenging to monitor".

1.2.5 Against the background information for the Study, it is important to elaborate on the facets outlined above. Furthermore, an outline of the Study requirements for the goal of a potential policy approach to biofouling control and aspirational GHG emissions reduction in the Mediterranean Sea region is needed.

1.3 Study Requirement

1.3.1 The Study requirement comprises:

1. Identification of current international practices and technologies for the control and management of ships' biofouling and their related efficacy in GHG emissions reduction;

2. Evaluation of the impact of biofouling on vessel hulls and niche areas upon fuel consumption and associated shipping GHG emissions;

3. Identifying proactive and reactive biofouling management and control measures on the impact of biofouling on fuel consumption and associated reduction of GHG emissions from ships; and

4. Developing policy intervention recommendations, best practice and technological innovations that may contribute to the reduction of GHG emissions from ships through control and management of ships' biofouling in the Mediterranean Sea region.

2. POLICY AND MANAGEMENT

2.1 Global Biofouling Regulations

2.1.1 Policy approaches towards biofouling management have grown in relation to concerns relating to potential NIMS transport and biofouling influence on vessel efficiency and GHG emissions, the focus of the Study. As noted by Davidson *et al*. (2016), the "negative consequences [of biofouling] provide a unifying purpose for the maritime industry and biosecurity managers to prevent biofouling accumulation and transfer". Davidson *et al*. (2016) also comment on the gaps between the aspirations of the maritime industry (greater efficiency and profit) and biosecurity managers (NIMS management) although, in theory, the two approaches could readily align. Even Davidson *et al*. (2016), whilst highlighting the synergy of biofouling and GHG emissions reduction goals, only give a brief overview of the latter as an aspiration. There is limited evidence of a united approach to what should be synergistic goals.

2.1.2 Historically, the main driver for biofouling management, and use of antifouling coatings has been the impact of biofouling on ship operations (Lewis, 1998). However the majority of academic research over recent decades has been concerned with the transport and possible impacts of NIMS by shipping although, in 1991, the annual cost of fuel to the US Navy was estimated at around $500 million, of which $75 - $100 million was attributed to drag caused by biofouling (Maty, 1991). Recent references to the impact of biofouling upon GHG release appears largely data limited, although authors recommend data gathering to inform the need for GHG management, while also acknowledging the difficulty of this task due to the nature of the variables required. This data paucity even applies for such important vessel routes as the Mediterranean Sea, which has been listed as carrying some 15% of global shipping. This figure is based on data that is more than 10 years old (see UNEP/MAP, 2012) so, with the growth in global shipping, this percentage is likely to have increased with associated rises in in GHG emissions (see UNCTAD, 2023).

2.1.3 The IMO is the relevant organisation for the development and implementation of global polices for biofouling management. However, unlike the International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004 which entered into force on 8th September 2017 (IMO, *Indet*[a]), the IMO Biofouling Guidelines, adopted initially in 2011 and updated in 2023 (IMO resolution MEPC.378(80), see here), are not mandatory. It should be noted, however, that non-mandatory guidelines for the management of ships' ballast water were first adopted by the IMO in 1991, 13 years before adoption of the Convention and 26 years before it entered into force. The IMO Biofouling Guidelines are, as their full title states, primarily intended "to minimize the transfer of invasive aquatic species", but do acknowledge, in paragraph 1.9, that biofouling management practices may also improve a ship's hydrodynamic performance and can be effective at enhancing energy efficiency and reducing air emissions from ships.

2.1.4 As a resource for biofouling managers and for future operations concerning biofouling and policy approaches, the IMO partnered with the GEF (Global Environmental Facility) and the UNDP (United Nations Development Programme) to create the GEF-UNDP-IMO GloFouling Partnerships Project. This provides resources for biofouling management and, in the context of national policy, together with documents considering management, shipping energy efficiency etc. a technical study is available which provides an analysis of regulations and standards for biofouling management (GEF-UNDP-IMO, 2022[a]).

2.1.5 To address the limited unity in approach to biofouling and GHG emissions reduction, some nations are using the IMO Biofouling Guidelines as a "springboard" towards their own approach to biofouling control. This is largely under the banner of NIMS management, although the legislative approach will have a concomitant benefit for GHG management as one factor that affect emissions from shipping (Davidson *et al*., 2016). However, whilst the IMO Biofouling Guidelines do not impose a mandatory requirement to manage biofouling, as noted by

IRCLASS (2022), “some [IMO] Member States such as Australia, New Zealand, Canada [and states within the] United States of America [USA] etc. [recognise] the need to protect sensitive ecosystems within the coastal waters under their jurisdictions, [and] mandate ships calling at their ports to develop and implement a plan to manage biofouling”. IRCLASS (2022) goes on to comment that “ship owners / operators are advised to take cognisance of such specific local regulations implemented in certain countries with respect to biofouling management”.

2.1.6 For the USA and “applicable vessels*”* (Rao, 2024), the U.S. Environmental Protection Agency (EPA) requires vessels arriving at a USA port to have in place a Vessel General Permit (VGP). This mandates reporting of where, type and date of antifoul application plus information on hull cleaning etc. to minimise the attachment of living organisms. Required management methods comprise:

1. Selecting an appropriate anti-foulant management system and maintaining that system;
2. Conducting an in-water inspection;
3. Cleaning and maintenance of hulls; and
4. Thorough hull and other niche area cleaning when a vessel is in dry-dock (see: Kelley, 2014).

2.1.7 Kelley (2014) goes on to note that “Some States have additional requirements applicable to underwater ship husbandry and hull fouling within their State waters (e.g., additional limitations on underwater ship husbandry)” (see below).

2.1.8 The EPA website (EPA, 2023) notes that the Vessel Incidental Discharge Act (VIDA) was signed into law in 2018. Under this act, the EPA is required to “develop new national standards of performance for commercial vessel incidental discharges and the U.S. Coast Guard (USCG) is required to develop corresponding implementing regulations”. Full implementation of the Act is anticipated by 2026.

2.1.9 As mentioned above (Kelley, 2014), there are USA state level requirements for biofouling management. California and Washington State, in particular, have six year strategic biofouling management plan requirements. These were put in place in 2017, and are therefore due for update by 2026. Washington State was considering a ban on copper (Cu)-based antifoul paints (Washington State, indet) based on concerns about emissions to the marine environment and possible impacts on non-target species. The Cu ban was due to come into effect in 2016, but was put on hold to enable further consideration of Cu effects data. A review is due by 2029. Washington State banned antifouling paints containing the biocide cybutryne from 1st January 2023. This move is consistent with the IMO’s 2021 amendment to the AFS Convention which banned cybutryne in antifouling paints from the same date. As another example of differing state approaches, the State of Maine prohibits in-water hull cleaning even with updated capture technology (see sub-section 3.4).

2.1.10 On an apparent rise in the availability of in-water cleaning (IWC) options / organisations, likely in response to the IMO guidelines, awareness raising by the GloFouling project, and tailored national approaches (of which operators are encouraged to be aware), some researchers suggest care is needed to avoid further exacerbating the impacts of vessel fouling (see Tamburri *et al*. (2020, 2021[b])).

2.1.11 Elsewhere, Canada has issued voluntary guidance closely aligned with the IMO Biofouling Guidelines, and Mauritius has mandated the use of advanced hull cleaning technologies. The latter encompasses “capture” technology to address the perceived risks of in-water cleaning (see Hyun *et al*. (2023)). Some nations, such as South Africa, require permission to be sought from the relevant harbour authority in advance of any in-water cleaning activity (Transnet, 2010).

2.1.12 The most stringent approaches to biofouling management, requirements and in-water cleaning are in New Zealand and Australia.

2.1.13 In New Zealand, the Craft Risk Management Standard (CRMS) on Biofouling on Vessels Arriving to New Zealand entered into force in May 2018 (Lewis, 2020[a]). The requirement of the CRMS was that every type of vessel must arrive in New Zealand with a "clean hull". A "clean hull" was defined as a hull with no biofouling of live organisms beyond defined thresholds, with separately defined thresholds for "short stay" (20 days or fewer in NZ waters and only visiting designated "Places of First Arrival") and "long stay" (21 days or more in NZ waters and/or visiting places other than designated "Places of First Arrival"). For long stay vessels, the biofouling threshold was no more than a slime layer and / or goose barnacles, with a slime layer defined as "a layer of microscopic organisms, such as bacteria and diatoms, and the slimy substances they produce" (MPI, 2014). For "short stay" vessels, there was an additional allowance for some algal growth and one type of macroinvertebrate at the wind and water line and on the hull, and some algal growth and two types of macroinvertebrates in niche areas.

2.1.14 Acceptable methods for meeting the CRMS were cleaning to remove all biofouling less than 30 days before arrival or within 24 hours of arrival, continual "best practice" maintenance (e.g., following the IMO Biofouling Guidelines), or application of MPI-approved treatments (MPI, 2014).

2.1.15 In 2023, NZ combined the Craft Risk Management Standard for Biofouling (2018) and the Craft Risk Management Standard for Vessels (2018) into the Craft Risk Management Standard: Vessels (CRMS Vessels) (Ministry for Primary Industries, 2024). (see MPI (2023), here). This merger brought together topside and biofouling biosecurity risks associated with vessels entering NZ waters but excludes the biosecurity risks associated with ballast water. The 2023 revision adds a third ship category, cruise vessels, which must comply with the requirements for "long stay" vessels. Also specified within the revised standard is the requirement, within the list biofouling information to be provided to MPI prior to arrival, to provide the latest biofouling inspection report that meets the detailed "minimum evidence requirements" and reporting criteria specified in the CRMS.

2.1.16 The NZ CRMS Vessels also states that "the operator...of the vessel must ensure that…no removal of biofouling from an international vessel is undertaken in New Zealand territory other than through use of an MPI-approved haul-out facility or MPI approved treatment".

2.1.17 Within Australia, National Biofouling Management Guidelines, which predated and informed the IMO Guidelines, were developed for different maritime sectors, which included commercial vessels, non-trading vessels and petroleum production and exploration vessels (Lewis, 2020). However, the State of Western Australia was the first to introduce biofouling requirements on vessels arriving in that State's waters. Ministerial Conditions imposed on oil and gas development projects required vessels arriving from overseas or other Australian states were to be free of "marine pests". In part, this required vessels to be inspected by a government-approved biofouling inspector, in their last overseas port of call before arriving in WA, to ensure freedom form marine pests (Lewis, 2020).

2.1.18 The Australian Government has now introduced biofouling management requirements that obligate the operator of a vessel to accurately report on how biofouling has been managed prior to arrival in Australian territorial seas (DAFF, 2023). These were introduced in June 2022 with an 18 month "education first" period, followed by enforcement from December 2023. Vessel operators are required to report if they can demonstrate compliance with one of three proactive biofouling management options:

1. Implementation of an effective biofouling management plan and record book;

2. vessel cleaned of all biofouling within 30 days prior to arriving in Australian territory;
3. Implementation of an alternative biofouling management method pre-approved by the department.

2.1.19 Vessels that demonstrate compliance are eligible for less intervention for biofouling. Those that do not comply will be subject to further pre-arrival questions and may be subject to an inspection on arrival in an Australian port.

2.1.20 Georgiades *et al*. (2020) claimed that, as the New Zealand approach was aligned with the IMO Biofouling Guidelines, “there is the potential to develop consistent global and domestic practices for managing marine NIS introduction and spread”; a point that may be useful in developing a Mediterranean Sea policy. The authors also quoted data from Inglis *et al*. (2012) that indicated that >80% of international vessels inspected for that research, carried hull fouling. Georgiades *et al*. (2020) added that “there are anecdotal reports that vessels arriving from regions with biofouling regulations are often cleaner than those without”.

2.1.21 Australia and New Zealand have worked collaboratively on guidelines and standards for antifouling and in-water cleaning. The initial, 1997, Code of Practice for Antifouling (ANZECC, 1997) had appended a “Code of Practice for In-Water Hull Cleaning and Maintenance” that had been drafted and issued by the Victorian Channels Authority in January of that year (Parliament of Victoria, 1997). This effectively banned in-water cleaning. The Code of Practice for Antifouling included the IWC addition was reviewed and redrafted in 2009 (NIWA, 2011). Based on this work, new antifouling and in-water cleaning guidelines were issued in 2015 (DoE/NZMPI, 2015).

2.1.22 The redrafted code differed in acknowledging that regular and appropriate in-water cleaning could be a useful tool to prevent the development of mature biofouling and that the biosecurity and contamination risks posed by IWC depended on the type and origin of the targeted biofouling, the type of antifouling, the cleaning method, and the capacity to capture and contain cleaning waste (NIWA, 2011).

2.1.23 One shortcoming of the 2015 guidelines was the lack of attention to the release of chemical contaminants, namely the antifouling biocides, during cleaning and these addressed by the simple statement: “discharges [must] meet local standards or requirements” DoE/NZMPI, 2015). A further revision has therefore been drafted (DAFF, 2024[b]). This has two sections: anti-fouling coating guidance and Australian in-water cleaning standards. The latter is “voluntary decision-making guidance and framework for regulators to assess biosecurity and chemical contamination risks associated with in-water cleaning of biofouling from vessels in Australian territorial seas”. The chemical contamination standard specifies that the effluent does not contain toxicants (=antifouling biocides) in concentrations that exceed Australian and New Zealand environmental quality guidelines (ANZG, 2018). An alternative is for a mixing zone for the effluent to be specified by the relevant regulator.

2.1.24 To address the increasing number of requests for IWC, several Australian States have issued their own guidelines for the assessment of applications (Agriculture Victoria, 2024; Biosecurity Tasmania, 2024). Of note, in the latter, hull grooming and main propeller polishing / cleaning may be approved without requiring biofouling capture if specified conditions are met.

2.1.25 On the basis of the research available, the “clean before you leave / arrive” (Lewis, 2020; Tamburri *et al*., 2021[a]) approach appears to be having some useful success at managing biofouling species (also see best practice for the Baltic (Watermann *et al*., 2018)). This includes cleaning (grooming – see sub-section 3.4.5) of the “slime” stage which facilities greater establishment of macrofouling (see sub-section 3.1), and concomitantly affects vessel passage efficiency and GHG emissions. However, a press article (Zelinski, 2023) highlighted a drawback of the approach at the time of it going to press. Eight vessels were listed as having been “interrupted” in their passage to New Zealand. Some vessels were barred from entering sensitive areas and stated that they had been waiting an extended period for divers to attend to the hull. The largest impact was to the cruise vessel Viking, which had to stand offshore at 17 miles for two days whilst it was cleaned. Comment was made that the limited access to cleaning operations was an issue for vessel operators; alternately, a view is that vessels have a duty to be clean before they arrive as stated in the regulations. However, restrictions on cleaning in previous ports can force vessels offshore to meet the requirements which can be an occupational health and safety risk to divers.

2.2 GHG and Atmospheric Pollution Regulations

2.2.1 As highlighted below, there are numerous papers considering the impact of biofouling on vessel power and increase in fuel use. A very recent example uses a neural network to predict fuel savings and carbon dioxide (CO_2) reduction over differing time periods for active propeller and hull maintenance. A four month periodicity for maintenance was found to be optimum (Park *et al.*, 2024). However, on a practical day-to-day operational basis, such approaches may not be realistic and need adaptation to real world application. Furthermore, there is still limited information regarding how such research translates into every day GHG release (see sub-section 3.3) from shipping. This is perhaps unsurprising as the variables required to give accurate information per ship / per biofouling load are considerable and related to both intrinsic, e.g. hull design, hull coating, time stationary etc. and extrinsic elements, e.g. weather, local environment, biofouling species etc.

2.2.2 Fundamentally, an overriding approach to the policy-based management of GHG release from shipping is problematic, due to the aspects noted above. The IMO has taken a robust overall approach toward GHG from shipping management, with the introduction of the IMO Strategy on Reduction of GHG Emissions from Ships (Resolution MEPC.377(80), adopted on 7 July 2023 (IMO, 2023[b], initially MEPC.304(72) (April 2018)) (hereinafter referred to as the 2023 IMO GHG Strategy). Considering the IMO policy strategy, with specific regard to biofouling management, reasonable standardisation of the assessment variables may help with normalising GHG release assessment. This could create a baseline for vessel class / vessel. It may be some way off, but should nonetheless be an aspiration, not least in the face of data showing the growth of shipping and associated GHG levels (see sub-section 1.2).

2.2.3 At present, global efforts to reduce GHG emissions from shipping are subject to international approaches and regulation from the IMO (see sub-section 2.2.5). As discussed below (see sub-section 3.3), IMO 2020, pursuant to the International Convention for the Prevention of Pollution from ships (MARPOL), is focussed on sulphur emissions reduction associated with heavy fuel oil (HFO). Rather than engine modification or changes to fuels, such as to marine gas oil (MGO), some ship-owners have fitted closed or open loop scrubbers (also referred to as exhaust gas cleaning systems (EGCS)) as an alternative compliance method to reduce atmospheric release of sulphur from HFO. Scrubbers are effective at removing sulphur compounds, heavy metals and polycyclic aromatic hydrocarbons (PAHs). However, the waste water from the scrubber process is dumped overboard from both closed and open loop scrubbers where used (Comer *et al.*, 2020). The waste water can contain high levels of the “scrubbed” contaminants, with potential implications for marine life. Efforts to reduce shipping air pollution have shifted the impact into the water. Furthermore, HFO scrubber systems still emit higher levels of CO_2 than alternative fuels such as MGO (Comer *et al.*, 2020). Thus, it is evident that efforts to reduce shipping atmospheric pollution needs consideration prior to implementation, even if operating within the IMO requirement.

2.2.4 The Fourth IMO Study (IMO, 2020) showed a general increase in GHG release from shipping. GHG emissions rose from “977 Mt in 2012 to 1,076 Mt in 2018 (9.6% increase)”. In 2012, 962 Mt of these were CO_2 related, but by 2018, this had grown to 1,056 Mt of CO_2. The Fourth IMO (2020) study also indicated that emissions for “a range of plausible long-term economic and energy scenarios” were projected to increase to 90-130% of 2008 emissions by 2050.

2.2.5 To temper this, the Fourth IMO Study (2020) study did find that “Carbon Intensity” (CI) had improved from 2012-2018. CI is a value of a ship’s energy efficiency given in grams of CO_2 released per nautical mile and per cargo capacity (see DNV, *indet*). CI values had reduced by 29% from 2008 levels, indicating that whilst vessel numbers increased over that period, their efficiency had improved; an achievement of the GHG targeted IMO regulation.

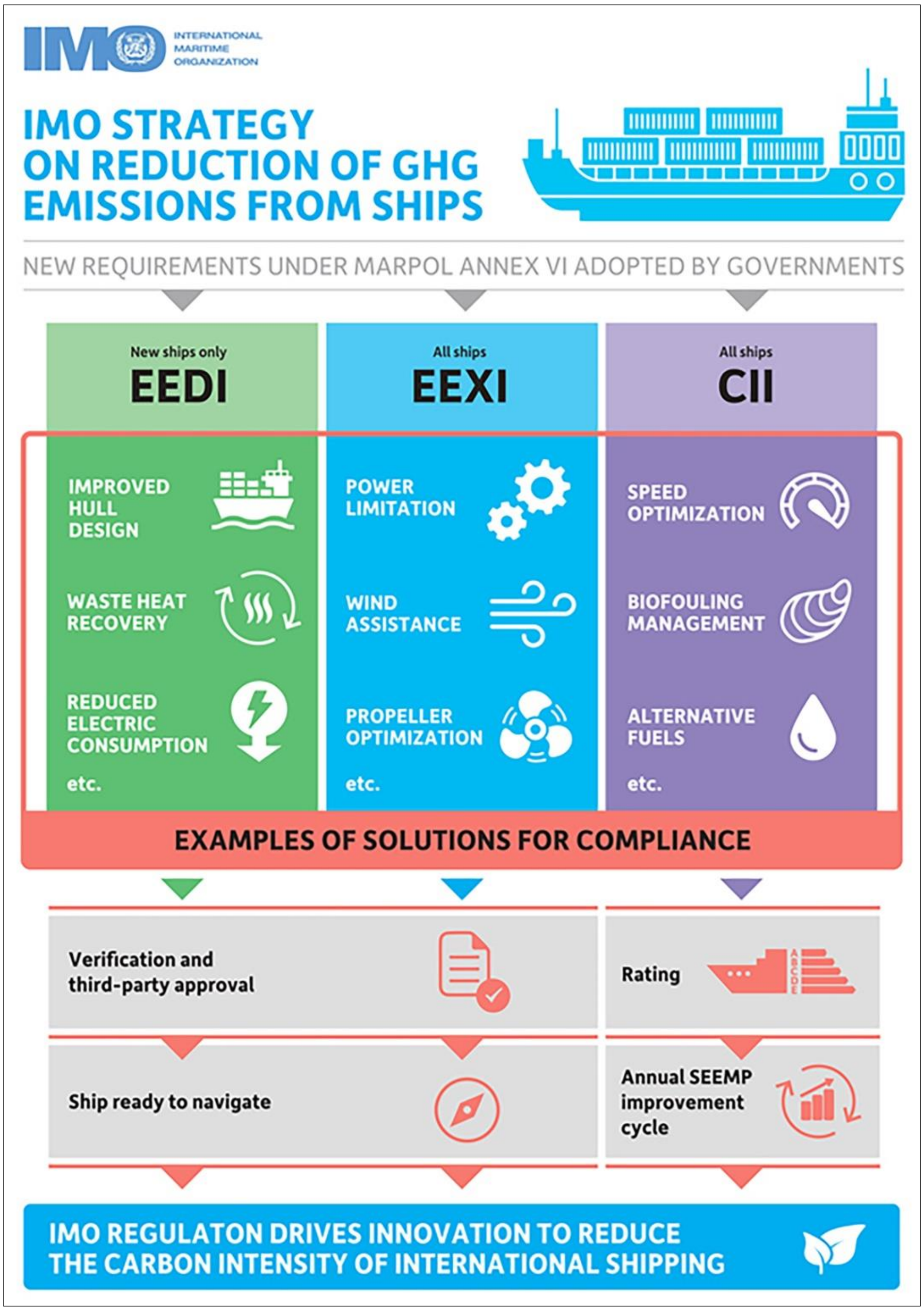

Figure 2.1 IMO requirements and approaches adopted under MARPOL Annex VI to reduce GHG emissions from ships[2]
Source: IMO, (*Indet*[b])

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[2] EEDI: Energy Efficiency Design Index; EEXI: Energy Efficiency Existing ship Index; SEEMP: Ship Energy Efficiency Management Plan.

2.2.6 IMO targeted GHG emissions reduction is through regulations which entered into force as amendments to MARPOL Annex VI (Regulations for the Prevention of Air Pollution from Ships). These are focused on the IMO goal of halving ship GHG emissions by 2050 compared to 2008 levels. The IMO has introduced (January 2023 – vessels >5,000 Gt) metrics aimed at improving vessel efficiency through measurements and environmental management systems (Figure 2.1); information on these metrics is given on the IMO internet resource (see IMO, Indet[b]). Fundamentally, they aim to drive continuous improvement under ship design and operational goals. However, as noted by Hoffman (2022), the approaches are imperfect "because they cannot effectively allow for measures where the impact on emissions is not constant"; i.e. as also discussed in sub-section 2.2.1, due to the variability of factors influencing the metric (weather, fouling level, time etc.), continuous CII improvement may be somewhat like trying to hit a moving target.

2.2.7 The CII section of Figure 2.1 does show biofouling as a factor in the overall CII management approach and a regulated, international approach to biofouling management may be a robust way to achieve quick wins for GHG management and reduction from shipping. Hoffman (2022) notes that "biofouling regulation remains to be a national matter, despite IMO guidelines". Readily recognisable national approaches to biofouling control (mainly focussed on invasive species management) are given above, and as Hoffman (2022) further notes, an "initiative [has been] set to provide pilot projects to demonstrate technical solutions for biofouling management in developing countries". This is through the IMO GloFouling project (see here) and is complimentary to the wider 2023 IMO GHG Strategy (IMO, 2023[b]).

2.2.8 Overall, GHG regulation in shipping is receiving attention at the international level from the IMO and, for biofouling management, this benefits from efforts focussed on invasive species management. However, laudable efforts are progressing to focus attention on proactive biofouling management as a quick way to reduce GHG emissions under IMO targets and regulations. Aligning the two goals to one synergy would be a valid part of global and regional / national policy of GHG reduction through biofouling management.

3. BIOFOULING BACKGROUND AND UNDERSTANDING

3.1 Biofouling Overview

3.1.1 A common, broad definition of biofouling is the “unwanted accumulation of biological material on man-made surfaces” (Fleming *et al*., 2009). In the context of shipping, biofouling refers to the attachment of biological organisms, from the initial settlement of the micro-fouling slime layer, comprising unicellular bacteria, marine algae spores and diatom species, to the final stages of macro-fouling comprising larger organisms (Figure 3.1) such as ascidians, bryozoans, barnacles, tubeworms, bivalves (mussels, oysters etc.) and macroalgae (fucoids, kelps, etc.).

Figure 3.1 General biofouling and mussel / barnacle matrix on hulls
Source: Smulktis, (2024); Adobe Shutterstock, (2024)

3.1.2 The process of marine biofouling development is largely accepted to comprise four stages (Figure 3.2). The biofouling process starts as soon as a surface is immersed in the sea (see Candries *et al*. (2003) for overview of process). The surfaces of the hull and niche areas (propellers, sea chests, etc.) (Figure 3.3) quickly accumulate dissolved organic matter, proteins etc. in a process known as conditioning. After this, a biofilm (the slime layer) develops comprising unicellular diatoms, bacteria etc. The spores and larvae of macroorganisms then settle and grow from within the primary biofilm as outlined above and in Figure 3.2.

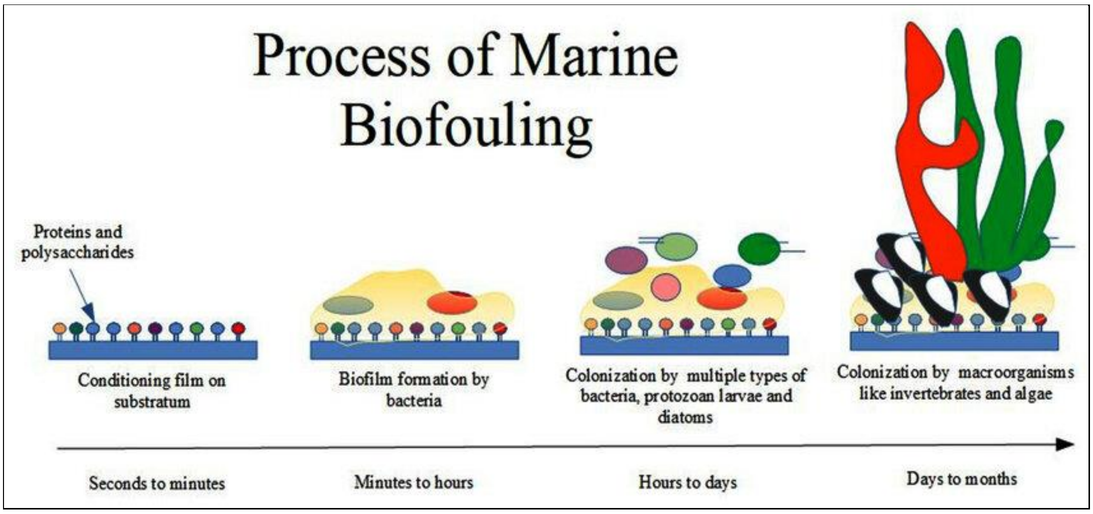

Figure 3.2 Stages of marine biofouling
Source: Subbaiyan *et al*. (2023)

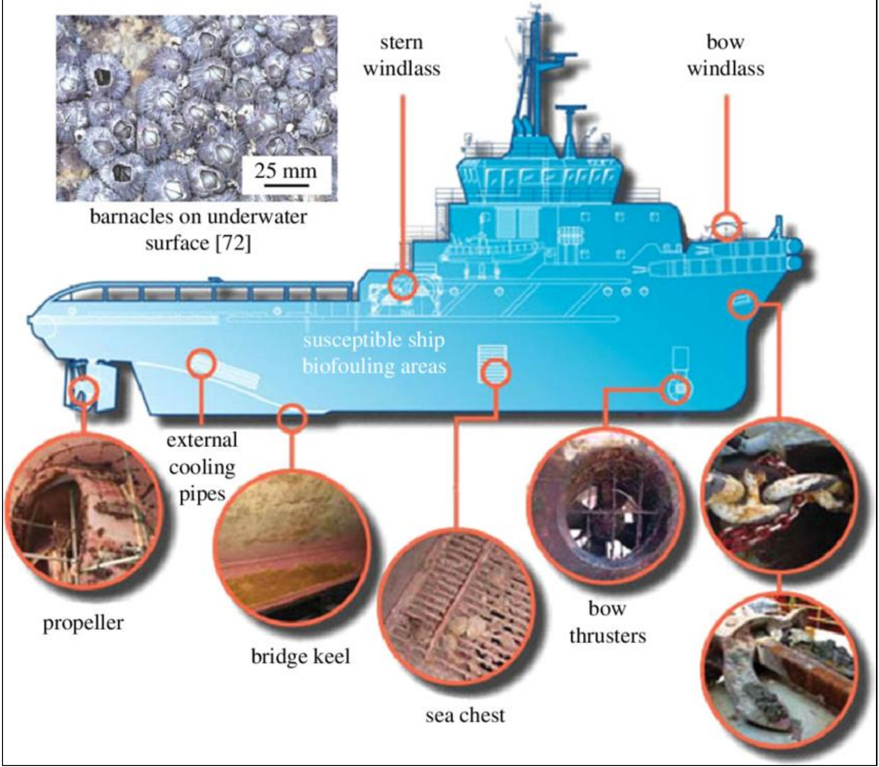

Figure 3.3 Example areas of biofouling on ships
Source: Bixler and Bhushan (2012)

3.1.3 The development of macrofouling is the most recognisable element of hull biofouling on commercial and recreational vessels and this is generally understood to be the major factor in reducing vessel efficiency, increasing hydrodynamic resistance, consequently increasing fuel use and associated GHG release. However, what is less well recognised is that the biofilm / slime layer (Figure 3.2) also increases hull resistance and consequent fuel and GHG penalties (see sub-section 3.2). Surprisingly, research indicates that the slime layer can impact vessel efficiency to levels which may result in three times as much frictional drag as that of a smooth hull through the water (Murphy *et al*., 2018). Another study found that a layer of microbial slime 1 mm thick could increase hull friction by 80% and cause a 15% loss in ship speed (Lewthwaite *et al*., 1984). Candries and Anderson (2003) reported the slime layer to only have an up to 3.5% impact on total hull resistance. However, this is was after the sloughing off of an initially thicker slime layer in turbulent water flow to leave a harder, but thinner, base layer. Nevertheless, over time, even the lower estimate would significantly impact on operational expense, efficiency and GHG emissions, particularly if time / voyages are factored in.

3.1.4 Recognising the development of fouling (Figure 3.2), whilst not a major focus of the Study, the subject of NIMS warrants further consideration in their role as part of the fouling community. NIMS, and particularly biofouling NIMS, are by nature robust in their physiology and environmental tolerance. The hydrodynamic conditions on a vessel hull, and the tolerance of species to biocidal antifoul compounds, has selected for an association of organisms with a composition and characteristics unique to that community (Lewis, 2020). Accordingly, NIMS can attach to ship hulls coated with biocidal or “slippery” antifoul coatings if not performing effectively. Piola *et al*. (2009) discuss that Cu based antifoul may facilitate a “competitive advantage” to Cu tolerant NIMS “over similar native taxa” and thus facilitate their spread to new areas as biofouling (also see Dafforn *et al*. (2011)).

3.1.5 The common use of Cu antifouling coatings on ships for more than a century has allowed those species with a higher tolerance to copper to be spread around the globe, When the release rate of copper from an antifouling paint drops below that critical to prevent all macrofouling settlement, it is these copper tolerant species that are the first species to appear, , Additionally, these tolerant NIMS, such as encrusting bryozoan species and calcareous tubeworms, can create a “buffering” surface habitat on which other less tolerant NIMS can establish (Floerl *et al*., 2004). The choice of biofouling and NIMS control versus the hull efficiency of vessels, the increasing risk in the face of global policy changes, and the cost / benefit of control methods (e.g. Georgiades *et al*. (2020)) is a complex, but significant decision for vessel operators.

3.1.6 Biofouling management is the major approach for fouling control to both enhance ship efficiency and to minimise the possibility of non-native species transport. Biofouling control approaches and details of guidelines for best practice provided by IMO GloFouling studies (and others) are considered in appropriate detail below (see 3.4). However, as an overview at this point, control methods comprise:

1. Methods to prevent or reduce fouling settlement rates (hull coatings and niche area management systems), or proactive measures to remove initial slime layers (grooming – see Tribou and Swain, (2010) and 3.4.5);
2. Reactive in-water hull cleaning to remove established biofouling using mechanical methods (brushes, HP water, manual scraping) operated by divers or robotically, or dry-docking and cleaning, the most costly option (see Song *et al*. (2020) for review and sub-section 3.4.5).

3.1.7 At worst case, when the presence of potentially invasive NIMS is suspected, this has resulted in costly orders for vessels to leave or not enter national waters and for biofouling removal by divers either beyond outside the 12 nm limit (e.g. Cropp, 2019) or to travel to a country where the vessel can be dry-docked.

3.2 Biofouling and Shipping Efficiency

3.2.1 A primary goal of the Study is to consider the effects of biofouling on vessel efficiency, fuel consumption and GHG release. There has been an increasing drive to consider GHG management from shipping. To provide context on earlier work on the matter, taking commentary from the late 2000’s, Crist (2009) commented that, in 2007, the IMO found that shipping accounted for “843 Mt of CO_2 [which was] 45% more than previous emission estimates”. This can also be considered against Figure 1.1, showing steady CO_2 emissions growth since 2023. Crist (2009) further commented that “significant interventions” would be necessary to achieve uptake of measures such as “significant speed reductions and more intensive use of low-carbon fuels”. The latter being said, there has been a growing upswing in conferences discussing approaches to low carbon shipping, with several listed (industry and IMO) in 2023 and in 2024, and an IMO event in 2025 (6th Decarbonising Shipping Forum). Furthermore, the IMO has already taken significant steps towards management of GHG emissions from shipping (e.g. new operational requirements under MARPOL Annex VI – see sub-section 2.2.6).

3.2.2 Conference outcomes have been reported to some extent, although mention of biofouling and GHG emissions initially appears sparse. Although perhaps surprising, the IMO GloFouling project highlights that there is a “poor understanding” in the shipping industry of the impact of biofouling on fuel consumption and resultant GHG emissions (IMO, *Indet*[b]). This information, and other supporting preliminary study outcomes, were presented at the “‘Managing Biofouling – A Win-Win Solution to Help Curb Climate Change and Preserve Ocean Biodiversity’ side event at the 26th session of the Conference of the Parties (COP26) of the UN Framework Convention on Climate Change (UNFCCC), (04/11/2021).

3.2.3 In 2022, the GloFouling project produced a key study on the impact of biofouling on shipping energy efficiency (GEF-UNDP-IMO, 2022[b]). Importantly this study further clarifies the difficulty of assessing the impact of biofouling upon vessel performance (see also sub-sections 2.2.1 and 2.2.6). The report considers the variety of ship types, varied operating conditions and the differing measures of assessing hull roughness with biofouling development. Somewhat confoundingly, there is also variation in approach of assessing biofouling-induced power escalation impacts using parameters “such as increased frictional resistance, effective power or shaft power”. GEF-UNDP-IMO, (2022^b) comment that “these [latter] parameters are not easy to understand from the perspective of non-specialists in ship hydrodynamics”.

3.2.4 Using the 2022 GEF-UNDP-IMO document to clarify parameters as best as feasible, Table 3.1 shows the parity levels between hull roughness measures for differing classification systems. The qualitative measures shown by the Naval Ships’ Technical Manual (NSTM) number and the IMO (1-5) value have been related to the roughness coefficient value (k_S); see Schultz, (2007), for a full explanation of the model derivation. The GEF-UNDP-IMO study goes on to clarify and summarise all readily available data “in the form of increase in GHG emissions from ships for different categories of biofouling”, thus enabling summary of “how surface roughness relates to the energy (fuel) requirements of ships and the equivalent estimated GHG emissions”.

Table 3.1 Approximate equivalency of hull biofouling roughness classification systems
Source: GEF-UNDP-IMO, (2022^b)

DESCRIPTION OF CONDITION	NSTM RATING[3]	SCHULTZ (K_S)	IMO (IN DEVELOPMENT)
Typical as applied antifouling coating	0	30	0
Deteriorated coating or light slime	10-20	100	1
Heavy slime	30	300	2
Small calcareous fouling or weed	40-60	1,000	3
Medium calcareous fouling	70-80	3,000	4
Heavy calcareous fouling	90-100	10,000	5

3.2.5 The 2020 GEF-UNDP-IMO work resulted in a graphical summary of the effect of biofouling on GHG emissions (Figure 3.4). Although acknowledged as a generalised approach, it is a useful visualisation of the relationship between the slime layer (see sub-section 3.1.3), growing surface roughness, and ship hull efficiency. This study states that a 0.5 mm thick layer of slime, covering over 50% of a given hull, would result in a GHG penalty increase of 25-30% (Figure 3.4). However, it should be noted that this is a generalised model and would need to be assessed in a Mediterranean Sea context. That being said, in REMPEC (2021), a figure of 54% contribution of sulphate aerosols from shipping was given for the Mediterranean region in summer. Whether transitory or short shipping (see sub-section 5.1), the effect of biofouling upon these emissions (SO_X, NO_X and CO_2) requires consideration. This is particularly the case for Mediterranean Sea ports that lie in or adjacent to urban areas where localised atmospheric conditions may entrain shipping emissions and significantly affect local air quality (Schembari *et al.*, 2012; Toscano, 2023).

3.2.6 In Figure 3.4, the slime layer stages are seen as significant in fuel / energy penalty, with the curvilinear relationship less pronounced after this. When macrofouling stages are reached, the positive residuals around the line of best fit show a 55% increase in fuel consumption / GHG emissions for a tanker with “1% coverage of 5 mm barnacles” (GEF-UNDP-IMO, (2022^c).

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[3] NSTM: Naval Ships’ Technical Manual (NTSM, 2002). Source: Schultz (2007)

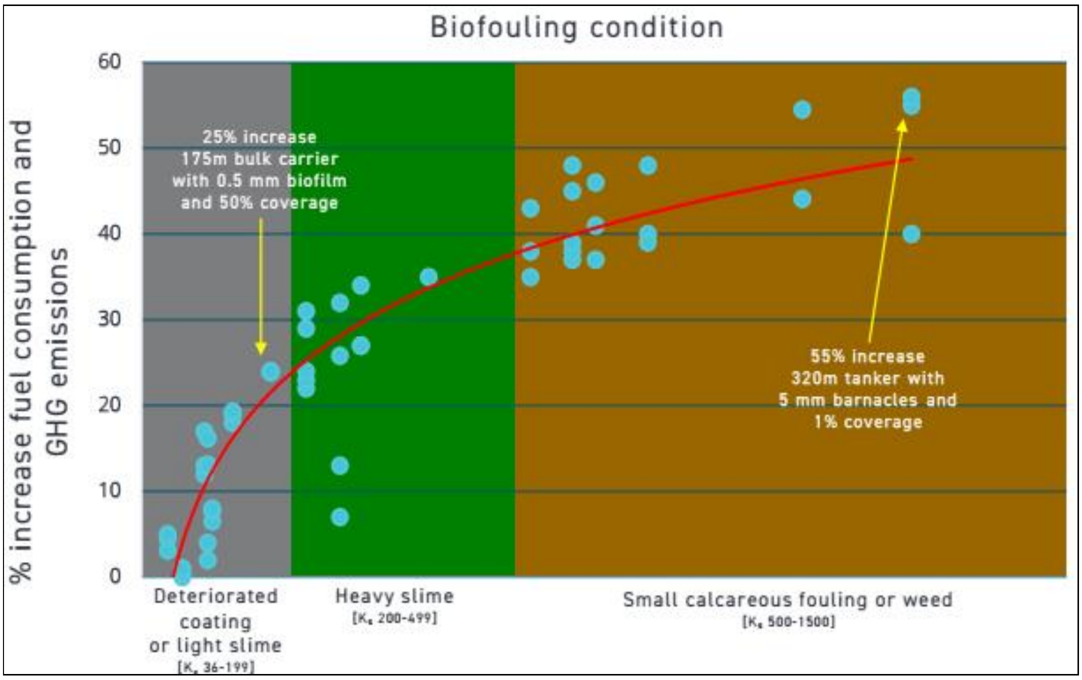


Figure 3.4 Research summary effect of ship biofouling levels upon GHG emissions
Source: GEF-UNDP-IMO, (2022^{b})

3.2.7 The above model, and the review and study by GEF-UNDP-IMO (2022^{b}), are based on published papers on biofouling and its impacts upon vessel efficiency / GHG release. In research papers focussed on biofouling impact assessment, Lewthwaite et al. (1984), Murphy *et al*. (2018) and Candries and Anderson (2003), all cite impacts of biofouling (Section 3.1.3). Other examples highlighting the biofouling penalty include:

1. Schultz (2007) noted that "the results indicate that slime films can lead to significant increases in resistance and powering and heavy calcareous fouling results in powering penalties up to 86% at cruising speed";
2. Demirel *et al*. (2013) compared the Frictional Resistance (R_F) for differing antifoul paints (including remaining applications of tributyltin (TBT) paints, although banned by the IMO by that time) They reported that "the increases in [hydrodynamic resistance] of fouled hulls are around 47%, 68% and 88% for SPC [self-polishing co-polymer] TBT, ablative Cu and SPC Cu coated hulls respectively". This highlights the efficacy of TBT SPC coatings versus tin-free alternatives available at that time, though the impact of TBT on non-target species was so pronounced that its ban was considered overdue by some by the time of the 2008 TBT ban ratification;
3. Uzun *et al*. (2019) highlighted that a "percentage increase in frictional resistance of [a] 176 m vessel was predicted to be ~32% at a ship speed of 14 knots at the end of one-year long ship operation".

3.2.8 The GEF-UNDP-IMO, (2022^{b}) study presents the considerable evidence that highlights the impact of fouling upon ship efficacy and performance, including initial slime layers. More recent works continue to consider the issue, and Zou *et al*. (2023) suggest that "ship resistance research on marine biofouling is an old but hot topic". These authors note that previous work uses "a single parameter, for example, height of the biofoulers, to describe the hull roughness [and their] research indicates that any single factor affecting ship hull roughness cannot completely reflect the compositions of ship resistance". The authors considered that a modified model encompassing tangential shear stresses created by "rotating, jetting, surging and swirling of fluid flowing over ship hulls due to characteristics of the marine biofoulers" simulated a responsibility of "up to ~80% of total resistance" for vessel power in heavy fouling conditions (Zou *et al*., 2023).

3.2.9 The continuing and abundant research available on the subject of biofouling and effects on ship efficiency, demonstrates significant impacts upon vessel power, fuel use and GHG release, even by the slime layer. Recent considerations of biofouling management have focussed on the issue of invasive aquatic species (the basis of the IMO 2011 Biofouling Guidelines), with GHG emissions perhaps a *relatively* modern consideration of the biofouling issue.

3.3 Shipping and GHG Emissions

3.3.1 The IMO and the GloFouling project have been leading efforts to decarbonise and reduce GHG emissions from shipping and to manage biofouling. Towards this end, the 2023 IMO GHG Strategy has been driving change, including in approaches towards biofouling management.

3.3.2 The biofouling induced increase in power to achieve practical forward progress obviously leads to an increase in fuel use and subsequent GHG emissions. Based on IMO efforts to promote reduction in shipping GHG emissions, there is a drive to move shipping away from HFO dependence and, in 2020, the IMO put in place what is commonly known as IMO 2020, pursuant to MARPOL Annex VI. This is stated to have "brought about a 70% cut in total sulphur oxide emissions from shipping" (IMO, 2021) through a requirement for the sulphur content of HFOs to be reduced from 3.5% to 0.5%. To meet IMO 2020, some shipping companies changed fuel types, changed engines, or installed sulphur scrubbers. Scrubbers, in themselves, can impact the marine environment through the discharge of scrubber water (e.g. Endres *et al*. (2018), see sub-section 2.2.3). It should be noted that the efficacy of IMO 2020 has recently been queried on both the overall effect (Watson-Parris *et al*., 2024) and the possible disbenefits of an increase in global temperature due to SO_X reduction (Gettelman *et al*., (2024).

3.3.3 SO_X released from internal combustion tends to form aerosols in the lower atmosphere that can impact general air quality and human health (Eyring *et al*., 2007). Counterintuitively, Kontovas (2020) discuss how SO_X can ameliorate the impacts of GHG emissions by creating aerosols which block / reduce solar radiation and thus radiative forcing. Thus, a drive to improve air quality may have implications for GHG impacts and, as reported by Hausfather and Forster (2023), "Some researchers have proposed that the drop in SO_2 as a result of the IMO's clean air regulations could be behind a recent spike in global sea surface temperature [due to a reduction in aerosol particles]. Carbon Brief analysis shows that the likely side-effect of IMO 2020 to cut air pollution from shipping is to increase global temperatures by around 0.05°C by 2050. This is equivalent to approximately two additional years of emissions" (also see Eyring *et al*. (2010); Gettelman *et al*., (2024)).

3.3.4 In the wider terms of shipping and GHG emissions, CO_2 is the most abundant gas from associated emissions, with methane (CH_4) (a powerful GHG) a possible by-product of carbon monoxide (CO) release. However, NO_X, also released by combustion, can "lead to a rise in methane destruction" (Crist, 2009). With the rise of GHG emissions from shipping, as outlined above (see sub-section 1.2), clarifying the contribution of biofouling to GHG emissions from shipping is complex because of the influence of ship specific variables such as biofouling status, management type, vessel hull type, prevailing weather conditions etc. Nevertheless, biofouling has a significant role in vessel propulsion efficiency (Weber and Esmaeili, 2023), or lack of, and is a possible significant "win" in potential GHG emissions reduction if managed in an appropriate and targeted fashion.

3.3.5 Although shipping "significantly contributes to global temperature rise" (Weber and Esmaeili, 2023), Poloczanska and Butler (2010) note that shipping is the most energy efficient option to move global cargo, but add that biofouling management should be optimised for both hull and propeller maintenance (see sub-section 3.2). Ironically, they also comment that with global climate change inducing warmer waters, shipping time in these climes may exacerbate fouling.

3.3.6 Whilst achieving a figure per vessel for GHG increases for differing levels and forms of biofouling is both impractical and unlikely, the GEF-UNDP-IMO, (2022[b]) study quotes Swain *et al*. (2022) who use IMO global estimation data to calculate that “if all international ships maintained a smooth condition, free from biofouling, global GHG emissions from ships could be reduced by at least 19% per year (or 198 million tons of CO_{2e})”. The IMO further add that, in addition, if domestic fleets were included in the calculation, the figure would be increased in this and the 2023 IMO GHG Strategy (IMO, 2023[b]).

3.4 Biofouling Management

3.4.1 History

3.4.1.1 Biofouling has bedevilled mariners since they first set sail (Lewis, 2020). Over 2,000 marine species have been listed as biofouling organisms (Evans, 1970) and barnacles, the archetypal biofoulers, are noted as the most significant (Christie and Dalley, 1987). However, even a slime coating can have a significant fuel use penalty on shipping (Edyvean, 2010).

3.4.1.2 Early efforts to control biofouling are recorded as long ago as 300 BC (Stebbing, 1985; Dafforn *et al*., 2011) when lead sheets were used to cover hulls. From the United Kingdom of Great Britain and Northern Ireland (UK), and the reign of Henry VIII, when the English Navy was substantially increased (Herman, 2004), there are records of antifouling coating trials of lime or oil laced with sulphur, arsenic and gunpowder (Clare, 1995, 1998; Ten Hallers-Tjabbes, 1997). However, until the latter part of the 18th century, the only effective method of managing fouling was to regularly beach or careen vessels to allow manual removal of the marine growth (Lewis, 2020). Copper sheeting was later used as a relatively effective coating and this led to the development of the first antifouling paints at the turn of the 19th century containing mercury, arsenic and Cu (Dafforn *et al*., 2011). Cu was an effective biocide, but the effective life of copper-based antifouling coatings rarely exceeded 18 months (Lewis, 1998) so dry-dockings for paint reapplication were required regularly.

3.4.1.3 In the 1960s, organotin compounds were found to be more effective antifouling biocides and the first organotin antifouling paints were commercialised (Evans, 1970; Lewis, 1998; Dafforn *et al*., 2011). A significant advance in the technology of antifouling paints came with the formulation of tributyltin (TBT) self-polishing copolymer (SPC) antifouling paints (Champ and Pugh, 1987; Lewis, 1998). The biocide discharge rate of these paints was regulated through the reaction of seawater with the copolymer and the leaching rate was consistent throughout the life of TBT paint (up to 5 years). The other benefit of SPC coatings was that self-polished / self-smoothed in use to remove surface micro-roughness that led to fuel savings (Lewis, 1998). In 1986 the US Navy estimated that fleetwide use of organotin paints would have reduced annual fuel consumption by 1.8 million barrels and avoided $110 million in fuel costs (NSSC, 1986). However, in the late 1970s, TBT released into the marine environment from these paints were recognised as highly toxic to non-target marine organisms, including commercially-grown oysters and stenoglossan gastropods, and to bioaccumulate in higher organisms, including whales (Tanabe, 1999; Barreiro *et al*., 2001). This led to the global ban on organotin antifouling coatings under the International Convention on the Control of Harmful Anti-fouling Systems on Ships, 2001 (AFS Convention) (see here), which entered into force in 2008. Of note, not all CPs are, as yet, parties to the AFS Convention.

3.4.1.4 Despite the ban, organotin compounds (TBT and the somewhat less toxic degradation products of dibutyltin (DBT) and monobutyltin (MBT)) are still found, and are of continuing risk, in marine environments. Organotins partition between sediment and water, with levels often orders of magnitude higher in the particulate phase. Consequently, organotins have a strong affinity to create sediment “hotspots” (Ruiz *et al*., 1996). Hotspots are present globally, e.g. in ports and harbours, near vessel repair facilities and, in some cases, dredge spoil disposal sites. Contemporary research and review continue to identify the apparent, and ongoing, legacy (Beyer *et al*., 2022), with figures of 30-40 years sediment residence time quoted (e.g. see Maguire, 2000; Langston *et al*., 2015; Little *et al*., 2016).

3.4.1.5 Overall, the situation is improving, but TBT and its derivatives resident in sediment, continued illegal use (e.g. Lofrano *et al*., 2016) and organotin use as a catalyst in later foul release coatings has given some cause for concern (Pretti *et al*., 2013); though an overview suggests the use of organotin catalysts has declined, perhaps in the face of controversy. Furthermore the continuing management of residual TBT pollution, particularly in in-water cleaning areas and dry-docks from where TBT was last allowed to be removed (see Soon *et al.* (2021)*;* Kucharski *et al*. (2022)), remains a problem requiring continuing management (e.g. Jupp *et al*. (2023).

3.4.1.6 The realisation that antifoul paints can have wider unintended environmental impacts and implications led to calls for greater product scrutiny, particularly some of the "booster" biocides added to Cu based antifoul compounds (see Dafforn *et al*. (2011) for overview). Some researchers previously stated that the time to ban compounds found to be toxic to non-target organisms is too slow and that an independent board should be set up (see Champ, 1999), plus, as noted above, some have raised queries over catalytic compounds (organotins) used in queried non-toxic paints (Pretti *et al*., 2013), though they were compliant with IMO requirements (Appendix to MEPC 104(49), paragraph 6.3). Being mindful of such possible environmental consequences should be an iterative process for any regulating body. Registration processes for antifouling biocides and products are now established in countries including the UK, US, Australia and New Zealand, and the biocides are under scrutiny by the EU. Also, the IMO added the biocide cybutryne to the AFS Convention effective from the 1st January 2023 and all applications of this compound are to be removed "no later than 60 months following the last application to the ship of an anti-fouling system" (IMO, *Indet*[c]) (also see sub-section 2.1.9).

3.4.1.7 The impending ban on TBT antifouling coatings catalysed research into TBT-free alternatives that could match the long effective lives of the TBT SPC coatings. Relatively few biocidal compounds have the necessary combination of physical, chemical and toxicological properties to make them effective antifoulants (Lewis, 1998). Cuprous oxide continues to be the best alternative, albeit with added secondary, or booster, biocides to control copper-tolerant algal foulers. Cu SPC coatings, based on copper, zinc or silyl acrylates, are now widely used and can achieve effective lives that match or exceed those of TBT SPCs. However, these coatings are expensive and many ship operators opt to apply cheaper products with lesser performance.

3.4.2 Biocidal, Foul Release and Hard Coatings

3.4.2.1 The above brief antifoul history is given to set the context of fouling management against the aspirations of GHG emissions reduction from shipping. Fouling reduction can be a relatively quick win in shipping efficiency and GHG emission reduction (though also see recent development of a surface / ship borne CO_2 capture technology (Larkin *et al*., 2023)). However, the implications of irresponsible toxic antifoul use can result in a transferred impact (albeit at a somewhat less than global effect as with GHG), in some cases reported as potentially exacerbated due to in-water cleaning operations (Tamburri *et al*., 2020; 2021[b]; Hoffman *et al*., 2022) (see sub-section 3.4.5).

3.4.2.2 Of coatings applied to hulls, the most widely used approach is still biocidal antifoul (largely Cu based), followed by "slippery" silicone based foul release coatings (FRCs) (Figure 3.5) and non-toxic hard, scrubbable coatings (Inglis *et al*., 2012; Weber and Esmaeili, 2023). Biocidal coatings are formulated to function in one of three ways (Figure 3.5). In controlled depletion, or ablative, coatings, the biocide is freely dispersed through a sparingly soluble paint matrix (traditionally natural rosin) and the biocide dissolves as the coating ablates. In contact leaching (insoluble matrix, diffusion) the paint matrix is insoluble and the biocide dissolves as seawater penetrates micro-channels within the coating created by previously dissolved copper. TBT-free SPC coatings function similarly to the TBT SPC coatings, with the paint matrix polishing by hydrolysis, but with the biocide dispersed through the coating, not part of the copolymer. Of relevance to hull efficiency and GHG emissions, the surface micro-roughness of ablative and contact leaching coatings increases during service, whereas in SPC coatings it decreases.

3.4.2.3 The relationship between an antifoul type on GHG release is difficult to assess due to the lack of data for all the variables (GEF-UNDP-IMO, 2022[b]; Weber and Esmaeili, 2023) (see Section 2.2). With the industry mostly reliant on biocidal products (see Weber and Esmaeili (2023) for a relevant product overview), use of these coatings had raised concern as environmental levels encountered in marinas and harbours have been recorded as high enough at some sites to impact marine species and communities (e.g. see Chesworth *et al*. (2004); Neira *et al*. (2013); Nendza. (2014)). The issue has continued to be considered with researchers raising concern at larger ports (e.g. Abreu *et al*., 2020) and a later review identifying risk levels for biocides and coastal ecosystems (de Campos *et al*., 2022). This includes potentially facilitating NIMS (Piola *et al*., 2009; Dafforn *et al*., 2011), reducing biodiversity and biomagnification to higher organisms; for example in manatee species (Srinivasan and Swain, 2007). Assessment of the potential impacts of antifouling biocides in in-water cleaning areas (e.g. Bay of Algeciras (Floerl *et al*., 2020) where cleaning companies currently operate) is therefore needed. There is potential for poorly regulated growth in the industry for biofouling control and vessel efficiency without appropriate consideration of environmental risks (Soon *et al*., 2021; Scianni *et al*., 2023).

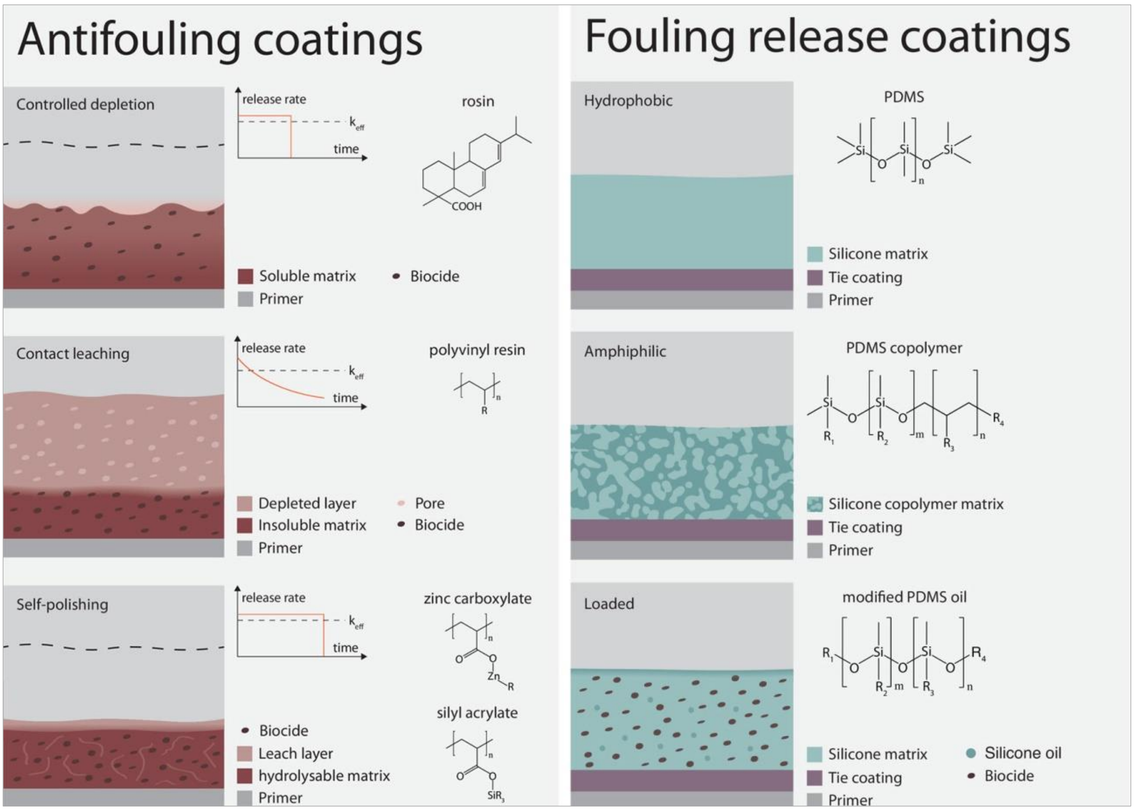


Figure 3.5 Most commonly applied biofouling prevention coatings; antifouling (AF) and foul release (FR)
From: Weber and Esmaeili, (2023)

3.4.2.4 Even though biocidal products are significantly less toxic than the organotin products, there is a continued drive towards finding more environmentally / ecological sustainable approaches to biofouling control. This reflects growing public awareness of marine and atmospheric pollution aspects (e.g. see here) and corporate insurance and Environmental, Social and Governance (ESG) industry pressures.

3.4.2.5 Some moves to restrict the use of biocidal coatings have occurred with some nations banning the use of high biocide release coatings (e.g. Canada, Denmark (Dafforn *et al*., 2011)) and controls on application and use in California. There are also previously mentioned (see sub-section 2.1.9) curtailed plans for Washington State to ban Cu based antifouling paints from January 2026. EU Member States are considering the future with partial controls in place, e.g. Sweden (Dafforn *et al*., 2011) and the Netherlands; the latter of which ran a Government consultation on the issue in 2018. The US congress is also currently discussing antifoul performance (SEC 1084 “Assessment Regarding Antifouling Coatings”) in particular mentioning “an assessment to evaluate the feasibility of moving away from Cu based coatings” (US Congress, 2024); the bill is currently in discussion and may yet be subject to amendments and part of the delay in banning Cu based products is the delay in fully viable alternates.

3.4.2.6 As noted, a major issue with moving away from biocidal coatings is that there are currently no *equally* effective alternatives for most of the global fleet. FR and hard coatings are suitable for some vessels, but only those with an operational profile that enables sufficient fouling release or regular cleaning. The current consequence of widespread bans is potentially greater biofouling levels on ships that, in the context of this study, may not only increase fuel consumption and GHG emissions, but also increase the risk of NIMS spread.

3.4.2.7 Few publications attempt the complex task of assessing the benefits of one hull coating over another. Farkas *et al*. (2021) undertook “detailed analysis of the potential benefits of the application of antifouling coatings with lower roughness in terms of fuel savings and [GHG] emission reduction [...] for the first time” (Farkas *et al*., 2021). Further to this, Oliveira *et al*. (2022) utilised a tool known as HullMaster that “simulates emissions to air and water, to calculate the differences in economic cost for operators, as well as health- and environmental damage costs between different hull maintenance scenarios” (Oliveira *et al*., 2022).

3.4.2.8 Farkas *et al*. (2021) reported that “the application of antifouling coating (AF) with lower roughness [new ships reported at an average hull roughness (AHR) roughness of 150 µm] is important for the reduction of ship resistance for new ships” as well as during the use period; 150 µm is the value given by the “leading organisation” (Farkas *et al*., 2021) assessing ship hydrodynamics. In this study, the authors found that a hull roughness of 81 µm was achieved by coating improvements on a car ferry. Despite this, and other papers discussing potential fuel savings and CO_2 reduction (different fuel, hull design, etc.), a figure for an example biocidal coating in terms of GHG emissions reduction was not readily available. Values of broadly 5-10% fuel use reduction are given for smooth and managed coatings such as foul release (see below), but, as noted by Weber and Esmaeili, (2023), “although up to 10% of fuel can be saved by an optimal hull surface, alternative fuel saving [and efficiency (see 3.4.6)] techniques must be taken into consideration” (See Bouman *et al*. (2017). As a correlatory comment, in a dissertation by Alshawi and Avtandil, (2019) considering biofouling impacts on GHG released from vessels operated by the General Company for the Ports of Iraq (GCPI), it was “revealed that fouling contributed to around 5,746.1 tons of extra CO_2 emissions, which equals 9% additional carbon dioxide emissions from the whole fleet”; there are no data on whether biocidal or FR hull coatings etc. were used on the GCPI vessels.

3.4.2.9 For biocidal coatings, Weber and Esmaeili (2023) comment that the majority of these are still Cu based, and that these are rougher in nature than, for example, FRC systems. However, as stated above, roughness of biocidal coatings varies with type and SPC systems self-smooth. Accordingly, whilst data was not readily apparent, it is likely that the fuel use / GHG emissions rate for rougher biocidal coatings will inherently be greater and potentially less of a possible quick win. In contrast, the use of the more effective SPC coatings can do this through not only minimising biofouling, but also having lower surface roughness. Again, data would ideally be needed for all options (later SPCs and FRCs etc.) to make suitable industrially relevant comparisons for best overall options

3.4.3 Foul Release Coatings (FRCs)

3.4.3.1 Silicone-based FRCs were initially developed for use in 1993 (Han *et al*., 2021); they provide for a low level of algal and faunal attachment via physical rather than chemical means (Lagerström *et al*., 2022), through what is known as low surface free energy (SFE) (Murthy *et al*., 2022). Although in original form FRCs are prone to fouling when vessels are static, or making slow passage, the release of fouling species is achieved by interaction with the base material and bio-adhesives (Murthy *et al*., 2022). The result is that the release of fouling occurs through forward motion and hydrodynamic pressure shear forces (Daehne *et al*., 2017). Early work on FRC efficacy and longevity by Almeida *et al*. (2007) showed that, after approximately three years of use, the FRC had deteriorated in efficacy such that organisms were only detached from the coated surface at speeds ≥22 knots. Conversely, later work states that silicone based FRCs “have poor antifouling performance under static conditions, where they cannot prevent the growth of a slime layer consisting of diatoms and bacteria” (Hu *et al*., 2020). However, in contrast to the comments made by Hu *et al*. (2020), work is ongoing at developing greater efficacy for FRC paints. A practical example of an available product discussed in Wang *et al*. (2018), is an FR (Hempaguard) coating with very low levels of Cu pyrithione biocide although Wang *et al*. (2018), did note that “most of the biocides in [the product did] not dissolve during the experimentation period”. Furthermore, and in the context of this study, the researchers commented that “that in real life conditions, newly applied FR coatings cause less skin friction than newly applied [biocidal antifoul] coatings at the same sailing speed”.

3.4.3.2 On a more research basis, Selim *et al*. (2017) considers that FRCs are “environmentally friendly”, but also that silicone-based FRCs benefit from increased efficacy through the introduction of coating enhancing nanomaterials designed to enhance FRC performance above that from the original concept. The research considers enhancing nanoparticles to increase FRC efficacy, not least in terms of their recognised drawbacks, which are poor hull adhesion and relative ease of damage (Liu *et al*., 2023), plus the levels of effectiveness over time, though, as outlined, work is ongoing to address these factors that will be necessary to achieve the robustness required for regular cleaning to enhance hull efficiency and reduce GHG release rates.

3.4.3.3 Weber and Esmaeili (2023) comment on ongoing research to enhance FRCs with biocides and, in the research paper by Selim *et al*. (2018), organometals are listed (Cu_2O, ZnO, TiO_2, and Ag) as component factors of some explored nanoparticles. Research by Tian *et al*. (2019) shows the effect of silver (Ag) nanoparticles when encompassed in a silicone-based coating, with a significant anti-microbial / diatom layer (the slime layer base of macrofouling (Figure 3.6). Further to this, later work by Padmavathi *et al*. (2021) explores the efficacy of polydimethylsiloxane (PDMS) – the most common silicone FRC type). These are silicone coatings enhanced with nanofiller Cu composite. This effectively creates a Cu based antifoul that inhibits larval settlement through surface toxicity (Padmavathi *et al*., 2021), as with other more “traditional” Cu based antifoul paints, albeit with a silicone base that allows the sloughing of organisms when vessels are underway. Regarding toxicity, the paper by Selim *et al*. (2018) refers to work by Quigg *et al*. (2013), which explores the toxicity of engineered nanoparticles and recommends future research. This highlights that over recent and ongoing periods research is still required to understand toxicity of FRC enhancing nanoparticles, even if latterly listed as low toxicity in Liu *et al*. (2023) and Murthy *et al*. (2022).

3.4.3.4 Further to nanoparticles, amphiphilic molecules (molecules that contain a hydrophilic, peptide head) have been conjoined to create composites, plus metalliferous combinations also have been developed with zwitterions (“polymers that bear a pair of oppositely charged groups in their repeating units” (Li *et al*., 2023), which also are hydrophilic). This leads to a “hydrogel” layer instead of the hydrophobic standard silicone coating. The advantage being that the hydrogel layer leaves the surface less able to be identified by biota as a stable substrate and organisms are less able to repel the water layer enabling them to "glue down" (e.g. barnacle larvae (cyprids) and the slime (diatom) layer (see Wang *et al*., 2022; Liu *et al*., 2023)).

Figure 3.6 Mediterranean Sea antifoul coating trial with PDMS hydrogel enhanced FRC (a) compared to PDMS with Hydrogel (b) and Polymer (c)
From: Thorlaksen *et al*. (2010)

3.4.3.5 A useful summary by Arndt *et al*. (2021) discussed efficacy. It stated that "silicone hydrogel coatings effectively protected the ship's hulls from slime and algae for up to 25 months with an estimated activity of 60% of the time and average cruising speed of 13 knots" (Thorlaksen *et al*., 2010, in Arndt *et al*., 2021). The data presented by Thorlaksen *et al*. (2010) shows the efficacy of hydrogel enhanced "3rd generation" FRC coatings in minimising fouling rates in comparison with a basic PDMS silicone coating, one with co-polymer fluorinated oils content (Figure 3.6). From this, it can be seen that the hydrogel coating confers significant protection after 90 weeks immersion in Mediterranean Sea waters versus PDMS FRC with co-polymer and plain PDMS paint (border fouling are areas of no coating). Thorlaksen *et al*. (2010) also state that the hydrogel layer can "self-regenerate" if damaged for example by "mechanical abrasion".

3.4.3.6 Antifoul coatings are designed to be robust to mechanical damage as a necessity of docking and towage procedures etc., plus to impact with random debris at sea and to withstand greater levels of in-water cleaning or grooming (e.g. Olivera and Granhag, 2016). A drawback of earlier silicone based FRCs is that they were "susceptible to scraping or gouging damage, which can frequently happen on the sides of ships as they are moored alongside" (Townsin & Anderson, 2009) and to "cutting, tearing, and puncturing, which reduces [paint] service life" (Hu *et al*., 2020). However, improvements in toughness were achieved by means such as incorporation of fluoropolymer technology (Townsin & Anderson, 2009). The other drawback of FRC coatings, their propensity to accumulate biofouling under static conditions, has been successfully addressed by the incorporation of low concentrations of biocide into the formulation (see 3.4.3.1).

3.4.3.7 Dahlgren *et al*. (2022) investigated cleaning methods upon FRCs, and concluded that, for some of those tested, damage was sometimes evident particularly when organisms with calcareous structures were entrained within the cleaning brush. Furthermore, they recommended that the brush head may need "tailoring" to the specific coating (also see Olivera and Granhag, (2016)). This damage may lead to wider scale loss of the FRC in affected areas and, as Lewis (2020) notes, "although these coatings are biocide free, the coatings are elastomers which are pliable plastics. Flakes are therefore a form of plastic pollution and release into the marine environment should be avoided".

3.4.3.8 One controversial aspect of FRCs, is the use of the organotins dibutyltin dilaurate or dibutyltin dioctanoate as catalysts in their production, similar to their use in PVC products. Organotins have been used as catalysts for some time (see Piver, 1973), and though controversial in this context, are currently allowed for antifoul products under the AFS Convention (Appendix to MEPC 104(49) paragraph 6.3). The AFS Convention states that organotin not acting as a biocide in a hull coating is allowed up to a threshold level of 2,500 mg Sn/kg dry paint (IMO, *Indet*[d]). Irrespective of this, manufacturers are moving away from using DBT in FRC formulations.

3.4.3.9 The need for organotins as a catalyst in the manufacture of FRCs has been questioned (e.g. Rittschof *et al*., 2011; Feng *et al*., 2012; Pretti *et al*., 2013), which is perhaps unsurprising noting the history of organotins in the marine environment (see sub-section 3.4.1), and with the apparent availability of effective catalyst alternates (Pretti *et al*., 2013). Concern has been raised regarding leaching of organotin catalyst into marine systems from FRCs and the matter has also been raised with regard to flakes of damaged FRC falling to the benthic ecosystem and leaching out organotins over time. Conversely, Lewis (2020) reports that tests at International Paint found that the DBT content of a “ten year old flake” of their Intersleek® silicone product was 0.4% compared to 0.6% when new. It should, however, be noted that this is a 33% loss over the 10 year period which magnified by hull numbers and sizes, may need greater consideration, particularly in the face of the growth of, and need for, in-water cleaning, although the product had a very low starting organotin concentration and was not in a form designed to actively leach.

3.4.3.10 With regard to the efficacy of FRCs to reduce shear stress and improve hull efficacy / fuel use, as with biocidal coatings, work regarding the specific improvements in GHG emissions reduction is limited, nevertheless the comments are noteworthy. Laboratory research to compare the roughness and drag of an FRC coating with a tin-free SPC proved to be practically difficult (Townsin & Anderson, 2009). However, it was clear that FR surfaces are inherently smoother, resulting in lower drag, at least initially. Townsin & Anderson add that, “it must be recognised, that any fuel saving due to smoothness will be negated if a coating becomes fouled. Weber and Esmaeili, (2023) quote an overall broad figure of up to 10% saving in fuel by an “optimal hull surface”. Allowing that such optimisation will be a reduced roughness (value below 150 µm) to lessen shear stress, Farkas *et al*. (2021) go into more detail for an example FRC (Intersleek® 1100SR).

3.4.3.11 Farkas *et al*. (2021) looked at two voyage scenarios for two ship types, with three differing hull roughness conditions. For savings in fuel oil and CO2 emissions, the authors found a range of results from -5.37% to -9.02%. Farkas et al. (2021) stated that their results corresponded broadly with what Bouman et al. (2017) reported, and commented “it is clear that quite substantial relative decreases in FOC [Fuel Oil Consumption] and CO2 emission due to the application of [FRC] are obtained, and they are similar for both investigated ships”. These savings translated into significant tonnages of CO2 saved per route at slow steaming speeds (also discussed as an option for long passage and short shipping GHG emissions reduction in relation to IMO CII targets (see Zincir, (2023) and sub-section 2.2)). For concerns potentially raised regarding fouling attachment or non-removal at slow speeds, the authors stated that the manufacturer of the product tested by Farkas et al. (2012) claims that slime removal occurs at “very low ship speeds”. However, this conflicts with observations of persistent low profile marine growth within the hydrodynamic boundary layer on hull surfaces and the need for turbulent flow, such as around hull protrusions, to remove established growth (Peyvasteh Nejad, 2024).

3.4.3.12 Accordingly, in the absence of measured data on fuel use / GHG release for biocidal coatings and even if initial hull roughness is evident (Weber and Esmaeili, 2023), FRCs appear more able to create smoother hull conditions and GHG emissions reductions appear “potentially” significant for these products over biocidal ones.

3.4.4 Hard Coatings

3.4.4.1 Apart from biocidal coatings and FRCs, hard coatings are another option. They are based on the premise of being highly mechanically resistant (Lewis, 2020), bonding to the surface substrate (hull) with all trace of bonding chemicals evaporating, thus are marketed as entirely non-toxic. However, Wijga *et al*. (2008) commented that some trace chemicals were released during cleaning, but "are thought to have no toxic effects on marine life".

3.4.4.2 The strategy of combining a non-toxic scrubbable coating with frequent cleaning was tested in a trial on recreational boats in California (Lewis, 2009). Epoxy and ceramic-epoxy coatings were tested and in-water cleaning by divers was undertaken at intervals of between 15 and 18 days. The life of the coatings was considered to offset the costs of the frequent cleaning. A similar scenario applying a hard, smooth anticorrosive system (epoxy, ceramic-epoxy or glass flake) and to maintain it by regular underwater cleaning, was considered by Waterman (1999). For the system to be economic, he considered that sophisticated, possibly robotic (now available), cleaning systems would be required with a network of hull cleaning stations on all important trade routes. Even with automated cleaning systems, he commented that areas such as bilge keels, rudders and stern arches would still require manual cleaning, though later robotic systems could be investigated for such efficacy.

3.4.4.3 There is limited independent research on these coatings regarding efficacy and fuel / GHG implications (but see ERM, 2010), with most researchers and reviewers briefly mentioning their mode of action, application and two prevalent available products, Brunel® and Ecospeed®, though options will not be limited to these.

3.4.4.4 The major advantage of these coatings is given as their long-life after application (quoted as up to 25 years versus a maximum of 5 years for biocidal coatings / FRCs (ERM, 2010)) and their tough performance, meaning that they have been used on ice passage vessels for example (Erdogan, 2016; Arndt *et al*., 2021). Furthermore, they are designed to be "conditioned" by regular polishing (grooming), thus becoming smoother over time and reducing shear stress. Accordingly, a 10% reduction in fuel use (and presumably concomitant reduction in GHG emissions, as noted by Farkas *et al*. (2021)) *was* reported for a Disney cruise ship (Munoz, 2012), which is broadly in line with values given for smooth FRCs. However, in a study by ERM (2010), it was commented that no overall difference could be seen in fuel use, "which may have been a result of the large number of assumptions used in the model and the non-optimal conditions for [the product] in the experiment" (ERM, 2010).

3.4.4.5 The discussed disadvantage of hard non-toxic coatings is that regular cleaning is required to achieve fuel efficiency and GHG emissions reduction. If neglected (long idle periods), this leaves the hulls open to potential establishment of macrofouling and NIMS (Figure 3.2). To repeat the comment by Townsin & Anderson (2009) in relation to FRCs, any fuel saving due to smoothness will be negated if a coating becomes fouled. Of the limited commentary available, it is suggested that regular grooming / cleaning (and debris capture where needed) of these coatings should take place at the slime layer stage (Inglis *et al*., 2012; Davidson *et al*., 2016; Arndt *et al*., 2021). However, it should be considered, that as clean before you leave and regular grooming (see below) are increasingly considered as optimal management options, this appears to bring hard coatings further into play.

3.4.4.6 Notably, some ports that do not generally allow in-water cleaning were reported by the manufacturer of Ecospeed® as allowing hard inert coatings to be cleaned within their administrative areas (e.g. Port of Barcelona (Spain), Port of Rotterdam (The Netherlands)) due to established non-toxicity (Hydrex, 2010). Furthermore, the Port of Bremen (Germany) states that hard coatings should become an option of standard practice (see sub-sections 4.2.8 and 4.2.9).

3.4.5 Hull Cleaning and Grooming

3.4.5.1 Whether biocidal, FR or hard coatings (or alternate not discussed here), use of coatings is a key for GHG emissions reduction by providing a clean and initially low friction (< 150 µm) hull that reduces shear stress / hydrodynamic resistance is key. Macrofouling, particularly hard fouling (Figure 3.2), is the greatest contributor to biofouling induced hull speed inefficiency. Although, as discussed, even the slime layer can result in adverse effects (see section 3.2). Accordingly, to optimise GHG emissions reduction opportunities from biofouling alone, hull cleaning practice and options should be considered for both efficacy and possible adverse effects. It is acknowledging that "although up to 10% of fuel can be saved by an optimal hull surface, alternative fuel saving techniques must be taken into consideration" (Bouman *et al*., 2017) (see sub-section 3.4.6).

3.4.5.2 Apparent growth in the hull cleaning industry may be a consequence of the IMO Biofouling Guidelines, with focus on national and state level requirements (see sub-section 2.1) and guidance provided through the GloFouling project. However, concerns have been raised on the risks of "uncontrolled in-water hull cleaning" (Morrisey *et al*., 2013) and, more recently, Scianni *et al*. (2023) commented that "it is unlikely that these [IWC mitigations] approaches will eliminate environmental risk". Awareness of the potential environmental risks associated with in-water cleaning is growing and responsible risk management increasingly promoted. The 2023 IMO Biofouling Guidelines (IMO, 2023[a]) preface Section 9, Cleaning and maintenance, with: "Cleaning is an important measure to remove biofouling from the hull and niche areas, but may physically damage the AFC, shorten coating service lifetime and release harmful waste substances and invasive aquatic species into the environment". Interestingly, the industry bodies BIMCO (Baltic and International Maritime COuncil) and the International Chamber of Shipping (ICS) have developed an industry standard on in-water cleaning with capture (BIMCO/ICS, 2021[a]), an approval procedure for in-water cleaning companies (BIMCO/ICS, 2021[b]), a procedure for testing and certification of in-water cleaning companies (BIMCO/ICS, 2023), and published a book, "Biofouling, Biosecurity and Hull Cleaning" (BIMCO/ICS, 2024).

3.4.5.3 Policy makers should be aware of the full suite of risks related to ship IWC and the trade-offs to consider when balancing mitigation approaches. Accordingly, caution should be exercised when recommending IWC as a policy approach. This is with particular regard to suppliers not following safety requirements for divers and / or not using suitable waste material capture technology (see below), being mindful of pollutant release and sensitive marine areas with associated ecological implications (Tamburri *et al*., 2020, 2021[b]).

3.4.5.4 An overview of hull cleaning methods is necessary to provide context on when and where to apply suitable actions. The most thorough and generally most expensive is dry-docking which is part of normal hull coating maintenance schedules, and hull survey requirements (nominally 3-5 years). Where local legislation applies, waste will be contained and require removal as a controlled material (due to the presence of the antifouling biocides in paint wastes). If not legislated, environmental awareness should be encouraged. Methods for hull cleaning in dry-dock include manual scraping, abrasive or high pressure water blasting and, less commonly, cavitation jet blasting and / or laser cleaning. These options plus ultrasound are also available for IWC (see Song and Cui, (2020) for review).

3.4.5.5 Intervals between dry-docking intervals are usually predetermined by class survey requirements or vessel specific maintenance needs. The underwater coating system applied is specified to meet the operational profile and planned service interval to the next dry-docking. The underwater hull will be cleaned after docking and the underwater coating system either spot repaired with a full coat of antifouling applied or, if the system is in poor condition, the hull fully blasted, and a new coating system applied. Interim dockings may occur for, for example, hull or propeller repairs, and the hull and niches will be cleaned, and the antifouling coating renewed if required. However, as noted by Hadžić *et al*. (2022), a "most profitable" hull maintenance schedule can be created with forward planning based on the ITTC-1978 relationship (International Towing Tank Conference). To maintain a clean hull, particularly without slime, to maintain optimal hull performance and GHG emissions reduction, regular dry-docking is not financially viable or practical as a method of biofouling control. In countries such as Australia and New Zealand, dry-docking facilities are limited, or for the few able to hold large vessels they are booked out for months or years in advance. In New Zealand, if a vessel is directed to dry-dock for biofouling removal, dry-docking “is only available for smaller vessels” (MPI, 2024[b]). Vessels may be required to leave New Zealand territorial waters to access dry-docks in, for example, Singapore or Indonesia at the added costs involved in the unscheduled voyage, including additional GHG emissions. Proactive attention to biofouling management is consequently recommended by the shipping industry (e.g. see UK Defence Club, (2019)).

3.4.5.6 In-water cleaning (IWC) is potentially an effective and cost-efficient method of maintaining hull cleanliness and, by extension, minimising NIMS and GHG emissions. Until recently, hull cleaning was largely unregulated and ships at anchorage were commonly cleaned by divers using brush carts and no capture of dislodged wastes. The US Navy, for example, was never permitted to use TBT SPC antifouling paints, so persisted with non-ablative or ablative copper-based antifouling paint systems. The normal service life of a non-ablative antifouling was 2 years and this was extended to 7 years by regular inspection and hull cleaning (NSSC, 2002).

3.4.5.7 Regulation of IWC is increasing, with consideration of location, method, equipment, etc. The GloFouling project is promoting responsible IWC as an effective method of managing NIMS and enhancing shipping efficiency. The responsible management and authorisation of IWC systems has become a necessity and the presentation on the risks / benefits issue from Tamburri *et al*. (2023) is discussed in a GloFouling meeting proceedings document (Khodjet *et al*., 2023).

3.4.5.8 Environmentally sound IWC operations require management of materials released. Waste will predominantly be removed biofouling growth but, if the paint system is degraded, or the cleaning method is too aggressive, there will also be flakes and particulate material from the present hull coating (biocidal antifoul, FRC or hard etc.), Care is necessary when cleaning FRCs with IWC brushes as they are susceptible to abrasion damage. Cleaning carts with non-contact brushes or blades, which remove the growth by hydrodynamic force, are often used for cleaning these coatings. Lin *et al*. (2024) highlighted a long-term study on the management of FRCs in which it was reported that longer term cleaning resulted in surface damage, but shorter term cleaning had no significant effect. However, in both instances the authors noted that “despite these damages, the cleaned surfaces still exhibited a higher fouling resistance compared with the ones without cleaning”. This highlights the importance in IWC of matching the force / brush type to the level of foul cleaning required and the nature of the underlying hull coating to withstand abrasive brush action (see Oliveira *et al*. (2016). In this way, hull resistance and, consequently, GHG emissions can be minimised.

3.4.5.9 As noted above, Scianni *et al*. (2023) commented on the unintended outcomes of legislation and highlight the risks of unregulated IWC growth. Apart from direct risk to human health, with poorly regulated services using divers in unsafe or unprotected situations, the other major consideration of IWC is the potential release of viable biological material and chemical contaminants from the hull coating. Numerous research papers, Government and commercial reports (Floerl *et al*., 2010; Morrisey *et al*., 2013; Lewis, 2020; International Chamber of Shipping, 2021; Soon *et al*., 2021; Tamburri *et al*., 2020, 2021[b]; Scianni *et al*., 2023; Hyun *et al*., 2024), highlight the risks of viable NIMS and chemicals from hull cleaning. Scianni *et al*. (2023) discuss the release of contaminants such as dissolved Cu, Zn, and associated biocides, which may adversely affect larval marine organisms in the water column. Metals and organic biocides can also accumulate in sediment to create a contaminant reservoir adversely affecting the benthic community (e.g. see Soroldoni *et al*. (2017); Muller-Karanassos *et al*. (2021)). Further to this, there is also recognition that abrasive cleaning of hull coatings may also release a pulse of microplastic (MP) material (e.g. see IMO, (2019); Tamburri *et al*. (2022)), which can mechanically affect the digestive tracts of organisms when ingested. MPs can also sorb contaminants onto a surface organic layer, further exacerbating contaminant bioaccumulation potential (Frias *et al*., 2022).

3.4.5.10 I In relation to the above, for more abrasive hull cleaning activity, an Industry Standard for IWC with capture has been developed (BIMCO/ICS, 2021[a]). Certification for an IWC system under the standard would require that:

1. “The [IWC] process removes at least 90% of macrofouling (i.e. individuals or colonies visible to the human eye).
2. The separation and/or treatment of captured materials during [IWC] both: (1) removes at least 90% (by mass) of material from seawater influent and (2) at least 95% of particulate material in effluent water is 10 µm in equivalent spherical diameter (ESD);
3. Local water quality parameters of Total Suspended Solids (TSS) are not elevated above ambient levels during the same time period”; and
4. that “Local water quality parameters of dissolved and particulate biocides found in AFC are not elevated significantly above ambient levels during the same time period”.

3.4.5.11 Some companies are addressing the above points. For example one company claims that all cleaned material is held within a closed loop, and that soft jets are used rather than abrasive brushes (see here). Another (see here) states that a filtration system is used and “is always considered for locations that require biofouling management, hull cleaning spoils recovery, and particulate matter filtration”. This suggests the filtration system is optional and may not be used in areas adjudged to be less sensitive. This would be consistent with the Australian IWC guidelines that do not capture if the biofouling is locally acquired (DAFF, 2024[b]).

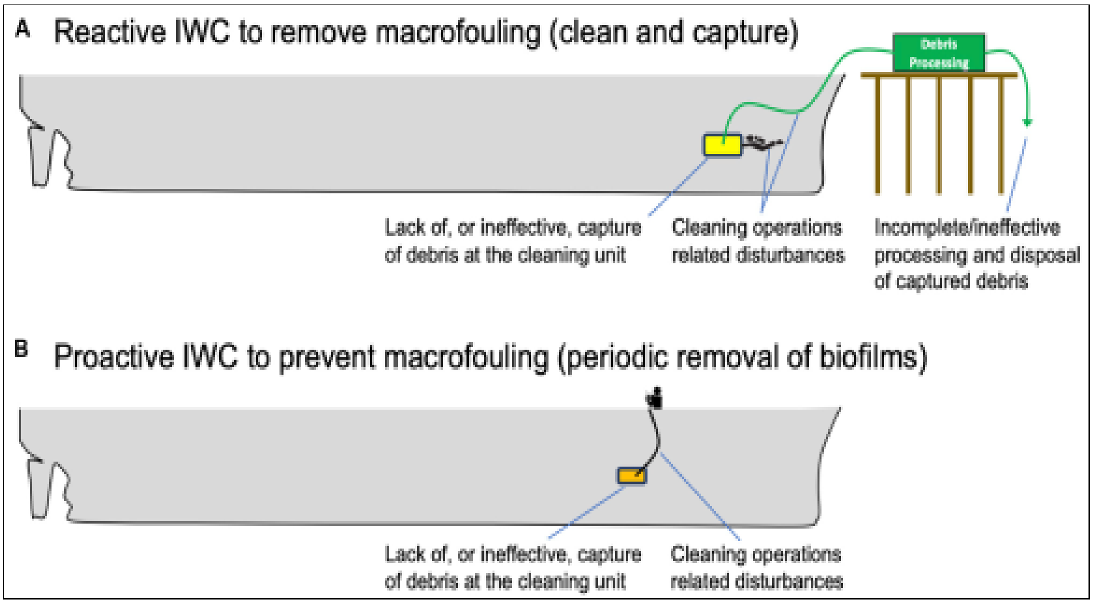


Figure 3.7 Potential harmful material sources from IWC for A reactive intermediate and macrofouling and B proactive biofilm, slime layer cleaning

From: Tamburri *et al*. (2021[A])

3.4.5.12 The above statements on closed loop and filtration systems should ideally be audited for environmental efficacy in areas of operation (where permitted locally and/or regionally), particularly if such approaches may be developed in a policy context for the Mediterranean region (see Scianni *et al*., (2023)). However, in terms of legislation, climate policies have been found to be more effective when integrated into a comprehensive policy mix, rather than as independent policies. Policy requirements also differed between developed and developing countries, with emission pricing more effective in developed countries, while regulatory measures had greater effect in developing countries (Stechemesser *et al*., 2024).

3.4.5.13 For the capture efficiency of IWC systems, Tamburri *et al*. (2020) addressed the "paucity of data" on IWC effectiveness and standardisation of a suitable method to test system ability. In testing one system on two vessels, they found that water quality parameters were exceeded in some cases for particulate, dissolved and total Cu levels (see Figure 3.7 for possible sources). This risk has been raised by others and the development of any policy to make IWC compulsory is recommended to be based on sound audit data (using suggested methods – e.g. Tamburri *et al*. (2020), BIMCO, (2023)) on the effectiveness of IWC systems in a variety of conditions before any associated regional or local licence is given.

3.4.5.14 The above addresses reactive IWC of macrofouling (Figure 3.2). However, there is increasing promotion by carbon management groups of proactive cleaning (e.g. see Bellona). Proactive cleaning of hull coatings, together with clean before you leave / arrive policies, may be a more effective approach if undertaken in a timely and regular manner. Cleaning at the slime layer stage, before the settlement of macrofouling, has been termed grooming (Tribou and Swain, 2010; Swain and Tribou, 2014). The need to capture wastes when grooming may not be entirely necessary as viable fouling organisms / NIMS are unlikely to be present at the slime layer stage.

3.4.5.15 It needs to be noted that biocidal antifouling coatings act by preventing the attachment of the early microscopic stages of macrofouling (e.g., algal spores, invertebrate spat) and their development, effectively holding the biofouling at the third stage (illustrated in Figure 3.2. The slime that develops on these coatings is mostly formed by biocide tolerant bacteria, diatoms, and their extracellular exudates. These slimes differ in composition to those on non-toxic surfaces (Molino & Wetherbee, 2008; Molino et al., 2009[a], 2009[b]). Macrofouling only establishes on biocidal coatings when the biocide release rate drops below that critical for macrofouling prevention due to biocide depletion in the coating or obstruction of the release by surface deposits.

3.4.5.16 In nature, grooming is described as "the physical removal of biofouling from the host, which effectively controls slow- and fast-growing biofouling" and is practised in aquatic systems by e.g. decapods and crustaceans (Bixler and Bhushan, 2012), thus perhaps creating an analogy to IWC companies. Tribou and Swain (2010) were the first to discuss grooming as an approach to biofouling management. . Using a Cu based biocide coating, an FRC, a marine epoxy coat and a sheet of "polytetrafluoroethylene plastic" they showed that, after 120 days with 3, 6, 12 and 24-day grooming intervals and biofouling was prevented on the Cu coating. For the FRC, grooming was effective for 3 and 6-day intervals, until fouling became more intense, and the latter two became "fouled at all grooming" intervals. However, except for the FRC (further highlighting the commentary on matching brush to coating / fouling (Oliveira and Granhag, 2016)), forces required to remove fouling had to be increased over time). Frequent grooming had positive effects and, in ongoing research (e.g. see sub-section 3.4.3) there are improvements in FRC (and others) performance and robustness.

3.4.5.17 The Bellona (a climate change lobby and action group) Clean Hull Initiative promotes biofouling management for GHG emissions reduction outside the academic sphere. The website quotes the 2023 IMO GHG Study (IMO, 2023[b]) regarding the "9 % of [shipping GHG] emissions is the direct result of biofouling on vessel hulls causing increased drag through water". This may be a slight oversimplification of figures, but broadly reflects values calculated of between 5-10% (see sub-section 3.4.2.8) and the site goes on to highlight the benefits of proactive cleaning (grooming) in comparison with reactive.

3.4.5.18 Proactive grooming of the slime layer stage as a clean before you leave / arrive approach is mentioned in an Australian Government report by Lewis (2020) who quotes the New Zealand Government MPI document from Georgiades *et al*. (2018). In this, it is stated that "proactive in-water cleaning or treatment is an effective measure to limit biofouling accumulation". Furthermore, it is stated that "reactive in-water cleaning or treatment should not be used to routinely remove or treat mature and extensive macrofouling. Reactive in-water cleaning or treatments are not substitutes for earlier or better maintenance practices". This clearly highlights an informed opinion that grooming at an early stage with appropriate equipment (see **Error! Reference source not found.**) designed to deal with the applied hull coating is a more effective approach at biofouling management with, ideally, a clean before you leave / arrive regime (see Georgiades *et al*. (2018) p 11 for a summary of applicable proactive practice guidance). Not only is clean before you leave by proactive grooming suggested by New Zealand and Australian Government documents, it is also discussed for operation in the Baltic by Watermann *et al*. (2018), which may be similar in sea traffic etc. to the Mediterranean Sea; a Mediterranean Sea example (GEF-UNDP-IMO, 2022[b]) of proactive cleaning / grooming results is discussed below (see sub-section 5).

3.4.5.19 Swain *et al*. (2022) summarise "many years of research" on grooming approaches and consider GHG reduction through appropriate proactive measures; also see Hunsucker *et al*. (2018) on the benefits of grooming and hull resistance reduction at the slime layer stage. As noted previously here, Swain *et al*. (2022) comment that "the absolute [GHG] penalties incurred by hull roughness and biofouling are difficult to predict due to differences in hull form, hull speed and the heterogeneous nature of the hull condition and biofouling" and weather; i.e. multiple factors with changing relevance in time and space. Swain *et al*. (2022) observe that there are "limited data on the [prevailing] outer hull condition on the worlds fleet", but reported on research showing that, in two studies, 40-50% of the world's fleet had significant fouling (greater that 40-50%). They also comment that, if the world's fleet could be proactively maintained in a smooth, i.e. lower hydrodynamic resistance, state (see **Error! Reference source not found.** for groomed and ungroomed fouling progression), then reduction in CO_2 and exhaust gases would be significant to a figure of a 19% overall reduction in shipping emissions – just for maintaining smooth hulls (see Swain *et al*. (2022), p 10, for full explanation of calculations).

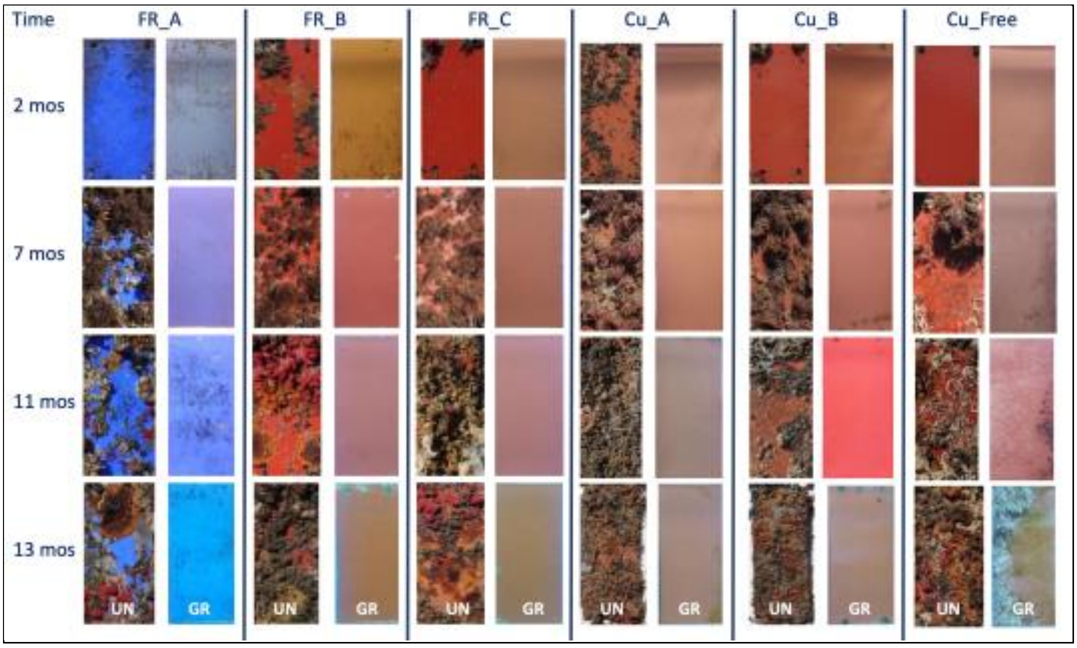


Figure 3.8 Fouling progression on three FRC and three biocidal coatings subject to immersion and groomed versus ungroomed weekly
From: Swain *et al*. (2022)

3.4.6 Propellers and Propeller Polishing

3.4.6.1 The surface area of a ship's propeller is relatively small, but the effect of a fouled propeller on fuel consumption is large. In absolute terms, it has been stated that the effect of the surface condition is less than the hull condition, but significantly more important in terms of energy loss per unit area (Atlar *et al*., 2002).

3.4.6.2 The IMO Guidelines for the development of a Ship Energy Efficiency Plan (IMO (Indet[b])) state that “propeller cleaning and polishing or even appropriate coating may significantly increase fuel efficiency [and that] the need for ships to maintain efficiency through in-water hull cleaning should be recognized and facilitated by port States”. This fuel efficiency equates to reduced GHG emissions, so the coating or regular polishing of propellers needs to be facilitated and encouraged. For uncoated propellers, propeller cleaning twice a year is considered a good measure for preventative maintenance and “a commonly stated length of time after a dry dock polishing that performance deterioration for larger ships is 4-8 months (Kane, 2012). Alternatively, application of a paint system with a surface finish equivalent to that of a new or freshly polished propeller can prevent the significant losses in propulsion efficiency resulting from propeller fouling (Atlar *et al*., 2002).

3.4.6.3 In terms of fuel savings and economic terms, propeller maintenance can generate a high return on a relatively cheap investment (Korkut and Atlar, 2012). While, traditionally, propellers were not coated, in part because coatings would be eroded or delaminated by the turbulent flow or cavitation of water across the blade surfaces, coating propellers with an FRC is becoming more common. Korkut and Atlar (2012), report that, as of that time, more than 250 ship propellers were painted with FRC.

3.4.7 Options in addition to Biofouling Management

3.4.7.1 Whilst not a primary goal of the Study, in addition to biofouling management, alternative technologies and approaches may be considered in reducing fuel use or type or capturing GHG emissions from shipping (e.g. Weber and Esmaeili, (2023); Bouman *et al*., (2017)) and put in place by some national Mediterranean region policy makers (Brewer, 2020). Weber and Esmaeili, (2023), list potential approaches other than biofouling control, or in synergy with, e.g. including hull design changes, already encompassed in requirements adopted under MARPOL Annex VI to reduce GHG emissions from ships (IMO, *Indet*[b]), (Figure 2.1).

3.4.7.2 Shipping carbon capture technologies plus IMO approaches (EEDI) are reviewed in Wang *et al*. (2017). Furthermore, Xing *et al*. (2020) undertook a review of all possible measures for carbon management from shipping. Wang *et al*. (2017) mainly concentrate on carbon capture and storage (CCS). The three main carbon capture technologies are listed as pre- and post-combustion capture and oxy-fuel capture. The feasibility of these approaches for ships is discussed, with the pre- and post-carbon capture considered the most viable. However, space limitations are a likely restrictor for such methods, but research continues. For example, Larkin *et al*. (2023) used three scenarios (two terrestrial and one shipping) to investigate the use of smaller carbon nanotube capture units. The shipping scenario (and another for trucks) showed potential for retrofitting a carbon nanotube system based on its smaller size compared to “conventional” capture systems. Combined with hull design and practical options, such as weather-passage management, etc., carbon capture may offer extra alternates to minimising carbon release in conjunction with biofouling management.

3.4.7.3 Carbon capture and reduction may address atmospheric pollution from shipping and, for example, urban heat island effects from emissions in Mediterranean Sea ports (e.g. Brewer, (2020)). Wang *et al*. (2017) suggested weather routing, whereby an optimised voyage (spatially and temporally) utilising unspecified “IMO guideline for safety voyage” (Wang et al., 2017)), may also be used to reduce GHG emissions.

3.4.7.4 Other than operational approaches (e.g. slow steaming / arrival on time (lessening biofouling risk) and weather optimisation), fuels (e.g. Liquefied Natural Gas (LNG) or ammonia) or alternate power sources (e.g. electric, wind) (see **Error! Reference source not found.** and

Figure 2.1) for IMO requirements adopted under MARPOL Annex VI to reduce GHG emissions from ships, the other primary approach to GHG emissions reduction from shipping is alternate fuels to heavy fuel oils. Alternate fuels are listed as “fossil-based (containing less carbon), biomass-based (containing biogenic carbon) and non-bio renewable energy-based (mainly electricity and resulting hydrogen)” (Thepsilthar *et al*., 2020). At the time of the study (2017), “none of alternative fuels today possesses performances comparable with those of conventional fuels, except environmental performance” (Thepsilthar *et al*., 2020). The author also comments that to reach 2050 GHG emissions targets for shipping, the industry will not meet IMO targets without adopting biofuels or “renewable H_2”.

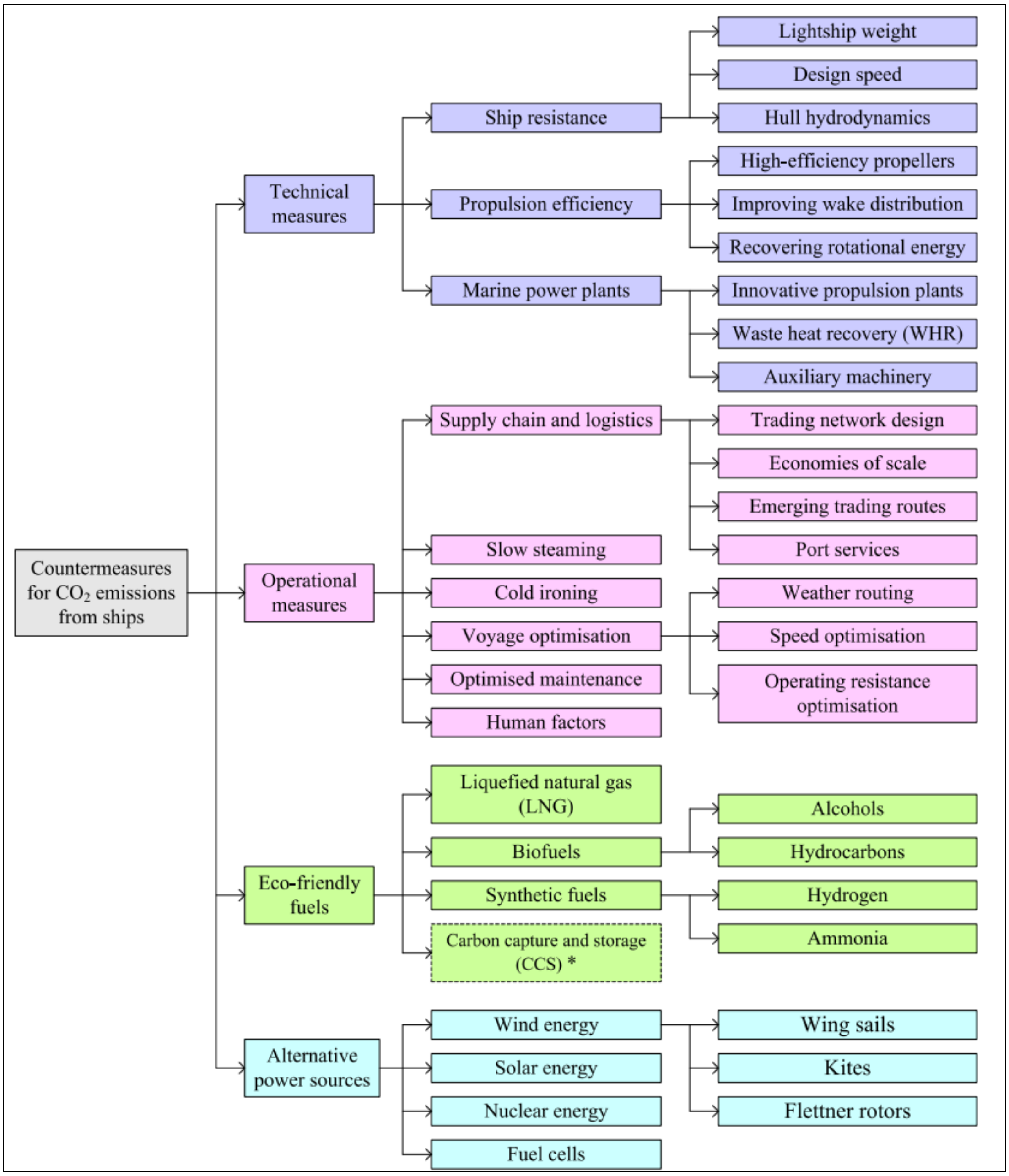


Figure 3.9 **Potential alternate and synergistic measures to manage shipping CO_2 emissions**
From: Xing *et al*. (2020)

3.4.7.5 As a final comment on some biofouling management alternates for GHG emissions reduction, short shipping (see also 5.1) from Croatian ports was investigated by Perčić *et al*. (2020). All three routes considered were in the Adriatic Sea, with the longest 30.2 nm (Split to Vis – vessel name: Petar Hektorović). The authors noted that the three vessels were all powered by diesel, and also commented that all the research they reviewed did not consider short shipping routes (Mediterranean Sea and otherwise), which appears a significant factor in Mediterranean regional shipping.

3.4.7.6 The Perčić *et al*. (2020) study considered biofuels and electric powered alternates and concluded that through both Life Cycle Assessment (LCA) and Life-Cycle Cost Assessment (LCCA) electric power was the most cost effective and environmentally friendly option for short routes. Accordingly, this approach may prove a useful consideration for other Mediterranean Sea short routes where GHG, SO_X, NO_X, etc. levels may be locally reduced in conjunction with proactive biofouling management, weather considerations, etc.

3.4.7.7 As previously noted, overall, biofouling management is generally considered to provide a relatively readily available 10% reduction in GHG emissions from shipping. That being said, as shown here, there are other possible synergistic options (Bouman *et al*., 2017; Weber and Esmaeili, 2023; Xing *et al*, 2020) that may allow a wider approach in conjunction with biofouling reduction and hydrodynamic optimisation. Where possible, policy in the Mediterranean region and elsewhere should be developed using these diverse options to build robustness into application. For application, this should be developed with the combined knowledge of vessel masters, engineers, owners / operators and environmental scientists, etc. to understand how best to minimise adverse effects whilst achieving GHG emissions reduction. This should involve discussion on what is practical and feasible and should ensure LCA is undertaken on all options. For example, if electric vessels are considered in a Mediterranean regional theatre, the primary electricity source should be sustainable (see Perčić *et al*. (2020)) and the on-board batteries should have been developed considering ethical and environmental aspects (e.g. Rachovides *et al*. (2024)).

3.4.7.8 Finally, it should be noted that the EU also promotes shipping GHG emissions reduction. Although this does not apply to all Mediterranean Sea coastal States, only those that are EU Member States, it may offer future opportunity for observation and / or adoption of methods by CPs. The EU actions comprise:

- Details of the EU Emissions Trading System (EU ETS) in which maritime shipping has now been encompassed;
- Details of the EU legislative process that allowed for maritime emissions to be included in emissions trading;
- Details of how the EU is engaging with and achieving “implementation of the internationally agreed energy efficiency rules and standards – Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP)” in line with IMO methods (MARPOL Annex VI (Regulations for the Prevention of Air Pollution from Ships) (see sub-sections 2.2.5 - 2.2.7).

4. PRACTICAL BIOFOULING MANAGEMENT

4.1 Aspiration

4.1.1 There is no one size fits all circumstance towards biofouling management. Ideally, practice will need to be tailored to vessels (e.g. hull and coating type), regions, local and wider environment as well as route and port risks from fouling species. This is particularly in the face of climate change where some predictions are that "fouling management will become an even greater challenge" (e.g. Dobretsov *et al*. (2019)).

4.1.2 As discussed, in the main, the choices are biocidal coatings, FRC and hard coatings as well as reactive post fouling cleaning (in-water interim, or at end of coating life in dry-dock) and proactive cleaning which, as discussed, is largely under the term of grooming. The current optimum approach to minimise biofouling to minimise GHG emissions, by maximising hull efficiency, would be to apply a long life biocidal SPC antifouling to prevent macrofouling, combined with regular proactive cleaning (hull grooming) to remove slime. However, consideration should be given to developing FRC options and to hard coatings depending on vessel usage and type, and when more data on the latter regarding smoothness, are available. Additional to this, propellers should be regularly cleaned and polished, or painted with an FRC or hard coating, to maximise propulsion efficiency. There are pressures to move away from biocidal coatings, but many of the major marine coating manufacturers remain committed to the biocidal approach, but alongside FRCs for specific applications. The move away from toxic compounds should be a longer term goal for when the practicality and efficacy of a non-toxic coating / proactive IWC regime is proven and sufficient systems / companies are in place to support proactive cleaning (see sub-section 2.1.25); i.e. the number of policy enacted audited and licensed cleaning companies is there to meet need / demand of proactive NIMS and hydrodynamic management.

4.1.3 The option of clean before you leave with grooming appears to be a more health and safety, socially and ecologically acceptable option that equally appears the most effective proactive way of managing GHG release and increasing vessel efficiency. However, the infrastructure is not yet in place to support regular grooming of transitory or resident vessels within the Mediterranean Sea (or elsewhere). Furthermore, vessels owners / operators / charterers would need to understand the implications of such a regular (potentially more costly) biofouling management approach. Pricing for these operations would need to be included in their overall activity, which has potential to affect end pricing of goods carried. Such pricing for carbon management would potentially affect geographically remote areas (e.g. small island states) more detrimentally (Kachi *et al*., 2019; Rojon *et al*., 2021).

4.2 Example Government and Port Requirements and Operations

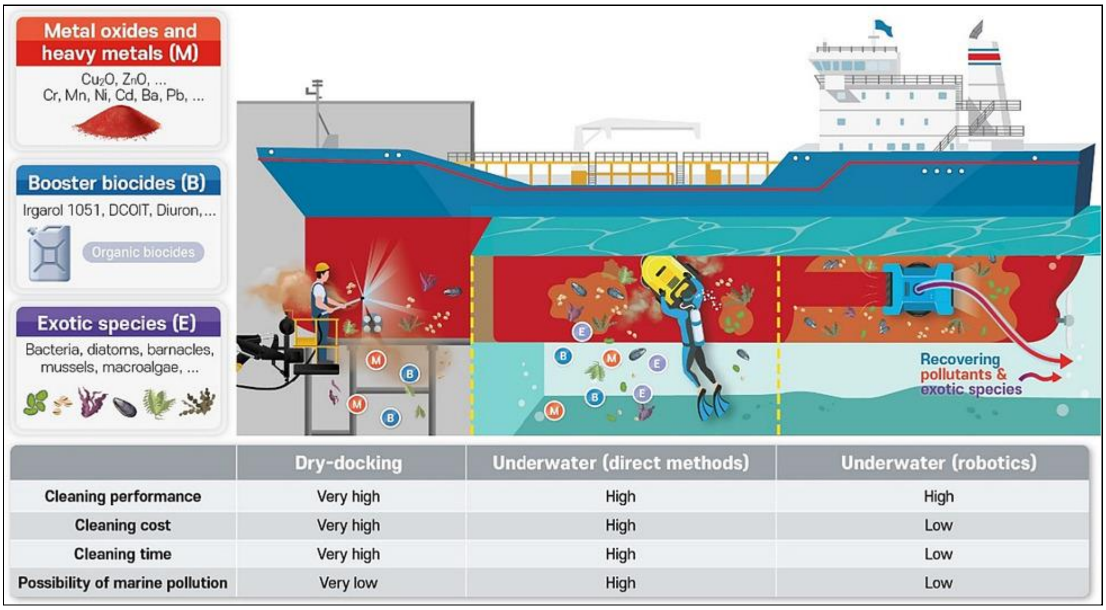
4.2.1 To provide context for possible future approaches of regular grooming and current general practice of intermediate coating cleaning, an overview of example current facilities is given here. It should be noted that, as Tamburri *et al*. (2020) commented, "the widely used approach of ship [IWC], without any attempt at debris capture, has not been evaluated for efficacy and environmental safety in any comprehensive or consistent way using quantitative measures". This foretells findings in research for the Study that the IWC industry is largely unregulated and unaudited, but growing in the face of increasing demand without suitable auditing, etc. If both cleaning and / or grooming are to develop to support biofouling management for the synergistic goals of NIMS and GHG emission management, capacity needs to increase with due attention to quality and safety.

4.2.2 Australia and New Zealand lead the present drive for biofouling management to manage NIMS, but GHG emissions reduction is a consequence. Significantly, Australia is developing an IWC standard and recently released an "Exposure Draft" (DAFF, 2024[b] However, it should also be noted that the hosting Department of Agriculture, Fisheries and

Forestry (DAFF) website states that “The approval process to conduct in-water cleaning or treatment in Australian waters is complex. The application process varies between locations and can involve many government agencies and port authorities. They will consider the biosecurity and toxicant risks and impacts the activity may have on the environment”, (DAFF, 2024^{b}). Approval of IWC is the responsibility of the States and Port authorities and “the standards are voluntary and do not change the roles and responsibilities of relevant regulators in assessing in-water cleaning activities” (DAFF, 2024^{b}). Shipping Australia has approached the Federal Department of Agriculture, Water & the Environment to ensure that the new standards align with those presented by BIMCO (see sub-section 3.4.5.2). Shipping Australia also requested the new standards should apply in all states and territories whilst also making a comment on the expense of operating shipping and that they “should therefore not be delayed insofar as it is reasonably practicable” (Shipping Australia, 2024).

4.2.3 As Australia and New Zealand will have developed the most mature approach towards IWC and biofouling management, the companies that operate there could be assumed at the forefront of environmental awareness and responsibility. Accordingly, they may make useful case studies (through dealing with the most stringent regulations) on which other organisations elsewhere (e.g. in the Mediterranean region) may be licensed for operation to reduce NIMS and encompass GHG emissions reduction whilst capturing debris and minimising environmental impacts. However, only one diving company in Australia has the equipment and capability to meet the proposed DAFF IWC standard and the cost of acquisition of the necessary waste treatment systems by other companies is not financially justifiable

4.2.4 Cleaning of vessels in overseas ports ahead of voyages to Australia and New Zealand has proven to be the most effective approach to meeting those countries requirements. For example, a China based company (Neptune Robotics, 2024) describes services (inspection, cleaning including propeller and niche areas (see Figure 3.3)) on their website that enable compliance with Australian and New Zealand biofouling management and entry requirements. The service is to clean hulls pre leaving ports in which it operates (e.g. Ningbo, China) before voyages to Australia or New Zealand, i.e. clean before you leave / arrive. The company uses robotic cleaning equipment, but significantly, makes no mention of capture technology and imagery from the system in operation does not indicate the presence of any, though it may be present



	Dry-docking	Underwater (direct methods)	Underwater (robotics)
Cleaning performance	Very high	High	High
Cleaning cost	Very high	High	Low
Cleaning time	Very high	High	Low
Possibility of marine pollution	Very low	High	Low

Figure 4.1 Ship hull cleaning options and projected costs and impacts
From: Kim *et al*. (2023)

4.2.5 A review document on improvement in China’s engagement with the IMO, as well as stewardship of marine areas and environmental protection is available, (Bai and Li, 2021).

However, no mention is made of in-water cleaning impacts management or regulation (also see Kim *et al*. (2023) and Figure 4.1). This perhaps highlights the need to consider the wider implications of ensuring a supplier of cleaning services is providing environmental and social care as would be expected by, e.g. the BIMCO standard.

4.2.6 On the other side of the globe, the Port of Southampton (UK), at the head of Southampton Water, has companies offering or exploring in-water cleaning services. Southampton is a major UK port for cruise and container vessels, together with oil and Liquefied Petroleum Gas (LPG) vessels, amongst others, using the Fawley and Hamble oil terminals towards the mouth of the relatively sheltered Southampton Water.

4.2.7 A company resident in the port claims management ofNIMS and, usefully the importance of CO_2 reduction, plus water quality aspects. Clean and capture are highlighted in the services offered. One client review states that "we are able to clean our vessels from about once a year to 8 times within a 6-month period" and further comments on "noticeable fuel reductions". Approval of IWC is required, and a hull cleaning request form can be downloaded here from the Associated British Ports (ABP) website. The form does not stipulate cleaning type and evidently allows diver operations (extra notification required), but asks for details of where a vessel is arriving from, of the fouling control system in place, and of the cleaning system to be used.

4.2.8 Within Europe, though not in the Mediterranean region, the Port of Bremen (Germany) highlights membership of the "CLEAN project group which aims to promote transparency and provide clear specifications for environmentally compatible underwater hull cleaning. Until more sustainable antifouling strategies, such as hard coatings, have become standard practice…". The comment regarding hard coatings is notable, as may provide an alternate approach (considered in overview at sub-section 3.4.4) to both biocide coatings and FRCs.

4.2.9 In the guidelines for the Port of Bremen (Germany) applying to permissions to clean, it is clearly stated that, if a coating is biocide based, cleaning will not be allowed, and that "cleaning may only be performed on abrasion-resistant, biocide-free underwater coatings". Few vessels could therefore be cleaned. Further to this, and perhaps key to the Study and indications of a possible move towards more proactive versus reactive cleaning, the document also states that "basic cleaning is also not permitted" (basic cleaning is not defined in the document). The ban on basic cleaning means that a vessel which is covered with macrofouling may not be cleaned in the water and that cleaning is only permitted in the dry-dock. Once this is completed, regular IWC may be scheduled and carried out at the biofilm stage [i.e. proactive cleaning] within the framework of fouling management". It should be noted, however, that in high fouling periods, harder organisms (barnacles, tubeworms etc.) can settle within days, thus it is not just the slime stage that may require cleaning.

4.2.10 Perhaps the most widely recognised area for biofouling management in the Mediterranean Sea is the Bay of Algeciras which has a longer history of IWC than elsewhere. The IWC industry is well established in the area and concerns have been raised that benthic (sea bed) communities are stressed due to pollution with communities dominated by transgressive marine species that are "typical of biofouling and categorised as pioneers and opportunists" (Naranjo *et al.*, 1996).

4.2.11 Recognition that the area is sensitive, but not well protected, and that shipping is a potentially significant impact (Kloff *et al*., 2002), was heightened through a local campaign to afford the area greater environmental protection. Two sets of work highlighted the significant anthropogenic stress in the Bay of Algeciras and investigated metals in sediments. Diaz-de Alba *et al*. (2011) found that "sampling sites [they investigated] were affected by anthropogenic activities". Gonzalez-Fernandez *et al*. (2011) determined by analysis that heavy metal pollution explained most of their findings. The sediments "had high positive loadings on Cu, Zn, Ag, and

Cd, which are heavy metals commonly associated with anthropogenic sources, such as urban wastewaters or antifouling”.

4.2.12 Poor flushing due to limited tidal movement has been noted for the wider Mediterranean with, in particular, parts of the Adriatic and the Mediterranean southern shore commented as suffering pollution related to limited flushing (UNEP / MAP, 2012).

4.2.13 There appears to be limited later work on the ecology and pollution of marine systems in the Bay of Algeciras. However, it is evident that IWC is continuing in the area. Some companies operating in the Bay of Algeciras practice clean and capture, with one requested by the Port of Algeciras Bay Authority to provide a hull cleaning system with capture and filtration (see here). However, other research on IWC in the Bay of Algeciras indicates that some companies may be cleaning here, and at other locations in the Mediterranean region, without waste capture. This supposition may be due to a lack of clarity in the company websites e.g. see here. Nevertheless, centres of IWC such as the Bay of Algeciras may benefit from clarified regional guidelines that require companies to demonstrate adherence to agreed standards, such as those of BIMCO. Should the guidelines approach result in limited efficacy, CPs could discuss the development of regulatory measures to achieve long term management to the betterment of the marine environment, whilst ensuring effective IWC.

4.2.14 Finally, Finally, in regard to proactive grooming, there is growth in robotic systems that may be used either in port, or transported with vessels to allow on demand cleaning when the vessel is on short-term layover, or even whilst in transit (e.g. here). Robotic cleaning systems are reviewed in Kim *et al*. (2023) who firstly comment that the removal of human labour in hull cleaning is a benefit from health and safety as well as efficiency aspects, plus robotic cleaners are not time restricted. All, whether fully remote or semi-autonomous, are angled towards proactive cleaning with an on demand nature to reduce the need for expensive reactive removal of macrofouling. They are marketed for reducing hydrodynamic resistance at the slime stage, thus reducing fuel costs and GHG release. A regional requirement to carry such equipment on board in a given region (e.g. the Mediterranean region) could be considered, but prior liaison with shipping lines and operators would be beneficial in promoting uptake of effective systems.

5. MEDITERRANEAN GHG AND BIOFOULING MANAGEMENT: CHALLENGES AND OPPORTUNITIES

5.1 Biofouling and GHG Emissions: Mediterranean Sea Context

5.1.1 The contribution of shipping to global GHG, NO_X and SO_X emissions has been discussed (see sub-section 3.2). The Mediterranean Sea is the primary route for shipping from Asia to Europe, with 51% of European goods value traded from outside the European Union (Fink *et al*., 2023). Also, Fink *et al*. (2023) comment that not only is the Mediterranean Sea (via the Suez Canal), the major through route for Asia – Europe traded goods (with concomitant increase in CO_2 levels over time (e.g. see levels at Straits of Gibraltar, Sicily, Suez Canal and the Bosporus, Figure 5.1[4]), the Mediterranean Sea is also "the principal route for short sea shipping within Europe". This, as identified by Toscano (2023), will contribute to air quality issues for Mediterranean region port areas and, by extension, inputs to overall GHG emissions.

5.1.2 As documented by REMPEC (2021), shipping emissions can be carried hundreds of miles and, even if emitted some distance at sea, and can significantly impact terrestrial air quality. The CO_2 emissions will add to the overall GHG total. Because of issues raised on air quality impacts from shipping in the Mediterranean region, REMPEC (2021) note suggested solutions such as reduced speed zones, shore side electrical supply and Emissions Control Areas (ECAs). Furthermore, with the importance of the Mediterranean region as a short shipping area, this sector of the shipping industry is a potential major win for biofouling management with potential concomitant changes in other approaches (electric power, alternate fuels etc.).

5.1.3 The opening of the Suez Canal, and its major role in global trade and as a through route to major ports of the Mediterranean Sea, has resulted in a significant t movement of NIMS through the Suez Canal (e.g. Ulman *et al*. (2019); Bereza *et al*. (2020). Of around 700 multicellular, non-native species recorded in the Mediterranean Sea, more than half have arrived through the Suez Canal (Otero *et al*., 2013; Kacimi *et al*. (2021). This movement, known as the Lessepsian migration, is almost completely unidirectional, with species moving from the highly biologically diverse Red Sea, to the relatively depauperate eastern Mediterranean, with shipping as one vector. For example, the lessepsian mussel (*Brachidontes pharaonis*) from the Red Sea is reported as having arrived by biofouling (Otero *et al*., 2013) and is now recorded as far west as the Iberian Peninsula (Murcia Requena *et al*., 2020). Further to this, the Mediterranean Sea is an exporter of the noted biofouling species (e.g. Godwin, 2003; Vinagre *et al*., 2020) the Mediterranean Sea mussel (*Mytilus galloprovincialis*) (Figure 5.2).

5.1.4 Despite the abundance of information on NIMS in the Mediterranean little information was found on GHG release from shipping in the Mediterranean region, and consideration of biofouling as an exacerbating factor, though the GEF-UNDP-IMO, (2022[b]) devotes a section to it. However, notably in this context, the important biofouling species the Mediterranean Sea mussel (Figure 5.2) has been found to foul, albeit stationary, oil platforms off the coast of Ravenna (NW Italy) at a weight of up to 150 kg m^{-2} (Relini *et al*., 1998). Thus, fouling and implications from slime to macro are important considerations for maintenance and fuel use on shipping in the region from both indigenous fouling organisms and NIMS.

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[4] Shipping CO_2 emissions data sourced from Emissions Database for Global Atmospheric Research (EDGAR), EDGAR v8.0_GHG release (1970–2022), published October 2023. EDGAR provides independent emission estimates distinct from those reported by EU Member States or Parties to the United Nations Framework Convention on Climate Change (UNFCCC). These estimates are based on international statistics and a consistent methodology from the Intergovernmental Panel on Climate Change (IPCC), available on their website. (https://edgar.jrc.ec.europa.eu/).

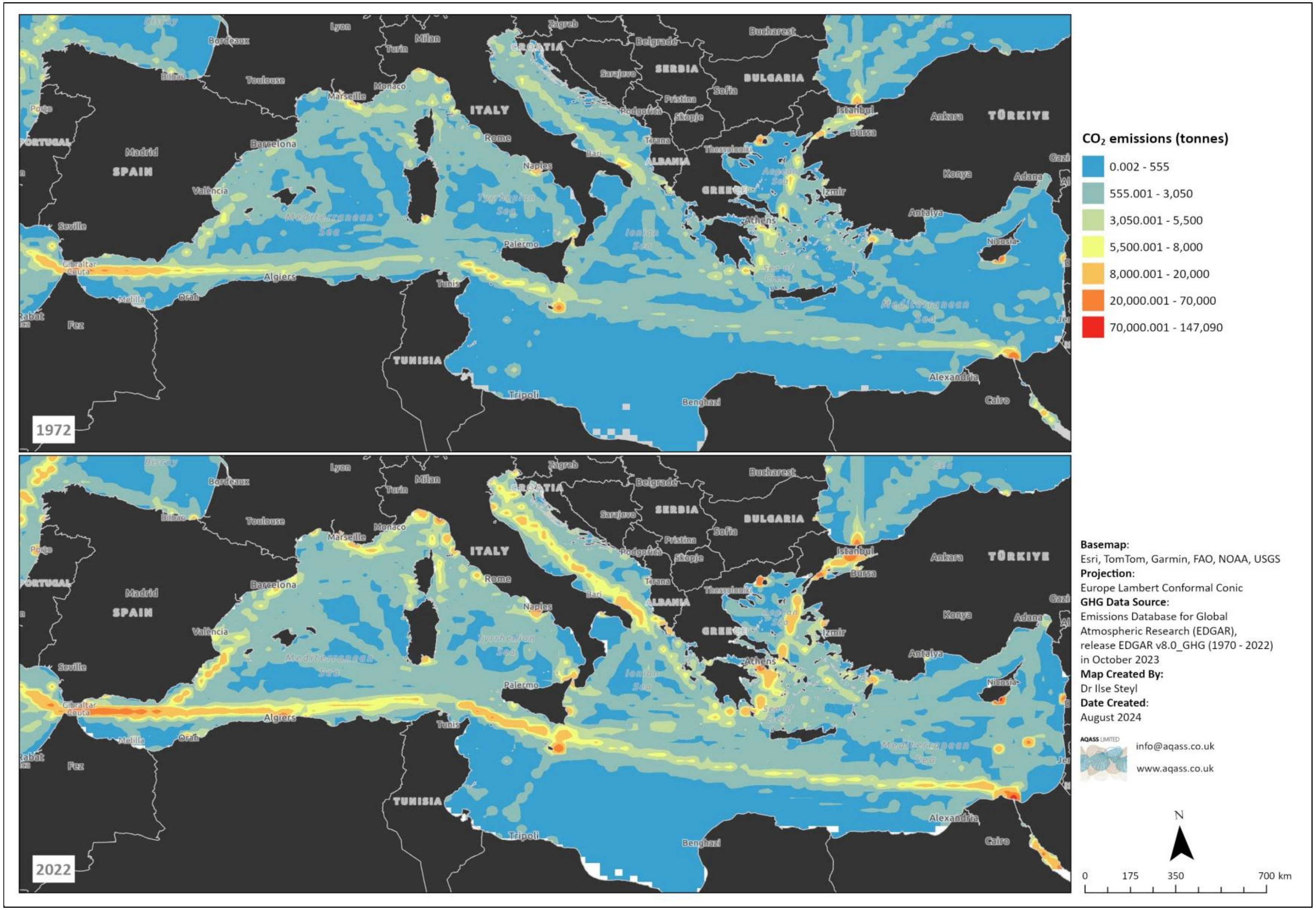


Figure 5.1 CO_2 levels on Mediterranean Sea shipping routes, 1972 and 2022

Data obtained from EDGAR, (2024)

Figure 5.2 Lessepsian mussel, green caviar / sea grape and Mediterranean Sea mussel
Source: Murcia Requena *et al*. (2020); Vinagre *et al*. (2020)

5.1.5 Hadžić *et al*. (2022) used a fishing vessel to test hull roughness measurements and a fluid dynamics model against the development of biofouling and effects of ship powering, plus dry-docking and the reproductive rates of marine organisms. The validating studies on the vessel, based in Croatia, were undertaken in the Mediterranean Sea. The vessel operated for an 18-month period, after which fouling growth was measured. Coincidentally, or from the owner's experience of maintenance requirements, the optimal period for combining wetted surface maintenance costs and costs of biofouling related increased fuel consumption was 18 months. This proved the most advantageous period for vessel maintenance with new antifoul painted on the hull (Figure 5.3).

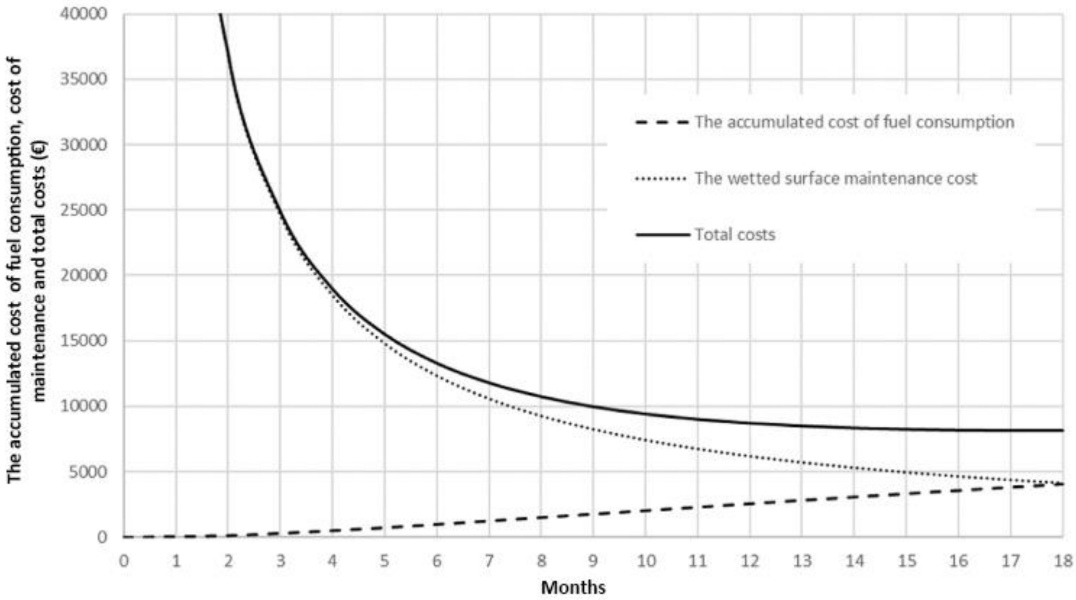


Figure 5.3 Biofouling management and fuel optimisation, evaluation of best feasible dry-docking time for Mediterranean Sea based fishing vessel
Source: Hadžić *et al*. (2022)

5.1.6 The GEF-UNDP-IMO, (2022[b]) study provides a comprehensive comparison of biofouling between equatorial and Mediterranean regions, and also considers results for biofouling rates and effects for a given bulk carrier scenario (over 5 years) using differing cleaning options (Figure 5.4). Fouling growth rates in the Mediterranean region were relatively slow compared to the equatorial region. However, the results were for the specific scenario and that this further highlighted the multiple variables to consider when aiming to manage biofouling levels related to GHG emissions.

5.1.7 The GEF-UNDP-IMO, (2022[b]) study also highlighted that cleaning and hull management could significantly reduce engine power requirement and thus fuel use / CO_2

release (Figure 5.4 and Figure 5.5) (further scenario results are given in the full report). Figure 5.4 shows that, as expected, the no clean scenario has a significant penalty upon engine power to overcome the increased biofouling frictional hull resistance with the concomitant release of CO_2. This study showed that, under a no hull cleaning scenario for the bulk carrier, fuel costs for the 5-year period would be "up to $26.70 million", and, through the various other management techniques (Figure 5.4), pro-active cleaning (grooming of hull and propeller) reduced fuel use to $21.80 million

5.1.8 Importantly, this study shows that proactive measures of "hull cleaning", "hull and propeller cleaning" and "hull cleaning + ultrasonic for propeller" show the best effect for engine power requirement, based on the frequency of cleaning intervention within the 5-year period (years three and four on the X-axis). Obviously, the intervention is more effective than doing nothing. One question is if the cost of regular intervention over the less active approaches is less than the fuel savings and improvement in GHG release levels.

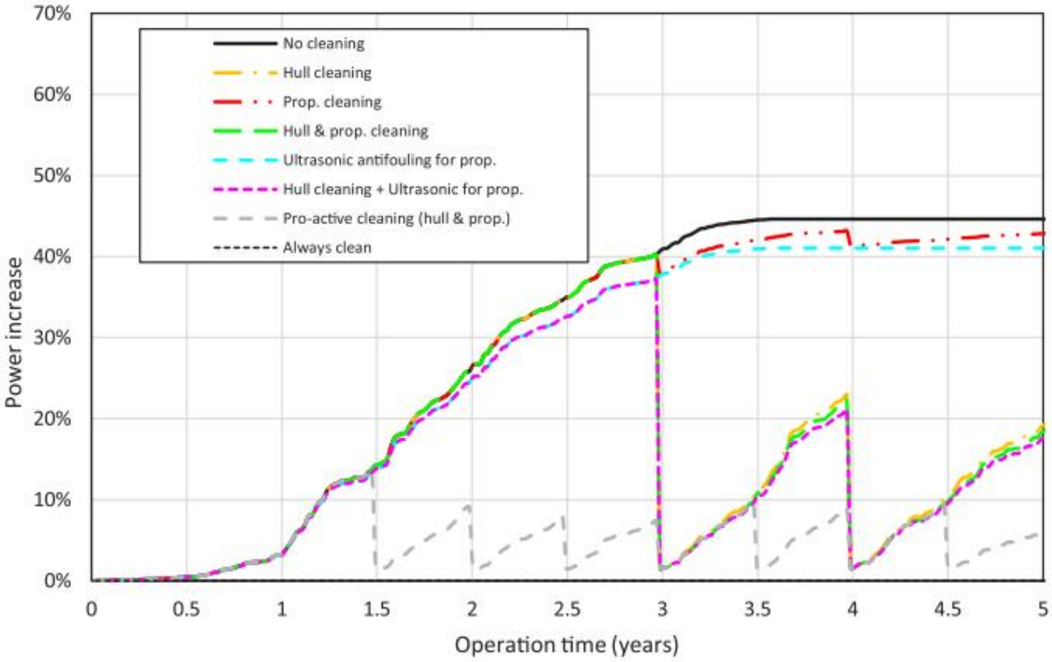


Figure 5.4 Differing hull management scenarios efficacy for engine power requirement, Mediterranean Sea
Source: GEF-UNDP-IMO (2022[b])

5.1.9 Total CO_2 emissions are shown in Figure 5.5. As to be expected, the "No-Cleaning" scenario generated the greatest levels of CO_2 release from the consequent increase in biofouling induced engine power. Conversely, the proactive cleaning strategy (see Tribou and Swain, 2010; Swain *et al.*, 2022) was the most effective at reducing CO_2 emissions from the bulk carrier. This approach saved 31,795 tonnes of CO_2 over the worst case approach. Savings in CO_2 release were also significant over some of the more reactive management practices s (Figure 5.5), but cost-benefit analysis may be needed on a vessel (type) by vessel basis to determine the best option.

5.1.10 On costs for vessel type), the study authors emphasised that data in the literature used were simplified and that interpreting findings for individual vessel types is still difficult. They add that, for the Mediterranean region and other scenarios considered, there is a need for primary data on ship cleaning, dry-docking, performance and power or speed loss. This information would "enable more precise and reasonable estimations of ship performances with different biofouling conditions and/or anti-fouling strategies" (GEF-UNDP-IMO, 2022[b]).

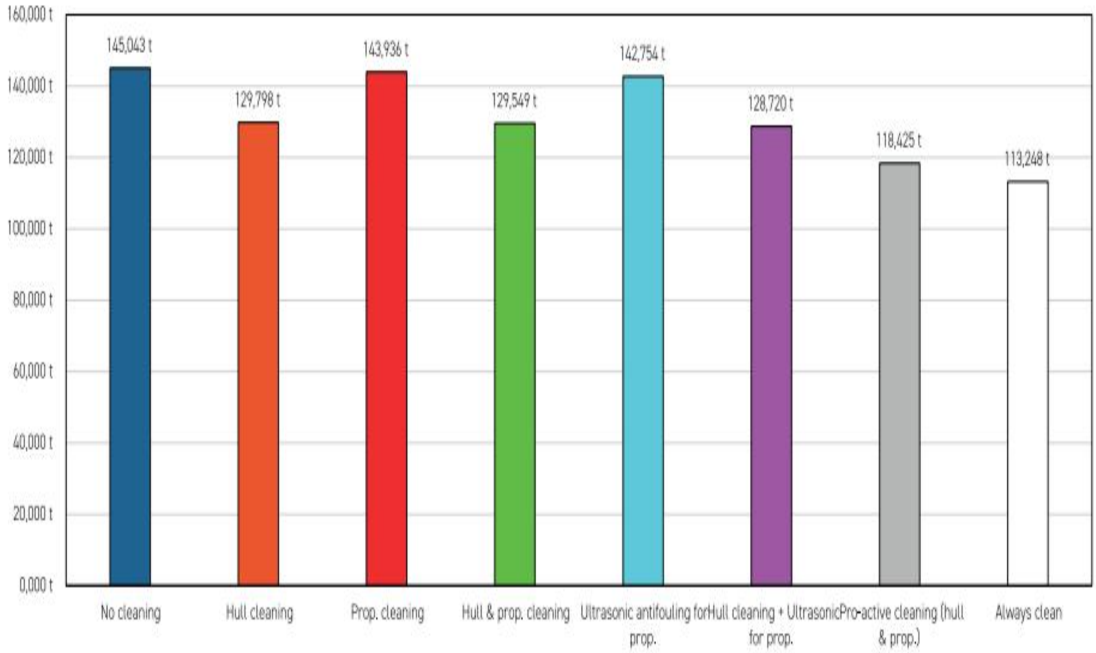


Figure 5.5 **Total calculated CO_2 emissions from the bulk carrier over a five-year period under differing biofouling management strategies**
Source: GEF-UNDP-IMO (2022^b)

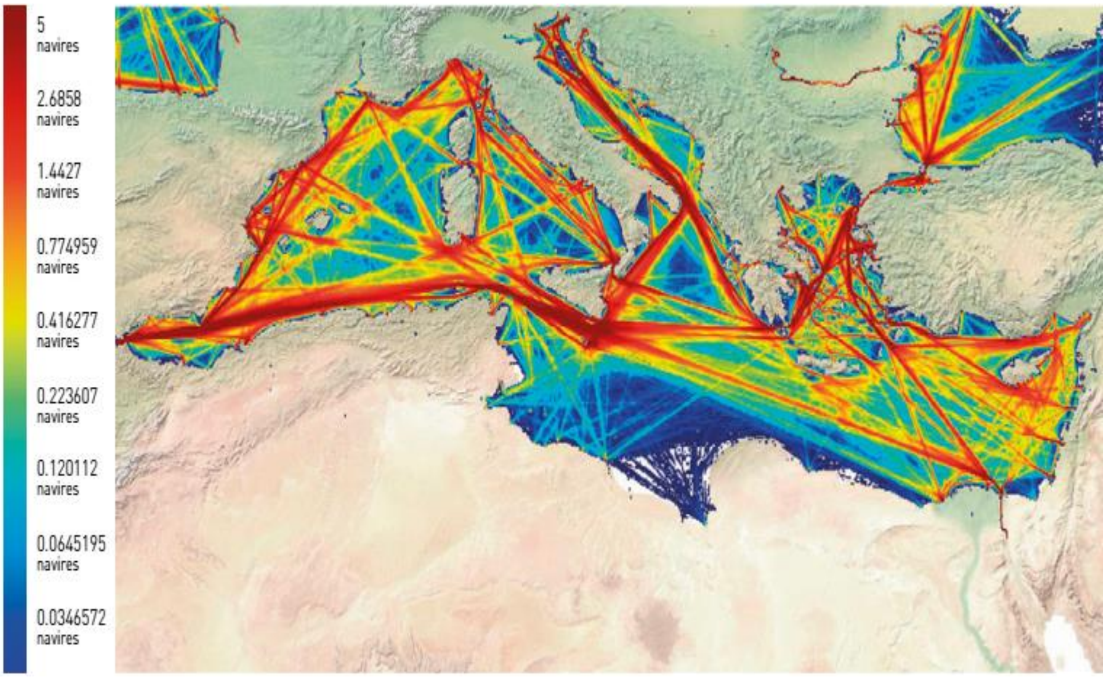


Figure 5.6 **Main traffic routes and density from AIS data, Mediterranean Sea**
Source: Ineris (2019)

5.1.11 GEF-UNDP-IMO (2022^b) reiterates that the dearth or real data from shipping is a hindrance to accurate assessment of biofouling impacts on fuel efficiency and CO_2 release from shipping. In particular heavy traffic levels through the Suez Canal) are significant for the Mediterranean region (**Error! Reference source not found.**), in goods transport and source of “hitch-hiking” biofouling species (Bereza *et al*., 2020). **Error! Reference source not found.** also shows that the Mediterranean Sea has significant “localised” short shipping routes which, as noted above (see sub-section 5.1.1), will contribute to overall fouling transfer and raised GHG emissions (e.g. see Kelmalis *et al*., 2023). Equally, short shipping in the Mediterranean region may present a biofouling and GHG emissions control opportunity. Overall, the GEF-UNDP-IMO, (2022^b) study demonstrates the value of cleaning approaches and that proactive options are best with the “clean before you leave” (see sub-section 3.4.5.18) approach supported. However, Tamburri *et al*. (2021^{b}) highlight practical and policy requirements needed before such an approach could become the norm. This would require discussion in the Mediterranean regional context.

5.1.12 Although work on biofouling and GHG emissions in the Mediterranean region is limited (see 5.1.4), a useful case study was undertaken on the effects of biofouling cleaning on a short ship ro-ro ferry (the *Carthage*) route between Tunis (Tunisia), Marseille (France) and Genova (Italy) (Desher, 2018). The vessel was subject to annual hull maintenance.

5.1.13 Data on hull speed performance after the planned maintenance period of 25 days dry-dock time in May to ensure readiness for peak season, were examined (Desher, 2018). Pre hull maintenance the vessel attained 21.6 knots mean speed, then 24 knots mean speed for same engine power post-maintenance.

5.1.14 All parameters for the year on year data comparisons (2015-2017) were the same: “ship draft and trim conditions for these comparisons are at the same values with which the ship operates typically at the majority of the time. In addition, it was assumed that the weather encountered by the ship for the same periods had the same conditions, which is correct at a very low difference because the Mediterranean region has the same climate for the same periods in the year” (Desher, 2018). Also, the same hull coating was used over the three years of data investigated and that, “as a result, a significant improvement in the ship speed that has reached 24 knots was achieved with the hull maintenance”. It was concluded that the hull maintenance regime was responsible for the marked speed increase and that fuel efficiency (and by extension GHG emissions reduction) would result.

5.1.15 The Desher (2018) research also considered monthly average (2015-2017) fuel consumption for the *Carthage.* A “significant decrease” occurred between July to September compared to the months before the dry-docking. The average saving during the three months post dry-docking was calculated to be “about 15 kg per mile”. From the few practical case studies available, this work is an indication of the benefits of hull maintenance in the Mediterranean region. For a round trip of approximately 2,100 km (i.e. 1,313 miles), the total fuel saving, based on15 kg per mile, would be 19,687 kg per trip for the first three months of new coating service. This equates to approximately 62 tonnes of CO_2 per voyage based on 3.15 tonnes of CO_2 per tonne of heavy fuel oil (see Marine Benchmark, 2020).

5.1.16 Whilst not a refereed paper or formal commercial study, the work by Desher (2018) provides a significant insight into the potential benefits of regular biofouling management. Given the paucity of wider data and general information on the practical effects of biofouling on vessel performance / GHG release, a precautionary principle approach could be adopted and a proactive stance applied by CPs in the Mediterranean region. Such a Mediterranean Sea wide aspiration may encourage broader engagement on biofouling management requirements and other options to manage both GHG emissions and air pollution from shipping.

5.2 Multi Criteria Analysis

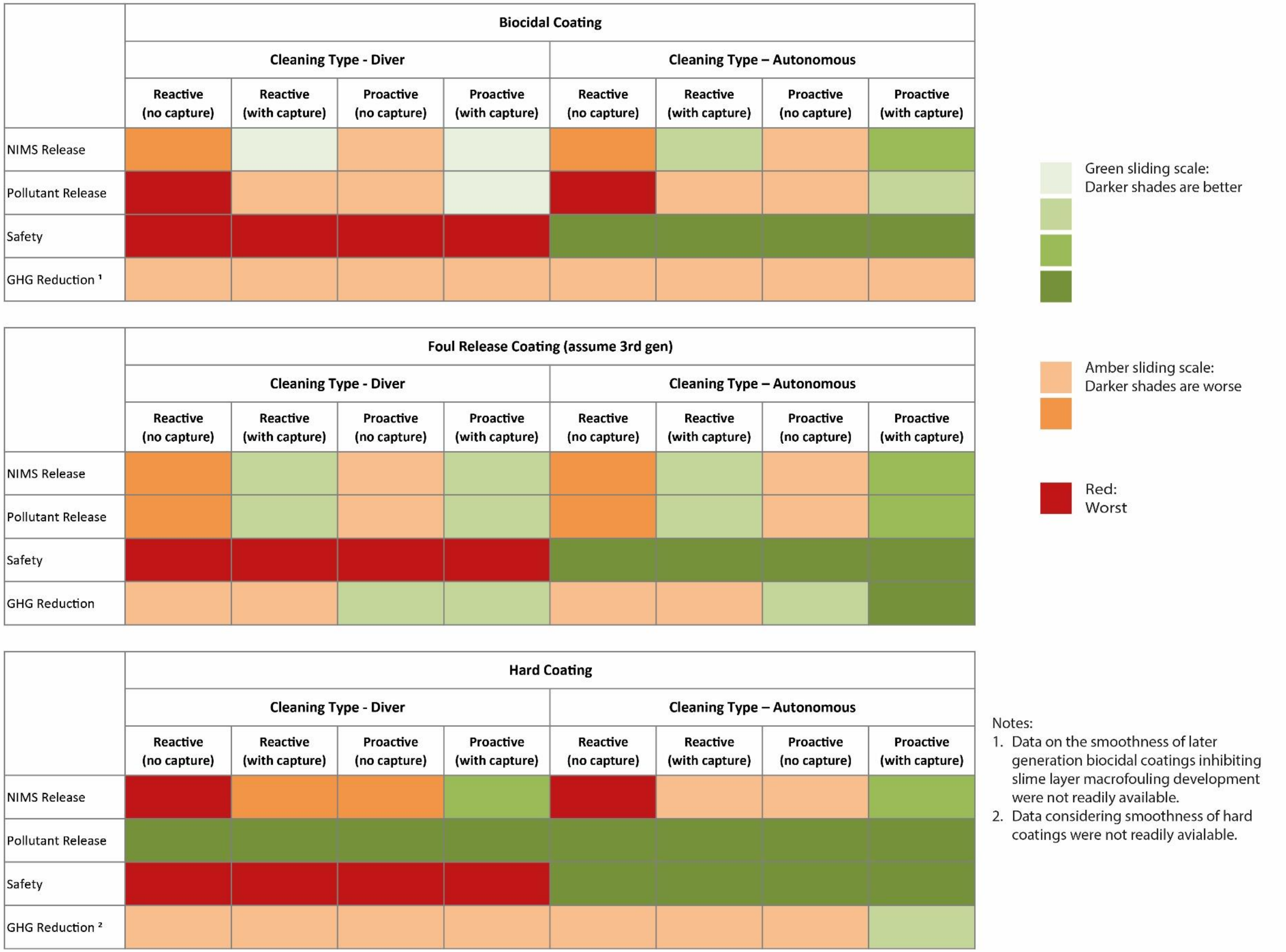
5.2.1 At the start of the Study was a survey of CPs was undertaken that requested information on any national or local policies on biofouling management and any detail on cleaning options already in existence, whether nationally registered or administered by ports, etc. This information was to be placed into a Multi Criteria Analysis (MCA), to establish the nature of best potential course of policy action and practical implementation for CPs.

5.2.2 Unfortunately, neither feedback nor comments to the survey were forthcoming from CPs during the consultation period. However, an MCA has been undertaken which highlights an approach to biofouling / GHG management based on the criteria of the coatings considered (see sub-section 3.4.2), cleaning methods and safety aspects. At this stage, these data are presented (Figure 5.7) to promote discussion at the Mediterranean regional level. The overall aim is to facilitate consideration of practical management approaches towards national and regional policy for biofouling management and optimal GHG emissions reduction.

5.2.3 The MCA undertaken on biofouling management options is conducted using a sliding scale for categories. As an example, in the context of GHG emissions reduction and overall hydrodynamic efficiency, biocidal coatings are generally less smooth than FRCs (see sub-section 3.4.3.10).

5.2.4 From the MCA the current and developing optimal situation to reduce GHG emissions via biofouling management is suggested as FRCs with proactive grooming (cleaning). This has also been highlighted in a recent (26/11/2024) online seminar regarding carbon reduction in shipping where in one presenting silicone coatings were described as the “Low Hanging Fruit of Fuel Energy Efficiency” (Malmberg, 2024). This will aim to maximise GHG emissions reduction due to the smoother nature of the coating, and the stated performance of later FRCs. However, data considering smoothness of hard coatings (i.e. <optimal 150 µm – see 3.4.3.10) were not available, thus this may need further clarification with researchers or manufacturers. Furthermore, data on the smoothness of later generation biocidal coatings inhibiting slime layer to macrofouling development were also not readily available, though some paint manufacturers do claim that TBT-free SPC coatings smooth or polish during operation as with the formerly available TBT coatings (e.g. see Intersmooth® 7465/60HS SPC).

5.2.5 Ideally, data on both hard and later generation SPC coatings in relation to hydrodynamic resistance in comparisons with FRCs, would assist in more informed decisions as to optimal options for GHG reduction. This is particularly regarding the “trade-off” of concerns re biocidal coatings, versus their performance in inhibiting fouling.



	Biocidal Coating							
	Cleaning Type - Diver				**Cleaning Type – Autonomous**			
	Reactive (no capture)	**Reactive (with capture)**	**Proactive (no capture)**	**Proactive (with capture)**	**Reactive (no capture)**	**Reactive (with capture)**	**Proactive (no capture)**	**Proactive (with capture)**
NIMS Release	🟧	░	🟨	░	🟧	▒	🟨	▓
Pollutant Release	🟥	🟨	🟨	░	🟥	🟨	🟨	▒
Safety	🟥	🟥	🟥	🟥	█	█	█	█
GHG Reduction [1]	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨

	Foul Release Coating (assume 3rd gen)							
	Cleaning Type - Diver				**Cleaning Type – Autonomous**			
	Reactive (no capture)	**Reactive (with capture)**	**Proactive (no capture)**	**Proactive (with capture)**	**Reactive (no capture)**	**Reactive (with capture)**	**Proactive (no capture)**	**Proactive (with capture)**
NIMS Release	🟧	▒	🟨	▒	🟧	▒	🟨	▓
Pollutant Release	🟧	▒	🟨	▒	🟧	▒	🟨	▓
Safety	🟥	🟥	🟥	🟥	█	█	█	█
GHG Reduction	🟨	🟨	▒	▒	🟨	🟨	▒	█

	Hard Coating							
	Cleaning Type - Diver				**Cleaning Type – Autonomous**			
	Reactive (no capture)	**Reactive (with capture)**	**Proactive (no capture)**	**Proactive (with capture)**	**Reactive (no capture)**	**Reactive (with capture)**	**Proactive (no capture)**	**Proactive (with capture)**
NIMS Release	🟥	🟧	🟧	▓	🟥	🟨	🟨	▓
Pollutant Release	█	█	█	█	█	█	█	█
Safety	🟥	🟥	🟥	🟥	█	█	█	█
GHG Reduction [2]	🟨	🟨	🟨	🟨	🟨	🟨	🟨	▒

░ ▒ ▓ █ Green sliding scale: Darker shades are better

🟨 🟧 Amber sliding scale: Darker shades are worse

🟥 Red: Worst

Notes:
1. Data on the smoothness of later generation biocidal coatings inhibiting slime layer macrofouling development were not readily available.
2. Data considering smoothness of hard coatings were not readily avialable.

Figure 5.7 Multiple criteria analysis for physical biofouling management options

5.3 Mediterranean Regional Practice and Policy: The Future

5.3.1 The information presented in the Study sought biofouling management options in relation to GHG emissions from shipping. Although there is a relative paucity of data on the effects of biofouling on vessel efficacy and there are also multiple variables that can impact the relationship that differ between ships, a reduction target, 5-10% of emitted GHG, seems possible. This, in theory, is an achievable aspiration if there is a consensus to which CPs can aspire and take up at an agreed pace.

5.3.2 Globally, IMO Member States are engaging with the IMO Biofouling Guidelines to guide policy development and requirements for arriving vessels. As previously discussed, Georgiades *et al*. (2020) claimed that the New Zealand approach is aligned with the IMO Biofouling Guidelines and commented on the opportunity this approach presents globally to develop consistent and proactive methods of biofouling management (see sub-sections 2.1.15 – 2.1.16). However, the NZ MPI impose a greater level of scrutiny on the vessels arriving in NZ territorial waters than required by the IMO Guidelines by applying a biofouling standard on arriving vessels (MPI, 2003). Australian biofouling requirements better reflect the IMO Guidelines by admitting vessels that have a ship specific Biofouling Management Plan and up-to-date Biofouling Record Book (DAFF, 2023). In respect of the above, for the Mediterranean Sea, it is recommended to align with the IMO Biofouling Guidelines and to learn lessons from other IMO Member States that have already done so.

5.3.3 CPs, including those not yet Parties to the AFS Convention, are and will be in a position to cooperatively take a collective regional stance on the management of biofouling for the reduction of GHG emissions. The management of biofouling induced hull resistance and, concomitantly, possible NIMS transfer (allowing for niche area cleaning) into and out of the Mediterranean Sea are mutually inclusive goals. Regional policies applied at the national level on coating selection, “clean before you leave / arrive”, hull grooming, and IWC and capture, etc., are available tools for consideration.

5.3.4 Through discussion and communication with stakeholders, a phased approach to biofouling management for GHG emissions reduction on short shipping and transitory vessels could be developed, to be managed through port and harbour facilities in the Mediterranean region. Realistically, what can presently be expected is development of a policy that is aligned to the IMO Biofouling Guidelines for proactive biofouling control. National, and thus regional, auditing of IWC supply and practice further aligns with best practice, such as presented by BIMCO / ICS, to ensure that biofouling control is undertaken in and environmentally responsible and safe manner.

6. RECOMMENDATIONS

6.1.1 Based on the available information on challenges and opportunities to manage biofouling to optimise shipping performance, and thus reducing GHG release, it is possible to create an initial list of recommendations for the Mediterranean region context. These are intended as guideline recommendations and will require discussion and cooperation amongst CPs. Appropriate representation and cooperation from relevant regional legislative bodies in CPs (central Government and national environmental regulators), economic advisers, and environmental scientists, etc., would be required to assess options by all those involved in the economics and practicalities of vessel operation in the Mediterranean region.

6.1.2 Recommendations are as follows:

- All Mediterranean Sea coastal States should also become Parties to the AFS Convention (see sub-section 3.4.1.3), as appropriate. This would ensure the continuity of care of the marine environment in the Mediterranean Sea and provide a unifying approach to biofouling management and agreed hull coating products. This would further act as a pre-cursor to a united approach on the more practical requirements;
- CPs should explore the possibility for the IMO Biofouling Guidelines (see sub-section 2.1.5) to be mandated or a regional management requirement and the time scale over which this could happen. This could be undertaken in cooperation with the IMO and the GEF-UNDP-IMO GloFouling Partnerships Project with the aim a unified and aligned biofouling management for the Mediterranean Sea region;
- CPs should explore the possibility of requiring that all vessels operating in the Mediterranean Sea, both transitory traffic and short shipping, abide by the IMO Biofouling Guidelines (see sub- section **Error! Reference source not found.**) or Australian biofouling requirements;
- That discussion between CPs be towards developing and enacting a policy of standardised approach to biofouling management that is auditable upon a vessels arrival, such as the Vessel General Permits (USA EPA, see sub-sections 2.1.6- 2.1.8);
- That discussion between CPs is for a regionally harmonised policy approach to ensure that vessels entering the Mediterranean Sea, have undertaken a “clean before you leave / arrive” policy (sub-section 3.4.5.16) at the previous port or ports. This pre-arrival cleaning would minimise the risk of NIMS introduction and reduce GHG emissions. This would apply to vessels arriving in “the Mediterranean Sea area, as defined in the Barcelona Convention;
- That national audits of IWC companies present within CP boundaries be undertaken to produce an accessible database of resources to ensure that IWC facilities are available, should this become a requirement for vessels arriving in / moving within the Mediterranean Sea. Further to the above, all IWC facilities should be expected to comply with the BIMCO / developing ISO (or similar) standards for IWC on capture rates etc. (see sub-3.4.5.9 - 3.4.5.13);
- That CPs discuss and consider promoting the use of 3rd generation FRCs, or high performance minimal biocide SPCs, or hard coatings (for the latter two subject to greater available research on efficacy at minimising hydrodynamic resistance and for hard coatings, data considering ease of foul removal beyond the slime layer stage, with grooming (see sub-section 3.4.2) that will minimise hull friction, limit NIMS transport and be able to be regularly groomed to remove slime;
- That, combined with policies and processes to manage and minimise biofouling in the Mediterranean Sea, slow steaming policies are investigated for transitory vessels, and that for short shipping routes, research and policies

are investigated towards alternate fuels or power systems (see sub-section **Error! Reference source not found.**); and

- That liaison between CPs and appropriate international research bodies, facilitated by REMPEC / IMO, is made towards the development of models for the calculation of biofouling effects on hull efficiency with attention to factors such as hull type etc. (see sub-section 2.2.1) to enable better management and estimation of the biofouling influence on hull friction and consequent GHG emissions.

7. ROAD MAP AND ACTION PLAN

7.1.1 To achieve the outline goals described above, a consensus amongst CPs will need to be reached and then implemented, noting the comment about climate policy goals given above (see sub-section 3.4.5.12).

7.1.2 An outline roadmap to achieve the recommendations given in section 6 is presented below. Such recommendations developed in a research / desk based environment will require updating as aspirations towards the goals identified develop; i.e. this is an iterative process. The proposed roadmap is intended as a guide to possible policy processes to follow towards biofouling management at the Mediterranean Sea level. A flexible and cooperative approach will be key to achieving agreed baseline levels amongst CPs, such as developing region wide IWC and biofouling management policies for arriving vessels.

Table 7.1 Proposed road map

<table>
<tr><td colspan="3">TOPIC:
Assessment of the ratification status of the AFS Convention</td></tr>
<tr><td colspan="3">TIMELINE: Short-term (circa 2 years)</td></tr>
<tr><td>MILESTONES</td><td>ACTIONS</td><td>RESPONSIBILITIES</td></tr>
<tr><td rowspan="3">All CPs to become Parties to the AFS Convention.</td><td>Identify and engage key stakeholders, including national maritime authorities and relevant international bodies.</td><td rowspan="3">CPs, with support of REMPEC and IMO</td></tr>
<tr><td>Conduct a series of initial consultations to align on objectives and expectations.</td></tr>
<tr><td>Develop report summarising stakeholder input, agreed objectives.</td></tr>
<tr><td colspan="3">TOPIC:
Development of models to calculate biofouling influence on GHG emissions management</td></tr>
<tr><td colspan="3">TIMELINE: Short- to medium-term (circa 2 to 4 years)</td></tr>
<tr><td>MILESTONES</td><td>ACTIONS</td><td>RESPONSIBILITIES</td></tr>
<tr><td rowspan="2">Develop and validate models calculating biofouling influence on GHG emissions, considering factors such as hull type.</td><td>Gather available data and summarise existing research studies</td><td rowspan="2">Research and commercial groups funded through industry and regulatory body (e.g. Govt.) sources</td></tr>
<tr><td>Develop and refine models using real-world data</td></tr>
<tr><td colspan="3">TOPIC:
Assessment of the potential for the application of the IMO Biofouling Guidelines towards practical GHG reduction</td></tr>
<tr><td colspan="3">TIMELINE: Short- to medium-term (circa 2 to 4 years)</td></tr>
<tr><td>MILESTONES</td><td>ACTIONS</td><td>RESPONSIBILITIES</td></tr>
<tr><td rowspan="3">Agreement timeline for Biofouling Guidelines application in the Mediterranean region.</td><td>Evaluate the technical and regulatory feasibility of making the IMO Biofouling Guidelines applicable in the region.</td><td rowspan="3">CPs, national legislative bodies with support from REMPEC and IMO / the GEF-UNDP-IMO GloFouling Partnerships Project.</td></tr>
<tr><td>Draft a timeline for the application of the IMO Biofouling Guidelines.</td></tr>
<tr><td>Finalise and formalise agreements amongst CPs.</td></tr>
</table>

TOPIC:
Regional implementation of the IMO Biofouling Guidelines towards greater GHG reduction

TIMELINE: Medium-term (till 2030)

MILESTONES	ACTIONS	RESPONSIBILITIES
All vessels operating in the Mediterranean Sea, including transitory traffic and short shipping, to comply with the IMO Biofouling Guidelines.	Gather input from CPs on potential challenges and timelines for implementation.	REMPEC facilitating lead, CPs, national legislative bodies, IMO, GloFouling
	Engage with policymakers to draft policy.	
	Include specific provisions for both transitory traffic and short shipping, ensuring a comprehensive approach.	
	Monitor and report on guideline adoption progress.	

TOPIC:
Regional Coordination and Standardisation

TIMELINE: Medium-term (till 2030)

MILESTONES	ACTIONS	RESPONSIBILITIES
Establish a standardised and auditable biofouling management policy in the Mediterranean region.	Draft a policy based on e.g. the USA EPA Vessel General Permits approach and other best practices.	CPs, with support of REMPEC and IMO
	Obtain agreement from all CPs on the standardised policy.	
	Develop and implement auditing mechanisms to ensure compliance.	

TOPIC:
Development of a regionally harmonised Clean Before You Leave Policy on Biofouling Management

TIMELINE: Medium-term (till 2030)

MILESTONES	ACTIONS	RESPONSIBILITIES
Establish a regional framework for standardised "Clean Before You Leave / arrive" biofouling management practices for vessels arriving in the Mediterranean Sea area	Draft policy framework outlining requirements for biofouling management prior to entering the Mediterranean Sea, ensuring alignment with existing international standards and best practices to facilitate compliance.	REMPEC (lead), UNEP/MAP, Mediterranean CPs
	Present the draft policy to all CPs for review and refinement.	
	Formalise the policy through regional agreements or integrate it into national regulations.	

TOPIC: **National Audits and Standardisation of In-Water Cleaning (IWC) Facilities**		
TIMELINE: Medium- to Long-term (till 2030 and beyond) (plus continual updates)		
MILESTONES	**ACTIONS**	**RESPONSIBILITIES**
1. Complete national audits of Mediterranean region IWC companies and facilities. 2. Ensure that all IWC facilities comply with BIMCO / ISO (or similar) standards.	Develop an audit framework and guidelines, detailing the criteria for assessing IWC facilities, including capture rates and related environmental compliance.	National maritime regulatory authorities, with support from REMPEC, IMO, GloFouling
	Collation of audit results and development national records of IWC facilities.	
	Provision of technical assistance and guidance to IWC facilities on meeting BIMCO (or similar) standards for capture rates and environmental performance.	
TOPIC: **Promotion of smooth coatings**		
TIMELINE: Long-term (beyond 2030)		
MILESTONES	**ACTIONS**	**RESPONSIBILITIES**
1. Utilise existing research on the FRC, SPC AFC and hard coatings efficacy to develop a cost / benefit framework for their appropriate regional sanction / uptake. 2. Investigate and propose e.g. slow steaming policies for transitory vessels and alternative fuels or power systems for short shipping routes.	Review existing research and disseminate key findings to relevant stakeholders.	CPs national maritime regulatory authorities with support from REMPEC, IMO, GloFouling, Shipping Industry, research institutions
	Organise stakeholder workshops to discuss research findings, potential benefits, and the regulatory pathway for recommended national / regional / EU adoption.	
	Commission pilot studies.	
	CPs, with support from REMPEC, IMO, explore the possibility of establishing a regulatory framework for FRC / hard coatings based on clean before you leave approach.	

7.1.3 As part of the action plan, the following **capacity building and technical assistance** actions are proposed to be provided by relevant regional stakeholders:

- Design and deliver training courses focused on biofouling prevention and management;

- Offer certifications to trained personnel;
- Pilot innovative technologies; and
- Provide technical support and incentives for early adopters.

7.1.4 The following **financial support and incentives** are proposed:

- Secure funding from international donors and CPs to assist with the implementation of biofouling management measures;
- Provide grants or low-interest loans for biofouling management projects;
- Offer tax breaks or reduced port fees for compliant ships; and
- Recognise and award innovation in biofouling management.

7.1.5 In relation to **stakeholder engagement and awareness**, the following actions are recommended:

- Engage with all relevant stakeholders, including ship owners, port authorities, and environmental NGOs;
- Organise workshops to discuss the benefits and challenges of biofouling management;
- Develop communication strategies to raise awareness among stakeholders;
- Launch campaigns on the importance of biofouling management; and
- Collaborate with media to promote best practices.

8. CONCLUSION

8.1.1 This Study has considered the potential for GHG reduction through biofouling management options and approaches, pertinent to the Mediterranean region. There are limited data on the efficacy of biofouling management and GHG reduction, largely due to the variety of variables both intrinsic and extrinsic that are needed to calculate GHG reduction / hydrodynamic efficiency improvement. However, researchers and practical studies indicate that reasonable GHG reduction of up to 10% can be achieved with proactive biofouling management by selection of the optimal hull coating and fouling management by cleaning.

8.1.2 Local air quality in the Mediterranean Sea region is influenced by shipping emissions with evidence of GHG increase over time, in line with global shipping growth. The key transitory shipping route through the Mediterranean, together with the level of short shipping, offers significant opportunities for CPs to work together to develop regional guidance and policy decisions. These factors can be tailored to achieve management that will reduce biofouling, and concomitantly NIMS transport, in the Mediterranean Sea, and thereby reduce GHGs and improve local air quality whilst contributing to global GHG reduction in line with the 2023 IMO Strategy on Reduction of GHG Emissions from Ships.

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