Lloyd's Register Foundation

Foresight review of ocean safety

Engineering a safe and sustainable ocean economy

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About Lloyd's Register Foundation

Our vision

Our vision is to be known worldwide as a leading supporter of engineering-related research, training and education, which makes a real difference in improving the safety of the critical infrastructure on which modern society relies. In support of this, we promote scientific excellence and act as a catalyst working with others to achieve maximum impact.

Lloyd's Register Foundation charitable mission

- To secure for the benefit of the community high technical standards of design, manufacture, construction, maintenance, operation and performance for the purpose of enhancing the safety of life and property at sea, on land and in the air.
- The advancement of public education including within the transportation industries and any other engineering and technological disciplines.

About the Lloyd's Register Foundation Report Series

The aim of this Report Series is to openly disseminate information about the work that is being supported by Lloyd's Register Foundation. It is hoped that these reports will provide insights for research, policy and business communities and inform wider debate in society about the engineering safety-related challenges being investigated by the Foundation.

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Executive summary

Covering over 70% of the Earth's surface, the oceans are home to a large range of industries including fishing, oil and gas production, and shipping. Those who work at sea have some of the most dangerous jobs in the world. Our global energy, food and other supply chains are dependent on the ocean economy with 80% of our goods transported by ship. The oceans contribute over $1.5 trillion each year to the global economy and this is predicted to double by 2030 with direct employment in ocean-related industries increasing to 40 million jobs by 2030. A just transition to a low carbon, sustainable ocean economy necessitates investment, education, infrastructure, innovation, and decent, safe jobs.

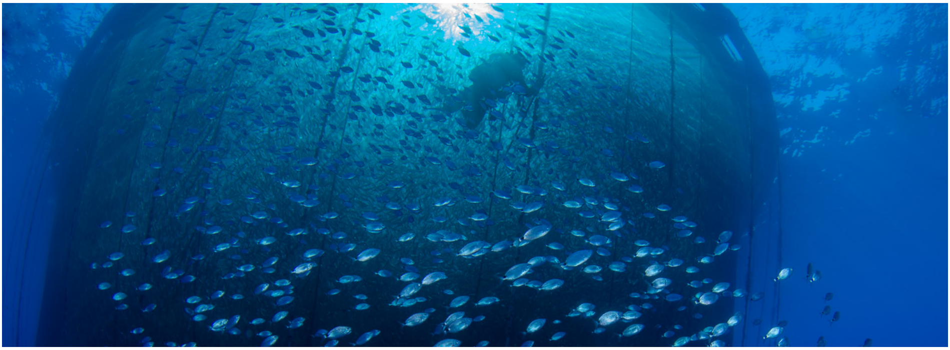
Covering over 70% of the Earth's surface, the oceans are home to a large range of industries including fishing, oil and gas production, and shipping.

But our oceans are poorly governed, over-exploited and largely unmapped. While our oceans host vast, biodiverse habitats, provide the largest global carbon sink, and produce over half of the oxygen in the atmosphere, the health of our oceans is already damaged.

How can we keep our oceans safe and sustainable as the economic activity they support grows?

Established and emerging industries require ocean infrastructure. It is estimated that $90 trillion will be invested over the next decade on infrastructure alone, much of which is near or around the ocean[1]. Blue finance can support solutions that address rising sea levels, climate change, pollution, labour and safety challenges and opportunities related to a sustainable ocean. But financial, policy and regulatory frameworks need clear principles, data, standards and metrics to catalyse responsible policy and business practices, across land and ocean interfaces.

Holistic and sustainable ocean infrastructures will require new approaches to ocean engineering. Ocean engineering encompasses science, innovation and technology, knowledge systems, skills and techniques, communities and workers, and facilitates the relationship between humans and the oceans. Its



application covers the design, construction, maintenance and decommissioning of all human activity in the oceans: the structures, platforms, pipelines, boats, ships, underwater vehicles, aquaculture farms, subsea and digital systems necessary to sustain a more populous and safer world. Its practice should minimise harm and offer restorative abundance in the long term for overall global benefit.

This review presents issues which will drive demand for new engineering approaches. These include emerging ocean industries, climate change and coastal development, energy needs, marine biotechnology and nature sensitive engineering to strengthen and protect natural capital. It considers innovations in floating assets, cabling and pipelines, aquaculture and transportation and issues associated with deep ocean mining.

Ocean engineering must overcome the challenges associated with a relatively unmapped, unexplored and poorly understood environment, and the dynamic nature of the ocean space. International cooperation, underpinned by better public awareness, will be needed to strengthen governance and ensure engineering accounts for the interests of a wide set of stakeholders across international boundaries. The new jobs that are created must be safe and decent, and not propagate existing inequalities nor create new ones.

Finding robust evidence for the most pressing safety challenges in and around our oceans, and making it widely accessible, will support decision makers to think in a longer -term, strategic manner and inform governmental, business, and financial intervention. It will support increased public awareness and engagement, driving better policies and consumer choices, and highlight the skills needed for the future blue workforce.

The review suggests broad interventions that would support better ocean engineering. These include: better understanding of our oceans; new materials; new design methodologies, including multi-use structure designs that incorporate decommissioning issues; better whole system economic tools; enhanced sensing, data sharing and autonomy; ocean maintenance approaches; and new approaches to ocean education and skills.

Finally, the review makes recommendations on where Lloyd's Register Foundation can act to make a distinctive impact in delivering its charitable mission. Suggested priority areas for action are:

Public awareness and policy: Lead communication efforts to increase public awareness, develop ocean citizens, embed safety and sustainability principles, influence the financing mechanisms that will enable the new ocean economy and build on our maritime heritage.

Evidence insight and ocean data: Stimulate sharing of ocean data and transparency about ocean-related activities, impacts and dependencies. Build actionable insight on all aspects of ocean safety, supporting others to share their data, and developing new tools, for example an ocean safety index.

Decent work at sea: Build a body of evidence and insight supporting the safety and welfare of those who work in the ocean economy; support others to ensure high standards of welfare and safety, actively protecting workers and vulnerable groups; and supporting equity, diversity and inclusion in a just transition.

Infrastructure and systems: Support knowledge transfer across sectoral and geographic boundaries and catalyse cooperation and action in areas where new approaches and thought leadership is needed. Build on its investments in areas such as autonomy and robotics, data centric engineering, decarbonisation and complex systems and accelerate new research and development in emerging areas such as multi use infrastructures, nature-based engineering, marine spatial planning and full life cycle assessments.

Education and skills: Build the evidence needed to understand industrial and geographical skills requirement in the future ocean economy; develop new curricula, new methodologies and new skillsets requiring a wide range of interdisciplinary integration; and lead a global conversation about the safety skills needed in the new ocean economy, especially in disadvantaged or informal work settings.

Ocean Foresight: Monitor and forecast new trends, including trade and supply chain effects, support technology and skills road mapping, and highlight the safety risks and opportunities throughout dynamic and interconnected emerging ocean industries.

By building and sharing actionable evidence and insight, convening partnerships across international and sectoral boundaries, and supporting development of new knowledge, skills and methodologies, Lloyd's Register Foundation can play a strong role supporting a safe and sustainable ocean economy.

Foreword

The first astronauts looked back to Earth from space and observed a beautiful 'blue marble' planet, an image dominated by the oceans. Our oceans connect us, protect us, sustain us and regulate our weather and climate. Wherever we live in the world we are deeply and powerfully connected to the sea. We are ocean citizens. But low levels of awareness and understanding mean the oceans are largely 'out of sight and out of mind'.

Early civilisations were built along coastlines, with trade and fishing facilitated by small boats. Exploration changed our ambitions and our horizons and reach extended further into ocean spaces. We built larger ships and created infrastructures in our coastal areas allowing us to prosper. Today our ocean economies are growing at an unprecedented rate. The infrastructures built in our oceans and along our coastlines underpin the critical lifelines and supply chains on which modern society depends. But alongside this growth comes damage: damage to the habitats and biodiversity hosted by our oceans, and harm to many whose livelihoods are made at sea.


NASA/Apollo 17 crew

Lloyd's Register was built in the early days of the global ocean economy with a mission to protect life and property. As ships became larger and traded further, the Register of Shipping has, since 1760, provided an early example of trusted, open and transparent data, built on engineering skills and understanding. It supported better decision making and helped target financial investments.

We are once again at an inflexion point for ocean engineering. The ocean economy is booming with ocean based industries expected to double by 2030[2]. And yet at the same time we face great crises and the corresponding need to mitigate against catastrophic climate change, marine pollution and the imperative for a 'just transition', ensuring equity, diversity and inclusion for all peoples in a safe and sustainable ocean economy. Even more, our understanding of our oceans, whilst still partial, has advanced. We must value and protect our ocean ecosystems – the 'natural capital' which underpins human health and welfare. As our engineers build out the infrastructures to underpin our ocean economy, we must pursue nature-based solutions which allow us to work with and not against our planet.

Lloyd's Register Foundation is a charity that supports safety of life and property, and public education. With a deep maritime heritage we have developed this review to bring attention to the need for new paradigms of ocean engineering. Of all the UN sustainable development goals, SDG fourteen 'Life under water' receives the lowest investment[3], and in this review we set out the challenges and opportunities to invest and build safe and sustainable ocean economies. We are committed to action to reach this goal, building on a large portfolio of work to date, including the capabilities and services built within Lloyd's Register Group. We will address these challenges in partnership with others: building evidence and insight, raising awareness, and drawing on deep capabilities and rich maritime heritage in pursuit of our vision to engineer a safer world.

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Lloyd's Register Foundation

Background

This foresight review is the latest in a series commissioned by the Lloyd's Register Foundation, helping the Foundation target its interventions and funding for a safer future. It was developed from workshops, interviews and desk-based research, building on published studies as well as expert opinion and industry insights. In 2018, Lloyd’s Register Foundation commissioned Professor Mark Cassidy to lead a foresight review on ocean engineering. Workshops were held in Asia, Europe and North America, bringing together experts and researchers from a wide range of industries, academia, public bodies and others. This work underpins much of the content of this foresight review, especially around technological, science, research and education issues.

However, there have since been a number of significant new studies published examining the wider contexts and drivers of the ocean economy, including the emergency need for climate action, the imperative to ensure growth is equitable, inclusive and just, and growing ideas around the value of the natural capital of the ocean economy and ocean engineering that embraces nature-based solutions, building in resilience. An additional focus on the ocean economy is being built through initiatives such as the UN Decade of Ocean Science for Sustainable Development. Hence while this review reflects some of these recent developments, in the fast-moving decade to come we anticipate new drivers, opportunities and challenges, and so continued foresight is embedded as one of the recommendations resulting from this review.

We are grateful to all participants who contributed to the workshops and interviews, and to Mark Cassidy, Intent Communications and Foundation staff for all their inputs to this review.

The ocean economy

Our planet is two-thirds blue. The oceans connect us, protect us, and regulate the climate of our beautiful planet. But our oceans are poorly governed, over-exploited and largely unmapped. The health of our oceans is already damaged through habitat and biodiversity loss, acidification and climate change, pollution from many sources including plastics and agriculture, and the increased urbanisation of coastal areas.

The oceans connect us, protect us, and regulate the climate of our beautiful planet. But our oceans are poorly governed, over-exploited and largely unmapped

The oceans are the home to a large range of industries including fishing, oil and gas production, and shipping, with those who work at sea having some of the most dangerous jobs in the world. Our global energy, food and supply chains are dependent on the ocean economy with 80% of our goods being transported by ship.

The global population is estimated to grow to 8.5 billion by 2030 and 9.7 billion by 2050. With this will come increased pressure on ocean resources - increasing demand for food, energy, jobs, transportation, and coastal land. OECD estimates predict employment in ocean-related industries to increase to 40 million by 2030. The oceans contribute over $1.5 trillion to the global economy each year and this number is predicted to double by 2030 (see figure 1)[2,4]. Countries and businesses are preparing for that future and there is a growing body of work supporting planning[5,6,7].

Climate change is already a major threat to our oceans and those who live and work on them. Despite willingness and commitments to reduce carbon emissions and other greenhouse gases, the decarbonisation process remains complicated with variable access to technological advances, financial support, and suitable local infrastructure.

The ocean is an important setting for climate action. It is estimated that 21% of the greenhouse gas (GHG) reduction that needs to happen by 2050 in order to keep the world on the 1.5 degrees trajectory will happen in the oceans[8]. And at the same time the oceans provide vital functions with at least half of the earths oxygen coming from oceanic sources. The natural capital of the oceans must be protected and strengthened.

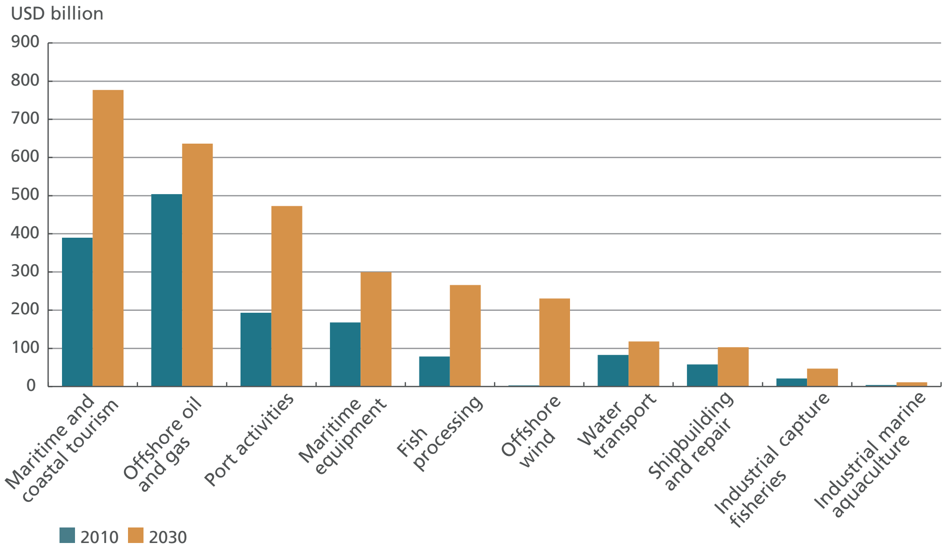


Figure 1: Overview of industry-specific value-added 2010 and 2030[2]

We all depend on our oceans. We rely on them for our basic needs but our awareness is limited. We must become better ocean citizens. How can we keep our oceans safe and sustainable as the economic activity they support grows?

Countries and industries across the world must be willing to coordinate and communicate solutions that enable us to continue our essential relationship with the oceans. We need to meet global demand, while simultaneously safeguarding human life and property, encouraging sustainable use of resources, and providing opportunities for future generations.

Ocean-based industries must provide essential services while ensuring that this is done by safe and sustainable means. To enable a sustainable future we must build and invest in holistic infrastructure that ensures the ocean economy and its peoples can maintain resilience, while also ensuring that this is not done at the further expense of our planet’s increasingly fragile ecosystems.

Ocean engineering

Any undertaking that seeks successful economic development relies on proper infrastructure[9] (see figure 2), and this in turn relies on ocean engineering. Ocean engineering connects the requirements around equipment and infrastructure with the ocean environment, the protection of people working or travelling at sea, and other activities that involve the ocean as a site of interest. Ocean engineering encompasses science, innovation and technology, knowledge systems, skills and techniques, communities and workers and the relationship between humanity and its ecosystem. Its application covers the design, construction, maintenance and decommissioning of all human activity in the oceans: the structures, platforms, pipelines, boats, ships, underwater vehicles, aquaculture farms, subsea and digital systems necessary to sustain a more populous and safe world. Its practice should minimise harm and offers restorative abundance in the long term for overall global benefit.

The role that ocean engineering plays is examined more deeply later in this report.

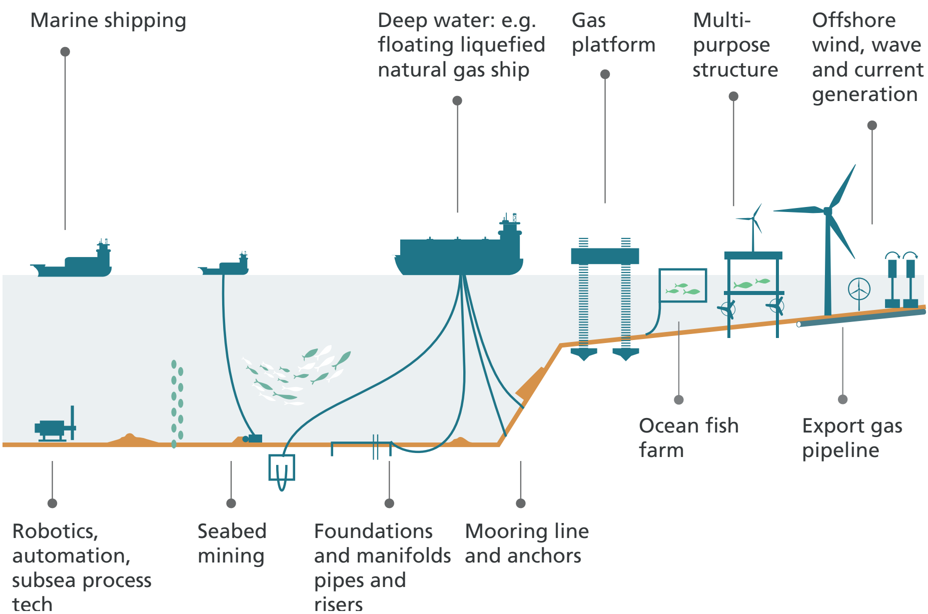


Figure 2: Examples of infrastructure requirements for the ocean economy

Decent work in the ocean economy

As we move toward a sustainable ocean economy, we must plan for a just transition of the workforce that leaves no one behind. Efforts to address climate change should create better, safer work rather than job losses or economic disadvantage[10,*]. Anticipating and undertaking investment and social policies is key to addressing this issue. Public engagement will help decrease fear and resistance to change within stakeholder communities.

Stakeholders across governments, businesses, unions, and citizens should make plans and policies that account for the social protection and transition of the existing workforce to non-polluting sectors. This will require open dialogue between stakeholders, the creation of new industries, development of new skills or upskilling, redeployment to different sectors, efficient enterprise development and job creation, and community development and renewal.

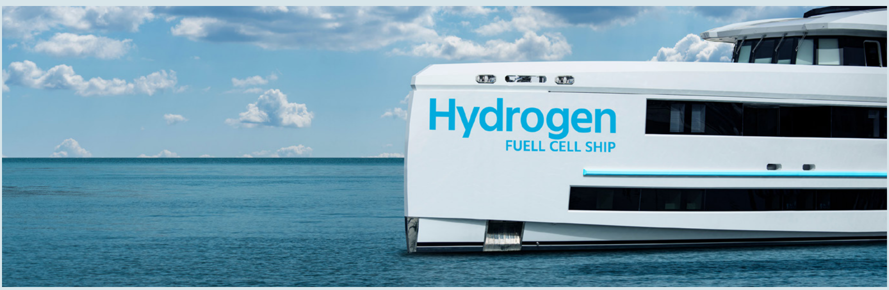
A just transition to a low carbon, sustainable ocean economy therefore necessitates investment, education, infrastructure, innovation, and dignity of work. These must foreground occupational safety and health, actively protect workers and vulnerable groups, offer technology and knowledge transfers between countries, and ensure diversity and inclusion across programmes and sectors. From a skills perspective, workers should not be left behind.

* As acknowledged by the Paris Accords (2015), any agenda addressing climate change and sustainable development requires "the creation of decent work and quality jobs in accordance with nationally defined development priorities."

Just transitions in the maritime transport sector: Ensuring green jobs are decent jobs[10]

To meet the 1.5°C target the international shipping industry must decarbonise by 2050. The maritime industry needs to work together to understand the impact of the low carbon transition on workers and society. By doing so, the industry will minimise potential risks while maximising opportunities for all workers and communities. Factors include:

- Skills development and safety training access: Reskilling, upskilling and new skills must be incorporated into transition plans to ensure the sustainability and safety of the sector. Doing so requires knowledge around the skills required for zero carbon shipping. In addition, access to proper training will ensure the safe handling of new fuels such as ammonia and hydrogen.
- Equitable knowledge-transfer: Many developing countries are well-positioned to become future suppliers of zero-carbon bunker fuels, for example green ammonia and hydrogen. To unlock this potential, there is not only need for technology and infrastructure support, but also ensuring knowledge and skill-transfer so that the economic and job opportunities from a zero carbon fuel industry are accessible to local populations and communities.
- Social dialogue: Incorporating a human-centred approach to decarbonisation through appropriate and inclusive social dialogue mechanisms can help to ensure decent jobs and gradual shifting in roles.
- Environmental justice: communities living near ports having to deal with pollution and emissions.



Marine spatial planning for a well-managed ocean[11]

As demand for marine space and infrastructure grows, conflicts will arise. Collaboration and forward thinking are vital aspects to creating sustainable infrastructure and undertaking the transition to a more just, sustainable and equitable future. Marine spatial planning (MSP) offers proactive measures that rely on a rights and value-based framework for principled operations in a sustainable ocean economy, whilst optimising efficiency of infrastructure, and accounting for necessary biodiversity.

MSP regulatory frameworks must be climate smart, nature positive and respect the rights of the users and communities co-existing in this space. International relationships between governments, industries and users must offer an enabling environment for innovative and adaptive approaches to industry activities that prioritise safety. This will help mitigate risks and enable trust and co-operation whilst developing new industries and scaling up old ones. Marine space and infrastructure must be viewed with an eye to being multi-functional, collaborative, and able to contribute to conservation efforts and support biodiversity.

A well-managed ocean is the key to reconciling otherwise disparate goals of industry productivity and growth, biodiversity protection, future job creation, climate justice and community rights. This requires that a primary aim of MSP must be a just transition, ensuring that people not only have the skills they need for new industries and innovative approaches, but that this is done in a manner that prioritises indigenous community knowledges, the safety of all users, and their ability to undertake decent work. It will not only allow for restorative, regenerative and nature-inclusive approaches to ocean planning, but also safeguard global futures.

Ocean industries, sustainable business and blue finance

Established ocean industries include capture fisheries, shipping, naval and defence activities, ports, shipbuilding and repair, offshore energy, oil and gas, marine manufacturing and construction, maritime and coastal tourism, marine business services, dredging, and marine research, development and education.

Alongside these established industries, newer business interests are emerging. These include aquaculture, deep and ultra-deep water oil and gas, renewable energy (wind, wave, tidal, solar, biomass), marine and seabed mining, maritime safety and surveillance, marine biotechnology, high-tech marine products and services, higher quality connectivity and transmission, ocean conservation and maintenance, and desalination. All these are expanding into the ocean, through construction of floating platforms or subsea developments, termed "ocean space".

These established and emerging industries require a great deal of ocean infrastructure. It is estimated that $90 trillion will be invested over the next decade on infrastructure, much of which will be on the coast. Capital to finance this infrastructure is readily available. If grounded in global principles and standards, finance can help catalyse responsible policy and business practices across the land-sea interface[1].

Financing the ocean economy

The 'blue economy' comprises sectors that can sustainably use the ocean for commercial activities, such as shipping, tourism, aquaculture, wild capture fisheries, marine renewable energy, and industries that use coastlines and ports for trade (figure 3). These sectors contributed US$1.5 trillion to global gross added value in 2010 with expectations of doubling in excess of US$3 trillion by 2030. Many ocean economy industries are widely forecast to outpace global economic growth[2].

In 2021, the World Wildlife Fund reported that up to 66% of publicly listed companies are exposed to, and to some degree dependent on, the need for a healthy ocean[12]. Yet for such a dominant feature of the natural world and the global economy, it is under-funded. Of the 17 UN Sustainable Development Goals, SDG14, on the conservation and sustainable use of the ocean and its resources, attracts the lowest share of investment (3.5%)[13].

However, there is a growing understanding of the importance of the oceans to our future health and prosperity. Investor interest in the sector, which has been dubbed "blue finance", is growing. The global 'blue economy' is expected to expand at twice the rate of the mainstream economy by 2030[3], recognising that investing in the ocean economy makes good

sense. For example, investing $1 in key ocean actions can yield at least $5 in global benefits, often more, over the next 30 years. Specifically, investing $2 trillion to $3.7 trillion globally across four key areas – conserving and restoring mangrove habitats, scaling up offshore wind production, decarbonising international shipping and increasing the production of sustainably sourced ocean-based proteins – from 2020 to 2050 would generate $8.2 trillion to $22.8 trillion in net benefits, with rates of return on investment between 450 and 615%[14]. Moreover, investing $1.8 trillion in projects to mitigate the impact from rising seas and greater storm surges from 2020 to 2030 could generate a net benefit of $7.1 trillion[15].

Blue finance can redirect funds from harmful activities to the development of blue solutions that address rising oceans, climate change, pollution, labour and human and other challenges and opportunities related to a sustainable ocean. Financial policy and regulatory frameworks can evolve to support investments in marine and coastal ecosystem protection. For this to happen, there is the need for clear standards and metrics against which investments can be measured to assess that they are indeed being channelled into sustainable ocean uses. The evolution of existing industries alongside the creation of new industries, and the scaling up of infrastructure all therefore rely on trusted data to uphold standards underpinning private or public funding to facilitate green jobs and a blue economy.

Safety and risk indices for ocean investment

Greater transparency and awareness are needed to help target financial investment in sustainable ocean engineering and infrastructure. There are a number of ocean related indices[16] which appear to generate useful data. However, they lack a specific safety focus that target both private and public stakeholders, as well as an ability to shine a light on data gaps; an important step in encouraging action. There is a growing need for a mechanism that foregrounds safety and transparency as necessary measurements when designing and planning a sustainable blue economy.

Finding robust evidence for the most pressing safety challenges in and around our oceans, and making it widely accessible will support decision makers to think in a longer-term, strategic manner and inform governmental, business, and financial intervention. It will also lead to increased public awareness and engagement that becomes increasingly less tolerant of harmful ocean behaviour, and highlight the skills needed for the future blue workforce (e.g. SDG aware, digital ocean engineer).

Case study: Blue bonds

Governments need to move beyond concessional and impact investing to create the conditions for sustainable ocean investments to attract fully commercial capital. Enhanced policy and regulation, innovative financing instruments, transparency and easy access to sustainability data will all help.

Blue bonds are one of an emerging finance asset class which funds sustainable ocean action. Funding from these bonds falls into two major categories:

- projects directly operating in or by the ocean (such as investment in infrastructure, ports, shipping, tourism, fisheries, aquaculture, offshore energy and water management)
- projects that have a direct impact on the ocean, seas, and freshwaters (such as agriculture, textile, fresh water, sanitation, and infrastructure).

Although blue bonds have tended to be public and largely focused on marine conservation and restoration, they can also fund business and infrastructure opportunities that positively impact the ocean and support sustainable development. For example, the Bank of China issued the equivalent of $942.5 million in December 2020 as Asia's inaugural blue bonds[17]. These bonds were designed to expand the sustainable blue economy through marine-related green projects across domestic and overseas markets. As such, they are part of a larger governmental push by the Chinese government to mitigate negative environmental impacts and support transition to a low-carbon economy. Subsequently, the Thai Union Group PCL closed its inaugural Sustainability-Linked Syndicated Loan (SLL) in both Thailand and Japan in February 2021[18]. The SLL was oversubscribed by a factor of more than two times the initial facility size when first launched to the markets, representing a significant step for blue finance.

UN Global Compact Sustainable Ocean Principles

The UN Global Compact is the world's largest corporate sustainability initiative, aligning businesses with universal principles and taking action to advance societal goals[19]. Companies signing up to the Sustainable Ocean Principles commit to assess their impact on the ocean and integrate them into their overall strategy. The principles provide a framework for responsible business practices in the ocean.

Ocean health and productivity

- Principle 1: Assess the short and long-term impact of activities on ocean health and incorporate such impacts into strategy and policies.
- Principle 2: Consider sustainable business opportunities that promote or contribute to restoring, protecting or maintaining ocean health and productivity and livelihoods dependent on the ocean.
- Principle 3: Take action to prevent pollution affecting the ocean, reduce greenhouse gas emissions in operations to prevent ocean warming and acidification, and work towards a circular economy.
- Principle 4: Plan and manage use of and impact on marine resources and space in a manner that ensures long-term sustainability. Take precautionary measures where activities may impact vulnerable marine and coastal areas and the communities that are dependent upon them.

Governance and engagement

- Principle 5: Engage responsibly with relevant regulatory or enforcement bodies on ocean-related laws, regulations and other frameworks.
- Principle 6: Follow and support the development of standards and best practices that are recognised in the relevant sector or market contributing to a healthy and productive ocean and secure livelihoods.
- Principle 7: Respect human, labour and indigenous peoples' rights in the company's ocean-related activities, including exercising appropriate due diligence in their supply-chain, consulting and engaging with relevant stakeholders and communities in a timely, transparent and inclusive manner, and addressing any identified impacts.

Data and transparency

- Principle 8: Where appropriate, share relevant scientific data that supports research on and mapping of relevance to the ocean.
- Principle 9: Be transparent about ocean-related activities, impacts and dependencies in line with relevant reporting frameworks.

Trends for ocean engineering

A growing ocean economy needs engineering to deliver it, and there are many challenges and opportunities that will underpin safe and sustainable development in the ocean space.

Coastal communities and climate

Forty percent of the global population is affected by ocean activities and lives within 100 km of a coast[20]. A further 10% live at elevations less than 10m above sea level. Extreme weather changes and other disasters are likely to have devastating effects on communities and industries such as tourism and fishing, and beyond this the UN's sixth IPCC report[21] makes clear that weather and climate extremes affect all regions of the globe. While the public may be aware of some high profile events, the losses felt within coastal communities and ocean industries are often 'out of sight and out of mind'.

The 2021 Inmarsat's Future of Maritime Safety report[22] examined maritime data between 2018 and 2020, noting a rising trend of extreme weather in the northern hemisphere during November and December. This included five tropical cyclones in the Arabian Sea and three major tropical cyclones in the Bay of Bengal, while in 2020, super cyclonic storm Amphan cost an estimated $14.1 billion in damages.

Similarly, hurricanes are an annual feature of life in the Caribbean and southern United States, with 2005's Hurricane Katrina killing over 1,800 people and causing nearly $108 billion in damages. It caused widespread damage as it crossed the Gulf of Mexico, destroying 46 oil platforms, causing extensive damage to a further 20, and damaging over 100 pipelines. Six platforms broke from their moorings with one running aground on an island near Alabama. Hurricane Rita followed only three weeks after Hurricane Katrina, and destroyed more than 50 further oil platforms and damaged nearly 350 pipelines. Even newer semi-submersible mobile floating drilling rigs were not immune to the force of the hurricanes, 12 of which experienced complete failure. Hurricanes Ike and Gustav destroyed over 60 oil and gas platforms in 2008. 2012's Hurricane Sandy caused nearly $70 billion in damage, killing 233 people across eight countries.

Other mass scale events include the 2004 tsunami that affected Sri Lanka, Indonesia and Thailand resulting in almost 250,000 lost lives and an estimated US$10 billion in damage. The 2011 North Pacific Coast tsunami led to over 15,000 deaths and a nuclear emergency at Fukushima, one of the biggest industrial catastrophes in history, with costs estimated at $180 billion, and which resulted in the largest recorded radioactive contamination of the world's oceans.

Good ocean engineering to mitigate the impact of such events needs investment. It must allow for the ongoing realities of climate change when designing infrastructure for vulnerable coastal communities and ocean industries, mitigate losses to life and property, and help support health and sanitation, access to energy, human rights, labour, agriculture, sustainability, resilience and more.

Informed advocacy is particularly important where infrastructure projects may be fuelled by commercial interests that would compromise sustainability principles and have a negative impact on the local environment and communities.

Sustainable tourism

Coastal and island populations are often hubs for tourism. The closure of Boracay Island in the Philippines for six months in 2018[23], to allow it to recover from unsustainable tourism, makes clear the dangers of a lack of large-scale engagement, planning and the absence of sutainability principles. Exploitation of local resources and poor sewage and waste management[24] harmed the biodiversity in the region, and the closure of the island created conflict as tourism had come to be a primary source of income for local communities and migrant labour. Boracay's issues serve as an important example of the double-edged sword of tourism which can be of great benefit to economies when managed sustainably, or which can devastate a region in ways it is difficult to recover from. The planned development of the Andaman Islands off the coast of India is a further example[25].

Energy from the oceans

The world's demand for energy has doubled in the last four decades and continues to increase at a rapid pace[26]. The main source of energy from the oceans currently remains oil and natural gas. A depletion of oil reserves in shallow waters and temperate regions has led to offshore developments moving into deeper waters and harsher environments.

Thirty-seven percent of proven oil reserves are offshore, of which roughly a third are located in deep water[2]. Construction taking place at a depth greater than 3,000m will require new ocean engineering and substantially new technologies such as mooring, anchoring and subsea systems. Arctic developments would offer even more challenges as remote and harsh environmental conditions would make any essential or emergency intervention during operations more difficult, substantially increasing risk to life and property. These challenges illustrate the potential demand for innovative infrastructure designs that address these issues while bolstering energy production.

In trying to limit greenhouse gas (GHG) emissions there is increasing action to drive energy production towards cleaner natural gas and renewable solar, wind, wave and tidal energy sources. As governments across the world put forward carbon emission reduction strategies, offshore renewables are an increasingly appealing energy source, offering enticing new opportunities for technological advances, careers and investment.

Currently Europe, China, and North-West America lead offshore developments, with the levelized cost of energy from offshore wind farms now approaching that of traditional generation. Oceans are predicted to produce an even greater proportion of the world's energy beyond 2050, with numerous innovations already under consideration. For example: ocean thermal energy conversions may allow for the circulation of cold water from ocean depths[27]; subsea gas hydrates may provide estimated reserves twice that of traditional hydrocarbons[28]; and ocean biomass may support energy production, for example through microalgal torrefaction[29,†].

† A thermochemical process that converts biomass into solid fuel

The ocean space is also a potential site for floating nuclear generators. Russia has pioneered the design and construction of the Academik Lomonosov, a floating nuclear power plant[30]. Floating nuclear generators could supply reliable, durable power generation in remote locations where the costs of building an on-site facility would be prohibitive. However, concerns remain regarding design safeguards, the necessity of emergency procedures, and the potentially changing natural conditions of any proposed site (e.g. weather conditions, soil conditions for moorings, risks of natural disaster etc.).

Such high-risk developments highlight the importance of the UN's Sustainable Ocean Principles as a foundation. A regulatory landscape that safeguards the ocean, the environment, and other users of the ocean is needed, with international cooperation key to addressing these issues for our shared ocean future.

Marine biotechnology and natural capital

The oceans hold a wealth of potential natural assets. These assets enable life on our planet and shouçld be seen as part of the ocean economy (figure 3). The oceans are also home to a diverse range of biological materials and marine biotechnology which may provide solutions to food production, cleaner fuel and the development of new pharmaceuticals, offering significant benefits to society[31]. It is estimated the marine biotechnology sector may grow by approximately 10% per year[32], but sustainable access to biomaterials (which may be in difficult polar or deep water environments) requires infrastructure and planning to reduce the significant risk to the environment, life and property.

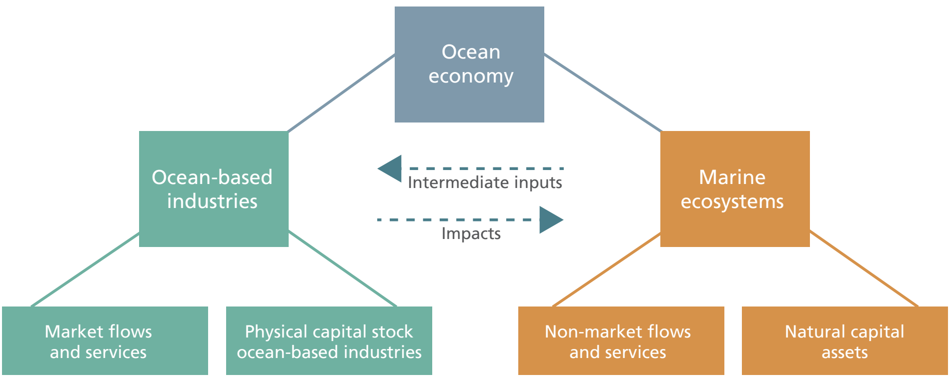


Figure 3: The concept of the ocean economy

A seaweed revolution?

Seaweed Revolution: A Manifesto for a Sustainable Future[33], offers a wide range of benefits for sustainability and development that could be promoted by growing the seaweed industry. As well as providing vital global carbon sinks and habitats for threatened biodiversity, seaweeds have a wide variety of uses, including the treatment of waste water, creation of biomatter used for food, livestock feed and fertiliser, production of biodiesel, and materials that can be used in wider manufacturing. Offshore algae stations could implement large-scale developments including farming and harvesting[26]. However, the seaweed industry is currently hampered by barriers such as: fragmentation, lack of standards, lack of technologies, and the need for social licence, advocacy, finance and spatial planning. The seaweed manifesto is a call to action to state shared goals and support cooperation between stakeholders in the burgeoning but fragmented seaweed economy.

Floating spaces

Although the global population continues to rise and is projected to reach nearly 9.8 billion by 2050, available space for housing and infrastructure remains largely fixed. However floating space projects like Space@Sea and Schoonschip are evidence of demand and financial investment in alternative options for housing and infrastructure.

Such ocean engineering projects come with massive challenges, for example how best to preserve marine life and habitats during construction. Data and awareness on ongoing environmental conditions and remote and emergency scenario planning are vital for sustainable development of floating islands. New floating, coupling and mooring technologies are needed to ensure safety and sustainability at every stage of the project, from planning, designing and construction to decommissioning.

There are also regulatory challenges to be overcome[32]. Will these floating spaces be governed by land-based urban planning regulations or maritime regulations overseen by the International Maritime Organization (IMO)? As relatively new developments, there is currently no regulatory framework that governs floating islands or floating spaces, making insurance difficult and leaving stakeholders at risk.

Schoonschip and Space@sea

Floating space structures already exist on large and small scales. An example of a small scale infrastructure project of this nature is Amsterdam's floating urban neighbourhood development, Schoonschip[34]. Dutch architects Space & Matter designed the project to offer 46 dwellings across 30 water plots with decentralised and sustainable energy, water and waste systems. While many may see such floating spaces as potential solutions to dense populations and the issue of overcrowding, Schoonschip was specifically designed as a way to mitigate the potential effects of climate change and rising sea levels.

The European Maritime Technology Platform Waterborne launched the Space@Sea project in 2017 to develop multi-use platforms on a larger scale with a stated objective of developing safe and cost-efficient deck space at sea[35]. It specifically allows for additional housing, logistics and energy hubs (such as floating wind turbines), and infrastructure (required to support fish, algae and seaweed farming industries). The project, led by MARIN, has 17 European partners consisting of companies, research institutes and universities and received funding from the EU's Horizon 2020 research and innovation programme. It promises to validate and develop three floating islands: an energy hub in the North Sea, aquaculture in the Mediterranean, and a floating logistics hub in the Black Sea.

Connectivity

Connectivity has become fundamental to human life, with access to the internet acknowledged as a catalyst for the enjoyment of human rights by the UN[36]. Therefore, investment in underwater fibre optic communication networks, which will boost this connectivity with increased reliability, is an ongoing priority. The global increase in demand for cloud and internet services drives a clear need for a significantly expanded subsea network infrastructure and capacity. While undersea fibre optic cables were previously owned by telecom carriers, growing demand means new infrastructure is being built and invested in by multinational content providers such as Google, Facebook, Microsoft and Amazon. Examples include the MAREA fibre optic cable[37] that was completed in 2017, while Google is involved in the installation of 16 submarine cables[38] over the last decade. As of June 2021, Google also plans to construct the world's longest open subsea cable, called the Firmina Cable[39], which will stretch from the East Coast of the US to Las Toninas in Argentina (with additional landings in Brazil and Uruguay).

Ocean-based industries that currently experience limited connectivity at deep sea or in polar regions would be able to reap the benefits of reliable, fast internet. This will spur innovation as remote operations, smart / autonomous ships[40], remote and/ or floating platforms, and autonomous marine robotics all rely upon connectivity in some form. Marine robotics technology has steadily emerged over the last few years as the key to executing complex and challenging operations supporting science, industry, and society at large. Advances in marine robotics are likely to be hampered without adequate supportive infrastructure[41].

Food, fishing and safety

The coming decades are likely to see a sharp rise in the generation of food from oceans. Forty percent of the world's population currently consume fish as their primary source of protein, and nearly 120 million seafood workers depend on wild capture fisheries for their livelihood[42] (with nearly 90% of this number working in small scale fisheries). Global consumption of fish already outstrips that of beef, with worldwide fish production set to expand by a fifth by 2026[43]. However predictions show an increasing shift from wild capture to aquaculture of fish, shellfish and seaweed in coming years[44,45].

The potential shift to fish farming may mitigate traditional capture fishing's poor record of safety and environmental concerns. However this shift is likely to have a negative impact on coastal fishing communities that are already having to increase output to remain competitive with commercial fishing and would have limited financial resources to transition to aquaculture.

The financial pressure on fishing communities in developing countries to increase their catches - irrespective of sea conditions - is likely to play a large role in the safety record for the sector. Lloyd's Register Foundation's 2018 Insight report on safety in the fishing industry: a global safety challenge[46] points to a previously undocumented estimate of approximately 24,000 fatalities per year in the fishing industry.

A multi-stakeholder fishery: The Koli fishers

Mumbai's Indigenous fishing community, the Kolis, are experiencing dwindling numbers of fish in coastal waters. The expansion of the city's infrastructure projects have extended into traditional fishing waters and breeding grounds, with fishers being forced to sea for longer and in deeper waters than before, leading to unsafe conditions. Rising sea temperatures and escalating urban pollution (particularly in the case of Mumbai's floundering sewage disposal system[47]) are additional factors contributing to dwindling fish numbers.

Tensions arise between the Kolis, government-led initiatives and larger commercial fishers. Low financial resources, an inability to access previous supplementary systems such as eating part of the catch, destruction of boats in extreme weather, and increased risk from the need to fish longer and in more dangerous waters to meet minimum needs are all ongoing concerns for the community.

As climate change and extreme weather events continue to intensify, the effects on these communities are stark.

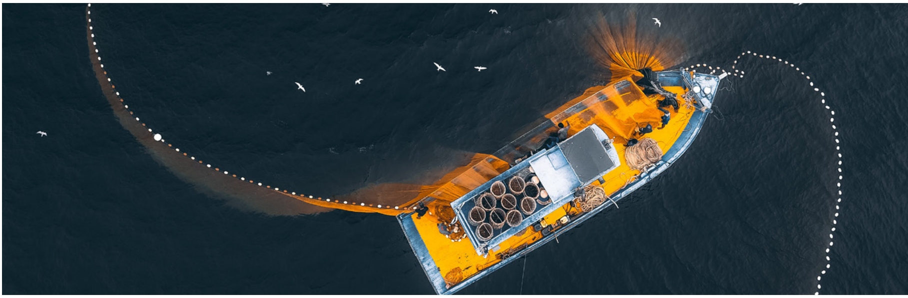


Photo by Pok Rie from Pexels

The IMO's 2012 Cape Town Agreement (CTA)[48], which is still in the process of being ratified, is the latest addition to two existing pillars of fishing safety legislation: The 2007 International Labour Organization (ILO) Work in Fishing Convention, 2007[49], and the 2009 FAO Port State Measures Agreement (PSMA)[50]. The CTA sets out minimum safety standards for fishing vessels of 24-metres in length and over. However the global fishing fleet, which the IMO has estimated[51] at 4.6 million vessels is mostly smaller vessels with only 64,000 fishing vessels operating in marine waters being greater than 24 metres in length.

There is an urgent need to invest in education and infrastructure, including financial investment, that would allow for those involved in the fishing industry to seek safer ways of fishing. However, the fishing industry is a multi-stakeholder industry that has regional, cultural, and economic concerns that make prescribing broad guidelines or restrictions unlikely to succeed, and may also carry the additional risk of alienating different stakeholders in the industry.

While the high number of fatalities in capture fishing might position fish farming as a more attractive option, this sector faces its own challenges. For example, sea cages may experience operational failures that can lead to unacceptable farmed fish escapes. A Norwegian studyshowed 3.93 million Atlantic salmon, 0.98 million rainbow trout and 1.05 million Atlantic cod escaped from farms in Norway between 2001 and 2009[52].

Challenges within the aquaculture sector are likely to be exacerbated as it inevitably extends from sheltered coasts into the harsher, more remote open ocean. However, if successfully built and operated, open-ocean fish farms will be able to increase production capacity, improve fish quality and welfare, and reduce the habitat destruction and pollution being caused by fish farms in coastal waters. It will help save lives and reduce poor social practices, such as modern slavery that is entrenched in parts of the world's fishing industry.

Transportation

Shipping is the backbone of the global economy, transporting roughly 80% of global trade[53]. The growing world population and increased prosperity is driving greater demand for global freight, with the OECD estimating that trade will triple by 2050[2]. Global shipping GHG, if unchecked, could rise from the current estimate of 2-3% to a possible 11% by 2050[6]. In an internationally competitive market, shipping operators will need to reduce both expenditure and carbon emissions.

Many investors are looking to increase vessel automation using artificial intelligence to deliver optimal operating requirements. This has the additional safety benefits of reducing crew exposure to harm (as well as costs) while reallocating accommodation space to cargo. However, these advanced operations will require a high degree of confidence not only in the engineering of the vessels themselves, but in accurate data about ocean conditions and alternative measures to prevent oil and cargo spills.

There are multiple autonomous operation pilot projects underway, with plans for over 100 fully automated vessels under the Russian flag alone by 2023[54]. As of July 2021, Hyundai Heavy Industries Group (HHI) successfully conducted a test-run of a degree four fully autonomous 12-person cruise ship backed by its own autonomous navigation system and a local mobile operator's 5G network in South Korea[55]. More projects are sure to follow.

In the nearer future, there is large-scale investment in infrastructure to transition the shipping sector to low carbon fuels. While fuels such as biofuels and LNG are more established, other fuels including ammonia and blue hydrogen are also being explored. These alternatives are far from straightforward however, with technical pathways being developed for example by the Lloyd's Register Maritime Decarbonisation Hub[56], and with the total lifecycle analysis GHG burden of hydrogen under scrutiny[57].

In addition to shipping South Korea, China and Japan are exploring the possibility of submerged floating tunnels (SFT) in the ocean. Such tunnels would potentially extend across large swathes of the seabed and could revolutionise international travel. Challenges to the design, construction, operation and maintenance of SFT abound, including wave load determination, vortex-induced vibration, immigration, accidental loading, durability, risk identification and control etc[58]. The technological advances needed will require a new generation of methods and ocean engineers.

Alongside the need for advances in planning, design, construction, maintenance and decommissioning for ocean engineering, the transport industry faces long term safety challenges. Passenger transport by sea is likely to continue even if autonomous shipping becomes the norm. Nearly 3,000 persons die annually as a result of passenger ferry accidents[59]. Some of the most prominent causes of accidents are crew error or incomplete training and awareness, overcrowding, the vessel not being seaworthy, missing or inadequate life-saving and fire-fighting appliances and/ or equipment, and an inadequate search and rescue capability.

In addition, there is a growing spotlight on the loss of life through unofficial immigration. Since 2014 over 45,000 people have gone missing[60] with many making hazardous journeys by sea; improved engineering and capacity development for search and rescue could reduce loss of life.

Mining

Deep sea regions constitute nearly 95% of the ocean[61]. Their mineral resources and metal-rich ores are seen as a means to address rising concerns about an otherwise dwindling supply of metals. While the increased recycling of metals may offer interim relief, the reality of rapidly growing industrial and consumer demand will easily outpace this effort. The UN's International Seabed Authority (ISA) has stated that minerals from deep seabeds may be a way forward[62]. Countries that lack secure sources of supply on land, as well as small island developing states that lack opportunities for economic development, may see sea-bed mining as an attractive development, but it is one requiring strong regulation and consideration of human and environmental safety.

Only 5% of the deep sea has been explored at the scale necessary to identify mineral resources. Improved surveying of the ocean surface, advances in deep-sea mining technology (machines are already under development), and clarification of international laws has the potential to grow deep-sea mining into a major industry[31].

The International Union for Conservation of Nature (IUCN)[63] notes that while the timeline for legal and regulatory uncertainties has now been somewhat clarified, and marine mining and environmental technology has advanced such that deep sea mining appears to be a sector poised for rapid advances, the fact remains that there is little to no information available regarding its environmental impact[64].

Nauru's petition to the International Seabed Authority

In July 2021, the Pacific Nation of Nauru partnered with mining company DeepGreen petitioning the International Seabed Authority to demand quicker clarification of the rules and regulations governing deep-sea mining[65]. Their action has triggered a clause in the Law of the Sea requiring that the process for regulating deep-sea mining be expedited and finalised within the next two years, outside of which Nauru may receive provisional approval to proceed. This is a particularly controversial scenario, as without agreed upon rules and regulatory oversight, environmental safety and life may be at risk. The Deep Sea Conservation Coalition has noted this sets a dangerous precedent for deep-sea mining operations where rushing negotiations of regulations will lead to haphazard and unsafe operations under hastily thrown together rules for compliance[66].

Challenges for ocean engineering

The ocean is a fundamentally challenging location for engineering. Salt-water corrosion, remote locations, deep water pressures and metocean‡ conditions all provide safety and structural integrity challenges.

An unknown and changing environment

Only 5% of the ocean floors have been explored, mostly in shallower waters. Despite advances in remote and autonomous sensing, the seabed and ocean water column are difficult and expensive to characterise.

As sea levels and sea temperatures rise, ocean currents are shifting and marine habitats are changing, moving or disappearing altogether. While traditional engineering assumes a stationary system with design requirements unlikely to change from decade to decade, ocean engineering must be dynamic considering the relatively unpredictable effects of climate change. Extreme weather, rapid changes in seabed, changing habitats and biodiversity, and other dynamic risk factors all require different design approaches. In polar regions additional challenges such as iceberg scour on buried pipelines and well heads, must be considered while coastal industries (such as tourism and aquaculture) and communities will need different design approaches for safe and sustainable growth under changing environmental conditions.

‡ In offshore and coastal engineering, metocean refers to the syllabic abbreviation of meteorology and oceanography.

Technical hurdles

Significant technical hurdles arise as emerging ocean industries seek to build infrastructure further offshore into deeper, more remote and increasingly hostile environments. Specific deep water technologies include durable risers and offshore foundations and mooring technologies to safely harness large remote structures such as offshore aquaculture fisheries, wind farms and floating liquefied natural gas facilities. Access and new technologies for safe maintenance are also needed. Remote and autonomous operations (removing people from harmful jobs) for deep water, seabed or floating facilities require innovations in power supply, which would prove useful across a range of ocean industries.

While increasing advances in sensors, automation, robotics, and big data may have significant impact on the industry – removing many human interactions and reducing cost and danger to life – their safety, resilience, and sustainability must be assessed. For example, 'smart' ships and other infrastructures may be susceptible to cyberattacks and need robust security systems.

International and public cooperation

Oceans are borderless and fluid. Their resources are mobile and traditional understanding of borders, such as laws governing local waters, fail to account for the reality that these waters are not isolated. With legal and safety frameworks largely embedded in land-based understandings of space, the lack of responsibility and stewardship for the ocean as a whole remains a significant source of risk.

International cooperation is key to effective ocean engineering. Disputes may arise from conflicting demands on the most sought-after construction sites. Countries at different levels of development need to improve the sharing of technology and innovation in order to see genuine benefits to safe and sustainable ocean resource management[2]. There is potential for systemic inequality as countries have different levels of access to finance, technology, resources, development, skills, infrastructure, etc, leading to certain sectors and/ or countries advancing much faster than others. Complications will arise from geopolitical risks such as territorial clashes or a lack of international cooperation, especially as ocean resources move further offshore into deeper and disputed waters.

Governance must account for future trends in ocean engineering. Future ocean structures are likely to be on a scale and number far beyond present realities, with trends in construction already moving from large one-off multibillion dollar oil and gas platforms, to arrays of thousands of structures, for example in offshore wind turbine farms in Europe and China. There is a need for ocean engineering to transition from a project-based approach to production-based solutions that can be built and implemented quickly, safely and effectively.

With heightened public awareness of the effects of climate change, the need to further expand activities in the ocean environment, and rapid technological advances, the ocean engineering sector must build trust to gain public acceptance of plans and innovations. Carbon capture and storage in ocean spaces could provide huge benefits but ocean engineers must clearly demonstrate safety and sustainability to receive the long term public investment and support that is essential for success. Emerging ocean industries such as mining raise concerns about damage to unique, fragile, and under-studied deep-sea ecosystems[67]. Undertaking a holistic approach sensitive to environmental and political issues remains a challenge for the future.

Keeping people and the environment safe from harm

Sources of risk come from anthropogenic hazards such as fire, oil spills, gas leakage, explosions, human error, cyberattacks, piracy and acts of terrorism, and natural hazards such as storms, earthquakes, tsunamis, giant waves, icebergs, rising sea levels, erosion, scour, and geohazards (for example, submarine landslides, diapirs, overpressure, gas hydrates, mudflows, shallow gas). All these may cause harms such as loss of human and marine life, infrastructure fatigue and collapse, broken mooring systems, environmental damage, reductions in ocean sustainability, and the loss of critical services.

When things do go wrong, ocean conditions create challenges for emergency, evacuation and rescue services. With moves to deeper and more remote waters for future ocean facilities, it will become increasingly difficult to plan for and accommodate emergency safety systems.

Regulatory reform often happens in the wake of disasters such as Deepwater Horizon[68] but ocean engineering should be proactive in safeguarding life. It should anticipate risk, and while rapidly changing environment, contexts, and methods of operations make it impossible to plan for all possible outcomes, improved data sharing could underpin better decisions. Investments in sophisticated simulation models, continuously calibrated and validated through measured ocean data, are increasing but are often held in regional or sectoral data silos.

Supporting better ocean engineering

Given the challenges, what can be done to support better ocean engineering? This section suggests eight interventions and annex A provides further details on individual projects and programmes which could be pursued.

Characterising the ocean and seabed

To protect life, property and the environment we need wider and deeper knowledge of our oceans. Technologies and models should be employed to predict frequency and impacts of hazards. Planning requirements should be imposed on ocean developments to characterise, catalogue and understand remote ecosystems. Overarching safety systems should be established, such as having metocean forecasting held to the same standards as meteorological forecasting, composing offshore risk maps with similar resolution to that of onshore, and having a global standard and monitoring system for the health of the ocean.

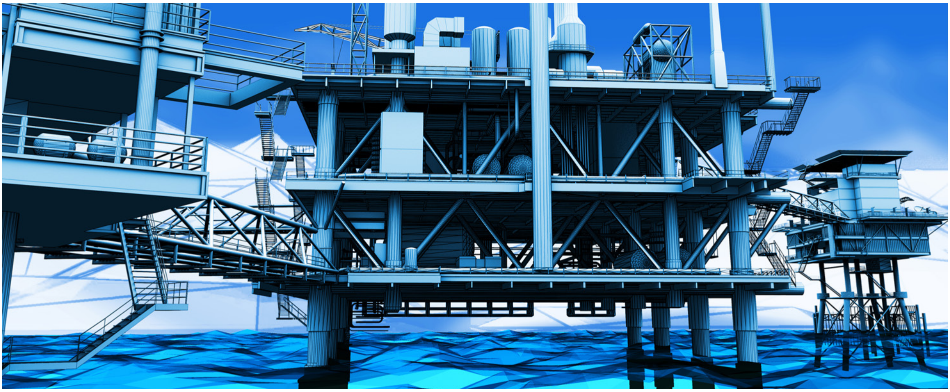
New materials for ocean engineering

The development of new composite materials with higher strength, and resistance to corrosion and UV degradation may act as replacements for conventional steel and concrete infrastructure, particularly where weight and maintenance are issues (as is the case with deep water installations). Emerging additive manufacturing techniques (such as 3D printing) also offer new paradigms for construction and maintenance in remote ocean conditions. Alternative materials and their production should be conceived in a holistic manner and across sectors.

New ocean design methodologies

As global conditions, infrastructure and our understanding of the ocean evolves, we will require new design methodologies which are adaptive to new conditions and evolving technologies. With safety as a priority, new research and design philosophies will be needed. Automation, new materials and sensor technology, remote operations and maintenance practices should be built into design practices rather than being conceived solely as technological add-ons. Locally appropriate methods that account for fluctuating oceanographic and seabed conditions would still be required.

An example would be platform design, which would ideally account for the entirety of the equipment's life, ranging from installation and inspection to maintenance and disposal. Platform array structures should be capable of being scaled through modularisation and standardisation to allow for the level of mass production required in renewable and/ or aquaculture industries. The design methodologies needed to ensure proper structural integrity will be unique to ocean engineering as the industry evolves towards the unprecedented designs necessary for safe and sustainable ocean futures.



Stronger, more adaptable and thicker materials will be required as ships and offshore structures grow in scale. Large ships designed with very high strength steels will see larger elastic strains and more deformation as they are loaded in ways for which we currently have very little experience designing. Such vessels may function in previously inaccessible areas, such as very deep water regions and the Arctic.

Multi-use marine structures and planning for decommission

Future ocean platform facilities should have multiple uses (in contrast to the single-purpose facilities we see today) to increase efficiency and productivity. This is especially important when we consider the cost and effort of construction, the platform's marine footprint and potential crowding, and the need to reduce carbon and the environmental impact.

A systems approach to design, operations, and decommissioning will encourage the development of synergetic solutions. For instance, combining wave energy generation with a floating wind turbine is being considered as a solution to reduce turbine movements, making access to the facility easier. Other multipurpose structures could include mixing aquaculture with energy generation (such as building seaweed farms around wind turbines), and housing integrated energy and food generation.

The next generation of ocean infrastructure must be designed to encompass a full life cycle, with safe, sustainable, and responsible approaches to deal with decommissioning. This paradigm shift is required before the proliferation of new offshore developments occurs.

Planning should consider the entire life cycle and full systems costing of infrastructure. Some sectors such as the offshore energy industry intend to decommission thousands of platforms and installations in the coming decades. If these installations are not removed or repurposed they will create legacy hazards which need managing and add to problems of crowding.

Novel use of ageing infrastructure can provide potentially advantageous solutions – such as when oil and gas infrastructure is sunk to become artificial reefs that enhance local ecosystems and fisheries or repurposed as futuristic aquaculture facilities. However, we must improve how we remove aged infrastructure from harsh environments and create safer and more sustainable ways of disposing of installations, including managing in situ cleaning, stabilising and monitoring for decommissioning.

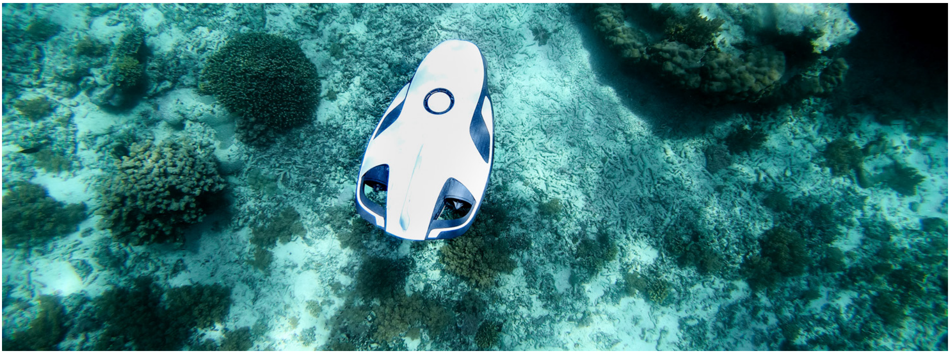
All of these concepts need review, research, testing and verification. Design by itself does not guarantee safety. We must acknowledge the trade-offs between multiple-use platforms and additional complexities to risk assessment and extra initial costs, if anchors and moorings, offshore construction, and maintenance are not made more affordable.

Whole system economics

New methods for evaluating the true costs and benefits of the ocean economy and its infrastructures are needed. These will help to guide safe and sustainable investments and to understand the true return to society.

Considerations include entire lifecycle costing, including non-monetary values. Values should be derived related to safety, carbon costs, environmental impact and whole sector gross value added. Societal and equity issues would be addressed to assess if the system was responsive to local and global requirements. Research could look at existing or new methodologies to integrate obvious costs (such as capital, operation, decommissioning, clean up, accidents, etc) with those incurred due to risks, intangibles, alternatives, or inaction.

Historical and/ or proposed developments could be used to trial methods and test evaluations. One approach might divide the ocean into smaller ‘zones’ with similar characteristics such that custom solutions can be applied to specific areas and scalable solutions addressed. A holistic understanding of the scope of this investment would help resolve decision-making, promote international harmonisation in ocean developments, and allow for safer, fairer ocean use.



Remote sensing, ocean data and autonomous marine machines

Engineering fields such as automation and robotics are evolving rapidly and these advances may support the safe and sustainable use of oceans. Sensors embedded in structures and ships and carried by fleets of autonomous underwater vehicles, boats, drones and satellites are supporting the rapid growth of autonomy and advanced ocean models.

Data-centric engineering presents opportunities to verify and calibrate design models and establish real-time digital twins. In turn, this might offer the ability to update and improve the reliability of ocean facilities over the course of their operational lives. However, challenges regarding the selection of data and the process of analysis remain to be addressed.

Advanced robotics in remote operations can reduce the risks associated with human exposure and offer tailored solutions to minimise damage to the marine environment and ecosystem. Advanced robots may allow selective mining of minerals from the seabed, avoiding large scale damage from the removal of extensive tracts of the ocean floor. Increased control, capacity and dexterity in robotic systems could enable the complete replacement of offshore divers in the oil and gas industry, support scientific missions through retrieval of otherwise unobtainable deep water samples, and automate much of the asset inspection, maintenance and repair industry[69].

Combined with improvements in telecommunications, it is already possible to control remote systems from the safety of an onshore base, reducing risk to life. In the longer-term, drones and other automated devices will be enlisted in construction, maintenance and restoration applications that we can only imagine.

Ocean cleaning and maintenance

Non-biodegradable marine debris are a rapidly escalating threat to marine life and the sustainability of our oceans, with plastic products a particularly prominent cause of marine pollution. Even as the world moves to ban certain plastic products the amounts already released mean the problem will persist for decades. Ocean engineering innovations and clean-up technologies[70] may be deployed, however, solutions to tackle the build-up of toxins and plastics in oceans have yet to find commercial drivers. Public and charitable funding underpin current efforts, but the assignment and assumption of financial responsibility remains an ongoing challenge to scaling up.

Ocean education and skills

Oceans are fundamental to the health of our planet and its peoples. Ocean industries such as shipping, fishing, energy production, cables and pipelines, underpin our critical infrastructures and supply chains. Forty percent of the global population lives near the coast and many poorer countries are almost wholly dependent on the ocean economy. Oceans also provide vital natural capital. They are integral to the functioning of our planet's weather and climate, capturing carbon and providing half of the oxygen we breath. However they remain invisible to most.

To ensure safe and sustainable growth in the ocean economy we must support good choices by policy makers, investors and by wider consumers, raising general awareness and creating good ocean citizens.

In addition, more specialist education will be needed. The ocean engineering outlined in this review will need new curricula, new methodologies and new skillsets. And, to achieve a just transition in the ocean economy, that knowledge and skills will need to be built in new places.

Public awareness, ocean literacy, and technical specialists are needed to drive solutions required for a safe and sustainable future ocean. Distinctive artisanal and educational pathways will be needed. Designing and creating such pathways and global ocean engineering solutions at scale will require international collaborations bridging educational and private sectors.

Findings and recommendations

The projected expansion of the ocean economy, and the associated challenges to safety, sustainability and a more just future, have been described in this report. This future economy will require new approaches to engineering and the previous chapter suggested interventions to help build those approaches. Such interventions will require a collective effort involving large scale partnerships across public and private sectors and engaging civil society.

Interventions will require a collective effort involving large scale partnerships across public and private sectors and engaging civil society

Lloyd's Register Foundation should act in areas where it can best make a distinctive impact in delivering its charitable mission. It can play a strong role in building and sharing actionable evidence and insight, convening partnerships across international and sectoral boundaries, and supporting development of new knowledge, skills and methodologies towards a safe and sustainable ocean economy.

This review sets out high level strategic directions and priorities based on expert judgement and desk research. Given the breadth of the challenges and the large number of stakeholders, further work will be needed to decide implementation details, including priorities and projects for investment. In line with the Foundations strategy, evidence and insight and strategic partnerships will support impactful interventions.

The table on the next page outlines priority action areas where the Foundation could make a distinctive impact.

Ocean safety: Priority action areas

Public awareness and policy	Evidence, insight and ocean data	Decent work at sea	Ocean engineering: infrastructure and systems	Ocean engineering: education and skills	Ocean foresight
Ocean citizens	Ocean safety evidence and insight	Just transitions	Autonomy and robotics	User need and geographical requirements	Global ocean trends
Sustainable ocean principles and ocean finance	Shared and open ocean economy data	Safety and welfare of ocean workers	Full life cycle assessments and circular economy	The future ocean engineer	Technology and skills road mapping
Maritime heritage	Ocean safety index		Design methods and multi use ocean spaces	Skills for ocean safety	Safety issues for emerging sectors
			New materials and nature based engineering		Trade and supply chain effects
			Whole system approaches, including de-carbonisation		

Public awareness and policy

We all depend on our oceans and rely on them for our basic needs, but wider public awareness is limited. The Foundation can lead communication efforts to increase public awareness and support good choices by policy makers, investors and by wider consumers. It can raise general awareness and develop ocean citizens who understand and act on rights and responsibilities towards a safe and sustainable ocean.

Working in partnership with the UN Global Compact and others, the Foundation can support the adoption of safety and sustainability principles into future ocean engineering, including by influencing the financing mechanisms, as well as the underlying standards and criteria, that will enable the new ocean economy.

The Foundation's unique maritime heritage collections will support growing public awareness, and the Foundation will work with others to ensure future generations can learn from the heritage being created today.

Evidence insight and ocean data

There is comparatively scarce data on the ocean economy, and where data exists it is fragmented or held in silos. The UNGC sustainable ocean principles call for interventions to stimulate sharing of relevant scientific data and transparency about ocean-related activities, impacts and dependencies. Such data will also be needed to support marine spatial planning.

The Foundation can be a leader in building and sharing actionable insight on all aspects of ocean safety, in supporting others to share their data, and in developing new tools, for example an ocean safety index, bringing together diverse data into actionable insight to support investments and decision making by others.

Decent work at sea

The Foundation should continue to build out its body of evidence and insight supporting the safety and welfare of those who work in the ocean economy. Working in partnerships the Foundation should support others to ensure that new jobs created in the ocean economy have high standards of welfare and safety, that actively protect workers and vulnerable groups, and support equity, diversity and inclusion.

Ocean engineering: infrastructure and systems

The infrastructures and engineered systems of the future ocean economy will require a wide range of technologies and new engineering approaches, the development of which are beyond the budgets of any single organisation. However, the Foundation can act in a distinctive way by supporting knowledge transfer across sectoral and geographic boundaries and by catalysing cooperation and action in areas where new approaches and thought leadership is needed. The Foundation can build on its investments in areas such as autonomy and robotics, data centric engineering, decarbonisation and complex systems; and accelerate new research and development in emerging areas such as multi use infrastructures, nature based engineering, marine spatial planning and full life cycle assessments.

Ocean engineering: education and skills

The Foundation's mission gives it a distinctive role in supporting engineering education and skills. The Foundation can build the evidence needed to understand industrial and geographical skills requirement in the future ocean economy. The ocean engineering outlined in this review will need new curricula, new methodologies and new skillsets requiring a wide range of interdisciplinary integration. The Foundation can convene and support development of the requirements for future ocean engineers through international collaborations bridging educational and industrial sectors. The Foundation should lead a global conversation about the skills needed for ocean safety in the new ocean economy: whilst established ocean industries might have well developed concepts of safety skills, workers in more informal employment such as fishers, and in poorer settings are often left behind.

Ocean foresight

This review has described possible future directions for a wide range of dynamic and interconnected emerging ocean industries. Rapid new developments in the ocean economy are expected, driven in part by climate change and our response to it, but also by changing population needs and demographics. The effects of these ripple out into wider trade and supply chain effects. The Foundation can monitor and forecast new trends, support technological and skills road mapping, and highlight and promote the safety risks and opportunities in emerging sectors.

Annex A: Ocean engineering solutions - examples, impact and timeframe

The following are specific research and interventions suggested through expert workshops. The scope of such interventions is vast and far beyond the capabilities of single organisations or funders. Nevertheless it illustrates the opportunity for substantial additional action in support of ocean engineering.

1. Characterise the ocean and seabed

Example solutions and scientific underpinnings:

- Improve technologies for:
  - o cheap hydrographic and bathymetric surveys
  - o characterising engineering properties of seabed soils (e.g. strength, stiffness, cyclic degradation)
  - o measurement systems for extreme waves, allowing local properties to be defined
  - o crowd sharing of local sea state and weather data for more accurate forecasting and efficient navigation.
- Accurately predict the occurrence and consequence of natural hazards, including:
  - o the rate and severity of hurricanes and storms
  - o sources of earthquakes and geohazards
  - o study of past submarine slides to assess topographies that pose a future threat of instability
  - o mechanical models for geohazard assessment, within the constraints of limited soils data
- Expand global weather modelling:
  - o Extend data collection points and continental weather models, aiming for same standards as onshore.
  - o Improve metocean forecasting that provides short (1-3 days), medium (4-10 days) and long-term (10+ days) predictions which can then be used to safely underpin ocean infrastructure projects and operational planning.
- Characterise seabed geomorphology and mobility, as well as engineering properties of soil. Use this data to determine susceptibility to triggering geohazards (e.g. submarine slides, gas hydrates), and options for anchoring and building on soft and mobile seabeds.
- Understand the effects of climate change on ocean physics (such as extreme wave heights, storm surges).

- Catalogue and understand the ocean ecosystems, particularly those of which we have limited current knowledge.
- Create a global standard and monitoring system for the health of the ocean.
- Compile hydrographic surveys of northern arctic routes and ports.
- Build regional geostatistical risk maps, aiming for accuracy equivalent to onshore.

Potential impact

By 2030: There will be greater use of sensors and greater connectivity, which will have opened up unseen and uncharacterized ocean environments, allowing physical models of natural hazards, ocean currents and extreme waves, as well as biological models of uncatalogued ecosystems, all to be developed and verified by real ocean data. This data will form the basis for improved designs and operations in the ocean. Risk maps will be developed, providing the data required for evidenced-based assessment of future developments. We will start to understand and predict the impact of climate change on ocean infrastructure and coastal communities.

By 2050: We will have a similar understanding of the ocean environment to that of the terrestrial. This will allow similar assessment of risks to life and property to that on land. With biodiversity and ecosystems characterized, impact of any developments can be understood, assessed and mitigated against. We will also have a clear understanding of the richness of the earth's oceans and this will provide the public with a scientific basis to grant a social license for ocean use.

2. Advanced materials for and from the oceans

Example solutions and scientific underpinnings:

- Increase use of long-life light weight composite materials in ocean applications
- Introduce the use of new materials into engineered structures, including accommodating steels with yield strengths as high as 1300 MPa (more than three times the current typical strength).
- Research alternatives to plastics (or other materials) derived from marine bio-materials
- Develop materials for subsea infrastructure to operate in super deep (>5000m) water.
- Utilise additive manufacturing (3D printing):
    - o design lightweight and optimised shapes of structural components through 3D printing
- Increase the efficiencies of ships, through novel materials
- Use of biological and genetic material from deep ocean

Potential impact

By 2030: Initial developments of bio-materials based on marine plants and/or fish production waste. Adaptation of synthetic or composite materials to offshore structure installations for wind farms or aquaculture structures. Resulting reduced maintenance from corrosion and increased fatigue resistance. Use of additive printing to create low cost ocean sensor buoys and seabed instruments.

By 2050: Widespread use of bio-materials from the ocean in disposable and high-waste applications where rapid breakdown is desirable. New medical applications for marine bio-materials eg.for wound dressing and anti-infection treatment.

3. Ocean design methodologies

Example solutions and scientific underpinnings:

- Tailor structural design for new platform configurations and the changing ocean environment, taking into consideration:
  - local wave and current characterisation
  - floating platform design (ultra-lightweight structures, such as for floating solar farms, that will have very little structural rigidity and will rely on buoyancy for most of their support)
  - anchoring, geotechnics, and mooring
- Design novel platform configurations that remove the need for humans.
- Develop more accurate modelling of hydrodynamic loads, including interactions between wind, currents and waves, considering:
  - both those on the surface (driven by large cyclones), and internally (driven by changing water densities)
  - their interactions both within the seabed boundary layer (where pipelines and subsea infrastructure reside), and at the surface layer (home to floating oil and gas facilities and renewable energy turbines)
- Utilise advanced statistical tools for risk-based design methods, and transfer knowledge from developed oil and gas industries to nascent renewable and aquaculture applications.
- Provide "adaptable design" solutions to mitigate change in climate (e.g. structures that can increase tolerance to air gap).
- Design of subsea infrastructure, including:
  - ultra-long pipelines on soft seabeds and over continental slopes
  - cheaper anchoring technology
  - design and construction for modularity of sub-systems
- Employ sloshing mitigation in liquefied natural gas tanks and in relation to whole-of-vessel motions.
- Conduct accurate stability analysis of offshore pipelines for long tiebacks, including improved hydrodynamic modelling (complex geometry), interactions with a mobile seabed, and problematics soils.
- Optimisation of floating liquefied natural gas hull designs, and mooring and anchoring configurations

Potential impact

By 2030: The most significant impact will have been to mitigate any loss of life and property in the ocean due to higher structural integrity. With better analysis techniques to predict the loads on any new structural configuration and to then design it to withstand these over time, minimal loss of infrastructure will result. By concentrating on designs and configurations that take humans off the platform, loss of life will have also been mitigated. New structural designs will be developed to push oil and gas developments into deeper waters, facilitate the predicted explosion of thousands of offshore renewables, and initiate the use of large offshore aquaculture. New designs for complex environments will promote expansion of mining, aquaculture and energy activities into complex basins.

By 2050: We will have improved our use of stronger materials and new design methodologies, thereby allowing the creation of larger ships and lighter offshore floating systems. Because of safer designs, deep water aquaculture will have taken over from world fisheries and hundreds of thousands of renewable wind, wave and tidal energy devices will be in operation.

4. Multi-use marine structures

Example solutions and scientific underpinnings:

- Understand, model, and verify combined physical systems (e.g. the addition of wave turbines to floating wind turbines which could reduce the global displacement of the floating system).
- Measure and model the biological and environmental benefits of multi-use solutions (e.g. the possibility of marine reforestation of kelp, seaweed, seagrass and algae).
- Conduct a feasibility study of the humanitarian impact of humans living in the ocean.
- Collate/conduct "Rigs to Table" studies on how to reuse or adapt existing offshore structures/infrastructure for food based ecosystems.
- Develop energy from wind/wave/tidal power, and store heat with good economical returns.
- Investigate placing floating renewable energy structures into deeper waters, and the economic feasibility of energy storage and transportation from far shore to onshore.
- Conduct field trials of prototype multi-use structures.

Potential impact

By 2030: We will start to see hybrid structures, most probably in niche applications where the additional component shows some physical, biological or environmental benefit to the overall system. As pressures from ocean congestion increase, more solutions will be adapted and found. Field trials will start to emerge as practical demonstrations of technology.

By 2050: Safe designs, underpinned by understanding of combined physics, will optimize the use of ocean spaces with multi-purposes. More efficient structures will result, as will be proven by higher level sensors, real-time monitoring and whole of life costings.

5. Whole system economic analysis

Example solutions and scientific underpinnings:

- Develop "whole system" models, and then trial on historical and/or proposed development activities
- Ensure better certification
- Research asset management, maintenance and reliability engineering, including:
  - asset risk modelling, non-intrusive inspection, alternatives to dry docking
  - removing humans from logistics and maintenance operations
  - reducing and managing corrosion and biofouling through automated sensing and robotics
- Manage the life cycles of offshore structures. Further understanding of marine operations (e.g. inspection, maintenance) is necessary to lead to safe and cost effective processes.
- Develop solutions for decommissioning, including:
  - safe and more sustainable ways of disposing of infrastructure, whether offshore (as reefs) or onshore
  - safe ways of managing in-situ decommissioning, including cleaning, stabilizing and monitoring
  - an evidenced based decision framework to de-risk decommissioning
- Move from 'ocean exploitation' to 'ocean stewardship', (e.g. from hunter to farmer).
- Achieve a 'social licence' based on increased social awareness and the resolution of motivation conflicts.
- Extend the whole systems costing approach to "product life cycle", thereby allowing holistic decisions to be made on product use decisions (including long-term environmental and social impact).

Potential impact

By 2030: There will be case study demonstrations of the utility of the methods and draft standards for fully costed economic evaluations which will include intangible costs and procedures. This will initiate a change in attitude and approach by governments and regulators, as well as the engineering service companies providing design and construction in the ocean, which starts to account for the true cost of ocean activities to be evaluated either prior to implementation or during operation. Some changes to designs and constructions will be seen.

By 2050: A validated and widely adopted process will be in operation. This will allow proposed developments and activities in the oceans to be evaluated on a widely accepted basis with public confidence that all factors are reasonably accounted for. This will reduce conflict and protests associated with ocean activities and developments and provide regulators and governments with a fully rational and accepted basis for decision making.

6. Remote sensing, ocean data and autonomous marine machines

Example solutions and scientific underpinnings:

- Support subsea and remote operations technologies, including developing:
  - small data collection modules for ocean vehicles, structures, buoys and cages
  - smart and reliable sensing technology
  - long distance communications
- Investigate the use of sensors / satellites to monitor pollution (e.g. oil spills, pollutants in shipping lanes, waste movements - including plastics).
- Use sensors and open data sources to monitor offshore structures and facilities, allowing for:
  - monitoring of loads and displacements
  - verification of physical models used in design
  - development of real-time predictive tools for hazard risk assessment
- Use fibre optic sensors in the integrity monitoring of offshore infrastructure (such as pipes, risers, and cranes).
- Introduce robotics and automation into remote operations (e.g. automated shipping, unmanned oil, gas and renewable energy developments, construction, maintenance and asset inspection).
- Develop precise robotics to:
  - recover rare metals in a sustainable manner
  - collect scientific samples
  - repair deep water infrastructure
- Develop autonomous vehicles to:
  - map the seafloor by quantitatively measuring soil properties in the upper five metres of the seabed
  - take physical and biological measurements of large tracts of the ocean
  - inspect and maintain offshore structures and vessels

- Use sensors, long distance fibre optics, and big data technology to measure environmental impacts and monitor ocean conservation (e.g. measuring fish numbers, monitoring algae plantations from satellites, tracking ocean wildlife, listening to whales, detection of pipe leaks).
- Develop early warning systems for natural disasters (e.g. the use of networked sensors and buoys to detect tsunami events and transmit early warnings to at-risk coastal communities).
- Improve the warning systems for boats in distress, based on current ocean data.
- Conduct data cleaning to make good use of historical data.
- Focus on providing remote shipping routes (such as across the arctic, the North West Passage and into Antarctica) with:
  - new search and rescue capability
  - complete hydrographic surveys for better navigation
  - better ice and weather predictions

Potential impact

By 2030: We will see a decreasing number of people working offshore due to changes in platform design, automation and development of remote operation technologies. Autonomous cargo vessels will be commonplace. There will be greater use of sensors, with cheaper methods to install and maintain these in the ocean environment. As a result, our knowledge of the oceans will be semi-transparent with plenty of data in well trafficked areas.

By 2050: We will have a world-wide ocean sensor network in place, providing volumes of data yet to be imagined. In fact, these streams of data will be making the oceans as well understood as land. Navies of autonomous drones will be used to build, operate and monitor multi-purpose infrastructure, minimizing the ocean as a human workplace.

7. Ocean cleaning and maintenance

Example solutions and scientific underpinnings:

- Encourage student or corporate design challenges or competitions to develop new ideas.
- Establish goals for plastic recovery.
- Develop or investigate funding models through charitable organizations or international consortia.
- Develop vessel and gear designs that can recover solid plastic marine pollution.
- Develop polymers that break down and biodegrade with time.

Potential impact

By 2030: International ocean cleaning funding regime established. Initial technologies developed and active. Ten percent of existing plastic waste removed from ocean and overall content of plastic in ocean no longer increasing.

By 2050: Recovery technologies in second or third generation and able to recover micro-plastics. Volume of plastic waste in oceans being reduced by 20% per year. Waste recovery will be taking place in the oceans via vessels for cleaning up plastics and other pollution.

8. Ocean education

Example solutions and scientific underpinnings:

- Promote the area of ocean engineering as a field of study that attracts the young and brightest.
- Provide material for documentaries and public awareness campaigns.
- Within ocean engineering education:
    - develop a globally accessible platform to support ocean engineering education and curriculum content.
    - develop a curriculum alongside industry for use in universities worldwide.
    - ensure industrial sponsorship and engagement.
    - make education open source to promote public understanding and competency, available to both specialists and the general public.
    - broaden the current engineering curriculum, allowing this to become more holistic and interdisciplinary, including topics such as human centred design, governance and safety.
- Establish common/global requirement standards amongst different nations.

Potential impact

By 2030: Public education will close the gap between those creating the risk and those who suffer the consequences. Using information to support decisions, evidence-based public policy will improve public confidence and provide ocean engineers with the social license to operate. Increased professional education will also improve the human resources and knowledge base available.

By 2050: As education is intergenerational the impact of changing the approach to ocean engineering education will take time. We will see the development of holistic engineers, able to cross disciplines (such as environmental awareness and design), and thereby present complete infrastructure solutions. The public will have a greater understanding of how the ocean can be safely and sustainably developed, providing confidence that scientifically rigorous decisions are being made.

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