BLUEAIR

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Executive summary

The foresight exercise developed in the framework of the BLUEAIR Project is addressed to innovation players active in blue economy sectors and is intended to broaden technological horizons and help develop shared perceptions of challenges and opportunities. By gathering intelligence insights from several sources, foresight aims at both providing a better understanding of the forces that may shape the mid- to long-term future and at having a shared comprehension considered in policy formulation, planning, and decision-making processes. Within the scope of the BLUEAIR project, a **technological foresight (TF),** intended as a probabilistic prediction of technological changes that may be affecting **machines, systems, or procedures,** was carried out with studies and interaction with technical experts**.**

In the framework of BLUEAIR TF activities quadruple helix actors are offered insights into future scenarios within the blue economy sectors. Specifically, the TF aims at endowing policymakers and stakeholders with a methodological approach, a tool and studies on a selection of foresight focus areas defined both during framework scanning activities and as emerged from the analysis of trends and priority areas. The focus of the technology foresight exercise is on marine and maritime technologies and fields of activities which are **clean** and **ICT-supported** and, in other words, technologies which share **decarbonisation and sustainability** as common objectives.

The document is structured into three main sections based on the technology foresight methodological approach and comprises **designing the foresight exercise**, **collecting the inputs** and **analysing the results**.

The first section, **designing the foresight**, outlines the framework activities needed to implement the fundamental steps of a foresight process and implies the definition of the target users, the setting of the objectives, the focus identification, the approach definition and the scope framing within a timeframe and a time horizon. The designing of the foresight exercise sets the scene for the studies and analyses that will follow by providing the borders of intervention.

The second section, **collecting the inputs**, focuses on a review of the state-of-the-art in technology and product development in the five selected blue economy areas: alternative fuels, robotics, ICT, waterborne transport, and aquaculture. This review describes the available technologies and products, analyses their relevance to sustainability goals, assesses the current market and industry status, and explores their potential, advantages, drawbacks, and critical areas for further research and development.

The third section, **the analysis**, comprehensively examines technologies and products related to the blue economy. It covers perspectives and key areas for future research and development, potential applications, and expected advancements and commercialization outlook from 2018 to 2030. Detailed technological profiles are provided for a selection of technologies and products, where the experts described their advantages compared to the current state of the art, their fields of application, the

enabling factors or barriers, the leading players involved and the technological status. This section incorporates expert interviews and interactions to gather opinions and insights on prospects.

Designing the Foresight

Aim of the Research

The **main goal** of the **BLUEAIR project** is enhancing the *institutional capacities* of ADRION countries/regions in the definition of a common approach towards the implementation of **S3 policies on Sustainable Blue Economy** at the macro-regional level. Blue Economy can represent a **space of opportunities** where it is possible to achieve innovative growth on the principles of **sustainability** and **protection** of the seas. “EU’s Blue Economy encompasses all sectoral and cross sectoral economic activities related to the oceans, seas and coasts, including those in the EU’s outermost regions and landlocked countries. This includes the closest direct and indirect support activities necessary for the sustainable functioning and development of these economic sectors within the single market. It comprises emerging sectors and economic value based on natural capital and non-market goods and services”.
Among other specific objectives, the BLUEAIR project aims to identify Blue Economy areas of macro-regional interest and exploit potentials for transnational cooperation in innovation and Smart Specialisation Strategy (S3) development on Blue Economy in the Adriatic-Ionian Sea areas.

The Technology Foresight Process

The Technology foresight (TF) process is reported in the image below and encompass all the steps that were illustrated in the DT2.2.3 Technology Foresight tool.

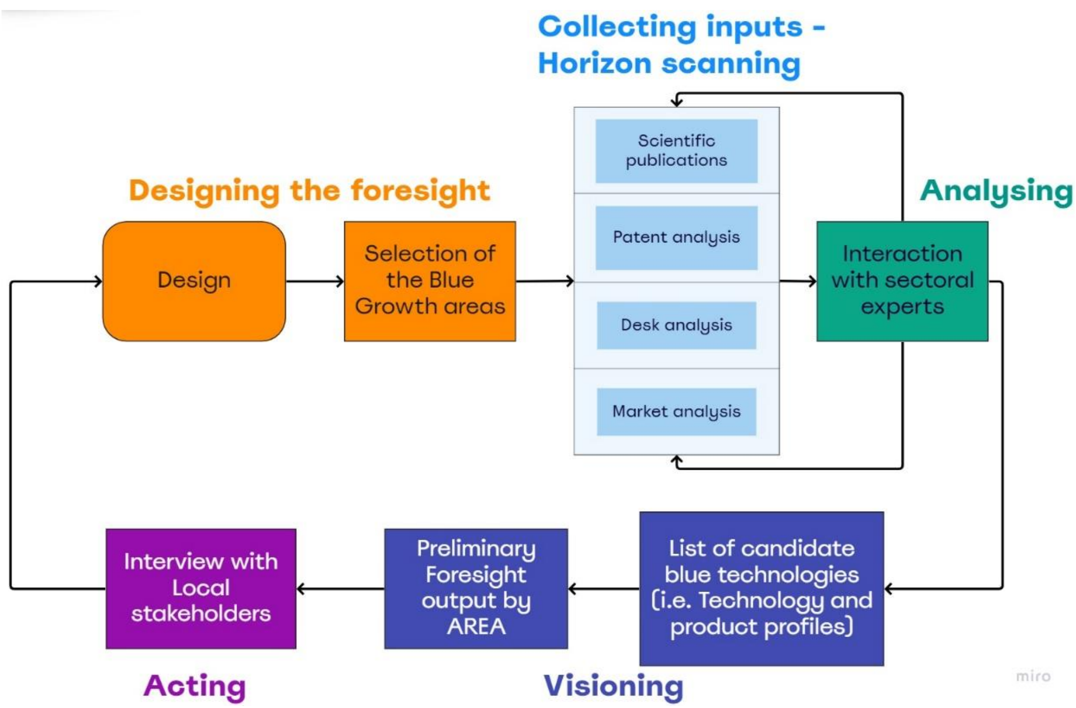


Figure 1. The technology foresight process developed within the context of the BLUEAIR project.

Overall, the TF process has been drafted according to the following five steps:

- Designing the foresight
- Collecting inputs – Horizon scanning
- Analysing
- Visioning
- Acting.

Defining the User

The objectives will be reached with the involvement of the **quadruple helix actors** in defining a shared strategic vision using **enabling tools**, capacity-building initiatives and effective EDP practices and instruments. With the support of scientific experts and technical documentation, the **quadruple helix actors** and, in particular, **policymakers** will obtain a view of the future scenarios of the Blue Growth sectors enabling them to take advantage of the sector's transnational opportunities.

Setting the Objective

In the Adriatic-Ionian regions, Blue Economy Innovation policies are fragmented, with pioneering and lagging areas searching for a **joint knowledge-based approach** to their innovation strategies to enhance the blue growth sectors in their territories.

Moreover, regions and countries overlooking the same seas and rivers need harmonizing Blue Economy policies to plan future innovation initiatives on sea transport, water pollution, energy connectivity, marine environment protection, promotion of sustainable tourism etc.

Through the development of a Macro-Regional S3 on Blue Growth and the setting up of a dedicated Innovation Community, foresight studies within BLUEAIR aimed at:

- enhancing institutional capacities of ADRION territories in the definition of a shared S3 policy on Blue Economy;
- guaranteeing the alignment and coordination approach of local initiatives with the EUSAIR strategy;
- improving competencies of innovation players on the Blue Economy;
- identifying sectors of macro-regional interest;
- exploiting potentials for transnational cooperation;
- supporting the development of a single Macro-Regional S3 on BG in the Adriatic- Ionian.

This project aims to endow policymakers and stakeholders in the quadruple helix with a methodological foresight tool and studies on a selection of foresight focus areas defined both during framework scanning activities and as emerging from the analysis of trends and priority areas.

Identifying the Focus

To face the challenges of climate change, the European Union (EU) has adopted a growing range of adaptation options and policies to deal with current and future climate risks. In particular, the EU has started modernising the economy while reducing emissions. Specifically, the European Commission drafted the European Green Deal (EGD)[1] in 2019 to set up a strategy to overcome climate change and environmental challenges and transform the EU into a fair and prosperous society with a modern, resource-efficient, and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use. The EGD also builds on and connects to the United Nation's 2030 Agenda and its seventeen Sustainable Development Goals[2]. Under the EGD, the EU has been preparing several initiatives to reach its ambitious climate targets of reducing net emissions by at least 55 % by 2030 compared to 1990 and being the first climate-neutral continent by 2050.

[1] A European Green Deal | European Commission (europa.eu)
[2] Transforming our world: the 2030 Agenda for Sustainable Development | Department of Economic and Social Affairs (un.org)

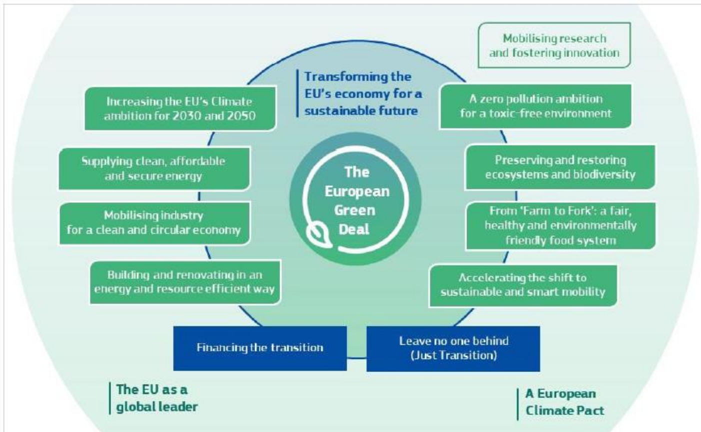


Figure 2. The European Green Deal[1]

Several EGD strategies and elements also influence different aspects of the marine and maritime environments, highlighting how the role of oceans and sea in mitigating and adapting to climate change is increasingly recognised. The EU blue commitment started back in 2012. In contrast, the European Commission focused on the potential of the EU's marine and maritime sectors through the publication of the Blue Growth Strategy[3], which explored the potential of the EU's marine and maritime sectors to contribute to the sustainable economic development, creation of new jobs and foster innovation. This strategy aimed to promote innovative, sustainable, and inclusive growth and employment opportunities in Europe's maritime economy. The strategy focused on the sectors of the "blue economy", which comprises all activities that are linked to the water, the sea and the ocean relying not only on more traditional forms of utilisation (e.g., fishing and aquaculture) but also combining a broader vision of activities that can offer important sources of sustainable economic development. Specifically, the sustainable blue economy aims at the sustainable utilisation of seas and oceans resources allowing their long-term ability to regenerate and endure such activities through the implementation of sustainable practices also helps the efforts to face climate change that is core in the new European policy strategies (European Commission, 2022).

Overall, the blue economy encompasses all sectoral and cross sectoral economic activities based on or related to the oceans, seas and coasts as defined in the EU "Blue Economy Report"[4]:

- **Marine-based activities** such as fishery and aquaculture, marine non-living resources, marine renewable energy, desalination, marine transport and coastal tourisms
- **Marine-related activities** which use products and/or produce products and services form the ocean such seafood processing, biotechnologies, shipbuilding and repair, port activities, technology and equipment, digital services, etc (European Commission, 2022).

[3] COM(2012) 494 final

[4] [The EU blue economy report 2022 - Publications Office of the EU (europa.eu)]

Specifically, in the EU "Blue Economy Report", the blue economy is further divided into **established sectors** defined as those that traditionally contribute to the blue economy and **emerging sectors** which are less mature industries linked to the marine environment (European Commission, 2022). The detailed list of blue economy sector is reported below:

Table 1. Established and emerging sectors and subsectors as reported in the Blue Economy Report (European Commission, 2022)

Established Sectors	Sub-sectors
Marine living resources	Primary production
	Processing of fish products
	Distribution of fish products
Marine non-living resources	Oil and gas
	Other minerals
Marine renewable energy	Offshore wind energy
Port activities	Cargo and warehousing
	Port and water projects
Shipbuilding and repair	Shipbuilding
	Equipment and machinery
Maritime transport	Passenger transport
	Freight transport
	Services for transport
Coastal tourism	Accommodation
	Transport
	Other expenditure

Emerging sectors	Subsectors
Ocean energy	Floating offshore wind
	Wave and tidal energy
	Floating solar photovoltaic energy
	Hydrogen generation offshore
Blue bioeconomy and Biotechnologies	Algae (micro and macro)
	Bacteria
	Fungi
	Invertebrates
Desalination	
Marine minerals	
Maritime Defence, Security and Surveillance	Defence
	Security
	Surveillance
Research and Education	Research
	Education
Infrastructure and Maritime works	Submarine cables
	Robotics
	Underwater drones
	Maritime airborne drones

From the above policy documents and strategies adopted by the European Union, it is evident how all blue economy sectors, including fisheries, aquaculture, coastal tourism, maritime transport, port activities and shipbuilding, will have to reduce their environmental and climate impact. Tackling the climate and biodiversity crises requires healthy seas and sustainable use of their resources to create alternatives to fossil fuels and traditional food production. Hence, innovative technologies and products must be implemented to accelerate the sustainable transition. Moreover, a consistent technology and knowledge transfer must be performed from industry to stakeholders to policymakers to identify the most promising technologies to shape a blue future. For this reason, within the context of the BLUEAIR project, a **technological foresight analysis was developed to predict the rate and the possibility of technology advance in the blue economy sectors by bringing present and future technology into focus based on several inputs**. Therefore, the **focus of this technological foresight** is to pinpoint **marine technologies and fields of activities (as identified below) which are clean and ICT-supported and, in other words, technologies which share decarbonisation and sustainability as a common objective**.

Deciding the Approach

In the TF analysis two main approaches were selected:

- **Horizon scanning**: the identification of the "thing to come" through the collection of information about new science and technology including socio-economic information, environmental issues and other small signals from:
    - Scientific publications,
    - Patent analysis,
    - Desk analysis,
    - Market analysis.
- **Analysing**: understanding the dynamics and drivers of technical areas to identify critical issues and develop possible solution from:
    - Emerging trends, drivers, system dynamics and model potential impact,
    - Interaction with sectoral experts.

Framing the Scope

This report shows a TF exercise including studies and analyses on specific sectors of Blue Growth within the scope of BLUEAIR. The TF was developed to better understand the future evolution of selected foresight focus areas. To this purpose, a framework scanning and focus areas selection of the foresight focus areas to be explored was initially performed considering both macro-regional interest of potential transitional cooperation and the efforts towards a green transition as put in place by the European Union. Investigation in blue technologies, fields of activity and blue solutions, as emerged and defined during the mapping activity (DT2.1.1 Identification of Blue growth areas), was based on a framework scanning activity which considered all major EU reports produced on the subject of Blue Economy. The scanning activity was followed by a selection process which reduced redundant and overlapping thematic areas down to sectors and technologies in a prospective view starting from the current efforts and policies that are shaping the Adriatic-Ionian region. Details on the process regarding the framework scanning activity and the selection of thematic areas and technologies is described hereunder and finally reported in **Errore. L'origine riferimento non è stata trovata.**Figure 3.

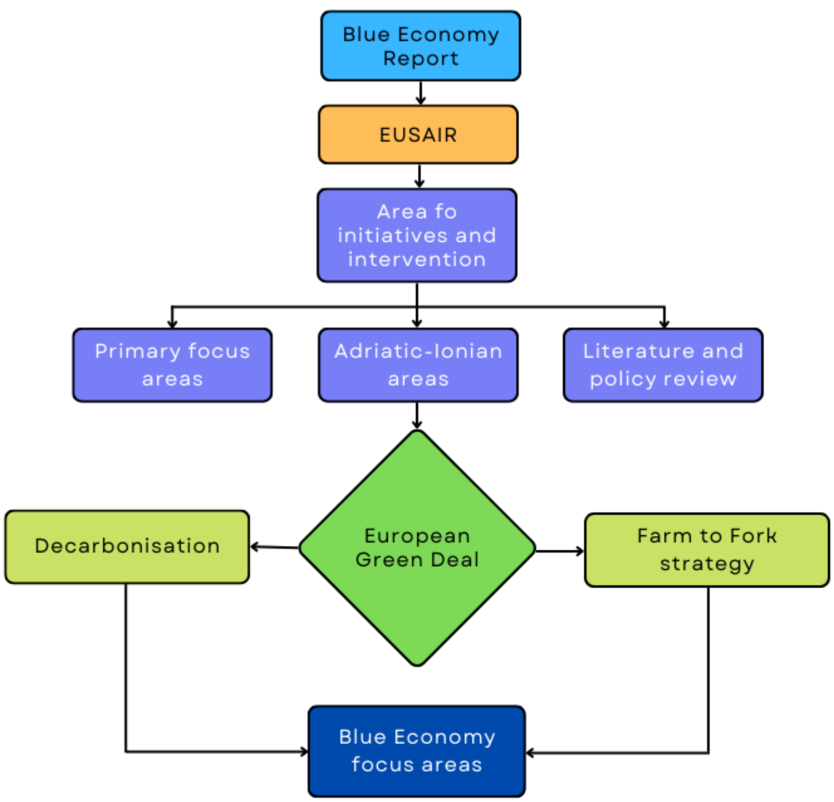


Figure 3. Framework scanning and focus areas selection

To frame the analysis and focus the investigation on the green efforts and on blue economy prospects, an initial selection of the Blue Growth areas was performed as outlined in **D.T.2.1.1 "Identification of Blue**

Growth areas"[5]; this project deliverable was based on the EU Strategy for the **Adriatic and Ionian region (EUSAIR) macro-regional strategy** adopted by the European Commission and endorsed by the European Council in 2014[6]. The strategy was jointly developed by the Commission and the Adriatic-Ionian Region country which agreed on creating and fostering coordination among all territories as envisaged in the EUSAIR in four thematic pillars:

1. **Blue Growth**
2. **Connecting the Region**
3. **Environmental Quality**
4. **Sustainable Tourism.**

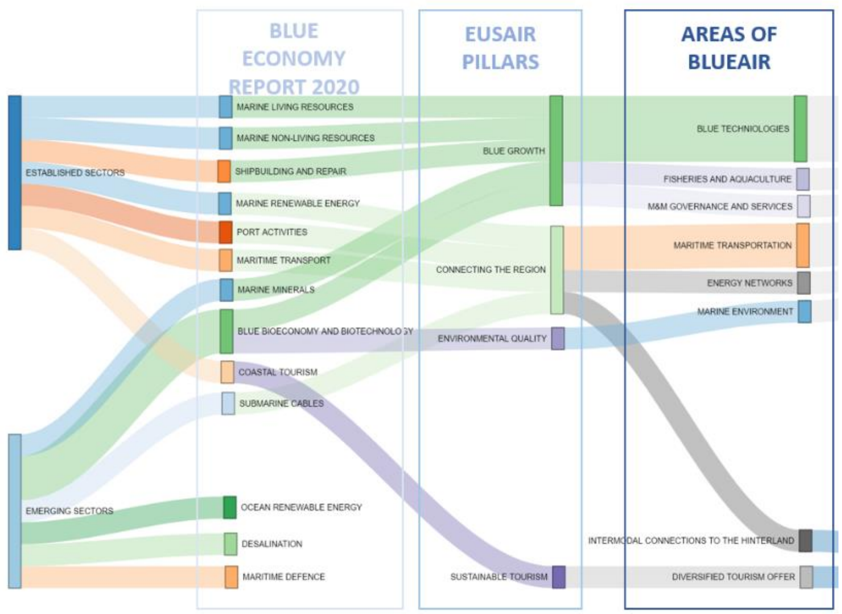


Figure 4. Transition maps to BLUEAIR potential areas

Therefore, a linkage between EUSAIR pillars and potential areas of BLUEAIR project scope was performed by grouping sectors into several socio-economic or environmental impact groups. The resulting functional framework was divided into **areas for initiatives and interventions**:

[5] https://blueair.adrioninterreg.eu/library/identification-of-blue-growth-areas
[6] About EUSAIR - adriatic-ionian.eu

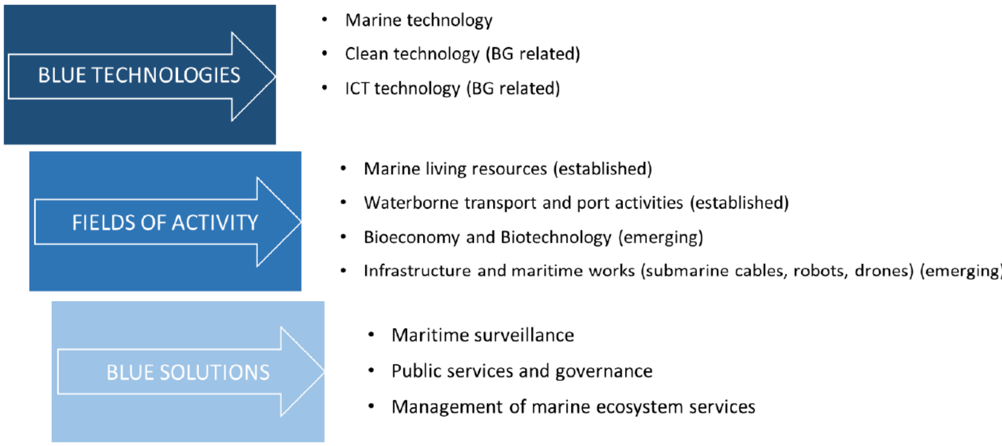


Figure 5. Areas of BLUEAIR as reported in the deliverable D.T.2.1.1 "Identification of Blue Growth Areas".

The BLUEAIR areas for initiatives and intervention were further developed into **sectors**, **activities**, **technologies**, and **solutions** that are or could be developed within the context of Blue Growth. The complete list is reported in Table 2.

For a better definition of the scope of the foresight analysis, a further selection of BLUEAIR areas for initiatives and intervention was developed in order to explore specific technologies and applications that may have the potential to shape the blue economy future of the Adriatic-Ionian region in a climate-action view. To this aim, a further delimitation of BLUEAIR areas for initiatives and interventions was based on **priority focus areas** and **relevant sectors for the Adriatic-Ionian region**, as highlighted in the DT2.1.1 document and as resulting from deliverable **DT2.1.4 "Position Paper on key Common Technologies"**[7] concerning patent performance and blue invention in the Adriatic-Ionian region.
Firstly, the **Primary focus area** represents groups of blue economy sectors which have direct socio-economic, environmental, or other important impact within Adriatic-Ionian Sea basin and strongly rely on first Blue Growth pillar of EUSAIR strategy. That impact may already have influence on the region with positive or negative trends with recorded data over the years or may cause significant impact in the following years. Only **priority focus areas** were considered in the TF analysis:

[7] https://blueair.adrioninterreg.eu/library/position-paper-on-key-common-technologies

PRIMARY FOCUS AREA		SECONDARY FOCUS AREA	
ESTABLISHED SECTORS	EMERGING SECTORS	ESTABLISHED SECTORS	EMERGING SECTORS
Living resources • Fisheries • Aquaculture	• Blue bioeconomy & biotechnology	• Coastal tourism	• Desalination
Waterborne transport • Transport • Port activities	• Submarine cables and underwater robots	• Shipbuilding and repair*	

Figure 6. Primary focus areas of the BLUEAIR project as reported in the DT2.1.1.

Table 2. BLUEAIR areas for initiatives and interventions and the related sectors, activities, technologies, and solutions as reported in the deliverable DT2.1.1 "Identification of Blue Growth Areas".

Blue technologies	Marine technologies	Propulsion and powering			
		Smart ship			
		Shipbuilding			
		Robotics			
		Autonomous systems			
		Advanced materials			
		Sensors			
		Sustainable energy generation			
		Advanced Manufacturing			
	Clean technology (Blue Growth related)			Technologies under these lead markets that provide solutions to help preserve ecosystems, but also help to meet	Environmentally friendly power generation, storage and distribution
					Renewable energy
					Energy efficiency
					Cross-sector components
					Material efficiency
		SIX LEAD	*Environmentally friendly power generation, storage and*		Renewable resources
			Energy efficiency		Protection of environmental goods
			Material efficiency		Sustainable mobility
			Sustainable mobility		Alternative drive technologies
			Waste management and recycling		Renewable fuels (eFuels38)
					Technologies to increase efficiency
					Transportation infrastructure and traffic management
					Sustainable water management
					Wastewater cleaning
					Wastewater treatment methods
	Information and Communication Technologies -ICT (Blue Growth relat	Communications and connectivity			
		Big data analytics			
		Unmanned and autonomous systems			
Fields of activities	Established sectors	Living resources	Fishery	Primary sector	Capture fishery
					Aquaculture sector
				Processing of fish produc	Processing and preserving of fish
					Manufacture oil and fats
			Aquaculutre		Prepared meal and dishes
					other food products
				Distribution of fish	Whole of other food
					Retail sale of fish
		Waterborn mobility	Maritime transport	Passanger transoirt	Sea and coastal passanger water transport
					Inland passenger water transport
				Freight transport	Sea and coastal freight water transport
					Inland freight water transport
				Services and transport	renting and leasing of water transport equipment
					other transportation actvities
			Port activites	Cargo and warehousing	Cargo handling
					Warehouse and storage
				Port and water projects	service activities incidental to water transport
					Construction of water projects
	Emerging secotrs	Bioeconomy & biotechnology			
		Submarine cables			
Blue solutions	Maritime surveillance				
	Public services and governace	Maritime space			
		Spatial planning			
		Legislation			
	Management of marine ecosystem services				

Within the **macro-regional context**, according to employment and Gross Value Added (GVA) and estimates of future trends, five established sectors have strong socio-economic impact in the **Adriatic-Ionian region**:

- Marine living resources,
- Marine transport,
- Port activities,
- Shipbuilding and repair,
- Coastal tourism.

Also, deliverable **DT2.1.4 "Position Paper on Key Common Technologies"** shows how innovation activity and opportunities for sustainable innovations are more evident for green shipping, sustainable aquaculture and fisheries, as well as maritime and coastal tourism in the Adriatic-Ionian region.

Finally, to focus the perspective view of this study on the current efforts enacted by the EU to face climate change and the need for more sustainable development, all the resulting sectors and the related technologies were aligned with the EDG. As previously mentioned, several EGD strategies and elements impact various aspects of the blue economy, specifically, two strategies:

1. **Accelerating the shift to sustainable and smart mobility**
2. **Farm to Fork strategy (F2F)**.

The EGD aims to reduce emissions across all forms of transport by 90% by accelerating the shift to sustainable mobility. Blue economy can boost the achievement of these climate objectives by fostering **decarbonisation** mainly through marine renewable energy and zero-emission maritime transport. The European Commission targeted the decarbonisation of waterborne transport across different funding periods from the 7th Framework Programme (FP7) to Horizon 2020, which developed numerous projects. The projects focused on a different aspects of the decarbonisation problem such as new hull design, innovative propulsion systems and alternative fuels and energy sources (European Commission, 2022). Thus, exploring innovative decarbonisation activities seems fundamental to better understanding the future development of Adriatic-Ionian's blue economy.

The **F2F strategy** is a crucial element of the EGD and highlights the challenges of sustainable food systems by recognising the inseparable links between healthy people, healthy societies, and a healthy planet. The strategy emphasises the role of Aquaculture production as a means to accelerate the shift to sustainable fish and seafood production by ensuring food supply and security. Specifically, organic farming, including aquaculture, could respond to the growing societal demand for quality food produced at high environmental and animal welfare standards while contributing both to the protection of nature and reversing the degradation of ecosystems by spurring the EGD ambition for sustainable food production and consumption (European Commission, 2022). Hence, in the technological foresight, innovation underlying sustainable aquaculture production has been thoroughly analysed to better understand the most promising technological options.

As a result of the above scoping activities, the framework scanning and focus areas selection resulted in 5 thematic segments which link the BLUEAIR areas for initiatives and intervention with the regional relevance and the strong need for the green transition that is significantly influencing the economic development of green and blue sectors.

This framework scanning and focus areas selection activity contributed to defining the **scope** of the technological foresight analysis by selecting the most relevant blue economy focus areas (*Figure 7*).

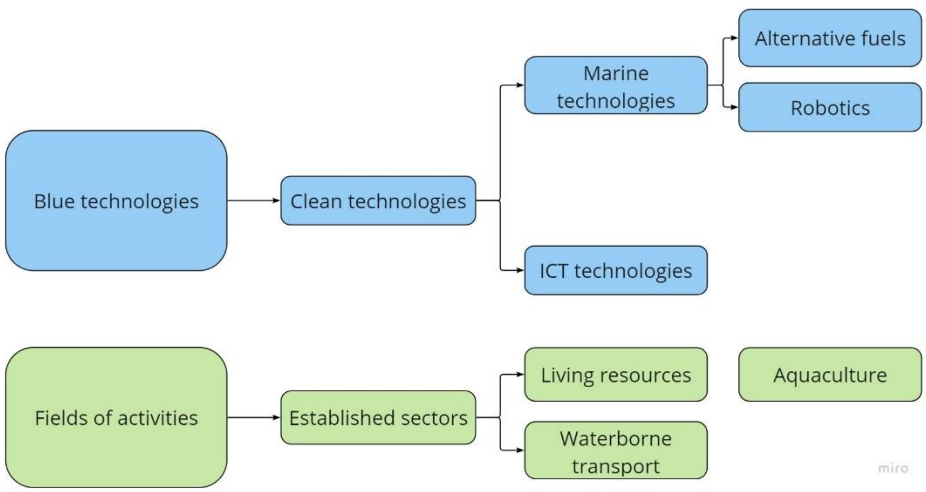


Figure 7. Blue economy focus areas explored in the Technological foresight

Scope Technological Areas & Fields of Activities

To better address the complexity of the analysis, **the TF scope** has addressed five areas:

1. *Power & Propulsion/Alternative Fuels*
2. *ICT Technologies*
3. *Robotics*
4. *Aquaculture*
5. *Waterborne mobility*

Setting the Timeframe and the Horizon

Within the scope of the project the TF analysis was performed to highlight near term blue economy innovation considering current sustainability and decarbonisation issues. Hence the desktop analysis was performed starting from **2018** up to **2050** to better explore and identify future trends and undetected signals.

Blue technologies

Alternative Fuels: Horizon Scanning

Why it Matters

Shipping is the backbone of the global economy. It is by far the most efficient mode of freight transport and moves approximately 80-90% of world trade volumes. While contributing only 11% of global transportation emissions, the shipping sector remains the “dirtiest” emitter due to its use of high-sulfur content heavy fuel oils. Over the next three decades, the expansion of global trade, booming demand in commerce, and emergence of new manufacturing hubs, are expected to cause a consequent rise in its CO2 emissions as well8. Growing energy security, environmental and economic concerns summon both policymakers and maritime stakeholders who have already started to shift their attention away from fossil fuels. Interest, also evidenced by market surveys conducted by Shell and Deloitte, regarding decarbonization of the maritime sector is consistently growing (Mallouppas & Yfantis, 2021).
Maritime decarbonization as the process of reducing greenhouse gas (GHG) emissions produced from the global maritime sector has now become an urgent and crucial issue.

In 2018, the International Maritime Organization (IMO), the UN body that regulates the shipping industry, adopted its greenhouse gas emissions strategy (IMO 2050). The first wave of **regulations**, effective since January 1 2023, (DNV, 2023b) is set in a strategy with a multipronged approach for overall emissions **reduction including regulatory tools, data collection on fuel consumption, and sustainability and energy efficiency targets**.

The shipping industry recognises therefore the importance of decarbonising to help reach the goals that the International Maritime Organization (IMO) has announced: to at least halve international shipping greenhouse gas (GHG) emissions by 2050, while reducing CO_2 emissions intensity by at least 40% by 2030, and pursuing efforts towards 70% by 2050, relative to a **2008** baseline. Their impact, in particular the application of stricter limits for sulphur content in marine fuels since 2020 is yet to be evaluated. Nonetheless, these ambitions send a signal to the industry that change is coming, and all parties involved need to prepare. Even though growing pressure to reduce carbon emissions across the global economy has opened new opportunities, decarbonization still appears to be one of the biggest **challenges** that the maritime industry faces. For this reason, the industry has already started uniting, forming coalitions, launching pilot projects and exploring new ways to lower shipping emissions. Making this happen requires

[8] LUX – Patent Trends: technologies for decarbonizing shipping

collaboration within the shipping industry itself, across the broader shipping ecosystem and with other sectors.

Across the maritime industry, a number of initiatives support shipping decarbonisation. Among these, the United Nations-IMO backed Global Industry Alliance (GIA) supports a transition towards an energy efficient and low carbon future for shipping. The Getting to Zero Coalition, a broad alliance of companies from the maritime, energy, infrastructure and finance sectors, is seeking to put commercially viable deep sea zero emission vessels powered by zero emission fuels into operation by 2030 toward full decarbonization by 2050. The International Windship Association, with broad a membership of industry and research actors promotes wind propulsion for commercial shipping. Global shipping banks have developed Poseidon Principles, framework rules for promoting climate considerations. Also EU funded projects stimulate knowledge and collaborations at different levels on green shipping in the Adrion area (e.g. SHIPmEnTT, Neorion, etc).

The maritime industry and green maritime transport require high-level agreement on a global basis on what to do and coordinated action to implement industry-wide agreed solutions; the strengths of organizations and an ecosystem approach can spur the right discussions and swifter action.

Apparently, the fundamental **key drivers** that will push decarbonization in shipping in the coming decade are: **regulation and policies, technological progress and development, access to investors and capital, and cargo-owner and consumer expectations, in relation to costs of both traditional and alternative fuels**.

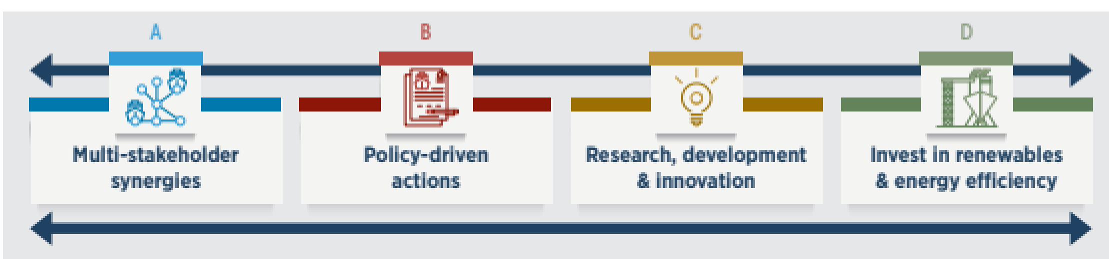


Figure 8. (Source and illustration by IRENA - Renewable Energy Agency, 2021)

Decarbonisation and environmental regulations such as the Carbon Intensity Indicator (CII)[9] will continue to drive fleet renewal decisions by vessel owners in 2023, who will be prone to include traditional fuels as

[9] The Carbon Intensity Indicator (CII) is a rating system for ships that the International Maritime Organization (IMO) developed. This will be a mandatory measure under MARPOL Annex VI, which came into force on the 1st January 2023 (Carbon Intensity Indicator (lr.org))

well as alternative ones in their investments. Propulsion systems can be hybridized at various extent from auxiliary system power to integrated into propulsion system and alternatives to ICE (e.g. FC) are possible too. Decarbonisation processes in the shipping sector are then expected to include both new approaches and operational measures and the optimisation and the development of **new technologies.**

As elaborated in Figure 2, many enablers can contribute to decarbonize the shipping sector and may range from logistics and digitalization to hydrodynamics and machinery, to investigation on new propulsion systems and synthetic fuels and energy sources to after treatment measures and include wind powering, air lubrication systems and several design, operational and machinery measures.

Table 3. Decarbonisation enablers as elaborated from DNV and IRENA (DNV, 2023a; IRENA, 2021)

Logistics & Digitalization	Hydrodynamics	Machinery	Fuels & Energy	After Treatment Measures
Just in time Arrivals - Speed Reduction Optimisation	Hull coating	Machinery Improvement	LNG, LPG	Carbon capture & storage
Weather Routing/altermative routes	Hull-form optimization	Waste-heat recovery	Biofuels	
Vessel Utilization/size/Maintenance	Air Lubrication	Engine de-rating	Electrification	
Energy Mangament Systems (Onboard power demand/ Fuel quality and consumption)	Cleaning	Battery Hybridization	Methanol Ammonia Hydrogen	
			Wind/Solar/tidal energy	

Although undergoing significant uncertainty, **fuels and energy** appear to promise the most significant reduction potential in the long run. However, the shipping industry faces the challenge of complying both with **short term local emissions regulations**, (IMO 2020 sulphur cap) and the long-term climate legislation under consideration by IMO, **while remaining economically competitive.** Shipping companies and investors need to be sure that the assets in which they are investing will not require major additional investment to comply with future regulations or be rendered obsolete by them. A combination of innovative and technical solutions accompanied by economic and operational measures which may contribute to achieve the IMO Strategy goals, as exemplified in Figure 3 below, are therefore being considered and enacted.

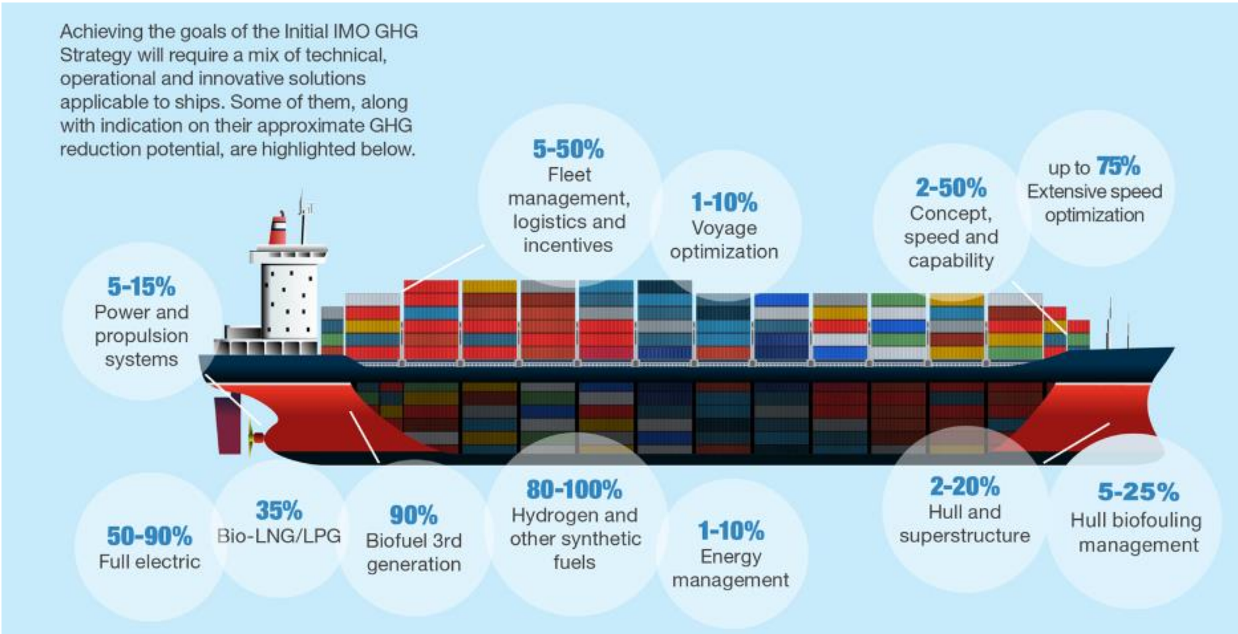


Figure 9.Mix of design, operational and economic solutions to achieve goals of the IMO Strategy

Alternative fuels (hydrogen and other synthetic fuels) are then expected to significantly reduce emissions and impacts, as well as environmental risk associated with spills of heavy fuel oil (HFO) and other marine oils. Short-term solutions are also considered and may include using liquefied natural gas (LNG), a fossil fuel that produces fewer CO2 emissions than traditional marine fuel but comprises the potent greenhouse gas methane. The sector is also exploring ways to reduce fuel consumption. One option for lowering consumption is lengthening transit times; reducing the average speed of a fleet could cut at least 20% of its emissions, according to Wallenius Wilhelmsen[10], with for example, AI-implemented optimal route and vessel speed.

A range of alternative fuels and technologies are available for ships to reduce emissions. Their reduction potentials may vary significantly depending on:

- the primary energy source;
- the fuel processing;
- the engine type/converter;

[10] https://www.walleniuswilhelmsen.com/

- the supply chain.

Consistently also multiple factors influence the market uptake of alternative fuels, some of which are specific for the maritime sector while others are common to road and aviation.

According to Prussi et al., 2021, the vast majority of the available literature focus on the cost differential for the alternative fuels against the HFO and diesel, and the potential environmental benefits of the proposed solutions. Costs are broadly accepted as the main enabling factors for fuel market penetration but there are several other factors that need to be taken into consideration, among others: specific **engine requirements**, **regulatory drivers**, **fuel supply availability**, v**olume requirements according to ship size and industry's expertise**, etc. The approach used in the current analysis is presented in Figure 3.

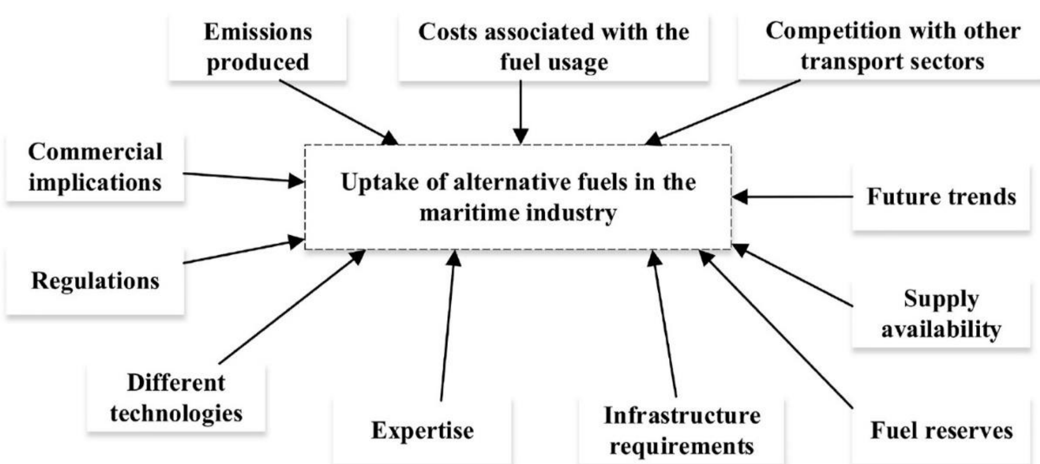


Figure 10. Potential and limiting factors in the use of alternative fuels (Source Prussi et al., 2021)

The various alternative fuels and their diverse characteristics make it difficult, and potentially irrelevant at this stage **to clearly identify winners and losers in the long run.**

Value Proposition

The maritime industry is a complex ecosystem composed of various value chains that require efforts by all stakeholders. Decarbonization goals may be achieved by steering actions across the three major value chains: the marine fuel value chain, the shipbuilding value chain and the maritime operations value chain. (Lind Mikael et al., 2022).

The fuel chain

The well-to-wake marine fuel value chain encompasses **exploration; transportation; processing; transportation of fuel to the fuelling spots and consumption** by the ship operator. These are interdependent components that need to be functional simultaneously to avoid bottlenecks and shortages of equipment or fuels.

Today, maritime operators do not have sufficient **price-competitive alternative fuels options** to commit to charter agreements that include a premium for next generation dual-fuel engines. Some shipbuilders and engine manufacturers are already building ships with engines which can operate on methanol and fuel oil, or on LNG and fuel oil. Currently, due to the lack of alternative and cost-equivalent low-carbon/zero-emissions fuels, ships equipped with dual-fuel engines run primarily on conventional fuel oil. A wide range of low-carbon/zero-emission fuel is under development, such as **green LNG, green methanol, green ammonia, and green hydrogen, with different timelines of availability on the market**.

The shipbuilding chain

All phases relating to the shipbuilding chain materials, ship-assembly, maintenance, refitting, dismantling and end-of-life recycling should be designed for minimal GHG emissions in a variety of ways, including optimized hull design**, wind support when sailing, dual-fuel and multi-fuel high efficiency engines**, digital systems to optimize routing and port arrival and steel should be sourced from suppliers using low carbon production methods. **Circularity principles** should be applied to design and construction to maximize reuse when a ship has to be dismantled.

The operations chain

The maritime operational value chain encompasses all operational phases of ships travelling from port to port and include **fuelling/provisioning, loading/boarding, voyaging, unloading/disembarking, and refuelling**. In order to reduce CO2 emissions, ship operators should **leverage size and speed of ships and fleets and seek for hydrodynamic designs and dual-fuel engines or ships** (partially) powered by biodiesel and electricity. **Ports** are then a crucial part in the operational chain as, on the path to decarbonization, they also need to rely **on infrastructure for storing and bunkering of alternative fuels and onshore power supplies.**

Strategies on the maritime decarbonization ecosystem, need to be aligned in order to work simultaneously on the critical enablers across the three key maritime value chains.

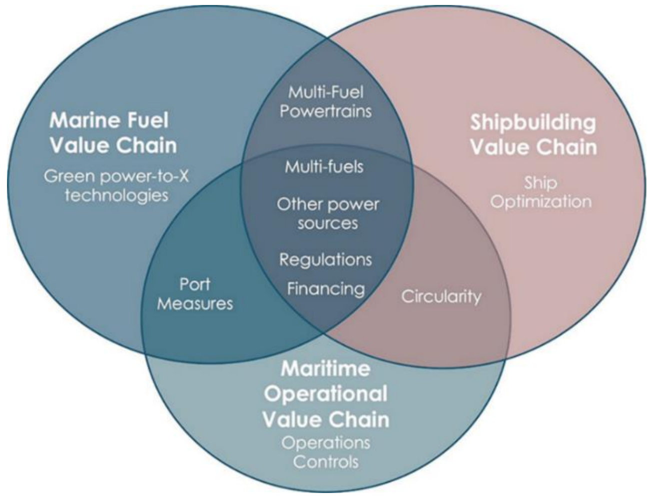


Figure 11. Value chains and selected decarbonization enablers (Source and illustration: Mikael Lind and Wolfgang Lehmacher, 2022)

Decarbonization efforts involves the full cluster of critical value chains, and the decarbonization enablers are sitting across the cluster. Each enabler may be driving decarbonization in one, two or all the three maritime value chains.

One **key enabler** that cuts across all three maritime value chains is **the availability of alternative fuel at market compatible prices.** As an output of the marine fuel value chain, **alternative fuels determine ship design, engines, and tanks, and ship operations.**

Weather routing is another enabler that cuts across two value chains: first, the shipbuilding value chain as it needs sensors on ships, and second, the operations value chain as it requires the adoption of the systems by the operators.

Finally, enablers that support decarbonization in only one single chain are hydrodynamics and low carbon emission hull design in shipbuilding, **green power-to-X technologies which refers to technologies used to produce green fuel,** and **operations controls** utilizing collaborative platforms for energy efficient maritime operations.

Zero-carbon shipping is an ambitious target without at the moment defined technical solutions, set of fuels or affordable pathways available to push the process fastly ahead. So while the shipping sector is committed to decarbonize, the alternative fuels and the technology needed to power much of the industry's fleet, are still being developed. For now, shipping companies are looking at **short-term solutions to bridge the gap until new fuels become available**. Decarbonisation of shipping has to address several challenges relating to all the value chains in the maritime sector, most of which relate to the adoption of alternative fuels and on their impact both on the adaptation and growth of the maritime industry and on pathways that will cut across all port, marine and shipbuilding infrastructures. **Here are some of the factors that are driving change in the maritime sector and their major impacts**.

Stringent environmental regulations for decarbonizing shipping

The path toward shipping decarbonization involves not only technological **upgrades and improvement of ship design** but also the use of **alternative fuels** and **the use of engines that are compatible with such fuels**. As a result of the new IMO emission requirements, shipping companies faced low earnings and uncertainties about compliance with the norms and **postponed placing orders for new vessels**. Also, the new regulations will require **replacing some of the existing fleets**, which will entail **significant costs for the operators**. Apart from creating a degree of uncertainty, this could **reduce the capital** available to expand the fleet to cater to the growing requirement. This may affect the orders for new vessels, which may ultimately impact and **restrain the growth of the marine engines market as well.**

Reduction of harmful emissions

Government legislation on CO_2 emissions has created **new markets and opportunities for alternative fuels**, including **renewable methanol, green hydrogen or green ammonia** (Markets&Markets, 2023). Europe's first biofuel policy was introduced in 2003, setting blending targets for 2010. This policy was integrated in the Renewable Energy Directive (RED) in 2009, which set an obligation of 10% renewable energy in transport for 2020. In 2018 the European Union agreed on the Renewable Energy Directive II (RED II), requiring 14% renewable energy to be used in transport by 2030. RED II has created new markets for conventional biofuels like ethanol and biodiesel and for **alternative fuels** such as renewable methanol, especially when made from wastes, residues or renewable electricity. Other European policies which also impact the potential uptake of renewable methanol are the Fuel Quality Directive, the Alternative Fuel Infrastructure Directive, and the Air Quality Directive, among others. Beyond national policies, the marine sector has also introduced their own mandates. The International Maritime Organization (IMO) introduced the Emission Control Areas to significantly reduce SOx and NOx emissions. Making and using alternative fuels, as **renewable methanol,** doesn't only reduce CO_2 emissions, but it also reduces other **harmful air pollutants including nitrogen and sulfur oxides (NOx and SOx), volatile organic compounds (VOCs), particulate matter and other toxic pollutants.**

Table 4. Comparative analysis of alternative fuels for shipping sector (Prussi et al., 2021)

Type of Fuel	Note	Emissions (WTT)	Costs	Availability	Technical maturity	Blendability	Supply and infrastructure availability	Interaction with other sectors	Expertise	Competition with other technologies	Commercial implications
HFO	Benchmark	-	-	-	-	-	-	-	-	-	-
LNG	*from fossil sources*	No Significant Advantages	LOW (but retrofitting needed)	YES	YES	NO	YES/NO	YES	YES	YES	Existing technology with an existing market
	Bio-derived	YES	HIGH	YES/NO	YES	YES with fossil LNG	YES/NO	YES	YES	YES	Costs and availability
Methanol	*from fossil sources*	No Significant Advantages	TbD	TbD	YES	Partly	NO	Partly with Road and Aviation	NO	YES	TbD
	Bio-derived	YES	HIGH	TbD	YES/NO	YES with fossil Methanol	NO	Partly with Road and Aviation	NO	YES	TbD
FAME	*Biodiesel*	YES	HIGH	YES	YES	Partly	YES	YES	YES	YES	Costs
HVO		YES	HIGH	YES	YES	YES	YES	YES	YES	YES	Costs
Ammonia		YES/NO (depend on the source of H2)	HIGH	TbD	NO	NO	YES/NO - Easy to store	NO	YES/NO - Toxic and corrosive	TbD	Ammonia tankers already interested
Electricity		YES/NO - Depend of source	TbD	TbD	YES/NO	NO	NO/YES	YES	NO/YES	YES - with other alt.Fuels	TbD
H2 from RES	*From NG*	No Significant Advantages	TbD	YES	NO	NO	NO	Possibly	NO	YES	Costs, tech. Maturity and availability
	From RES	YES	HIGH	NO	NO	NO	NO	Possibly	NO	YES	Costs, tech. Maturity and availability

Potential **negative** impact
Potential **positive** impact
TbD
YES/NO - **Possibly**

There is a **huge global demand for marine fuels, with fleets and volumes of goods shipped increasing year on year**. Globally transport supply of chemical tankers and general cargo ships grew by 15%, cruise ships by 11% and container ships by 9% in the last decade (2010-2020). Because of the volume of shipping fuel in demand, **renewable fuels substitution for heavy fuel oils could have great potential to reduce greenhouse gas emissions** (Markets&Markets, 2021c)**.**

Independence from oil prices

A majority of the world's **fuel demands are met by fossil fuels**, mostly oil & gas. According to the BP Statistical Review of World Energy 2021, oil & gas collectively accounted for a staggering 56% of global energy consumption by fuel in 2020. **Oil & gas prices are volatile and apart from demand and supply, are also affected by a large number of factors, including geopolitical issues**. Many countries are dependent **on a single commodity, either oil or gas, for their exports and revenues, and this renders them extremely vulnerable to market volatility**. According to the Organization of Economic Cooperation and Development (OECD), oil & gas make up the majority share of over 60% of total merchandise exports in a range of developing countries, including Algeria, Iran, Iraq, Libya, and Timor-Leste. The onset of the pandemic in 2020 saw oil prices touch historic lows, with the West Texas Intermediate (WTI) benchmark logging a negative value for the first time in history. Also, the current geopolitical scenarios, such as the US-China trade tussle and the Russo-Ukrainian war, which may see harsh sanctions being imposed upon Russia by the European Union, will affect the supply of gas from Russia to the rest of Europe and may also affect the transport of such commodities globally. There is also the risk of oversupply of oil & gas, which results in a plunge in the oil & gas prices. All the major economies have chalked out plans to reduce their greenhouse gas emissions and achieve carbon neutrality, in line with the Paris Agreement. As a result, economies are shying away from increasing their usage of oil & gas and focusing more on **renewables** to fulfill their energy requirements. This may again lead to a drop in oil & gas prices and a decrease in the trade of these commodities globally. Low oil prices impact the oil & gas exploration & production industry, thereby propelling organizations to re-evaluate their exploration strategies. The **decline in oil & gas exploration & production activities affects the demand for merchant vessels,** SUM as 011 tankers and bulk carriers, and subsequently the demand for marine propellers and engines. Wars, geopolitical tensions, and unprecedented global medical emergencies may lead to fluctuations in oil & gas prices. High crude oil prices also have a direct impact on the price of bunker fuels. **Fuel costs** represent as much as **50-60% of the total ship operating costs**, depending upon the type of ship and service. Ocean carriers are required to recover these costs to maintain levels of service and profitability. Hence, high bunker fuel prices will lead to an increase in maritime transport costs and an overall reduction in global maritime trade as the profitability reduces. Therefore, **volatility in oil & gas prices poses a major challenge to the growth of maritime market** (Markets&Markets, 2022c).

Since the **prices of gasoline have increased, alternative fuels are a viable option for vehicle operators**. Though alternative **fuel prices can also fluctuate based on location, time, and political conditions**. In January 2019, the average retail price of gasoline and diesel was decreased by USD 0.09/gallon and USD 0.03/gallon, respectively, as per the Alternative Fuels Data Center (AFDC). The national average retail price of CNG was decreased by USD 0.02/gasoline gallon equivalent (GGE), while liquefied natural gas (LNG) prices increased by USD 0.08/diesel gallon equivalent (DGE). Ethanol prices remained the same as of October 2019. As per a study conducted by Nomura Research Institute Ltd. on 'Transforming Mobility Through Natural Gas,' the implementation of BS-VI emission norms from April 1, 2020, will increase price differential between CNG and diesel vehicles, making CNG vehicles more attractive. Thus, gasoline engines will be modified to run on alternative fuels like LNG, electric power and others (Markets&Markets, 2020)

With the development of new composites, solar and wind energy costs are continuously on a fall. The cost associated with renewable energy majorly consists of a fixed cost of installation and marginal maintenance. Therefore, the cost of producing **alternative fuels** deriving from renewable sources, as **green hydrogen**, **will also decrease with continuous operations.**

Figure 12.*Source and illustration by IRENA (IRENA, 2021)*

Alternative Fuels: Analysis

As maritime continues to expand its adherence to the International Maritime Organization (IMO)'s goals to reduce emissions, a diverse choice of energy carriers including methanol, biofuels, synthetic fuels, LNG, batteries, hydrogen, ammonia, and even solar-, wind-, and nuclear-powered vessels have emerged. While some of them are applicable for a variety of use cases, the jury is still out on several others. It is quite likely that most, if not all, of the technologies will find a place in the fuel mix for marine transportation. The three most relevant to Blue Area's growth, in context to their decarbonization potential and level of activity are listed below.

- Hydrogen
- Ammonia
- Methanol

Hydrogen

While liquified natural gas (LNG) continues to enjoy the lead position amongst the alternative energy source for powering the shipping sector, it is only an immediate option for decarbonization and alone would not meet the target set for 2050. In their 2020 report – pathways to sustainable shipping, the American Bureau of Shipping (ABS) defined **three paths for maritime fuel transition**, depending on the type of vessel and its operating profile in terms of trading route and cargo. Hydrogen, which is emission-free and has the highest energy density and flame speed, features as the ultimate solution for future zero-carbon marine vessels via the light gas pathway. Although it requires cryogenic storage and fuel supply, it has solid prospects for the Blue Area since over 60% of European sea trade is handled by short-haul shipping allowing for more manageable refueling.

Low-carbon hydrogen comes in different colors depending on how it is manufactured. The most common variant is blue hydrogen, produced via methane reforming, where the CO_2 emissions caused by the process are captured and sequestered. Methane reforming can take different forms, the most prominent being steam methane reforming. Although blue hydrogen is a low-carbon source, its dependency on natural gas makes it a transition fuel that would eventually pave the way to green hydrogen. Green hydrogen is the more popular – although still expensive – due to its independence from natural gas. It is produced locally by water electrolysis powered by renewable energy from wind, solar, and nuclear. Due to an immense interest in green hydrogen across all sectors, many technology developers, densely centered in the EU, are developing different variations of electrolyzer units in all shapes and sizes. Other less-known variants, such as turquoise (methane pyrolysis) and pink (electrolysis via nuclear), may have potential in specific use cases and are unlikely to be mainstream anytime soon.

Hydrogen is most commonly stored in **compressed gaseous form at 700 bar on ships**. However, the low volumetric energy density of about one-seventh of that of diesel makes it challenging to store sufficient amounts for extended voyages with little refueling opportunity. Thankfully, the **Adriatic-Ionian region offers plenty of opportunities for short-distance transportation** when hydrogen as a fuel will have a crucial role to play.

SWITCH Maritime has awarded All American Marine an order for 84-passenger hydrogen powered hybrid ferry. Source: [All American Marine]

Although still in the early stages of development, the use of hydrogen as a fuel has been demonstrated in internal combustion engines (ICEs). Recent developments targeting the use of **liquid hydrogen** in a dual-fuel engine can potentially increase the range of the vessel that is otherwise limited due to the capacity to store gaseous hydrogen onboard. Another more developed pathway to use hydrogen as a shipping fuel is the fuel cell, which offers a higher energy efficiency (50% - 60%) than combustion engines and higher energy density than batteries. Primarily three types of fuel cells are being explored, including alkaline fuel cells (AFC), proton exchange membrane fuel cells (PEMFC) and solid oxide fuel cells (SOFC); the PEMFC being most sought-after, thanks to their relatively higher power density and lower weight. While both pathways, fuel cells and ICEs, have their pros and cons, their development landscape remains active, especially for short-distance shipping, inviting an increasing number of engine developers and shipbuilders to take advantage of diminishing hydrogen prices and carve out a place in the future of marine transportation.

Promotors & Inhibitors

Albeit a general consensus on the need to expand the penetration of hydrogen in the energy system to decarbonize specific hard-to-abate sectors, uncertainty remains about how its production, consumption, and geographical distribution will evolve.

Promoters

- **Nations pushing industries to transition to hydrogen.** If governments work to scale up hydrogen in a coordinated way, it can help spur investments to bring down costs and enable the sharing of knowledge and best practices, including harmonized international standards and support for hydrogen-fueled transportation.

- **Reducing cost of fuel cells.** Hydrogen engines are still at their nascency, whereas fuel cells remain expensive due to high system complexities and the use of expensive platinum catalysts. However, the momentum in the technical space is already bringing this cost down by benefitting from economies of scale.

Inhibitors

- **Fluctuations in the price of natural gas.** Before green hydrogen scales, a significant contributor to the cost of hydrogen production is the cost of natural gas. An abrupt rise would make turquoise hydrogen (methane pyrolysis) economically less favorable, specifically for places that import most of their natural gas supply.

- **Challenges in storage.** Storage of hydrogen is a challenge and is susceptible to losses such as boil-offs, and while type IV tanks can help avoid that, they tend to get expensive and require a lot of space. Liquid hydrogen offers a higher volumetric energy density but requires temperatures below -253 °C to liquefy, which ends up increase the cost significantly.

- **Lack of infrastructure.** From transportation to storage to onboard bunkering, a hydrogen-powered transportation system requires significant overhauling of infrastructure which requires a large upfront investment. The technology, hydrogen supply, and infrastructure to support the hydrogen-powered vessels need to convolve simultaneously for hydrogen to become a leading maritime fuel.

Key Players

HYDROGEN

Recent Developments

- **Flagships (European Union).** Funded through the Clean Hydrogen Partnership under EU Horizon 2020, the consortium led by ABB Marine & Ports and Ballard Power Systems is developing two commercial hydrogen fuel-cell vessels operating on compressed green hydrogen. The first one, named Zulu, powered by two 200 kW PEMFC from Ballard, is expected to hit the waterways in the river Seine in Paris in 2023. The second demo vessel, called FPS Waal, is a 1.2 MW retrofit that will ply between Rotterdam, Netherlands and Duisburg, Germany, on the Rhine by the summer of 2023.

- **Carisbrooke (United Kingdom).** The shipping company has partnered with Carnot, who claims to develop a fuel-agnostic engine with 70% thermal efficiency, to kick off a 40-day trial of a 50 kW, 100% hydrogen engine mounted on a cargo vessel. The test is expected to start in 2025, suggesting there are still some technical hurdles the company needs to abate.

- **University of California: San Diego (United States).** The Scripps Institute of Oceanography in San Diego, California, has partnered with ship manufacturer Glosten to design a coastal research vessel that will run on a dual engine with hydrogen fuel cells and a diesel-electric generator, the former able to run 75% of the mission for the 45.7-meter long vessel. The vessel's design is anticipated to take a year, followed by three years of construction.

Carnot's fuel-agnostic engine's model. Source: Carnot

- **Rolls Royce (Germany).** The shipbuilding major recently tested their mtu engines to run on 100% pure hydrogen. The company successfully ran a 12-cylinder mtu 4000 L64 engine on hydrogen and claimed to achieve excellent efficiency without quantifying the results. Rolls Royce aims to launch the first installation for the enerPort II lighthouse project at the port of Duisburg, Germany by 2024.

Future Prospects

Hydrogen has built a strong momentum globally as arguably the cleanest fuel option with zero well-to-wake emission if green hydrogen is used. This has translated into a growing interest amongst marine engine manufacturers in using liquid hydrogen as fuel for marine vessels and fuel cells as a powertrain for shorter voyages. Nevertheless, this transition must address significant challenges associated with the lack of hydrogen infrastructure, storage cost and space consideration, the high production cost of green hydrogen, and the lack of relevant safety standards in addition to the maturity of engine and fuel cell technology itself. While the **activities will continue to grow in this space, hydrogen as a fuel, requiring a significant overhaul of the shipping value chain, will likely be a longer-term bet for a 2035 and beyond timeframe.** Due to their flexibility to refuel frequently, small ferries and riverway transportation will be the first to deploy hydrogen-fueled engines, for which the Adriatic-Ionian region is an excellent breeding ground.

Ammonia

A distinctly different molecule, ammonia, has primarily shared the fuel R&D space with hydrogen for direct combustion in a modified engine or to generate electricity via fuel cells. Both share similar qualities in terms of emissions, neither emitting CO_2, SO_X, or other particulates when combusted. However, liquid ammonia can be stored and transported at milder conditions (-33 °C and 8.6 bar) than hydrogen, making **handling and transportation of ammonia considerably more manageable and less expensive**. Ammonia has a high octane number and low cetane number, while it also offers a higher volumetric energy density (12.7 MJ/l) than hydrogen (8.5 MJ/l) and is comparable to methanol. Due to these chemical properties, ammonia is **tagged as the long-term replacement fuel in the ABS' heavy gas pathway**.

Catalytic generation, commonly known as Haber-Bosch, is today's only commercial technology available for ammonia generation. The process converts nitrogen and hydrogen into ammonia over a solid catalyst at temperatures between 400 °C – 500 °C and pressures between 100 bar – 200 bar. The catalysts used in industry are iron- and ruthenium-based, with iron-based catalysts by far the most common choice due to their high activity and lower cost. However, ammonia production currently accounts for around 1.8% of global CO_2 emissions. Therefore, the development of distributed, affordable, and renewable energy-based ammonia synthesis, which can be operated under mild conditions while still producing at high, practical rates and efficiency, has attracted significant momentum in the last few years. Innovation in catalytic technology takes a two-pronged approach: for large-scale facilities the focus is on energy and cost optimization, which is achieved chiefly through novel engineering designs; for the emerging small-scale, distributed ammonia generation units that can operate intermittently, innovation focuses on improved catalyst formulations and novel sorption-based techniques for ammonia separation. Other more novel approaches include electrochemical nitrogen reduction reaction (e-NRR), chemical looping, and photocatalytic synthesis, but they will require many more years of R&D before commercialization.

One of the most abundantly produced chemicals in the world, ammonia enjoys a century-old market-ready supply chain and the potential to provide an emission-free alternative to fossil fuels that has led to a significant uptick in interest in using ammonia as a hydrogen carrier. However, reconverting ammonia to hydrogen for end use results in a substantial loss of energy during cracking. Therefore direct use of ammonia as carbon-free fuel either via combustion-based routes or a source of electricity using electrochemical reaction is being actively pursued.

Ammonia can be used in conventional reciprocating internal combustion engines with minor modifications in the fuel container and supply line to avoid corrosion, as well as compression ratio in the spark ignition system. Engines can operate on 100% ammonia or in dual-fuel mode together with diesel. Ammonia engines have yet to be commercialized, but several companies are developing the technology, including two-stroke and four-stroke ammonia engines. Companies such as Wärtsilä are currently testing different fuel ratios for both dual-fuel and spark-ignited gas engines.

The other route to use ammonia to power shipping is direct ammonia fuel cell (DAFC) which is currently at the laboratory stage. There are two main types of fuel cells for direct ammonia use: low-temperature alkaline fuel cells (AFC) and high-temperature solid oxide fuel cells (SOFC). The direct use of ammonia in a fuel cell faces several technical challenges, such as high-temperature requirements, corrosiveness, longer startup and cooling time, and there are very few players active in the space.

Equinor’s Viking Energy to be powered by SOFC from alma. Source: Alma

Promotors & Inhibitors

Ammonia’s fate as a fuel is largely intertwined with hydrogen, with both competing and complementing each other at different levels. A fully mature infrastructure and well-established production technology make it a logistically attractive and affordable fuel, inching ahead of its competitors, but timing will depend on how soon engine manufactures can abate unresolved technical challenges.

Promoters

- **National reliance on renewable energy imports.** Hydrogen is emerging as a critical vector for transporting renewable energy globally, and ammonia is its leading carrier. The demand for hydrogen is set to grow by 480% in the **IEA's Net Zero Emissions** scenario to decarbonize heavy mobility and industrial applications. As low-carbon ammonia facilities come online to support the growing hydrogen economy, innovation within engines for shipping will ramp up. While direct ammonia fuel cells will remain a long shot, the development will also continue in that field.

- **Mature supply chain for a low carbon fuel.** Liquid ammonia can be stored and transported at milder conditions compared to hydrogen. It also offers a higher volumetric energy density (12.7 MJ/l) than hydrogen (8.5 MJ/l), comparable to methanol. Ammonia emits virtually no CO2, SOx, particulate matter, or unburned hydrocarbons. It can be a zero-emission fuel if produced with green hydrogen, and unlike many other potential options, it has commercially mature transportation technologies, infrastructure and supply chain.

- **Ability to blend.** Ammonia blending with other liquid fuels is much easier and provides a smooth transition toward 100% ammonia combustion engines. Shipbuilders and policymakers will find it easier to adapt to a small blending percentage with minimum retrofit in the near term.

Inhibitors

- **High ignition temperature.** Ammonia exhibits a higher ignition temperature of 650 °C, has low flame velocity, and poor chemical kinetics compared to other fuels and therefore requires either mixing with traditional fuels such as gasoline, diesel, or hydrogen, or modification in engines to aid complete combustion of 100% ammonia. Due to the sizeable volume-to-surface ratio, low speed and better confinement, marine engines offer tolerance to poor ignition of ammonia. Still, much research is warranted to realize 100% ammonia engines at commercial scales.

- **Corrosiveness.** Ammonia, due to its alkaline nature, is quite corrosive and threatens system integrity if using systems designed for conventional fuels. Companies are aware of this challenge and conducting studies and trials to use reinforced double-walled fuel tanks and connectors made with corrosion-resistant materials. However, this means that retrofitting existing vessels is limited in scope.

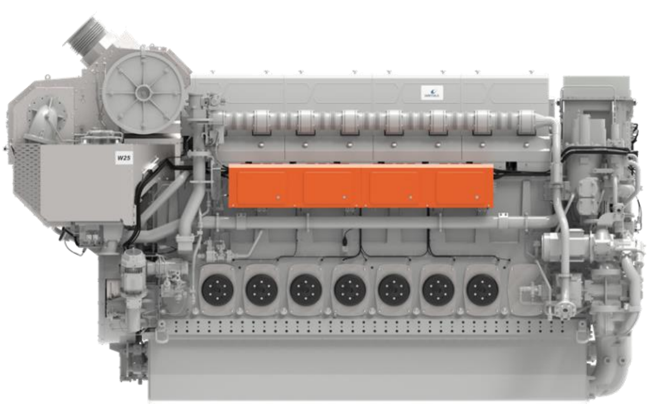
- **High NO_x emissions.** Although CO_2 and SO_x-free, combustion of ammonia, mainly by burning it in an ignition engine or turbine, causes significant NO_x emissions. An ammonia-based combustion system, therefore, requires additional De-NO_x equipment or catalysts that can reduce in-situ NO_x into nitrogen, both of which add to the cost.

Key Players

AMMONIA

Recent Developments

- **Wärtsilä (Finland).** The leading engine manufacturer is [developing](#) a four-stroke ammonia engine named Wartsila 25. The company aims to finish the concept design within 2023 and will offer modular engines with cylinder configurations ranging from 6 – 9 liters and output power between 1.9 – 3.4 MW.



Wartsila 25, a medium-speed four-stroke engine under development. Source: [Wartsila](#)

- **WinGD (Switzerland).** The Swiss marine power company and CMB Tech from Belgium are [developing a two-stroke ammonia engine](#) for large vessels, although the ship capacity isn't yet announced. The WinGD's X-series engine, X72DF, will be mounted on ten x 210,000 DWT bulk carriers owned by CMB.TECH by 2026.

- **Grieg Edge (Norway).** Grieg Edge and partners LMG Marin and Wärtsilä have received the approval in principle for their conceptual design of ammonia fueled tanker from DNV. The initiative is a result of Zeeds initiative for zero-emission fuels. The conceptual design is a 120 meter long tanker with a cargo capacity to carry 7,500 cubic meters of ammonia. The vessel powered by a Wärtsilä W25DF ammonia engine is expected to be ready by 2025 if economic challenges are mitigated.

- **Mitsui O.S.K. Lines (Japan).** The three-way joint-venture that also includes Tsuneishi Shipbuilding and Mitsui E&S Shipbuilding is developing an LPG carrier ship powered by a MITSUI-MAN B&W type S60 two-stroke dual-fuel ammonia engine. The engine is currently under development by Mitsui and Man Energy Solutions and is expected to bring the 180-meter-long, 30-meter-wide vessel online by 2026.

Future Prospects

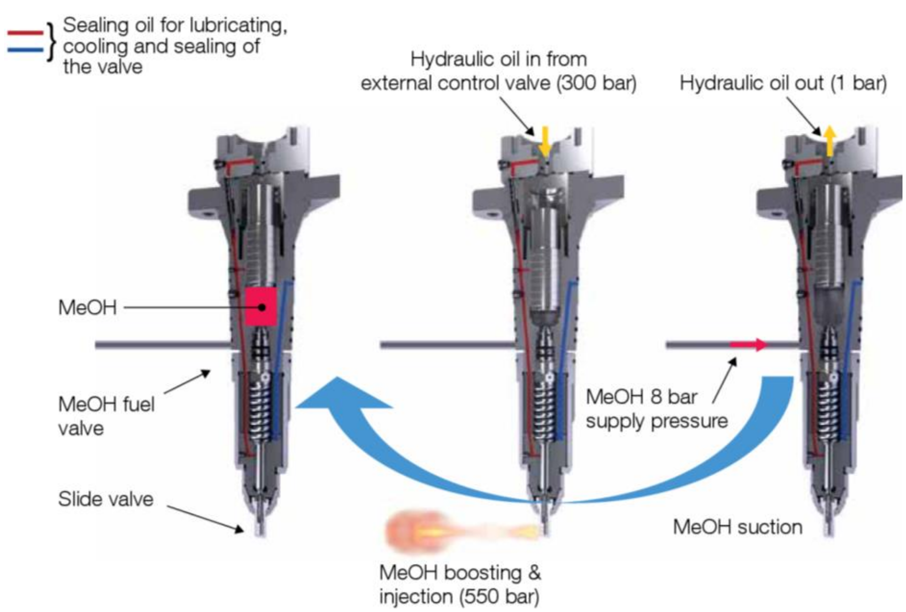
Ammonia draws many parallels with hydrogen in terms of emissions, neither emitting CO_2, SO_X, or other particulates when combusted, but it scores over the former in two most critical aspects – **easier storage and transport** and **higher volumetric energy density**. Both have **shifted the momentum toward ammonia as the choice of future fuel for maritime decarbonization**. The newest entry in the race, ammonia, has an uphill battle to fight to get the engine technology right to burn 100% ammonia without releasing NO_x. The engine manufacturers are looking to IMO to set guidelines, primarily related to **NO_x removal**, to get further clarity on the specifications they need to aim for. The strong market force caused by national reliance on renewable energy imports, for which ammonia is currently the leading prospective energy carrier, momentum in ammonia power generation for shipping is, however, quite strong. As low-carbon ammonia facilities come online within the decade, we expect innovation within engines for shipping to ramp up even further. The Adriatic-Ionian region will also witness their fair share and should invest in technologies related to **ammonia as a shipping fuel for 2030 and beyond**.

Methanol

Methanol has one of the highest C/H content ratios compared to conventional fuels. Although the energy density is relatively lower than heavy fuel oil (HFO) at 15.7 MJ/l, it causes significantly lower CO_2, SOx, NOx and particulate matter emissions. Methanol and other alcohols have, therefore, rightfully created a lot of **stir as a potential blendstock and complete drop-in replacements**. Methanol is liquid at ambient conditions and exhibits a low reactivity which makes for convenient storage and transportation compared to other alternatives.

The most developed industrial pathway for producing methanol is by producing syngas from natural gas or coal via **steam methane reforming or gasification, respectively**, which in turn is converted to methanol in a methanol reactor in the presence of $CuO/ZnO/Al_2O_3$ catalyst. However, it can also be produced via **bio-based** and **CO_2-based pathways**, making it a carbon-neutral fuel, and it has been actively pursued lately to take advantage of regulatory premiums. The bio-based method involves the gasification of lignocellulosic biomass to generate syngas before it is converted to methanol. On the other hand, the CO_2-based pathway dubbed **e-methanol** is the youngest variation trying to find a foothold in the methanol production market. It involves the conversion of CO_2 captured into syngas via reverse water gas shift (RWGS). However, the hefty price gap between fossil-based and CO_2-based methanol pathways has limited its widespread adoption.

Methanol is an attractive option as a drop-in replacement in existing two-stroke and four-stroke diesel internal combustion engines with minor combustion systems and bunkering modifications. Since methanol has a high octane number and low cetane number, it requires an ignition source in the form of pilot diesel injection. Several engine manufacturers have developed dual-fuel engines with **booster diesel-injection valves** for initial methanol combustion. A lower volumetric energy density means that the bunkering frequency for a methanol vessel is about twice that of a diesel vessel of equal capacity.



Working principle of MAN Energy Solutions B&W ME-LGI engine's booster fuel injection valve. Source: MAN Energy Solutions

This project is supported by the Interreg ADRION Programme funded under the European Regional Development Fund and IPA II fund.

While most fuel cell applications involving methanol have focused on using methanol as a hydrogen carrier, a few direct methanol fuel cells (DMFC) have also been explored in the past. It operates at lower temperatures (50 °C – 120 °C) without noise, but a low energy efficiency of 20%, and the risk of methanol crossing over the membrane to the cathode makes it unfit for large energy requirements of marine shipping.

Promotors & Inhibitors

Shipping emits approximately one gigatonne of CO_2, and while still produced primarily from natural gas, methanol is vital to achieving IMO's 2050 emission reduction targets. While several advantages regarding manufacturing, handling, and transportation play in favor of methanol as a shipping fuel, it is not immune to challenges.

Promoters

- **Well-developed infrastructure.** Just like ammonia, methanol also enjoys a mature transportation and distribution infrastructure. Mild storage temperature (-93 °C to 65 °C) and liquid ambient state makes storage and transport of methanol significantly cheaper than LNG, hydrogen, and even ammonia. Methanol does not require cryogenic storage and can easily use slop tanks, ballast tanks, and double-hulled bottoms for bunkering.

- **Technology of today.** While ammonia, and potentially hydrogen, will likely eventually take the driving seat, in the literal sense, methanol is the most mature alternative fuel for the near future. Backed to be the 2030s solution for the heavy gas pathway before ammonia takes over, methanol is already successfully deployed in a handful of vessel engines, and several other dual-fuel engines are under development.

- **Structured regulations.** Unlike alternative fuels, including **ammonia**, where there is a cloud of uncertainty around the regulatory framework, methanol already has a guideline issued by **IMO** that engine manufacturers and fuel providers can leverage to confine their production lines around it. Taking a cue, several large shipping and logistics companies, including Maersk, have **announced** an increase in their methanol-powered fleet.

Inhibitors

- **Almost an unachievable scale.** Although the methanol production industry is well established, with 98 million tonnes being produced in 2021, it still needs to catch up to what is required to cater to global shipping, which has a bunkering capacity of 658 million tonnes. This level of scale-up will require not only heavy capital expenditure and land but also feedstock that is primarily natural gas today. The challenge is even more severe if the e-methanol route is to be pursued.

- **Emission-free methanol is still very expensive.** The success of e-methanol entirely rests on a cheap supply of CO_2 and renewable electricity for hydrogen production. Despite the falling cost of renewable electricity and regulations such as the U.S. Inflation Reduction Act (IRA) providing impetus to CO_2 capture, ensuring a cheap and abundant feedstock supply is a daunting challenge ahead for the e-methanol pathway. Bio-based methanol production also suffers the same feedstock-related challenges.

Key Players

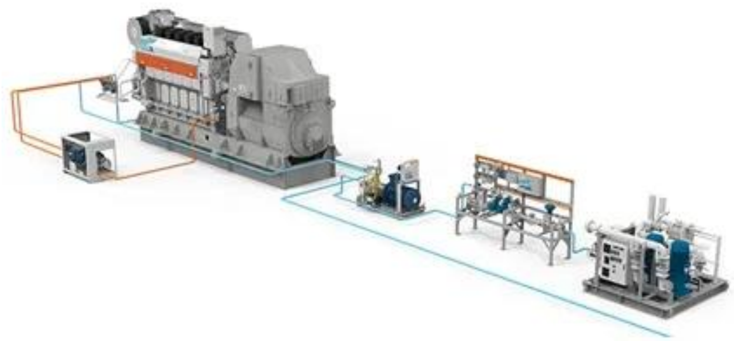
Recent Developments

- **MAN Energy Solutions (Germany).** After receiving an order of 8 methanol dual-fuel engines for Mearsk's containerships, MAN has clinched approval for its four-stroke 32/44CR engine from DNV, which they aim to commercialize in 2024. The 600 kW engine uses an electronic injection to kickstart combustion and turbochargers to impart high efficiency.

- **Sanlorenzo (Italy).** The yacht builder has partnered with Rolls-Royce to build a large luxury yacht with a mtu series methanol propulsion system. The proposed vessel will be between 40 and 70 meters and run on two mtu series 4000 engines. The project kicked off as an MOU in late 2022 and is expected to take its maiden voyage in 2026.

- **Wärtsilä (Finland).** Wärtsilä will supply five methanol-fueled engines, Wärtsilä 32, to Van Oord to power their offshore wind installation vessel (WIV) being built at Yantai CIMC Raffles shipyard in China.

- **Maersk (Denmark).** As the company ramps up its fleet of methanol-powered ships, they have struck several deals with suppliers such as Orsted, Proman, European Energy, CIMC Enric, and WasteFuel to secure a methanol supply in excess of 730,000 tonnes per year by the end of 2025.

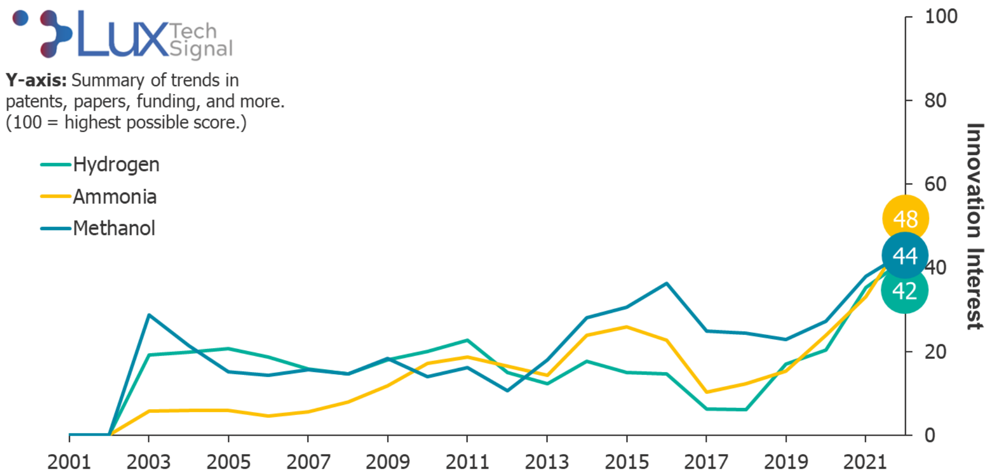


Wärtsilä 32 Methanol Engine. Source: Wartsila

Future Prospects

Methanol being an important chemical has a well establish supply chain infrastructure. It offers several advantages as a fuel, such as high knocking resistance and latent heat of vaporization, while causing a lot less emission than conventional shipping fuels. Although not at scale, **methanol engines are already commercially available**, with ship operators continuously increasing their capacity. There are still challenges associated with making methanol carbon neutral. Technical hindrances are relatively easier to abate with some retrofitting of the engine's ignition system and the need for refueling. Issues related to feedstock supply and associated costs will be the most intricate piece of the puzzle for carbon-neutral shipping via methanol. Eventually, methanol derived from natural gas will find a place in the mix of near-term drop-in fuels, **driving the transition until ammonia takes over** as the primary fuel by 2030-2035. ADRION region is already witnessing activity in this space, which is expected to grow and support the Blue Area's growth through the next decade.

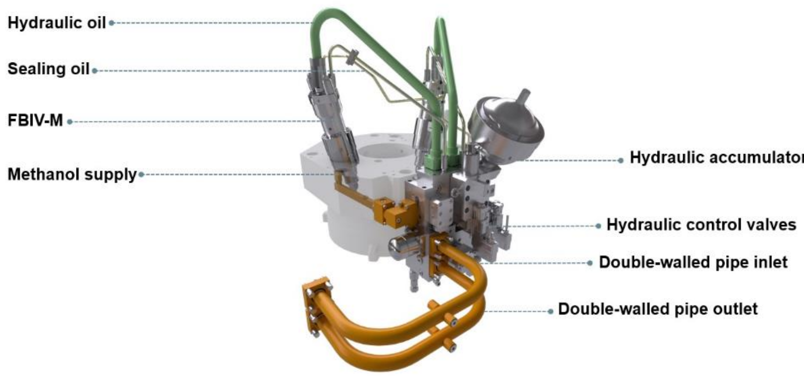
Innovation Trends



*The **Lux Tech Signal** is a composite score, combining data in patents, papers, and funding, plus Lux Research's proprietary data. It quantifies the progress of each technology, against a maximum innovation interest score of 100. Changes over time indicate growing (or shrinking) innovation interest, while inflection points may point to commercial opportunities or challenges ahead.*

The shipping sector has been fragmented with more than a dozen conventional and low-carbon fuels, including LNG, bio-based fuels, batteries, hydrogen & ammonia, methanol, synthetic fuels, and renewables being pursued in different capacities depending on regional feedstock supply and technology available with the shipbuilding companies. All three marine fuels discussed here have broadly followed the same humbling innovation trend for the century's first decade.

Interest in methanol started as a potential blendstock, eventually growing into a full drop-in replacement. While it failed to gain significant traction as a blendstock with diesel fuel, R&D activities picked up in 2012, soon after MAN Energy Solutions introduced their dual-fuel MAN ME-LGI engine that could accommodate liquid methanol for ship propulsion. Struggle in obtaining feedstock for other fuel technologies, such as expensive plant oil for producing Hydrotreated vegetable oil (HVO) or renewable diesel, helped methanol enjoy momentum.



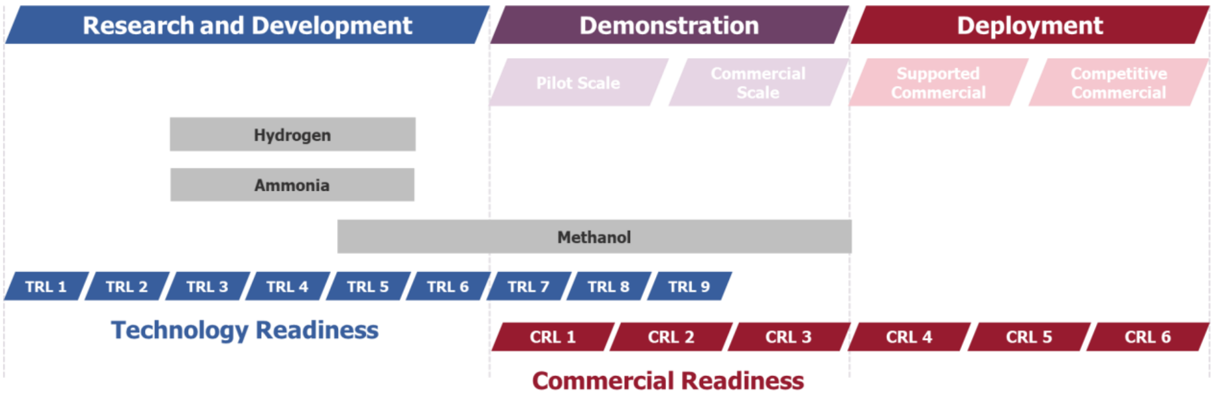
Main Energy Solutions ME-LGI Dual-engine. Source: MAN Energy Solution

When interest in other routes picked up, primarily driven by the economic benefits, the innovation in methanol, hydrogen, and ammonia stalled for two – three years. The rising interest in the hydrogen economy over the last seven to eight years is reflected in the innovation landscape of ammonia and hydrogen as shipping fuel as well.

While ABS, in collaboration with Sandia National Laboratories and other industry partners, received approval in principle for a hydrogen PEM fuel-cell passenger ferry under the SF-BREEZE project in 2016, Havyard started a similar project in Norway, paving the way for other similar innovations. IMO's adoption of the greenhouse gas emissions strategy in 2018 during its 72nd session – IMO 2050 – has led to a rise in innovation activity across all variations of potential energy sources. Ammonia, while starting slow, trailing behind hydrogen, has emerged as its leading carrier. Innovation in utilizing ammonia as a direct fuel to power ships has soared in the last 3-4 years, with most major players such as Wartsila, MAN Energy Solutions, and Rolls Royce betting on ammonia as a future fuel.

Overall, the **technology landscape is still in its early stages**, with no single energy source receiving significantly more attention from the industry despite the wide range of technology readiness levels across the several possible solutions. A lack of consensus by the shipping industry today and numerous pathways being developed means that the outlook for the decarbonization of shipping remains unclear. This is, however, **changing slowly, with ammonia trying to create a gap**. More extended history and better know-how in handling, storage, and transport could lower the barrier to adoption for any of these energy sources and stimulate adoption by a typically conservative shipping sector.

Technology Status



Hydrogen and Ammonia as maritime fuel are still at early stages of development. While fuel cells have been piloted and are slightly ahead of the spark ignition engines, neither variations are commercial yet. Dual-fuel methanol engines are commercially mature, but a 100% drop-in replacement methanol engine is not yet commonplace. E-methanol through green pathways is still quite immature with development is geared towards weeding out commercial challenges associated to its production and end-use.

Alternative and Competing Technologies

Other forms of ship propulsion, like **electric ship** or **other zero-carbon energies**, such as **solar and wind.**

can be regarded as alternative and competing technology, with respect to alternative fuels.

An **electric ship** is a vessel, which is powered by a battery system and has diesel generators to back up the battery system during high power requirements, or when the batteries are drained out (Markets&Markets, 2021a). The growth in the adoption of **hybrid vessels** can be attributed to the demand for lower emissions from the maritime transport sector and the development of advanced hybrid battery power systems for ships/vessels. Several vessels have already received electric hybrid notation. **Batteries** play a pivotal role in the success and wide adoption of electric ships. The main **limitations** for the development of electric ship are related to the long downtime in retrofitting ships and to the limited range and capacity of full electric ships. Ship operations need to be stopped for a while when changing the propulsion system and installing scrubbers, and this would result in revenue loss. Shipowners with big revenue pockets can incur the retrofit cost; however, for small operators, it would be challenging to retrofit ships due to budget constraints. Limited travel distance and capacity are major restraints of full-electric ships (Markets&Markets, 2021a).

To supply the energy needs of ships, alternative energy as **solar energy** is readily available at sea and has low maintenance costs. Furthermore, solar energy can be used as the main energy source, especially for the main engine of small ships, while for large ships, it can be used to meet electrical energy for lighting, navigation systems and communication devices (I.S. Arief and AZM Fathalah, 2022).

Recently, **wind energy** has become a consideration for alternative fuels to reduce emissions. As a clean, free, limitless, and readily available resource, wind generates sustainable electricity. This is the reason investments in the development of this renewable energy source are growing. In the maritime industry, this alternative power source is urged to play a key role in decarbonizing the sector. Some companies are already looking toward ships that are 100% powered by the wind but there is still a long way to go before fleets are only composed of such vessels (Valentin L., 2022)

However, solar and wind energy has a low density, and availability is not continuous. How to overcome this requires energy storage for a long time. The wind applications in the maritime industry are at various stages of development, some being already implemented whereas some are still at the concept stage.

Moreover, while inland solar energy is a relatively mature technology with wide-ranging applications, its marine use remains limited. Most solar installations in the marine industry supply static lighthouses and buoys, or battery charging for small sailing yachts (Ben Pilkington, 2022). With current technology, researchers estimate that solar energy investments for ships could take between 10 and 27 years to pay themselves back in reduced fuel costs, depending on solar radiation levels and fluctuations in fuel costs.

A zero-emission propulsion technology on board ships using green hydrogen from liquid organic hydrogen carrier (LOHC) on a megawatt scale. The concept is based on the combined use of LOHC and solid oxide fuel cells (SOFC) as a powertrain, providing a significant improvement from conventional internal combustion engines (Source and image Hydrogenious)

Commercial Outlook

Oil and gas is a major industry in the energy market and plays an influential role in the global economy as the world's primary fuel source. The processes and systems involved in producing and distributing oil and gas are highly complex, capital-intensive, and require state-of-the-art technology. The oil and gas industry is highly **volatile**, and the biggest factor controlling the **price of oil** is the relationship between **supply and demand**. Supply factors that affect the price of oil include production decisions made by the Organization of the Petroleum Exporting Countries (OPEC), geopolitical issues, and severe weather conditions. Demand factors include reliance on oil, the price of the US dollar, and global economic performance (Markets&Markets, 2021c).

The cost of oil fuel directly affects also the costs of maritime transportation. Following a contraction in 2020 due to the COVID-19 pandemic, global oil demand is expected to rise sharply amid the restart of global economic activities. According to the International Energy Agency (IEA), between 2019 and 2025, global oil demand is forecast to grow at an average annual rate of just below 1 million bpd.

Regarding the alternative fuels deriving from renewable sources, the **prices of green hydrogen** depend mostly on renewable energy cost, electrolyzer cost and transportation costs. Energy cost contributes to nearly 50%-75% of the final price of green hydrogen, while electrolyzer contributes 20%-40% of the final cost. As the acceptance of solar and wind energy is increasing and the technologies are developed, the cost of electricity production using these sources has decreased, affecting the price of green hydrogen. On the other hand, the infrastructure to transport hydrogen is not well developed and still needs significant investments and projects to efficiently transport hydrogen from point A to point B. The technological advancement in green energy has revolutionized for the past decade, with price drops ranging between 40% and 80% in various components. These factors show an **optimistic future for the growth of the green hydrogen market** to be competitive with other forms of hydrogen in terms of price (Markets&Markets, 2021b). Blue hydrogen, created from fossil fuels and carbon capture and storage, now costs twice as much as green hydrogen (CCUS) (Markets&Markets, 2022b).

Regarding the market expansion of green ammonia, the capital-intensive nature of this fuel is the main barrier preventing the market from expanding. The typical lifespan of a modern ammonia plant is 15 to 20 years. For each tonne of ammonia produced, a greenfield project's CAPEX costs typically range from USD 1,300 to 2,000. Green ammonia, however, is 1.5 times more expensive than ammonia facilities powered by natural gas. The green ammonia average levelized cost for Grid PPA is expected to reach the value of USD 610 – 640 per ton in Europe by 2050, starting from a value of USD 870 – 890 per ton in 2020 (chapter 5.11 report) (Markets&Markets, 2022a).

Methanol is a global commodity and its price is directly impacted by changes in its supply and demand. Based on the diversity of end products in which methanol is used, the demand for methanol is driven by a number of factors including strength of global and regional economies, industrial production levels, energy prices, pricing of end products and government regulations and policies. Methanol prices have historically been, and are expected to continue to be, characterized by **cyclicality**. In Europe, the methanol average selling price is expected to reach the value of USD/TON 397 by 2026, starting from a value of USD/TON 275 in 2019 (Markets&Markets, 2021c).

Conclusions

The lack of a clear roadmap for the decarbonization of the shipping industry presents a series of challenges and opportunities. The path towards decarbonization does not only involve technological upgrades and improvement of ship design, but also the use of **alternative fuels** from renewable alternative sources and the use of engines and propulsion systems (e.g. fuel cells) that are compatible with such fuels. Digital technology will also play a contributory role to raise energy efficiency. The uptake of digital innovations within the maritime sector has indeed accelerated and other enablers are GHG emission calculators, digital twins of engines, ships, and port infrastructures.

The three alternative fuels most relevant within the BLUEAIR framework, in context to their decarbonization potential and level of activity, are **hydrogen**, **ammonia** and **methanol**. Many players are active at the European level in the development of research & development projects regarding these technologies.

Overall, **the technology landscape is still in its nascent stage with no single energy source receiving significantly more attention from the industry despite the wide range of technology readiness levels across the possible solutions.** Corporations active in the space are primarily patent holders given the direct impact the various technologies will have on future shipbuilding strategies and requirements. None have scaled-up offerings, outside of LNG-powered vessels, and developments are primarily driven by manufacturing and services providers such as Wartsila, ABB, and Siemens. Out of the categories above, **LNG and bio-based fuels have the largest historical body for work, though adoption of either remain minimal.** Mid term solutions could be bridged by the use of bio fuels even if their limited use could be explained by the low energy/agricultural land ratio and the long term ongoing competition with food industry.

While interest in batteries and electrification has quickly risen and presents the most robust technology landscape out of the seven solutions, it remains to be seen if small-medium enterprises and large corporations will be able to replicate the success that has been seen for road transportation. **Despite a relatively smaller technology landscape, hydrogen and ammonia continue to gain traction for both its potential zero-carbon attributes and high energy density, respectively.**

The technology landscape for decarbonizing shipping appears to be one that has yet to emerge with a clear roadmap for the future. With the potential use of hydrogen, ammonia, or methanol, opportunities also present themselves for the chemicals industry, which is largely excluded from most fuel decarbonization roadmaps. **Extensive know-how in terms of handling, storage, and transport could possibly lower the barrier to adoption for any of these energy sources and stimulate adoption by a typically conservative shipping sector.** However, with a lack of consensus by the shipping industry today and numerous pathways being developed, the outlook for the decarbonization of shipping remains unclear.

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Robotics: Horizon Scanning

Why it Matters

Maritime transport has always been at the forefront of economic development, catalyzing over 80% of international trade. It needs to show resilience to increasing threats of climate change while still catering to the increasing demand for the **transport of goods and people**. Vessel manufacturers, operators, and ports need to not only expand shipping and handling capacity but to improve vessel performance, reduce emissions, and safeguard operations.

Oceans are not only a mode of transportation of goods, but home to precious elements including **hydrocarbons**. Almost one-quarter of the oil and gas today is produced from beneath the oceans and this share is only going to grow further in the foreseeable future. The rise of offshore wind farms, floating wind and solar, and the aspiration to tap on ocean's thermal energy is pushing operations not only farther but deeper in the oceans. This is particularly challenging from an operational standpoint to drill deep-water wells and offshore wind platforms at high-pressure subsea conditions and rough wind and tides on the vessels and platforms.

The Adriatic-Ionian region, also known as the ADRION region, hosts a heterogeneous mix of **70 million people** spread across nine countries. With the marine highways taken care of by nature itself, the cobweb of thousands of km long coastlines and several large and small ports handles the bulk of goods transport and more than 30% of passenger transports, including tourists in the heart of Europe. The geological basins in the Adriatic and Ionian regions also represent the second-largest area for hydrocarbon exploration and production in Europe. With onshore operations shrinking, offshore oil and gas activities will likely continue to grow, at least for the near future, and balancing their conflict with tourism in the area and maneuvering around possible environmental threats will be critical to shaping the blue growth in the area.

Real time ship tracking in the Adriatic-Ionian region. Source: Marinetraffic

Add **fishing** to it, maritime affairs quickly become the kingpin dictating the economic and social development of the region. Therefore, it is paramount that the marine industry in the Adriatic-Ionic region not only continues to survive but grows and thrives in a sustainable manner, especially in the light of risks the blue water faces. It is no surprise that European Union and participating countries have increased focus on developing a resilient transport maritime network and strengthening maritime safety and security of the marine industry across sectors and nations supporting regional prosperity and the global economy.

Climate risks such as **shrinking aquatic life** due to change in **ocean temperature** and operational risk like **oil spills** continue to grow at an alarming rate. Arresting these risks while still managing the demand of the ever-growing world requires tremendous support from all directions, including limited use of fossil fuels, increasing electrification, strict and uniform regulatory compliances, and ensuring highly efficient, safe operations at large scale.

Oil leakage from a refinery pipeline on the coast of Rijeka, Croatia. Source: Global Voices

Substituting **manual labor with an automated force**, while guiding and controlling it remotely to perform regular tasks such as lifting, cleanup and transport has been happening for decades, if not centuries. Better sensors and control, enhanced capacity to gather and analyze data and make intelligent decisions to alter the course of action have dramatically improved the utility and reach of robots today. Modern robotics, thanks to the digital revolution, promises to address most of the challenges faced by the maritime industry as mentioned above. It is, therefore, unsurprisingly spreading across almost all walks of life, including the maritime industry allowing safe, consistent, and efficient operations in hard-to-access spaces in challenging environmental conditions. Moving away from **heat to electricity** as the force driving the industry has provided further impetus to using digitally connected and remotely operable robotic equipment supporting operations on ports and the ships relating to them. Deep intrusion robotics have made to the inspection, monitoring, and small delivery by using unmanned aviation vehicles (UAV), popularized as drone and unmanned surface vehicles (USV) in an almost industry-agnostic fashion is almost astonishing.

This project is supported by the Interreg ADRION Programme funded under the European Regional Development Fund and IPA II fund.

Skeyetech autonomous drone monitoring a restricted port area. Source: Azur Drones

More recently, the **global pandemic has shown the impact remote-controlled operations** can have on processes that require continuity in operations and can be seriously impacted by restricted labor mobility, causing significant economic losses. A judicious adoption of robotics technology in the maritime industry has thus become essential for the healthy growth of the naval sector. Whether it is ensuring environmental conservation such as **saving pelagic species** and marine life by standardized surveillance and **monitoring in the near-shore fishing waters**, **regular hull cleaning** of cruise vessels and yachts offshore and managing deepwater oil and gas and wind farm operations in extreme weather conditions, advanced robotics has already made significant inroads in the sector. It goes without saying that robots are not only changing the marine landscape but shaping the future of a digital maritime industry that will require to withstand extreme regulatory rigor and unforgiving security standards under a stringent testing environment.

Value Proposition

As ships venture out in the oceans, away from the land, an atypical array of challenges unfold **due to complicated and variable economic, environmental, cultural, and historical interactions** resulting from differently-abled countries with variable demand, supply, and regulatory coefficients. Marine robotic vehicles, including **autonomous underwater vehicles (AUVs), gliders, unmanned surface vehicles (USVs), and unmanned aviation vehicles (UAVs)**, offer deeper and farther access to the ocean, allowing them to understand better and maintain marine environments. Marine robotic systems are critical for surveillance, environmental monitoring, and core operations. While marine platforms equipped with robotic systems are rapidly shrinking and getting cheaper, their data collection and analysis capabilities are increasing astronomically as they continue to get equipped with greater sensing and computing power.

Innovative robotics can allow the maritime industry to address several challenges with minimal impact on safety and operational reliability. Here are a few key examples where the adaptation of robotics will impact or is already impacting the survival and expansion of the maritime industry, particularly in the Adriatic-Ionian region.

- **Environmental security and restoration.** Together with the Ionian sea, the Adriatic sea breeds and nurtures almost half of the marine flora and fauna in the Mediterranean region. Due to this richness in aquatic feedstock supply, its' geographic location, and regional demand, especially in Italy, Greece, and Croatia, fishing and trawling are of prime importance. Decades of trade, tourism, overfishing and bottom trawling activities have made deep escarpments in the health of the marine environment and biodiversity in the region.

Technological leaps to reduce emissions are generally canceled out by increasing energy and transport demand. Efforts are, therefore, still needed to **restore and maintain general soil conditions, water resources, air quality, fauna, flora, and biodiversity**. While fisheries restricted areas (FRAs) can be established, guidelines for fishing and operations can be placed; their implementation requires investment in inexpensive and highly effective failsafe monitoring and reporting tools and methodologies.

Robotics can help solve these challenges with minimal human intervention and much smaller footprints by carrying out activities such as in-situ water sampling using small USVs equipped with bio-sensors, temperature and bathymetry mapping using UAVs, **eco-friendly seabed geophysical surveying to monitor and restore fauna, and inexpensive reporting against illegal fishing using wave gliding robots**. There is also increasing interest in developing trash collection and wastewater treatment robots that can help control pollution generated due to activities at the port. If powered by locally generated solar, geothermal, or wind energy, they will reduce the requirement of capital-intense charging infrastructure, making themselves fully independent and autonomous.

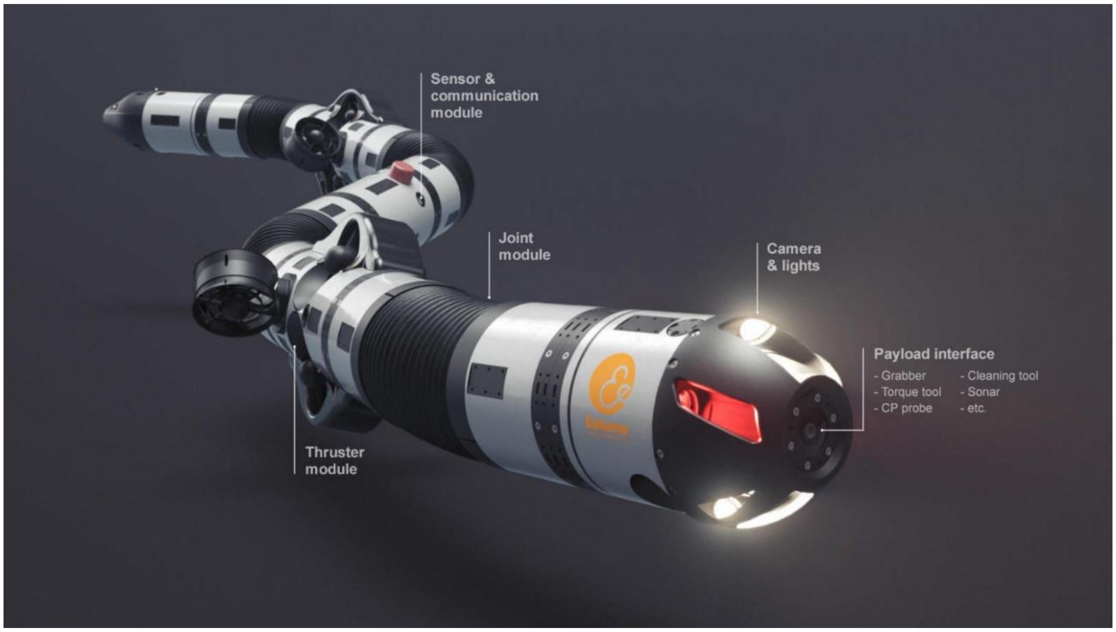
Autonomous USV for water sampling and surface surveying. Source: H2O Robotics

- **Expanding deep-sea and offshore operations.** Freezing temperatures, ocean storms, and dramatically changing tides are not the only threat as vessels venture out to farther and deeper blue waters. Water pressure, lack of light and oxygen, and the unknown perils of marine life make operations at deep-water oil and gas rigs, construction and maintenance of offshore wind platform, turbine and anchor, and transoceanic transportation some of the most challenging operations on the planet. With **significant financial, regulatory, and livestock resources at stake**, any minor breach can be fatal, as seen on several occasions in the past. Robots come to aid by replacing human life to work in some of the most challenging and hazardous environments ranging from **cleanup, maintenance, repair, and towing activities**.

Modern robots equipped with state-of-the-art sensors and communication tools allow continuous data collection and analysis and will enable the backend central teams to deploy predictive maintenance. The oil and gas industry is already well placed to use robots for a range of **roughnecking at the seabed** and drill rigs. The extensive use of robotic grippers and automated submersible robots has thoroughly changed the underwater maintenance process, making it safer, more flexible, and much more affordable.

Home to large oil and gas basins, the Adriatic-Ionian region is undoubtedly a playing field where robots are already installing drill pipes and collecting rock and oil samples. Thanks to their promise for **hazard-free, highly efficient, and low-cost operations**, robotic activities are set to ramp up dramatically in the challenging marine environments and the associated ports, enabling them with better handling capabilities to match the inflow from the farther and deeper horizons.

This project is supported by the Interreg ADRION Programme funded under the European Regional Development Fund and IPA II fund.

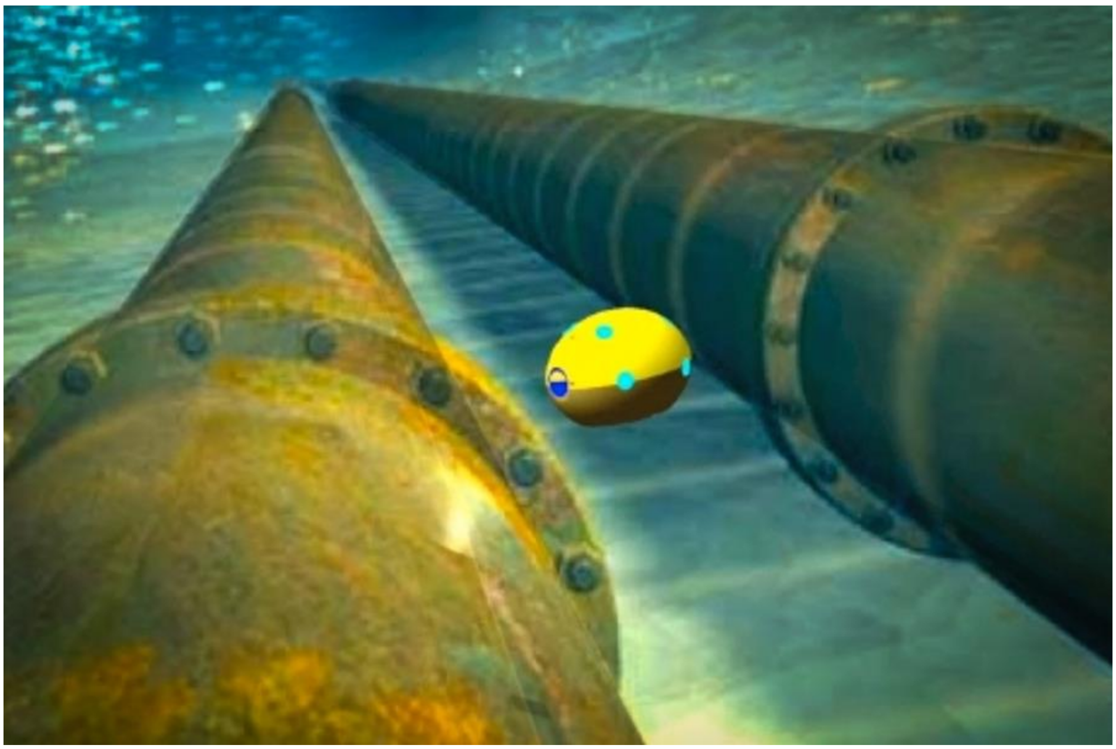


Modular robotic vessel for subsea inspection, maintenance and repair (IMR). Source: Eelume

- **Improving security against piracy and immigration threats.** The Adriatic-Ionian region is full of resources, not just aquatic but oil and gas and tourism attracted by culturally diverse landmass along the expansive coastline. This geographical medley creates a complicated mesh of national and regional borders and overlapping resource bases that require better coordination to ensure maritime safety. An unbalanced infrastructure prowess between nations and a **lack of uniform policies and regulations** has culminated in a long-standing history of loopholes in safety and security in the region. Physical immigration risks, as well as cyber threats causing severe loss of revenue, are on the rise. Illegal immigration via countries with **suboptimal security**, and crimes such as theft and smuggling has grown manifold over the last few years. Piracy backed by digital technology is on the rise. Events like the global pandemic and war fuel these activities posing threats to maritime transport.

Robots armed with inbuilt radars and navigation devices can warn ships, help them optimize and reroute their path, and inform security services to take preventive actions. **Anti-piracy tactical robots**, such as those manufactured by Recon Robotics, can perform discreet inspections and transmit video and audio in real-time to the operator at the deck. These miniature robots eliminate the requirement of extensive and costly monitoring and surveillance of stationary ships with almost non-existent physical footprints and very high discretion. Using robotics in navigation and data transmission can also help prevent one of the most common forms of cyber-attacks, ransomware, a possibility to threaten to publish the victim's personal data unless a ransom is paid.

Beyond waters, keeping ports and harbors secure is another daunting task and cannot always be guarded without a hefty financial burden over prolonged periods. A network of automated USVs and UAVs fitted with modern sensors, including IR/optical cameras, LIDARs, and SONARs connected with central data consolidation and analysis systems powered mainly by AI/ML technologies, provides a **higher degree of security at a much lower cost**.



MIT has developed a football-sized submersible robot that can slide along underwater surfaces at the port to perform and transmit ultrasound scans. Source: MIT

- **Safe, low-cost, uninterrupted transportation.** The livelihood and socio-economic prosperity of coastal countries are primarily, and sometimes entirely, dependent on the sea. The impact of oceans on maritime transport, fisheries, and tourism is nothing less than decisive. The Adriatic-Ionian sea is home to some of the most treasured world heritage, including historic cities and natural wonders, alongside some of the busiest cargo ports along the coasts, such as Koper in Slovenia and Venice in Italy. **Safe, collision-free, and uninterrupted maritime movement is pivotal** for the rapid growth of the Adriatic and Ionian coastal areas and neighboring inland states dependent on them. Global events such as pandemics and war in the recent past have threatened the continuity of operations to the extent of bringing them to an abrupt halt on certain occasions. Isolating the entire crew due to covid restrictions in the absence of a replacement has potentially resulted in terminal damage to goods with shorter shelf life, causing substantial economic losses due to other delays.

Autonomous robotic boats such as those built by Open Ocean Robotics and powered by solar and wind energy are equipped with cameras and sensors to collect data related to the current direction, wind speed, variation in tide and temperature for real-time analysis that helps cargo vessels and transportation fleets design their **oil spill responses**, adjust to more fuel-efficient routes, conserve labor, and eventually limit the impacts on the ocean's natural state. On the other side of the spectrum lie **ship inspection robots** that run inside and over the ship to create a lightweight and versatile ship support system against leakage, breakdown, rusting, fire and storm.

Marine robotics is no longer limited to maintenance, dredging, and communication-related tasks. Still, it has crept in further to become fully autonomous vessels and docking platforms with minimal to no crew onboard. It might still be early to quantify, but potential gains are enormous. Rolls-Royce's efforts in their Marine R&D Center for Remote Control & Autonomous Ships and Artificial Intelligence in Turku, Finland, to develop autonomous ships by 2030 are fueled by a promise of an **80% reduction in transportation costs**.

Orca AI is helping bring full autonomy to cargo vessels that can be monitored and regulated from the fleet operations center in Tokyo. Source: Orca AI

With about 40 percent of the world's population living across the coasts, the fate of the livelihood of the people and the nation's growth is inextricably linked to the vast blue waters. The blue economy ecosystem holds diverse growth opportunities. However, defining the frontal lobe of the human population against the oceans, they also encounter existential challenges in the face of climate change and need aggressive momentum toward sustainable development.

The emerging trends in **cutting-edge technologies in infrastructure, digitalization, and communication** worldwide can help keep the oceans clean and protect blue area ecosystems without compromising on transportation, tourism, or the ever-expanding quest of exploring deeper waters. Marine robotics is a fascinating enabler, constantly innovating itself, that can bring consistent resilience in highly unpredictable environments. Robots are already protecting the sea, and the life of surfers, in many ways, from improving ship efficiency to removing garbage. However, robotics, particularly in the maritime industry, is only in its infancy. It is not immune to challenges that are needed to be complimented or resolved to realize its full potential.

As **complete autonomy** grows in **scale and complexity**, they must constantly develop and adapt new anti-collision, vision, control, and communication methodologies. When compared to humans, a **lack of insights** and **decision-making capabilities** has always been seen as the **biggest downside** of autonomous robotics. While artificial intelligence has shown promise, there is still a long way to cover. New developments to carry out tasks in harsh conditions with flexibility also require **superior materials** that are **immune to oxidation and weathering**, while also being lightweight and pliable and can integrated with evolving power systems. Ensuring an inexpensive supply of building materials for body parts, connectors, and communication devices will be vital to scaling robotics in the blue economy.

Non-technical factors, such as the lack of a **uniform legal framework** that regulates autonomous robots and data transactions, require a collaborative push from policymakers, public administrations, and industrial parties. Last but not least, there is a strong need for **user acceptance** for robotics to find a place to co-exist in the blue ecosystem as a supporter and enabler without being seen as a threat displacing human labor.

Robotics: Analysis

Covering over 70% of the planet, oceans have a direct impact on at least 90% of human life. Initially confined to scientific investigations for monitoring and understanding the sea-bed and aquatic life at unprecedented temporal and spatial extremes, robotics, being a swift enabler in virtually everything humans do concerning oceans, is now a helpful companion across the entire blue economy. Whether remotely operated through a joystick or autonomous in nature, robotics manifests in the achievement of challenging scientific, commercial, and societal goals across all domains.

One way to classify robotics in the marine ecosystem is **based on the business segment** they are used for and the family of functionality they provide:

- Port and near-shore surveillance and maintenance.
- Offshore inspection and maintenance.
- Autonomous vessels and ships.

Port and Near-Shore Surveillance and Maintenance

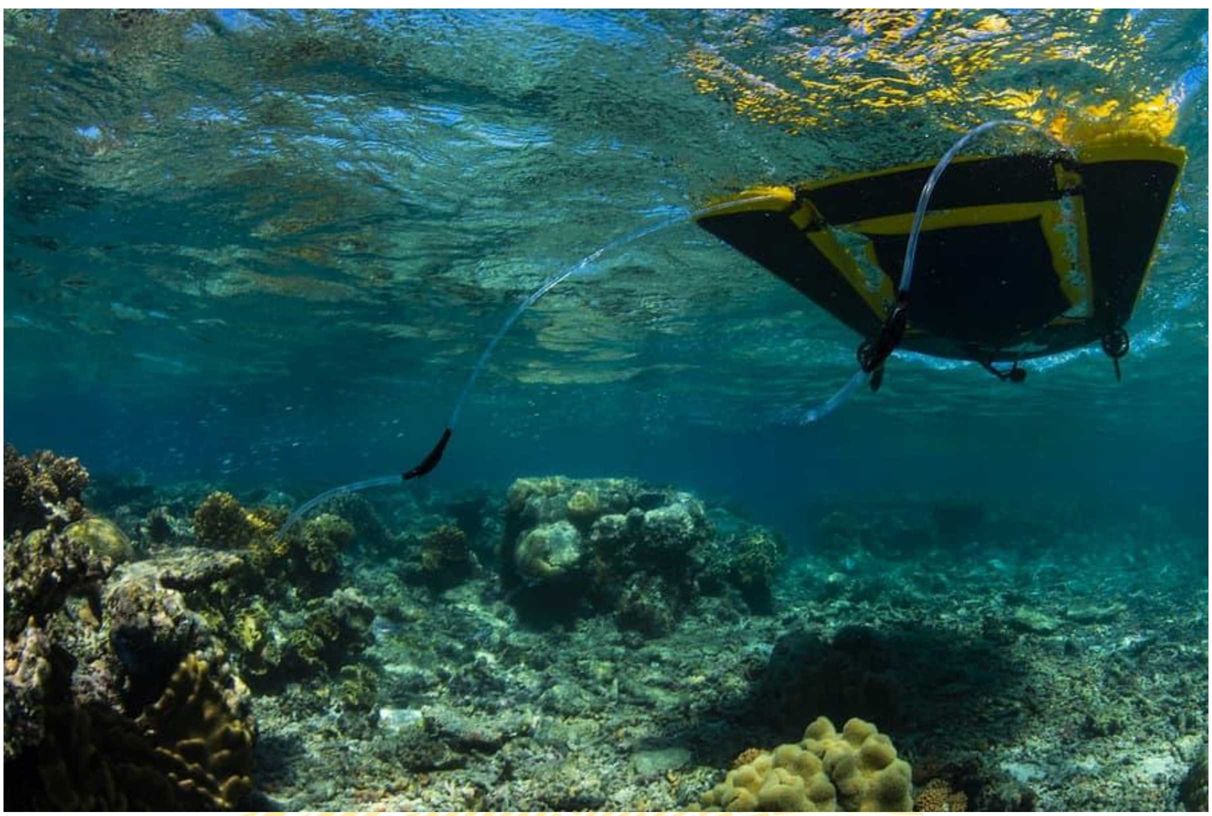
The maritime industry is rapidly evolving to comply with the emission reduction goals set by the International Maritime Organization (IMO) without compromising on the demand for transportation. While offshore waters eventuate complicated scientific challenges, near-shore and 'at port' challenges are no less arduous as variability increases.

The deployment of robots for carrying out repeatable tasks in port logistics is an industry in itself. Still, even beyond that, robots find applicability near the port, supporting transportation and tourism. **Performance monitoring** is an easy way to visualize and weed out inefficiencies in fleet operations. As data generation and computation power increase, robots are being deployed for collecting, analyzing, and reporting performance data, including fuel consumption, route travelled, and emissions caused. Robotics offers a higher degree of accuracy, consistency, and minimum risk of failure. A fleet-wide analysis using the same parameters helps make a recommendation to the crew for the next voyage and generates comparative performance indicators for shipowners and harbour managing authorities.

Fleets of **UAVs and USVs** equipped with sensors connected to a **centralized surveillance** control room at the ports help safeguard the port against physical and cyber threats with a minimal workforce requirement. Off-the-shelf robots are used for regular maintenance work on the docked vessels, including painting, repair, and cleaning. Drones are deployed close to the shore for vessel navigation and traffic control to minimize collision and near-collision incidents. These airborne devices have photogrammetry and LIDAR sensors to help map the 3D environment with precise georeferencing.

As the size and number of ships increase, ports need expansion and construction over land and water. Virtual reality (VR) based robots are finding greater usefulness in **dredging and excavation** activities without much damage to the water and aquatic life. New developments aim to push the envelope and develop robots that can perform construction and maintenance underwater farther from shore at a higher operational efficiency. Automated **construction robots** build ship parts and fulfill other infrastructure needs at the port to significantly impact staffing needs and manufacturing costs. They provide better power efficiency, higher precision, and standardized specialization. Robots help attain autonomy and the ability to safely perform processes, such as metalwork, that require very high temperatures (>800 °C).

These mechanical robots are now attracting extensive interest in environmental conservation. Watertracks, for example, is a maritime startup that develops a subsea excavator robot to decontaminate port areas up to 100 meters of water depth. **Pollutant scraping and wastewater treatment** are essential not only to the oceans but also to the river streams connected to the sea for inland urban transportation and expansion of tourism. Floating trash-cleaning robots that can be controlled via the internet can be a fuel-efficient, low-emission, inexpensive and effective way to support marine and river ecosystems. Robots inspired by fish **collect and analyze the water sample** on the fly to isolate and control oil spills near harbours. This robot is several times faster than a diver collecting a water sample and sending it to the lab before any action is taken to arrest the damage. USVs are now being used for shallow-water seafloor habitat mapping using hyperspectral imaging techniques. Although still nascent, pilot results are encouraging, and USVs can be used for mapping, monitoring, and preserving the coral reefs and other shallow-water ecosystems.



Queensland University of Technology (QUT) has developed an underwater bot, dubbed LarvaBot to safeguard the 2,900 km coastline of the coral reef. Source: QUT

Promoters & Inhibitors

Giant leaps in the industry 4.0 soldering physical engineering with intelligent digital technology are exhibiting a classic display that a robot revolution has been afoot. Port operations are leveraging robotics technology to achieve emission targets and create a better-connected, less polluted ecosystem for maritime transit. Robotized systems promise greater efficiency, tighter security, shorter operations cycles and a streamlined performance but also face a few challenges on the road to adoption. A few key drivers and barriers are enumerated below.

Promoters

- **Digital growth and innovation.** Understanding and beating marine pollution is the number one agenda in the United Nation's decade of ocean science for sustainable development. Advances in robotics and the digital technologies supporting them, including artificial intelligence, machine learning, and 3D printing, are rapidly improving performance at lower costs and a smaller carbon footprint. As AI impregnates further, autonomy will grow, resulting in further adoption of robotics in environmental and surveillance applications.

- **Electrification of ports.** Valencia Port Authority in Spain has pledged to become emission-free by 2030. They aspire to do so by electrification of docks by installing 60 MVA transformers in conjunction with using green energy by solar, hydrogen and wind. Valencia is not alone; Kappelskar and others are following suit. While electrification at such a scale with complex components is challenging, most operators and administrations recognize the need and importance of electrification. Electrification of port infrastructure and equipment provides natural support to robotics and automation as integration with sensors and communication devices becomes much smoother.

- **Exceptional maneuverability in narrow or challenging locations.** Detecting and repairing leaks in little gaps and paint-coating pipes without the need of dismantling is a considerable saving in non-productive time for ports and ships harboured at it. Biomimetic robots, inspired by flexible ocean creatures such as squids and jellyfish, are getting serious attention from companies developing next-gen robots with the fascinating ability to swim, float, and balance that can act efficiently and swiftly without causing any disruption to the marine ecosystem they navigate.

Inhibitors

- **Fragmented shipping industry.** "Zero-emission" is inching away from being a buzzword but is yet to be de facto, and so is robots due to the severely fragmented nature of shipping and yards. Not every yard owner or state authority can afford intense capital infrastructure that can support the modern robotic systems at the ports. One way to mitigate this challenge is a slow transition from conventional techniques to hybrid before maturing to full-scale robotics deployment. Unfortunately, this slows down the adoption and hampers the level of utilization.

- **Legacy equipment and methods.** The machinery, shipbuilder's appetite, communication technology, data transmission protocols and the skillset of the workforce handling them do not grow at the same pace. While communication technologies evolve rapidly, the growth rate for the expertise of the labour force is milder, potentially leading to less than the optimal potential realization of robotics. This has a negative impact on the shipbuilder's desire to adopt robotics in operations at ports, especially those in developing nations.

- **Data security risk, or the notion of it.** Robotics isn't very popular amongst the labour force, particularly in countries where cheap and abundant labour is available. Any minor risks have to go under the microscopic lens of criticism, sometimes rightly so. The adoption of robotics, especially autonomy, rides on digital data transactions and despite ever-improving security measures, some degree of vulnerability always remains. Since robots lack human intelligence or decision-making capabilities, any breach can be catastrophic, depending on how deep the scour is and can result in severe financial and human loss. Despite an array of remedial solutions, including multi-factor authentications, cryptographic algorithms and optimal human intervention, it is a daunting challenge to break the sentimental notion of the population and gain their faith in robotics.

Key Players

Recent Developments

- **Clearbot (Hong Kong).** Founded in 2019, after a long research history, clearbot has been making significant advancements with fleets of its AI-enabled autonomous robot that collect garbage from rivers and marine streams. A small size of 3 meters allows the solar-powered robot flexible maneuver inside and over water, even in narrower streams. Funded by Microsoft, the company is working on cleaning the urban waterways of river Gangas in Varanasi, India.

- **Port of Rotterdam (Netherlands).** Port of Rotterdam which is one of the busiest ports in the world, has recently conducted a pilot inspection on the port using drones manufactured by Avy. Live feed from long-range and high-speed UAVs was used to monitor water pollution, board-to-board and shore-to-board transshipment, hazardous substances, smoke, and soot and providing material for repairing on ships.

- **Seaclear (Europe).** Funded through the EU Horizon 2020, the team of researchers from Subsea Tech and several partner universities has designed an autonomous vessel that includes two remotely operated vehicles to clean water and scan the seabed, respectively. A floating USV hosts the two underwater vehicles and a UAV that enables air pollution detection. The ROV uses deep learning object recognition techniques to identify and pick litter. Currently conducting extensive testing, the development team aims to deploy the system commercially before the end of the project in December 2023.

SeaClear's multi-vehicle litter collecting system. Source: SeaClear

- **University of Southampton (United Kingdom).** In collaboration with the University of Edinburg, the research team has developed a squid-inspired robot. Its flexible bio-inspired design allows for quick and efficient swimming. Its soft and supple exterior makes it ideal for sensitive environmental applications such as safeguarding and relocating coral reefs and other near-extinct species. Once fully developed, 10-50 times more efficient propellers supported by eight 3D-printed flexible ribs make them a cost-effective alternative.

Future Prospects

Digital technologies are rapidly changing the way the maritime industry functions. Drone-powered surveillance and modern data collection and analysis techniques are quickly evolving and changing the industrial security and maintenance landscape. Stringent environmental regulation to arrest pollution and accidents means that the time to react has shrunk to the extent that pre-empts actions need to be in place. Thanks to superior processing powers, environmental resilience and improved maneuverability, **robots offer an efficient, quick, safe and potentially low-cost solution for monitoring**, surveillance, construction and maintenance work and pollution monitoring and cleaning functions on ports and water streams near shore. Already mature, the technology is not only improving on the technical performance front but is also **climbing up the ladders of adaptation at a larger scale**. The Adriatic-Ionian region can be seen as a slimmed-down version of the globe, housing every industrial problem of technical, environmental and political nature. No wonder it also offers every opportunity for robotics to grow in the region, as translated into several national and corporate initiatives. We **should expect a strong momentum over the next decade**, with most regional ports almost entirely adopting robotics for port and near-shore surveillance and maintenance-related activities with minimal human intervention.

Offshore Inspection and Maintenance

If operations on ports are varied and complicated, offshore opens a hornet's nest of hardships in the form of rough tides, rains, storms, temperature, pressure and aquatic life underneath. Increasing offshore operations to subsea platforms or oil and gas or renewable energy is causing increased demand for labour in construction, monitoring and maintenance in hazardous environments.

Hull cleaning and maintenance is a classical use case for robots away from the coast. The underside of the vessels that stay in the water need regular cleaning and maintenance to remove barnacles, dirt, corrosion and scratches. Conventionally performed by the divers, hull cleaning is a tedious and dangerous task. Modern robots, inspired by humans and sea creatures, are replacing human labour, offering safe and efficient vessel cleaning. **Real-time weather and ocean current monitoring** help predict the shortest and most energy-efficient transportation routes. Optimizing the ship's trim by advanced planning for weather has the potential to save up to 3% fuel.

Over the ship, the heterogeneous surface of large cargo and shipping vessels surface made with various materials in different colours makes **inspection for leakage and cracks** very challenging for human eyes.

Small ship inspecting robots (SIRs) with infrared sensors, wireless transmitters, and an overlapping wheelbase that allows them to move with a lot greater maneuverability are offering inspection capacities at a cost unattained in the past. Employing robots that can withstand high temperatures for **detecting fire and firefighting** over the ship with limited resources and trained personnel is a convenient application of robotics in the maritime industry and has caught attention in recent times. Oil and gas exploration has moved farther from the land, and wells that go deeper than 20,000 ft with a water depth over 1,000 ft are now a norm. Deep sea mining for rear earth minerals and offshore wind farms are also increasing rapidly across the ADRION region. No wonder these operations serve as the perfect breeding ground for robots to automate repetitive construction tasks that require higher mechanical strength over a prolonged period of time and need to survive a lot harsher environment. Robots today **perform drilling, erect platforms, lay geophysical survey cables and detect methane emissions**. Apart from saving on non-productive time and efficient performance, robots eliminate the need to provide housing, food, air-conditioning, and safety gear mandatory for human labour. Some oil and gas operators, such as Equinor in the North Sea, have taken it further and developed a **fully autonomous, crewless oil and gas platform**. The platform was delivered ahead of schedule at a cost 20% lower than estimated, which is an anomaly for First-Of-Its-Kind projects. Developed as a pilot, the platform doesn't compromise on safety and is operated remotely from the control room at the Oseberg field center 8km away. Equinor claims a potential reduction in CAPEX by 30% and OPEX by 50%. This seems a little too optimistic, but the benefits of autonomous platforms are undeniable. On similar lines are tethered crawler robots used to clean scale and biofouling from the surface of a windmill's monopiles. They can also carry a variety of inspection payloads, including wall thickness using ultrasonic testing and close visual inspection.

Equinor's fully automated oil platform Oseberg Vestflanken H, that hosts 11 wells in operation on the Norwegian Continental Shelf. Source: Equinor

Soft, tele-manipulative robots that provide a high level of dexterity and solid grip are proving extremely useful for biologists seeking to **study deep-sea organisms**. They are small-sized, require significantly less power, and are almost noise fee, resulting in a lower cost of sampling. Compared to rigid ROVs that may potentially damage delicate aquatic life during handling, the malleability of soft robotics allows safer and more effective interaction.

Promoters & Inhibitors

The application of robotics in the offshore environment has a more profound impact on operations. While they share some of the same drivers and barriers with the robotic systems deployed near shore, a few are unique to the offshore maritime environment.

Promoters

- **Increase in offshore oil and gas operations.** Surging oil prices, the Russia-Ukraine war, and ever-increasing energy demand will keep oil and gas thriving in the near future. However, the world recognizes the need to move away from the shore, and oil and gas manufacturers are spending more on offshore exploration and development of oil and gas, as well as carbon capture and storage in deep geologic reservoirs. Offshore operations are low emission, less disruptive yet fragile in nature and therefore will promote large-scale adoption of robotics.

- **Rapid scaling-up of offshore wind and solar facilities.** While onshore wind farms still generate the bulk of wind-generated electricity, offshore wind has rapidly increased and saw a nearly 60% jump between 2020 and 2021 globally. Although onshore development is expected to stabilize now, offshore installations are expected to accelerate further by several folds. Maximizing the life cycle of offshore wind farms demands quick and effective inspection and maintenance, supported by USVs, UAVs and gliders managed remotely.

- **Scientific interest in deep-sea ecosystems.** Oceans are pivotal to human existence as they have an intricate relationship with climate and food supply on top of the transportation they support. Over 95% of oceans are, however, still unexplored. Robotics is helping quench oceanographers' thirst to study the ocean’s chemical properties and biological diversity without venturing into the deep blues. Increasing curiosity to safely extract highly accurate data from deeper and farther waters to develop futuristic solutions will not only continue to push the increasing adoption of robotic technologies in the maritime sector but will bring significant investments to develop novel cutting-edge precision technologies.

Inhibitors

- **Lack of standardization of equipment and designed infrastructure.** Rigs and ships intending to host modern robots need standardized infrastructure to aid seamless adoption. Unfortunately, it has been a massive challenge since a typical offshore exploration project involves a complex conglomerate of various operators, service providers and manufacturers. Administrative regulations, such as by IMO and European Union, have addressed the issue partially. Still, an ideal harmonized standardization will potentially require a complete overhaul of production, procurement and installation – from equipment to project level.

- **Security and accuracy of sensors.** Offshore equipment is significantly more expensive and is subjected to severe environmental risks. Physical safety is paramount, as any malfunction on an unmanned planform may result in significant maintenance delays. Therefore, the adoption of robotics hinges on the accuracy of sensors installed on offshore platforms and the reliability of data transmission to the control center. Even a slight aberration sharply diminishes the viability of crewless operations.

- **Power-related challenges.** Most robots employed offshore are run on batteries and are not very energy-efficient. Much time is lost in transporting them to the docking station for charging, making the process quite inefficient. Energy-efficient, long-lasting and lightweight battery technologies must be developed and adopted to ensure unhindered, long-duration continuous operations economically.

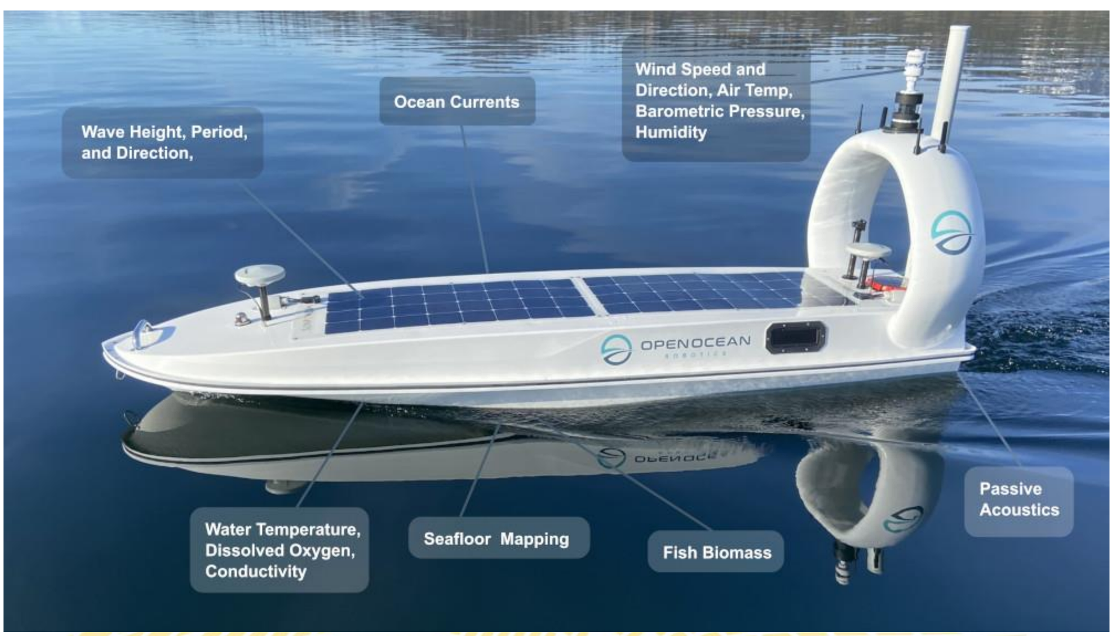
Key Players

Recent Developments

- **BladeBUG (United Kingdom).** The London-based startup develops robots for the inspection and repair of turbine blades. The six-legged robot that can crawl over the turbines and is equipped with non-destructive test and repair capabilities was developed using 1 million pounds of funds from Innovate UK. In 2021, the robot completed a remote lightning protection test on ORE Catapult's 7-MW Levenmouth Demonstration turbine off the coast of Fife, Scotland.

- **Eelume (Norway).** 2015 spin-off from the Norwegian University of Science and Technology (NTNU) has developed a snake robot in collaboration with SINTEF. They develop a modular 19 feet long robot whose slender body jointed by thrusters allows energy-efficient maneuvering, while both ends are capable of mounting tools such as grippers, cameras and scrapers to support an array of intervention and inspection tasks. Currently, at a demonstration stage, the company boosts a robust strategic partnership with Kongsberg Maritime and Equinor.

- **Open Ocean Robotics (Canada).** The company boosts a solar-powered USV for a long duration, up to months, of data collection and its real-time transmission to the control room through a custom sensor platform. Rightly named Data Xplorer, the vessel can travel up to 18 knots for short durations if needed and collect data on wave and wind direction, air temperature, pressure and humidity along with the ocean currents that can help in real-time route predictions. The USV also features several oceanographic sensors, such as fish biomass chlorophyll, turbidity, salinity, and dissolved oxygen knowledge, that can help understand and improve the ocean's aquatic life.



Data Xplorer, solar powered USV that collects environmental and ocean data. Source: Open Ocean Robotics

- **Nauticus Robotics (United States).** The company is founded by ex-NASA engineers and brings expertise from space engineering to ocean robotics. Their multi-purpose flagship underwater robot, dubbed aquanaut, is an electric power AUV/ROV convertible and can sustain up to a depth of 3,000 meters. Elastic joints and miniaturized load cells coupled with tension and infrared sensors allow for versatile data collection. Onboard image recognition and control help real-time processing with complete autonomy for service.

Future Prospects

Many countries in the EU, including those in the ADRION region, have announced several deepwater operations that will run at least until 2030, if not more. Similarly, offshore wind will continue with already a large number of ongoing operations and will require regular monitoring and maintenance as they age. As the industry increases its interference with nature, especially deep sea, aquatic life and habitat preservation will be of paramount importance. Extreme operating conditions and the fragility of marine life at disposal make offshore applications the most lucrative use case for maritime robotics. Despite some financial challenges related to equipment standardization and power availability, strong public acceptance will ensure that money keeps flowing for the innovation and development of robotics in offshore operations. **It will come as no surprise if the growth continues**. Almost all, if not all, offshore operations will be performed by robots by the end of this decade, with human supervision from the control stations based inland.

Autonomous Vessels and Ships

Deploying robotic technologies in the maritime industry has primarily been focused on bringing efficiency and safety to targeted segments. Still, a few players have started taking bolder steps toward an utterly autonomous ship. Essentially still an untested concept, advocacy of unmanned ships revolves mainly around reduction in accidents due to human errors, lower manning cost and more straightforward implementation of low-emission policies resulting in high ship efficiency. Astronomical growth in augmented reality (AR), AI and digital twinning supported by integrated control systems that can support seamless monitoring and control of offshore vessels' propulsion, maneuvering and communication that are managed by individual units from a central control room.

Entirely autonomous ships are still a little far out in the future. Rolls-Royce aims to develop remotely operated and fully autonomous unmanned ships that will employ cutting-edge sensor technologies and control algorithms for navigation and collision avoidance by 2030.

The Designing the Future of Full Autonomous Ship (DFFAS) consortium, led by NYK Group and comprises of 30 companies in Japan, has successfully conducted a 790 Km long trial of a **fully autonomous ship between Tokyo Bay and Ise Bay** over a 40-hour long voyage sailing for five days. This demonstration of 95 meters long, 750 tonne vessel navigating at a speed of up to 26 knots was part of MEGURI2040, a fully autonomous ship navigation project launched by The Nippon Foundation. The cargo ship named Suzaka was powered by Orca AI, an Israel-based firm that designed safety navigating and control systems providing real-time detection, tracking, and a 360° view, day and night. The consortium has been active, with several other pilots either completed or underway.

The Sunflower Shiretoko covered 750 km in18 hours of autonomous shipping between Tomakomai Port to Oarai Port in Japan. Source: Mitsui O.S.K. Lines

It is no surprise that IMO has already started developing a regulatory framework for Maritime Autonomous Surface Ships (MASS) to match the rapidly evolving technologies while improving the state-of-the-art risk assessment methodology. Kongsberg, the leading manufacturer from Norway, who has pioneered radar-based collision avoidance, is involved in several autonomous ship-building projects across Europe in line with MASS.

Promoters & Inhibitors

The momentum is extraordinary, with millions being pumped into the research and development of autonomous ships. This confidence is based on the glimpse technology has shown thus far in parts to make robotic systems work. The challenge now is to bring it all together to produce reliable and effective ships that are economically viable and several magnitudes higher in safety. Timing and scale of success will depend on the following promoters and inhibitors.

Promoters

- **All round efficiency.** Industry players that are piloting their programs today expect to scale up by the 2025-2035 timeframe. If today's projections are to be believed, the cost saving by then will propel adoption at scale. Full autonomy to the ship also cuts on several ancillary requirements such as crew decks, lodging quarters, kitchens, and medical facilities, resulting in either compact vessels or making entire real estate available for shipping. Autonomous vessels, therefore, can achieve higher fuel efficiency and thus lower the cost of transportation, with lower emissions per nautical mile.

- **Possibility of market expansion.** Perishable food items with meagre shelf life and products with relatively low-profit margins are still awaiting entry into the global market. With increasing globalization and demand in far-off lands pressing, aspiration to develop low-cost autonomous careers will continue to thrive.

- **Hydrogen and ammonia transport.** Shipping is the most cost-effective means to transport large quantities (>100 t/day) of ammonia over intercontinental distances exceeding 5,000 km. It could also be economical for smaller capacity and shorter distances if ammonia doesn't require conversion to hydrogen for end use. The growing hydrogen economy and interest in utilizing ammonia as a fuel will see increasing marine transportation of fuel as laying new pipelines tend to be costlier. Due to the safety and efficiency it offers, using autonomous ships to carry inflammable fuels has a strong value proposition.

Samskip and Ocean Infinity will develop hydrogen powered remote-controlled container ship to link the Netherlands and Norway. Source: Samskip

Inhibitors

- **Massive upfront investment.** Although operational savings are being quantified and projected, smaller companies may not have a strong appetite for significant capital investment in the early stages of their development. The initial investment is needed not just for the ship itself but also for the complete revamping of onshore maintenance, communication and monitoring infrastructure for fleet movements.

- **Uncertain regulatory guidelines.** The regulatory guidelines around autonomous vessels are still evolving. Ships can be built with different levels of autonomy, from semi-autonomous ships operating under human supervision to vessels enjoying complete autonomy under zero control. The current international maritime regulations are written around 'crew', and 'captain' and the liability them in case of any loss, accident or rescue. Autonomous transportation has already begun and is growing; the regulatory measures are, however, still awaiting, posing a threat in case of conflicts. This is particularly important for the Adriatic-Ionian region hosting a complicated checker box of international borders operated under different regulations. Vessel operators will hesitate to deploy autonomous variations in the area unless consistent guidelines are in place.

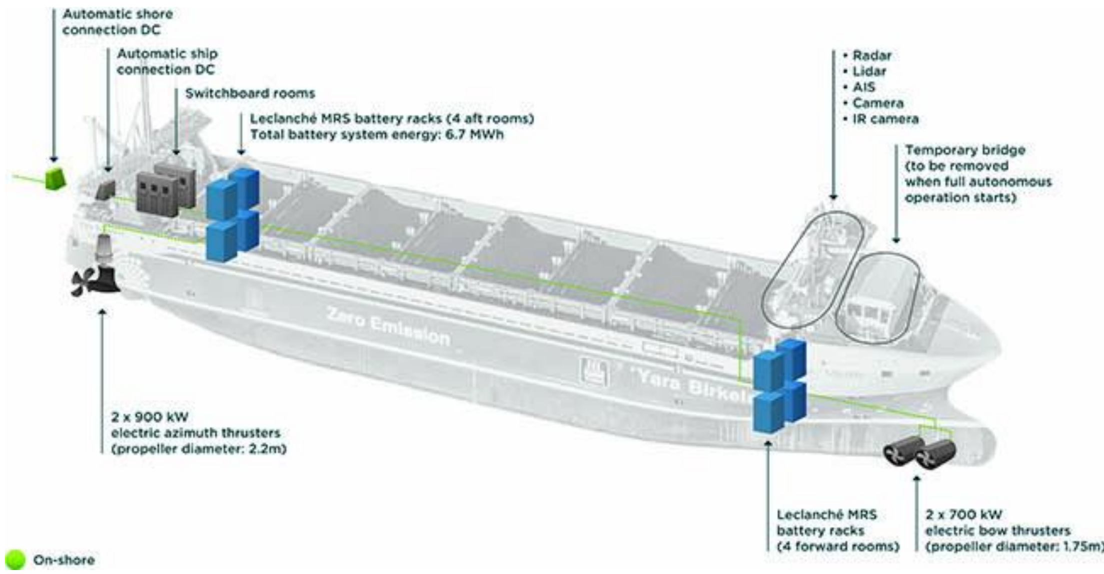
- **Missing human cognizance.** While the system is still in the evolutionary stages, the pilot projects and USVs are already churning out a vast amount of data. Number-crunching and fine-tuning using deep learning need to undergo the rigour of several stages of verification and assurance for a long time to prove data reliability at a scale equivalent to real-time operations. Deploying completely autonomous variations requires understanding and trusting the system's real-time decisions. Despite the leaps artificial intelligence and predictive machine learning algorithms have made, at least today, machines still lack human decision-making and cognizance. Getting operators, regulators and end users to accept complete autonomy without any human intervention will require unceasing convincing and, eventually, a massive mind shift.

Key Players

Recent Developments

- **Brodosplit (Croatia).** Located in the city of Split, Broadsplit shipyard started the construction of a completely autonomous ship in December 2022. The 23.95 meters long ship will use shipbuilding aluminum alloy to make most of the structural components, including the hull. Backed by the EU funding and technical partners Marine and Energy Solutions, the ship will support maintenance and operational activities, including firefighting, pollution control from an oil spill and managing dams. Given Broadsplit's strong history and robust program, we should see substantial progress in the coming months.

- **Yara International (Norway).** Touted as the world's first fully electric, autonomous cargo ship, Yara Birkland finished its first trial voyage in early 2022. Developed in collaboration with Kongsberg, the 80-meter-long ship is laced with sensors and cameras that can be controlled remotely from the coast if human intervention is needed. Running on 7MWh Lithium-ion cells from LeClanche, the ship estimates cutting CO_2 emissions by 1,000 tonnes each year. Yara will conduct further testing and data analysis until 2023 with an eye on getting certified by 2024.



Yara Birkland's propulsion system designed by Leclanche Marine Rack System. Source: Leclanche

- **ProMare (United States).** The research vessel dubbed Mayflower developed in collaboration with IBM, who provides AI controls and software for autonomous route-tracking, real-time analytics, rerouting, collision avoidance, and fuel-efficient voyage. The ship follows the transatlantic route, collecting data relevant to climate change and pollution. In 2022, the 50-foot-long boat, which can go up to 10 knots, completed its first journey from the UK to the USA, and while it fell a bit short on performance, the continued research will be pretty valuable in designing completely autonomous trans-oceanic voyages that need to be offshore for a very long time and adhere to maritime regulations.

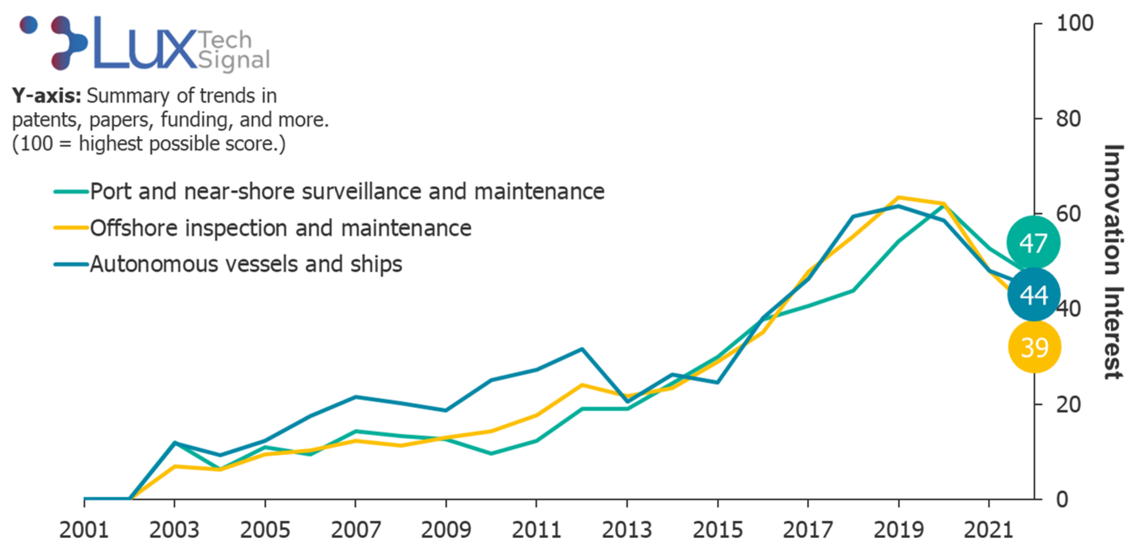
- **Rolls-Royce (Worldwide**). Rolls-Royce has partnered with Sea Machines to develop remote control and autonomous ship under their mtu NautIQ portfolio of vessels. Sea Machine is supposed to provide the control solutions to combine with Rolls-Royce's propulsion systems. The company has extended their offering with three new products - mtu NautIQ CoPilot, mtu NautIQ CoOperate and mtu NautIQ CoDirect, offering an increased level of autonomy. With the first stage, complete Rolls-Royce seems to be set on the course of manufacturing fully autonomous, ocean-going passenger ships by 2035.

This project is supported by the Interreg ADRION Programme funded under the European Regional Development Fund and IPA II fund.

Future Prospects

The apex of robotics in maritime, full autonomy, is still at its nascency. Still, the disruptive nature of the technology has led to remarkable progress in the last 7-10 years. However, handing out complete control to machines isn't the most popular concept. It will take multiple rounds of testing, refinement and demonstrations to get a green light from the regulatory bodies still evolving with the technology. Although small-scale applications, including cargo loading/unloading, maintenance, and river transport, will continue to rise without many roadblocks, **a large-size, 100% autonomous transportation or goods vessel beyond one-odd demonstration is unlikely for the next 10-15 years**. With the increase in ammonia and hydrogen transportation, fuel transport will be a more justifiable end-sue for fully autonomous vessels due to safety concerns. That said, it should not be doubted that the market share of limited autonomy to self-monitor, repair, navigate or communicate with the regulated, need-based human intervention will continue to grow.

Innovation Trends



*The **Lux Tech Signal** is a composite score, combining data in patents, papers, and funding, plus Lux Research's proprietary data. It quantifies the progress of each technology, against a maximum innovation interest score of 100. Changes over time indicate growing (or shrinking) innovation interest, while inflection points may point to commercial opportunities or challenges ahead.*

The concept of intelligent robotics in shipping is almost four decades old and can be traced back to Japan's intelligent ship computer simulation project in 1983, which ran for five years, but activities remained modest for the first couple of decades. The use of robotics across all businesses started to pick up around the dawn of the century, but credit for bringing it closer to oceans goes to [Kiva Systems] based out of

Boston, US, that first introduced remote control robot to pick and move shelves and boxes inside shipping fulfillment center warehouses. Motivated, initial research was focused on bringing robots to replace human labour for routine tasks in challenging environments.

The successful test of VolksWagen's self-driving car in 2005 provided a solid impetus for innovation activities in autonomous cargo vessels, but it was the rise of deep learning for image classification in 2012 that collectively bumped research in all things related to robotics, including those applicable to the maritime ecosystem. Concurrently, the Korea Research Institute of Ship & Ocean Engineering (KRISO) launched autonomous USVs for environmental survey and surveillance. At the same time, the EU kicked off Maritime Unmanned Navigation through Intelligence in Networks (MUNIN) in 2012.

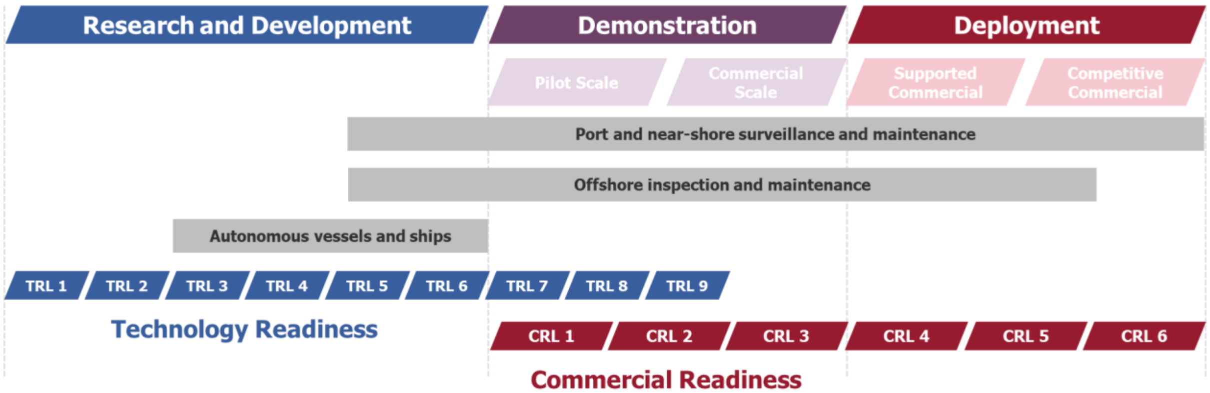
DNV's ReVolt project for battery-powered crewless ships for short voyages in 2013, Norway's AMOS in 2014 and Rolls-Royce's Advanced Autonomous Waterborne Application Initiative (AAWA) in 2015 kept the momentum ongoing in all segments of maritime robotics.

Innovation interest stalled around the 2019-2020 timeframe and has been on a slight declining trend in the last couple of years, indicating the technologies' maturity. Business activities, partnership deals and development announcements swiftly replace research activities and patents. In contrast, the center of innovations and patents is slowly moving towards enabling technologies, including material development, faster data processing, sensors and algorithm development. This coincides with the global pandemic stalling all activities but propelling the desire to make the maritime industry more autonomous and emission-free.

The continuous demand for the ocean's environmental preservation tied with the expansion of deepwater operations has resulted in many announcements for industry-led studies, pilot projects and full-scale operations. This will continue to grow as the maritime industry keeps on expanding its horizon and being one of the most prolific runway, the Adriatic-Ionian region will have a significant role to play as a testing and deployment ground for a bulk of activities in Europe to support, sustain and grow its economy.

This project is supported by the Interreg ADRION Programme funded under the
European Regional Development Fund and IPA II fund.

Technology Status



Alternative and Competing Technologies

Manual labour, fuel-powered mechanical work using a machine controlled by human force through a gear assembly, and operator's decision-making are the three technologies with which robots face competition. The first and foremost place where robotics finds applications is the most basic and repetitive maintenance and operation tasks at the port and on the ships. This includes manual monitoring, data entry and processing, painting, watering, cleaning and manual excavation. Another application area is carrying out machinery-based tasks such as welding, underwater hull cleaning, and drilling, generally performed by mechanical force but requiring manual controller working in harsher conditions. The biggest prize and most valuable competitor that still edges out robots is human intelligence and decision-making capabilities. Still, with the advent of AI, robots are making slow intrusions into this space, not necessarily to phase humans out but to let them focus on things that require more attention while still carrying out voyages with acceptable accuracy.

Commercial Outlook

The economic benefits of robots over time are founded on safety, operational and fuel efficiency, and reduced downtime across industries. However, a complicated mix of operational activities and different levels of autonomy means that quantifying the commercial benefits of robots, especially in port and near-shore maintenance, is not well reported. However, there is a uniform agreement with the understanding that while robots require high upfront capital expenditure, the benefits offered by the operational expenses by as much as 55% payout for the CAPEX rather quickly.

Direct economic savings shouldn't be the only indicator of savings robotics offer in offshore operations, maintenance and surveillance. Elevated safety concerns and almost inoperable conditions make robots not a choice but the only viable option. A 2021 study by the Offshore Renewable Energy

Catapult reports that robotics and automation in near-shore (<150 km) wind farms can reduce the OPEX by up to 9.5% in the near term while increasing autonomy may push it towards 16.5% by the 2040 timeframe. The models arguably make some liberal assumptions, and while the numbers may be slightly inflated, the economic value proposition is undeniable. Cost-saving by real-time hull fouling monitoring, cleaning and coating have the potential to save up to 7-12% on fuel costs for cargo and passenger ships. The oil industry, the largest adopter of robots offshore, generally refrains from quoting the cost savings, as they are directly equated with the sensitive topic of labour force redundancy, but indirect interpolations hint at the vast potential of cost-cutting of billions of dollars in wages only.

Autonomous ships offer direct commercial benefits over conventional ships that include efficient use of space, manpower and fuel, as well as indirect benefits such as optimization in operations based on real-time data and safety against human errors. It is too early to quantify them at this stage as the technology is still in development, but as activities grow, economies of scale will bring the cost down, further increasing the economic benefits. A recent study conducted at the Gdynia Maritime University in Poland summarizes the literature-based studies and prediction of various degrees of cost savings by deploying autonomous vessels in the maritime. While it highlights the uncertainties due to a lack of real-world data, the cost saving on operations is consistent throughout all studies.

Conclusions

The maritime industry faces stiff challenges to meet the global demand for transport and travel while under the pressure of navigating its way around the worldwide pandemic scare, lack of expert workforce and evolving environmental imperatives. Ships now need to carry more goods quicker, farther and safer; Oil rigs and windmills have found a new home next to delicate aquatic life.

Thankfully, emerging trends in energy transition and digital transformation, dubbed industry 4.0, have given a powerful impetus to the application of robotics across the entire value chain of the maritime industry. Starting from seamlessly carrying out maintenance and surveillance operations at ports to swiftly integrate with the logistics on one end and voyager fleet on the other, to safeguarding the shoreline against pollution-related threats such as oil spills, illegal fishing, leading up to oil and gas operations in the deeper shelf, the playing canvas for robots has grown and will continue to grow. Although full autonomy will require a significant shift in mindset and much refined regulatory control to grab a sizable market share, rapidly evolving technological leaps and industrial push will continue to impregnate robotics further in the DNA of the maritime universe. **The Adriatic-Ionian region sits at a cross-road where regional demand meets, technical knowhow of the EU-led projects and commercial experiences from Norway, which allows the host nations to not just employ and leverage but to develop, test, scale and commercialize new robotic technologies for their oceans**.

ICT: Horizon Scanning

Why it Matters

Improving competitiveness, **safety**, and **security** of European shipping is a major objective of the EU Maritime Transport Strategy, which in turn shapes the requirements for upgraded maritime transport information management. In recent years, advances in information and communication technologies have created a demand for new forms of surveillance and information management systems; these are increasingly driven by policy and governance addressing safety, security, and sustainability.

European shipping must remain at the forefront of innovation to stay competitive and sustainable. There is therefore a need to integrate shipping into the overall transport system and to improve vessel safety. More **efficient ports** and their **connection to the hinterland** are also needed as well as the provision of **real-time data** for ship operations from shore-based services. **Digital information** exchange technologies between the different actors involved in maritime transport, including automated data exchanges, have undoubtedly the potential to deliver huge opportunities and benefits.

The incorporation of ICT has led to the development of ships equipped with **new** and **advanced sensors**, which have improved **ship-shore connectivity**. These ships use **advanced software** tools and **algorithms** for carrying out and analyzing various ship functions. Moreover, the use of **Big Data, Internet of Things**, **Cloud Computing**, etc. has led to the development of new ways to collect, store, and process valuable data obtained from different sources. This, in turn, has led to an improvement in the efficiency and safety of ships. The use of ICT helps in the identification of faulty systems in ships and suggests corrective measures for them, it also leads to increased situational awareness and reduction in operational risks. Also, ICT adoption, changing the way ships are designed, built, and operated as it not only enables smart maintenance of ships but also leads to their automation and remote operations. (European Union, 2022; Ichimura et al., 2022; qinetiq U. of S. Lloyd's Register, 2017; Q. U. of S. Lloyd's Register, 2014; Michael Papageorgiou, 2020).

In the maritime industry, a reliable and **efficient communication infrastructure** and **protocols** are crucial for safe and efficient operations. Multiple technologies and protocols are utilized to facilitate effective transmission between vessels, ports, and other stakeholders. The most commonly used communication infrastructure in the maritime industry includes **VHF** (Very High Frequency) and **MF** (Medium Frequency) communications, which are used for short-range communications between vessels and with **shore-based stations**. **Satellite communication** (SATCOM) systems are widely used for **long-range communication**, data transfer, and internet connectivity. This technology is a valuable tool for the maritime industry, enabling direct communication between devices through the use of satellites as communication channels. This technology has historically been use by governments and large corporations, but advancements in miniaturization and materials have enabled privately funded nanosatellites and **CubeSats**, making satellite communication a viable alternative for **remote IoT use cases**. Additionally, there is an increasing demand for cost-effective broadband data and internet voice services. (MarketsandMarkets, 2020b) Remote satellite systems offer a maritime satellite communication service to recreational vessels and commercial fleets. Satellite communication promises **high bandwidth at a lower cost**, making it a new alternative for use cases requiring remote connectivity. In the maritime industry, it provides a reliable means of communication in remote areas. Although costs are still in flux, with established companies currently dominating the commercialization of the technology, new ventures are driving costs down and may scale fast. (DNV GL, 2015) (Lux Research Inc, 2022) (MarketsandMarkets, 2020b)

OneWeb by SpaceX and Google Loon, announced new projects, are believed to be able to bring structural changes to the maritime industry.(MarketsandMarkets, 2020b)

With the advent of **4G** and **5G networks**, some vessels and ports are starting to use these cellular technologies for communication, especially in coastal areas where coverage is available. The **5G technology** offers enormous potential in the maritime sector, enabling high-speed connectivity, low latency, and extended coverage, which can enhance **safety**, **efficiency** and **automation of operations at sea**. This could have particular significance in the ADRION region, where land is rarely more than 50 nautical miles away. However, these technologies are not yet widely adopted in the maritime industry due to the limitations of their coverage areas and the need for high-speed data transfer. Communication protocols include Global Maritime Distress and Safety System (**GMDSS**) and Automatic Identification System (**AIS).** These protocols play a crucial role in navigation, search and rescue, and vessel traffic management. The maritime industry continues to **evolve** as **new technologies** and **protocols** emerge. (Lux Reasearch Inc, 2020; MarketandMarkets, 2021b)

The utilization of **sensors**, along with communication infrastructure, has created new possibilities in the realm of **Internet of Things** (IoT) **technology**. These advancements have enabled various industries, including maritime, to collect and analyze data in **real-time**. Through the implementation of IoT technology, maritime companies can enhance their operations and increase **efficiency, safety,** and **automation**. Nonetheless, the adoption of IoT also presents new cybersecurity risks that need to be considered and addressed to ensure the safety and security of the maritime industry. At a macro level, IoT-enabled sensors can assist shipping companies in **tracking the location** of their ships, while at a micro level, they can provide live updates on **cargo containers** and monitor production and delivery data. (MarketsandMarkets, 2020a)(MarketsandMarkets, 2018) (MarketsandMarkets, 2015)

With the integration of 5G, WiFi and new-generation satellites, as well as conventional marine radio communication networks, we will see transformation everywhere. The integration of ICT has paved the way for **advanced data analytics** and **artificial intelligence (AI**) techniques such as **big data analytics**, **machine learning** and **AI**. These technologies have immense potential to transform the industry by enabling real-time data analysis and decision-making, optimizing vessel performance and maintenance, and enhancing safety and security. With further development of ICT, the maritime industry is poised to reap even greater benefits from these advanced technologies in the future. (Schnitger Corporation, 2021)

However, it is important to recognize that the adoption of these technologies also presents new challenges, for instance in the areas of **cybersecurity** which must be addressed to ensure the safe and secure operation of the maritime industry. Additionally, the rapid digital transformation brings new **threats** and **regulatory** requirements that must be taken into account (*Maritime Cyber Security - DNV*, 2021).

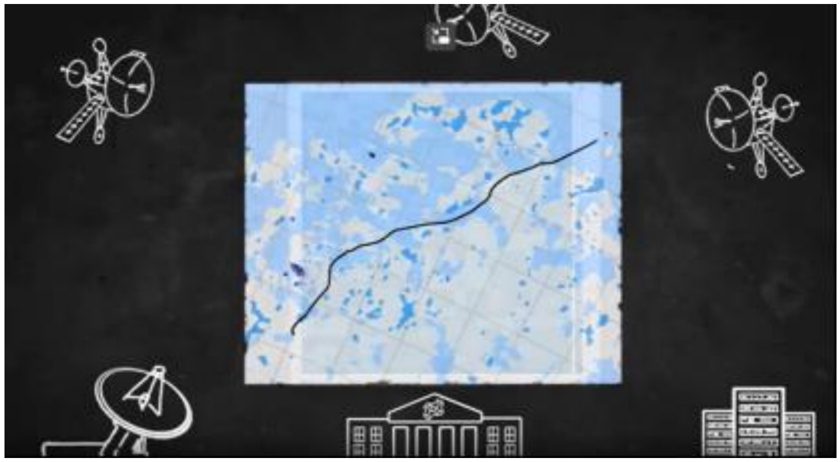
Value Proposition

Remote operation is the norm in the marine industry. Communication technologies have therefore been crucial for situational awareness and exchanging information between different parties. The marine industry was an early adopter of some traditional communication technologies, such as radio. The capability to connect, communicate and interact with different parties and systems at sea is unfortunately much more difficult than on land. It also comes at a higher price. **Radiocommunications** and **satellites** are examples of **state-of-the-art technologies**. As the technologies advance, we will begin to see fast market expansion and transition. For instance, maritime in-service units are expected to double in 15 years.

- **Satellite communication:** The maritime satellite communications industry is undergoing a transformation with the emergence of new technologies. A mix of established players such as **Inmarsat**, **Iridium**, and **Telesat**, as well as startups like **OneWeb** by SpaceX, **Google Loon**, and **Myriota,** are driving this innovation with a focus on low cost and increased connectivity. These companies are serving various industries, including mining, oil and gas, etc.. by providing remote location monitoring and supply chain tracking. The deployment of satellite systems from established players like Inmarsat and ViaSat has **increased satellite capacity supply** in **maritime regions**, leading to cheaper rates. This has enabled the use of modern wireless telecommunications systems in the maritime sector, facilitating **improved crew communication** and **supporting various onboard activities**. The demand for more bandwidth for enhanced connectivity is increasing with the availability of new satellite systems, and the number of active VSAT solutions is growing. The maritime industry is seeing an impressive development of wireless communication and data-intensive applications. **High-Throughput Satellites** (HTSs) using **Ku-band** are being launched in the market, alongside technology advancements such as **gyro-stabilized ground terminals**, **high-speed broadband modems**, **multi-frequency dish antennas**, and all-plastic designs that can withstand harsh offshore environments. The shipping and maritime industry are favoring **Ku-band** for their specific needs, while the **oil and gas sector** has been using **C-band services**. Companies are increasingly **adopting VSAT**, which is a comparatively less expensive technology that meets the communication needs of various end-users and maritime satellite communication service providers. VSAT services provide a guaranteed level of bandwidth for data or voice transmission. (Lux Research Inc, 2022; MarketsandMarkets, 2020b)

Maritime satellite communication is increasingly important, as officers, crew members, and ship owners require reliable communication services while sailing. The completed [maritime projects]() of the **European Space Agency**, which revolve around maritime services based on the integrated utilization of space-based systems, are of interest to a broad range of user communities and industries. Commercial vessels, including container ships and oil tankers, need satellite communication to stay connected to their main offices and support crew welfare activities. People onboard a vessel or on a platform rely on communication technologies to be socially connected to families and colleagues onshore. However, **communication technologies** allow for **emergency calls**, **geopositioning**, **marine-life tracking**, and **disaster warning.** The increasing diversity and capability of communication technologies will enable the acquisition and connection of data from different sources, representing a key to open the big data door.

- **Geo-positioning and collision avoidance:** The role of emerging technologies in geo-positioning and collision avoidance is becoming increasingly important, especially in the maritime sector. Communication technology is crucial for improving these areas, allowing ships and vehicles to navigate oceans and waterways with safety and efficiency. Among the most promising technologies are **LiDAR**, which uses lasers to create **3D maps** and can help detect obstacles and avoid collisions. **Artificial Intelligence** can analyze large amounts of data, identify patterns, and make informed navigation decisions. **Augmented Reality** can provide real-time information to ship crews about their surroundings. **Blockchain** can improve the accuracy and security of navigation data, reducing the risk of collisions and other incidents. Overall, these technologies have the potential to transform geo-positioning and collision avoidance, making navigation safer and more efficient in various industries. Among the examples of projects in the maritime sector that use enabling technologies, we can mention the Orca AI project aims to provide assistance systems for ports and offshore vessels (MarketsandMarkets, 2020a). The project combines sensor data from thermal and ultra-low-light cameras to add image recognition to positioning systems and maritime radars. This image recognition is powered by an ML algorithm, allowing for **collisions to be avoided** along with information overload in the ship's bridge when navigating busy waterways (Palmejar & Chubb, 2022).



Another project, Map Borealis by start-up Drift&Noise, is using satellite data to optimise the route across the Arctic Ocean and save considerable amounts of time and money in the process.

- **Marine-life tracking:** In the coming decade, several ICT technologies are expected to play a key role in improving the tracking of marine life. This will include the use of **more advanced satellite technology,** which will provide higher-resolution imagery and better coverage of remote areas of the ocean. Wireless communication systems will also become more prevalent, allowing for real-time data transfer between different devices and systems. In addition, the development of more advanced sensors and underwater **robotic systems** will enable more accurate and comprehensive monitoring of **marine life**. These **sensors** will be able to collect data on everything from the movements and **behavior** of individual animals to the **health** of entire ecosystems. This data will be analyzed using more sophisticated **machine learning** and **AI algorithms**, allowing for more accurate and insightful predictions about the health and **well-being of marine life**. Overall, these emerging ICT technologies will enable more effective tracking of marine life, leading to a better understanding of the complex and interconnected systems that make up our oceans.

- **Disaster warning and distress call** are critical for ensuring the **safety** of maritime operations. In the future, the use of advanced technologies such as **AI, ML, IoT,** and **5G networks** is expected to revolutionize the way these systems operate. AI and ML can analyze data from various sources to detect potential hazards and predict accidents, improving response times in emergency situations. **IoT devices** such as sensors and beacons can monitor ship systems and crew health, transmitting data in real-time to provide early warnings of potential hazards. **5G networks** can offer faster data transfer rates and lower latency, enabling real-time transmission of data and video feeds. By 2030, these technologies are expected to become more widely used, enabling faster and more accurate warnings of potential hazards, improving response times, and ultimately saving lives at sea.

- **Enhance efficiency in ports.** Governments around the world are implementing various technologies, including big data, artificial intelligence, and the Internet of Things (IoT), to digitalize the ports sector. This implementation not only makes ports smarter, but also ensures they are more sustainable and environmentally friendly. IoT in ports improves **efficiency, manages traffic, increases throughput,** and reduces **carbon emissions**. This growing adoption of Industry 4.0, which integrates physical manufacturing and operations with smart digital technology, is creating a more comprehensive and connected ecosystem. Through the use of technologies such as **IoT, cloud, AI,** and **blockchain, a cyber-physical network** is created in ports, allowing real-time data to flow to different stakeholders and enabling the collection of data for predictive modeling. Real-time data exchange allows **smooth traffic flow**, increasing the throughput **capacity and efficiency** of the port. With the help of AI and IoT, data is captured to create a digital twin model of the ports, helping authorities to better control and predict various activities more accurately, and to ascertain the time for **predictive maintenance** more accurately, **saving maintenance costs** and **reducing downtime** (MarketandMarkets, 2021b; Wärtsilä, 2020).

*Source: **Maersk** and Ericsson collaborate for IIoT success story (internetofbusiness.com)*

Maersk Line, a global container shipping and logistics company, is able to more cost-effectively manage container delivery and content preservation, as well as provide data transparency to its container customers. Based on a sensor network managed by Ericsson and a satellite network provided by

Globecomm, Maersk can track the condition of its cargo as wellas the status of its fleet, including the fuel consumption and electric condition of each vessel.

The implementation of IoT in ports has revolutionized modern shipping, as seen by the remote handling of cranes and increased cargo handling capacity. The **Port of Rotterdam** has also adopted IoT, with the creation of a **hydro/meteo IoT** network that provides precise data for shipping planning and management. The ship-to-shore communication movement has played a crucial role in the rise of IoT in shipping, as seen in the increased efficiency and productivity of modern ports.

*Envision Digital and **Port of Antwerp** to develop green port.*

General Electric (GE) was awarded a contract to create a digital twin of the **Port of Antwerp** in 2018. GE has effectively created a **digital twin** of the port using its **IoT tools**. This replica mirrors the port's operations and conditions, from ship movements to weather to water depth. Analysis of the digital twin is being used to track operations in real time, run test scenarios, and improve efficiency. The **Port of Hamburg** in Germany implemented a smart port initiative using big data analytics, IoT, and AI by improving logistics, adding intelligent railway points through sensors, harnessing shore power from renewable energies, and even providing an option to find free parking spaces. **Trelleborg**, a smart port service provider, incorporates docking, mooring, and environmental systems into a reasonable and simple-to-use MM (Marine Monitoring System) using IoT. This improves safety and improves the efficiency of operations by providing real-time data to the right people at the right time.

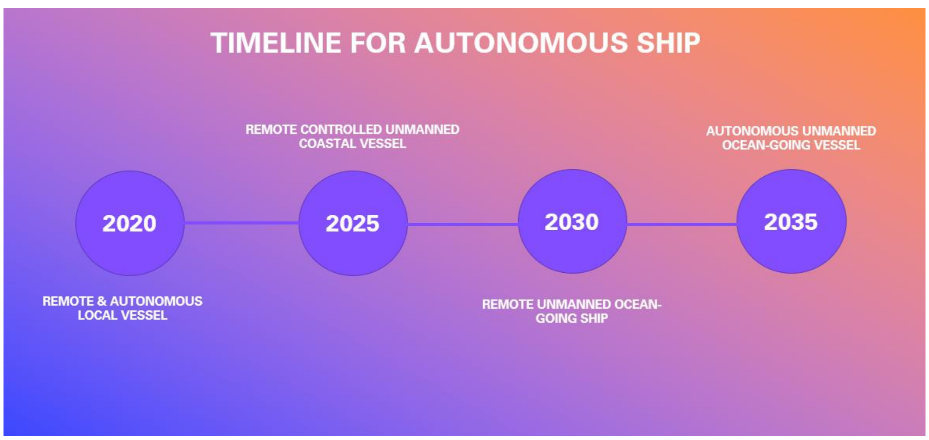
- **Monitoring of marine vessel:** Real-time monitoring of onboard systems using data from connected sensors and unified platforms, enhances the operational efficiency of marine vessels. IoT technology enables condition checking and remote monitoring of critical equipment, improving system **reliability** and **safety**. Ship variables such as **location**, **temperature**, **shock**, tilt of ship **components**, and **humidity** in ship compartments are continuously **monitored** and sent to control centers or shipping company offices. Continuous developments are being carried out in **IoT** technology using **deep learning computers** and **high-volume data analytics**, which are expected to further contribute to the effective management and performance of marine vessels including continuous monitoring of the status of the vessel and improving **predictive maintenance** to reduce the failure of machines or their parts. Integrating the IoT system with an **Augmented Reality** application for remote assistance, it is possible to bring on board all the knowledge and support needed to solve any failure or misfunction (Wärtsilä Corporation, 2018).

*The **LESS project** in the FVG region aimed to improve the energy efficiency implementing advanced monitoring and control systems.*

Fuel costs represent a significant portion of total ship operating costs, accounting for as much as 50-60% depending on the type of ship and service. To reduce these costs, sensors and monitoring equipment onboard can **collect vessel performance** data and send them to the main office on shore, which can provide the ship master and chief engineer with guidance when planning the most energy-efficient route. By identifying the **optimal speed** and **engine configuration** for each leg of the voyage, considerable amounts of fuel can be saved, and carbon emissions can be lowered. Many AI projects focus on optimizing processes and routes, and as a welcome side effect, they also help reduce fuel consumption.

- **Optimises voyage planning and reduces fuel consumption:** Many AI projects focus on optimizing processes and routes, and as a welcome side effect, they also help reduce fuel consumption. However, it's crucial to recognize that energy efficiency is also an essential aspect of these projects in their own right. Since 2018, **Stena Line** has been utilizing **AI** to **reduce energy consumption** on its ferry route between Gothenburg and Kiel. By analyzing data on weather, currents, and other variables, the company can identify the most efficient route at any given moment. Test results indicate potential fuel savings of up to 3%. Another example is **Marine Digital**, a German start-up that offers a fuel optimization system. Their system leverages ship and environmental data to optimize routes through automated processes (Deepsea, 2022).

- **Autonomous Ship:** Digital marine automation systems are expected to be the next advancement in the field of autonomous ships. These systems optimize the use of sensor information to enhance vessel safety, offer simulation capabilities for efficient vessel route planning and onboard training of crew members, and are based on the Mobile and Wireless Forum (MFW) principle. **Sensor fusion** solutions that incorporate inputs from different sensors, **control algorithms** for navigation and **collision avoidance**, conning systems for monitoring routes, and connectivity solutions are all integral parts of autonomous ships (Appen, 2021). **Autopilot systems** are being developed for precise steering performance and optimized handling, while mooring control and monitoring systems provide information about approaching speed, under-keel distance, and stern positions. **Navigation radar servers** (NRS) are replacing **automated radar plotting aids** (ARPA), and **electronic chart display** and **information systems** (ECDIS) are available in a client/server configuration. Communication systems are critical for internal onboard communication and external communication, which involves the integration of the Global Maritime Distress and Safety System. (MarketsandMarkets, 2020a). Here are two examples of projects developed in Europe: **AUTOSHIP** e **CAPTAIN AI.**



Autonomous Ship Roadmap 2020 to 2035 (Rolls-Royce plc, 2016)

Technological advances including artificial intelligence, the Internet of Things, blockchain, autonomous ships, and satellite technologies have the potential to maximize efficiency in the autonomous ships market.

Increasing demand for autonomous ship is expected to drive the demand for artificial intelligence during the forecast period: AI allows the machine to learn from experience, intercept new inputs, and perform human-like tasks. Technologies like machine learning and computer vision are used to train computers to perform specific tasks by processing large volumes of data. AI is gaining momentum as it can add intelligence to the existing ships. AI systems need highly effective and efficient hardware and software to display intelligent capabilities similar to the human brain. The software integrated into the system is responsible for carrying out complex operations and provide learning capabilities.

Information and Communication Technologies are essential for the development of modern society. While their adoption poses some challenges, these can be seen as opportunities to improve and overcome obstacles. The constantly evolving nature of ICT means that organizations must stay **up to date with the latest advancements**, which can lead to **continuous learning** and **growth**. Constraints such as **cybersecurity**, **data protection**, and **data integrity** can incentivize organizations to prioritize solutions that enhance the **security** and **integrity** of their **data.** While addressing these constraints may require significant investment, it can also lead to better processes and **stronger data management practices.** The shortage of talent with the specific skills needed for implementation highlights the importance of **investing in education** and **training programs** to develop the necessary **skills**. The lack of awareness about advanced services and reliance on high-cost equipment can encourage organizations to seek out alternative solutions that may be more efficient and cost-effective. By carefully considering these challenges and constraints, organizations can develop **strategies** to overcome them and successfully adopt ICT, **leading** to **improved processes**, **increased productivity**, and **enhanced competitiveness**. (Lambrou et al., 2019; Marios Miltiadouv, 2021; Thematic Technology Group TTG4, 2016; Tijan et al., 2021; Wärtsilä Corporation, 2023)

ICT: Analysis

Maritime ICT is not just an essential function but is **rapidly evolving** to keep up with the need for fast and accurate transfer and processing of enormous volumes of data generated and acquired at sea. As the whole system is increasingly being connected through the technology enabling the flow of information, instructions and operations, ensuring the security, usability and ease of communication becomes paramount. The vital technological levers that need to be watched out for, improved upon and developed to form a robust maritime ICT are founded on three pillars of **safety**, **speed** and **proactiveness** are listed below.

- IoT Security
- Predictive maintenance
- 5G communication

IoT Security

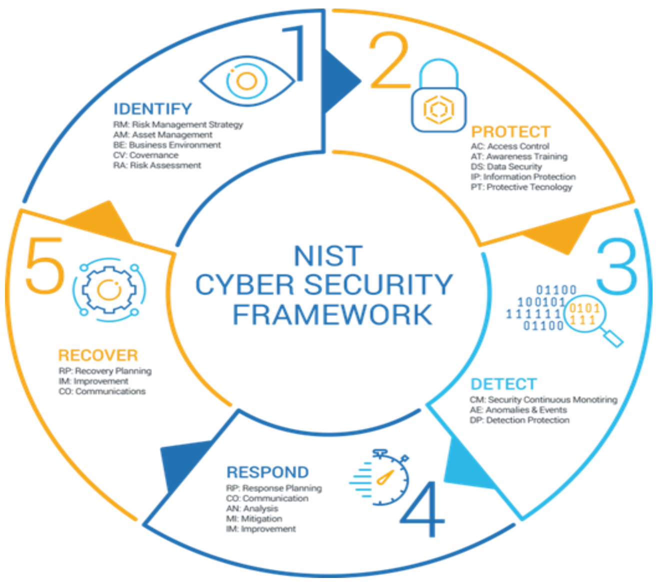
Autonomous or not, ships are getting smarter, and the expectations are increasing daily. Operators are under pressure to deliver efficient, streamlined services in an increasingly competitive maritime supply chain and less-forgiving environmental concerns. The **Internet of Things (IoT)** can support the concept of an intelligent vessel for a **situation-aware**, **sustainable** voyage. The IoT also improves connectivity between technical systems to improve automation and remote services. Integrating IoT with new communication technologies like 5G **enables increased use of sensors, faster tracking, and improved inspection** and analysis. Robots and automated systems are integral to IoT technologies, and as they continue to grow, ensuring the sanity of the IoT will be critical to swift operation.

Every IoT device is **vulnerable to cyberattacks**. As the IoT becomes ubiquitous, so do associated vulnerabilities that attackers can exploit to compromise the devices, vessels, and infrastructure. Most device developers, and especially maritime operators who adopt IoT devices, more often than not, either **lack the onboard security measures**, such as Secure Sockets Layer (SSL) certificates, or simply overlook the importance of it under pressure to get products to market on short timelines. This has resulted in disastrous security breaches originating from IoT devices, eventuating in the emergence of a market for security technologies focused on IoT devices and networks.

While IoT security parallels IT security in many ways, there are fundamental differences between protecting IoT systems and protecting IT systems, and therefore, the technologies and strategies for IoT security are different from those of conventional IT cybersecurity – although many IoT security solutions are inspired by and adapted from IT environments. In recent times several regulatory authorities, such as the National Institute of Standards and Technology (NIST) in the U.S. and the European Telecommunications Standards Institute (ETSI) in Europe, have developed **IoT security frameworks** to design, implement, and achieve basic security in IoT devices and surrounding systems. Although they differ in structure, their core guidance cross-references each other. The IoT security risks in the maritime are not drastically different from those in other sectors; their impact may be more significant given they sail in international waters crossing borders frequently. Recommendations from the International Maritime Organization (IMO) are, therefore, in alignment with the NIST framework.

Specific to maritime, IoT security breaches can have a more severe impact in the form of **delays, piracy, and collisions** resulting in loss of goods and life. A robust IoT security system is built upon five core functions; **identify, protect, detect, respond** and **recover**. Identify focuses on understanding the devices and data being used and their risks by employing software that identifies and gathers information on all IoT devices connected to a network without physical intervention.

Within the protect function, a more comprehensive range of approaches such as hardening, data protection, and access control are employed. While hardening refers to making the system more resistant to tempering by altering source codes and binary files or reinforcing trustworthiness via hardware like a trusted platform module. Distributed data fragmentation and cryptography are the most widely used data protection methods that require multiple nodes to work in tandem to reconstruct the key. The last bit of protection is done via authentication and authorization for access, more commonly known as Identity and Access Management (IAM), which verifies a device or user before granting access to the IoT system. Firewalls and data diodes, generally are, but not always, purely software-based, comes into play when the system needs protection from the outside world. This is particularly important for devices that continuously transfer data over the web and face consistent theft threats.



NIST's IoT security framework. Source: [Thales]

Intrusion detection that may operate at the network level, the application level, the device level or over a combination of these forms the 'Detect' function of IoT security. This is achieved via thorough analytics ranging from simple malware detection to using AI to identify anomalies. In an attack that is in process, IoT security needs to be equipped with response functionalities to react against the incident, gather and analyze data, contain and mitigate damage, and to the end of self-destruction to protect data security. Eventually, a well round IoT security system consists of provisions such as backup and restore for shipping systems to recover from a cyber-event.

Promoters & Inhibitors

The growth of IoT in maritime has brought with it enormous security risks, which affect the operations and life associated with it. IoT security has usually been playing the catchup game resulting in a series of high-profile and costly breaches. IoT security has therefore gained tremendous momentum in recent years. While factors behind this enthusiasm are plenty, there are some roadblocks IoT security will need to move out of its way.

Promoters

- **Adoption of robotics and autonomy.** As the application of robotics continues to make inroads into maritime operations at an increasing level of autonomy, they also bring a much-increased volume of digital connections. Transfer of data and instruction between offshore robotic devices and inland control units is seeing a meteoric rise, followed by a flurry of announcements to complete autonomous voyages. While integrated IoT-based devices connect these components to improve operations and monitoring, they are susceptible to cyber risks and subsequently promote the development of improved IoT security protocols, guidelines, and equipment.
- **The boom of AI and blockchain**. Within IoT security, artificial intelligence (AI) is most commonly used in anomaly detection systems to achieve higher accuracy than heuristic-based models, employing deep learning approaches. They are also instrumental in route optimization leading to an increase in fuel efficiency. Conversely, blockchain finds applicability in cryptographic distributed security control, such as in the IAM system, by creating a consistent and transparent digital ledger of transactional activities along the IoT processes. Blockchain, therefore, can prevent distributed denial-of-service (DDOS) attacks against IoT devices. However, it is essential to appreciate that the value proposition of blockchain in IoT security is still murky despite the trend, given it can still be quite complicated to implement for some operators.
- **Improved mindset and knowledge of human-IoT interaction.** Small, convenient, and cheap IoT devices and cloud-based platforms at the workplace and other daily walks of life have created a shift in the mindset over the last few years. Acceptance and ease of operation, clubbed with improved designs of the IoT systems, and the associated safety features, have come a long way – leading to an increase in crew members now skilled to handle the equipment easily. Appreciation for collaboration between machines for performance enhancement is slowly taking over the notion of machines replacing humans. As this understanding grows, IoT and the enabling security functions will expand.

Inhibitors

- **IoT security is defensive.** Pervasive IoT will exacerbate the security threats already faced by the maritime industry and peg back the onslaught of new cyber-attacks. However, by its very nature, security is defensive, so IoT security was never to be “solved”. Digital transformation will continue to bring new types of vulnerabilities more often to be chased by security improvements. This is particularly important to machine learning, where slight perturbations to input may result in incorrect interpretation, especially when human oversight is missing. Not necessarily a valid enough reason not to adopt IoT security, but this can cause a dip in enthusiasm to deploy security procedures in place, especially when complete overhauls require high investment.

- **Subpar level of security for the connected devices.** Market competition and technological advancements have improved the quality of security and forced them to embed security in product design and development. However, vulnerabilities outside the boundary of the device still remain, falling in the “not my problem” connector-pit between two devices. Developers or those adopting the technology need to consider security not only within the boundaries of a device but also in the ecosystem around it. The ever-evolving vendor landscape with a vast regional, market and regulatory variation, particularly in a diverse area such as the ADRION region, makes it harder to abate this threat.
- **Lacking global security standards.** Despite the astronomic rise of IoT applications in the maritime industry, legislation that governs IoT security remains fragmented. While NIST, OCF, and ESTI have become quite active over the last couple of years, the adoption is not yet up to an acceptable level. Thankfully the industry and users understand the need for securing interoperability within the IoT and network security for the communication technology supporting it. Consequently, they need to push for bespoke IoT security solutions rather than picking off-the-shelf variations that have a higher affinity to risks**.**

Key Players

Recent Developments

- **Adacom (Greece).** Adacom develops SSL/TSL certifications and protocols for reinforcing security for data sharing between IoT devices. The protocol uses asymmetric encryption and identity validation for the communicating parties and prevents the use of weak passwords for protecting critical information. The company offers qualified trusted services in two variations – managed and on-**premise security advisory services.**
- **Nozomi Networks (United States).** The company forged a partnership with ABS Consulting, under their flagship managed security service providers (MSSPs) program to develop operation technology (OT) and IoT management and security platform. The collaboration envisions providing clients access 24/7 monitoring and asset and vulnerability management services.

This project is supported by the Interreg ADRION Programme funded under the
European Regional Development Fund and IPA II fund.

- **ACUA Ocean (United Kingdom).** The USV manufacturer has signed a Singapore-UK MOU with Microsec to develop IoT security solutions to withstand quantum-based cyber-attack. The **solution will be designed** for ACUA Ocean's hydrogen USV control systems that have received approval in principle. The collaboration eventually aims to develop next-gen IoT security for multi-asset autonomous swarm deployments.
- **MAN Energy Solutions (Belgium).** Amazon Web Services (AWS) will provide cloud-based solutions for advanced analytics and IoT security for MAN's CEON platform, a digital platform that connects IoT equipment onboard. AWS IoT Greengrass and AWS IoT Core will be the critical technologies for running analytics on edge before securely ingesting data into the cloud. Having already developed on the AWS SageMaker platform, MAN CEON's platform aims to build in the security features swiftly.

Future Prospects

There remains no doubt about the applicability of and willingness to adopt IoT by the shipping industry. **Stitching data-driven insights to efficient automation**, IoT finds a place in almost every segment, from monitoring, maintenance, voyage, cargo-docking and traffic management. The **safety, efficiency and cost-related benefits will continue to boost the meteoric rise of IoT-enabled devices** in the ships and the ports hosting them. As IoT becomes ubiquitous, so do IoT vulnerabilities and the need to secure the IoT. IoT device manufacturers realize that thanks to the experience gained from other industries and reacting fast. Although still lagging behind, shipbuilders and regulatory authorities are now catching up. The last few years have seen several regulatory authorities worldwide defining IoT security frameworks and shipbuilders putting more stress on IoT security. Despite the challenges related to the adoption, technical know-how and security of connected devices, it is inevitable that **innovation and development activities will continue to grow in the area of IoT security** with patchy stitching of off-the-shelf solutions evolving into smoother customizable suites.

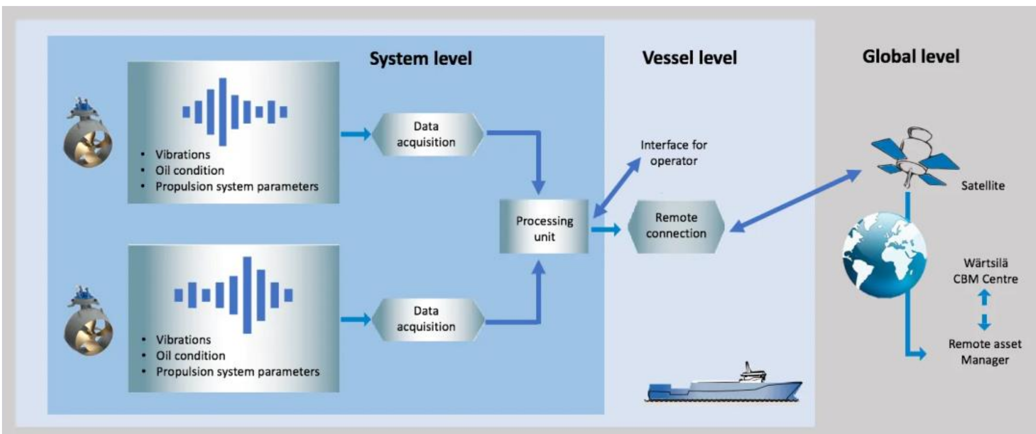
Predictive Maintenance

Maritime's tolerance against unplanned failure isn't great, and **heavy interdependence between equipment and machinery** often results in expensive downtime. For decades, the standard model has been a time-based preventative approach once the equipment approaches what is known as the mean time to failure (MTTF). However, the accuracy of this method has left too much to guesswork for an industry highly prone to unplanned failures.

For ships, resources, including fuel, spare parts, and crew, are limited. Prioritizing important tasks and utilizing available resources without delays is, therefore, quite imperative to safe and economic functioning. Onboard modern ICT systems at ships collect data, often big data, from sensors and either transmit them to the control center or analyze real-time to assess the health of the ship equipment and carry out repairs as needed. Predictive maintenance eventually helps the operational crew plan the timing for the next maintenance cycle cost-effectively and optimize spare parts inventory.

Conventionally, predictive maintenance, sometimes shortened as PdM, has largely been a manual process driven by individual readings with minimal automation and real-time analytics, but innovation in the industrial IoT has improved operation and performance. Widespread connectivity thanks to 5G, cloud, and satellite transmission has enhanced monitoring, big data, analytics, machine learning, and AI has enabled truly "predictive" solutions.

Condition-based or **predictive maintenance leverages various nondestructive testing mechanisms**, collecting data from monitoring systems and analyzing them in real time to change the course of action as needed. All PdM solutions begin with condition monitoring using vibration, temperature, infrared, sonic and ultrasonic flow techniques using sensor arrays and digital interfaces. Processing the historical sensor data to derive preventive conclusions follow.



Flow diagram of Wartsila's propulsion condition monitoring service. Source: Wartsila

While not a fundamentally new concept, predictive maintenance is experiencing something of a renaissance, primarily driven by advancements in sensors, connectivity, and analytics, and has **emerged as one of the most compelling applications of Industry 4.0**. The differentiation is visible throughout the six-step process, starting from improved sensing, quick and extensive data collection, faster transmission, more significant and secure storage, and fast and AI-based analysis leading to timely action.

Promoters & Inhibitors

Running maintenance silently in the background while equipment is in service, predictive maintenance represents a massive opportunity for operators to improve operator uptime and decrease operation costs while preserving high process quality. While these clear, tangible, and quantifiable benefits boast the growth and adaptability of PdM, a few challenges lie ahead.

Promoters

- **Expanding envelope of operational challenge.** Ship equipment is exposed to an extremely harsh environment, which will not roll back. Ships and maritime infrastructures are going farther and more profound, facing rougher waves. If unplanned failure is not already critical enough, it is increasingly becoming catastrophic regarding the damage it can do to equipment, goods, and human life. Operations such as offshore drilling and production, where continuity is paramount, especially cannot afford failure while waiting for periodic maintenance.
- **Increasing processing capacity and desire for autonomy.** Handling petabytes and gigabytes of data is not possible for the human workforce. Recent advancements in big data analytics, machine learning and AI-based modelling have not only pushed these boundaries of data handling capacities and accurate real-time monitoring but have also enabled cargo operators with better 24/7 visualization, analysis and real-time maintenance based on precision prediction.
- **Proven return on investment.** Across industries, PdM has largely shown a positive return on investment (ROI) for organizations. A few companies, such as Columbia Ship Management claim it to be as little as one year for some PdM measures. This is mainly due to significant improvement in breakdown frequency and the increased uptime of the system.

Inhibitors

- **Upfront investment and integration.** Predictive maintenance is a continuous daisy chain and cannot be implemented in isolation. Moving from existing infrastructure and equipment – many of which are still in good operation condition – is complicated, to say the least, and simply unjustifiable for the business on other occasions. Even if approved, it is a capital-intensive and time-consuming process to set up the equipment, integrate them into the system and design algorithms and key performance indicators (KPIs) for asset performance based on sparsely available historical data.
- **Inhouse expertise or ease of adoption.** Even when an excellent predictive model is in place, it is tailored for a specific ship, port, or facility. It may not work in a different scenario. Having specialist staff that knows marine equipment and has a technical background in predictive analytics is crucial to tailoring, maintaining, and manipulating the procedure as and when needed. A rapidly evolving landscape makes it increasingly harder to find this staff capability in-house, and operators are more often than not at the mercy of expertise from the service providers themselves. More and more PdM providers are therefore beginning to adopt an end-to-end business model of PdM-as-a-service that includes hardware and software analytics capabilities.
- **Future doesn’t always follow past trends.** Predictive maintenance will never be a foolproof answer for the industry. After all, it is merely an intelligent algorithm predicting the future based on the past.

Like everything else, it keeps getting better with maturing and increasing historic datasets, but every once in a while, the expanding maritime industry will face situations never faced before and will require to call upon human judgement. The industry needs to acknowledge the inherent limitation of predictive maintenance but should not let it come in the way of adoption.

Key Players

Recent Developments

- **Nippon Yusen Kaisha (Japan). Monohakobi Technical Institute and Nippon Yusen Kaisha (NKY) have deployed a pilot for** Wärtsilä's predictive maintenance services on two LNG carrier vessels, focusing the accuracy and quality of analytics and support services provided by the AI enabled Expert Insight module in combination with Wärtsilä optimized maintenance lifecycle solution.
- **Sealution (Belgium).** The company is **developing** predictive maintenance systems for IoT devices onboard a vessel. The patent pending technology used Bluetooth to connect devices and feed data to a central processing unit to monitor and maintain discrepancies. The company claims to have tested the full installation in January 2023 with Seatrade, the Dutch shipping company.
- **Trumarine (Singapore).** The turbocharger maintenance and repairing company has launched an intelligent predictive maintenance platform in 2022 to reduce turbocharger maintenance costs and downtime. The anomaly detection platform, named **TruCare**, is marketed as predictive maintenance-as-a-service (PdMaaS) and leverages a large suite of digital technologies, including IoT, edge computing, cloud-computing and digital twins for real-time data analysis and building failure models for predicting failure and recommending maintenance needs.
- **DeepSea Technologies (Greece).** The AI solution developer has partnered with Swiss University HES-SO Valais, the University of Cambridge and several universities from the US to predict fouling of the hull and propulsion systems. The Shifts project will use deep learning and image classification techniques to study distributional shift – the mismatch between training and deployment data – and ways to reduce it for safety-critical applications.

Future Prospects

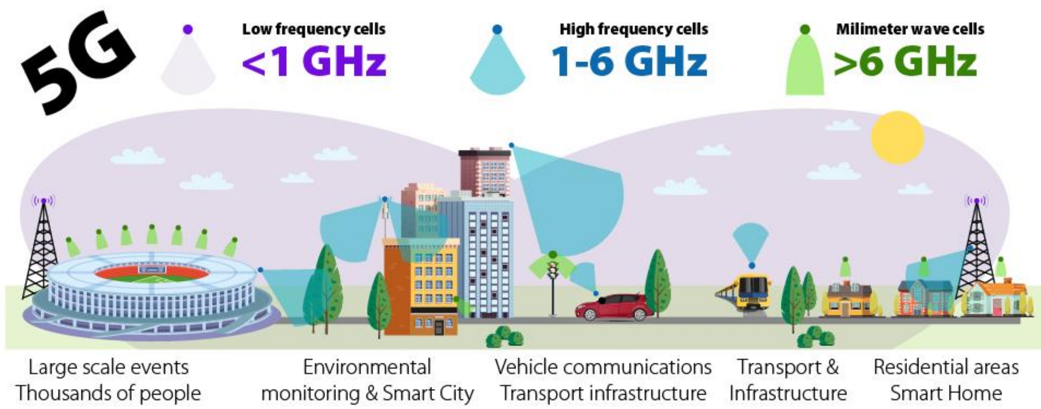
Although not a novel concept, predictive maintenance has emerged as one of the **most compelling applications of Industry 4.0**. The renaissance is driven mainly by sensors, connectivity, and data analytics advancements. Due to the operating conditions, the marine industry is susceptible to heavy losses due to downtime and failure – not just economical but also life-threatening. Predictive maintenance **represents a massive opportunity for ship operators to take a sneak peek into the future** – of sorts – and help improve asset uptime, decrease associated costs, and ensure the safety of those working alongside them. Increasing offshore activities, appreciation, and adoption of IoT devices on board in conjunction with a desire for autonomy will continue to propel machine learning based predictive maintenance for the maritime industry. A short history does represent a threat related to trust but also opens up opportunities for a very diverse market, including players evolving in a range of – operator-focused and maintenance-as-a-service business models. The Adriatic-Ionian region will also witness increasing investments and deployment in predictive maintenance technologies as more vessels adopt IoT and robotics.

5G

Remote operation is synonymous with the maritime industry, and it is no surprise that communication technologies have always been crucial for safety, navigation, and information exchange during voyages. Depending on the nature of communication, such as vessel-to-vessel, near-shore communication, on-vessel-communication, far offshore, and the associated costs, maritime has been using various communication technologies, including radio, 4G LTE, and satellites. The shipping industry has **embraced digital technologies with both arms wide open**, which is causing a ripple effect on maritime communication. Sensors and digital equipment mounted on ships generate an enormous amount of data that must be transferred to the control station for processing and hurried back to the machines and crew with instructions. The **electric mesh of IoT systems and predictive maintenance requires a wireless, low-latency, and fast communication technology** on board.

As digitalization continues to permeate all operations, the maritime industry requires better and faster connectivity to process data quickly and reliably. 5G is the **fifth generation of wireless networks**, an evolution of today's 4G LTE networks that aims to meet today's society's immense growth in data and connectivity. 5G **operates in three different bands**: low-band, <1 GHz; mid-band, 1 GHz to 6 GHz; high band, primarily 25 GHz to 35 GHz. The general promise of 5G is to create wireless mobile networks able to handle a far greater number of simultaneous connections, to improve network latency – the time taken for devices to communicate with the wireless networks – and to improve overall data rates.

As a result, 5G has evolved to a service-oriented network architecture, providing tiers for different types of network traffic. Each tier supports specific improvements in one or more of the above areas, supporting a diverse range of services and applications across the broader 5G network. The three tiers, or slices, comprising 5G networks are enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable low-latency communications (URLLC). eMBB primarily seeks to speed up data transfer rates – mostly for data-heavy consumer applications and leverages the millimeter wave (mmWave) technology. **mMTC**, while not a new technology, is **essential to IoT applications and employs massive multiple-input multiple-output (MIMO) systems** for connecting large numbers of devices simultaneously. The latest variation, URLLC seeks to lower latency for critical applications like self-driving vessels and connected safety devices requiring real-time decision-making and lightning-fast communications; the total data transfer rate may not be a challenge.



5G frequency bands. Source: [Sectron]

Satellite communication is the pinnacle of remote communication today, and while it still enjoys the top spot, 5G is carving out a space for itself. Most activity happens in ports, harbors, near shore, and at up to 1Gbps. 5G offers much superior speed for faster data processing – essential for latency-intolerant autonomous operations at a fraction of the cost of satellite communication. The range today **extends up to 25-30 nautical miles away** from shore and continues to grow. This is particularly significant in the ADRION region, where land is seldom more than 50 nautical miles away. 5G, despite its limitations for remote applications, is growing very fast and covers most business use cases for the Adriatic-Ionian region. The rate of development is steep, and it is set to emerge as a unifier to drive predictive maintenance, IoT and autonomous voyages either by itself or through a hybrid combination with satellite networks.

Promoters & Inhibitors

Already seen a meteoric rise in four decades since conceptualizing when Japan launched 1G in 1979, 5G has opened up endless possibilities in the digitalization of the maritime industry. They are already inching away from the competition riding on the potential advantages they offer in terms of speed and cost of data transmission. However, industry-wide adoption in the maritime will be underpinned not only by a range of factors supporting their deployment but also by their ability to circumvent the technological barriers they face.

Promoters

- **Increasing IoT and autonomous vehicles.** The digital transformation has seen onshore, and offshore activities evolve to operate safely, efficiently, and profitably. This has resulted in the large-scale adoption of UAVs, USVs, robots, and IoT devices for maintenance and operations on port and over the vessels. 5G enables efficient collecting, processing, and analysis of massive amounts of data generated by these devices with sub-millisecond latency. Development activities for autonomous vehicles are also betting on 5G solutions to aid in real-time decision-making.
- **Real-time inspection and monitoring.** Mission-critical tasks such as real-time audio/video monitoring for safety, traffic management, vessel navigation, and course rerouting cannot wait for the conventional time lag. This is more problematic on offshore rigs and wind platforms. Hybrid private 5G networks with satellite or low-power, wide-area network (LPWAN) offer an excellent, cost-efficient solution when most communication needs to happen within a small confinement of a rig or ship.
- **Onshore adoption.** Fishermen, coastguards, river transporters, and logistics operators have broadly adopted 5G technology daily. This has led to smoother integration of 5G in onshore activities. Several ports around the globe, such as the Port of Antwerp, are now implementing 5G connectivity on the port.

Inhibitors

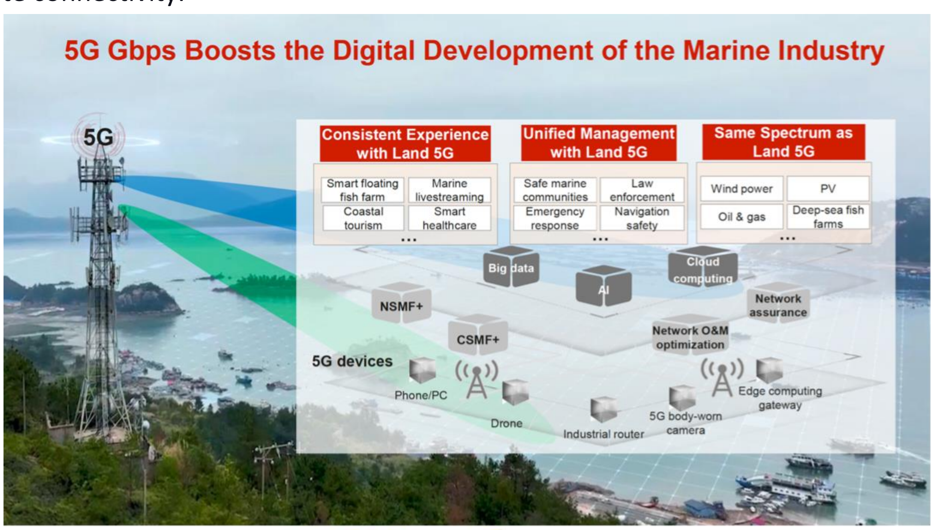
- **Lacking infrastructure could peg back deployment.** Roll out of the 5G technology is nascent and faces challenges in upgrading infrastructures, adding base stations, and overcoming airwave scarcity for spectrum allocation. Developers will require collaborative efforts to share the infrastructure cost while addressing regulatory concerns about safety standards for transferring data, which is ever trickier closer to international borders in the Adriatic-Ionian region.
- **Limited range.** One of the most significant drawbacks of 5G is its limited range. The low band offers some enhancements but at the cost of latency. This inevitably creates the infamous 5G go-slow cycle for offshore maritime activities. Thankfully, not every operation requires immediate data transfer in large quantities. In combination with edge computing – which processes and stores data close to the source, reducing the data traffic – 5G can improve the performance by rationalizing the data and picking a lite subset to be transmitted to the cloud.
- **Low Earth Orbit (LEO) and Middle Earth Orbit (MEO) satellites.** As 5G continues to evolve and penetrate, they face competition from small and low-orbit satellites, promising to bring communication costs down. However, it remains to be seen if these off-the-shelf, small LEOs will challenge 5G or form a synergy to create a low-latency and reliable mesh over the oceans complementing each other's strengths.

Key Players

5G

Recent Developments

- **Port of Le Havre (France).** After a two year long pre-deployment study, a joint-venture including EDF, Siemens and Nokia in partnership with the Port of Le Havre has deployed Orange's 5G network in the 26-GHz frequency band. The project also aims to help standardize technical specifications when using 5G technologies at ports.
- **Huawei (China).** In partnership with China Mobile, the company has built a 5G network supporting fisheries, tourism, and offshore wind farms near the coast of Fujian. The network extends up to 50 km into the ocean. The network is built on 700 MHz as the baseline frequency, rising to 2.6 GHz and 4.9 GHz for applications requiring higher capacities. The company claims to offer the service at 1% of the cost of satellite connectivity.



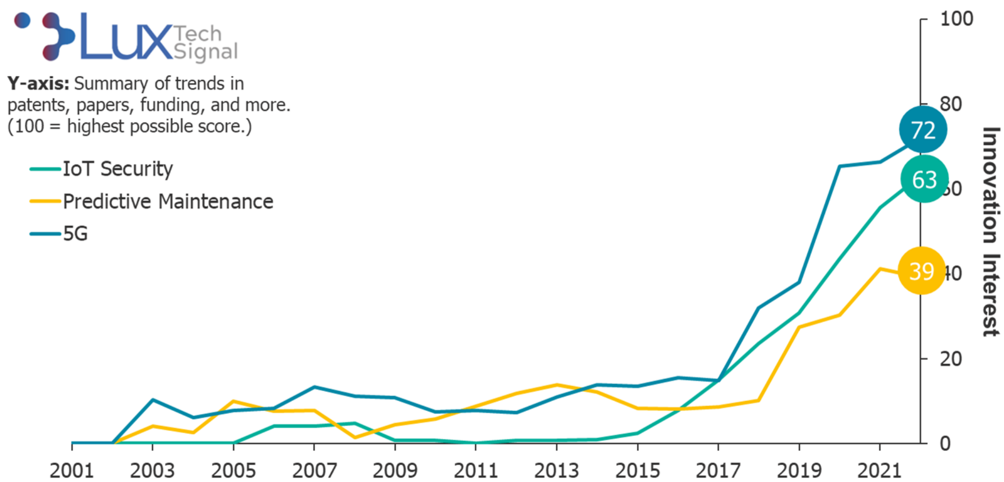
Range of use cases for China Mobile's 5G in Fujian, China. Source: Huawei

- **Jet Engineering System Solutions (United Kingdom).** Jet-4 Babel, a floating 5G base station, was deployed in the summer of 2022 to extend the capabilities of 5G beyond the shoreline to enable live streaming, data collection and processing. The deployment, a **proof-of-concept**, will allow JET to scale up to a fully functional floating 5G network at sea, primarily supporting safety and finish-related use case.
- **The Port of Singapore (Singapore).** In collaboration with the Infocomm Media Development Authority (IMDA), the Maritime and Port Authority (MPA) of Singapore aims to achieve full 5G coverage over the port of Singapore by 2025. The initiative will start with safety and port automation use cases, eventually scaling to autonomous shipping in the future.

Future Prospects

Communication in shipping has conventionally been very different than other industries. Waves of digitalization have bought sensors, data processors, edge computing, and video streaming devices to the unchartered territory of the ocean, where classical connectivity tends to fall short. No wonder the **maritime industry is exploring 5G to tap into their faster speeds and lower latency** with deep interest despite severe range challenges. The interest will continue to grow with the ports being the first adopter, followed by river transport before venturing into the deep sea. Thankfully, the Adriatic-Ionian region offers a plethora of use cases within a few kilometers from the coast, making it a highly fertile breeding ground for 5G pilot and testing activities and potential early adopters of the technology.

Innovation Trends



*The **Lux Tech Signal** is a composite score, combining data in patents, papers, and funding, plus Lux Research's proprietary data. It quantifies the progress of each technology, against a maximum innovation interest score of 100. Changes over time indicate growing (or shrinking) innovation interest, while inflection points may point to commercial opportunities or challenges ahead.*

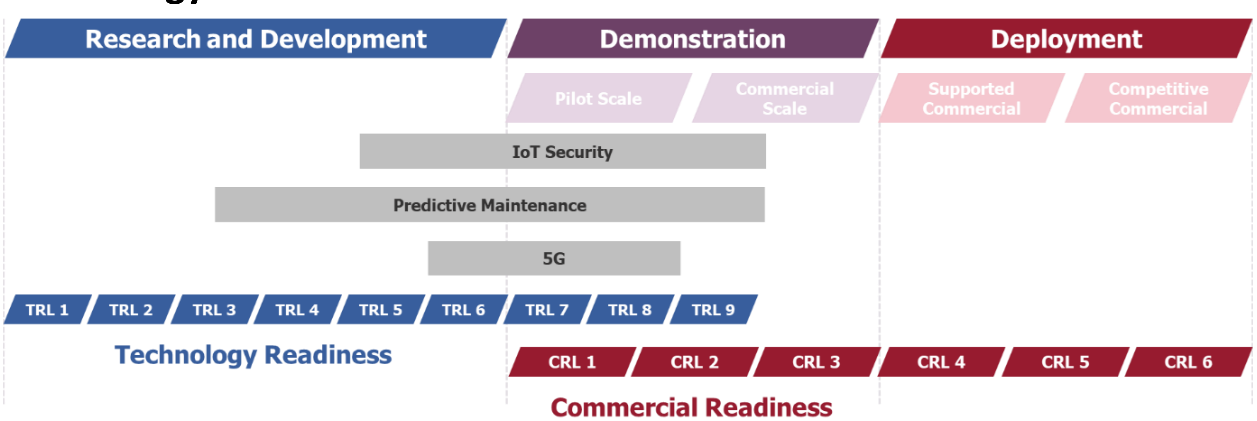
This project is supported by the Interreg ADRION Programme funded under the
European Regional Development Fund and IPA II fund.

None of the three technologies existed – at least in the form they are today – even ten years ago. Although IoT was "born" in 2009, it took a while before it started being considered an as serious emerging technology. When IoT devices started using sensors in 2014, security took center stage, and there has been a steep rise since then. First coined in 2015 by Klaus Schwab, the fourth industrial revolution, aka **Industry 4.0, is quite relatable with the metamorphism of maritime communication**. As AI and robotics continue to climb, so does the need for efficient and safe machine-to-machine communication.

Unsurprisingly, the first intrusion of IoT and IoT security into shipping was in port logistics, with key European ports coming together to explore IoT opportunities in 2016. Inmarsat, the British telecom, started their cloud-based IoT solution, which they named Fleet Data, to access and analyze vessel performance data on a secure platform. Predictive maintenance follows a similar trend, just trailing behind the technology adoption, with operators realizing the importance of PdM as digital transformations settle in.

5G is the latest development and is still unavailable globally, but its advantages are abundant. Starting in South Korea in 2008 as a research endeavor, 5G saw all major telecom players developing the technology for the next decade. Verizon's first field test in 2015 already seems a long way back, and **despite an underwhelmingly short deployment history** and challenges related to range, **innovation and deployment in 5G is expected to soar** in the coming years with several ports and offshore platforms adopting shared or private 5G networks as a standalone or hybrid communication solution.

Technology Status



Given the short history and variability within the technology itself, IoT security and PdM show quite a variable range in terms of their maturity status. Some of the more state-of-art variations using well established methods of analysis are commercially available and are already being demonstrated and deployed in maritime industry, the more advanced versions using deep learning and image classification lag behind and are still at concept stages. 5G is commercially available but not adopted at scale everywhere, whereas certain operators such as China Mobile have already implemented it on selected ports commercially.

Alternative and Competing Technologies

In recent years, the maritime industry has seen the emergence of several advanced digital technologies that are revolutionizing the way ships and vessels operate. One such technology is 5G, which promises to deliver faster and more reliable connectivity than the current 4G standard. This could have a significant impact on ship-to-shore communication, as well as on remote monitoring and control of vessels. Another technology that is gaining traction in the maritime industry is predictive maintenance. This approach relies on the use of sensors and data analytics to predict when maintenance will be required, allowing ship operators to schedule maintenance proactively and avoid costly downtime. In contrast, prescriptive and preventive maintenance involve scheduling regular maintenance based on established parameters, regardless of whether the equipment actually requires it. While these methods have their advantages, they are less efficient and can lead to unnecessary maintenance expenses. Overall, the maritime industry is undergoing a digital transformation, with new technologies and approaches emerging that promise to enhance efficiency, safety, and profitability. By considering the strengths and limitations of each technology, maritime operators can select the most suitable approach for their unique requirements, thereby improving their operations.

Commercial Outlook

The **global maritime digitization market** has experienced significant growth in recent years, with a forecast of further significant growth in the decade to come. **Projections** indicate that the market for maritime digitization is set to experience **notable growth over the next decade**. By the end of this period, the market is expected to have expanded significantly, reflecting the industry's increasing importance and potential. Below, we report some growth data related to specific **technology sectors:**

The shipbuilding industry in Europe is renowned for its construction of complex naval vessels, such as cruise ships, ferries, mega yachts, submarines, and dredgers, and holds a strong position in the global market. The marine equipment industry in the region offers a wide range of ship components, including propulsion systems, diesel engines, environmental safety systems, cargo handling systems, and related electronic products. The growth of the shipbuilding industry in Europe, which has been fueled by the development of **digital technologies**, has been one of the most significant factors contributing to the demand for autonomous ships in the region. In addition, increasing investments in the naval sector and restructuring efforts undertaken by ship manufacturing companies are driving the growth of the autonomous ships market in Europe. The autonomous ships market in Europe is projected to grow from USD 1,665 million in 2020 to USD 4,319 million by 2030, at a CAGR of **10.0%** during the forecast period, reflecting the continued development of digital technologies and the resulting demand for autonomous ships. (MarketsandMarkets, 2020a)

Connected ships are architectural management systems and solutions which link various components and systems of ships with onboard and onshore systems to provide the required information pertaining to the management, operations, and control functions of ships. These systems enhance the operational performance of marine vessels, ensure their safety, and enable seamless integration of various sensors on a common platform that can be operated from a single user environment. Sensors are installed on multiple locations on connected ships and are equipped with processor units known as Data Acquisition Units. Connected ships acquire information from sensors to regulate and monitor the operations of marine vessels. They also monitor power systems, propulsion controls, engines, and machinery controls of marine vessels to ensure safe and smooth operations. The connected ship market is estimated to be USD 5.92 billion in 2018 and is projected to reach USD 7.19 billion by 2023, at a CAGR of 3.95% from 2018 to 2023. Some of the major factors driving this market include the increasing global trade through seas, improving marine navigational safety resulting in lesser accidents, and growing maritime tourism. (MarketsandMarkets, 2018)

Europe's position in the information security landscape and its growing IoT market have significant implications for **cybersecurity**. While Europe is second to North America in terms of information security adoption and cyber-attacks, the region is expected to hold the second-largest share of the IoT security market. This growth is fueled by a rise in IoT products, which has led to the deployment of billions of new devices in recent years. However, this rapid growth also creates new vulnerabilities that can be exploited by threat actors. As a result, there is a growing need for strong security measures and compliance management in Europe, making the market more lucrative for vendors delivering information security consulting services. Economic and administrative incentives for IoT security in various business processes will further drive market growth in the region, enhancing cybersecurity. The increased digitalization and automation across manufacturing verticals in Europe is also driving market growth, as companies strive for better coverage capacity in their factories **(IoT security Market Global Forecast 2026).**(MarketandMarkets, 2021a).

Conclusions

In conclusion, the influence of information and communication technology (ICT) on the maritime sector in the years to come will be significant. The trend towards digitization and automation is clear, promising increased efficiency, safety, and profitability. However, there are also challenges to be addressed, such as cyber security threats and the need for skilled workers to manage these advanced technologies. Nevertheless, the overall outlook is positive, and we can anticipate continued innovation and growth in this dynamic industry. It is essential for all stakeholders to embrace these changes and adapt to the rapidly evolving landscape of the maritime sector.

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Field of Activities

Aquaculture: Horizon Scanning

Aquaculture is defined as the farming of aquatic organisms including fish, mollusks, crustaceans and aquatic plants. Farming implies some sort of intervention in the rearing process to enhance production, such as regular stocking, feeding, protection from predators, etc. Farming also implies individual or corporate ownership of the stock being cultivated, the planning, development and operation of aquaculture systems, sites, facilities and practices, and the production and transport (FAO, 2022a).

Figure 13. Gilthead seabream (Sparus aurata) in floating cage, Italy. @FAO Aquaculture photo library/F. Cardia.

Market in Brief

Importance of the Market

Aquaculture is a millennia-old activity that constantly evolves due to new technological development, needs, positive experience, errors, and cooperation. A significant growth in aquaculture has benefited from scientific progress in the last century allowing the sector to grow and supply more than half of the world's fish for human consumption (FAO, 2022a). In 2020, the global production of aquatic animals was estimated at 178 million tons, representing a slight decrease compared to the record production of 179 million tons in 2018. The production is divided between capture fisheries, which contributed with 90 million tons (51%), and aquaculture which held 88 million tons (49%) (FAO, 2022b). Moreover, aquaculture production accounted also for 35.1 million tons of algae for both food and non-food use (mainly from marine aquaculture) and 700 tons of shell and pearls for ornamental use, reaching a total of 122.6 million tons in live weight in 2020 (FAO, 2022b).

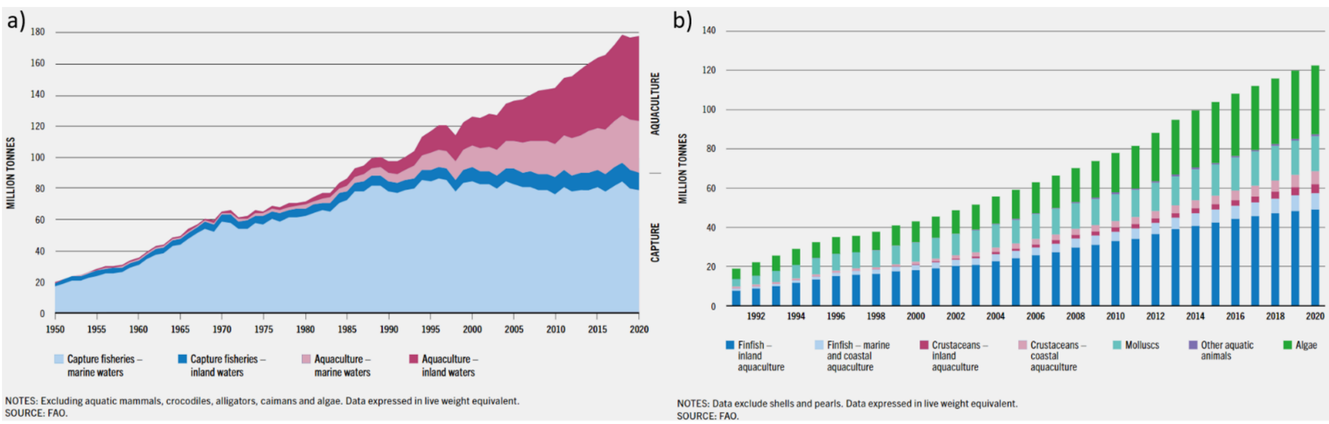


Figure 14. Graphs representing a) world capture fishery and aquaculture production, 1950-2020 and b) world aquaculture production, 1991-2020 (FAO, 2022b).

The total first sale value of the global fish production was estimated at USD 406 billion in 2020, divided between fishery and aquaculture with USD 141 and USD 265 billion, respectively (FAO, 2022b). Overall, the aquaculture product market is projected to grow at a CAGR of 7.2% from 2022 to reach USD 56,151.2 million by 2027 (MarketsandMarkets, 2023).

Based on cultured organisms, aquafarming can be performed in three environments: freshwater, brackish water, and marine. Freshwater is mainly performed in the fishpond, fish pens, fish cages or rice paddles. Brackish water is primarily located in fishponds near coastal areas, whereas marine culture employs fish cages or substrates such as stakes, ropes, and rafts. Overall, the freshwater market is the primary developed, especially in the Asia Pacific countries, and it is the one which is projected to increase the most in the next five years (MarketsandMarkets, 2023).

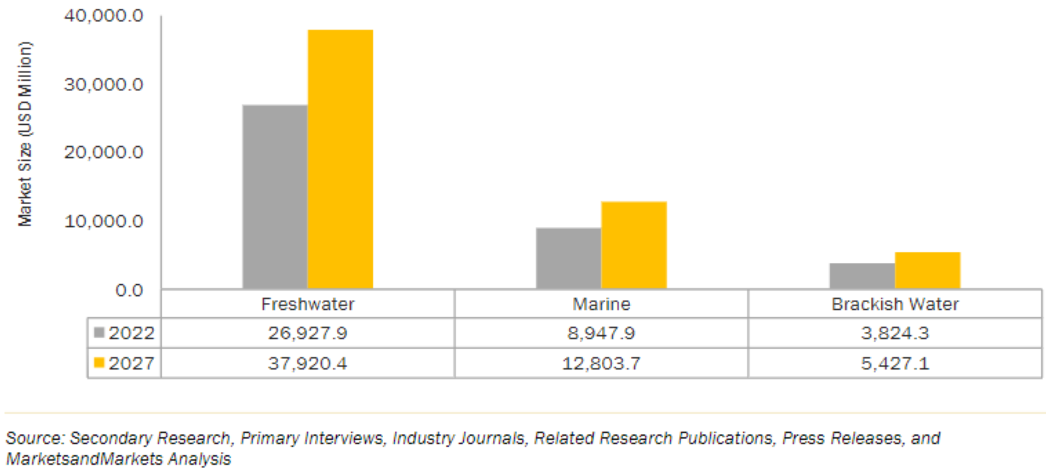


Figure 15. Aquaculture production market, by culture, 2022 vs 2027 (USD million) (MarketsandMarkets, 2023).

The aquaculture market, by species, is segmented into aquatic animals and aquatic plants. The animals segment accounted for a market share of 91.5% in 2021 and is projected to grow at highest rated of 2.7% util 2027. In 2022, the aquatic animal market was estimated at 36 USD million whereas the aquatic plant market reached 3 USD million. However, the market is projected to growth in the future (MarketsandMarkets, 2023).

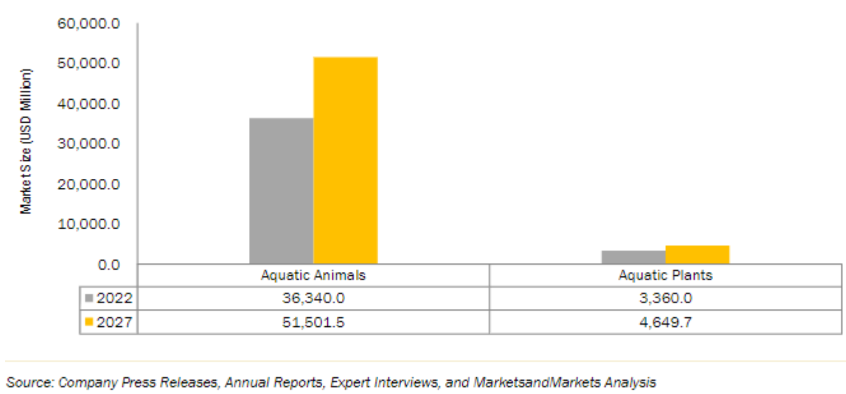


Figure 16. Aquaculture Products Market, by species, 2022 vs 2027 (USD million) (MarketsandMarkets, 2023).

Looking at the production, in 2020, farmed finfish reached 57.5 million tons, a total value of USD 146.1 billion. The production was divided between inland and mariculture with 49.1 million tons (USD 109.8 billion) and 8.3 million tons (USD 36.2 billion), respectively. Finfish rearing is closely followed by mollusks with 17.7 million tons produced (USD 29.8 billion), crustaceans 112.2 million tons (USD 81.5 billion), other aquatic invertebrates with 525 tons (USD 2.5 billion) and 537 000 tons of semi-aquatic species including turtles and frogs (USD 5 billion). Finally, global algae cultivation, mainly macroalgae, increased by half a million tons in 2020 compared to 2019 (FAO, 2022b).

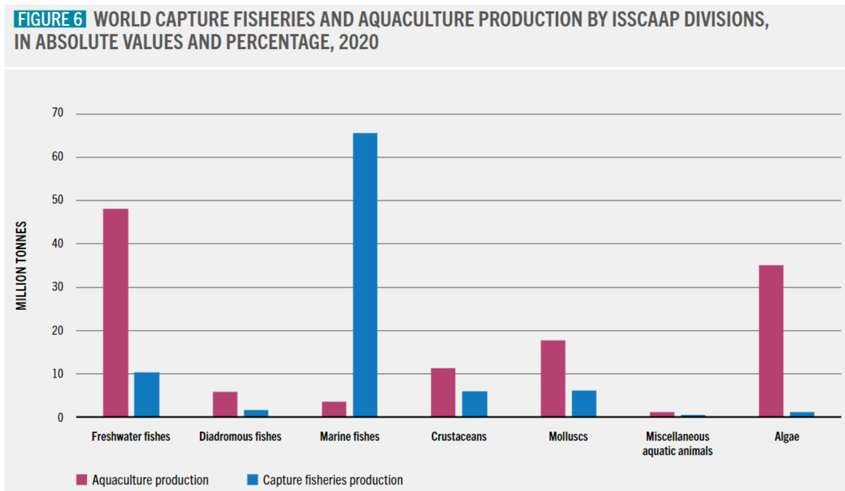


Figure 17. World capture fisheries and aquaculture production by ISSCAAP division, in absolute values and percentage, 2020 (FAO, 2022b)

According to Food and Agriculture Organization (FAO), 2022b in 2030, total production of fishery and aquaculture is expected to increase further and reach 202 million tons[11]. Most of the increase will come from aquaculture production which is expected to increase to 106 million tons in 2030 with an overall growth of 22% (FAO, 2022b).

[11] The Ukraine conflict adds another level of uncertainty to global value chains and trade. Prices of energy and inputs, including feed for aquaculture, have already started to soar. This is increasing operational costs resulting in higher prices of fisheries and aquaculture products (FAO, 2022b).

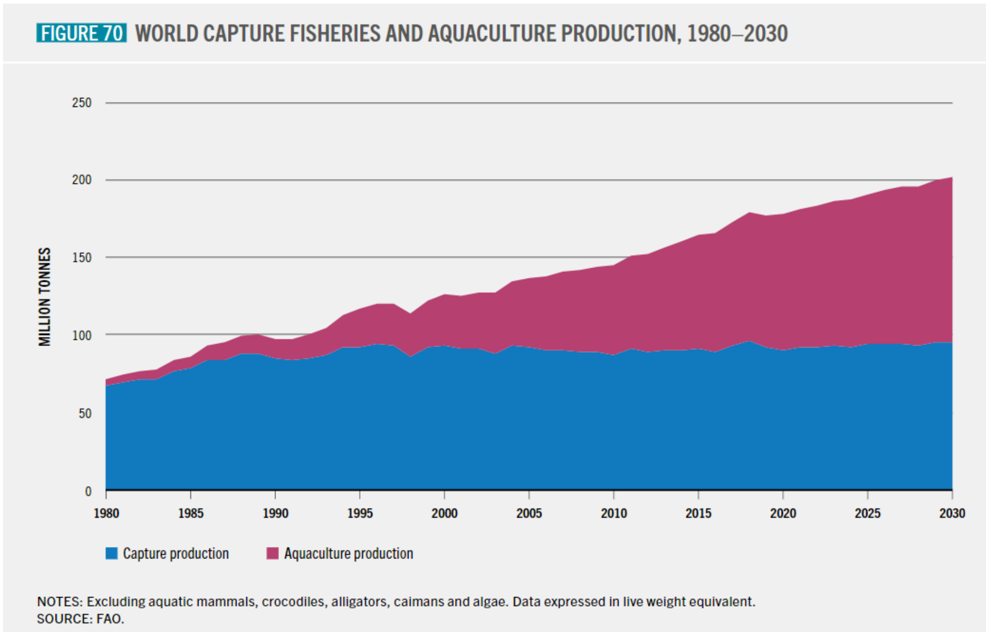


Figure 18. World capture fishery and aquaculture production, 1980-2030 (FAO, 2022b).

Yet, the average annual growth rate of aquaculture production should decline over the next decade to less than half of the rate currently observed, lowering from 4.2%, registered in the period 2010-2020, to 2.0 in the decade 2020-2030. This decrease will be related to the broader adaptation and enforcement of environmental regulations, reduced availability of water and suitable location and increasing outbreaks of diseases (FAO, 2022b). However, a steady growth is expected to continue in all continents and mostly in the Americas, Africa, and Asia. Moreover, all farmed groups of species will continue to increase with a slight delay of organisms that require larger proportions of fishmeal and fish oil in their diets due to the lower availability of feeds (FAO, 2022b). Finally, consumption of farmed products is expected to increase by 2030, reaching 182 million tons, coupled with the rise of aquatic food consumption that is projected to reach 21.4 kg pro-capita in 2030 (FAO, 2022b).

At European level, the volume of European Union (EU) aquaculture production remained steady over the last decades even if its value has increased. The EU aquaculture sector reached 1.2 million tons in sales weight and EUR 4.1 billion in turnover in 2018, about 5% increase compared to 2017 (European Commission, 2022c). In 2022, the European market for aquaculture products was valued at USD 3,141.8 million with Norway, France, Spain, the UK and Italy being the major countries engaged in the production. The EU also imports a wide variety of aquaculture species and products, mainly salmon from Norway and warm water prawns from Southeast Asia (MarketsandMarkets, 2023).

Table 5. Europe: Aquaculture products market, by Country, 2022-2027 (USD million) (MarketsandMarkets, 2023).

Country	2022	2023	2024	2025	2026	2027	CAGR (2022-2027)
Norway	1,714.7	1,829.7	1,955.9	2,094.4	2,246.7	2,414.3	7.1%
France	172.6	180.3	188.8	198.1	208.2	219.2	4.9%
Spain	123.5	128.4	133.8	139.7	146.2	153.2	4.4%
UK	286.1	300.4	316.0	333.0	351.7	372.1	5.4%
Italy	99.4	103.5	107.9	112.8	118.1	123.9	4.5%
Turkey	260.7	277.1	295.1	314.9	336.6	360.5	6.7%
Rest of Europe	485.0	514.1	545.9	580.9	619.2	661.3	6.4%
Total	**3,141.8**	**3,333.5**	**3,543.5**	**3,773.8**	**4,026.7**	**4,304.5**	**6.5%**

Source: Secondary Research, Primary Interviews, Industry Journals, Related Research Publications, Press Releases, and MarketsandMarkets Analysis

By species, the production of mussels (473.000 tons in 2019) (Directorate-General for Maritime Affairs and Fisheries, 2022), which is the main species reared in the EU aquaculture in weight has decreased in recent years due to adverse environmental factors such as algal blooms. Whereas, the production of other species, especially finfish, increased in the last period due to higher degree of control on the production factors (European Commission, 2022c). In 2019 the production focused also on trout (180.000 tons), oyster (100.000 tons), gilthead seabream (95.000 tons), European seabass (86.000 tons) and carp (80.000 tons) (Directorate-General for Maritime Affairs and Fisheries, 2022). Looking at the value, top species farmed in EU in 2019 were trout with a total value of EUR 623 million, gilthead seabream (EUR 494 million), European seabass (EUR 491 million), oyster (EUR 455 million), mussel (EUR 433 million) and bluefin tuna (EUR 308 million) (Directorate-General for Maritime Affairs and Fisheries, 2022).

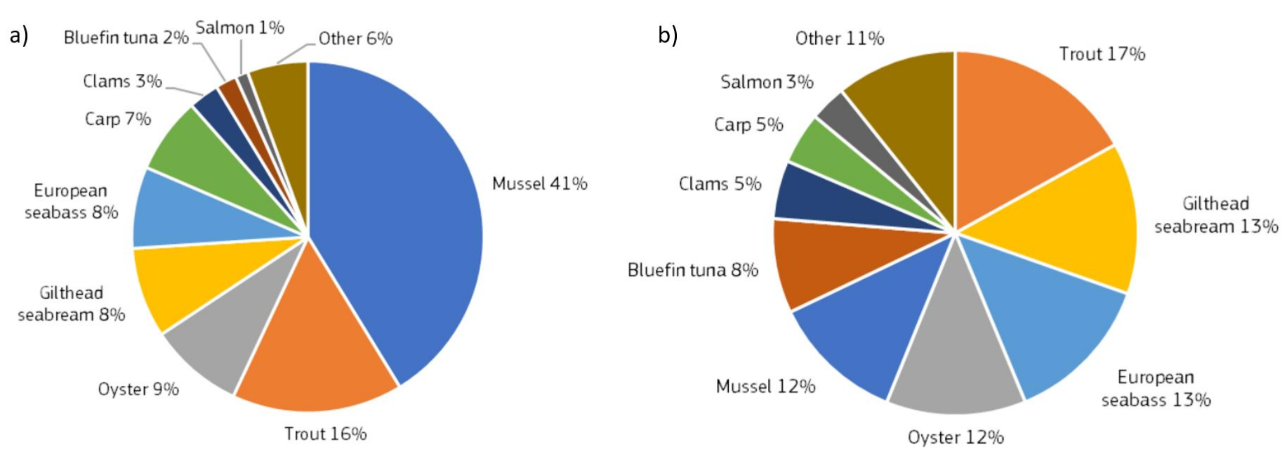


Figure 19. Pie charts of a) EU aquaculture production breakdown by main species in volume; b) EU aquaculture production breakdown by main species in value (Directorate-General for Maritime Affairs and Fisheries, 2022).

By region, EU aquaculture is mainly developed in Spain (27%), France (18%), Italy (12%) and Greece (11%). Production and consumption of organic fish and seafood[12], especially in the aquaculture sector, is still in its preliminary phase despite the increasing demand from consumers (Directorate-General for Maritime Affairs and Fisheries, 2022; European Commission, 2022c). Based on EU and national sources, the total production of organic aquaculture in Europe is estimated at 74.032 tons in 2020 accounting for 6.4% of the total EU production. Nevertheless, the production has increased by 60% compared to 2015 thanks to the rising of organic mussel production (Directorate-General for Maritime Affairs and Fisheries, 2022). Based on EU data, the main species produce by the organic industry are mussels (41.936 tons), accounting for more than half of the total organic market, followed by salmon (12.870 tons), trout (4.590 tons), carp (3.562 tons), oyster (3.228 tons) and European seabass/gilthead seabream (2.750 tons) (Directorate-General for Maritime Affairs and Fisheries, 2022). Finally, the main producers in the European region for organic products are Ireland (salmon and mussel), Italy (mussel and finfish), and France (oyster, mussel and trout). The sector presents several growth opportunities thank to the support of EU policy and the exponential increase of the sector especially for mussel's production (Directorate-General for Maritime Affairs and Fisheries, 2022).

Market Drivers

Several drivers are affecting the growing of the aquaculture market contributing to the world's supplies of fish and seaweed for both human and animal consumption. According to the FAO, seafood products demand is steeply increasing making them among the most heavily traded goods (FAO, 2020). This increasing demand relates to the growing population and the rising of income levels especially in India and Southeast Asia. Higher purchasing power allow the population to buy protein-rich aqua food, especially seafood, increasing consequently the demand (MarketsandMarkets, 2018). Finally, in the last years, consumer demand and awareness for sustainable products is increasing across Europe, hence, a new interest for organic aquaculture product is rising. Specifically, across Europe organic demand is growing and accounted for 4,7% of EU food consumption in 2020 (+15% compared to 2019) (Directorate-General for Maritime Affairs and Fisheries, 2022).

The growing attention to aquaculture products is also related to the steeply decline in wild capture fisheries. Overfishing is dramatically destroying the stock abundance by fishing to below the level of maximum sustainable yield (European Commission, 2022c). Thus, the number of different species of aquatic plants and animals reared is rising trying to fill world's demand of seafood (MarketsandMarkets, 2018).

[12]Organic farming is an agricultural method that aims to produce food using natural substances and processes. This means that organic farming tends to have a limited environmental impact as it encourages: responsible use of energy and natural resources; maintenance of biodiversity; preservation of regional ecological balances; enhancement of soil fertility and maintenance of water quality (European Commission, 2022d).

To allow a sustainable growth of the sector, appropriated actions need to be taken to reduce the production coast and the environmental impact. Lately, many private equity firms and venture capital firms have entered the market thanks to the profitable opportunities. Those companies are largely investing on the R&D activities focused new and advanced cultivation systems, improved feed alternatives, and better systems to assure animal welfare. Also, universities and research centres are focusing on reducing the environmental impact of aquafarm on the ecosystems through the better management of the farming sites and the selection of new species (MarketsandMarkets, 2019).

Another important driver for the aquaculture sector is the testing of new cultivation systems. Innovation is focusing on new advanced technological installations that could couple the increasing production with lower environmental impacts. Those new cultivation systems address sustainability and limitations challenges that traditional agriculture faces. For this reason, increasing investments on new cultivation systems is further expected both by businesses and governments (MarketsandMarkets, 2018).

Furthermore, the aquaculture industries have witnessed tremendous advances in aquaculture tools, techniques, and technologies in the last decade. The adoption of cutting-edge technologies, such as Internet of Things (IoT), machine learning, remotely operated vehicles (ROMs), artificial intelligence (AI), automatic feeders, and acoustic telemetry tracking systems, within aquaculture farms is more and more common.

Improve use of technologies in aquaculture farming helps also to increase the production, enhance the efficiency, minimize resources loss as well as improve accuracy, precision, and repeatability. Hence, investments in the sectors are steeply increasing thanks to the possibility of a better management of the farms influencing the growth of the market (MarketsandMarkets, 2019).

Finally, governmental institutions located in development countries such as China, India, Brazil, Indonesia, and Thailand are providing subsidies to local aquaculture farms for the adoption of advanced equipment and technologies. The productivity of aquaculture farms located in those countries is expected to increase substantially with the implementation of state-of-the-art equipment and the adoption of advanced technologies. Thus, the rising subsidies or need-based financial assistance by governments enable farmers to invest in modern technology-based aquaculture tools and reduce dependency on manual labour boosting economic growth in the sector (MarketsandMarkets, 2019). In EU, sustainable food production is strongly supported by public bodies through different initiatives such as EU's Farm to Fork Strategy (Directorate-General for Maritime Affairs and Fisheries, 2022).

Table 6. Drivers in the aquaculture sectors and their impacts (MarketsandMarkets, 2019).

DRIVERS	2 YEARS	5 YEARS	REASON
Surging adoption of advanced technologies such as IoT, RoVs, and AI in aquaculture farms	🔵	🟡	• Increasing number of technology based start-ups are entering into precision aquaculture. • Companies such as AKVA Group, Deep Trekker, and Sensaway have deployed IoT and AI-based fish farm monitoring systems in thousands of aquaculture farms around the world.
Growing investments in aquaculture technology and R&D Projects technological research efforts and equipment innovations	🔵	🟡	• The government in developing countries such as China, India, Brazil, Indonesia, Thailand, and various African countries provides subsidies to local aquaculture farmers for adoption of advanced equipment and technology.
Rising income levels and demand for protein-rich aqua food	🔵	🟡	• According to United Nation, by 2050, global population is expected to reach around 9.5 billion from current 7 billion people. Due to rising population, demand for protein rich aqua food is expected to rise exponentially in coming years.
IMPACT LEVEL :	🟡 HIGH	🔵 MEDIUM	🟢 LOW ⚪ VERY LOW

Key Trends

Industry Trends

Innovation in the aquaculture sector is at an all-time high driven by opportunities and regulatory pressure which are boosting R&D efforts to develop new technologies that could improve the conventional production.

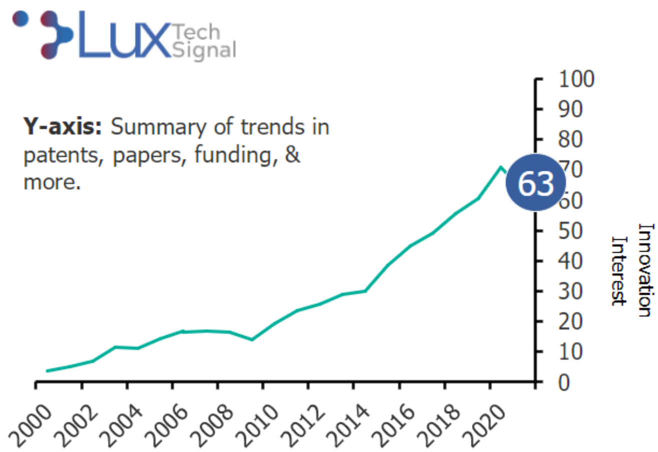


Figure 20. Lux Tech Signals: Harnessing innovation to Achieve Sustainability Across the Aquaculture Value Chain[13] (Lux Research Inc., 2023).

Overall, aquaculture value chain could be divided into three main segments which are reported as it follows:

- *Upstream processes* defined as the resources required for the production;
- *Production processes* identified as the rising and collection of the farmed organisms;
- *Downstream processes* defined as all the process needed for product preparation and supply of farmed food for the consumers.

Nowadays, the industry is developing innovation in each segment of the aquaculture value chain to assure a wide-scale sources of sustainable protein and nutrition.

[13] The Lux Tech Signal is based on our analysis of innovation data including patents, academic papers, venture capital funding, government funding and Lux proprietary data. The Innovation Interest score is calculated by analysing multiple, diverse datasets weighted based on our evaluation of the role innovation sources play in each stage of commercial technology development; empirically tested and validated against real world historical data.

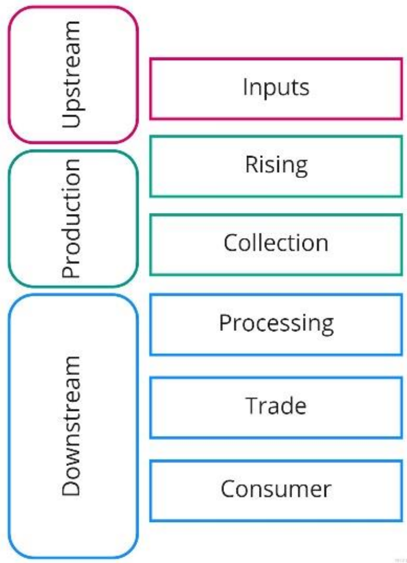


Figure 21. Scheme of aquaculture value chain (Lux Research Inc., 2023).

Starting with the first segment of aquaculture value chain, aquaculture industry is focusing on replacing the current production-limiting components with feasible alternatives, decoupling aquafeed form the consumption of wild-stocks. Hence, R&D are focusing on the development of alternative feeds which are novel ingredients or production methods that replace macronutrients improving sustainability of the process. Secondly, aquaculture farming is trying to improve animal welfare thought promoting the livestock immunocompetence and well-being deceasing stress and mortality. To achieve that R&D is focusing on preventing diseases as well as promote feed conversion and growth in the livestock.

Focusing on the production, aquaculture industry is focusing on reducing the environmental impacts of its facilities through mitigating the damage to water, land, and other ecosystem elements. Specifically, stakeholders are investing on the improvement of new cultivation systems to renew the infrastructures for the reduction of the consumption and resource use.

Finally, aquaculture is moving toward improving the traceability and transparency of the products remodeling the control over production processes. For this reason, technologies that provide real-time data collection and support analytics are developing. R&D is also focusing on fine-tune performance by monitoring feeding, fish health and environments as well as improving the exchange of information between sellers and buyers (Lux Research Inc., 2023).

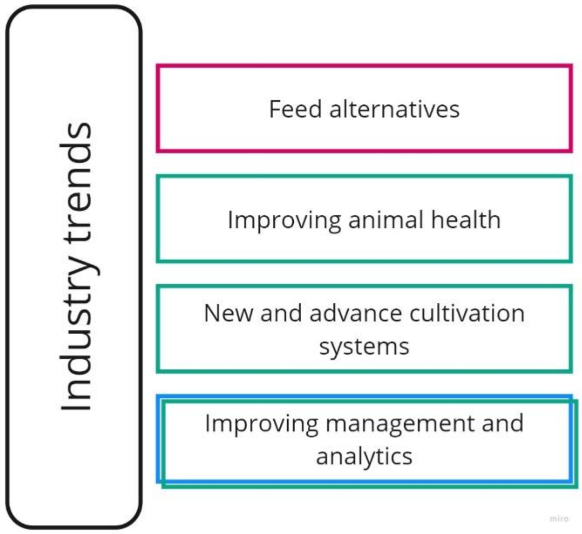


Figure 22. Industry trends within the Aquaculture value chain (Lux Research Inc., 2023).

Social Trends

The development of the aquaculture sector has strong impacts also on the social dimension. In 2020, almost 58.5 million people across the globe were engaged as full-time, part-time, occasional, or unspecified workers in fishery and aquaculture and, among them, 35% were employed in aquaculture. Besides, up to 80% of all fishers and fish farmers were in Asia and Africa, whereas, Europe, North America and Oceania had each less than 1% of the global population involved in the sector (FAO, 2022b)

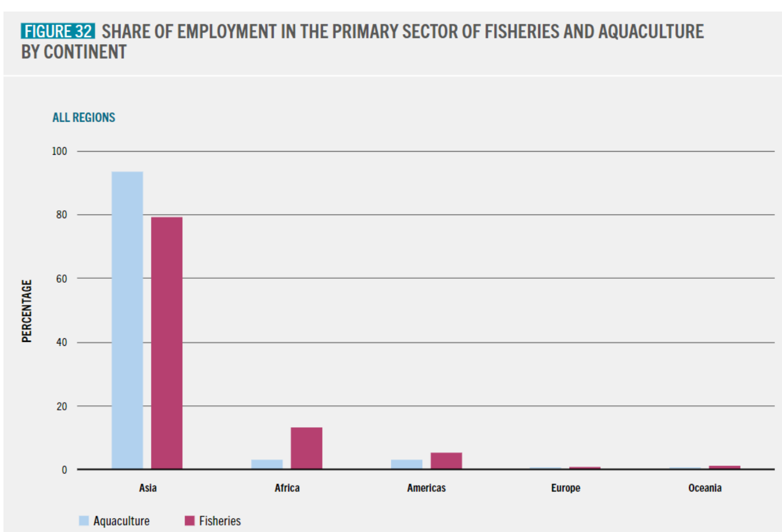


Figure 23. Share of employment in the primary sector of fishery and aquaculture by continent (FAO, 2022b).

Overall, total employment has been fluctuating in the last years due to COVID-19 repercussion. The entire value chain was severely disrupted as a result of the lockdowns and the employment rate decreased rapidly (FAO, 2022b). Looking at women employment, they account for 28% of the workforce in the primary sector and increase up to 50% across the pre- and post-harvest components of the value chain (FAO, 2022b). Considering the employment rate in Europe, the EU identifies aquaculture as one of the sectors with the highest growth and job creation potential (European Commission, 2012). Nowadays, the EU aquaculture sector provides jobs for 69.000 people in 15.000 enterprises (European Commission et al., 2021; European Commission, 2022c) which are mainly micro-enterprises, employing less than 10 employees (European Commission, 2022c).

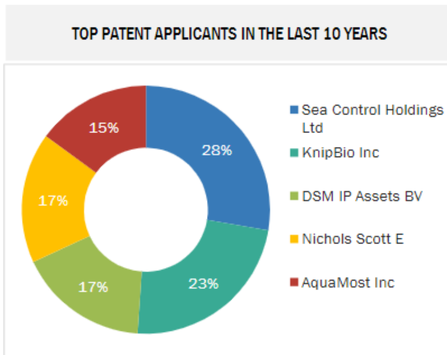
Looking at gender distribution, EU aquaculture industry employs 77% male and 22% female workers. This variation in gender equality might be explained by cultural and historical differences which need further research however, lately, aquaculture became more attractive for women helping consequently the development of rural areas (Nicheva et al., 2022). Overall, 35% of the aquaculture employees are younger than 40 years and, only in the fish processing sectors, the percentage of young workers increase (Nicheva et al., 2022). Looking at education rate, about 9% of aquaculture workers have a high level of education and 39% have a low level. Hence, the lower education rate of the employment makes the less educated or skilled workers most vulnerable to social changes caused by new development, especially towards the current technological implementation of the aquaculture industry (Nicheva et al., 2022).

Environmental Trends

The EDP and the Farm to Fork Strategy highlight the potential of the sector in the future as a valid source of protein for food and feed with a low-carbon footprint. However, currently the environmental impact of aquaculture is completely dependent upon the intensity of production, the species being farmed and the location of the farms. The fast development of the sector presented several critical issues for the environments from eutrophication and nutrient accumulation, spreading of new diseases among the native species, introduction of invasive species and pollution in the surrounding water bodies. For this reason, increasing pressures are forcing the sector into new solution to mitigate the adverse effect of aquaculture on the environment facing the different steps of its value chain (Ahmad et al., 2022).

Technology Trends

The growth of aquaculture market is strongly related to the technological advantage of the sector. The number of patents granted in the last year is increasing. (MarketsandMarkets, 2023).



TOP PATENT OWNERS IN THE LAST 10 YEARS	NO. OF PATENTS
Sea Control Holdings Ltd	13
KnipBio Inc	11
DSM IP Assets BV	8
Nichols Scott E	8
AquaMost Inc	7

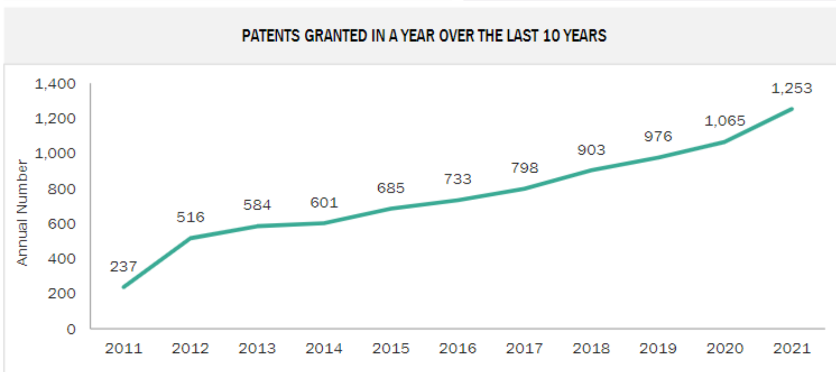


Figure 24. Number of patents granted for aquaculture products, 2011-2021 (MarketsandMarkets, 2023).

As anticipated in the industry trend section, R&D focused on aquaculture technological innovation is thriving. Cutting-edged technologies are being developed to answer the different challenges within aquaculture value chain focusing on a sustainable transition.

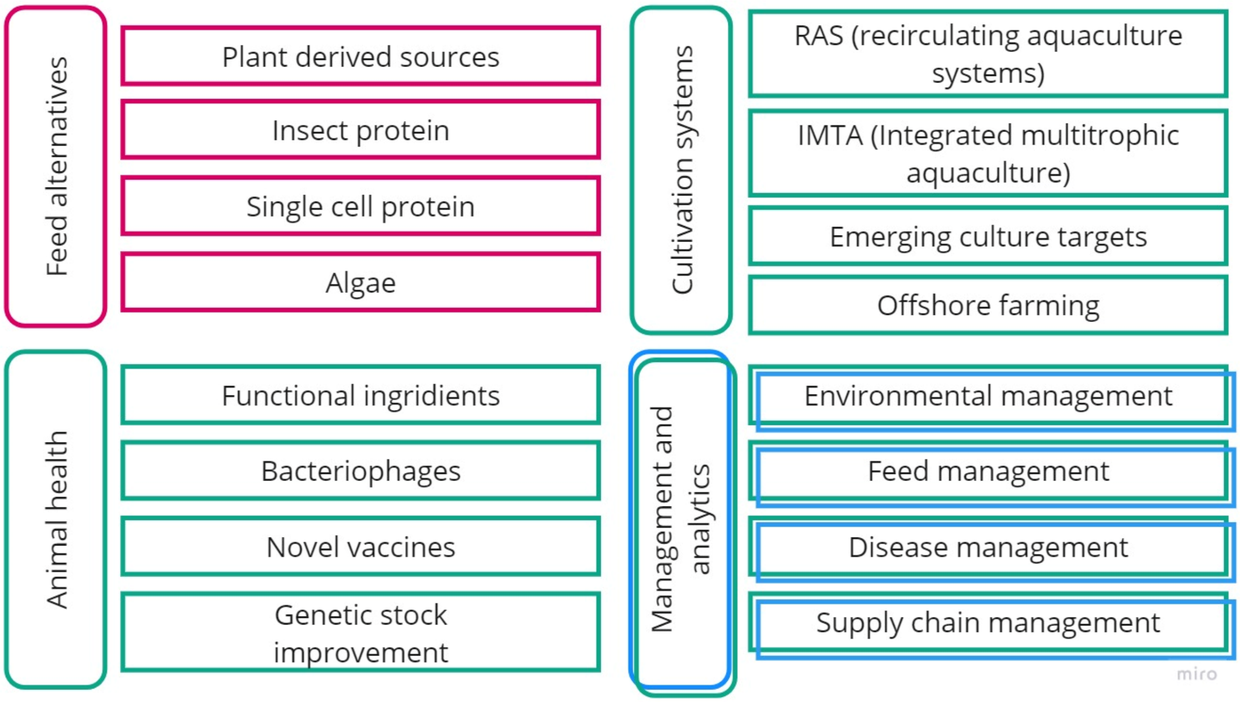


Figure 25. Emerging technology options in the aquaculture sector (Lux Research Inc., 2023).

Feed alternatives

Fish meal is the major dietary protein source in aquaculture feed, yet fish meal availability is destinated to decrease due to the unsustainable exploitation of wild fish stock. Moreover, feed cost is one of the main expenses related to fish farming. Life cycle assessment (LCA) studies have also indicated that aquafeeds are often the dominating contributor to harmful environmental impacts associated with commercial aquaculture activities (FAO, 2022b). By 2050, aquaculture is projected to expand and intensify further, consequently, large volume of feed will be needed. For this reason, aqua feed formulators are increasing the inclusion percentage of alternative protein sources and developing innovative products and processing techniques to remove pressure and answer those needs. While the search of feasible alternative feeds introduces its own challenges, the future of sustainable aquaculture is strictly connected on the sourcing of nutritionally balanced feed components that to substitute traditional fish meal (Lux Research Inc., 2023). To be considered economically and environmental viable, feed alternatives must achieve different criteria:

- Nutritionally adequate;
- Palatable to the framed organism;
- Obtained from sustainable production;

- Physically stable;
- Easily handled and stored;
- Low environmental impacts (FAO, 2022b).

Animal health

Improving animal welfare and reducing environmental impacts are also key challenges in aquaculture production. The intensification of aquaculture and the globalisation of trade in aquatic products have led to the increasing of infectious disease in the stocks (FAO, 2022b). For this reason, technological innovation is focusing on promoting livestock's immunocompetence and well-being reducing the overall mortality. Currently, antibiotics treat bacterial and parasitic diseases in different aquatic organisms, yet the amount of products used changes across regions and countries and are not typically reported. For this reason, farmers are searching for sustainable additives which can replace antibiotics as well as promote feed conversion and growth while overcoming the increasing concern for antimicrobial resistance and shifting regulations. Antibiotics alternatives are emerging technology options which include probiotics, bacteriophages, and vaccines. Overall, advantages focus on simplifying manufacturing for scalability and administration techniques as well as targeting multiple pathogens altogether (Lux Research Inc., 2023).

Cultivation systems

Improving the cultivation systems used in aquaculture facilities is one of the main challenges to reach aquaculture sustainability. Intensive farming practices have strong impact on the environment damaging both water and land. Moreover, cage farming could introduce waste that turns into marine litter and disease in the ecosystems. To overcome those problems an improve the infrastructure, new systems that can assure water quality, reduce energy consumption and resources used are tested. As well as unique approaches to rear multiple aquatic species. System developers are focusing in high-value, high-demand species testing technologies that could support offshore production, improve recirculating systems design, boost co-culture approaches and extensive production of non-conventional species (Lux Research Inc., 2023). In 2021, the aquaculture small-scale production accounted for the larger share of 72.3% of global market. The largest share of small-scale production is related to the growing demand of aquaculture product in developing countries and the growing support of various public and private organisation. Specifically, the small-scale production is projected to reach USD 40,808.3 million by 2027, from USD 28,782.0 million in 2022, at a CAGR of 7.2% during the forecasted period (MarketsandMarkets, 2023).

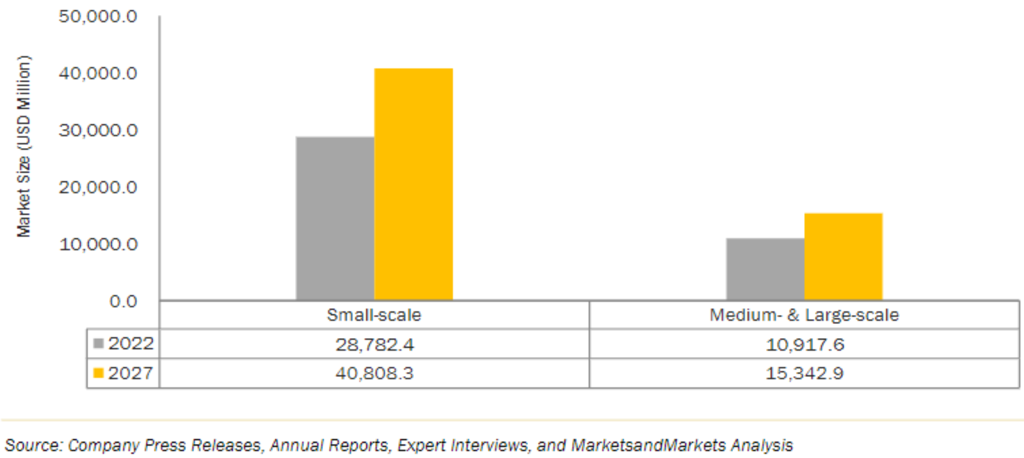


Figure 26. Aquaculture Product Market, by product type, 2022 vs 2027 (USD million) (MarketsandMarkets, 2023).

Management and analytics

Innovation regarding digital technologies in the aquaculture sector is steeply increasing. The demand of stare-of-the-art management and analytics tools are rising to assure real-time monitoring, improve treatability and mitigate environmental damage. Hence, with the expansion of digital technologies such as platforms, software and infrastructure, digital applications are more and more employed in aquafarms to improve farm stock management, environmental monitoring, risk prevention, biosecurity and automation of farm activities (FAO, 2022b). Technological improvement achieved through digitalization can lower feed usage and waste, better water quality, reduce labour cost and assure transparency within the value chain. Nowadays, different means are starting to enter the aquaculture industries such as remote sensing for real time monitoring; geographic information systems (GIS) for ecosystem management; sensors, robots and cameras for real-time and distant monitoring and operations(FAO, 2022b). These technological advances could reduce production cost by improve efficiency and use of input resources as well as reduce human errors. However, due to the high cost for management and installation of those advantage technologies as well as the expertise needed technological innovation is still low in aquaculture farms (FAO, 2022b).

Market Development

General Constrains

The growth of the aquaculture industry will be fundamental to support future protein demand however, intensification of aquaculture poses challenges to the environmental impact of its production. Nowadays, for many farmed aquatic species, almost all protein and fat needed in the feed comes from fish meal and fish oil derived from wild pelagic fish stock that are currently overfished or at maximum sustainable yields

(MarketsandMarkets, 2018). Although, new solutions are explored the complete replacement of fish meal in feeds with a sustainable source of inputs is needed to reduce aquaculture's impact on marine ecosystems. Looking at the cultivation systems, intensive farming practices can damage water qualities through the introduction of waste and disease into the environment. For this reason, new farming methods and a better management the systems are needed to decouple the growth of the sector with environmental degradation (Lux Research Inc., 2023)

Another major factor restraining industry's growth is the requirement for high initial investment for both the implementation of existing facilities and the establishment of new ones. To update the production farmers need to invest in new facilities and technologies which also require high maintenance cost, hence, innovation and implementation is not always possible (MarketsandMarkets, 2019).

Moreover, the installation needed for organic and sustainable aquaculture require specific and additional coast to comply with organic regulation, specifically for finfish. Those specific organic requirements lead to additional coast such separation of organic production from conventional production, organic feeds, organic certificate juveniles, and management of parasites with limited use of medicine (Directorate-General for Maritime Affairs and Fisheries, 2022).

Lack of technological awareness across aquaculture farmers constrains the adoption of innovative technologies for example automatic monitoring systems and improved management and analytics in each level of aquaculture value chain (MarketsandMarkets, 2019). Nowadays aquaculture is rapidly changing. More and more new technologies are used in the farming site to improve the effective management of the systems. As the aquaculture industry is growing, the need of highly skilled personnel becomes evident. Unfortunately, advanced cultivation systems equipped with cutting edge technologies required new engineering-related challenges coupled with ongoing adjustment to create the perfect environment for a more stable production. For this reason, farms management require a highly skilled workforce to allow a smooth growing of the industry (MarketsandMarkets, 2019).

Finally, an implementation of the regulation related to the aquaculture sector is needed to adjust a sustainable growth of the sector. For example, close recirculating systems are only allowed in the EU organic regulation for hatcheries and nurseries or facilities for the production of species used for organic feed organisms. Hence, stakeholders who invest in this method for on-growing purposes are not labelled as organic (Directorate-General for Maritime Affairs and Fisheries, 2022).

Challenges

The rapid expansion of the aquaculture sector is currently facing new and updated challenges.

Firstly, intensive aquaculture practices have armful impact on the environment and with the steeply growth of the sector the impact on the ecosystem are worsen. Despite its key role of future food security, current aquaculture production is related with substantial resource consumption and environmental impacts. From overconsumption of water and energy to greenhouse gasses emission and eutrophication (Jiang et al., 2022) to the realise of pollutes in the surrounding water bodies. Specifically, wastewater containing large amount of nutrients, suspended solids, chemical and pharmaceutical products are either discharged from the aquatic species farms (Ahmad et al., 2022) or directly dissolved in the medium. Also, fish feed is mainly based on wild stocks hence the lack of valid alternatives could lead to a higher exploitation and shortage of wild stocks (Lux Research Inc., 2023; MarketsandMarkets, 2018). Thus, decreasing the environmental pressure assuring a lower consumption of primary biotic and abiotic resources is fundamental to assure the sustainable growth of aquaculture.

Secondly, aquaculture is deeply affected from a historic lack of digital connectivity and communication. The lack of traceability and transparency in the production is among the greatest challenges of the sector. Aquaculture and capture fisheries shared the same markets leading to consumer confusion about product origin and quality. In addition, lack of transparency related to the trading and selling of aquaculture products compromise stakeholders' ability to certify products and sell them at competitive prices. Hence, uncoordinated activities and collaboration among processors, transported, brokers, wholesalers, traders and consumers result in delay of products transport promoting spillage and product loss (Lux Research Inc., 2023).

Regulatory Factors

Aquaculture, unlike fishery, is not an exclusive EU competence, however, EU rules such as those ensuring environmental protection or human and animal health, apply to aquaculture activities(European Commission, 2022a). In particular, the strategic coordination on aquaculture policy in EU is based on the Commission's Strategic Guidelines for the sustainable development of EU aquaculture, which was firstly adopted in 2013[14], and the Multi-annual National Strategic Plans (MNSPs)[15] for aquaculture prepared by EU Member states considering those guidelines (European Commission, 2022c).

The previous MNSPs were drafted in 2014-2015 focusing on the promotion of sustainable aquaculture with development targets until 2020. The implementation of these MNSPs was supported by the Open Method of Coordination, which promotes the exchange of good practice across EU, as well as by funding, made available in the European Maritime Fishery Found (EMFF) and other EU funds (European Commission, 2022c). Finally, stakeholders involved in the sector were involved through the Aquaculture Advisory Council (AAC) (European Commission, 2022c). Nowadays, the EU member states are reviewing their national plans based on the new Strategic Guidelines for EU aquaculture which was adopted in 2021 by EU commission[16]. The update guidelines aim to offer a common vision for EU Member States and all relevant stakeholders for the further development of aquaculture based on the European Green Deal (European Commission, 2021b). These guidelines focus on 4 objectives:

1. Building resilience and competitiveness;

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[14] EUR-Lex - 52013DC0229 - EN - EUR-Lex (europa.eu)

[15] Aquaculture multiannual national plans (europa.eu)

[16] EUR-Lex - 52021DC0236 - EN - EUR-Lex (europa.eu)

2. Participating in the green transition;
3. Ensuring social acceptance and consumer information;
4. Increase knowledge and innovation.

Those guidelines include concrete recommendations on a broad range of issues and propose specific action[17] on different challenges and propose specific actions by the Commission, EU Member States and the AAC. In the table below are reported the action related to objective 4 "Increasing Knowledge and Innovation".

2.4. INCREASING KNOWLEDGE AND INNOVATION			
Area	**Commission**	**EU Member States**	**Aquaculture Advisory Council**
	• Set up, as part of the EU aquaculture on-line platform mentioned in these guidelines, a site where all **EU-funded research projects** on aquaculture are registered and their results made publicly available. • Foster the development and **matching of research and innovation** strengths – across Member States and regions, as well as related business opportunities, including through Smart Specialisation Strategies aimed at building full value chains across the EU. • Foster the creation and implementation of solid **dissemination-and-exploitation** plans for funded projects on research and innovation. • Support research and innovation on sustainable aquaculture, in particular through Horizon Europe and its identified **priorities**. • Support (including with the use of EU funding) **skills development** in the aquaculture sector[12].	• Set up a **framework of cooperation** bringing together public authorities, industry, and research and educational institutions, and promote the development of clusters for aquaculture[13]. • **Disseminate** information on national research and innovation projects and their results. • Support (including using EU funding) **skills development** in the aquaculture sector and the regular training of aquaculture professionals. • Coordinate and support research and innovation in line with identified **priorities**, including those priorities reflected in the reports of the Standing Committee on Agricultural Research (SCAR-Fish). • Support the **upscaling and commercialisation** of innovative practices in the aquaculture sector.	• Encourage aquaculture producers and other stakeholders to **work together** with research and innovation institutes and public authorities to find solutions to the challenges of the sustainable development of EU aquaculture. • **Disseminate** information on research and innovation projects and their results among members. • Promote the **uptake** by the EU aquaculture industry of existing **innovation**. • Promote in the aquaculture sector the regular **training** of aquaculture professionals, in particular on how to incorporate innovative practices.

[13] EU cluster initiatives launched under the COSME programme to support SME innovation and growth are a good example of advancements in the area; e.g. the French aquaculture and marine resources cluster, which brings together over 170 members (including more than 60 SMEs).

Figure 27. Strategic guidelines for a more sustainable and competitive EU aquaculture for period 2021 to 2030. 4) Increasing Knowledge and Innovation (European Commission, 2021a).

Moreover, to assure the support in the implementation of the Guidelines, the EU aims at created and *EU Aquaculture Assistance Mechanism* in 2022 with the objective of assist the aquaculture actors to consolidate best practice on the areas covered by the Guidelines (European Commission, 2021b, 2022c).

[17] resource.html (europa.eu)

Aquaculture is also relevant for the achievement of different Sustainable Development Goals (SDGs) of the Agenda 2030 of the United Nation[18]. The SDGs are a universal set of goals and connected targets agreed by 194 United Nations member states to direct their development policies and initiatives towards sustainability (United Nations, 2015). For the aquaculture development, almost all the SDGs are relevant, however, aquaculture production is mentioned only in SDG 14 "*Life below water*" (FAO, 2022b).
Starting with Goal 14, topics and challenges related to a more sustainable development and management of the sectors are broadly discussed within different targets. The Goals highlights how, to achieve the sustainability of the sector, different action must be undertaken in the industries form the reduction of pollution related to aquaculture activities to the improvement of the economic benefit of sustainable use of marine resources in development countries (FAO, 2017, 2022b).

Table 7. Goal 14 "Conserve and sustainably use the oceans, seas and marine resources for sustainable development"[19] and its relevant target for the aquaculture sector (FAO, 2017).

14 LIFE BELOW WATER	14.1 By 2025, prevent and significantly reduce **marine pollution of all kinds**, in particular from land-based activities, including marine debris and nutrient pollution
	14.2 By 2020, **sustainably manage and protect marine and coastal ecosystems** to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans
	14.5 By 2020, **conserve at least 10 per cent of coastal and marine areas**, consistent with national and international law and based on the best available scientific information
	14.7 By 2030, increase the **economic benefits** to small island developing States and least developed countries from the sustainable use of marine resources, including through sustainable management of fisheries, aquaculture and tourism
	14.b Provide **access for small-scale artisanal fishers to marine resources and markets**
	14.c Enhance the conservation and sustainable use of oceans and their resources by **implementing international law** as reflected in the United Nations Convention on the Law of the Sea, which provides the legal framework for the conservation and sustainable use of oceans and their resources, as recalled in paragraph 158 of "The future we want"

[18] THE 17 GOALS | Sustainable Development (un.org)
[19] Goal 14 | Department of Economic and Social Affairs (un.org)

However, the sustainable development of the aquaculture sector could have also relevant impact on Goals not strictly related to the management and conservation of the marine environment. SDG 1 "No poverty", 2 "Zero hunger", 8 "Decent Work and Economic Growth", 12 "Responsible Consumption and Production" and 13 "Climate action" are all highly relevant to the aquaculture development (FAO, 2017). For this reason, improving the sustainability of the sector is challenging but could have important implication on global sustainability.

Opportunities

The steep rise of the aquaculture sector creates several opportunities of development. Governments around the world are promoting initiatives to support the aquaculture market especially in South Asia where aquaculture production is rising (MarketsandMarkets, 2018).

Looking at farm management, the adoption rate of aquaculture monitoring devices in developing countries is low due to high installation cost. However, with the increasing product demand and consequent investments, modernisation and automation of aquaculture farms is expected hence rising the demand for advanced aquaculture technologies such as remotely operated vehicles, sensors, cameras, and monitoring systems (MarketsandMarkets, 2019).

Overall, the number of aquaculture farms and fish farmers across the world has doubled since 1970. Since 1990, aquaculture has been the fastest-growing segment of food production by volume, with a compound annual growth rate of 8.3% (MarketsandMarkets, 2019). In Europe, the sector consists of around 15,00 enterprises, mainly small businesses or micro-enterprises in coastal and rural areas (European Commission, 2022b) which are destinated to growth in the next decade.

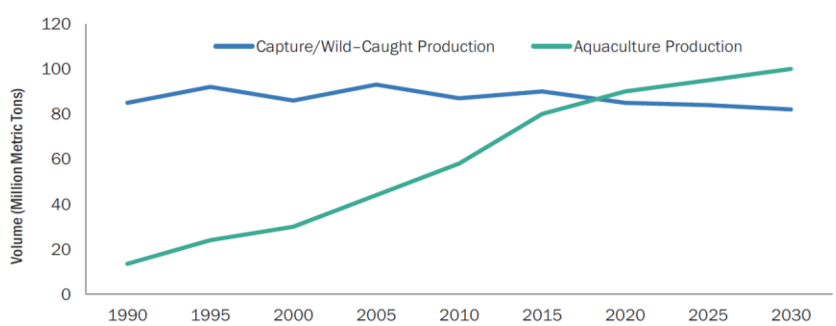


Figure 28. Aquaculture production is expected to surpass wild-caught fish production by 2024 (MarketsandMarkets, 2019).

Increasing popularity of new cultivation systems especially recirculating aquaculture systems are offering new opportunities in the market. Those new system could assure better environmental performance, higher production capability, reduced mortality, and greater control over production outcomes. Hence, advantages related to new cultivation systems are likely to make them commercially superior in the coming years (MarketsandMarkets, 2019).

Competitive Landscape and Players

The steep growth of aquaculture industry has been witnessing strong competition among key players thanks to the increase demand for products. Overall, aquaculture innovation is not exclusive to a particular region, yet the production is mainly centralised in the Asia-Pacific zone which accounts for 90% of the total production. Other states such as Norway, Chile and Egypt are also focusing on improving the production of their facilities, however, current innovation efforts span across the globe as the governments are providing increasing support to the industry's environmental and financial sustainability. Focusing on the businesses, aquaculture's landscape is mainly dominated by small to medium enterprises (SMEs). The technological development in the field is supported mainly by those SMEs, universities and research institutes which are developing innovative solution to decrease the impact on the environment and improve the efficiency of the processes. Overall, growth has been consistent and exponential focusing in areas where high-value fish are more easily produced, and consumers make aquatic organisms a larger part of their diet. Whitin the technology innovation, businesses are focusing on environmental management followed by feed management through digitalisation of the value chain (Lux Research Inc., 2023).

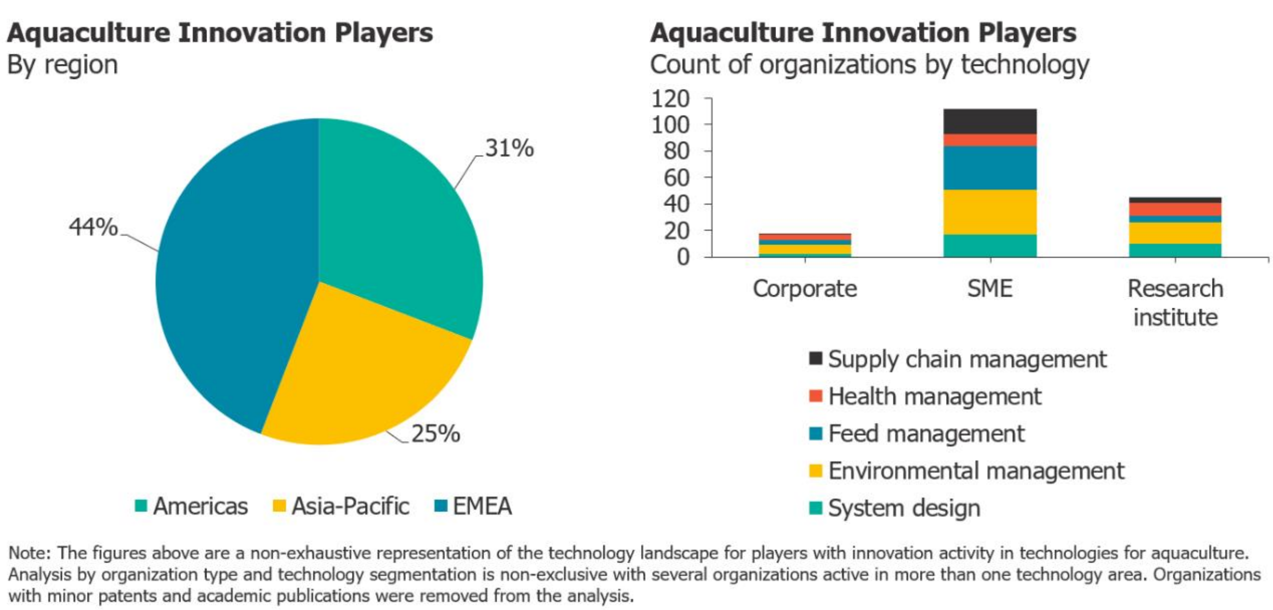


Figure 29. Aquaculture innovation players (Lux Research Inc., 2023)

R&D efforts are focusing on improving all the steps identified in the aquaculture value chain. Starting with upstream process issues many facilities are focusing on finding feasible feed alternatives. Most players are working to scale to commercially relevant levels new products such as insect and single-cell protein (Lux Research Inc., 2023). An overview of the main players in feed alternative production are reported.

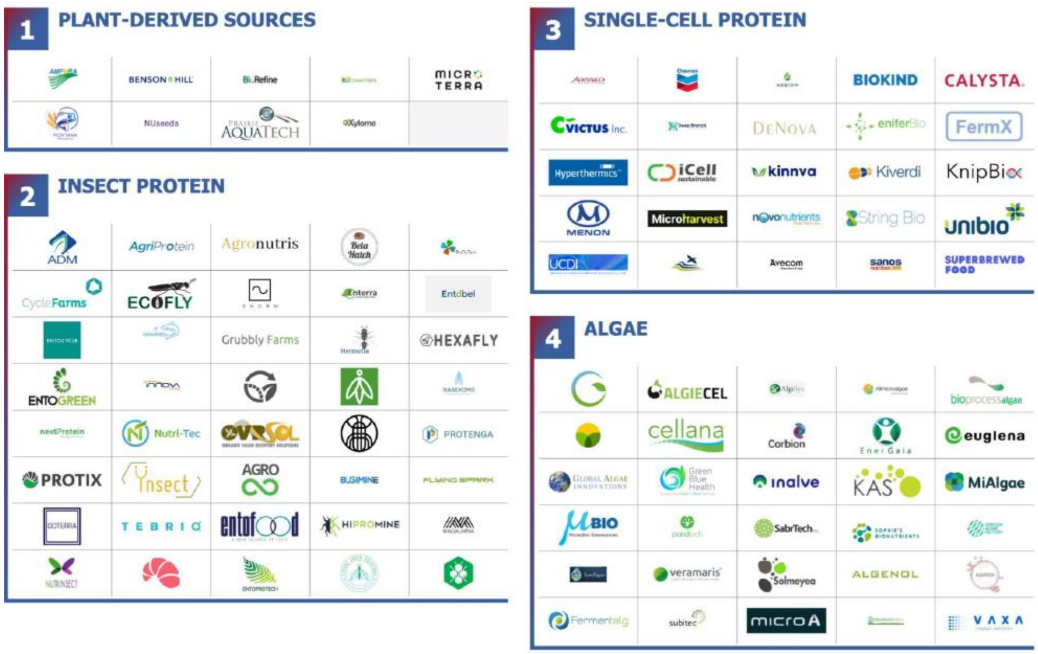


Figure 30. Main players involved in feed alternative innovations. 1) Plant-Derived sources; 2) Single-Cell protein; 3) Insect Protein; 4) Algae (Lux Research Inc., 2023).

Innovation related to the improvement of animal health is mainly focused on antimicrobial resistance, improved production resilience and shifting regulations. However, functional ingredients are the least regulated but largely used. On the other hand, bacteriophages, novel vaccines, and genetic stock improvement must overcome greater barriers to reach commercialisation. The main goal is to develop cheap and effective solutions to protect the organisms and overcome the strict regulatory process (Lux Research Inc., 2023). For this reason, only few have reached commercial-scale production as reported in the player overview in the figure below.

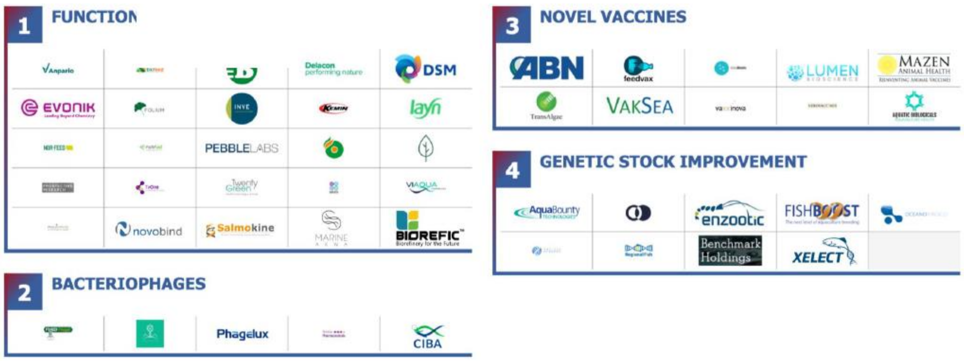


Figure 31. Main players involved in animal health innovations. 1) Functional ingredients; 2) Bacteriophages; 3) Novel vaccines; 4) Genetic stock improvement (Lux Research Inc., 2023).

Businesses cantered on system development are beginning to explore opportunities for diversification. Investment focused on RAS are growing thanks to the involvement of highly funded players. Moreover, development of aquaponics facilities is urban and desert areas are steeply rising despite limited capacity. Finally, deep-ocean and emerging culture targets are still at small-scale with technology development mainly involved in biorefinery approaches to processing (Lux Research Inc., 2023). An overview of the main global players is reported in the figure.

Cultivation systems

Figure 32. Main players involved in cultivation system innovations. 1) RAS (recirculating aquaculture systems); 2) Aquaponics; 3) Emerging culture targets; 4) Offshore farming (Lux Research Inc., 2023).

Finally, management and analytics tools are emerging to support real-time insight and encourage end-to-end visibility. R&D is mainly driven by start-ups which are focusing on management of food loss, AI and computer vision to monitor the stocks and remote sensing for advancing offshore farming (Lux Research Inc., 2023). For this reason, many players are involved in the development of those application as is reported in the figure.

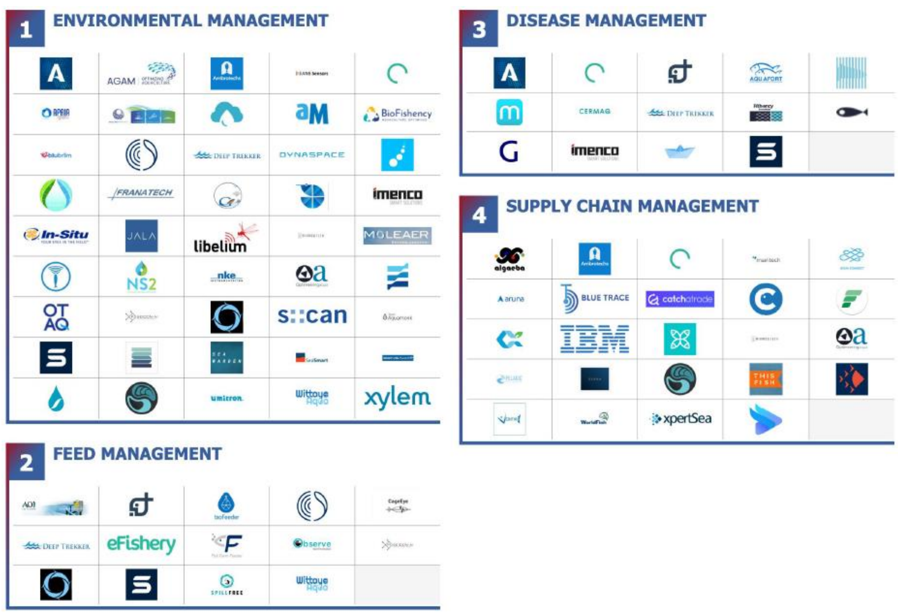


Figure 33.Main players involved in management and analytic innovations. 1) Environmental management; 2) Feed management; 3) Disease management; 4) Supply chain management (Lux Research Inc., 2023).

Aquaculture: Analysis

Fish meal and fish oil have historically been the most desirable ingredients for feeding farmed fish. However, overfished and depleted wild fish stocks pose a threat to fish meal and fish oil supply. Meanwhile, aquaculture production is on a significant rise and driving demand in feed ingredients. Even with significant research efforts ongoing to reduce the dependence on fish meal for aquaculture diets, the impact of rising fish meal prices on production costs for major farmed species is outpacing the impact of those research efforts. As aquaculture feed ingredients will continue to get more expensive, producers will be driven to seek lower-cost comparable alternatives.

While aquaculture in the Adriatic-Ionian region is still in its preliminary phase, production is growing due to an increased consumer demand for seafood products. Accordingly, the sector will face challenges surrounding tightening fish meal supply that may cause serious repercussions for the region's resources, socio-economic development, and environmental sustainability. Moreover, fish meal alternatives like insect protein and single-cell protein will have to rise to meet demand.

Insect Protein

Insects are a lean source of protein and have an amino acid profile that makes them highly nutritional for feeding farmed animals and show promising results in terms of animal growth and performance. It also represents a promising alternative due to the possible environmental benefits, as production technologies leverage insect biomass conversion and are frequently touted as contributing to food waste reduction.

Developers rear insects in enclosed and controlled environments, typically feeding larvae with food waste sourced from nearby food distributors. The end products are offered as wet or dried whole insects or powders. The most commonly favored insect species for feed applications are black solider fly (BSF) and mealworm larvae because of their high protein content and a short growth cycle. However, crickets and other insect types like fruit fly larvae are also exceptionally high in protein (reaching 70% protein content) and being explored.

Black soldier fly. Source: Shutterstock.

The BSF remains the dominant insect targeting aquaculture feed, as they can consume catering waste that contains animal byproducts and solids from municipal waste streams. Mealworms are pickier about the selection of waste as feedstock, limiting their feedstock to spent grains and pre-consumer vegetable matter. However, ground-based insects offer ease of management; given mealworm beetles' inability to fly, their production management is considered an advantage for scalability compared to BSF. This advantage enables the production process to be more easily automated, promoting increased efficiency and large-scale production.

Promoters & Inhibitors

Insect protein is making headway as an alternative ingredient to replace fish meal, spurring significant investment in research and development of production methods. Today, most developers remain at an early-stage and face technical hurdles and regulatory challenges. A few key drivers and barriers are outlined below.

Promoters

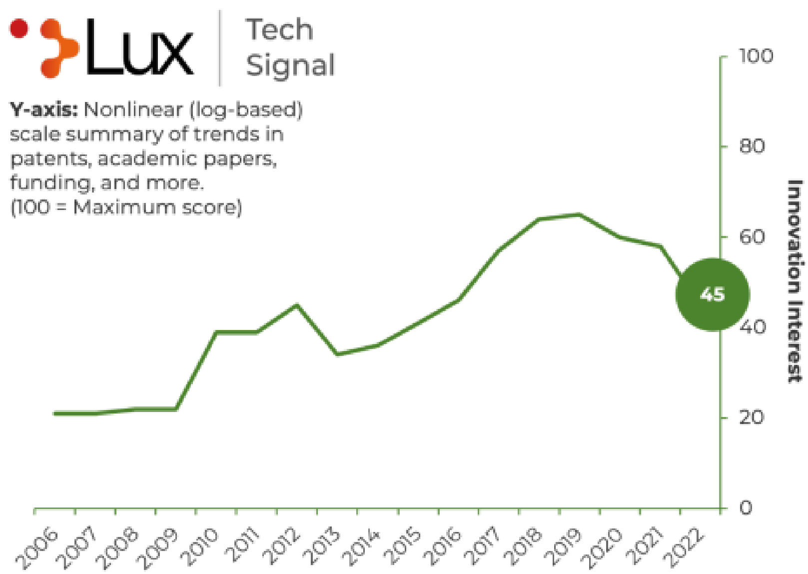
- **Changes in legislation.** Regulations promoting sustainability and decarbonization enable the use of insect protein within livestock feed, pet food, and human diets. In 2017, the EU authorized the use of processed animal proteins from insects in feed for aquaculture animals; support continues for food waste prevention and authorization for human consumption, promoting regional industry growth and opening the door for insect protein players.
- **Species development.** Advanced breeding techniques are leveraged to modify and improve traits for increased production efficiency and product quality. Many developers have significantly decreased the breeding cycle for greater productivity.

- **Product validation.** Insect protein for aquaculture applications requires strong feed trials data (e.g., increased or maintained biomass and quality, increased growth rate, or simplified value-driving certifications) for adoption to reach critical mass. Developers that test their insect-derived ingredients in feeding trials are most likely to secure partnerships that will drive growth.

Inhibitors

- **Low production scale.** Global production capacity is currently unable to match demand for insect proteins. While some Southeast Asian nations consume insects regularly as part of the human diet, production for use in animal feeds is still in its infancy and markets often require improvements in quality control. Most insect producers report production for feed meals in single-digit-tons-per-week ranges.
- **Production efficiency**. Technical hurdles for insect production include formulating high-efficiency diets and controlling the growth environment to maintain optimal insect health and growth. Moreover, securing a predictable, cheap, and effective insect feedstock is paramount to the success of an insect protein company. While global food waste is abundant, insect production is not strongly restricted by its waste stream.
- **Animal diversity**. Dietary requirements of livestock vary by animal species. The nutrient content of insects is affected by the food source more than the insect species, but chitin content differs by insect species. Therefore, there is room within the production process to manipulate production for specific applications; however, in most cases insect meal cannot be the only ingredient source to satisfy livestock dietary needs without impacting production performance.

Innovation Trends



*The **Lux Tech Signal** is a composite score, combining data in patents, papers, and funding, plus Lux Research's proprietary data. It quantifies the progress of each technology, against a maximum innovation interest score of 100. Changes over time indicate growing (or shrinking) innovation interest, while inflection points may point to commercial opportunities or challenges ahead.*

The Lux Tech Signal indicates that innovation interest in insect protein has decreased over the last five years. Prior to this decrease, interest in insect production was escalating across the globe as a promising strategy to capitalize on trends to minimize and valorize food waste and to support increasing protein demands for food and animal feed markets. Accordingly, up until 2020 insect protein experienced significant investment and rapid growth. It became crowded with players looking to test insect-derived ingredients in feeding trials and scale up production. Moving into the innovation downturn phase, leading insect producers are focused on improving adoption. Those capable of demonstrating strong business execution capabilities are experiencing scale up success. The largest insect production facility constructed to date produces about 15,000 MT of insect protein per year (InnovaFeed). Those operating at smaller scales or regional early-stage entrants, will need to secure capital to apply innovation to production efficiency, whether through automation, insect genetics, or production feedstock. Therefore, growth in insect protein production will be driven by the leaders rather than new entrants over the next five years. These players will continue to validate their products within a range of target industries, but insect protein will continue to generate the most interest for applications in aquaculture feed and pet food.

Key Players

Recent Developments

- **InnovaFeed (France).** [InnovaFeed's USD 250 Series D reaffirms BSF as a leading insect protein alternative]. InnovaFeed will use the funds to further expand existing capacity in France, accelerate international expansion in the U.S., and support ingredient R&D. The announcement is particularly notable for the ample size of funding that exceeds rounds raised by other black soldier fly larvae (BSF) producers.

InnovaFeed's production unit in Nesle, France. Source: InnovaFeed

- **Nutrition Technologies (Singapore).** Nutrition Technologies secured a USD 20 million to fuel its expansion plans for insect protein production. The funding will go towards Nutrition Technologies' expansion in Southeast Asia, including its site in Malaysia and a planned joint venture as well as support the company's product development and commercial launch in the European market.

- **Ynsect (France).** Ynsect is expanding its mealworm production footprint with two planned facilities in North America. Ynsect has partnered with Ardent Mills to build a 50,000-Mtonne facility in the U.S. by the end of 2023 and with Corporativo Kosmos to build a similar plant in Mexico that will export to the U.S. market. Neither location was disclosed. The move follows the commissioning of Ynsect's flagship farm in Amiens, France, that is claimed to be the world's largest insect production site with a capacity of 200,000 Mtonne/y of insect-based ingredients. Ynsect has already established a presence in the U.S. through its acquisition of Jord Producers in March 2022.
- **Entocycle (United Kingdom).** Entocycle raised USD 5 million for solutions to optimize black solider fly (BSF) farming. The investment will fund Entocycle's commercial rollout of its climate-controlled fly rooms and its computer vision platform (Entocycle Neo) for counting, handling, and weighing BSF larvae. Entocycle's market focus is Europe, eastern and southern Africa, and Japan, Singapore, and Korea for Asian markets.

Future Prospects

Feed formulators are increasing the inclusion percentage of insect protein. However, production scale-up, slow regulatory approval, and the need to reach cost parity with conventional ingredients impede widespread commercial adoption. To overcome these challenges insect protein developers are exploring the use of different production techniques including gene editing and varying levels of system automation as well as processing techniques like enzymatic hydrolysis to improve the nutritional value of ingredients. With the continued advancement of feeding trials and the resurgence of national and regional food and agriculture waste valorization initiatives, insect-derived ingredients warrant attention.

Creating and identifying differentiation among competitors remains a challenge. There is not one insect species that has emerged as the clear winner evidenced by the fact that corporate players are hedging bets by investing in companies across multiple insect species. As a result, expect three correlated company attributes – industry partnerships, industry trials, and validated sustainability certifications – to be the key differentiators to monitor in the short-term as opposed to key innovations.

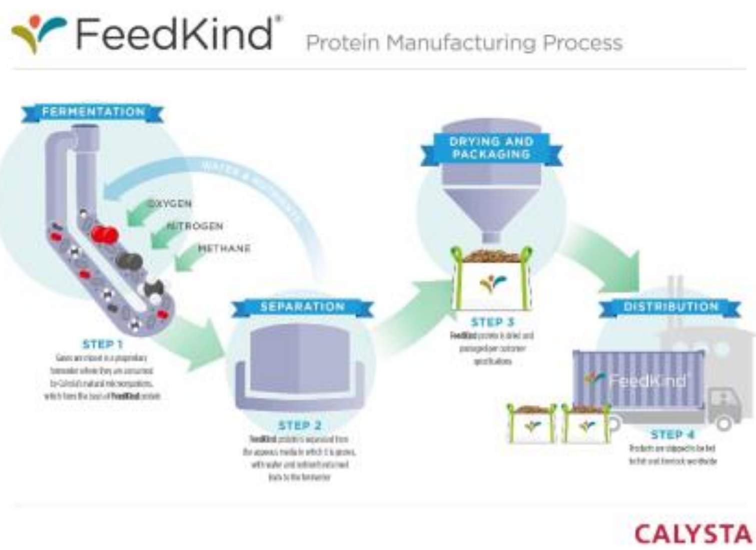
Expect continued investment in insect protein production in the Adriatic-Ionian region, particularly for more advanced or early-stage regional developers focusing on stringent validation and operational scale-up including production automation.

Single-cell Protein

Single-cell proteins (SCPs) show promise as renewable food and feed ingredients. Some fermentation processes use industrial waste emissions (e.g., CO_2), or food and agriculture waste residues as feedstock, which provide new opportunities for ingredient decarbonization and waste stream valorization. However, the most significant value addition for SCPs lies in its potential to reach industrially relevant scales given sufficient capital.

SCPs are grown from a variety of microorganisms, including bacteria, yeast, and other fungi, via fermentation. The microbes involved metabolize simple organic compounds like sugars, alcohols, organic acids, and hydrocarbons, which may be sourced from agricultural or industrial waste.

Single-cell protein meal. Source: NovoNutrients



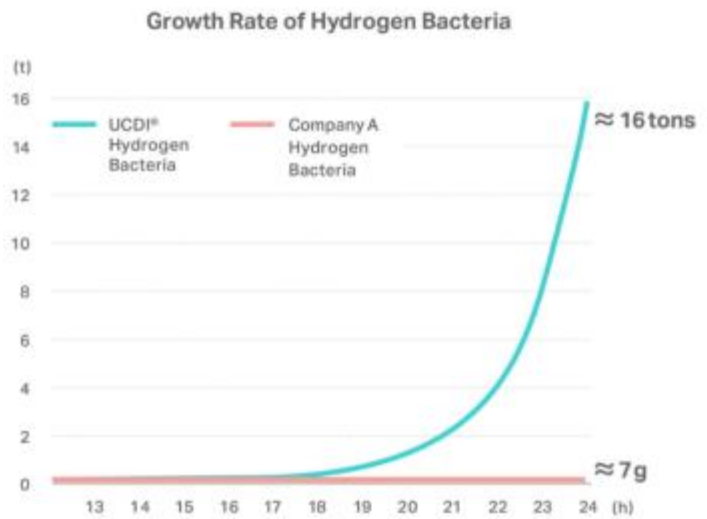
Calysta's FeedKind protein production process. Source: Calysta.

Promoters & Inhibitors

Challenges for this space are production scale-up and access to growth substrates and energy sources. Few SCP developers have achieved large-scale production due in part to high upfront costs and feedstock sourcing. Obtaining funding and support from aligning industries, governments, and the general public is critical for SCP scale up and market penetration.

Promoters

- **Fish meal demand.** Environmental, cost, and supply chain concerns surrounding current protein sources drives development of novel solutions; the emerging opportunity for single-cell protein lies with aquaculture or other livestock feed.
- **Ability to use nonfood carbon sources to generate protein.** Unlike competing technologies, SCP requires simple carbon source feedstocks that can be introduced into a fermentation system. Sources are available at industrial scale. Incentives for industrial facilities to reduce greenhouse gas emissions and collaboration for SCP feedstocks are seen through federal research funding and carbon emission fees.
- **High growth rate and protein content.** Single-cell protein production has potential to produce large protein quantities with less resources (e.g., land and water) in less time compared to conventional protein sources.

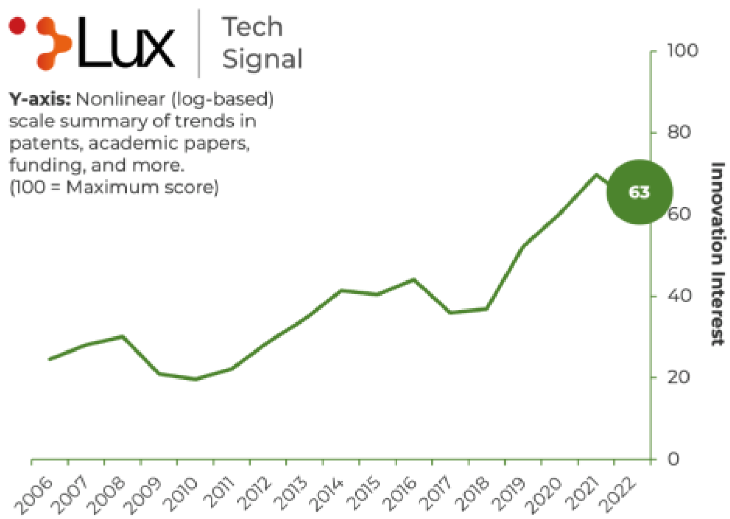


Utilization of Carbon Dioxide Institute claims its microbial strain has a doubling time of one hour and estimated to produce 16 tons in 24 hours. Source: UCDI.

Inhibitors

- **Long timelines to get to commercialization.** Single-celled protein is at an early stage of development; very few companies scaling at this point, and those with technologies using CO2 as a feedstock remain to be proven at the commercial stage.
- **Access to growth substrates an energy sources**. Production often requires proximity to a gas feedstock source (i.e., ethanol plants, flue gas, and biogas derived from agricultural waste) to minimize unnecessary production costs. Systems using CO_2 as feedstock also require hydrogen gas as a microbial energy source. Hydrogen sources include water electrolysis, which is the most expensive component due to today's high electricity prices, or a byproduct of concrete production. Therefore, CO_2-based protein developers in particular must co-locate production with H_2 emitters to alleviate high transportation costs.
- **Significant investment**. Single-cell protein produced at commercial scale will require large-scale fermenters that demand high investment costs. Construction costs for a production plant with a 20,000-tonne-y capacity is approximately USD 75 million; a facility with a 100,000-tonne-y capacity is estimated to cost four times that.

Innovation Trends



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As depicted in the Lux Tech Signal, interest in single-cell protein production is escalating across the globe as a promising strategy to capitalize on trends to support increasing protein demands. While the accessibility of gas inputs for SCP fermentation is a major barrier, in addition to high investment costs, recent support seen from federal governments and oil and gas players (BP Ventures) suggests SCP production will overcome scaling hurdles. Moreover, this support will enable SCP developers to conduct feeding trials and testing to validate their products with the industry.

While this market is nascent, developers are demonstrating high growth potential. Considering SCP's high growth rate and large production volumes from individual facilities, it furthermore takes less time to meet production capacities of conventional protein sources. For example, Deep Branch is expected to reach a 100,000 MT annual capacity by 2027 and aims to produce 600,000 MT per annum global capacity by 2030. Calysta and NovoNutrients both expect their capacities to increase to 100,000 MT of protein per year when fully scaled. Through those companies alone, SCP production could potentially reach 800,000 MT by 2030 and capture a large share of the market for fish meal alternatives.

Key Players

Recent Developments

While most SCP funding rounds are undisclosed, the few large amounts that have been announced are from a few companies that target the feed industry. In 2022, MicroHarvest raised EUR 8.5 million in Series A funding led by Astanor Ventures and Happiness Capital; Deep Branch secured EUR 4.8 million from the U.K. government's Department for Business, Energy, & Industrial Strategy; Arbiom was awarded EUR 12 million from the France Relance investment program; and Solar Foods received a EUR 10 million investment from the Pharmacy Pension Fund of Finland. Other notable investments in the SCP space include:

- **Unibio (Denmark)** received USD 15 million from West Hill Capital in August 2019, which was followed by an undisclosed investment from Mitsubishi Corporation in December 2019.
- **String Bio (India)**. In June 2019, String Bio's undisclosed round included investors Ankur Capital, the Oil and Natural Gas Corporation, Seventure Partners, Karnataka Information and Biotechnology Venture Fund, and Srinivasa.
- **Calysta (U.S.)** received a USD 30 million investment from BP Ventures.

These announcements were significant, as the funding supports the construction of facilities that will increase production capacity and decrease SCP costs. Particularly in String Bio and Calysta's cases, the investments were from oil and gas players, signaling potential collaboration for sourcing gas inputs.

Calysseo's single-cell protein production facility. Source: Calysseo.

Future Prospects

While SCP shows great potential to support increasing protein demands while also decarbonizing protein ingredients, SCP production requires close proximity to gas feedstock sources. As a result, SCP producers that have gained support from the energy industry and its gas waste streams tend to have higher business execution scores. Support from the energy industry, beyond just interactions with the aquafeed industry, will be critical for the growth of SCP production given the significant capital costs of starting an SCP production operation and the need for co-location near feedstocks.

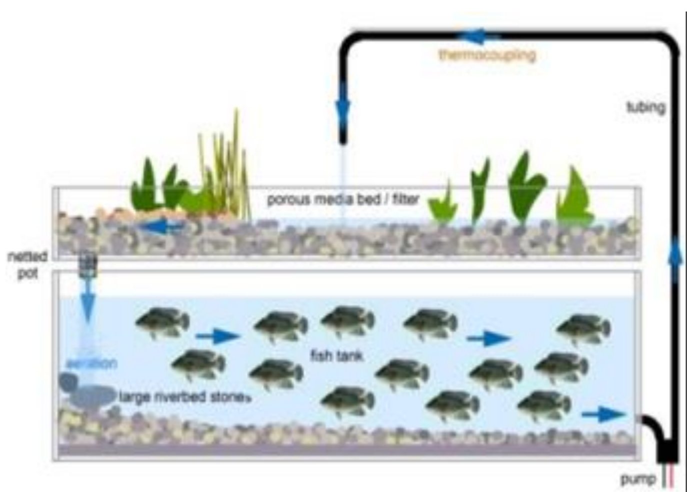
Given the nascent stage of development for SCP, the technology will not be readily available for commercial deployment in the Adriatic-Ionian region for another 3 to 7 years. However, SCP will produce large volumes with fewer facilities in less time, enabling the single-cell protein market to rapidly scale. With continued support from governments, aligning industries, and the general public, SCP has high potential to lead as an alternative protein source to fish meal.

Aquaponics

Declining stocks of ocean fish worldwide paired with regionally increasing consumer demand for fish and other aquatic and marine produced organisms challenges the ability for industry to meet demand. As a result, production has continued to be pushed more and more into the realm of aquaculture. Aquaculture techniques range from low-intensity farming using pens in naturally-occurring bodies of water to high-intensity outdoor pond and indoor recirculating farming operations. The sustainability of these practices is highly variable and hotly-disputed. For instance, poorly managed feeding regimes often result in the eutrophication of adjacent waters and environments, and in extreme cases results in the spread of pathogens.

Aquaculture system developers continue to focus on high-value high-demand species, such as salmonids, but innovators are beginning to explore opportunities for multi-species co-culture approaches, often referred to as aquaponics (e.g., growing leafy greens or macro algae and shellfish in a single system). Paired with growing consumer demands for low environmental impact food, national programs to make food systems more resilient, and the creation of improved accessibility to high-quality foods with shorter supply chains interest in aquaponics is growing.

Aquaponics is a hybrid approach to aquaculture that marries hydroponic plant production with recirculating aquaculture systems (RAS). Many physical designs exist, but the unifying factor is the relationship between a primary producing organism like a plant and an animal (e.g. fish or shellfish). The nitrogen-rich animal waste in the system provides a dilute fertilizer supplied at various intervals to the plant. The removal of the nitrogen waste by the primary producer maintains water quality. Together, a closed-loop system that requires less water treatment and is more productive is created.



Basic Schematic of aquaponics system. Source: Beckoi.

Plants and animals that are suitable for aquaponic farms must align to several criteria. Based on space and structural limitations, most aquaponic systems are best suited for plants with a short life cycle (lettuce is about six weeks to harvest) and animals that fetch a high enough premium price while matching the environmental requirements of the plant (e.g. salinity, temperature, turbidity, nutrient levels).

Promoters & Inhibitors

Despite the hype surrounding early-stage operations, aquaponic production faces numerous risks, including high costs, limited applicable areas, and constrains in production quantity, and the need to monitor the environmental and operational needs of organisms being produced along different timelines within a single system. Below, we highlight key promoters and inhibitors in the aquaponics space:

Promoters

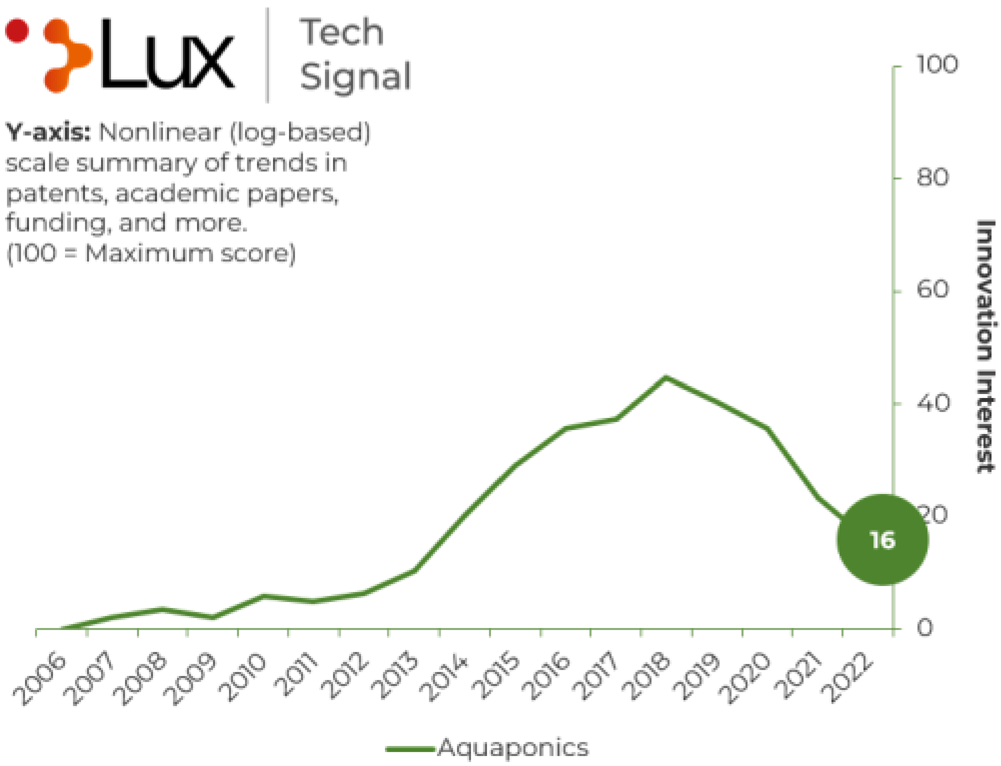
- **Localized production – lower transport burden.** One of the most common aquaponic selling points is the ability to shorten the trip from "farm to table". Aquaponic farms often set up operations in urban areas bringing high value, fresh food sources to the consumer, retail, and food service/restaurant markets. Those with an interest in the highest quality possible and wishing to mitigate transportation impacts and costs are often attracted.
- **Low chemical load and limited environmental impact.** Closed aquaponic systems create an optimal growing environment and allowing for reduced use of mined fertilizers, pesticides, and other inputs while producing plants and animals at higher densities per sqft than would be realized under conventional systems.
- **Growth in enabling technologies for operations and value chain management.** Digital technologies are enabling greater efficiency and system predictability for indoor and outdoor aquaculture and vertical farming operations towards increased profitability. While there is a need to better manage and understand nutrient cycling and demand within a larger system, these technologies offer an opportunity to overcome that hurdle.
- **Expanding markets for a growing aquaculture industry.** Aquaponics' potential broadens to regions with limited national food security or high import rates and offers a solution for nations to reduce import dependence globally, while offsetting related emissions challenges. In addition, local production offers high-end produce for premium markets. Again, these markets may be dependent on food and restaurant services or developed to alleviate reliance on expensive imports.

Inhibitors

- **Managing nutrients and water quality at large-scale.** X. Aquaponic operators must constantly maintain water quality to a very high standard. At the same time, aquaponics systems display issues in producing the appropriate nutrients for plants from the effluent produced by fish. The wastes in such systems mainly comprise fish feces and uneaten feed that cannot be delivered directly in a hydroponics system. Moreover, the scale of production is important given that nutrient flows from one part of the system need to be matched with the downstream production potential of other components.

- **Regulatory challenges faced from including horticulture and aquaculture.** Policies supporting aquaponics are limited for scaled operations. It is difficult to adhere to an expanded set of regulations for horticulture and aquaculture while also balancing regulations associated with production in urban areas. Aquaponics in the EU cannot currently be certified as organic.
- **High OPEX and CAPEX**. Initial setup costs for the infrastructure needed – plumbing, lighting, shelving, heat, monitoring systems – are high depending on the parameters of the building and aquaponics system being used. Additionally, aquaponics systems suffer from high production costs due to significant energy requirements, and those requirements increase when integrated with a photosynthetic organism.
- **High technology and knowledge intensity.** Beyond the large costs of operations, aquaponics requires in-depth knowledge of a wider diversity of organisms than conventional operations. The development of individuals with the expertise to develop and run operations typically arises from existing operations themselves rather than academic institutions. Beyond this constraint, the need to simultaneously manage multiple species creates an added layer of complexity, that at scale, is dependent on the application of monitoring technology. Therefore, individuals must understand in detail the needs of multiple species as well as the interactions, and how to deploy technology to manage those needs. As a side note, production quantities for an aquaponics operation tend to be lower than the system of a similar size but developed to produce a single organism due to managing the balance between different organisms’ needs (i.e. plants, animal, bacteria).
- **Impact limited to areas with local markets**. While opportunities in niche markets are attractive for early-stage developers, such markets also challenge industry maturity. Aquaponics will compete with vertical agriculture systems targeting the production of the same crops, and smaller production quantities means many retailers may not engage.

Innovation Trends



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The Lux Tech Signal indicates that innovation interest in aquaponics rose rapidly over six years but fell just as quickly over recent history. The decrease in aquaponics innovation interest as indicated by the Lux Tech Signal can be attributed to several factors. First, significant investment has gone into the development of plant focused controlled environment agriculture (e.g. vertical farming) and the improvement in automation of recirculating aquaculture systems. Given the large CAPEX need in all cases, funding has remained limited to niche groups.

Second, aquaponics systems' need to support plants and animals increases energy and labor costs and given the rising costs of energy and labor have challenged industry development. Those achieving some success often rely at least partially on alternative energy sources and technology for system automation.

Third, aquaponic production capacity is limited with very few large-scale farms and most individuals operating systems less than 500 gallons as hobbies or small businesses. The largest farms, which use upwards of several thousand-gallon systems can produce about 100 MT per year of fish, but are in the severe minority.

Nonetheless, there is a consistent but low level investment occurring for aquaponic production in urban or suburban areas as well as challenging production environments. EU initiatives like the [Innovative Aquaponics for Professionals](#) (INAPRO), The EU Aquaponics Hub, and feasibility studies conducted by [Central Finland FLAG](#) will continue to emerge but also remain small in scale with minimal impact thus far on innovation momentum. There is certainly a niche market for aquaponics, but optimizing nutrient cycling, water and energy use, as well as quality control strategies requires more research to exploit the full potential of most of these systems. The weaknesses stack up to point out that the current impact of aquaponics is low, but the long-term impact may be significant once developers have regulations in place to support co-culture systems, market access is improved, and technical, knowledge, and labor hurdles overcome.

Key Players

Recent Developments

- **Upward Farms (U.S.).** Following receipt of USD 121 million in 2021, Upward Farms announced construction plans of a 250,000 ft2 vertical aquaponics facility in Luzerne County, PA, which will provide leafy greens and hybrid striped bass across the U.S. Northeast. The new facility — the company's third farm — is expected to be operational in early 2023. Upward Farms claims that the facility will be two to four times larger than its competitors' vertical farms.
- **Jyväskylä University of Applied Sciences (Finland).** An aquaponics research project at the Jyväskylä University of Applied Sciences in Finland secured EU funding to support aquaponics technology development and establish a pilot aquaponics farm. The project has produced rainbow trout, mint and spinach, and mainly focused on technology development in improving

water quality, fish growth, plant growth, system maintenance and reducing the environmental load of nutrients.

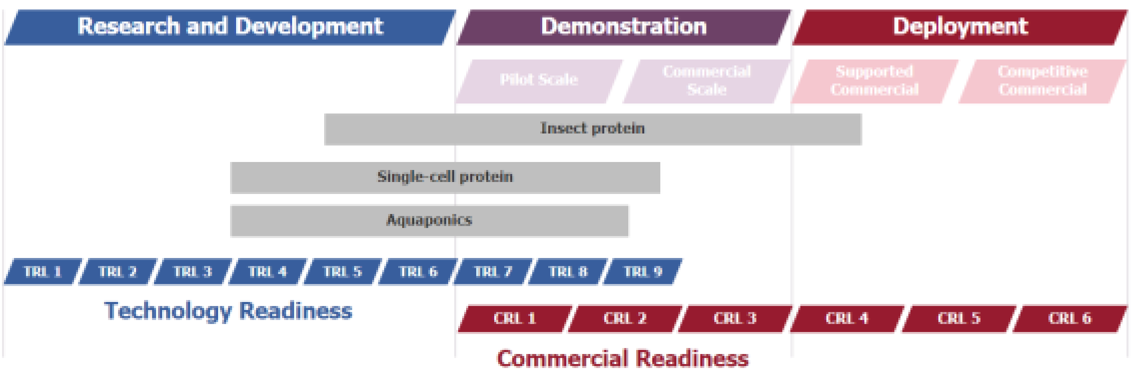
- **Baniyas (Abu Dhabi).** Baniyas, the world's largest aquaponics center, converts biologically ammonia-rich tilapia waste into nitrates and cycles the nutrient stream for vegetable production. Trials recently began on tomatoes, lettuce, cucumbers, and bell peppers, with an estimated 10 tonnes of production of each available in 2022, in addition to 7 tonnes of fish. The center's fertilizer waste stream is also used by the Sustainable Bioenergy Research Consortium – a group that advances sustainable aviation fuel production using oilseed from halophytic (saltwater-tolerant) plants.
- **Les Nouvelles Fermes (France).** Les Nouvelles Fermes raised USD 2.26 million to build one of the largest urban aquaponics farms in Europe. The project, which will be launched at the end of 2021 in the Bordeaux metropolitan area, will include the construction of a 5,000m2 urban farm and create 17 new positions.

Future Prospects

Aquaponics growth is investment- and innovator-led, although national support is requisite for success. Given this and other misalignments it is not surprising that more than a few formidable hurdles stand in the way of aquaponics contributing to support fresh produce and protein demand. Although small-scale solutions exist, there are obstacles to growing diverse primary producing crops. Aquaponics align best with crops that have short life cycles and simple nutritional needs, eliminating tree and permanent crops as an option. In addition longer grown crops may suffer challenges with fungal pathogens given the humid environment. When it comes down to it, aquaponic farming is less ground-breaking than its fan base will have you believe. To achieve success advanced monitoring systems that can lower labor and knowledge needs are critical, but competition with closed environment agriculture operations and expanding RAS operations challenge the value propositions of aquaponics. Targeting the multispecies production of macro or micro algae and fish or other species may have a better opportunity to satisfy the need for differentiation among the competition. While small operations exist that are looking to undertake this goal, capacity challenges remain. Aquaponics systems will likely continue to be developed and commercialized in the coming years in the Adriatic-Ionian region, but its growth into a mature industry will be heavily dependent on energy and resource costs, and market choices.

Technology Status

TRL/CRL



- In the past 2-3 years, insect protein production developers have achieved large-scale production at commercially relevant levels. However, this is limited to a few players in the Adriatic-Ionian region; currently most insect protein companies are amid constructing their first facility. Moreover, significant quantities of insect protein must be produced to make a tangible impact on the fish meal market. While the momentum behind insect protein production is escalating across the globe, it remains critical for developers to secure funding and partnerships to fulfill R&D initiatives and meet commercialization timelines.
- In roughly the past five years, the opportunity to produce single-cell protein has captured a great deal of interest from a range of industries. However, the technology remains early-stage, as few developers have established pilot facilities, making timelines for commercialization difficult to predict. Moreover, the space faces a number of hurdles, including high costs of production facilities and product validation as well as identifying strategic industrial emitters that are comfortable with building major infrastructure projects to reliably source feedstocks. Nevertheless, the aquaculture industry continues to grow in the Adriatic-Ionian region, and with that growth, the demand for fish meal alternatives will increase and accelerate SCP’s commercial adoption once developers have scaled.
- While aquaponics cultivation brings advantages in water conservation and the potential for year-round food production, the technology is complex as it requires the ability to manage simultaneously the production and marketing of two different products. Moreover, aquaponics sees even greater technical issues than conventional aquaculture systems and is most widely implemented at a small scale for educational and research purposes. From an industry perspective, large-scale aquaponic production success is limited and warrants a deeper technical and economic assessment to understand its potential growth in the Adriatic-Ionian region.

This project is supported by the Interreg ADRION Programme funded under the European Regional Development Fund and IPA II fund.

Alternative and Competing Technologies

Alternative feeds

Plant derived sources

Plant based feed are gaining momentum in aquaculture industries. The main plants used are soybean and corn. Soybean is among the non-fish sources of omega-3 fatty acids, protein, and unsaturated fats. Soy based feed is explored as an value alternative to traditional feed thanks to its high protein content and significantly lower price. Hence, in the last decades, the demand for plant-based feed and soybean meal has been growing in the market (Marketsandmarkets, 2020). However, due to the declining availability of freshwater, the decreasing amount of free land for cultivation and the intense competition for most currently used plant protein sources land based products are not the only answer (FAO, 2022b).

Algae

Algae are photosynthetic organisms that, through cultivation, CO_2, water, and light can grow and produce biomass that could be used in different application (Daliah Runeel, 2022). As a feed ingredient, algae are rich in omega-3 fatty acids, carbohydrates, beta-glucans, and other bioactive compounds that can assure and improve animal health. However, extraction remains a barrier for algae feed cost, yet genome sequencing is also being explored to modify and improve algal strains for increase digestibility(Lux Research Inc., 2023).

Animal health

Functional ingredients

Functional ingredients are probiotics, prebiotics, phytogenic or other immune-boosting feed additives that can support animal health. Functional ingredients are helpful to improve balanced intestinal microflora and enhance health of livestock bosting food intake and improving gut function. However, the market for new functional ingredients must face international quality standards and strict regulation to approach a wider market (MarketsandMarkets, 2022). Moreover, lack of understanding around modes of action makes difficult to predict the effect of the application (Lux Research Inc., 2023).

Bacteriophages

Bacteriophages are viruses that target and kill specific bacteria or other harmful microorganisms. Bacteriophages (phage) therapy has been gradually applied in aquafarms thank to its high efficiency, specificity and lower environmental impacts compared to antibiotics. For this reason, phage therapy could represent a valuable alternative to face photogenic bacteria in aquaculture (Khan Md. & Choudhury, 2021). Overall, bacteriophages face challenges on technology and regulatory aspects. Innovators are focusing on the stability of phage cocktails and the prevention of the resistance (Lux Research Inc., 2023).

Novel vaccines

Novel vaccines are identified as treatments that "train" the immune systems to recognise and protect against specific pathogens or pathogen groups. Novel vaccines could represent a valid alternative compared to current methods, however, improve methods of administration and sever regulatory requirement for market authorisation are needed to assure safety and efficiency (Lux Research Inc., 2023).

Genetic stock improvement

Finally, genetic stock improvement identified as the selective breeding and genomic selection of organisms to improve disease resistance and other performance traits is explored as an alternative to improve stock wealth. Genetic improvement of farmed fish could represent a feasible solution to increase farm's efficiency and the consequent impact on the environment by reducing feed, land, and water requirement for the production (FAO, 2022b). While aquaculture species have high specific genetic diversity which allow high selection intensity the industry is relatively young and lags far behind other food production sectors in terms of research and development. Moreover, the wide adoption of genetic tools in aquaculture is hindered by different factors such as the poor understanding of the risks and benefits of new molecular technologies, limited overall capacity and infrastructures, deficit of scientifically informed long-term breeding programmes and lack of private sector engagement (FAO, 2022b).

Cultivation Systems

Recirculating aquaculture systems (RAS)

RAS systems are closed-loop systems that requires extensive water treatment through biofiltration to reduce wastewater effluent volume and water-quality related toxicity. RAS technologies are growing in terms of investment and operation expansion thanks to land-based solution which are reducing the impact on the surrounding environment (Lux Research Inc., 2023).

Integrated multitrophic aquaculture (IMTA)

IMTA systems are a feasible way to increase the environmental and economic sustainability of aquaculture production. The IMTA approached is based on the co-cultivation of species from different tropic levels (2 or more) in which uneaten feed and excreted waste of farmed organisms (for example fish) become food for other species (for example plants), hence reducing nutrient realise into the environment while enhancing overall productivity (European Commission, 2022b; FAO, 2022b). IMTA installation required significant investment in the architecture of facilities and equipment to run large installation. For this reason, smaller scale facilities such as aquaponics farming are largely tested. Aquaponics is a hybrid approach that combines hydroponic plant with fish production in small recirculating close systems. Innovation in aquaponics is increasing thanks to the small production scale level which allow a higher profitability (Lux Research Inc., 2023)

Emerging culture target

Technological innovation is also focusing on the cultivation and harvesting of less exploited groups of organisms from algae to sea urchins to reduce the pressure on natural resources in specific areas and increase diversification of aquaculture (European Commission, 2022b). The exploitation of new organisms could also provide new range of ecosystem services when conducted in open water. Moreover, emerging culture targets focuses on new and innovative rearing systems that increase the sustainability of the farm reducing the environmental impact (Lux Research Inc., 2023). Nevertheless, emerging culture target is still at a very early stage of development in EU (European Commission, 2022b).

Offshore farming

The increasing competition for coastal space results in increasing innovation in offshore farming an innovative cultivation system which is carried out in an open ocean environment using floating, submersible, or moored cages (Lux Research Inc., 2023). Innovation related to offshore farming is steeply increasing thanks to its potential to achieve better economic scale while reducing environmental impacts. When well manage, offshore cages have lower impacts on water quality, on benthic organisms living nearby and lower operational risk associated with farming activities. However, business involvement in offshore activities is limited due to the high capital investment required and the need of highly skilled operators (FAO, 2022b).

Management and Analytics

Environmental management

Environmental monitoring focus on water quality is largely investigated by aquaculture management innovation. Water quality is key for disease prevention in the stocks, and, for this reason, real time sampling could steeply improve production. Start-ups and businesses are developing IoT systems and sensors capable of detecting changes in water temperature, pH, dissolved oxygen, salinity, ammonia, carbon dioxide and suspended matter to improve early warning (Lux Research Inc., 2023).

Feed management

Technological innovation related to feed management is also improving in the last years. Excess feeding has negative impacts on profits margins and water quality. For this reason, monitoring platforms are focusing on fish well-being and growth by applying machine vision and sensor integration (Lux Research Inc., 2023).

Disease management

Digital innovation around disease management involved mixed technology platforms. Those platforms use sensors and image pattern recognition software to monitor physiology either in real time or to accompany schedule health assessment to detect disease outbreak and identify presence of parasites (Lux Research Inc., 2023).

Supply chain management

Finally, supply chain management is also increasing to face the growing costumers demand for traceability of aquaculture products. Technological innovations are offering better data collection and software systems that enable farmers to provide digital identity of their livestock. Moreover, blockchain technologies are developed to support ownership transactions (Lux Research Inc., 2023).

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Waterborne transport: Horizon Scanning

Waterborne transport includes maritime and inland waterways transport and represent the mode of transport mostly used worldwide (Luis Marques dos Santos & Ortega, 2021). Specifically, **Maritime transport** is the shipment of goods (cargo) and people by sea and other waterways. Overall, maritime transport includes the following sub-sectors:

1) **Passenger transport**: sea and coastal passenger water transport and inland passenger water transport;
2) **Freight transport**: sea and coastal freight water transport and inland freight water transport;
3) **Services for transport**: renting and leasing of water transport equipment (European Commission, 2022).

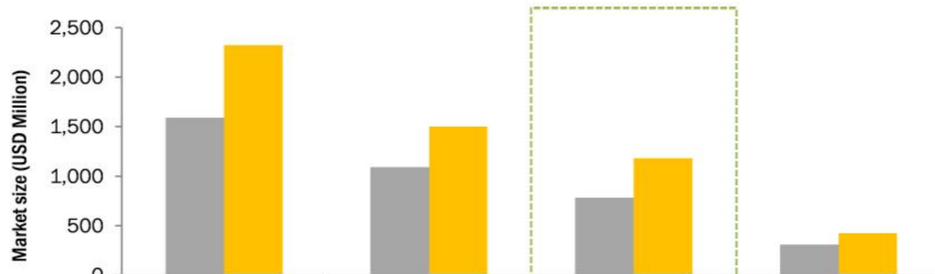
Within the project scope, only **freight transport** was considered in the technological foresight analysis.

Market in Brief

Port operations are a necessary tool to enable maritime trade between trading partners. To ensure smooth port operations and avoid congestion in the harbor, it is inevitable to continuously upgrade the port's physical infrastructure, invest in human capital, foster connectivity of the port, and upgrade the port operations to prevailing standards. Hence, port operations can be defined as all policies, reforms, and regulations that influence the infrastructure and operations of port facilities, including shipping services.

Maritime transport is the backbone of the increasingly globalized economy and the international trade system. The solutions include port operations management, vessel tracking, maritime software and others. Maritime transportation solutions and services incorporated all the policies, reforms, and regulations that influence the infrastructure and operations of port facilities, including shipping services.

The **smart transportation market by solution in maritime mode** is projected to reach USD 5,431 by 2025, growing at a CAGR of 7.6% during the forecast period. The maritime software segment is expected to grow at a CAGR of 7.9% during the forecast period. The vessel tracking segment is expected to grow at the highest CAGR of 8.6% during the forecast period (Markets&Markets, 2020).



	Maritime Software	Port Operations Management	Vessel Tracking	Others*
2020	1,590	1,091	781	309
2025	2,324	1,502	1,181	425
CAGR (2020-2025)	7.9%	6.6%	8.6%	6.5%

**Others include shipbroking, real-time weather information and warehousing*

Figure 34. Smart transportation market by solution in maritime mode, 2020 vs 2025 (USD Million)

Importance of the Market

More than 80% of world trade is carried by sea, constituting by far the most important means of transport of goods. The international maritime transport costs tend to be on average between two to three times as high as the customs duties of importing countries. Still, maritime transport is the cheapest way of transporting a large number of goods. The price of shipping a container depends largely on the route and the current economic situation. However, besides costs, available services to traders and ships as well as service quality concerning speed, reliability, frequencies, safety, and security are of increasing significance in the context of globalized production processes and just-in-time deliveries. Maritime transport is the backbone of the increasingly globalized economy and the international trade system. The maritime solutions include port operations management, vessel/container management, **freight information system**, and marine solution. Maritime solutions automate all the marine processes and streamline the operations associated with it. Maritime transportation solutions and services incorporated all the policies, reforms, and regulations that influence the infrastructure and operations of port facilities, including shipping services.

Looking at the different segments, **inland waterways** transported a total of 522 thousand tons of goods in 2021 between all the EU countries with Belgium and France accountable of the highest trade of goods weight. In the Adriatic-Ionian region, Romania and Bulgaria consistently used inland waterways registering a total transport of good weights of 32120 thousand tons and 18093 thousand tons, respectively.

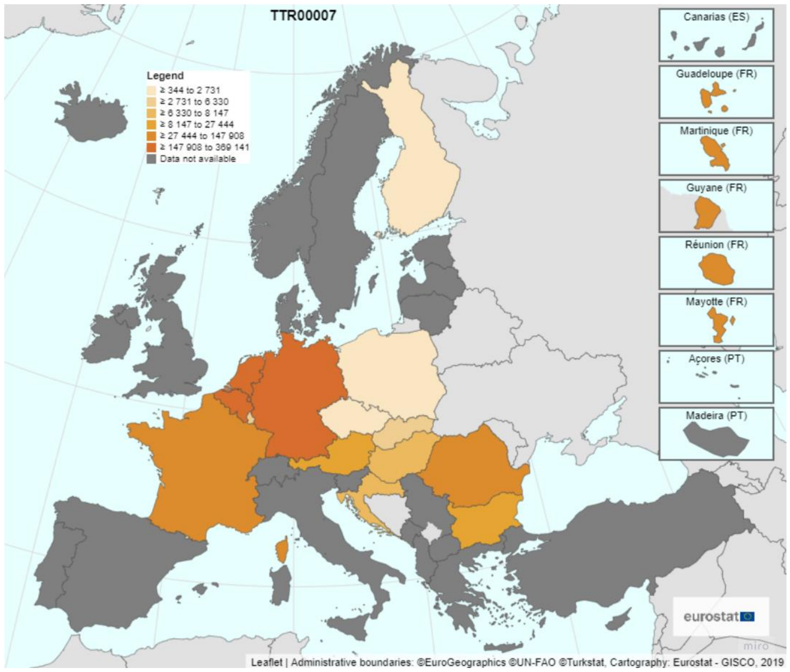


Figure 35. Goods transport by inland waterways in thousand tonnes[20]

The inland water transport performance in Europe (defined in million tonne-kilometre) registered a decreased compared to 2021 mostly due to COVID-19 pandemic and Russian war aggression against Ukraine[21] which affected the exports of Ukraine goods from and the state also altering trade and commodity flows in the region (Central Commission for the Navigation of the Rhine (CCNR), 2022)

[20] https://ec.europa.eu/eurostat/databrowser/view/ttr00007/default/table?lang=en

[21] This term is based on a publication of the EU Commission, see the document Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions (2022).

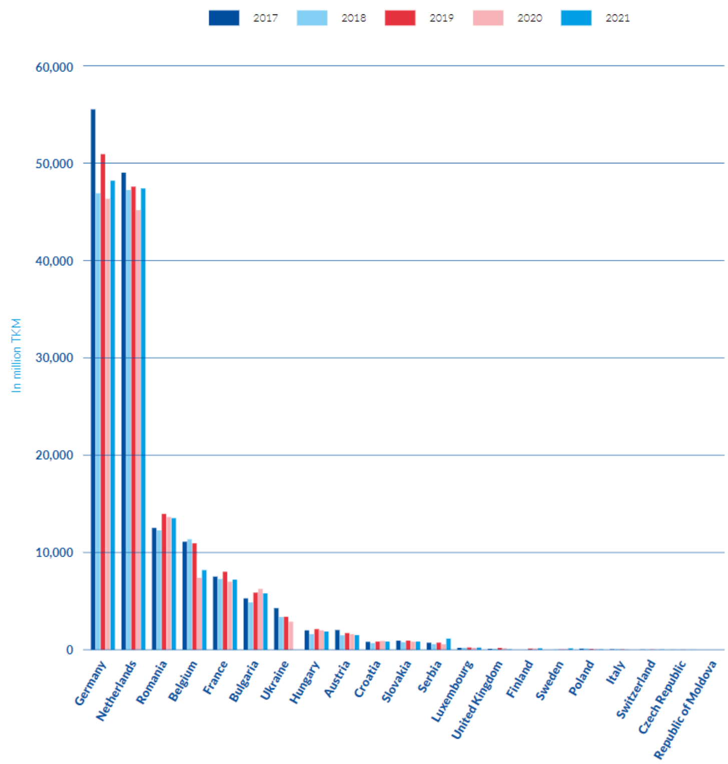


Figure 36. Inland water transport performance from 2017 to 2021 in main European Countries (Central Commission for the Navigation of the Rhine (CCNR), 2022)

Concerning the **maritime transport** in EU, the 27 countries registered a total of 2.90 M ktons in gross weight of goods transported to/from main ports in 2021 with Netherlands and Spain leading the sector (Statistics | Eurostat (europa.eu)). In the BLUEAIR region of interest, maritime transport, for freight purposes, is mainly developed in Italy and Greece with a total gross weight transported to/from main ports of 400K ktons and 145K ktons, respectively. The gross weight of seaborne goods handled in ports reached a total of 3 M ktons in 2021 with Netherlands and Turkey handling the most gross weight of goods, 589K and 519K ktons each.

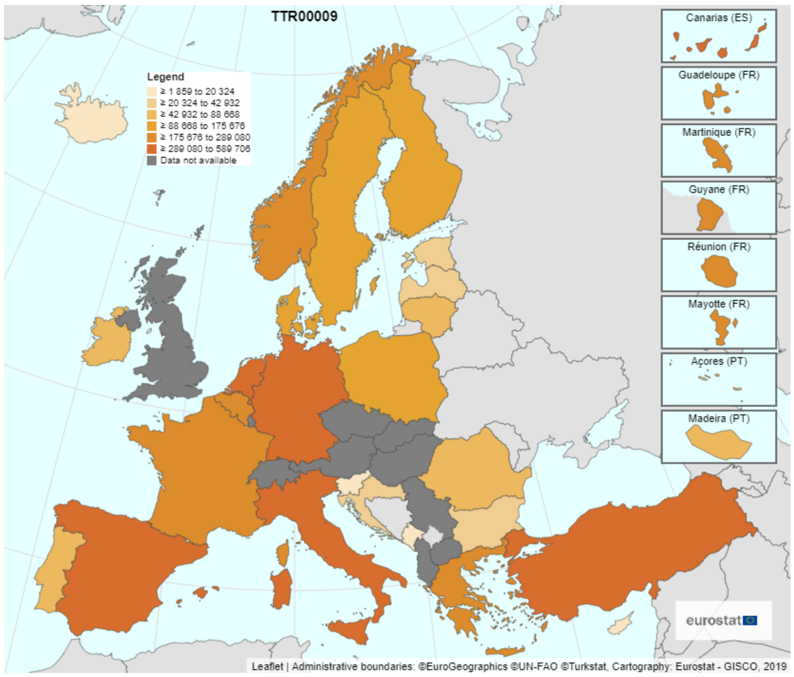


Figure 37. The gross weight of seaborne goods handled in ports (goods unloaded from vessels plus goods loaded onto vessels). Data are collected according to Directive 2009/42/EC of 6.5.2009[22].

Concerning the market value, in 2019 freight transport coverer over the 43% of the sector's gross value added (GVA), registering up to euro 14.8 billion followed by Services 32% (euro 11.1 billion). Overall GVA increased compared to 2009 with Germany (euro 12.2 billion), Denmark (euro 6.3 billion) and Italy (euro 4.9 billion) leading the freight transport sector. Overall, maritime transport was also affected by COVID-19 pandemic and suffered a decreased compared with the last decade (European Commission, 2022).

Market Drivers

The advances in shipbuilding, propulsion, smart shipping, advanced materials, big data and analytics, robotics, sensors, and communications in conjunction with an increasingly skilled workforce are all having monumental shifts in how the maritime industry are approaching new challenges and opportunities.

The advancement of **technologies** in the maritime transportation industry, such as big data analytics, robotics, advanced materials, autonomous systems, advanced manufacturing, energy management, cyber and electronic warfare, human-computer interaction, and human augmentation technologies, has led to the growth of the transportation mode in the upcoming year which will be reflected also on inland water

[22] Statistics | Eurostat (europa.eu).

transport. The implementation of these technologies will depend on a favorable regulatory framework, technical standardization on a worldwide scale, and cooperation between marine stakeholders.

The advancements in technologies in the maritime industry, such as loT, RFID, and Automatic Identification and Data Capture (AIDC) technologies for improving the order fulfillment process. The blockchain technology allows the exchange of information in the shipment industry by connecting multiple parties of the global shipping ecosystem.

An increasing need for managing **freight**, fleet, and carriers in the marine transportation mode is expected to drive the smart transportation market by maritime. The yard management solution is expected to grow rapidly due to the development of new ports in developing countries.

Growth in international marine freight transport

Maritime transport is crucial for international trade. The main transport mode for global trade is ocean shipping, and according to the United Nations Conference on Trade and Development (UNCTAD), about 80% of the volume of international trade in goods is carried by sea, and the percentage is even higher for most developing countries. This channel of transport is cheaper and more feasible for international trade than road, rail, and air transport. Global shipbuilding is expected to further swell at a moderate annual rate from 2022 to 2027. The growth of the global shipping fleet showed similar trends. Maritime trade bounced back in 2021, owing to the unlocking of pent-up demand, as well as restocking and building inventory. The sudden boost in demand in 2021 after the grim situation in 2020 due to the COVID-19 pandemic resulted in shortages of shipping capacity and containers and equipment, forcing many shipowners to resort to procuring new build or used retrofitted vessels to bridge this demand-supply gap.

Asia Pacific has emerged as a global manufacturing hub in recent times, owing to its wealth of raw materials and workforce. Thus, the demand for container ships is significantly high in this region, owing to an increase in the export of manufactured and raw goods. The year 2021 witnessed increased oil demand due to the reopening of economies, an increase in OPEC production, and the expansion of Asian economies. This growth is ongoing and may lead to an increase in demand for very large crude carriers. The bulk carrier trade is expected to show similar trends, as it accounted for nearly three-quarters of total shipbuilding trade volumes during 2020-2021, and its share is expected to expand further. thereby driving the shipbuilding anti-vibration market during the forecast period (Markets&Markets, 2022a).

Improving maritime logistics infrastructure

Maritime logistics plays a dominant role in the global supply chain and is the backbone of world trade and globalization. Carriers, port operators, freight forwarders, and shippers are the key players in maritime logistics. The review of maritime transport published by the United Nations Conference on Trade and

Development (UNCTAD) reveals that 80% of the global merchandise trade, in terms of volume, is carried out by sea and handled by ports across the world. The deployment of intelligent transportation systems (ITS) in ports, particularly to facilitate co-modal transport, is less familiar at present, although it can improve productivity and security and make logistics more efficient, competitive and sustainable. However, port operators have started adopting advanced and **intelligent transportation technologies** to efficiently handle various ship and port operations and address large loading and unloading requirements. All these factors are propelling the adoption of ITS for maritime applications. Thus, the implementation and integration of ITS, to a large extent, propels the market for the maritime industry (Markets&Markets, 2023).

Key Trends

Industry Trends

Smart transportation is a technologically-advanced approach to effectively manage the operations of all the modes of transportation through quick sharing of transportation data across its infrastructure components, such as passengers, ticketing department, control centers, freight, and others. Smart transportation solutions are backed by various latest **technologies**, such as Internet of Things (IoT), cloud, analytics, big data and analytics, Augmented Reality (AR), Global Positioning System (GPS), Artificial Intelligence (Al), and ML, to make transportation operations more accurate and efficient day-by-day. The smart transportation approach carries out the integration of software solutions to optimize the usage of assets, from tracks to trains, Vehicle to Infrastructure (V2I), aircraft to ground, and ship-to-shore to meet the ever-growing demands of the citizens efficiently and provide safer services. The increasing importance of sustainability, regulations, demographics (growing traffic and ageing population), economics (limited public funding and price sensitivity), Information Technology (IT) innovations, and mobility is expected to spur the growth of the **transportation industry**. These inclinations are also expected to change each component of the value chain of the smart transportation market—from the passenger services to back-end organizations. The improving technological advancements in the **transportation industry** are having a significant impact on its growth.

ICT plays a vital role in the transformation of the **transportation industry**. Smart transportation involves integrating ICT technologies with existing transportation infrastructure and delivering real-time online information about the traffic flow and passengers/commuters. Using digital technologies such as advanced control systems and sensor technologies, transportation around the cities can be monitored and efficiently controlled. Smart transportation also includes interfacing smart intermodal technologies with other modes of transport and setting up or upgrading smart solutions, so that passengers can make informed decisions about their transportation requirements.

Technological developments including the containerization and **Machine-to-Machine (M2M) communication** in **waterway transport** have made a significant **impact on the industry**. Additionally, **new port developments** in developing countries, and advancements in transportation services and software technology focused at improving and lowering the operational cost of business have increased the demand for smart transportation technologies in the **maritime** mode of transportation (Markets&Markets, 2020).

Social Trends

Inland water transport employment overall registered a positive trend of growth in the passenger sector compare with the freight transport which registered a slight decrease in the employment rate.

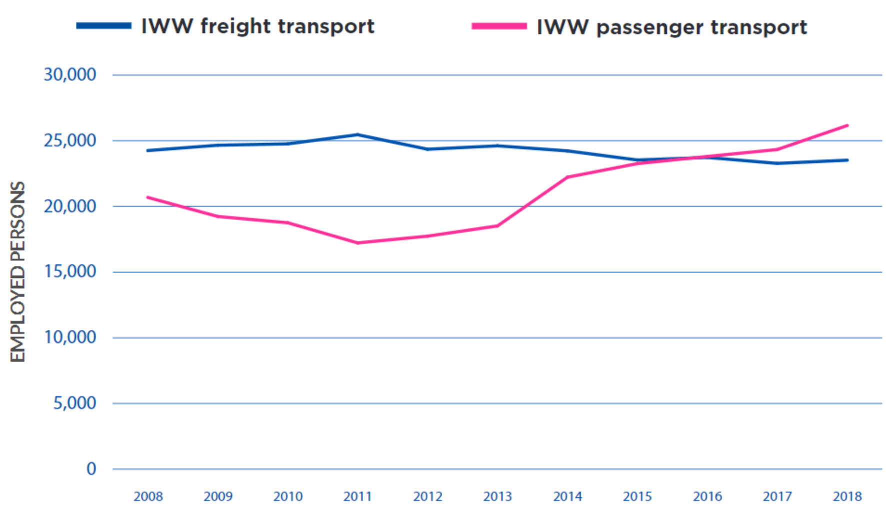


Figure 38. Employment in Inland waterway passenger transport and in inland waterway freight transport in EU (CCNR, 2021).

Freight inland transport employment registered a decreased especially in central and eastern Europe in the past ten years due to the low wage level. Easter Europe countries registered the lowest wage with an average monthly salary of euro 700 which are three to five times lower than western Europe country like Germany. Also, a higher migration rate of specialized workers is register from eastern to western EU countries and non-EU countries (Central Commission for the Navigation of the Rhine (CCNR), 2021).

Concerning the **maritime transport**, almost 403000 persons were directly employment in the EU states (13% more than 2009) with an average annual wage of euro 3900. Western European countries are leading the maritime transport with Germany contributing with 34% of the jobs, followed by Italy (18%) and Denmark (7%). Overall, employment in maritime freight transport decreased by 20% in 2019 mainly due to COVID-19 restriction (European Commission, 2022)

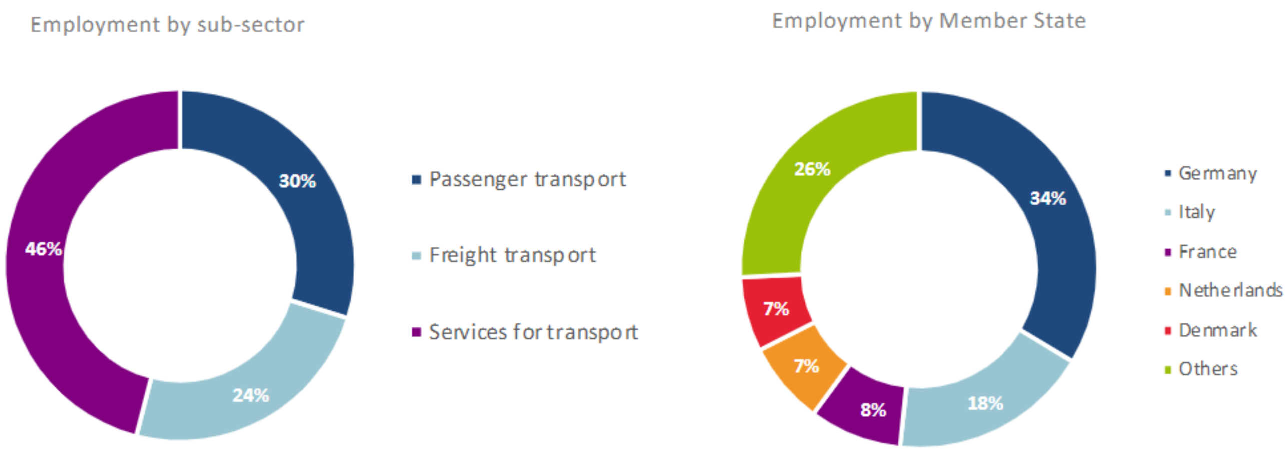


Figure 39. Share of employment in EU Maritime transport sector in 2019 (European Commission, 2022).

Maritime transport and port security have become a major concern, especially after the 9/11 terror attacks. Measures taken to enhance security, such as the International Ship and Port Facility (ISPS) code, had a significant impact on trade and port operations. As part of the Safety of Life at Sea (SOLAS) initiative, it is a comprehensive set of measures to enhance the security for the port and the ships in the harbor. The SOLAS program requires countries to permanently assess their prevailing security situation that corresponds to a certain set of security measures to be taken by ships, ports, and port authorities. A major challenge for the maritime industry is the piracy concerns in some regions. Although there is a general agreement about the threats by pirates and terrorists to international trade, stakeholders pursue different interests.

The rapid spread of **COVID-19 pandemic** worldwide has had a major impact on global markets. While the predictions for the recovery and future stability of the shipping industry seem rather slow and bleak, the disruption due to the pandemic will prove to be a catalyst for the radical **reshaping of the maritime industry**. The pandemic has exposed the glaring defects of the global supply chain network. Digitization and technology innovation will play a key role in resetting the distribution network. Greater investment in intelligent freight technologies will enable better tracking, monitoring, facilitation, integration, and information sharing. This will help in providing data analysis and increase the end-to-end supply chain management by connecting the different stakeholders and players of the maritime industry to optimize operations and industry resilience. The crisis will see an accelerated push for growth in autonomous transportation, paving the way for a cheaper, more efficient, and resilient industry.

The socioeconomic impact of the COVID-19 crisis is, however, vast and continues to grow as a result of the effects on the waterborne transport sector, impacting crews, workers and the communities that benefit from waterborne tourism. As one of the essential and vital sectors for society and industry, waterborne transport has to remain safe and in operation. The transition to zero-emission waterborne transport offers the opportunity to grow markets in the longer term following the COVID-19 crisis. To ensure preparedness in line with the European Green Deal, flexibility, creativity and financial effort from the sector will be required, backed by suitable policies and financial support. The sector is committed to realize zero-emission waterborne transport to the benefit of future generations (WATERBORNE TP, 2021).

Environmental Trends

Amid growing global and European societal pressure to resolve issues related to climate change, air pollution and the degradation of the world's oceans and inland water, political and regulatory attention has been increasingly directed towards waterborne transport. The **European Green Deal**, the **Paris Agreement Objectives**, the **Initial IMO Strategy** on the reduction of **GHG emissions** from ships and the CCNR Ministerial Mannheim Declaration are several key policy developments which provide a clear objective towards zero-emission waterborne transport (WATERBORNE TP, 2021).

The waterborne transport sector is committed to develop and demonstrate disruptive solutions to address the challenges and it focuses on three main environmental challenges such as:

- **Impact on climate change**;
- **Air pollution from ships**;
- **Degradation of waters and ocean** (WATERBORN, 2021)

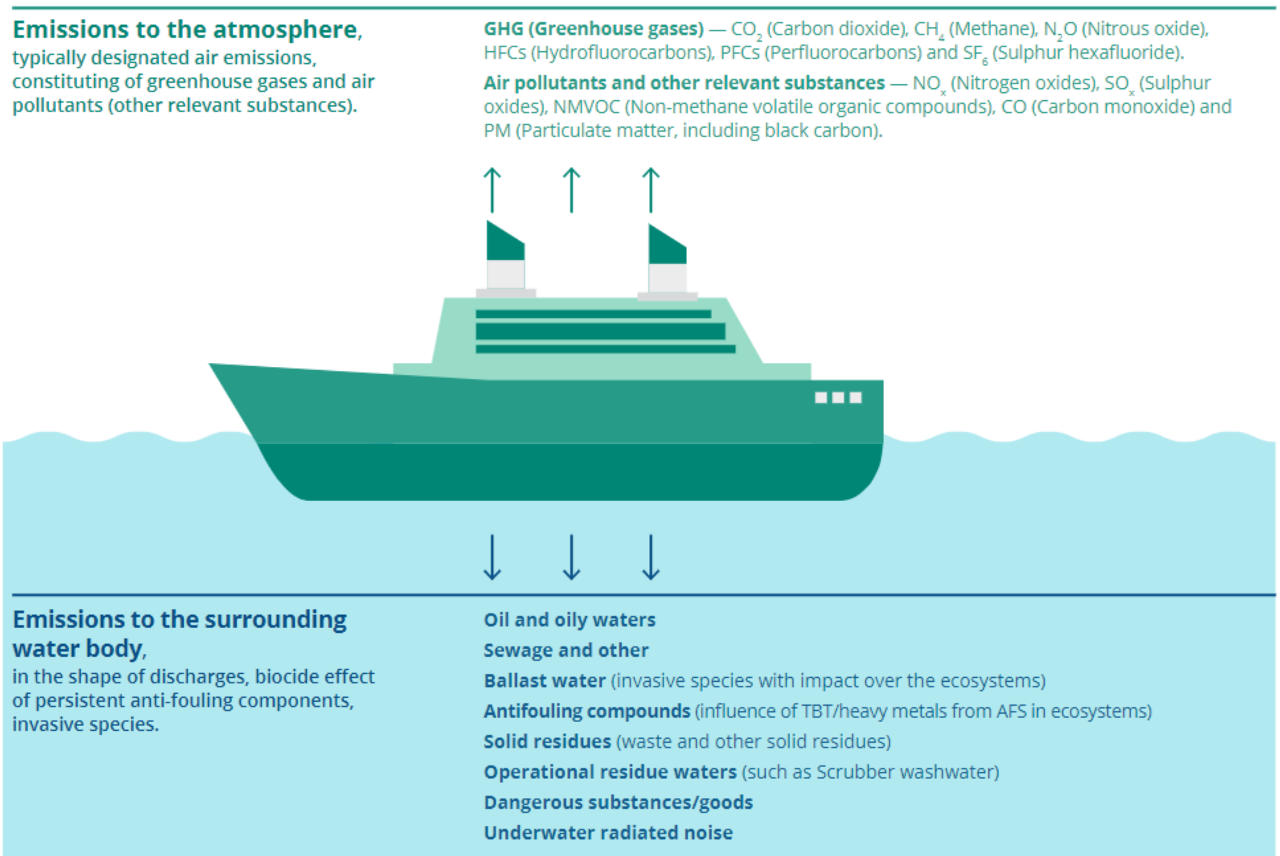


Figure 40. Pollutant emissions to the atmosphere and water body form a generic ship (Agencia Europea de Seguridad Marítima & Agencia Europea de Medio Ambiente, 2021).

Concerning **climate change**, emissions are still a major problem. In 2018, over 5.000 gross tonnage of carbon dioxide (CO_2) were emitted from marine ship visiting European ports whereas inland waterway transport results in 3.8 million tons of CO_2 emission per year. Overall, waterborne transport and in particular maritime transport contributed only to 13.5% of the total EU greenhouse gasses (GHG) emission in 2018 (Agencia Europea de Seguridad Marítima & Agencia Europea de Medio Ambiente, 2021) and, as far as today, shipping is the most carbon-efficient mode of transportation, with the lowest carbon dioxide (CO_2) emission per distance and weight carried (European Commission, 2022).

This data is confirmed also by a study commissioned by the European Environment Agency (EEA) related to the period 2014 – 2018 (European Environment Agency, 2021). Emissions **for freight transported by maritime shipping**, rail and inland waterway are very **low** compared with those for freight transported by heavy goods vehicle (HGV). Air cargo stands out as the mode with the highest emissions by far. However, over the 2014-2018 period, air cargo saw the biggest GHG efficiency improvement (12%) followed by rail freight (11%). Similar to passenger transport by air and rail, more efficient aircraft and the electrification of railway lines are behind this trend. HGVs only showed a slight improvement of 3%. The results presented above fully confirm the assumptions underpinning the EU's modal shift policy. However, not all modes are equally suited to all transport tasks. Therefore, it is not always possible to substitute one mode of transport for another. Issues related to geography (e.g., transport over water), the availability of infrastructure, as well as time criticality (e.g., for express delivery or perishable goods) limit what is possible. In addition, the most efficient motorised transport modes can only be used between **transport hubs** such as ports and rail freight terminals and, therefore, only function in combination with other modes.

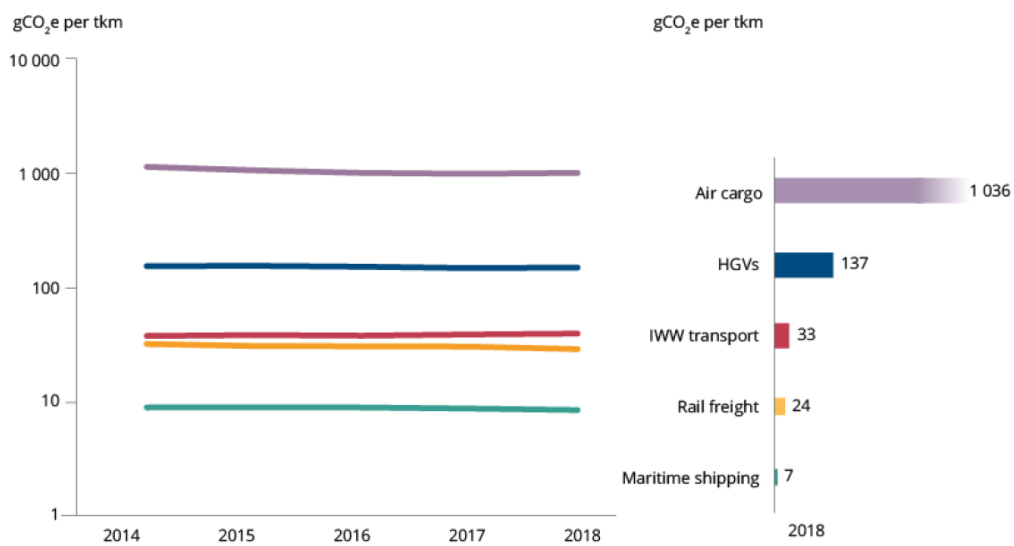


Figure 41. Average GHG emissions by motorized mode of freight transport, EU-27, 2014-2018 (Source: Fraunhofer ISI and CE Delft, 2020)

However due to the constant increase of the sector, emission related to waterborne transport in EU has grown over the years and the industry is actively searching new modes to reduce the current impact (Agencia Europea de Seguridad Marítima & Agencia Europea de Medio Ambiente, 2021).

Due to engine and other combustion and energy transformation onboard ships release different **air pollutants** to the atmosphere such as sulphur oxides (SO_x), nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO) (Agencia Europea de Seguridad Marítima & Agencia Europea de Medio Ambiente, 2021).The European Environment Agency reported that shipping is responsible for 11.05% of EU NO_x and 11.05% SO_x emissions with the higher concentration registered in coastal and port areas. Looking at the maritime transport, the future projection registered an increase in the emission of the main four air pollutants compared to land-based emission.

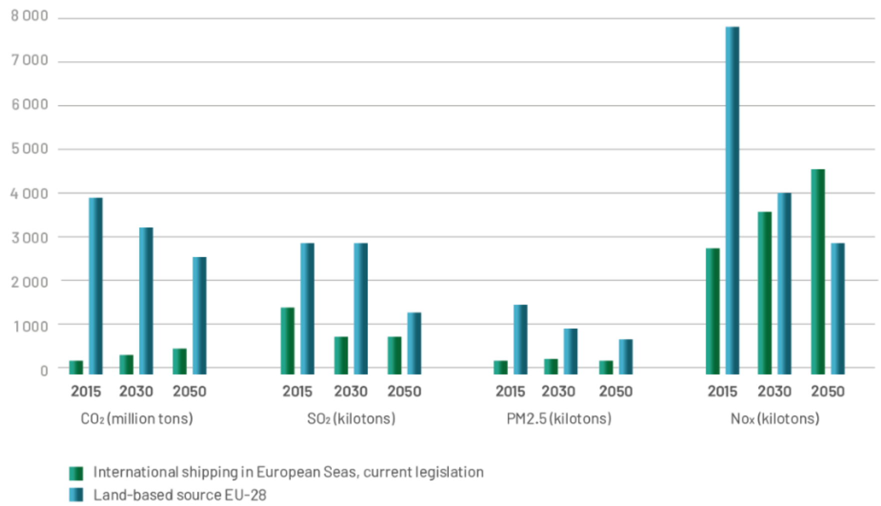


Figure 42. Emission form maritime shipping and projections (WATERBORN, 2021).

The same phenomenon appears in inland waterborne transport contributing to the pollution of the cities along rivers. Nowadays, other transport modes are becoming cleaner and waterborne transport faces the risk of falling behind (WATERBORN, 2021).

One possible solution is the introduction of the use of **Sustainable Alternative Fuels** in the waterborne transport domain that will enable the transition towards zero-emission operation. Although sustainable alternative fuels are associated with a high cost per avoided ton of CO_2, they form an instrumental and unavoidable part of decarbonizing the waterborne transport domain. Since the waterborne transport sector has committed itself to decarbonize fully, a transition towards the use of sustainable alternative fuels is clearly required. Fuel pathways will be checked for regulatory acceptance in close dialogue with IMO and CESNI members, as well as EU policies concerning both maritime transport and inland waterway transport.

Today, very few sustainable alternative fuels are in use in significant quantities in the waterborne transport domain. Small amounts of renewable diesel fuels are used. These are mostly waste cooking oil-based products that are limited in availability. Besides this, whilst the use of Liquefied Biogas is increasing, it is still extremely low. Trials with many other sustainable alternative fuels, such as ammonia and methanol, are emerging throughout the industry, but no single fuel has yet emerged to address all requirements and concerns.

Finally, **water pollution** is another great challenge that the waterborne transport must address. The impact on the environment span from underwater noises to ballast water which determinates different pressure and hazard on the surrounding water bodies (WATERBORN, 2021).

Technological Trends

The future transportation industry is expected to rely on the array of **smart and disruptive technologies** over larger transportation network infrastructure. New technologies such as **integrated service management, asset management, and predictive analytics** are expected to help transportation management companies to manage optimal routes, schedules, and capacity in near to real time. With the increasing presence of smart technologies in smart transportation, the associated solutions and services markets are also expected to grow at high growth rates, globally. **Emerging technologies such as smart ticketing, predictive analytics, cloud adoption, smart traffic, and operation solutions** will enable efficient and better transportation infrastructure. They would also improve timely decision-making for issues, such as asset deployment, utilization, and maintenance. With the help of disruptive technologies, smart transportation can efficiently manage the existing as well as new transportation systems to increase operational efficiency, reduce emissions, provide better safety, and ease the transportation needs of commuters at a low and efficient cost. The smart transportation technology comprises solutions and services for all the modes of transport, such as roadways, railways, airways, and maritime.

The advancement of **technologies** in the maritime transportation industry, such as **big data analytics, robotics, advanced materials, autonomous systems, advanced manufacturing, energy management, cyber and electronic warfare, human-computer interaction, and human augmentation technologies**, has led to the growth of the transportation mode in the upcoming year. The implementation of these technologies will depend on a favorable regulatory framework, technical standardization on a worldwide scale, and cooperation between marine stakeholders.

The increasing globalization of trade and the high complexity of port operations require the application of a sophisticated **id system**. In recent years, the size of ships has doubled and has added to the difficulty in managing port operations and demanded an even larger logistical effort. The trend toward just-in-time manufacture requires the continuous improvement of the information flow and the integration of the transport business in the production process.

Through **IoT**, ports are being integrated into a machine information network, where the relevant data is accessible and shared with shipment partners in a secure environment. The growing automatic processing of the cargo information across the maritime network provides transparency and efficiency in the container movement.

Digitalization technologies could have an impact also on port logistics and coordination, as reported by a study conducted in the **Adriatic Port of Koper** (Zanne et al., 2021). The Adriatic port of Koper is the only Slovenian international cargo port. The authors found that significant external costs are incurred due to a non-optimized situation caused by the lack of coordination and cooperation on all levels, although the port of Koper is one of European core ports. Further, previous cargo losses were probably derived from the unreliable operation of the supply chain by road, which has its origin in insufficiently digitized and under capacitated port gates and road port accesses.

Market Developments

General Constraints

Volatility in the crude oil price is impacting the water transport and therefore it is expected to **restrain the market for inland water freight transport** during the period 2021 - 2026. According to the United Nations Conference on Trade and Development, fuel oil is a major source powering the global economy and supplies 95% of the energy used in world transport. Water transport carries over 80% of global merchandise trade by volume and is highly dependent on oil. As the cost of oil rises, the carriers are forced to raise prices or bear losses. Usually, the receiver is charged more to make up for added costs. Higher fuel costs cause product inflation and affect every aspect of product transportation. When fuel prices fall, the consumer receives goods at a low price and logistic companies use the saved money to improve their operations. An increase or decrease in fuel price affects the operations cost directly.

Moreover, the successful deployment of **intelligent transportation systems** (ITS) in the marine sector can only be achieved by developing advanced services and applications for which customers are willing to pay(Markets&Markets, 2023). Although it is essential to invest in better infrastructure and technology in the logistics chain, it is also required to strengthen training and skillsets, as well as foster internal innovations. ITS for maritime is still in its primary stage. Only some developed countries, such as the US and China, have adopted ITS technology to improve maritime transport. There is a **lack of technological know-how and poor coordination** among concerned authorities that integrate advanced technologies in different types of ITS to make them compatible and interoperable. Additionally, varying and sometimes conflicting regulatory policies also serve as a barrier.

Challenges

The main challenges related to **maritime transport** are related to structural factors increasing maritime transport cost and to volatile oil and gas prices.

Shipping and port prices are expected to be driven by **structural factors** such as port infrastructure, economies of scale, trade imbalances, trade facilitation, and shipping connectivity in the longer term. All these factors will have a lasting impact on maritime transport costs and trade competitiveness. According to the UNCTAD-World Bank transport costs dataset, significant structural improvements have the potential to reduce maritime transportation costs by around 4%. Developing countries, especially the ones with poor shipping and port infrastructure, may experience the highest maritime transport costs in the coming years. Such structurally weak developing countries will also need help to mitigate transition costs and the lower connectivity that would result from decarbonizing maritime transport. Hence, improving structural determinants such as port infrastructure, trade-facilitating environment, and shipping connectivity will substantially bring down maritime transport costs (Markets&Markets, 2022b).

Smaller economies, such as Suriname, Guyana, and Romania, usually lack liner shipping connectivity, have a lower quality of port infrastructure, and inadequate trade facilitation measures. These shortcomings hamper the growth of maritime trade in such countries. Upgradation of ports to enable better shipping services and permit larger vessels to have shorter waiting times before entering ports will lower transport costs, offering a boost to maritime trade in such countries. Also, bilateral trade imbalances also affect the costs and overall trade. For instance, for sailings from high-demand to low-demand countries, many vessels have to return with empty containers having a negative impact on the shipping costs. As per the UNCTAD Review of Maritime Transport 2021, trade routes with trade imbalances have 2.4% higher transport costs on average for one direction than the other. Such factors hinder the growth of international maritime trade (Markets&Markets, 2022b).

Moreover, the majority of the world's fuel demands are met by fossil fuels, mostly oil and gas. Oil and gas prices are volatile and, apart from demand and supply, are also affected by a large number of factors, including geopolitical issues. Many countries are dependent on a single commodity, either oil or gas, for their exports and revenues, and this renders them extremely vulnerable to market volatility. The onset of the pandemic in 2020 saw oil prices touch historic lows, with the West Texas Intermediate (WTI) benchmark logging a negative value for the first time in history. Also, the current geopolitical scenarios, such as the US-China trade tussle and the Russo-Ukrainian war, which may see harsh sanctions being imposed upon Russia by the European Union, will affect the supply of gas from Russia to the rest of Europe and may also affect the transport of such commodities globally. All the major economies have chalked out plans to reduce their greenhouse gas emissions and achieve carbon neutrality, in line with the Paris Agreement. As a result, economies are shying away from increasing their usage of oil and gas and focusing more on renewables to fulfill their energy requirements. Hence, high bunker fuel prices will lead to an **increase in maritime transport costs** and an overall reduction in global maritime trade as the profitability reduces. Therefore, the volatility of oil and gas prices poses a big challenge to the maritime transport market (Markets&Markets, 2022b).

Regulatory Factors

The global pressure to reduce climate change falls also on waterborne transport. To achieve a feasible solution different long-term vision for a competitive and climate neutral economy were implemented:

- The **European Green Deal** and in particular the Commission Communication "*A Clean Planet for All: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral* *economy"*[23]. The overall objective is to achieve climate neutrality by cutting transport emissions by 90% by 2050 at the latest while also reducing GHG emission by at least 50% by 2030.

- **Initial IMO[24] Strategy on the reduction of GHG emission** from ships[25]. IMO plays a key role at international level, IMO's Marine Environment Protection Committee (MEPC) in 2018 adopted an initial strategy to reduce by 50% GHG emissions from seagoing ships. Currently, the strategy is reviewed to further decrease the emissions.
- The **Central Commission for Navigation of the Rhine's (CCNR) Ministerial Mannheim declaration**[26]. For inland water transport, the EU Parliament pushed the inland waterways transport sector to improve its sustainability, hence, CCNR in 2018 started its commitment to largely eliminate GHG and other pollutants by 2050 (WATERBORN, 2021).

Waterborne transport decarbonization is also relevant for the achievement of the Sustainable Development Goals (SDG) of the Agenda 2030 of the United Nation[27]. The SDGs are a universal set of goals and connected targets agreed by 194 United Nations member states to direct their development policies and initiatives towards sustainability (United Nations, 2015). The achievement of specific SDGs could tackle the environmental and social impact of the sectors which were previously mentioned in the chapter Environmental trends. The table below summarizes the goals helped by waterborne transport decarbonization.

Table 8. SDGs relevant for the waterborne transport (WATERBORN, 2021; World Bank & United Nations Department of Economic and Social Affairs, 2017).

Environmental impact	SDGs	How
Climate Change and GHG emissions		Zero emission waterborne transport solution such as alternative fuels
		Zero emission decision support systems
		Climate resilient port strategies and contingency plans
Air pollution		Reduction of air pollution in port city
		Reduction of air pollution along inland waterways and inland ports

23 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0773&from=EN
24 International Maritime Organisation (IMO)
25 UN body adopts climate change strategy for shipping (imo.org)
26 Mannheimer_Erklaerung_en.pdf (ccr-zkr.org)
27 THE 17 GOALS | Sustainable Development (un.org)

Water pollution		Improved implementation of shipping regulations will reduce sea-based pollution
		Improvement in management of ballast water, biofouling, and other transportation-related vectors of invasive species will improve overall resilience of marine and coastal ecosystems
		Implementation of more-sustainable and low-carbon transportation systems globally will require both capacity building and technology transfer
		Implementation of international law pertaining to the conservation and sustainable use of oceans and their resources, including, e.g., shipping.

Opportunities

One of the main **opportunities** for **maritime transport** is related to the improvement of **information and communication technologies.** Maritime transport has become more efficient and safer in developed economies owing to the adoption of information and communication technologies. However, ID applications have high costs and customized infrastructure. In the internet era, digital mobile communications and big data analytics have created a new global potential for low-cost and more powerful ITS (Intelligent Transportation Systems). Transport agencies deploy new and advanced tools, including cloud-based services, open data standards, and other smart applications to manage marine transportation assets and improve safety. These factors are expected to create growth opportunities for the ITS market in the maritime sector (Markets&Markets, 2023).

Moreover, another opportunity for the smart transportation industry is related to the development of semi-autonomous and **autonomous ships**, which are witnessing a rapid evolution with substantial technological advancements. Automatic vessels drive themselves with minimal or no human intervention. The deployment of autonomous ships is crucial for the growth of the maritime transportation industry, as these vehicles do not require drivers and would result in cost reduction transportation and logistics providers (Markets&Markets, 2020). Currently are increasing the R&D activities by leading manufacturers as well as system developers across the globe for the development of completely autonomous ships. For instance, companies such as Rolls-Royce and Kongsberg are developing fully autonomous ships (Markets&Markets, 2019).

Competitive Landscape and Players

The **main players** active in the **smart transportation sector in maritime** globally can be considered: Cisco systems (USA), Veson Nautical (USA), BASS software (Norway) and DNV GL (Norway).

Some of the major vendors **of waterway transportation software and services** market comprise: Accenture (Ireland), Aljex Software (USA), BASS (Norway), Cognizant (USA), Descartes Systems (Canada), DNV GL (Norway) and Veson Nautical (USA).

Major players in the **inland water freight transport market** are: American Commercial Barge Line (USA), Ingram Barge (USA), Kirby Inland Marine (USA), American River Transportation (USA), CMA CGM Group (France), McKeil Marine Limited (Canada), AP Moller - Maersk A/S (Denmark), Rhenus Group (Germany) and Imperial Logistics International (South Africa) (The Business Research Company, 2023).

Major companies in the **water transport market** include: A.P. Møller-Mærsk A/S (Denmark), China Ocean Shipping Company Limited (China), Cargill Incorporated (USA), CMA CGM S.A. (France), Hapag-Lloyd AG (Germany), Nippon Yusen (Japan), Evergreen Marine Corp (Taiwan), K-Line (Japan), Hyundai Merchant Marine Co. Ltd (South Korea) and Kuehne + Nagel International AG (Germany) (The Business Research Company, 2023).

Waterborne Transport: Analysis

Often swept away by a generalized definition of freight transport, waterborne transport is not only one of the oldest, but cheapest and most widely used modes of transport throughout the history of civilizations. Although aviation has taken over as the preferred mode for passenger transportation, waterborne transportation continues to touch lives by supporting fishing and leisure, and accounts for about 80% of international trade. Waterborne transport is going through an evolutionary change as it races to keep up with advances in robotics and communication in and around the ocean while safeguarding itself against the new age threats and, at the same time, complying with the pledge to reduce emissions. The following three, therefore, become vital to this transformation:

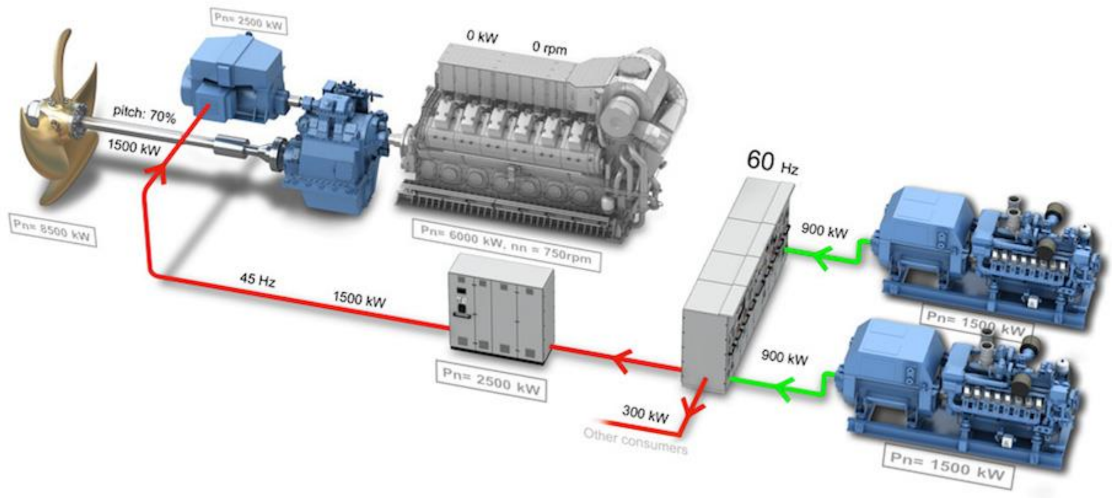
- Low-carbon vessels
- Multimodal transport
- Waterborne traffic management

Low-carbon Vessels

The International Maritime Organization (IMO) has made it clear that maritime transport emissions need to be reduced significantly by 2050. Efficient transportation alone, however, cannot achieve the targets. Voyages carried on low-carbon vessels present the most crucial pathway to decarbonizing shipping. As the industry continues to test and adopt a diverse variety of low-carbon fuels, it also needs to develop fit-for-purpose vessels, including hull designs, propulsion systems, fuel tanks, bunkering assembly, connectors, and emission handling mechanisms to support them.

Since lower energy density and limited storage capacity are not critical, river ferries and short-distance boats used for maintenance and monitoring activities present a strong breeding ground for the battery-electric powertrain. At the same time, a battery-diesel hybrid propulsion system is more suitable for long-distance cruising. These direct electrification pathways leverage higher efficiency than e-fuels and can benefit from cost reduction and improved battery energy density. While Wärtsilä manufactures fully electric ferries, tug-boats and inland waterway cargo vessels, Yara Birkland recently set their 3,200-tonne autonomous ship on the voyage. Several others, such as Ballard, have taken the hydrogen (and, to an extent, ammonia) fuel-cell route to mitigate the challenges related to the higher weight and lower power densities of conventional batteries limiting their applications.

A hybrid vessel is just like a plug-in hybrid car and has a conventional engine alongside the batteries to support high load demands at an additional cost. Most common hybridization today involves diesel and LNG, but biofuel hybrid boats are also gaining popularity.



Berger Maritiem's hybrid electric ship propulsion system utilizes battery power and diesel to power the voyage. Source: Berger Maritiem

Major ship engines manufacturers such as MAN Energy Solutions and Wärtsilä have also developed dual-fuel engine platforms that can use methanol and diesel with some retrofit modifications in the fuel-injection system. These dual-fuel engines are popular due to lower cost implications with a combustion-ready fuel supply before the maritime industry eventually transitions to next-generation green fuels – hydrogen and ammonia.

Ammonia engine developers, in particular, are betting on using the same dual-fuel assembly to use liquid ammonia as a fuel with additional De-NOx units to capture NOx emissions but largely remain at demonstration scale due to challenges related to corrosion and toxicity. MAN's ME-LGIM engine, designed to operate on a dual-fuel combustion mode with methanol and diesel, can be used with ammonia by injecting it into the cylinder at 600–700 bar.

As mentioned, hydrogen via fuel cells in the electric powertrain is a more explored pathway. Still, research efforts continue to use direct hydrogen in ICEs – specifically, MAN Energy solutions have been working on developing a four-stroke hydrogen engine since 1992. Recently, interest in a hydrogen-powered two-stroke engine is also on the rise. However, storage, transportation, and handling of hydrogen, including fuel injection and ignition through spark plug or pilot fuel, is still primarily an unresolved technical and feasibility challenge.

Aside from the powering propulsion, there are several other frontiers on which marine vessels are transforming to go on a low-carbon excursion, including improvements in efficiency by engine de-rating, waste heat recovery systems, trim and draft optimizations as well as employing innovative energy recovery technologies like using kites, wings, Flettner wind rotors, and sails to replace some of the propulsion power.

IMOFlexMAX by Stena Bulk, equipped with flettner rotors and solar panels to provide auxiliary power to dual-fuel LNG engine. Source: Stena Bulk

Promoters & Inhibitors

For the maritime industry to evolve and achieve IMO's decarbonization goals, fuels and the vessels burning them must also evolve. There is plenty of support and appetite to drive this change, but not without a handful of hurdles that need to be surmounted before the horizon of implementation is achieved.

Promoters

- **Global push for decarbonization**. Governments worldwide now agree to the need to decarbonize industries, including maritime. A coordinated push in the form of a solid and progressive regulatory framework to support investment for developing and implementing new vessel technologies will bring down costs and enable sharing of knowledge and best practices, building up to harmonized international standards and support for low-carbon transportation.
- **Electrification**. Electrification of ports, harbors, and ferry docking yards is experiencing a steady rise. As sensors, robotic devices, and processing units are deployed, the appetite for using electric propulsion will rise. Reducing battery size and costs, and improving fuel-cell technologies can help inland voyages and service vessels transition into the predominantly electric-powered waterborne transport system.

- **Opportunity for phased transition**. Ocean-going vessels are expensive and take a long time to construct, making it impractical for shipowners to quickly switch to low-carbon ships such as those powered by hydrogen and ammonia, requiring a complete vessel overhaul. Thankfully, there are diverse pathways, including those using transition fuels and the existing engines with little to no modification before moving on to the next generation of dual-fuel engines and finally running on emission-free fuels once the technology matures.

Inhibitors

- **High upfront cost.** If new vessels are prohibitively expensive, making changes to the existing ones is not without any expenses. Cargo operators can easily get caught in the dilemma of retrofitting vs. hanging on for a bit longer before buying a new and possibly non-existent "transformationa"' variation. A careful techno-economic assessment considering vessel lifetime, safety, efficiency, and emission-reduction potential is critical when considering the variation of a low-carbon vessel to adopt.
- **Fuel supply shortage.** From transportation to storage to onboard bunkering, hydrogen or ammonia-powered transportation requires significant overhauling of infrastructure which requires a significant upfront investment. Electrification or methanol pathways have yet to achieve the scale needed to support the global demand. The level of scale-up to support global waterborne transport needs will require not only heavy capital expenditure and land but also feedstock that is primarily natural gas today.
- **Technical challenges.** Most technologies at the end of the green spectrum, including fuels and engines, have major technical roadblocks. While storing hydrogen is a volumetric headache, ammonia has low flame velocity and poor chemical kinetics compared to other fuels. Ammonia is also quite corrosive and threatens system integrity if using systems designed for conventional fuels. The historical speed of changing maritime propulsion isn't encouraging, and diverse options may diffuse the efforts requiring a sharp and focused attack.

Key Players

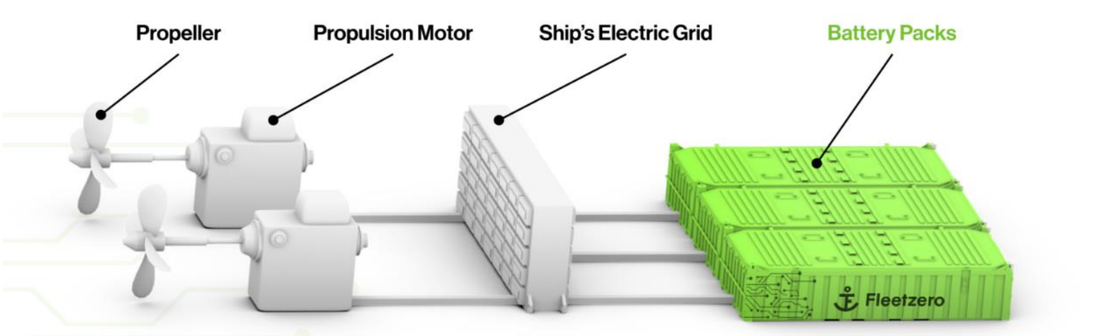
Recent Developments

- **BEH$_2$YDRO (Netherlands).** A joint venture between CMB and Anglo Belgian Corporation in Belgium has developed a low-pressure spark-ignited 100% hydrogen engine. The engines are available in four sizes with power ranging from 1 MW to 2.6 MW. The engine features a double-walled hydrogen system for safety and works on the principle of compressing hydrogen and air fuel mix in the combustion chamber before a pilot fuel (diesel) is injected to auto-start ignition. The company sees harbor tugs and inland shipping as the significant market for this engine.

This project is supported by the Interreg ADRION Programme funded under the
European Regional Development Fund and IPA II fund.

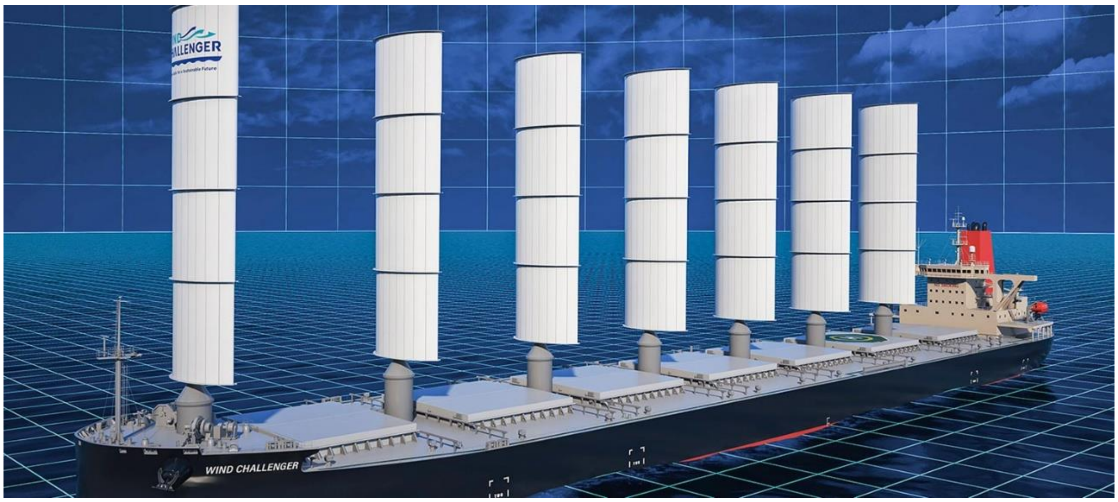
BEH$_2$YDRO hydrogen powered spark engine 6DZD model. Source: BEH$_2$YDRO

- **Fleetzero (United States).** The Alabama-based start-up is developing a battery-swapping container to charge ships during voyages. They claim to have developed their batteries based on lithium iron phosphate chemistry, with passive and active fire suppression measures in place during the battery design. Fleetzero aims to convert container vessels into charging ships by 2025 to follow with a commercial operation.



Fleetzero propose to replace the space occupied by onboard diesel generators with battery packs. Source: Fleetzero

- **Mitsui O.S.K. Lines (Japan).** The shipping company has developed "Wind Challenger", a sailboat that uses wind energy to generate vessel propulsion. Developed after 13 years of research in collaboration with the University of Tokyo, the installation was able to demonstrate up to 10% fuel saving on bulk carrier shipping.



Shofu Maru, MOL's first cargo ship based on the Wind Challenger Technology. Source: MOL

- **All American Marine (United States).** In collaboration with Switch Maritime, All American Marine has launched a 70-foot commercial ferry, they have named Sea Change. The boat, operational in California, is powered by 360 kW hydrogen fuel cells manufactured by Cummins supported by 100 kWh of a lithium-ion battery. Hexagon has developed the onboard hydrogen storage take with a capacity of 246 kg.

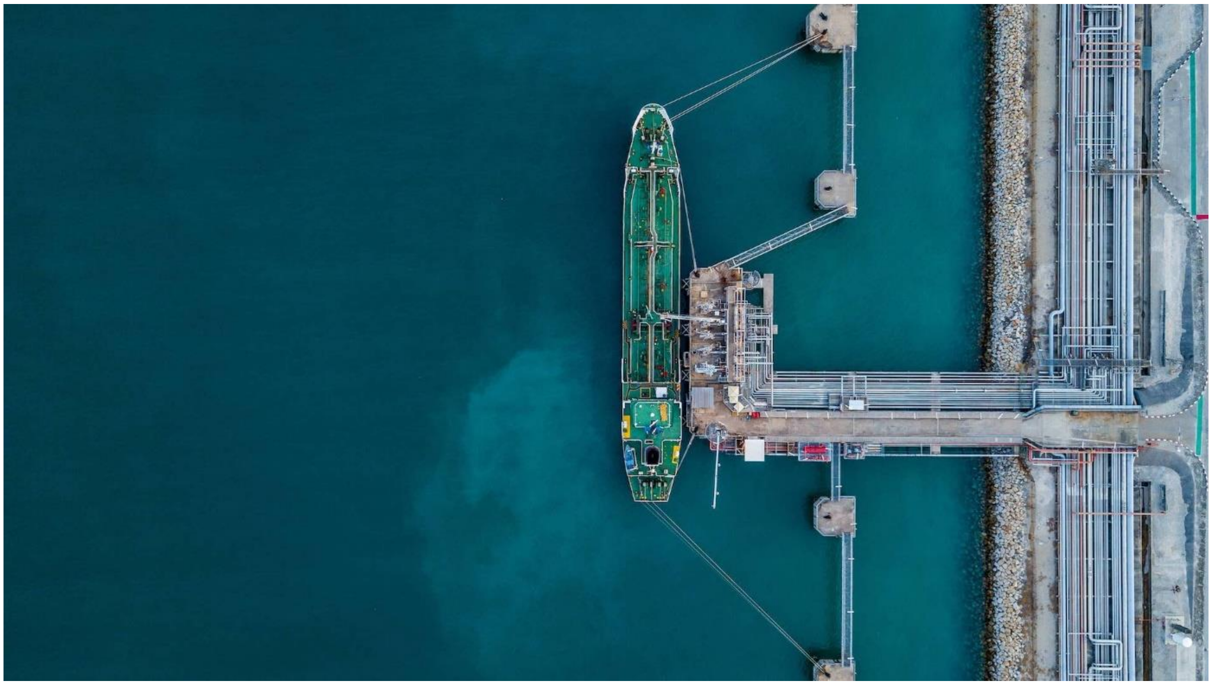
Future Prospects

While the jury is still out on choosing a low-carbon solution for maritime, there is no doubt about the transition itself. Therefore, low-carbon vessel development will continue to grow at a category level in the coming years. The growth appears to be scattered in the interim, with multiple new and retrofit designs that are either commercial or near-commercial being pursued. However, these fuels – LNG, bio-based, and methanol face carbon reduction limitations in the long term despite providing clear synergies for the oil and gas industry. Hydrogen and ammonia engines are shaping to emerge as leading shipping carriers in the future, while ferries will leverage chemical energy from batteries and fuel cells. Nevertheless, this transition must address significant challenges associated with lacking hydrogen infrastructure, storage cost and space consideration, the high production cost of green hydrogen, the lack of relevant safety standards and the maturity of engine and fuel cell technology. Although the activities will continue to grow in low-carbon vessel space, and rightly so, clear winners are unlikely to emerge before a 2035 timeframe. The Adriatic-Ionian region will benefit from testing and deploying several variations to find the right mix of these low-carbon vessels to not just achieve net-zero targets but also emerge as a world-leader in waterborne transport transformation.

Multimodal Transport

Waterborne transport has one of the smallest environmental impact along with rail, is low-cost and faces the least congestion compared to other means, but more often than not, coast-to-coast transportation isn't an absolute solution for transportation, mainly when goods are being transported over very long distances, such as across countries. Efficient, well-connected multimodal transport is essential for competitive and sustainable transportation of goods. Multimodal transport involves using two or more types of transport – which, in the context of the Adriatic-Ionian region, could be sea and rail, sea and road, or sea and inland waterways. On the one hand, multimodal transport presents vast opportunities to leverage the existing maze of transportation lines to design the most fuel-efficient, cost-effective, and sustainable pathway for transporting goods, but also invokes additional activities related to unloading, grouping, and reloading of goods to another transport unit. There are two forms of multimodal transport – intermodal transport, where the container is not opened and just changes the mode of transportation, reducing the risk of damage at the expense of flexibility. In contrast, combined transport involves unpacking/repacking for last-mile delivery, primarily by road transport.

The Adriatic-Ionian region hosts a vast coastline and a vivid network of inland national and international waterways, presenting enormous possibilities to optimize the entire process of transporting specific types of perishable goods (e.g. fresh food), using the sea in conjunction with land-based transport or inland waterways. The success of multimodal transport rests on various factors, starting with strong and uniform legislation for international trade agreements, market access, ship and container inspection and vessel traffic monitoring to the training of staff and improvement in the interoperability of equipment, including IT systems and solutions. Establishing efficient digital processes and communication services is also a significant building block of a successful multimodal transport system. Inland waterways may require additional regulatory consolidations to protect aquatic life and extra construction work, such as dredging needed to remove bottlenecks in transporting larger vessels.



PortXchange develops several port digitalization solution including EmissionINsider to monitor multimodal emissions.
Source: [PortXchange]

An increasing volume and variety in global trade and the availability of faster communication and digital technologies have attracted a copious amount of interest in studying and implementing multimodal transport worldwide. The European Union is also undertaking several collaborative actions, such as the Waterborne project, to increase collaboration between stakeholders and the Orchestra initiative, which will develop a multimodal traffic management ecosystem to define and implement guidelines for running smooth logistic operations. On the other hand, Pioneers, a consortium between the ports of Antwerp-Bruges, Barcelona, Constanta, and Venlo, is demonstrating green technologies across the multimodal network to transition towards zero-emission multimodal mobility.

Promoters & Inhibitors

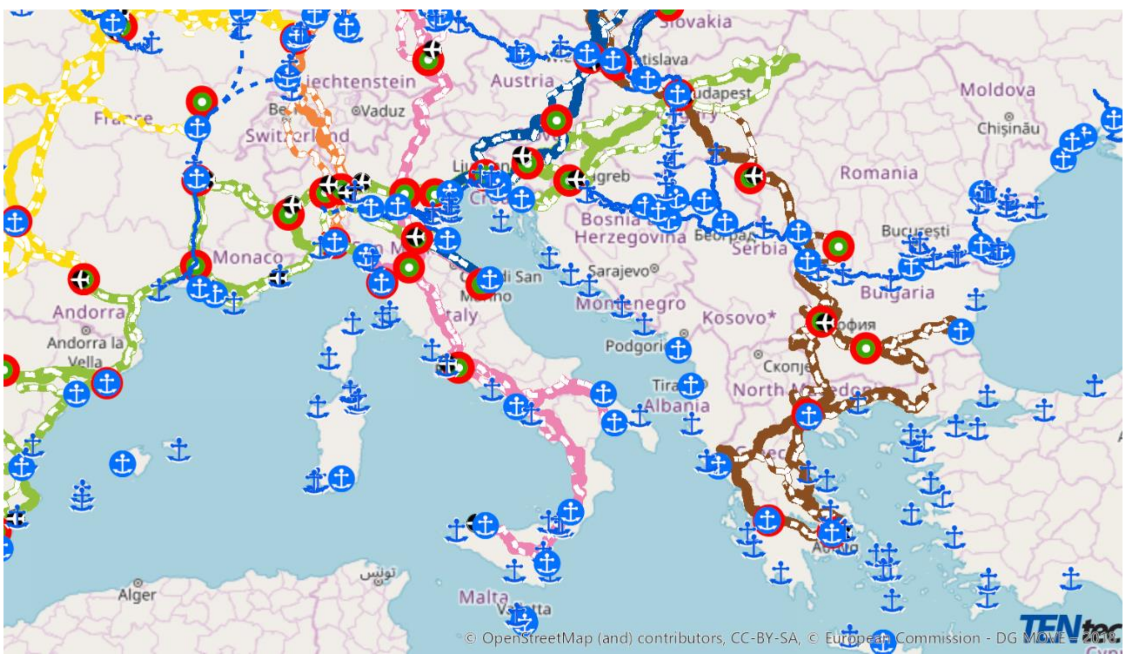
Multimodal transport is vital for a sustainable, low-emission, low-cost, end-to-end movement of goods. Most nations recognize the need for uniform regulatory legislation to support the development of sleek multimodal transport services and are using digital technologies to help design and implement new policies. However, several challenges remain to be resolved.

Promoters

- **Opportunity to reduce emissions**. Inland waterborne transport is a low-emission, low-noise alternative to road and rail in addition to being energy efficient. If nations push towards developing and promoting deeper impregnations of inland water transportation networks, it will culminate into a highly integrated multimodal transport chain.

- **Improving communication transparency**. Transparency in shipping-related updates, delays, changes in route, and interaction with connecting services is pivotal for a formidable multimodal transport. Thanks to digital developments, exceedingly integrated, low-latency communication networks are being established to exchange information, along with visual dashboards for real-time monitoring and optimization of cargo movement to save time and costs. Such development will lead to more extensive adoption of multimodal transport.

- **Regional interest by the TEN-T**. The EU has a strong push to develop a Europe-wide network of rail, road, maritime and inland waterway transport through the **Trans-European Transport Network (TEN-T) policy**. The policy aims to construct new physical infrastructure and strengthen regional collaboration in the EU to remove transport bottlenecks and technical barriers by supporting the development of innovative digital solutions. TEN-T vision essentially translates to a continent-scale multimodal transport. Being at the heart of it, the Adriatic-Ionian region sits at the hotbed of development activities.



TENtech's Interactive map viewer showing multimodal network with key ports. Source: TENtec

Inhibitors

- **Security and liability concerns**. On the one hand, multimodal transport offers an advantage in terms of having a single provider as the only agent responsible for the movement of the freight, making tracking and liability simple on the surface, the challenges related to monitoring and sharing liabilities behind the "single end-to-end contract" may be quite complicated and potentially insecure due to more significant number of "touchpoints".

- **Legal delays**. Multimodal transport across states and countries is still at an evolutionary stage despite being around for quite some time. It requires a mountain of paperwork around the declaration of goods accounting for differences in definition and quantity of restricted material and variability in auditing and approval processes. Improved adoption of ICT for collaborative communication and messaging, paperless invoicing, and uniform regulatory framework across borders will be fundamental to reducing delays threatening the life of perishable goods.

- **Transportation bottlenecks**. Draughts making the inland waterways impossible to use, national lockdowns, the limited size of inland roadways, and the capacity of trucks – need to be accounted for when mapping shipping with inland transportation. Navigational obstacles to multimodal transport traffic will differ for different modes of transportation. They will require curated handling on a case-by-case basis, sometimes involving infrastructure-related costs.

Key Players

Recent Developments

- **NOVIMAR (Europe).** A joint venture involving 22 logistics operators, public bodies, and research organizations in seven EU and two associated countries, led by the Netherlands Maritime Technology Foundation, has developed a vessel train concept that includes a lead vessel controlling several trailing follower vessels remotely. The conceptual design is expected to be commercially launched by 2025 and will deploy sensors and digital control systems for secure data transactions between vessels.

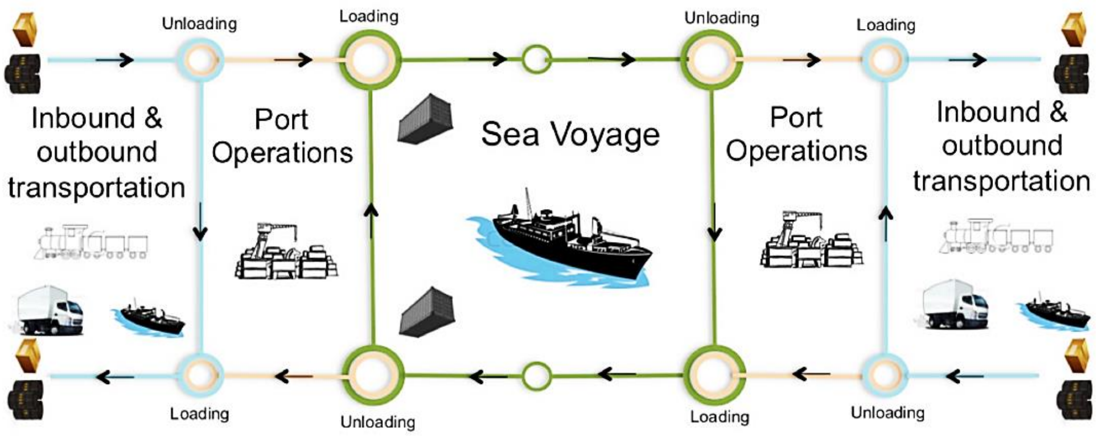
- **Pioneers (Europe).** Port of Antwerp and several other EU ports, such as the Port of Barcelona, Constanta, Venlo, and several research institutes, are working on developing an emission-free multimodal global trade ecosystem. The group aims to achieve the overarching objective through improved port infrastructure, digitalization and transportation automation and will demonstrate their green port masterplan at four participating ports.
- **NEWBRAIN (Europe).** The multinational collaborative project – Nodes Enhancing Waterway Bridging Adriatic-Ionian Network (NEWBRAIN) – funded by the ADRION program, is focused on conducting feasibility studies for implementing digital solutions at participating ports. Key program actions are geared towards enhancing the Adriatic-Ionian core node system to support an efficient and environmental-friendly multimodal logistic network.
- **PortXchange (Netherlands).** The Port of Rotterdam Authority spin-off, PortXchange, offers digital solutions for multimodal carbon emission accounting, optimization and reporting. In collaboration with BigMile, the company has launched EmissionInsider, which helps visualize emissions from all modes of transport and capacitates port authorities to take optimum preventative actions to reduce them.

Future Prospects

Multimodal transport, particularly in the Adriatic-Ionian region, has a critical role in improving the transportation of goods, fully utilizing different modes of transport, including inland waterways culminating in reduced fuel consumption, lower fuel consumption emission and faster delivery. Despite challenges around regulations and infrastructure, the regional momentum for multimodal is robust. It will continue to develop over the years to make waterborne transport more efficient in the future.

Waterborne Traffic Management

Roads, toll plazas, and railways bridges are the last few things that come to mind when one thinks about traffic and traffic management, but it is no less critical for the transport segment that carries 80-90% of goods around the globe. Waterborne traffic management, often incorrectly simplified as maritime traffic management, broadly involves controlling vessels' navigation paths and arrival/departure times at sea. It relates not only to managing the traffic in the ocean but also in the inland waterways, often the latter being significantly more challenging.



Schematics of traffic management in a multi-modal chain of operations. Source: [STM]

The safety of waterborne operations is of prime importance to avoid accidents leading to environmental damage, economic impact due to loss of goods or delays, and to the lives, impacting public perception of the waterborne transport. Conventionally regulated by the coastal authorities using classical technologies such as radar-based positioning, automatic identification system, and radio transmission, the vessel traffic services need to evolve. The changing ways of operations, type of powertrains deployed, size of ships, and trip frequency combined with the expansion of their operational areas to remote and challenging regions need a more significant emphasis on traffic management and new rapid, digital solutions to mitigate passenger and cargo risks, ensure high levels of safety, while at the same time preserving increased passenger expectations of comfort and on-board amenities in luxury transportation.

Using sensors with IoT devices for weather monitoring, analysis, and easy visualization can help reroute the vessels and weed out inefficiencies in fleet operations. As data generation and computation power increase, robots are being deployed for collecting, analyzing, and reporting performance data, including fuel consumption, route travelled, and emissions caused. Robotics offers a higher degree of accuracy, consistency, and minimum risk of failure.

Fleets of UAVs and USVs equipped with sensors connected to a centralized surveillance control room at the ports help safeguard the port against physical and cyber threats with a minimal workforce requirement. Drones are deployed near the shore for vessel navigation and traffic control to minimize collision and near-collision incidents. These airborne devices have photogrammetry and LIDAR sensors to help map the 3D environment with precise georeferencing.

The meteoric rise of ICT has not only augmented shore-to-ship and ship-to-ship connectivity, but it has also reduced the latency of data transfer at a fraction of the cost. Improved satellite and 5G communications are increasingly finding a place in traffic management applications. Especially for inland waterways, using 5G to communicate quickly is critical as the water freeways are narrower and more prone to congestion. On the other hand, simulation-based predictive models, in combination with real-time monitoring, can help manage operations in extreme weather and complex traffic fairways close to the nodes at ports and harbors.

The Adriatic-Ionian region enjoys an enormous coastline crisscrossed by many inland international waterways making it home to highly diverse waterborne traffic. Multimodal traffic management is therefore vital for the region to successfully transportation of passengers and goods in a safe and timely fashion, which calls for a strong need for uniform traffic regulations and digital processes and communication services in place to implement them.

The unmet need has been recognized by the European Union and culminated in several collaborative actions such as the Sea Traffic Management (STM) initiative, developed by the Swedish Maritime Administration, to make real-time data available for route optimization, enhanced monitoring and navigation, and ship-to-ship route exchange. Once fully deployed by 2030, the program aims to reduce accidents by 50% while making voyages 10% more cost-efficient and still consuming 7% lesser fuel. On the other hand, Orchestra is developing a multimodal traffic management ecosystem to define and implement guidelines for running smooth logistic operations. Eventually, developing and adopting new technologies, a regulatory framework for traffic management and building operational knowledge for the workforce will be vital for a successful waterborne traffic management system.

Promoters & Inhibitors

"Safety first, production must," a catchy slogan printed in the mining areas and ports in the early 2000s, still hasn't moved an inch in relevance for any heavy industry. Cost benefits, emission control and time savings aside, safety concerns alone make traffic management possibly the most critical aspect of the waterborne transport industry. The key factors that will define the pace of development for waterborne traffic management are as follows.

Promoters

- **Growth in communication technologies**. Increasing penetration of digital technologies such as robotics and sensors in waterborne transport has propelled the adoption of IoT and communication technologies at an exponential rate. The real-time access to data and the ability to communicate on the fly using 5G will be decisive factors in promoting the development of robust and cost-effective traffic management solutions.

- **Integration of the logistic chain**. Transportation via the sea or roads is no more untouched silos. As global transportation evolves with more multimodal hubs coming into play, the aspirations to integrate the whole logistic chain to fully realize the potential of each transportation mode along with efficient port operations is increasing. This translates into the need for voyages to be synchronized with ports for accurate prediction and preparation for the arrival and departure of ships as well as standardized ship-to-ship or ferry-to-ferry coordination for smooth sails.
- **Digital twinning**. Digital twinning and predictive maintenance require collection, visualization, and processing of the real-time location data and those related to the environment and ship's condition. These digital support systems can easily host logistics and traffic-related data for traffic decision-making without involving different processes.

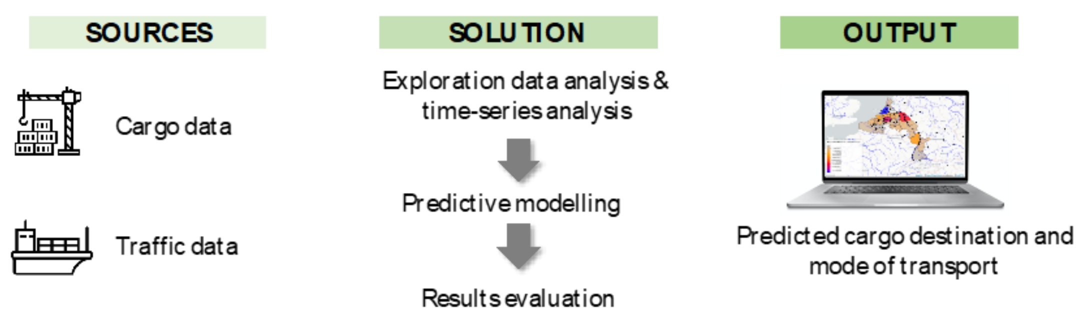
Inhibitors

- **Diversity in waterborne traffic.** If increasingly varying sizes, types, reach, and fuel choices in ships were not already challenging enough, their integration with inland waterways compounds the struggle to keep a congestion-free transport running. Given that the lifetime of a vessel is long, adopting new technologies will always be a challenge, mainly if it requires a significant overhaul of the system.
- **Regulatory bottlenecks.** Maritime transportation is neither as uniform as aviation nor as localized as rails and roads – at least for the most part – and is a complicated international business, to say the least. It is therefore regulated at different levels under different policies, which quite often create an incoherent landscape of conflicting dogmas. Without a cohesive agreement, smooth management of waterborne transport will be a far cry.
- **Infrastructure cost.** Inland waterways require significant investment to expand channels and port facilities, which may peg back the appetite for expansion of waterborne transport to more inland areas. Thankfully the EU recognizes it and has set up the Trans-European Transport Network (TEN-T) policy to construct new physical infrastructure in and around the Adriatic-Ionian region.

Key Players

Recent Developments

- **Corealis (Europe).** The collaboration between Barcelona-based data solutions firm MOSAIC and the ports of Piraeus, Valencia, Antwerp, Livorno, and Haminakotka to develop innovative solutions for waterborne transport for the 'Port of the Future' has launched a multimodal inland planner they have named Cargo Flow Optimiser. The tool has been deployed at the Port of Antwerp to predict and control multimodal traffic to and from the port.

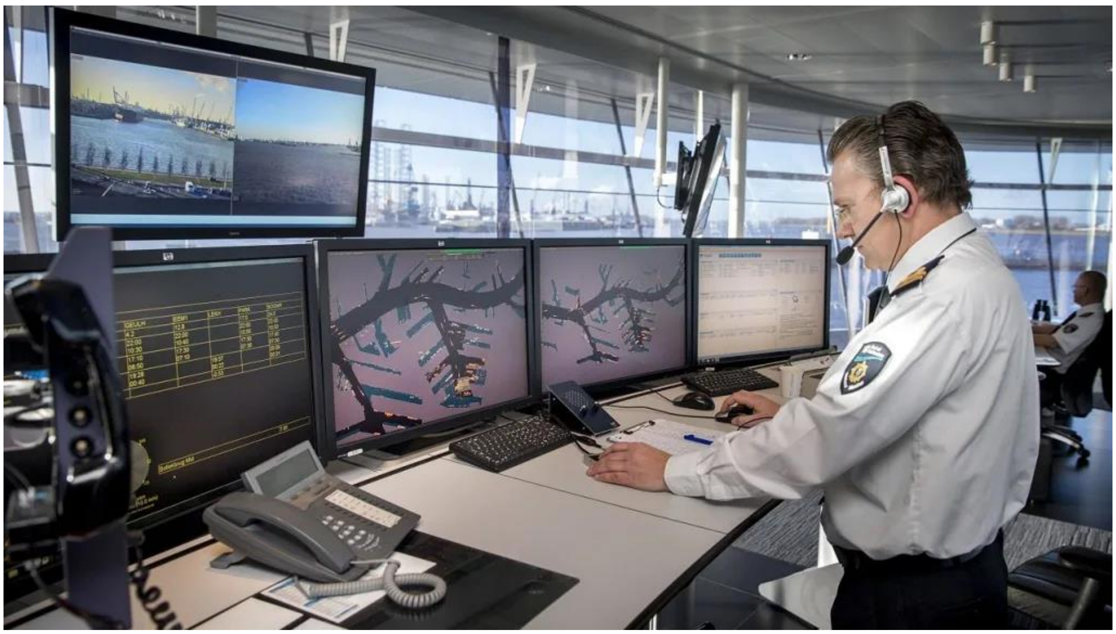


Process-flow diagram of Corealis Cargo Flow Optimiser. Source: Corealis

- **STEAM (Europe).** Sea Traffic Management in the Eastern Mediterranean (STEAM), funded by the Cyprus Research Promotion Foundation, uses digital technologies to transform the Port of Limassol and establish it as a multimodal transshipment hub.
- **Horizon (Europe).** As a part of their 2023-2024 work program for climate, energy and mobility, Horizon will invest ten million Euros in developing solutions for optimizing multimodal networks and managing traffic using data analytics. The program envisions improving multimodal traffic

flows and demonstrates at least a 30% reduction in the average travel delays and energy consumption.

- **SAAB (Australia).** The port of Melbourne has awarded SAAB, a security solution provider based out of Sweden, a contract for Saab's PortControl Port Management Information System (PMIS) for recording, managing and billing the ship traffic at the port. SAAB develops several digital solutions related to maritime navigation and traffic management.



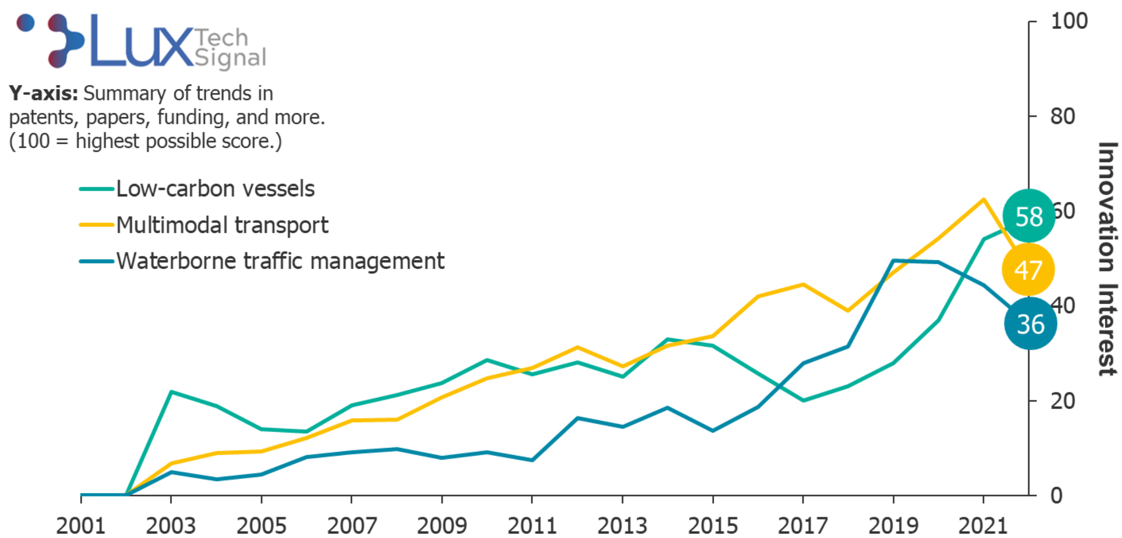
SAAB's MaritimeControl – Vessel Traffic Management Information System allows operator to visualize and control traffic. Source: SAAB

- **LeMO (Netherlands).** Another EU-funded project under the Waterborne program's umbrella, Leveraging Big Data to Manage Transport Operations (LeMO), aims to leverage big data analytics to monitor and manage maritime traffic.

Future Prospects

The impact of digital growth is evident in marshalling maritime and river-borne traffic. The growing number and types of ferries and vessels, coupled with the demand segments they address, is perplexing, to say the least. Modern traffic management solutions employing advanced monitoring and analysis methods are essential for smooth, accident-free, timely voyages. While most of these technologies remain at demonstration or pilot scales, they are set on growth in the next decade, supporting the EU's aspiration to build an emission-free, efficient transportation system with shipping being a critical component. Placed at the heart of the EU, port authorities and local governments in the Adriatic-Ionian region should definitely play a critical role in defining traffic management regulations for the wider region.

Innovation trends

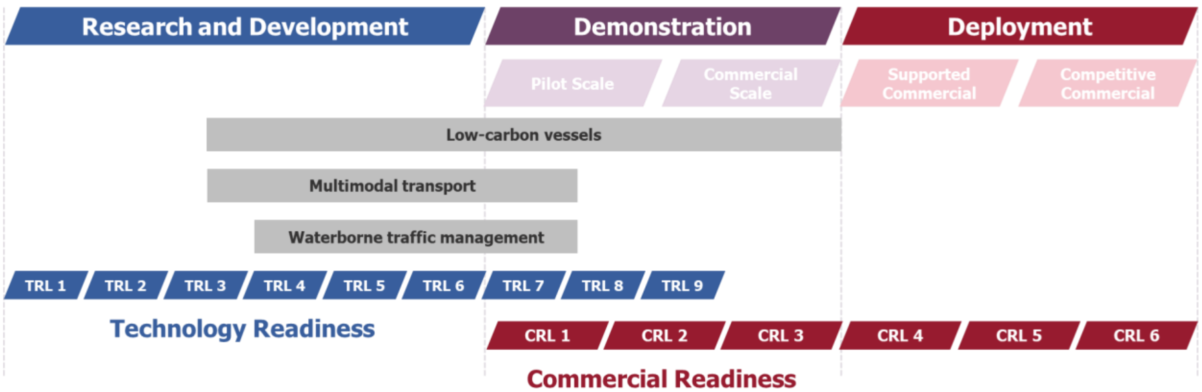


*The **Lux Tech Signal** is a composite score, combining data in patents, papers, and funding, plus Lux Research's proprietary data. It quantifies the progress of each technology, against a maximum innovation interest score of 100. Changes over time indicate growing (or shrinking) innovation interest, while inflection points may point to commercial opportunities or challenges ahead.*

The number of low-carbon fuels, including batteries, LNG, bio-based fuels, batteries, hydrogen & ammonia, methanol, synthetic fuels, and renewables and the powertrain technologies to utilize them in the shipping industry is quite extensive, making it hard to differentiate the primary force driving innovation at a specific point in time. Still, collectively, the research and development activities for low-carbon vessels have been on a consistent rise. In particular, IMO's greenhouse gas emissions strategy in 2018, dubbed IMO 2050, has been a defining moment that has provided a step-up boost to research and innovation for developing low-emission waterborne vessels.

On the other hand, Multimodal transport has been consistently gaining traction as communication, data generation, and processing technologies evolve and transportation and logistics continue to integrate. In 2016, the research interest in waterborne transport traffic management increased when the EU announced several programs under the HORIZON 2020 initiatives directly linked to waterborne traffic management to ensure safer operations. While the plateau in the last couple of years may seem surprising, it can be due to regulatory hurdles compounded by regional lockdowns due to the global pandemic arresting the ascent of development activities.

Technology Status



There are multiple low-carbon vessels in operations or development, given the overabundance of fuel choices. While methanol engines and battery or fuel-cell power ferries are ahead of the curve and are already operational, ammonia or hydrogen-powered vessels are still in the early stages of development. As digital technologies expand, multimodal transport will continue to evolve. Depending on the end-use and complexity of the nodes hosting multimodal transport, some areas, such as ocean-road, are witnessing more development than others. Proper waterborne traffic management has principally stayed in silos thus far and has only recently started to evolve following the maturity of multimodal transport. However, most of these technologies remain at demonstration or pilot scales.

Alternative and Competing Technologies

The **freight transportation** sector comprises 4 transportation modes, namely: **rail**, road, **ocean** and **air**. These transportation modes provide competitive and cooperative freight services and come with both advantages and disadvantages in terms of speed, price, accessibility, safety, and security. Each transportation mode needs different freight management system solutions to streamline the freight operations. It has been analyzed that there would be at least 80% growth in the volume of freight transport by rail, water, road, and air by 2035. The growing freight demand would also see advancements in technologies, communications, infrastructures, and solutions globally (Markets&Markets, 2018).

Another form of transportation that is expected to emerge in the coming years is **drone transport and logistics**. Drone logistics and transportation refer to the delivery of packages, cargo and/or passengers using drones. Freight drones can be used to deliver several types of cargo. Drone deliveries are certainly a huge trend across multiple industries, gearing up to revolutionize air-based transportation of both, essential and non-essential goods when they reach large-scale implementation. One of the areas in which they could prove to be really useful is shore-to-ship and ship-to-ship package delivery. Autonomous maritime package delivery would make sense in certain regions and seasons, where the costs and logistics of traditional delivery create significant barriers.

Conclusions

Freight transportation through ships over the **sea** is considered to be the oldest transportation mode. Use of sailboats for carrying shipments across continents in the olden days gave birth to the massive shipping industry that we witness today. Huge ships have the capacity to carry thousands of tons of cargo. **Ocean freight** is considered to be one of the cheapest transportation modes, taking into consideration the transportation distance. However, the low cost comes with a considerable delay in delivery time. Moreover, it is also the slowest transportation mode. Non-perishable and non-time-sensitive goods are the usual revenue earners in this transportation mode. As the transport load is very high in the seaways, the use of freight management system solutions would eliminate the complexities associated with ocean freight operations.

The **advancement of technologies** in the maritime transportation industry, such as big data analytics, robotics, advanced materials, autonomous systems, advanced manufacturing, energy management, cyber and electronic warfare, human-computer interaction, and human augmentation technologies, has led to the growth of the transportation mode in the upcoming year. The implementation of these solutions and services technologies will depend on a favorable regulatory framework, technical standardization on a worldwide scale, and cooperation between marine stakeholders.

Advancements in **communication technologies** in the maritime transportation industry provide connectivity from ship-to-ship communication and ship-to-shore communication. Moreover, port operation management increases the efficiency of terminal operators and make them cost-effective. It reduces manual operations significantly and provides navigational aids and vessel traffic separation facilities.

The development and acquisition of these **new technologies and systems** will impact and shape the waterborne transport industry in the coming years.

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