

From Grey to Blue: An Ocean Economy fit for the Future

Southampton Marine & Maritime Institute



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1. Introduction

The ‘blue economy’ or the ‘ocean economy’ are terms often used interchangeably to describe economic aspects of activities that take place in ocean waters, along coastlines or on land supporting those ocean-based activities.

Great subjectivity exists around definitions, but here we define the ocean economy as encompassing all economic activities connected to the ocean whereas the blue economy is a social construct, a nascent subset of the ocean economy, embracing the aspiration for sustainable use of the ocean (as later discussed in Section 2). To avoid major climate change and irreversible damage to marine ecosystems, environments and wider society, it is imperative that by the mid-21st Century, the global ocean economy will have transitioned from grey to blue.

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If the global ocean economy were compared to a national economy it would be the seventh largest in the world, and the ocean as an economic entity would be a member of the G7 [1]. The global ocean economy provides us with food, energy and other resources, enables global trade and transport, creates markets for marine and maritime manufacturing, technology and service industries, supports tourism, protects coastlines, hosts recreation and leisure activities, and enables the projection of power by both friendly and hostile nations and other actors. Throughout human history the oceans have been a final frontier for planetary exploration that have illuminated new opportunities and resources and led to waves of pioneering settlement and forced human migration. Consequently, the oceans and coasts are culturally significant for communities

worldwide. Coastal populations are increasing at accelerating rates with more than 1 billion people living along the coast and nearly 3 billion living within 100 km of the coast and depend on the oceans for food and resources [2] [3] [4]; 8 of the 10 largest cities in the world are coastal and half a billion people live on fragile deltas [5]. The ocean economy contributes 2.5% of global GDP and provides employment to an estimated 1.5% of the global workforce [6]; that is over \$2.5 trillion to the global economy each year [7]. In 2016, this value was \$1.5 trillion and predicted to double by 2030 [8]. The oceans cover more than 70% of our planet and have crucial moderating influences on Earth’s climate and biogeochemical systems, aside from the goods and services derived from our oceans from humans’ direct interventions. Our oceans produce about 50% of atmospheric oxygen, regulate climate and sustain

life. The oceans have absorbed ~30% of anthropogenic CO₂ emissions and heat that to date have mitigated some of the impacts of global warming. The future ocean must have a central role in climate action as sources of zero-carbon energy, fuels, food, resources and waste disposal including carbon dioxide reductions and negative emissions. Predictions have indicated that >20% of greenhouse gas reduction, or 11 GtCO₂e¹, that needs to happen by 2050 will happen in the oceans through ocean-based renewable energy; transport; coastal and marine ecosystems; fisheries, aquaculture & dietary shifts; and carbon storage in the seabed [9]. At the same time, the oceans provide vital functions to earth systems that sustain life on earth, and the natural capital of the oceans must be protected and current protections strengthened [10]. Wider context and drivers influencing the ocean economy, and driving it towards a blue

economy, include the imperative to ensure that growth is equitable, inclusive and just; and the implementation of effective nature-based solutions that embrace the value of the natural capital of the ocean. We need to meet global demand, while simultaneously safeguarding the global environment, biosphere, human life and property; insist upon the sustainable use of resources, and provide opportunities for future generations. However, the ocean continues to be approached as both an infinite supply of resources and an infinite repository for waste, be it CO₂, heat, chemicals, urban and agricultural effluents, or plastics.

Much greater use of the oceans is inevitable if we are to meet the demands of a 10 billion global population. These uses, however, must be underpinned by a recognition of the limits of ocean resources and the vulnerability of its ecosystems to the impacts of human activities. They must therefore be accomplished responsibly, justly and sustainably. Replication in the oceans of philosophies and practices borrowed or evolved from industrialised land agriculture, mining and urbanisation is occurring and continuation will be catastrophic. Consequently, our ocean futures stand at a bifurcation; a challenging route to sustainable use or a tragic pathway leading to accelerated violation of planetary boundaries.

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This report presents a current snapshot of the ocean economy alongside potential scenarios of the future ocean economy, and pathways for its transition from grey to blue. With a view to the mid-century, incoming possibilities and threats of the future facing the ocean are considered, regarding economy, society and the environment. The report is organised via four key perspectives: Context (Section 2), Looking into the Future (Section 3), Uncertainties and Shocks (Section 4), and Strategic Implications (Section 5).

The context of the blue economy is first set out in Section 2 including a narrative on the genesis of the blue economy concept, highlighting the subjectivity and overlap with the broader ocean economy. Sectors of the ocean economy that cause most damage to the natural environment or disproportionately consume ocean resources are discussed alongside assessment of the most important actors influencing the ocean economy and current geopolitical ocean hotspots and chokepoints. Future scenarios of the ocean economy are explored in Section 3, considering shifting foci and drivers for change, the impact of emerging and disruptive technologies, geopolitics, injustice and governance.

Anticipated changes in the ocean economy and the drivers for change are discussed alongside assessment of the components of the ocean economy that are likely to become increasingly important, fragile or contested. The impacts of climate change on the ocean economy is explored. Shifting power positions of actors who influence shaping the exploitation of the oceans is explored along with the role of and extent of the impact of emerging and disruptive technologies on the ocean economy, and how these changes might impact the current, and the emergence of future, geopolitical hotspots. The extent to which international law protects the ocean economy, and the extent to which international bodies, governments, NGOs and corporates are able (or willing) to deter damage and shape a sustainable and just blue economy future are examined. Potential uncertainties and shocks related to the future of the global ocean economy are explored in Section 4, and looking into the second half of this century various strategic implications that could arise out of the future demand and availability from the ocean economy are presented and discussed in Section 5.

¹ ‘e’ = equivalent, such that CO₂e accounts for carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O)) (IMO 2020)

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2. Context

Genesis, definitions, components and applications

As set out in the Introduction, in this report, the ocean economy is taken as encompassing all economic activities connected to the ocean whereas the blue economy is a social construct, a nascent subset of the ocean economy, embracing the aspiration for sustainable use of the ocean.

The blue economy concept has been gaining momentum in international, regional and national sustainability agendas with the recognition that “a worldwide transition to a low-carbon, resource-efficient green economy will not be possible unless the seas and oceans are a key part of these urgently needed transformations” [11]². As the term “sustainability” has continued to widen in scope since the 1970s, culminating in the United Nation’s 2030 agenda for sustainable development and the Sustainable Development Goals, economical, societal and environmental aspects have also become integral parts of the blue economy. Ten targets of sustainable development goal (SDG) 14 “Conserve and sustainably use

the ocean, seas and marine resources for sustainable development”, or often reduced to “life below water”, along with many of the 14 SDG sub-goals directly target the oceans. However, progress on many of the ocean-facing SDG has been slow and many of these have been highlighted as little progress made [14].

The genesis of the concept of the blue economy was arguably the Rio+20 outcome document ‘The Future We Want’ [15] in which United Nations member States pledged to ‘*protect and restore, the health, productivity and resilience of oceans and marine ecosystems, to maintain their biodiversity, enabling their conservation and sustainable use for present and future generations*’. However, there remains no internationally agreed definition of ‘the blue economy’ [16] [17]. This is despite a notable increase of its use in international settings and academic literature [18] and a growing recognition of the influences of the varying conceptual and practical applications of the concept by different actors [19].

Published but non-peer-reviewed reports and literature from various governmental, semi-governmental, industry and environmental groups reflect a general direction of travel whereby the blue economy is going through a marked transition towards sustainable activities consistent with improved human, economic, environmental and planetary welfare. “Most definitions include a focus on ‘triple bottom line objectives’ of environmental sustainability, economic growth and social equity” [19]. Nevertheless, these reports reveal inconsistencies giving rise to ambiguity around the concept: they either broadly delimit it, leaving ample flexibility for actors to align with specific national/local/regional agendas; or focus on “operationalising”/“enacting” different components of the blue economy, in the absence of a uniform definition. For example, the Organisation for Economic Cooperation and Development (OECD) adopted a broad definition of the ‘ocean economy’ as “*the sum of the economic activities of ocean-based industries, and the assets, goods and services of marine*

ecosystems” without setting the role that those activities and assets would play in any given society, economy or the natural environment [8]. The European Commission adopted an even broader definition providing that the blue economy encompasses “*all sectoral and cross-sectoral economic activities related to the oceans, seas and coasts*” [6].

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improved livelihoods and jobs, and ocean ecosystem health” [20]. In contrast with the foregoing, policy documents published by the governments of leading global economies tend to focus on “enacting” sets of components of an undefined ocean economy. For example, the US Department of Commerce, Bureau of Economic Analysis [21] focuses on measuring the role of “ocean-related production” in the US ocean economy without attempting to define the concept.

The blue economy is a socially constructed concept that influences negotiations amongst various stakeholders around the use and governance of the oceans and its related activities/resources, and generally academic literature has embraced the ambiguity surrounding its conceptual definition. The concept is viewed as a fluid/flexible concept which can be employed “differently in different contexts and by different actors” [17] [19] [22] who could “coordinate their action and proceed in joint activities while simultaneously disagreeing over local meanings” [23].

An analysis of the dominant themes in 37 international policy documents and key ‘grey’³ literature explores the different ways in which the blue economy is conceived by different actors or in different settings [19]. Four lenses through which the blue economy concept is perceived by different actors can be identified: 1. oceans as natural capital, 2. oceans as livelihoods, 3. oceans as a driver of innovation 4. oceans as good business, each of which comprise a number of sub-themes.

However, many of the sub-themes identified (e.g. employment and income, and sector-focused growth strategies) overlapped between different analysed documents and were not exclusive to any one particular lens. They added that most examined documents tended to prioritise one or two of the identified lenses, and that there appears to be a close relationship between the ‘oceans as natural capital’ and ‘oceans as livelihood’ lenses on the one hand, and the ‘oceans as good business’ and ‘oceans as a driver of innovation’ lenses on the other.

² The United Nations Conference on Environment and Development Rio de Janeiro, Brazil, 3-14 June 1992 (Rio 1992 Summit) built on the preceding Brundtland report (Our Common Future 1987) and recognised that growth and development policies should take account of the needs of future generations. However, the momentum created by the international push for the sustainable development of the global economy initially overlooked the role which the ocean and ocean-related activities play in it, until Small Island States (SIDS) started promoting the concept of a Blue Economy in international forums [12] [13].

³ Grey (or gray) literature stands for manifold document types produced on all levels of government, academics, business and industry in print and electronic formats that are protected by intellectual property rights, of sufficient quality to be collected and preserved by library holdings or institutional repositories, but not controlled by commercial publishers i.e., where publishing is not the primary activity of the producing body. Prague definition [24].



From an “oceans as natural capital” perspective, the examined reports prioritised aspects of environmental protection and sustainability and of human health and wellbeing over other aspects of the ocean economy (e.g. economic growth). Reports falling under this category include those produced by environmental groups and Non-Governmental Organisations (NGO) (e.g. [25]). Looking through the “oceans as livelihood” lens, reports from development organisations (e.g. [26][27]) and governments of the Global South and Small Island and Developing States (SIDS), emphasised sub-themes relating to human health and safety (e.g., food security, employment generation, poverty alleviation) [28][29][30][31].

With regards to the third “lens”, oceans as a driver of innovation, a consistent trend in reports from larger economies and organisations which represent them (e.g. [6][8][32]) is the intention to build on existing strengths and to become frontrunners in emerging components of the ocean economy, primarily for the purpose of economic growth and job creation, but while being cognisant of the potential impacts of human activities on the environment. For example, the

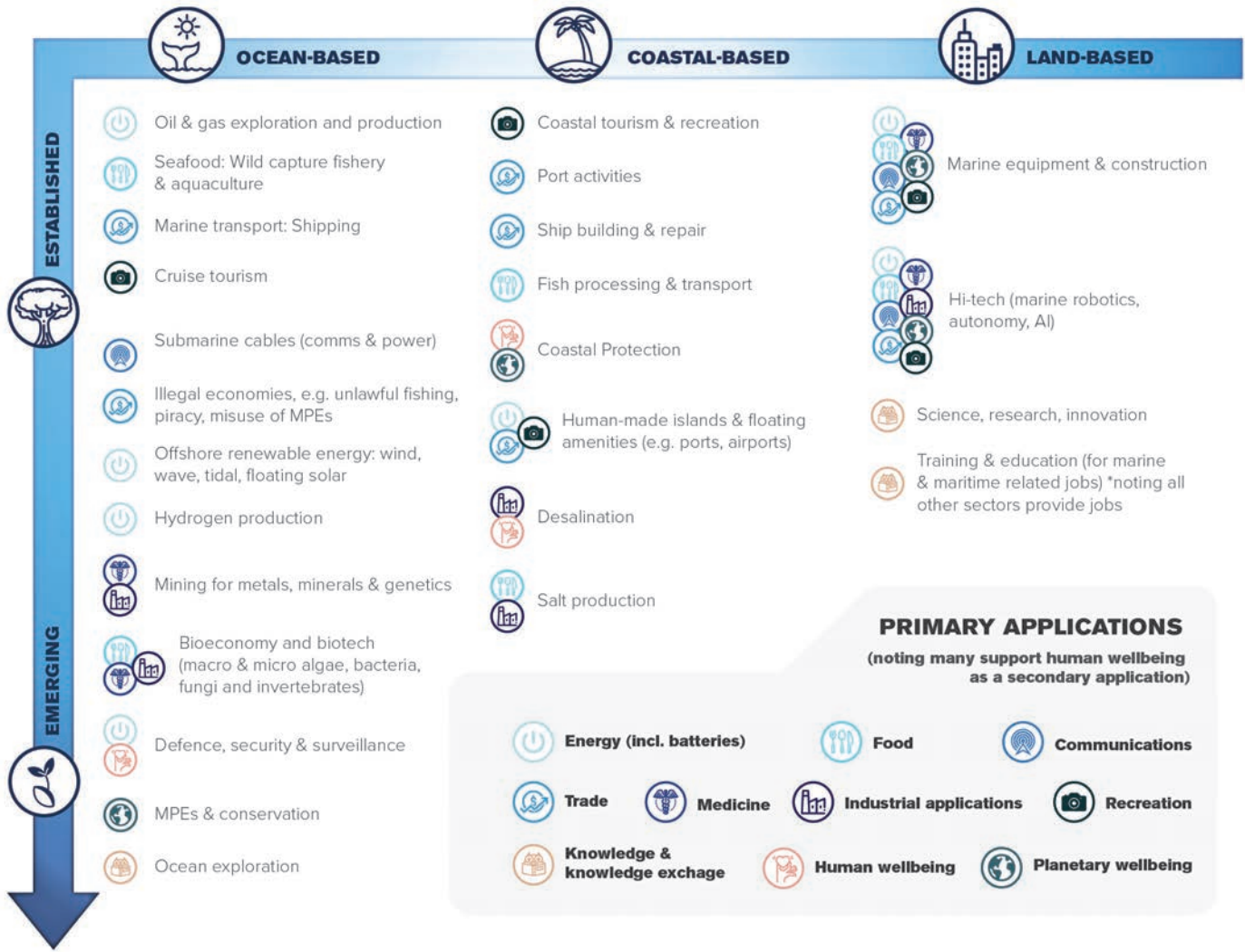
US Bureau of Economic Analysis [21] focused on valuing the contributions (value added) of ocean-related activities to the total US Gross Domestic Product (GDP) based on which the National Oceanic and Atmospheric Administration (US Department of Commerce; NOAA) devised its 2021-2025 plan around five components of the US “Blue Economy Pillars” (marine transportation, seafood production, ocean exploration, coastal resilience and tourism & recreation) [21]. The Norwegian Government’s Ocean Strategy [33] divided ocean industries into three main categories (the petroleum industry, the maritime industry and the seafood industry) while considering “the most important factor” to be that these are an “important source of value creation and employment in Norway”.

Accordingly, these reports highlight that awareness of new developments (opportunities and challenges) influencing ocean-related industries and marine natural capital is important for developing plans to drive economic growth through maximising the benefits of public and private investment in set sectors/industries and in research. This is reflected in the Norwegian Government’s updated Ocean Strategy [34] future-facing outlook

taking account of “future prospects” for Norwegian ocean industries, and the identification of policy developments which will influence those prospects such as climate change, regional and local value creation, and breakthroughs in technological development. The position in the UK is less clear, with difficulties in quantifying some ocean-related sectors and in separating them from terrestrial activities obscuring the definition of the role which the ocean economy plays in the UK’s wider economy. 2014 data had estimated that the UK ‘marine’ economy contributes 8.1% of the total UK Gross Value Added (GVA) [35]. However, recent literature found that “activities in the marine economy account for a much higher proportion of UK economy than was previously thought” [36][37]. This consideration of the ocean economy as part of wider national economies places a growing emphasis on the need to protect ocean-related industries as they shift/ emerge. This is underlined in the US NOAA’s recognition that “the prosperity and security of this nation is therefore predicated on the understanding, health, and sustainable use of our Oceans, Coasts, and Great Lakes” [21]. The Standardization Administration of China’s definition of the maritime economy encompasses the “exploitation, usage, and protection of oceanic resources and their associated activities” [38].

Lastly, from an “oceans as good business” perspective, the focus is on developing new ways of using the ocean either by changing our approach to managing “old industries” or developing emerging sectors. For example, reports focused on identifying a wider range of established sectors of the ocean economy, forecasting those that are emerging due to traceable developments, and highlighting the challenges and opportunities facing the sustainable transition towards the emerging sectors, with the intention of affording decision-makers with the tools to adopt policies at various levels (e.g. [11][39]).

Figure 1. Components and applications of the ocean economy



A range of components of the ocean economy and their applications, drawn from across the literature are illustrated in Figure 1. Components are organised on a spectrum of established to emerging sectors (based on categorisation adopted by OECD [8] and the EC [6]) and by where the activities take place, such as in the ocean, along the coastal zone or on land. The established-emerging categorisation is not binary but a continuum, recognising that there are “no hard and fast distinctions between established and emerging industries” [8] and that sectors emerging in one region may be established in others. For example, the blue bioeconomy, ocean biotechnology and desalination are considered emerging sectors in the European Union (EU), but established sectors with a significant

impact on the domestic ocean economy in China [6]. Some sectors listed as ‘emerging’ are arguably not ‘new’, for example, defence, security & surveillance, and ocean exploration, but can be considered emerging in the context of the future ocean and/or blue economy as sectors that offer significant potential for economic growth, sustainability transition, as well as employment creation [6]. Additionally sectors not considered ‘new’ may be considered ‘emerging’ by the key role played by cutting-edge science and technology in their forecast operations [8]. Other emerging sectors are more unambiguously nascent, particularly at a scale to be globally significant, e.g. offshore renewable energy and blue biotech, while others are yet to emerge e.g. offshore

hydrogen production, carbon storage, and seabed mining, but which could play a significant role in the future ocean economy if conditions are such as to enable these sectors to grow. The primary applications of each component are drawn from a range of sources but principally based on those defined by OECD [8] and it is noted that some components have derived applications that are not captured in the figure. For example, many of the primary applications indicated subsequently support human well-being (including food and energy production), while human well-being is only explicitly defined in Figure 1 where this is the primary application of the component (such as defence and security, or coastal protection).

Impact of the ocean economy on the natural environment

The three greatest uses of the ocean are for food, energy and shipping.

Each year, 115 Mt of fish is harvested from the ocean from wild capture ('fishing') and aquaculture: 84.4 Mt from capture and 30.8 Mt from aquaculture in 2018 [40][41].

Approximately a quarter of global oil and gas supply comes from beneath the ocean floor [42], extracted from some 3000 structures installed principally on the continental shelves [43]. Although offshore wind has grown exponentially in the last decade [44], with over 10,000 turbines installed offshore worldwide at the close of 2022, it still provides <1% global power. In excess of 80% of global trade (by volume) is transported by ship, moving over 10 bn tonnes of cargo annually and 350 m passengers with a fleet of nearly 100,000 merchant ships [45].

By the scale of intervention of these three sectors in the oceans – i.e. food, energy and shipping, they currently contribute the greatest risk and damage to the ocean. Damage in the context of this report is taken to include any degradation of the environment and the 'natural capital'⁴ of the ocean, and can occur either directly, such as by overfishing or pollution in the ocean or indirectly, such as through emissions from fossil fuels extracted from beneath the oceans but burnt on land, subsequently leading to global warming and ocean acidification. Examples of damage to the ocean and the wider natural environment caused by each of these three key sectors are elaborated on in this section.

Overfishing has already caused tipping points in marine ecosystems

25%

global oil and gas supply extracted offshore

Global shipping responsible for

3%

of global CO2 emissions



Seafood

Poorly enforced and insufficient stock management, and illegal, unreported and unregulated (IUU) fishing is one of the most damaging anthropogenic impacts on ecosystem equilibrium for 50 years [47]. Marine littering caused by Abandoned, Lost and Discarded Fishing Gear (ALDFG) also poses a serious threat to marine species, although is a relatively small percentage of total marine littering [48]. Nonetheless, entanglement or ingestion of macro-plastics (including but not limited to ALDFG) by marine animals (seabirds, mammals, turtles and fish) is widespread [49], and for endangered species can have population-level consequences [50].

Threats to the natural environment from aquaculture include fish escapes/infiltration leading to introduction of invasive species and disease, use of pharmaceuticals especially antibiotics, organic waste and chemical discharges, copper which is used as antifouling coating on nets, and marine littering [48]. Aquaculture has been a major contributor to mangrove deforestation with nearly a third of the loss of mangroves in Southeast Asia between 2000 and 2012 traced to aquaculture [51]. Mangroves provide important habitats and ecosystem services, natural carbon capture, and critical coastal protection, defending populations living on deltas and other low-lying regions from coastal erosion and flooding from storm surges and rising sea levels. Consequently, mangrove deforestation can cause detrimental knock-on effects to land-based environments and communities, including destruction of crops, dwellings and climate induced migration.

Ocean-based energy

The greatest direct risk to the natural environment from the ocean-based oil and gas sector is oil spills during extraction and production, and to a significantly lesser extent drill cuttings left on the seabed during the formation of oil or gas wells [48]. The greatest indirect threat of ocean-based energy to the natural environment is global warming from burning the oil and gas for energy production. The embodied carbon in the offshore infrastructure to exploit hydrocarbons (e.g. rigs, pipelines) is also detrimental to the natural environment, although to a significantly lesser extent than emissions from burning the extracted hydrocarbons.

Offshore renewable energy, of which wind is by far the most mature technology, can benefit the natural environment by reducing greenhouse gas emissions (as an alternative to fossil fuel energy), and causes little pollution to the air, water or sediments during operation compared to oil and gas activities. The greater volume of offshore wind structures required compared to oil and gas structures, given the lower energy yield per structure [52] leads to construction, installation and decommissioning phases to pose the greatest impacts on the natural environment. These impacts may be direct, such as noise pollution and degradation of ecosystems during installation or removal of infrastructure, or indirect, including embedded carbon in the offshore renewable infrastructure, damage to the natural environment during mining of required raw materials (e.g. iron ore for steel or rare-earth metals for magnets in the motors) and disposing of the infrastructure at the end of the design life. Particular potential end of engineered life challenges include disposal at scale of composite wind turbine blades, which are currently primarily sent to landfill or incinerated [53].

⁴ Natural capital is considered as the stock of renewable and non-renewable resources (e.g. plants, animals, air, water, soils, minerals) that combine to yield a flow of benefits to people. The term is attributed to economist E.F. Schumacher who introduced the concept in *Small is Beautiful* in 1973 [46].

Shipping

Threats to the natural environment from shipping include discharge of operational water contaminated with chemicals or oils from spills, leakages and washing cargo holds, and introduction of invasive species through ship ballast water and from biofouling. Major oil spills from ships have declined since the introduction of double hulls following legislation introduced in the 1990s [54] but small spills occur regularly during loading and unloading. Other threats to the environment from shipping include waste disposal, noise pollution and the effect of shipping lanes on important ocean species [48]. Significant risk to the ocean-, coast- and land-based environment, is posed by the widespread ship recycling practice of beaching [55].

The vast majority of the embodied carbon in a merchant vessel is from emissions during operation although there is also embedded carbon in the construction of a large ship. Global shipping accounts for around 3% of global carbon emissions, 866 million tonnes CO₂e¹ in 2022 [56]. If shipping were a country it would be the 6th largest polluter globally, just behind Japan and ahead of Germany [57] [58]. The International Maritime Organisation (IMO) the UN's international shipping regulator has set a weak target to reduce the industry's overall greenhouse gas emissions by 50% from 2008 levels by 2050 [59]. A few countries are aiming for net zero by 2050 to encourage more ambitious targets globally (e.g. [60]). However, some current estimates predict emissions from shipping to increase from about 90% of 2008 emissions in 2018 to 90-130% of 2008 emissions by 2050 for a range of plausible long-term economic and energy scenarios [61]. In order to achieve the objectives of its initial GHG Strategy, the IMO laid out a non-exhaustive list of short-term measures (e.g., energy efficiency and carbon intensity requirements) and mid-term measures (so called 'market-based measures' such as a carbon levy or an emissions trading system) to be deliberated upon in the scheduled sessions of the Marine Environment Protection Committee [59]. A key objective of the latter is to incentivise a transition towards carbon-neutral alternative fuels for shipping that have considerable potential to reduce damage to the wider natural environment [61] [62]. The IMO published a revised GHG strategy in 2023 based on emissions data from its Data Collection System [63].

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The natural environment beyond the oceans is damaged as a result of the activities of the ocean economy, such as land-based climate change impacts that result in extreme weather events, caused by burning of fossil fuels that have been extracted from beneath the ocean floor, or from GHG emissions from shipping. Equally, the ocean, and the ecosystem that the ocean economy depends on, is damaged not just from the activities of the ocean economy but by a range of land-based activities quite detached from the ocean economy.

Further considerations

It is important to acknowledge that the natural environment beyond the oceans is damaged as a result of the activities of the ocean economy, such as land-based climate change impacts that result in extreme weather events, caused by burning of fossil fuels that have been extracted from beneath the ocean floor, or from GHG emissions from shipping.

Equally, the ocean, and the ecosystem that the ocean economy depends on, is damaged not just from the activities of the ocean economy but by a range of land-based activities quite detached from the ocean economy. For example, all anthropogenic greenhouse gas emissions causing global warming contribute to ocean acidification, and excess fertiliser and other run offs from land agriculture eventually drains into the ocean causing eutrophication and increased turbidity that damages important ecosystems particularly coral reefs. Millions of tonnes of plastic waste mostly derived from land-based activities finds its way into the ocean each year (estimates vary from 9 M to 23 M tonnes [64] [65], with most entering the oceans via ten major rivers, mostly in Asia [66] [67]. There is improving understanding of the surficial dispersion of plastics (e.g., [68] [69]) but the great majority of plastics end up on the seafloor where they are mobilised by deep sea currents and incorporated into sediments (e.g. [70] [71]). If not entering the ocean as a microplastics (<5000 µm) most plastics weather into nanoparticles with time, and can be ingested by marine animals, thus entering the food chain. Should rates of plastic pollution increase there are fears that a tipping point could be reached leading to the collapse of habitats and species with consequent impacts on fisheries and changes to the way in which the ocean removes atmospheric carbon

dioxide [50]. However, to date, good evidence suggesting the likely catastrophic impacts of plastic pollution on major fish stocks remains elusive despite this being an active topic of vigorous investigation. However, there is abundant evidence that micro- and in particular nano-plastics are taken up by marine organisms (e.g., [72]) especially when fibrous, and these materials are persistent and can bioaccumulate. Some of these particles may enter cells or engage in other biological processes. Microplastics can also enter food chains via the use of fishmeal for animal and aquaculture feed [73] that is the use for ~25% of global marine fish landings. There is evidence from terrestrial settings that close proximity to anthropogenic sources of rubber, for example, can lead to acute mortality in salmon in urban creeks (e.g., [74]). Due to the huge range of plastics used by society, knowledge of low-dose, long-term, hereditary or mixed chemical effects have not yet been studied systematically. Plastic particles can also be passive samplers for other anthropogenic contaminants (e.g., plasticisers, toxic metals) that they commonly absorb and have subsequently been associated with the accumulation

of other toxins such as PCBs. The UN-sponsored Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) is developing a risk framework for marine plastics, but this is likely to highlight many knowledge gaps in our understanding of the impacts of fine plastic particles on fish stocks and food chains.

Some emerging industries of the ocean economy have potential to cause significant damage to the natural environment. Seabed mining has attracted particular controversy and evidence is currently lacking to quantify how and to what extent the oceans could be damaged by seabed mining activities [75] [76].

To gather the evidence base needed to make informed and responsible decisions going forward, it is essential to monitor the health of the oceans from local to global scales and correlate observations and trends to our anthropogenic activities, both those related and unrelated to the ocean economy.

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Damage to the ocean, irrespective of the source of the damage, will negatively impact marine biodiversity and the health of the ocean ecosystems. A healthy ocean is required to support an ocean economy, and the transition to a blue economy, the ocean's ability to moderate damaging climate change and global warming, and is essential for the ocean to play its central role as a regulator of global ecological systems and climate.

Influential actors in the ocean economy

Actors in the ocean economy include (1) the corporate sector and the governments of countries of the major corporations (either state-owned or private) that dominate the ocean economy; (2) the public and third sector, including governments, intergovernmental organisations, environmental actors, think tanks and charitable organisations; and (3) traditional users of the ocean. The influence of the different actors is markedly varied, as discussed in the following sections.

Corporate sector

There is increasing recognition of the corporate sector having the capacity to control aspects of the ocean economy. The so-called ‘Ocean 100’ – the 100 largest corporations operating in the ocean economy account for 60% of total revenues [77]. Of the ‘Ocean 100’, 60 are publicly listed on stock exchanges (though several are majority state-owned), 21 are wholly state-owned enterprises and 19 are private companies. The oil and gas industry dominates the list with 9 of the top 10 largest companies in the ocean economy, while only one offshore renewable energy operator is listed in the Ocean 100.

The pie charts shown in Figure 2 illustrate the distribution of revenue of the ocean economy in 8 core ocean industries – offshore oil and gas, marine equipment & construction, seafood, container shipping, ship building & repair, cruise tourism, port activities, and offshore wind (2a), the concentration of revenue by the ‘top ten’ companies in each industry (2b), and the countries with the highest density of Ocean 100 HQs (2c). Figure 2 is created from data compiled for the year 2018 [77] and using OECD definitions [8].

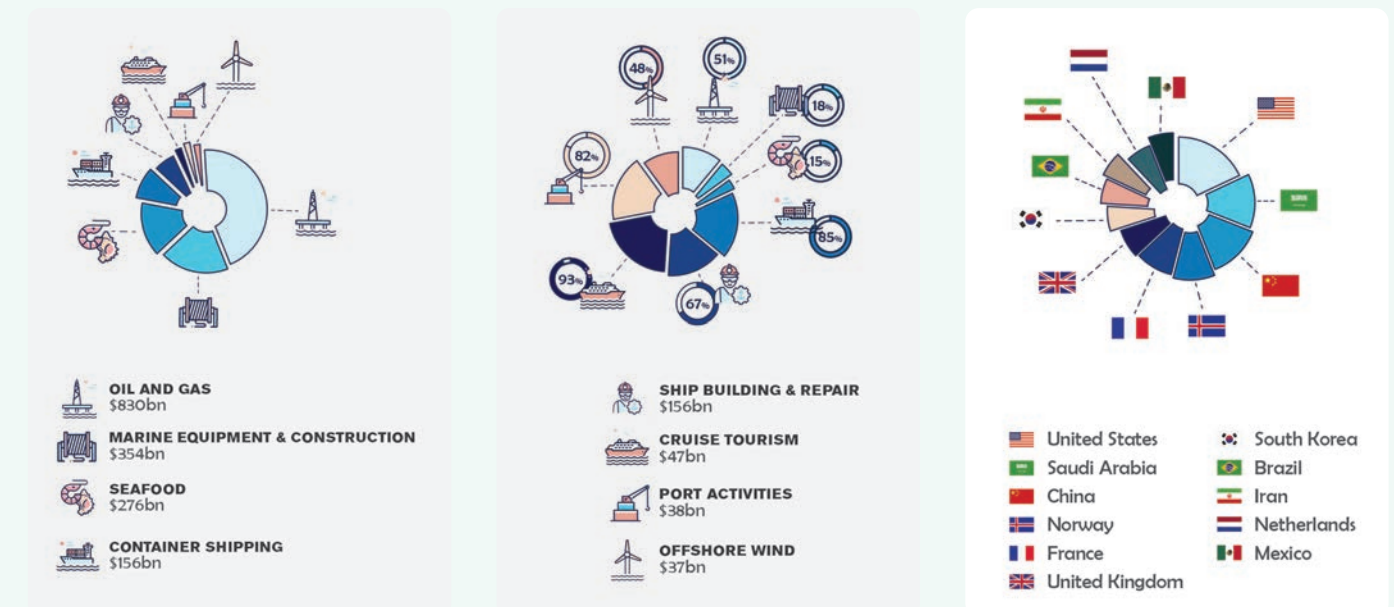
It is clear from Figure 2a that the largest industry by revenue in the ocean economy is offshore oil and gas, receiving (in 2018) US\$830 bn, 45% of the total revenues of the ocean economy. The second largest ocean economy industry is marine equipment and construction (US\$354 bn, 19%), which includes the manufacture of equipment and materials for various sectors, including oil and gas, shipping, aquaculture and offshore wind but dominated by the former; the third largest sector by revenue is seafood (US\$276 bn, 15%) including capture fisheries, aquaculture and fish processing activities. In contrast, the industries with the most substantial concentration of control by the top ten corporations (Figure 2b) are related to shipping; cruise tourism (93%), container shipping (85%) and port activities (82%). The top ten offshore oil and gas corporations control a relatively moderate 51% of the total revenue of the industry, although by value an order of magnitude more than controlled by the top 10 corporations in cruise tourism. Seafood is the most distributed industry with just 15% of revenue being controlled by the top 10 corporations – although by value, about the same as that controlled by the top 10 corporations in cruise tourism, but accounting for 93% of that sector.

Figure 2. Distribution of revenue:

(a) across core ocean economy sectors

(b) within the ‘top ten’ companies in each sector

(c) by country of Ocean 100 HQ



While the Ocean 100 are transnational corporations that operate worldwide, the concentration of location of their headquarters (HQ) indicates geographical power spots (and domestic economies that most benefit from the ocean economy). Figure 2c shows the density of locations of Ocean 100 HQs by share of ocean economy revenue, indicating the field is led by the US, Saudi Arabia and China, and with the top 10 countries receiving 66% of the global ocean economy revenue. Geographical centres of sectors are also apparent, with Saudi Arabia, Brazil, Iran, Mexico and the US respectively hosting the largest oil and gas corporations, whereas China, South Korea and the US host the largest shipbuilding and repair corporations; and South Korea, China and Italy host the largest maritime equipment and construction corporations. The governments of these countries are also influential actors in the ocean economy, either by facilitating the ocean economy through subsidies and as recipients of tax revenue.

Large transnational corporations operate across extended supply chains and exercise considerable capacity to capitalise on and monopolise markets [78]. This concentration of power affords both threats and opportunities for achieving a sustainable and just future blue economy. Large transnational corporations have been compared to keystone species in an ecosystem and conceptualised in the age of the Anthropocene as “keystone actors” [79] or as “keystone companies” by the World Benchmarking Alliance [80], identified as those companies that are going to shape our future.

Other private sector actors have the power to drive more sustainable behaviour from these keystone companies or actors. Financiers are increasingly demanding a range of requirements in order to invest. For example, Norway’s Government Pension Fund, the world’s largest sovereign wealth fund, recently pledged to divest from ocean-polluting corporations [81] [82], although it will take time to see how this unfolds and the impact. Stock exchanges and shareholders can also influence ocean stewardship, through requiring sustainability via listing rules and through shareholder voting rights and engagement with corporate leadership.

Examples also exist of private sector coalitions, self-organising to address sustainable practices in ocean-based sectors. For example, the Getting to Zero coalition [83], a partnership between the Global Maritime Forum and the World Economic Forum, and an alliance of more than 150 companies within the maritime, energy, infrastructure and finance sectors, supported by governments and IGOs, that is committed to getting commercially viable deep sea zero emission vessels powered by zero emission fuels into operation by 2030.

Public and third sectors

Governments, government agencies, intergovernmental organisations, environmental actors, think tanks and charities have demonstrated ability to raise awareness and mobilise support or collaboration, even between actors with conflicting priorities. The public and third sector have capability to put pressure on the private sector to demonstrate ethical, sustainable or responsible behaviour, for example through providing a social licence to operate and providing opportunities for voluntary action from the private sector. This can include transparency initiatives to increase corporate accountability in global supply chains [84] [85]. For example, the UN Global Compact Sustainable Ocean Principles [86] is a non-binding United Nations pact to encourage businesses and firms worldwide to adopt sustainable and socially responsible policies, and to report on their implementation. Similarly, the Poseidon Principles [87] establish a global framework for assessing and disclosing the climate alignment of ship finance portfolios. Other transparency initiatives include The Sustainable Blue Economy Finance Principles [88], The Principle for Investment in Sustainable Wild-Caught Fisheries [89], or The Task Force on Climate-related Financial Disclosures [90].

It is essential that voluntary frameworks are science and evidence based, highlighting the necessity of involvement and integration of research organisations. As highlighted in 'Ocean's Futures 2050' [48] "Sustainable industry trajectories in the Blue Economy will rely on robust scientific knowledge, reliable data, and on greater understanding of the ocean system and potential impacts of ocean-related activities. This is central to the UN Decade of Ocean Science for Sustainable Development vision to 'harness, stimulate and coordinate interdisciplinary research efforts at all levels, in order to generate and use knowledge for the transformational action needed to achieve a healthy, safe, and resilient ocean for sustainable development by 2030 and beyond'".

Traditional users

Notably lacking global influence of the ocean economy, and often politically marginalised, are the traditional users of the ocean. For example, loss of access for small scale fisheries, by far the ocean's largest employers, threatens human rights and exacerbates inequality [91] [85] [92].

Geopolitical hotspots

Ocean geopolitical hotspots have emerged from strategic tensions resulting from geography creating competition or power dynamics over (1) maritime transit routes, (2) ocean resource competition, whether living (e.g. fish and seafood) or non-living (e.g. oil and gas or other seabed minerals) and (3) ocean assets, including submarine pipelines, cables and power interconnectors.

Traditionally, ocean geopolitical hotspots most commonly occur at the **global chokepoints** where ocean space is narrowed such as the Straits of Gibraltar, Malacca, Taiwan, Skagerrak, Bosphorus, Dardanelles and Hormuz, the English Channel, the approaches to the Suez and Panama Canals, and the South China and Red Sea. These locations are significant for global peace and security because a large proportion of world maritime shipping must transit through these points. For instance, **30% of all the oil traded on the world's oceans passes through the Strait of Hormuz** [93]. Sometimes these sites also pose structural risks, as demonstrated in the 6-day blockage of the Suez Canal by the Ever Given in 2021 [94].

These maritime chokepoints are integral to meeting global food and energy supply: chokepoint risk is a resource security risk, as seen with grain supply being impacted by the unprovoked Russian invasion of Ukraine [95]. The potential of opening new sea lanes in the Arctic made possible by the melting of Arctic Sea due to global warming is likely to increase rather than decrease geopolitical tension in the polar region [96].

Whilst there is still a strong tradition of cooperation in the Arctic, as enshrined in intergovernmental organisations such as the Arctic Council, opening of new sea routes means that the area is likely to see increasing geopolitical competition between the US, Canada, China, and Russia [97]. The (then) USSR opened the Northern Sea Route, along Russia's northern sea coast, as early as 1931, opening it to the world in 1991. This remains the only trans-Arctic sea route that sees regular commercial traffic, mostly LNG transports; in 2022, 314 vessels made 2994 voyages in this sea space [98]. Experience suggests that chokepoints will continue to pose risks for geopolitical stability in maritime trade on the global ocean resulting in the need for mitigation and risk management aimed at preparing for future shocks [99].

In the 21st Century new geopolitical hotspots have and continue to emerge in the ocean because of renewed competition for mineral resources, with multiple interest groups laying claim to the non-living resources of the ocean.



The oil and gas sector is currently the largest ocean-based economy [8] – see Figure 2, and furthermore 70% of major discoveries of new hydrocarbons between 2000-2010 are offshore [100]. As shallow-water fields are depleted, production has moved into deeper water pushing further in to national EEZs, towards their limit, or where EEZs meet [100]. Transnational corporations have also been exploring new fields in countries without their own offshore hydrocarbon industry [101]. A recent case of this was in the Eastern Mediterranean where discoveries were made in Lebanon’s EEZ [102]. This has prompted a rush to exploit, that has heightened regional tension [103]. In the Arctic, potential hydrocarbon exploitation, whilst controversial, has drawn the interest of non-Arctic states including the UK and China, which risks deepening geopolitical rivalries in a region sensitive to the impacts of climate change [104]. Further, there has been a surge of interest in deep-sea minerals linked to the growing demand for high-tech products [105]. Exploratory mining licenses have been granted for more than 1.4 million km² of the seabed in areas beyond national jurisdiction [76]. Some developing small island states have been taken advantage of in this scenario. Papua New Guinea lost \$157 million in grants that it awarded to a seabed mining concern (Nautilus) that went into administration [106]. Ocean-based resource competition is postured to increase as terrestrial mineral resources become more contested or scarcer, although this reasoning generally originates from deep sea mining proponents [107]. It is clear that more research is needed to fully understand the global geopolitical implications of seabed mining, as well as the potential environmental consequences [100] [107].

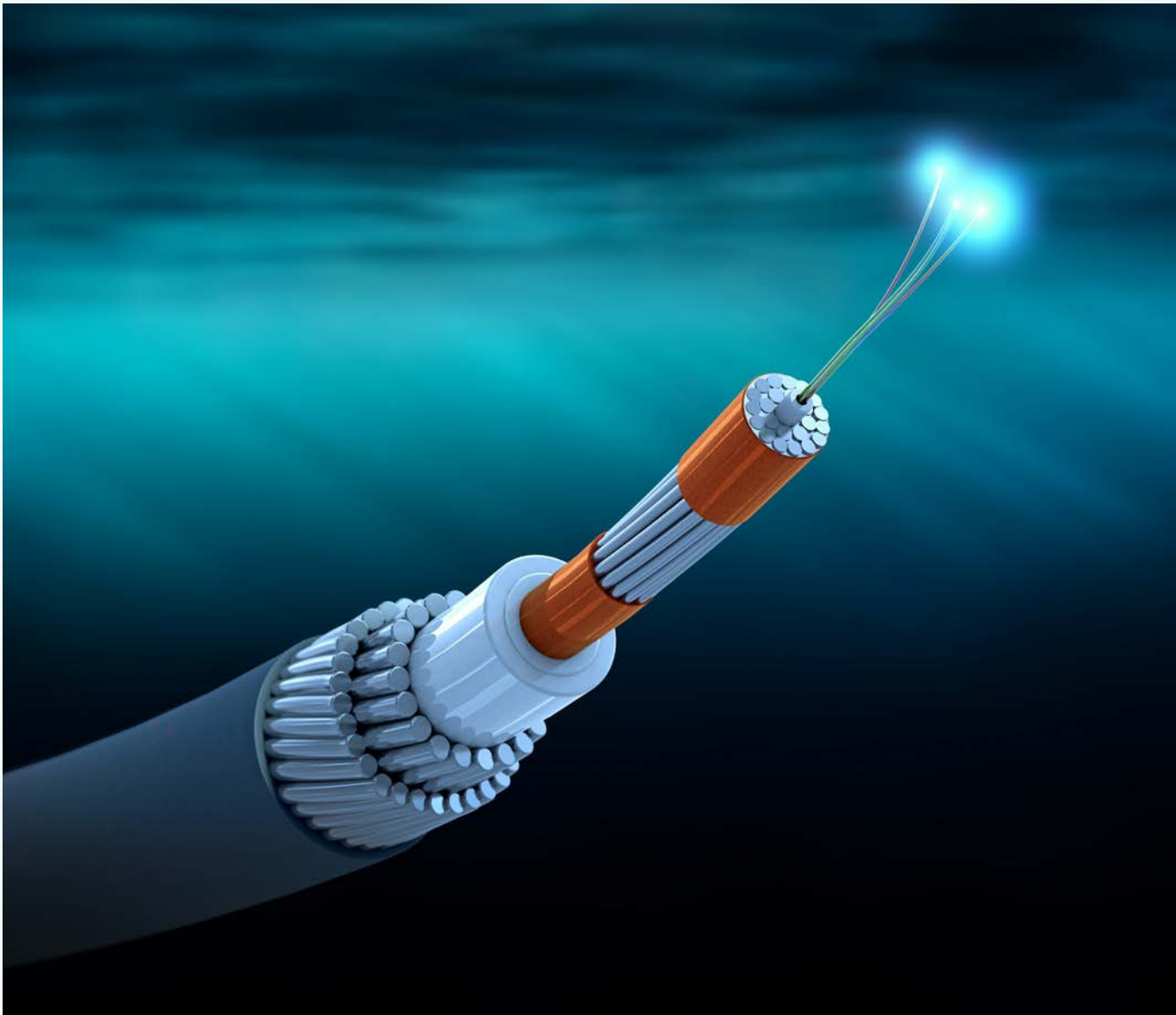
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There has been a surge of interest in deep-sea minerals linked to the growing demand for high-tech products.”



Offshore assets and infrastructure can also be the focus of geopolitical tension, as seen in recent times with the Nord Stream pipelines; the Russian owned pipelines connecting Russian gas to European markets via the Baltic Sea. Following the recent completion of Nord Stream 2 “critics, including several EU Member States, describe Nord Stream 2 as a Kremlin project to export malign Russian influence as well as gas to Europe. The pipeline looks set to perpetuate Russia’s stranglehold on EU energy markets and compromise European strategic autonomy.” [108]. Explosions in September 2022 ruptured 3 of the 4 Nordstream pipelines [109] [110], coming after months of tensions around Russia reducing gas supplies to Europe after sanctions were imposed over Russia’s invasion of Ukraine [111]. Many actors have cited sabotage as the cause given evidence of explosives, and an enquiry is currently underway [111].

Below image credit: NOAA Ocean Exploration, <https://www.flickr.com/photos/oceanexplorergov/27485515902>



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Submarine cables carry 99% of the world’s intercontinental internet traffic, through more than 1.5 m km of fibre optic cables running along the ocean floor.

Submarine cables are also potential targets of geopolitical tensions as are power interconnectors that transfer electricity between countries and regions (e.g., Interconnexion France-Angleterre 1&2, BritNed, North Sea Link) enabling optimised use and storage of renewable and nuclear energy. Fibre-optic telecommunications cables carry 97% of internet communications globally, including untold security operations and trillions of dollars of financial transactions each day.

The consequence of damage to these cables is a recognised existential threat to UK economy [112]. Although the UK has invested £1.9 bn since 2016 to protect its essential networks from cyber-attack [113], the physical infrastructure of 50 subsea cables connecting the UK to the rest of the world remains largely unmonitored and unprotected [114]. Globally, countries find

themselves in a similar position due to the lack of current technology to effectively and efficiently monitor submarine cables. In October 2022, damage to the subsea communication cables connecting Shetland to mainland UK [115] highlighted the vulnerability of critical subsea infrastructure and the impact of damage on the everyday lives of UK citizens. Similarly, internet users across Asia were impacted from a damaged submarine cable in November 2022 and the population of Greenland was severely affected by major submarine cable repairs in August 2022 [116]. Although these incidents were the result of accidental damage – either natural hazards (e.g. earthquakes or submarine slides) or anthropogenic (e.g. damage from fishing vessels) – the critical role of internet communications makes submarine cables a target for sabotage –physical or cyber.

3. Looking into the future

Shifting foci and drivers for change



The ocean economy of the mid-21st century will be shaped by (1) evolution and upscaling of established industries (e.g. oil and gas, shipping, seafood and their related service industries and supply chains), (2) emergence of new commercial scale industries employed at globally significant levels, and often at pace (e.g. offshore wind and in particular floating wind, other marine renewables such as floating solar, wave and tidal energy, seabed mining, marine biotechnology and biofuels, carbon storage, ocean monitoring, control and surveillance), and (3) demonstrator or fledgling industries (e.g. marine bioenergy with carbon capture and storage (BECCS) and management of ocean scale marine protected areas (MPes)).

Future trajectories of different ocean economy industries vary markedly. For example, strong growth is forecast globally in offshore wind, marine aquaculture, fish processing, cruise and coastal tourism [8], some sectors show limited potential for growth, such as capture fisheries [40][41] and ship building,

while other sectors are forecast to decline to 2050 and beyond, for example oil and gas and related commodity shipments [48]. Similar to the narrative accompanying the definition of influential actors and sectors in Section 2, 'strong growth', even a multiple-fold increase, in small ocean economy sectors may have a negligible impact on the overall ocean economy, while a declining but significant ocean economy sector, such as oil and gas, still retains an influential role in the global ocean economy.

Forecasts of ocean economy trends can be considered in terms of direct monetary values or volume of product or activity, which although intrinsically linked are not necessarily proportionally correlated due to free-market forces and improvements in efficiency. The future of the ocean economy is viewed in this section through both lenses; firstly via capital and operating expenditure across the ocean economy, and secondly by sector focussing on volume of product or activity. In the following discussion, forecasts for the ocean economy can be viewed against a backdrop of a global population forecast to increase from 7.8 bn in 2020 to 8.5 bn by 2030 and 9.7 bn by 2050 [117][118] and a world economy that has been predicted to more than double by 2050 [119], far outstripping population growth.

Capital and operating expenditure (capex and opex)

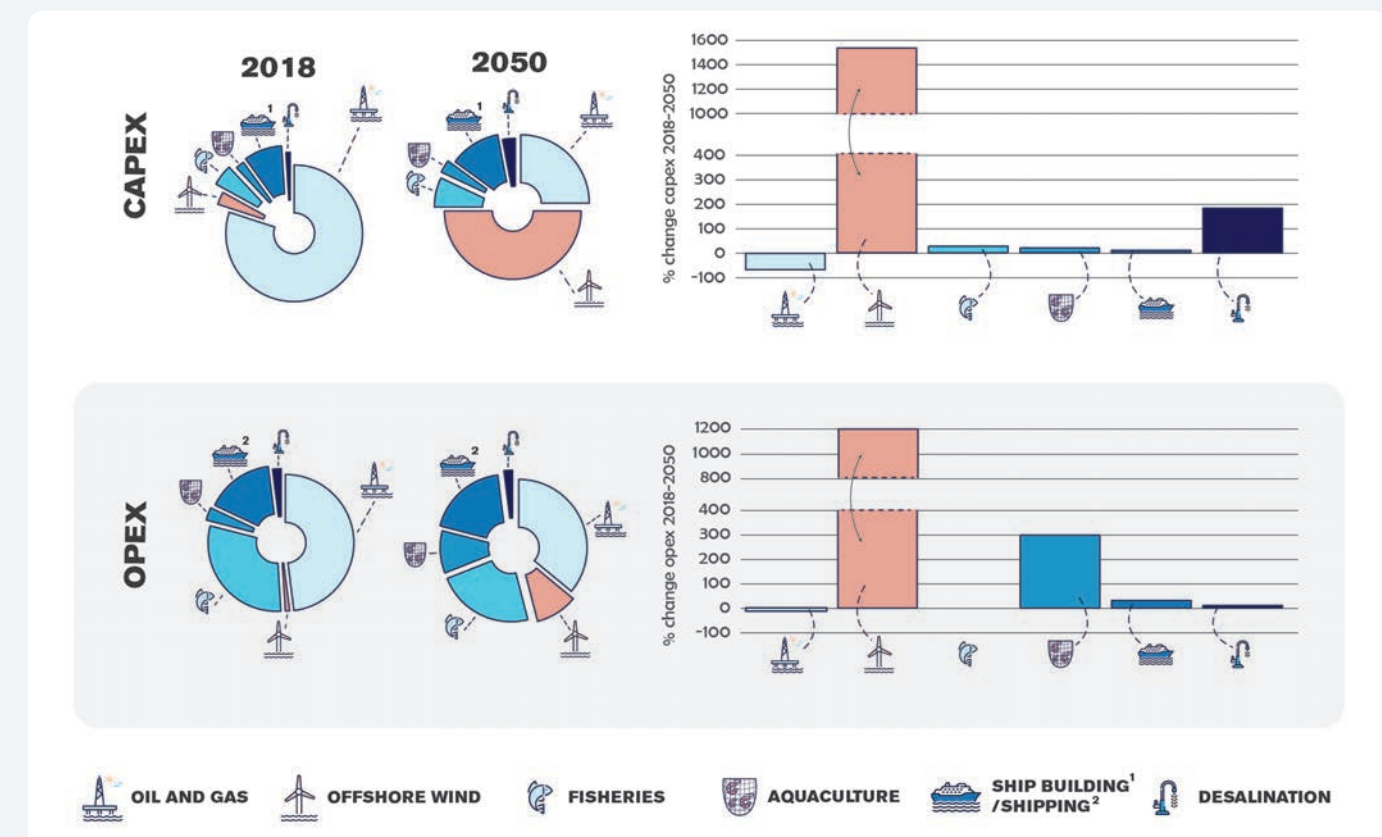
Total capital expenditure (capex) in the ocean economy is forecast to reach US\$461 bn in 2050, the lowest capex since 1990, and compared to US\$ 517 bn in 2018 with a peak of over US\$ 675 bn forecast for the mid-2020s [48]. Perhaps more significant are the major shifts in what sectors capex will be directed to (Figure 3), and the geographical shift in global capex expected in the coming decades (Figure 4). Figures 3 and 4 were created based on forecasts

of the ocean economy set out in 'Ocean's Future to 2050' [48]. Currently, 80% of ocean capex comes from the oil and gas industry compared to < 3% spent by offshore wind; by 2050 oil and gas is forecast to have shrunk to 25% of total capex and offshore wind grown to account for 50% of capex. In the same period, aquaculture is forecast to increase its share of total capex in the ocean economy by half to 3.4%, and desalination to triple to 2.7% of total capex in 2050. Cruise (not included in Figure 3) is expected to experience a doubling in share of total capex, but bringing it to only a 2% market share. In contrast, shipbuilding is forecast to experience just a small (2.5%) increase in share of the ocean economy, but overall occupying a larger market share, bringing it from 9.4% to 11.9%. China is forecast to experience steady growth from the current level of 10% of global capex to 26% in 2050 becoming the dominant actor, while Europe will maintain a strong position growing from 11% to 14% in the same period. Yearly capex is forecast to decline in the Middle East and North Africa, in line with reduced fossil-fuel demand (Figure 4).



Expenditure on offshore wind is forecast to increase from < 3% to 50% of total offshore capex, while share of capex on offshore oil and gas is forecast to reduce from 80% to 25%

Figure 3. Distribution of (a) global capex and opex in the ocean economy by industry 2018 and 2050 and (b) % change in capex and opex over the same period



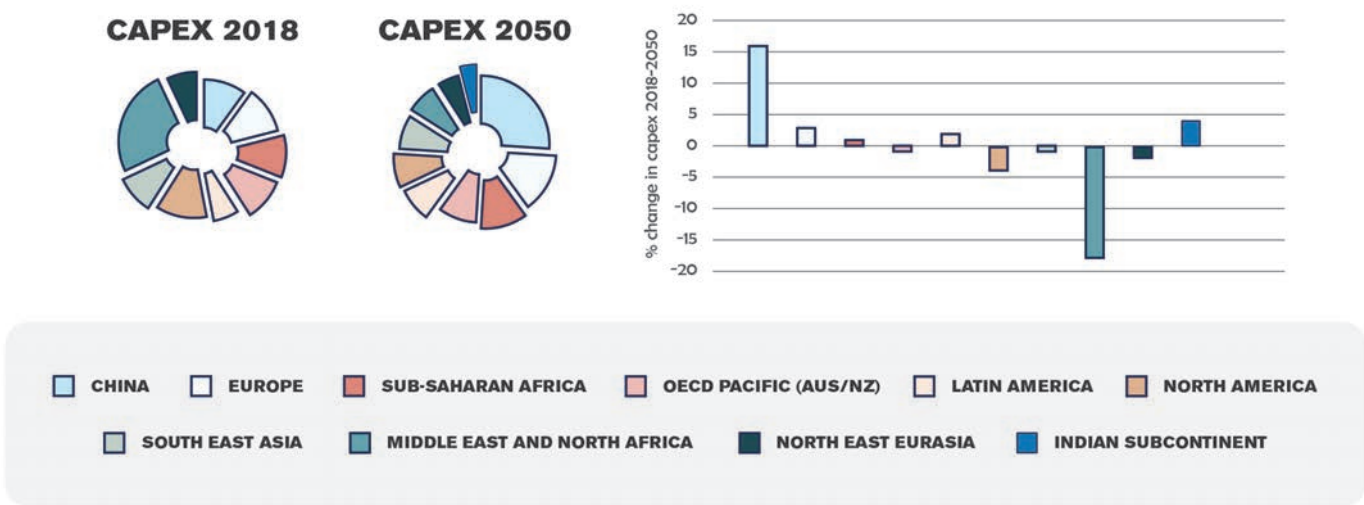
Contrary to total capital expenditure, total operating expenditure (opex) in the ocean economy is forecast to increase - from US\$668 bn in 2018 to US\$793 bn in 2050, with similar shifts between sectors as seen for capex (Figure 3). Offshore wind currently represents less than 1% of global opex in the ocean economy, but is forecast to reach almost 10% in 2050, compared to a 50% share of total capex, while offshore oil and gas opex is forecast to decline from 48% to 36% by 2050. Aquaculture opex is forecast to more than triple in the same period to 10.5%. Other sectors with increasing opex between now and 2050 are shipping and desalination. Opex, like capex, is forecast to decline significantly in the Middle East and North Africa due to the effects of the energy transition and a declining offshore oil and gas market [48].

The increased activity in aquaculture and offshore wind to the mid-century will generate new employment. Starting from a low level of employment in 2018, it is expected that 250 times as many people will work in offshore wind in 2050 and marine aquaculture will employ 58% more people compared to now [48].

Narratives for the forecasts to 2050 for established and accelerating emerging industries of the ocean economy are set out below, in terms of volume of product or activity, and shifting dominant geographies. Outlooks for some potential, but not yet emerged, sectors are then introduced.



Figure 4. Shifts in global capex in the ocean economy by region 2018-2050



Ocean-based energy

Ocean-based energy is predicted to dominate the global ocean economy through to the mid-century (Figure 3), with the most significant changes in the ocean economy driven by the energy transition and the acceleration of offshore wind capacity, and is therefore considered in more depth in this section than other sectors.

Offshore energy production as a whole is forecast to grow towards 2030, then slowly decline to 2019 levels in 2050. Growth to 2030 will be driven by the acceleration of projected offshore wind capacity and continued offshore gas developments, with the subsequent decline to 2050 due to a slower rate of increase of offshore wind capacity compared to rate of decrease in offshore hydrocarbon production (both oil and gas) post 2035. Offshore hydrocarbon production, while forecast to decline, is forecast to retain a significant proportion (71%) of the offshore energy supply into the mid-century. For offshore oil and gas, the Middle East and North Africa are projected to remain the largest producer region to the mid-century; in contrast, Europe is predicted to reduce offshore hydrocarbon production significantly; and output in Sub-Saharan Africa is predicted to grow towards 2050 [48].

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Despite the acceleration of offshore wind, the current rate of growth is insufficient to reach the Paris Agreement targets or net zero by 2050. At current rates of installation, less than two-thirds of the required wind energy capacity will be installed by 2030 for a 1.5°C and net zero pathway



Currently, more than 80% of the world's primary energy consumption comes from fossil fuels [121], while forecasts indicate that by the middle of the century, non-fossil energy will account for half of global energy production, with ocean-based renewables poised to deliver a significant proportion. A fifty-fold scaling of offshore wind capacity from present levels is forecast to 2050 such that offshore wind could supply 13% of global electricity by 2050, a 14% average annual growth between 2019 and 2050. This equates to 29% of offshore energy supply in 2050, compared to 1% in 2019, and about as much energy as provided by offshore oil, although 31% less than by offshore gas [48].

The rate of offshore wind growth is evident year on year, and accelerating. In 2021, 21 GW of offshore wind was installed, three times more than the previous year, and bringing the world's total offshore capacity to 57 GW. China made up 80% of the offshore wind capacity added worldwide in 2021, bringing its cumulative offshore wind installations to 27.7 GW [44] – a level of growth over a few years that took three decades to achieve in Europe. More than 90 GW of offshore capacity is expected to be added worldwide in 2022-2026 [44] and European governments have set a target of 450 GW of offshore wind by 2050, 18 times current installed capacity [122].

Floating wind, an emerging technology, is forecast to grow significantly to 2050, with approximately 6.6 GW of floating offshore wind energy expected by 2030 (more than a 200-fold increase from that currently installed worldwide in 2022), with significant capacities in Asia (e.g. South Korea and

Japan) as well as European markets (e.g. UK, France, Norway, Italy, Greece, Spain). No significant floating offshore capacity is expected in China in the mid-term due to good wind resources in extensive shallow waters [123]. In 2018, 80% of global offshore wind capacity was found in Europe, and 19% in China. By 2030, Europe's global share is forecast to decrease to 43%, even though its capacity quadruples, and in 2050 the dominant regional shares are forecast to be China (40%); Europe (26%); North America (11%); OECD Pacific (9%); and South East Asia (6%) [48].

Despite the acceleration of offshore wind, the current rate of growth is insufficient to reach the Paris Agreement targets or net zero by 2050. At current rates of installation, less than two-thirds of the required wind energy capacity will be installed by 2030 for a 1.5°C and net zero pathway [44].

Marine renewables such as tidal and wave energy are considerably less mature than offshore wind, and are deployed at scales orders of magnitude less than offshore wind. At the beginning of 2020, the total installed capacity of marine renewable energy worldwide, not including wind, was of 528 MW, mostly tidal range projects (494 MW) and mostly located in France [6]. While installation of these technologies will continue to mid-century, offshore wind is considered to be the dominant technology for offshore renewables.

Production of hydrogen offshore is a potentially significant technology shift in the coming 35 years, although to date is not even an emerging sector.

Seafood

Marine seafood production is forecast to grow by 25% to 2050, principally driven by aquaculture. Capture fisheries are expected to experience a slight downturn, 95 Mt in 2050 (including reported, 77 Mt, and unreported, 18 Mt, catch) from 102Mt (2018), driven by effects of climate change and overfishing on fish stocks. However, the forecast catch sizes still exceed the maximum sustainable yield for capture fisheries [124], reinforcing the need for stronger fisheries management to avoid whole food chain collapse.

Aquaculture yield is anticipated to double, from 32 Mt in 2018 to 73 Mt by 2050, to be about equal in size to capture fisheries, in order to meet the growing need for food from the oceans. Seaweed production is predicted to reach 50 Mt in 2050 from 30 Mt in 2018 [48]. South East Asia, China and Latin America together account for about half of the marine capture. Future catch is predicted to decline except in South East Asia, Sub-Saharan Africa, and the Middle East and North Africa. South East Asia is forecast to remain the largest fishing region in the mid-21st century. China is currently

and is forecast to continue to be the largest aquaculture producer (by gross weight) in 2050, producing approximately three times more than any other individual region. South East Asia, Europe and Latin America are, and will remain to mid-century, the next largest marine aquaculture producers [48].

Shipping

Measured in billion tonne-miles, shipping or seaborne trade is forecast to increase 35% to the mid 2030s and then plateau to 2050. Within the sector, coal, oil and gas transport will reduce (currently accounting for 40% share of shipping), whereas container shipping is forecast to increase 90% between 2018 and 2050, driven by increased consumption in Asia. Bulk carriers transport the greatest deadweight tonnage of goods globally – at least double that of any other individual vessel type, and although forecast to experience only a 20% increase in deadweight tonnage to 2050, will still be the largest mover of trade. The forecast growth of the shipping sector to 2050 indicates a marked slowing down, after years of faster-than-GDP growth. The capacity of so-called ‘special vessels’ that carry out a specific functions at sea such as maintenance

windfarm or support aquaculture rather than transport goods from one place to another, are forecast to increase by over 30% measured in deadweight tonnes (or over 50% measured by dollar value). It is forecast that in 2050, around 90% of special vessel capacity will provide services to offshore wind projects [48].

Port activities

Port throughput is forecast to remain relatively constant to 2050, though shares of trades will change and regional loci will shift. Manufactured goods are forecast to grow most, from 4.3 million tonnes (Mt) in 2019 to 7 Mt in 2050 (reflected by the increase in container shipping). Throughput of bulk and petroleum products are forecast to grow until the early 2030s before declining towards 2050 to their respective levels in 2010 and 2015. Petroleum products throughput are forecast to move east and south, whereas bulk trade is forecast to level off in Europe and North America, while significantly decreasing in China and North East Eurasia due to much lower coal consumption there [48].



Shipbuilding and recycling

Shipbuilding is expected to stay at current levels to 2050, concentrated in China and South Korea, with passenger and cruise shipbuilding remaining strong in Europe. New special vessel segments are also emerging to serve the offshore wind industry. Shipbuilding capacity saw strong growth between 2005 and 2010 then dropped 40% between 2010 and 2020 [125], and is forecast to stay at current levels of 75 to 110 million dry weight tonnes (MdwT) per year to 2050 with construction dominated by bulk vessels [48]. The yearly decommissioning rate for ships is forecast to double to 2050, reaching 89 MdwT/year, due to the increasing and ageing fleet [48]. The Indian subcontinent (Bangladesh, India and Pakistan) will retain dominance in ship decommissioning to 2050. Growing concern over environmental impacts and worker health and safety in ship recycling yards in the Indian subcontinent that adopt a so-called ‘beaching method’, where ships are dragged into the intertidal zone for dismantling, has generated regulatory action from the EU and others [55].

Cruise and coastal tourism

Demand for cruising days is forecast to more than double to 2050 (from 279 M to 716 M tourist days per year), corresponding to around 100 m passengers a year. Currently the greatest share of cruise demand comes from North America (33%) with China taking the second largest share (28%). A reduction in share of demand is forecast in North America (to 22%) and Europe while an increase in share of demand is forecast for China (to 37%), becoming the region of highest demand in 2050. Predicted increased demand in China, and also South East Asia, is attributed to GDP per capita rising faster outside OECD countries [48]. Coastal tourism is forecast to double from 4 bn – 8 bn days per year from 2018 -2050 and spending is forecast to more than triple over the same period, to US\$ 1.52 trillion, reflected by greater affluence of tourists [48].

Desalination

Desalination capacity will almost triple by 2050, from 58 million m³/day in 2018 to 143 million m³/day in 2050 driven by growing prosperous coastal populations, and by rising water stress, much of which is linked to climate change. The Middle East and North Africa have the least freshwater resources and currently are, and are predicted to remain, the dominant producer of desalinated water (47 % - 62% of total capacity from 2018 - 2050); North America, China, OECD Pacific and Europe are all predicted to increase desalination capacity to the mid-century but reduce the percentage share (11%-7%, 11%-6%, 9%-6%, 7%-5% respectively) while Sub Saharan Africa is forecast to increase share reaching the same level of production as Europe (2%-5%) [48].



Potential sectors not yet emerged

Seabed mining

Seabed mining for minerals and marine genetic resources (MGR) are much smaller and less mature markets than even the smallest of the sectors discussed above. Nonetheless, both sectors have the potential to escalate rapidly should regulation and technology permit. Demand for seabed minerals is driven by the energy transition, for example for metals like cobalt, copper, lithium, and nickel for batteries [125]. Other commodities include rare earth elements, diamonds (already an established industry), other abrasives, iron sands and phosphate. For many commodities, terrestrial resources are generally less costly and of larger scale and exploitable with known technologies compared to deep seafloor deposits. But concerns about security of supply or geopolitical issues due to the concentration of some resources in unstable regions may make seabed mining attractive for some commodities such as cobalt. However, in the past, industry has proved extremely adaptable at finding substitute materials for many strategic commodities (e.g., platinum Pt and palladium Pd for catalytic converters).

Demand for marine genetic resources is driven by pharmaceuticals, and while the number of marine-derived pharmaceuticals approved for clinical use is small, it is growing. Marine-derived drugs currently focus on anti-cancer applications [126] [127], with novel antibiotics also being researched amid rising microbial resistance to widely used existing antibiotics [128]. MGRs have also been proposed for improved enzymes for catalysing industrial processes [129] and remediating environments [130].

Concerns related to commercial deep-sea mining are widespread, as the potential effects on the marine environment have not yet been researched sufficiently and the risks are not yet understood (e.g. [75] [107]). However, international regulation is weak and the International Seabed Authority has few enforcement powers.

The favourable economics of terrestrial mining is probably the best safeguard against seabed mining, but should demand and geopolitical instability drive huge commodity price rises, then seabed mining may become economically feasible. Some national states may decide to undertake seabed mining just to ensure security of supply of critical commodities, and to bank the know-how of technological knowledge until commodity prices are more favourable.

Hydrogen production (offshore)

Hydrogen is expected to play an important role as an option for zero carbon liquid or gaseous fuels as it emits only water when burned [131] [132]. To be a truly zero carbon fuel rather than just zero carbon at the point of combustion, production of hydrogen must also be zero carbon. The term ‘green hydrogen’ has been applied to hydrogen produced by electrolysis using renewable energy to split water into two hydrogen atoms and one oxygen atom. Using offshore wind could be a practical solution to clean electricity generation at sufficient scale for green hydrogen production, and using surplus electricity from offshore wind for green hydrogen production has been proposed as a solution to the challenge of storing excess electricity [132].

The European Commission Hydrogen Strategy states the ambition to build 40 GW of green hydrogen electrolyzers by 2030 [132], requiring 80 to 120 GW of renewable energy sources to power the green hydrogen electrolyzers. Overall, the Hydrogen Strategy estimates that from now to 2030, investments in electrolyzers could range from €24 to €42 bn. In addition, over the same period, €220-340 bn would be required to scale up and directly connect 80-120 GW of solar and wind energy production capacity to the electrolyzers to provide the necessary electricity.

Carbon storage

Carbon capture from industrial clusters and storage in geological reservoirs such as depleted oil and gas reservoirs or deep saline aquifers is an essential vector for decarbonising society and establishing a net zero society [133]. Indeed, carbon dioxide storage via enhanced oil recovery has been undertaken in the United States and other jurisdictions for some years (e.g., [134]). The Sleipner Vest field off Norway has been storing CO₂ captured from gas production since 1996 with more than a million tonnes of CO₂ injected into the formations annually since 2018 (e.g., [135]). In western Europe, including the UK, the most likely reservoirs for carbon storage are offshore, and the first to be developed will be close to major industrial sources and clusters such as Humberside, Teeside and Merseyside (e.g., [136]). The UK has world-leading experience in offshore oil and gas exploration and production and this expertise will be essential for offshore carbon geostorage. Additional challenges remain in the accounting, monitoring and verification of long-term carbon geostorage both onshore and offshore (e.g., [137] [138] [139]).



Investors and governments need to channel capital away from damaging activities such as overfishing and hydrocarbon extraction, and into low carbon food and energy solutions, nature-based solutions and marine conservation.

Macro and micro algae – the blue bioeconomy and biotechnology

Algae (macro- and micro-), bacteria, fungi and invertebrates are among the important marine resources used as feedstock in the blue bioeconomy. This biomass is used for a variety of commercial applications including food and food supplements, animal feed, cosmetics, fertilisers and plant biostimulants, and commercial uses as biomaterials, bioremediation or biofuels. Macro and micro algae also provide significant restorative benefits to oceans, for example, using excess phosphorous and nitrogen in the ocean, providing hatchery and feeding locations for fish and shellfish, and serving as a carbon sink.

In 2018, the total export value of macro algae, i.e. seaweed, traded for direct human consumption or as raw materials to produce other food or non-food products, was close to US\$ 1 bn. OECD countries accounted for over 60% of the export value and Europe accounted for nearly half of the world import value (US\$ 1.3 billion) of seaweed-based thickeners, while more than 99% of seaweed production is found in Asian countries [140]. In 2018, the global seaweed production was 33 million tonnes (wet weight), of which 97% was farmed and 3% came from wild seaweed. However, the seaweed industry can still be considered nascent with considerable potential to provide low carbon food security and raw materials for a range of non-food applications. Predictions indicate that biophysical limits to global seaweed aquaculture will not be reached by mid-century even with the most ambitious growth rates (of 20% per annum), and possibly not until into the 22nd century. Biophysical limits may be reached sooner for specific nations, in particular China, where the seaweed sector is already mature [141]. Development of technological solutions is required to enable large-scale automated offshore cultivation for the global expansion of seaweed aquaculture [142].

Marine robotics, autonomy, AI

The opportunities for deployment of robotics, autonomy and AI at scale in the ocean economy are manifold, enabling tasks to be carried out in remote and harsh environments, enabling tasks that are too complex for human operation, or cannot be achieved by human interpretation at the spatial scale or temporal rate required to provide meaningful data. Applications include (1) site characterisation to derive the engineering parameters for design of ocean developments such as wind or aquaculture farms (e.g. [143] [144], (2) monitoring, inspection, operation, maintenance and repair of offshore infrastructure once installed, including submarine cables and pipelines as well as offshore wind farms or aquaculture developments (e.g. [145] [146]); (3) improving efficiency of shipping and port activities through automation and real-time optimization of processes (e.g. [147] [148]) (4) surveillance and policing to prevent or prosecute blue crime (e.g. illegal fishing, pollution, piracy, people, narcotics or arms trafficking by sea (e.g. [149]); and (5) monitoring of the ocean environment at a meaningful spatial scale [150] to better understand the oceans and the impact of our interventions in the ocean and indeed our activities on land on ocean health and resilience.



Summary

In summary, the drivers for anticipated shifts in the ocean economy in the coming three decades are the competing demands of a global population of nearly 10 bn for food, energy, raw materials, goods, space and more; and the necessity to decarbonise our economies and societies, and reduce biodiversity loss, waste and pollution globally. The potential of the ocean to help meet these needs is immense, but requires substantial expansion of many ocean-based economic activities, which must be achieved responsibly and sustainably to avoid irreversible and irreparable damage to the ecosystem that ultimately sustains us. As such, investors and governments need to channel capital away from damaging activities such as overfishing and hydrocarbon extraction, and into low carbon food and energy solutions, nature-based solutions and marine conservation. Evidence indicates that investing across offshore wind, sustainable ocean-based food production, decarbonizing international shipping, and conserving and restoring mangroves would generate benefits more than five times the costs by 2050 [151].

Components likely to become increasingly important, fragile or contested

The global blue economy is intended to be economically viable (prosperous) and environmentally sustainable, but also culturally appropriate and focused on social equity and well-being [85].

However, plans from governments, trade associations, civil society and inter-governmental organizations tend to focus primarily on the resources necessary for industrial expansion and economic growth of multiple ocean sectors, i.e. the broader and often unsustainable ocean economy, instead of equitable outcomes from these sectors [152]. This discourse of business-as-usual development downplays worrying trends toward overexploitation that will have an impact on ocean health and ultimately coastal economies [153]. Without careful balancing of the competing demands of economically viable and environmentally sustainable development, many components of the ocean economic and geopolitical ecosystem are likely to become increasingly fragile and contested [154].

Many of the problems of today, will likely get worse over the next 30 years. **Overfishing** stands as a good example. Depleted fish stocks are already pushing the industry further from land, with large fishing boats making huge catches far offshore [155]. Globally fishing is not equitably managed and is therefore not environmentally sustainable, and therefore risks the economic viability of this key coastal industry [156]. There is risk both of a fragile ecosystems being pushed beyond sustainable limits, as well as increasingly contested stocks and fishing grounds [157] [158]. At the same time an increasing global population, especially in the global south, relies ever more heavily on protein from marine organisms to feed the population [20]. The juxtaposition of economic viability and environmental sustainability is the most significant factor in understanding which components of the ocean or blue economy are likely to become increasingly important, fragile, and contested in the future.

At its core these tensions are driven by the **uneven distribution of resources** we currently extract from the ocean and those which we are looking to in the future, and overlapping/competing spatial constraints/needs from different sectors. This is placing increasing pressure on ocean space, as well as on the infrastructure and methods we use to manage it. The oceans offer over 360 million km² of space globally, with c. 140 million km² within Exclusive Economic Zones [48]. The majority of human activity, however, is focused on shallow areas close to land. Currently nearly 40,000 km² of this space is occupied by infrastructure related to energy and food production, but this is projected to rise nine fold to 368,000 km² by 2050 [48], with growth in demand occurring across the globe, but particularly in the Indian subcontinent (50% projected growth), North America, the Middle East and North Africa.

Close to shore, shallow (sub 50 m) waters will continue to be of critical importance, but as technology continues to develop, deeper waters will open up, as evidenced with the emergence of floating offshore wind. As activities in deeper water expand, so too will the desire/need to monitor, manage and protect strategic interests. Being able to ensure maritime security will be increasingly important across four areas as the ocean economy grows; 1) sea power – being able to protect national interests and assets through naval power, 2) marine safety; being able to safely support activities in an increasingly used sea (search and rescue etc.) and respond to natural disasters, 3) Law enforcement with regard to resource use; being able to monitor and enforce application of legal frameworks 4) Human security (e.g. food security) preventing illegal fishing and human trafficking [19]. The oceans are vast and remote, hence the need for integrated systems of satellites, monitoring networks, and autonomous high endurance robots to protect the environment and assets, and prosecute parties that do not comply with regulation.

With greater awareness of the role that the ocean economy has in creating jobs and in diversifying and boosting national economies around the globe, public and private investment in ocean-related activities [employing the broad sense of the ocean economy] is expected to grow over the coming decades [160] [161]. This applies both to established activities which must overcome pressures such as climate change adaptation, and emerging technologies which present opportunities for the creation of new markets which could reshape/influence the global economic landscape. As coastal activities (ports, recreational activities, coastal tourism, shipbuilding, shipping, aquaculture) continue to multiply and with increasing demand from a growing population, it is expected that offshore waters will become a “particular focus of blue economy expansion over the next decade” [162]. For example, despite the disastrous *Deepwater Horizon* incident in the Gulf of Mexico in 2010 [163], deepwater and ultra-deepwater oil and gas production, which has grown 13% annually since 2019, is expected to continue to grow during the coming decade [164]. Deepwater hotspots have been identified due to recent discoveries of new oil and gas fields, most notably in Brazil and the USA [164]. Plans for offshore wind development in coastal states’ EEZ is another example of the expected pattern of expansion of the ocean economy [165].

In some parts of the world, other components of the ocean economy are becoming increasingly fragile due to the particular vulnerability of Small Island Developing States (SIDS) - including British Overseas Territories (BOTs)⁵ - to the consequences of climate change [166]. Sea level rise, extreme rainfall, tropical cyclones and droughts make SIDS some of the most at-risk countries in the world to climate change impacts [167]. This includes flooding, the disruption of recreational and shipping activities, coastal tourism, and the loss of natural capital (e.g. seagrass; mangroves; coral reefs).



Sea level rise will lead to significant coastal land loss globally, impact millions of people living on fragile deltas, and potentially threaten coastal-based ocean economy assets and activities such as ports, energy infrastructure for bringing offshore power onshore, fish processing, desalination and tourism, along with threatening the general urban and residential infrastructure of coastal cities and towns. Cumulative 21st century land loss has been predicted between 60,000 to 415,000 km² and coastal migration from 17 to 72 million people (0.23%–0.97% of the global population in 2015), depending on the scenario adopted [168]. Coastal protection to avert migration has been shown to be favourable from a cost-benefit analysis perspective for 3.4% of the world’s coastline, which although a small proportion of coastline, corresponds to 25% of the global 1-in-100-year floodplain, 78% of global floodplain population, and 92% of the global floodplain assets, based on 2015 data [168]. Without adaption, annual flood costs could range between

\$1.4tn and \$27trn depending on sea level rise scenario adopted (11 – 180 cm); and reaching 2.8% of global GDP in 2100 [169] [7] – noting this is more than the value of the entire ocean economy in 2021 [7]. Failing to address climate change and achieve temperature targets will increase sea level rise and worsen the impacts. Even reducing greenhouse gas emissions and stabilizing global temperatures, sea level rise will continue at a reduced rate for centuries as the changes in the ocean and cryosphere which contribute to sea level rise take long timescales to respond [170]. It is noted that sea level rise in arctic regions – where temperatures are rising twice as fast as the global average [171] – causes thawing of permafrost and emittance of significant carbon dioxide and methane to the atmosphere. Currently permafrost stores twice as much carbon as is circulating in the atmosphere such that even modest thawing will magnify and accelerate the effects of climate change on ocean economy.

From a workforce perspective, the technological development of established components of the ocean economy and the emergence of novel ocean-based activities highlight the need for re-skilling and up-skilling existing workforces and for adequately training future generations to perform their activities safely and efficiently [172]. A notable example of the established ocean-based activities that are going through a marked transition is shipping. The industry is being transformed through the introduction of digitalisation and autonomy, and the ongoing debate about the shift towards the reliance on greener alternative fuels to help decarbonise it. These trends aim to promote higher levels of safety at sea and to limit the negative environmental impact of an industry which has been heavily criticised for falling behind in comparison to other modes of transport [173]. However, they equally pose challenges for the workforce employed by different stakeholders across its value chain – including ports [174] and seafarers [175].

⁵ British Overseas Territories (BOTs) account for 94% of the known unique species for which the UK is responsible [167].

Effect of climate change on the ocean economy

Developments in traditional maritime industries will be shaped by climate change, as shifts in temperature, ocean acidity and rising sea levels affect movements of fish stocks, open up new trading routes, affect ports, and create new tourist destinations and attractions, whilst destroying others [8].

Climate change is also shaping the future ocean economy driving the demand for low carbon energy, food and shipping to achieve the decarbonised society and economy required to mitigate the effects of global warming. Figure 3, for example shows that offshore wind and aquaculture are the biggest changers in the ocean economy to the mid-century; while conversely hydrocarbons that have dominated the ocean economy historically is declining. As discussed in the section above, the juxtaposition of economic viability and environmental sustainability define the future of ocean economy components, such that much of the narrative above, particularly around small island developing states (SIDS) and sea level rise, is equally relevant in this section.

The expected impacts of climate change on the ocean economy is explored in a blue paper commissioned by the High Level Panel for a Sustainable Ocean Economy [176]. In the foreword, the authors note:

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“Underscoring the recent Intergovernmental Panel on Climate Change Special Report on the Ocean and Cryosphere in a Changing Climate [177], this Blue Paper on the ocean and climate change brings a stark reminder of the serious economic consequences of our changing climate for ocean industries, and assesses the adaptations that will be needed across key parts of the ocean economy to ensure that we can continue to benefit from the valued functions the ocean can provide. Confirming the central importance of the ocean economy to our global health and wealth, the paper highlights that society simply cannot afford to lose these important sectors.”

In the accompanying press release⁶ Gaines, co-author of the analysis states “Only now are we starting to comprehend the full force that unabated global heating will unleash on our key ocean industries. To avert an impending economic crisis, widespread devastation to communities, hunger and resource conflicts in coming decades, we must urgently restore ocean health. That means taking rapid and ambitious action to curb climate change, while easing the other enormous pressures we put on the ocean. Fortunately, bold actions today could have dramatic benefits for most countries.”

The analysis details the wide ranging and severe impacts that climate change will have on the ocean and ocean economy. For example, a key finding of the analysis is the extent to which fish will migrate to cooler waters as the ocean warms and becomes more acidic under future climate scenarios. This will jeopardise fishing communities in some regions and increase the potential for conflicts over shifting resources. The combined effects of ocean warming and acidification result in predictions of negative impacts on coral reef cover and tourism values for all countries, with magnitudes dependent on the strength of climate change. For a high emissions scenario, coral cover is expected to decline by 72–87%, causing on-reef tourism values to decrease by over 90% in 2100.

⁶ <https://oceanpanel.org/wp-content/uploads/2022/05/BP2-press-release.pdf>



Emerging and disruptive technologies

Technology has been central to human intervention in the oceans and pushing the frontiers of those interventions to provide food, energy, transport and more, that enable an ‘ocean economy’.

Innovations in advanced materials, subsea engineering and technology, sensors and imaging, satellite technologies, computerisation and big data analytics, autonomous systems, biotechnology and nanotechnology will potentially affect every sector of the ocean economy. History shows that our interventions in the oceans that support an ocean economy have positive and negative consequences; providing food, energy, transport and more, supporting livelihoods worldwide, alongside causing damage to the environment that the ocean economy relies on caused by the same activities e.g. overfishing, oil spills and other pollution, GHG emissions. The UN Global Compact identified five tipping points for a healthy and productive ocean [178] - Fully traceable sustainable seafood, Zero emission shipping, Harnessing ocean electricity, Mapping the ocean, and Ending waste entering the ocean - each of which is grounded in technology developments. As also highlighted earlier in this report, many land-based activities that are disconnected from the ocean economy also damage the ocean environment on which the ocean economy relies. Scientific and technological advances in the coming decades are expected to play a crucial role both in development of ocean-based economic activities and addressing many ocean-related environmental challenges [8].

Emerging and disruptive technologies may impact the future of the ocean economy in a variety of ways. A selection are outlined below, the effects of which may or may not be desirable from an environmental or societal perspective or support equity from an economic perspective. The aim is to set out how and to what extent emerging and disruptive technologies may impact the future of the ocean economy.

Enabling increased capacity of ocean economy sectors – e.g. technology for upscaling offshore wind and aquaculture deployment to forecast levels, future fuels to enable the predicted increased shipping with required reduced emissions.

Enabling greater efficiency of ocean economy sectors – e.g. through technology to improve energy efficiency of offshore wind turbines, vessels, ports desalination plants or the supply chains – via new hardware and materials or autonomous approaches to optimize operations.

Providing demand for raw materials to be sourced from the oceans for the energy transition and hi-tech goods – e.g. minerals and metals for electric vehicle batteries, mobile phones or computer components), in turn driving offshore technology developments for seabed mining.

Enabling baseline data collection and evidence base for changing ocean health in real or near-real time and the impact of ocean interventions to inform on future ocean economy developments.

Enabling effective protection of marine protected areas, fishing activities, ocean infrastructure and any remote ocean-based operations.

Changing employment – whether reducing workforce from e.g. increased automation and autonomy, increasing employment from increased capacity of sectors enabled by technology developments, or changes in the nature, required skills or location of employment.

The UN Global Compact identified five tipping points for a healthy and productive ocean [178]



Fully traceable sustainable seafood



Zero emission shipping



Harnessing ocean electricity



Mapping the ocean



Ending waste entering the ocean

each of which is grounded in technology developments.

Focus on ocean energy

As seen in Figure 3 and in the associated discussion, the future ocean economy will continue to be dominated by offshore energy accounting for about 75% of total capex of the ocean economy and nearly half of total opex to 2050. Particular advances are forecast for offshore wind to support the energy transition to achieve a decarbonised society and economy – with a forecast 1200% increase in capex and 1500% increase in opex. Fixed offshore wind is now a financially competitive option for electricity generation compared with other energy sources, including gas generation of electricity [179], although the contracts for difference scheme contributes to the competitive costs and many innovations are still required to responsibly upscale to the projected levels to achieve net zero in 2050 (e.g. UK Government Environmental Audit Committee Inquiry ‘Technological Innovations

and Climate Change: Offshore Wind’, [180]. In this section we take a deep dive into some of the emerging technologies that could enable the offshore wind transformation.

The Industrial Strategy Offshore Wind Sector Deal [181] highlights technology innovation priorities around four key areas: (i) Turbines, (ii) Sub-structures (including foundations, moorings and anchors), (iii) Electrical infrastructure and (iv) Operations and maintenance and wind farm lifecycle. Technology roadmaps for each area are published by the Offshore Wind Innovation Hub [182]. The various roadmaps rely on a range of new and emerging technologies including new high performance and recyclable materials for blades, substructures, cables, mooring lines and anchors; new design concepts for each of these system components; automated, autonomous and

optimisable control systems; efficient energy storage at scale; remote and autonomous monitoring and interventions; dynamic cables; and design methods including total system design, regenerative approaches and design for decommissioning. Smarter mooring and anchor solutions are critical to reduce capex and opex for floating offshore wind. Foundations currently contribute up to 25% of the overall capex to an offshore wind project [183] and this will increase as developments move further from shore, to deeper water [184][185]. The EU Research Roadmap [184] specifically highlights foundations and anchor/mooring systems as a priority for reducing costs of offshore wind, particularly for floating arrays. Cost reduction of moorings and anchors for floating wind through technological advances include ductile mooring systems that absorb peak loading to reduce the size of anchors

required [186][187]. Confidence in smaller, novel mooring systems can be achieved through minimum-data informed machine learning models coupled with physics-based methods to assess response of the system through life [188].

Seabed survey is absent from the above-mentioned sector plans, yet a critical area for innovation if the CAPEX of offshore wind is to be reduced. Deriving engineering parameters of the seabed for design calculations for offshore foundations, anchors and moorings and cables requires geotechnical site investigation, which is currently evolved from the offshore oil and gas industry and increasingly recognised as not fit for purpose for offshore wind where seabed areas are much greater and project time lines and margins are much smaller. Offshore geotechnical testing tools that can be deployed with reduced vessel support are critical to reduce the cost of offshore renewables developments. This economic challenge arises due to the much greater area required for survey because of the many more structures required for the same energy yield, given the significantly lower power output per renewable energy structure compared to an oil and gas facility. A specialist offshore geotechnical site investigation vessel could cost in the region of £100,000 per day and a renewables site investigations require tens or hundreds of locations to be investigated, as opposed to a handful of locations for a single oil and gas platform. Opportunities for cost reduction of site investigation for offshore wind through technological advances include intelligent geotechnical site characterisation tools for remote or autonomous deployment or operation, to upscale capability without upscaling cost [189] and machine learning methods to correlate continuous geophysical data with discrete geotechnical data to optimize development of an engineering ground model of a development area [143].

Harnessing emerging and disruptive technologies will enable next generation engineered systems to be cheaper and more resilient, will enable smarter site



characterisation, stationkeeping solutions, monitoring and late life and end-of-engineered-life management of offshore wind, which will accelerate the economic competitiveness necessary to scale up the UK market [189]. It is also necessary to ensure that the advances that enable this upscaling to meet our needs from the ocean also meet the needs of the ocean to protect ocean health [190]. The industry specific innovations and emerging technologies described above, in turn rely on a range of generic EDT including machine learning, artificial intelligence, internet of things, data classification and utilisation and cybersecurity, self-healing materials and advanced manufacturing processes.

Offshore gas (as well as onshore gas) will also remain significant to the mid-century as the lowest carbon option of fossil fuels and particularly as a transition liquid fuel

for shipping (and aviation) which are more remote from electrification than land-based forms of transport. Many of the emerging technologies being driven by the energy transition will also improve the cost-effectiveness and efficiency of new offshore gas developments and in the more distant future offshore hydrogen production facilities. Notwithstanding other technical challenges facing green hydrogen production onshore or offshore (see for example evidence to UK Government Environmental Audit Committee Inquiry ‘Technological Innovations and Climate Change: Hydrogen’ [191]). An assessment of the UK’s opportunities in integration of offshore wind and offshore hydrogen production, along with R&D, supply and value chain needs to achieve this are presented in a joint report by the ORE Catapult and the Offshore Wind Industry Council [192].

Shipping

The shipping sector is poised to be transformed by emerging and disruptive technologies driven by the need to decarbonise voyages and port activities through future fuels, electrification increased automation, autonomy and machine learning approaches to operate complex systems with reduced risk to human operators, and optimally for greatest efficiency. The UK's Maritime 2050 Strategy [36] sets out a future vision for maritime technology

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“Smart shipping and autonomy will make the sector a cleaner, safer, and more efficient place to work. Technology will create new, highly-skilled, job opportunities - helping to make maritime careers more attractive to a more diverse range of people. Digitalisation, big data analytics, and more robust communications will ensure that ships and ports are better connected and improve business decisions. Effective management of huge data-sets by increasingly sophisticated artificial intelligence will realise significant cost savings and ensure more efficient logistics and supply chains. Distributed manufacturing and 3D printing could lead to a ‘post-container’ society with a correspondingly drastic impact on ship and port design, port location, and the nature of maritime traffic.”

Alternative fuels are essential for the industry to reach emissions reduction targets by 2050 and the transition will have significant implications for vessel and engine design and for production and port infrastructure for bunkering. Electrification has potential for short-haul vessels whereas alternative liquid fuels are imperative for long-haul voyages. The challenge to date is that there is no clear future fuel trajectory and none are desirable. There may be a range of solutions for different tasks (e.g., batteries versus liquid H₂). However, what is clear for long-distance trans global shipping is that current practices are unsustainable and that large ships will need to bunker more than just a few times a year (currently where and whenever marine fuel oil is cheapest). None of the future fuel vectors are ideal and all have serious challenges with safety, security, supply, range, training and disruptive changes in operational modes. An accident in a port with a ship powered by liquid hydrogen, ammonia or a nuclear reactor would have regional to national consequences akin to the worst industrial disasters (e.g. Halifax [193], Bopal [194]; Chernobyl [195], Fukushima [196]). There will need to be a step change in the training and treatment of seafarers entrusted to use and maintain new complex and potentially dangerous equipment.

Seafood

The second largest change in expenditure in the future ocean economy is forecast in aquaculture, with 300% increase in opex from 2018 -2050 and production expected to double in that period, driven by a range of emerging and disruptive technologies (Figure 3). Disruptive technologies that will increasingly offer novel ways to enhance the global seafood production and profitability for aquaculture include [197]: genomic selection (GS) [198] [199] [200], genome editing (GE) [201], information/digital technology [202], recirculating aquaculture systems (RAS) and solar energy [203], offshore farming [204] [205], oral vaccines [206], novel marketing strategies with blockchain, and the integration of different parts of aquaculture with the internet of things (IOT) [207] and others. Development of technological solutions is also required to enable large-scale automated offshore cultivation for the global expansion of seaweed aquaculture [142].

The first of the five UN Global Compact tipping points for a healthy and productive ocean [178] identifies ‘Fully traceable seafood’ as a key priority. A major challenge in the seafood industry is illegal, unreported and unregulated (IUU) fishing, which leads to biodiversity loss, pushes harvests past their natural carrying capacity, and is often associated with forced labour. New technology for greater monitoring and control to prevent IUU, as well as wider industry transparency and traceability across the value chain to prevent negative environmental and social impacts is needed. Example innovations include the ability to genetically tag thousands of fish species and populations and present the data on a publicly accessible map-based interface allowing fish to be traced back to their home area [8], and ‘virtual watch room’ enabled by satellite technologies and automatic identification data (AIS) on board fishing vessels [208].

Emerging sectors

Emerging ocean-based industries and activities can be characterised by the key role played by cutting-edge science and technology in their operations [8]. Enabling technologies may support emergence of new aspects of established sectors to realise the projected upscaling (e.g. floating wind, automated deepwater aquaculture or autonomous ships), or evolution of nascent sectors to a global commercial scale such as the bioeconomy or seabed mining. Effects of emerging and disruptive technologies for acceleration or innovation in established sectors are discussed above. In this section the role of emerging and disruptive technologies on enabling emerging ocean economy sectors is touched on.

Advances in autonomous underwater vehicles (AUVs) in conjunction with machine learning algorithms for automatic object classification (e.g. [209]) have clear applications to identifying seabed resources. Equally such technology has immense potential for observing the impact of mining seabed resources or other human interventions in the oceans – both established and emerging - at a meaningful spatial scale and in a time frame in which adaptations to those interventions could be made if observed impacts are shown to be detrimental. AUVs also have a valuable role in inspection of seafloor assets (cables, pipelines, carbon storage reservoirs; submarine server farms). Considerable value can also be derived from ultra-endurance passive “super-Argo” like floats that collect a greater range of data beyond seawater properties, including sound (pings from downed aircraft; rain at surface) in deep water >4000 m.

Long range AUVs have the potential to carry out a large range of tasks that currently require specialist research or geotechnical vessels – that themselves have limited endurance (~2 months). In the next decades, we can expect to see fully automatic and remotely controlled systems with surface motherships that provide power, communications, edge computational resources and spatial reference points for deep autonomous surveys that will be required to fully map the ocean floor at desired spatial scales that will take many decades at current rates. Clearly such approaches all have scientific, commercial as well as defence values. A future ocean is likely to be so highly instrumented with will be impossible to hide with major geopolitical implications for the deterrence doctrine and post 1960s cold war approaches that continue today.

Summary

Emerging and disruptive technologies to enable development of established and emerging ocean industries and on a scale that would allow them to contribute in a meaningful way to global prosperity, human development, natural resource management and green growth will require considerable research and development (R&D) effort, investment and coherent policy support [8]. In the context of rapid change driven by emerging and disruptive technologies, regulation and governance will struggle to keep up. The world is increasingly multi-polar and has experienced growing difficulty in forging international consensus on global and regional issues key to the ocean environment and ocean industries (and recently even global trade of essential commodities e.g., grain and sunflower oil). At least for the foreseeable future, regulation of ocean activities is expected to continue to be largely sector-driven, with efforts focusing on the integration of emerging ocean industries into existing and fragmented regulatory frameworks [8].

Geopolitics and injustice

The ocean is a lawless place. Despite the existence of laws, rules, and governance mechanisms the ocean is largely un-policed; especially beyond national Exclusive Economic Zones (EEZs). Blue crime, which includes but is not limited to such activity as maritime piracy, the illicit trafficking of people, narcotics, arms or waste by the sea, and environmental crimes such as illegal fishing or pollution are increasingly important elements of ocean governance, security and international politics [210].

The issue has drawn the attention of the UN Security Council in 2019 in a debate where representatives agreed that marine crime was a significant risk to international peace and security. Despite there often being a legal regime designed to combat blue crime, the realities are that these local events can have a global impact. This makes quantifying the true scale of the problem exceedingly difficult. However, the impact of crime even at a geographic distance can have significant impacts globally. From the seizure of vessels through piracy increasing shipping costs to illegal fishing proceeds being used to fund land-based organized crime, to the many cases of people trafficking, modern slavery, and crimes against women and children, that drive migration [210]. Blue crime is a major contributor to transnational organised crime, the impact of this is global, a bigger ocean economy will offer even opportunities for criminals (e.g. [211].

It is difficult to forecast where new geopolitical hotspots might emerge. Whilst it is likely that existing hotspots will be the sites of increased tensions, such as the Horn of Africa, Straits of Hormuz, Gulf of Guinea, South China Sea, Taiwan Straits, the Arctic Maritime Silk Road and the Black Sea, there is the potential for the ocean economy to create new hotspots [212]. In the South China Sea, China continues to exert military influence, engineering barely emergent rocks into islands and military bases in regions where China has no established traditional influence and there are well substantiated competing sovereignty

claims, subverting the implementation of a rule-based order in the region [213]. In the Arctic, the potential of a new Maritime Silk Road linking the Pacific and the Atlantic via the northern coast of Russia has brought closer cooperation between Moscow and Beijing, directly challenging EU/US/Canadian influence in the Polar region in its support for Russia [214] [215]. The Black Sea has become a site of international tensions since the Russian annexation of Crimea in 2014, although there is a long history of geopolitical competition in this region (e.g. [216]). The 2022 Russian invasion of Ukraine has been suggested to stem from the energy resource potential of the region [217]. Geostrategic considerations are also at play - Russia wants its Black Sea Fleet to operate without competition, in a Russian lake [218]. It is not just geostrategic posturing that risks geopolitical conflict; new transnational corporations are building offshore industries that will themselves increase tension within the maritime arena. One such example could be seabed mining.

Seabed mining has always stoked geopolitical tensions [219], especially between developing and developed countries. When a resource is found, the political reality of that sea space is changed, its potential value increases, and difficult issues of sovereignty often emerge [220]. Part of this is due to the multi-dimensional nature of ocean. Seabed mining operates from the surface, the first dimension; through the water column, the second dimension; and into the seabed where the minerals are sited, the third dimension [221] – and water moves, providing a fourth temporal dimension. Each of the spatial dimensions operate within a different legal regime, and each can therefore create competing ownership claims. Any significant discovery beyond national jurisdiction is likely to cause increased geopolitical tensions, much as discoveries close to EEZ boundaries do today [222]. Seabed mining is also likely to become increasingly economically attractive to transnational companies as the global demand for mineral resources to support the transition to a low carbon economy expands [223]. Most exploratory work is being carried out in the deep sea (areas covered with >200 m

depth of seawater), under the International Seabed Authority, and is taking place globally but with a significant focus in the Pacific Ocean [76]. Nonetheless, it is most likely that the preliminary seabed mining will take place in the shallower waters (generally <200 m depth of water) of nations' states' EEZs, depths at which offshore hydrocarbon extraction has been on-going for over 100 years [224], although not at these locations. Mining within EEZs is under the authority of Nation States, however, when new sources of minerals are discovered, they have the potential to cause terrestrial vs. coastal state geopolitical tensions. For example, the initial ocean speculation around manganese nodules during the 1970s by the United States stemmed from the exhaustion of indigenous US supply [225]. Alternative sources involved careful negotiation with nations in other continents who were not necessarily sympathetic to the needs of the US. Extracting oneself from dependence on another State for a particular resource is an attractive driver for governments to invest in offshore industries [226]. However, there may well be unintended consequences of this course of action. In the US case this caused a backlash within the UN from the landlocked African states who worked hard to protect their mineral monopolies against the threat of seabed mining, holding up international law of the sea negotiations through the 1970s and into the 1990s [139]. Ultimately, the ocean economy has an increased potential to create new geopolitical tensions in the near future, compared to traditional sites of geostrategic competition.

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When a resource is found, the political reality of that sea space is changed, its potential value increases, and difficult issues of sovereignty often emerge.



In considering the living resources of the sea, fish do not respect the boundaries of ocean governance as defined by humans, moving from one EEZ to another. The area beyond the EEZ has been left unregulated by the Law of the Sea (UNCLOS) and therefore fisheries legislation, regulation, and treaties have tended to operate as local and regional arrangements. It is in these waters where huge catches of marine life are being taken by fishing vessels that operate at a considerable distance from their “home waters”. In recent years there has been an attempt to protect these waters by extending UNCLOS, rather than an attempt to pass global fisheries conservation legislation that would prove difficult and bring many economic entities into conflict with one another. Therefore, the world's governments have been locked in negotiations over a new legal agreement covering ‘Biodiversity Beyond National Jurisdiction (BBNJ)’. The most recent draft BBNJ Treaty was published in July 2022. If it enters law, this treaty will provide a new governing framework for the exploitation of marine life in the High Seas and on the deep seabed. It would help fill a critical ‘governance gap’ left unaddressed by the Law of the Sea Convention, although the

extent to which the treaty will be able to resolve some of the challenges of global ocean injustice is ambiguous [227] and requires both signature and pro-active compliance by the major international fishing nations to be effective.

Injustices are also evident towards the workforce involved in the ocean economy, and in particular seafarers including seafarers on carriers and fishing boats. In 2013, the Bangladeshi media reported that at least forty fishermen had been bound and thrown into the sea to drown, but despite video evidence of the killings, no prosecutions followed [228]. The covid pandemic resulted in hundreds of thousands of seafarers being trapped at sea for many months. The current Law of the Sea has little to say about the human rights of those at sea and UNCLOS includes no sustained discussion of workers' rights [227]. Fishing crews are vulnerable to abuse because of their physical isolation. At the extreme, the contemporary fishing industry has now become a major global site for forced labour. In the Indian Ocean and the South China Sea, the fishing and aquaculture industries rely extensively on trafficked workers [229]. The fishing

industry in these regions regularly exposes workers to violence and mistreatment, as well as to dangerous and unsanitary working conditions [230]. The emergence of large ‘mother ships’ capable of processing hundreds of thousands of tonnes of fish out at sea means that many fishing boats now visit those vessels to unload rather than going into port themselves, making abuses easier to hide. Even where foreign workers are employed legally, they may not be protected as well as local fishers. For example, the thousand Filipino fishers who work off the coast of Scotland are employed by British companies but earn considerably less than British fishers would for the same work, and often face inferior working conditions [231]. Though some regions are hotspots of abuse and exploitation, these problems have been witnessed throughout the ocean, including within the marine territories of wealthy liberal democracies. Navies that operate in the global ocean are increasingly likely to come across such cases exposing them to transnational organised crime syndicates, hostile local governments (who may turn a blind eye to the abuses), as well as an unclear legal regime.

Governance

In this section, “governance” is understood to mean the ability and/or willingness to respond to the current and emerging threats facing our oceans and to shape the future framework for their sustainable management. As discussed in Section 2, there exist myriad actors that influence both those propositions. This section aims to unpack their role in ocean governance and the interplay between them, to review how the current framework for ocean governance operates, and to present its limitations, particularly in relation to threats of a global scale such as climate change, overfishing and seabed mining.

Who governs the oceans?

The approach to ocean governance is rooted in institutional arrangements and the development of legal and policy frameworks at international, regional and local levels. The most notable such framework is the quasi-global legal regime established by the United Nations Convention on the Law of the Sea [232],⁷ which delimited the maritime zones (internal waters, territorial waters, the contiguous zone, the continental shelf, and the exclusive economic zone [EEZ]) in which States have sovereign rights over the oceans’ exploitable resources. Areas beyond these zones – including the high seas (covering most of the world’s oceans) and the ‘Area’ (defined as the “seabed and ocean floor and subsoil thereof, beyond the limits of national jurisdiction” [UNCLOS, Article 1]) and commonly referred to as ABNJ (‘areas beyond national jurisdiction’) - are thus regarded as global commons that fall outside of any given State’s jurisdiction (UNCLOS, Article 87, 137). Other instruments influencing the governance of the oceans and their assets have also been adopted during the past decades, coupled with the establishment of different sectoral and regional organisations (e.g. Regional Fisheries Organisations, Regional Fisheries Management Organization, International Maritime Organization; the International Seabed Authority, UNCLOS, Article 156) to regulate specific sectors and the threats they could pose to the environment [233][234][235]. Moreover, some of the aforementioned instruments included provisions for the establishment of dispute resolution bodies such as the International Tribunal for the Law of the Sea to ensure compliance with the rules they provide for (UNCLOS, Section 5 of Part XI, Part XV and Annex VI) (UNCLOS, Article 2).

However, it is recognised that ocean governance goes beyond these formal institutions and legal/policy instruments, and literature emphasises the role which the processes that operate between and within various actors in the ocean economy play in steering these institutions and instruments [236][237][238]. This includes the interplay between individuals who work within such institutions and shape their capacities to make decisions, implement them and influence government behaviour (Haas et al. 2022), as well as between civil society, local communities and various industries [239][240][241]. This challenges the traditional State-centric approach to ocean governance, strongly rooted in the concept of State sovereignty, but has simultaneously resulted in a complex and fragmented framework for ocean governance marked with a multitude of actors and instruments acting for a variety of often conflicting services and uses amidst an increasing dominance of transnational corporations [242][243][244].

How effective is the current framework for ocean governance?

Various shortcomings in the current ocean governance framework which led to evidence-supported negative outcomes at different levels are reported in the literature. These are best understood when weighed against the growing emphasis in the definitions of the ocean economy on the ‘triple bottom line objectives’ of environmental sustainability, economic growth and social equity, and the multi-dimensional and interconnected role that the ocean plays in it – i.e. a blue economy. The mismatch stems from the unsuitability of the current governance framework for our ocean with its perception as a complex global system of intertwined socio-ecological dynamics involving a multitude of influential actors [245].

As discussed in Section 2, the fluidity of the ocean economy concept has been generally positively viewed in the academic literature which disfavoured attempts to develop an all-encompassing universal definition for it. The advantage sought is to ensure that States and other actors can devise contextualised ocean economies that respond to specific local/regional needs. Indeed, many actors have proceeded with “enacting”/“actioning” the ocean economy, as reflected in the adoption of the instruments and establishment of the different sectoral and regional organisations mentioned above. However, the potential conflicting tensions of such sectoral and/or localised policies which reflect the desire to move towards specific objectives presents potential trade-offs in the ocean economy, including: jobs creation/economic growth and development vs livelihoods/environmental protection; and/or emerging assets/resources vs competition for assets/resources). Consequently, the governance aspect of the ocean economy becomes incoherent and inefficient [243][246][247][248][249][250]. This is aggravated by complexities in the design, development and implementation of such policies, including conflicts of interest amongst various actors influencing them, and disjointed communication between governing bodies [243][251].

The current framework for ocean governance is also lacking in that it fails to adequately address pressing challenges facing our oceans, most notably the impacts of climate change on the various components of the ocean economy, the over exploitation of finite resources many of which are endangered, the emergence of new technologies, and particularly poor governance of activities beyond national jurisdictions [252][253][254]. With regards to climate change, the challenge stems from international climate law and the law of the sea have developed as two largely separate legal regimes that need to be reconciled in the way the law of the sea is interpreted, developed and applied [255][256][257]; whereas existing instruments would need to be updated to apply to new technologies such as the use of autonomous maritime vessels [257].

Another key aspect shaping ocean governance is the aptitude of dispute resolution bodies to enforce the rules of international law enshrined in existing instruments as well as customary international law. In this regard, State practice suggests a generally high degree of compliance with the provisions contained in UNCLOS [257] and, where conflicts arise, an overwhelming implementation by developed and developing States of the majority of decisions rendered by UNCLOS dispute settlement bodies [258]. However, on the one hand, the high levels of voluntary compliance with UNCLOS should be analysed with caution, given that the Convention is widely viewed as an “umbrella” treaty which establishes the broad framework governing ocean-based activities rather than providing detailed substantive rules governing the exercise of those activities (which are covered by the sector-focused instruments mentioned above). On the other hand, the positive record for the implementation of judgements and orders under the auspices of UNCLOS is limited by a general scepticism around the lack of effective means to enforce many of the duties the Convention stipulates [259] due to inherent limitations of public international law. In particular, and given that the jurisdiction of international courts/tribunals is “ultimately always founded on consent”, the enforcement of the law of the sea which primarily attempts to reconcile the competing tensions inherent in the two central principles of the freedom of the high seas and the exclusive jurisdiction of the flag state is regarded as one of its “weak points” [257].

Therefore, despite a noticeable move from the traditional State-centric approach to ocean governance towards a global approach that takes into account the embeddedness of the ocean and associated actors in the wider planetary system [260], compliance with rules of international environmental law is difficult to predict

given its continuous dependence on the concept of State sovereignty [261]. This results in poor outcomes for marine ecosystems from overfishing [262] and marine pollution [263], as well as wider businesses and society⁸ [264].

In light of the above, the shortcomings of the current ocean governance framework are three-fold. (1) Current frameworks are ineffective and do not provide adequate protection to ensure ocean sustainability, most notably with regards to the governance of ABNJ [257][244]; (2) due to the emergence of new technologies and challenges, gaps were identified in the instruments governing ocean-based activities that are no longer fit-for-purpose and require updating [257][243][235]; and (3) as we continue to witness a proliferation of actors influencing the ocean economy aiming for potentially competing objectives, the risk of reinforcing inequalities between those involved in decision-making is becoming more and more prominent [235].

Looking ahead

Thirty-five years on from the World Commission on Environment and Development’s early recognition of the “fundamental unity” of our oceans and the interconnectedness of its resources and their uses [265], recent literature heavily relied on these features as it renewed the urgency to reform existing governance structures and systems to address ongoing and emerging challenges facing our oceans and those who depend on it. It highlighted the need to move away from the dichotomy under the existing framework for law of the sea - according to which the ocean is split between areas that fall under State jurisdiction and ABNJ - toward an integrated approach according to which the ocean is perceived as a global commons that is shared and governed by a multitude of actors and users [244][243][252][266]. Improved scientific evidence (and awareness of limitations in knowledge/ uncertainties) of the complexity of ocean systems and human activities’ impact(s) on them is being matched with a growing recognition of the intertwined nature of the various actors/bodies shaping the framework for ocean governance and the importance for it to reach out to all actors involved in ocean protection and stewardship [235]. There is therefore a stronger need for clearer communication around the different ways in which the ocean and blue economy is conceived and understood by different actors to help identify areas of future potential conflict, as well as those on which consensus-based, diplomatic approaches might be built [19]. Moreover, authors called for stronger accountability processes, and transparency and participation mechanisms to be part of a global model for ocean governance that would allow for a response to the global challenges facing our oceans which is fair and equitable for all [235]; which is supplemented by propositions for the establishment of a “powerful” overarching global Authority to overlook such a global governance system [227].

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need to move away from the dichotomy under the existing framework for law of the sea - according to which the ocean is split between areas that fall under State jurisdiction and ABNJ - toward an integrated approach according to which the ocean is perceived as a global commons that is shared and governed by a multitude of actors and users

⁷ UNGA, Convention on the Law of the Sea (adopted 10 December 1982, entered into force 16 November 1994) 1883 UNTS 397.

⁸ From a social equity perspective, issues surrounding compliance with environmental duties, traditionally only invoked in inter-State dispute-resolution forums, are increasingly recognised as instrumental hurdles for ensuring fairness and justice for all.

4. Uncertainties and shocks

An important lesson from the COVID-19 pandemic is our recognition that the ocean economy (and its components) is also susceptible to being negatively impacted by less predictable external risks which need to be considered when devising long-term strategies around it.

The outbreak of the pandemic posed significant challenges to the shipping industry's ability to ensure the global movement of goods, including medical supplies, personal protective equipment and food. These impacts were felt far beyond the traditional stakeholders in the industry such as shipping, ports and seafarers. Indeed lockdowns in Shanghai and other ports resulting from China's covid elimination strategies continued to send logistic shockwaves around the globe well beyond the lockdown period. As highlighted by UNCTAD, "the sector works as a transmission channel that sends shockwaves across supply chains and regions" [267]. A coordinated response covering different aspects was therefore necessary in order to tackle the risk of disruption of links of supply chains and trade flows, and these included operational adjustments, financial/ economic adjustments, sanitary protocols & processes, and adjustments to working practices and organizational aspects [267].

The unprovoked 2022 Russian invasion of Ukraine has greatly impacted the global economy already weakened by the covid pandemic, with sanctions and only partial energy restrictions on Russian supplies resulting in energy-price driven inflation. Europe's dependence on Russian gas has been brought sharply into focus, prompting many countries to reprioritise domestic energy security, which in cases will be via ocean-based energy whether hydrocarbons or wind. Attacks on Ukrainian infrastructure including ports, waterways and assertion of Russian naval superiority in the Black Sea has stopped the export of Ukrainian grain, and sunflower oil. The Turkish/NATO closure of the Bosphorous subsequently halted all exports by ship out of the region, demonstrating that maritime chokepoint risks are food security risks.

Aside from unforeseen global pandemics and conflicts, the future of the global ocean economy, and its transition towards a blue economy, can be seen to pivot on five key uncertainties:

1. The manner in which tensions between sustainability and growth are resolved.
2. Speed of technological development.
3. Rate of decarbonisation.
4. Emergence of new markets and commodities.
5. Cumulative impact of anthropogenic activity.

As discussed at the beginning of this document, the concept of the blue economy is rooted in the discourse of sustainability, with both the UN and the World Bank placing it at the forefront of their definitions. However, the achievement of sustainability requires cooperation amongst stakeholders across borders and jurisdictions, including an agreement of how to manage at times competing interests between economic growth and protection of vulnerable spaces [19][268]. Thus one of the greatest uncertainties over achieving the shift from the current grey ocean economy to a blue economy in the future is the degree to which collective values and priorities are both clearly identified and adhered to. A breakdown in consensus would lead to different patterns of exploitation, use and impact. This could effectively redirect modes and methods of engagement with the world's oceans and seas in a number of radically different ways, from restriction of access to pursuit of unsustainable extraction practices for rapid economic gain.

The rate of technological development, and rate at which adoption of new and emergent technologies occurs, will have a profound role in shaping the ocean economy to the mid-21st century. This has the potential to shape not only the form of activities taking place on and in the world's oceans and seas, but also the infrastructure to support them and the legal systems to manage them. The clearest examples of this at present are increasing levels of automation in shipping and sensing, as well

as developments in renewable energy. With increased autonomy in shipping and ocean observation comes the opportunity to move goods, extract resources as well as monitor and observe the ocean in very different ways to current modes of operation. This has the potential to disrupt both practice and markets in a number of different ways; with cargoes rerouted more rapidly in response to fluctuating prices, through to improved observation and enforcement of legislation. Developments in offshore energy infrastructure may also see a change in the use of ocean space, with the potential for larger and greater numbers of 'energy islands', creating new physical spaces in our oceans and seas to enable conversion and storage of power.

The rate and commitment to decarbonisation, and from this the use of offshore renewables, is another area of uncertainty. The 2007-8 financial crisis had a significant impact on the growth of the renewables sector, with considerable differences seen across the globe with regards to how this played out [269]. In the US, investment in the renewables sector shrank rapidly, while in parts of Europe it continued along previous trajectories and in China it led to the government taking on a more direct role. At the time of writing the offshore renewable sector is rapidly expanding, in response both to a push to reach Net Zero as well as for countries to become more energy independent in light of rapid price fluctuations driven by the



The rate of technological development, and rate at which adoption of new and emergent technologies occurs, will have a profound role in shaping the ocean economy to the mid-21st century.



2022 Russian invasion of Ukraine. The shape and nature of the ocean economy is thus highly connected to broader global events. This has also been borne out in the recent Covid-19 pandemic, where impacts were felt across all aspects of society from transportation and shipping to new patterns in tourism – all of which heavily impact on the nature and shape of the ocean economy.

The emergence of new markets and commodities stands as another area of uncertainty. Seabed mining remains a controversial topic, but one which could radically change areas of operation and potential points of conflict. So too could an increased focus on extraction of genetic material. Such shifts in scale of operation would create new resource hotspots, and potential tensions over access to resources and impact.

As activities in the ocean scale up so too does the potential for unrecognised cumulative impacts on ocean health, and thus human health and wellbeing. The interconnected nature of ocean



the degree to which sustainability is seen to be at the heart of the ocean economy, and thus its transition to a blue economy, and consensus as to what this means, which will have the biggest impact on the future of the ocean economy. It is this basis in shared values that has the potential to mitigate the potential impact of shocks (economic, political, territorial, health) and our responses to them.

ecosystems creates challenges for accurate prediction of large up-scaling of human activity. Overfishing of Western Baltic cod remains one of the best examples of this [270]. While the gradual impact was realised, the impact of crossing the tipping point was not well understood until the threshold had been crossed. Following this, routes to recovery were also not well understood. Our ability to both identify these tipping points and act with sufficient speed and coordination to mitigate them is thus a critical uncertainty.

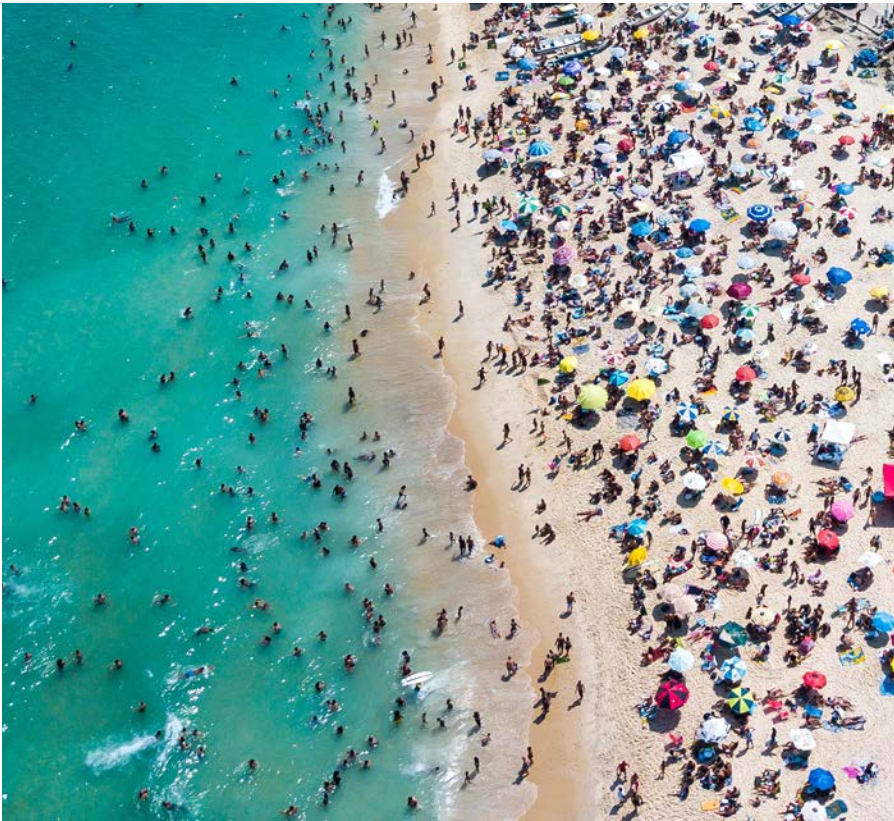
Within all of the above, it is the first point, the degree to which sustainability is seen to be at the heart of the ocean economy, and thus its transition to a blue economy, and consensus as to what this means, which will have the biggest impact on the future of the ocean economy. It is this basis in shared values that has the potential to mitigate the potential impact of shocks (economic, political, territorial, health) and our responses to them.

5. Strategic implications

As outlined in the Introduction of this report “If the global ocean economy were compared to a national economy it would be the seventh largest in the world, and the ocean as an economic entity would be a member of the G7” [1]. The strategic implications of the future ocean economy are hence of ‘major-power’ status, although more complex as the ocean and ocean economy interfaces with and impacts on countries and populations globally.

The ocean economy currently contributes something between US\$1.2 tr and US\$2.5 tr per annum to the global economy, depending on the source and what is captured in the calculation (e.g. [8] [48] [77]); providing employment for some 40 m people [8], and food, energy and other resources to nearly every one of us. The oceans enable global trade and transport, creates markets for marine and maritime manufacturing, technology and service industries, supports tourism and hosts recreation and leisure activities. The oceans also enable the projection of power by both friendly and hostile nations and other actors, and are culturally significant for communities worldwide. Looking to the mid-21st century, what is clear is that much greater use of the oceans is inevitable if we are to meet the demands of a 10 billion+ global population. However, aside from the tangible and intangible anthropogenic uses of the oceans, the oceans provide vital services to planetary health, producing oxygen, absorbing CO₂ and heat, regulating the climate and ultimately sustaining life on earth as we know it, and ocean health is under grave threat from our current strategies of engagement in the oceans.

Future uses of the ocean, and the scale of use, must be underpinned by a recognition of the limits of ocean resources and the vulnerability of its ecosystems to the impacts of human activities. As presented in the Introduction of this report, replication in the oceans of philosophies and practices [strategies] borrowed or evolved from



industrialised land agriculture, mining and urbanisation is occurring and continuation will be catastrophic. Consequently, our ocean futures stand at a bifurcation; a challenging route to sustainable use or a tragic pathway leading to accelerated violation of planetary boundaries. Strategies developed for engaging with the world’s oceans and seas and strategies to underpin the development of the ocean economy will determine the path taken.

Strategies for engaging with the ocean and developing the future ocean economy must weigh the tensions of meeting the needs (or demands) of an increasing and in many places, increasingly wealthy, global population, and the drive for growth of the corporate sector and governments; against the needs of the ocean. The resolution of these tensions underpins the concept of the blue economy; that responsible use and stewardship of the oceans can provide economic growth – and in particular to reduce inequalities, reduce world

poverty, and support a sustainable ocean environment. Strategies for the future ocean economy incorporating adaptability to deal with the five uncertainties outlined in Section 4 will perhaps afford the greatest potential for achievement of resolution of those tensions.

Competition for, as well as oversight and control of, marine space is likely to be of increasing significance in coming years. This will impact on international politics in terms of consensus building, monitoring and enforcement, as well as potentially providing points for friction and disagreement. There will be clear winners in the form of those countries with larger expanses of relatively shallow waters on the continental shelves; well suited to generation of power from offshore renewables, as well as the economic and technological infrastructure to support these activities. The 2022 Russian invasion of Ukraine has highlighted the pivotal role that maritime infrastructure plays in enabling global



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supply chains and the broader economy, and how rapidly these can be disrupted. Looking to the mid-century sees increased need to be able to monitor and enforce legal frameworks as well as protect assets, as pressures on space and multiple uses of space increase. Emerging and disruptive technologies have a critical role to play, to achieve extended monitoring and response capabilities to areas further offshore and those traditionally considered remote. Equally, emerging technologies present a host of threats to the ocean economy for example through breaches of cybersecurity on crewed or uncrewed vessels and offshore assets, to sabotage of subsea cables by remotely detonated equipment or autonomous vehicles, to dystopian visions of swarms of autonomous bots in targeted attacks on ocean-based assets or the environment. Strategies developed now that underpin the future ocean economy have the potential to either reduce or exacerbate existing tensions and

inequalities. Small island developing states (SIDS) are particularly vulnerable under the current strategies driving the ocean economy as well as to the consequences of climate change, in part driven by the ocean economy. SIDS are particular innovators of the blue economy and offer insight, expertise and opportunities in shaping the wider ocean economy through greater engagement, co-creation and collaboration.

Considering the ocean economy as encompassing all economic activities connected to the ocean, and the blue economy as a socially constructed concept embracing the aspiration for sustainable use of the ocean and a nascent subset of the ocean economy, the most significant strategic implication looking out to mid-century is the imperative to shift the ocean economy from grey to blue, to avert major climate change and irreversible damage to marine ecosystems, environments and wider society.

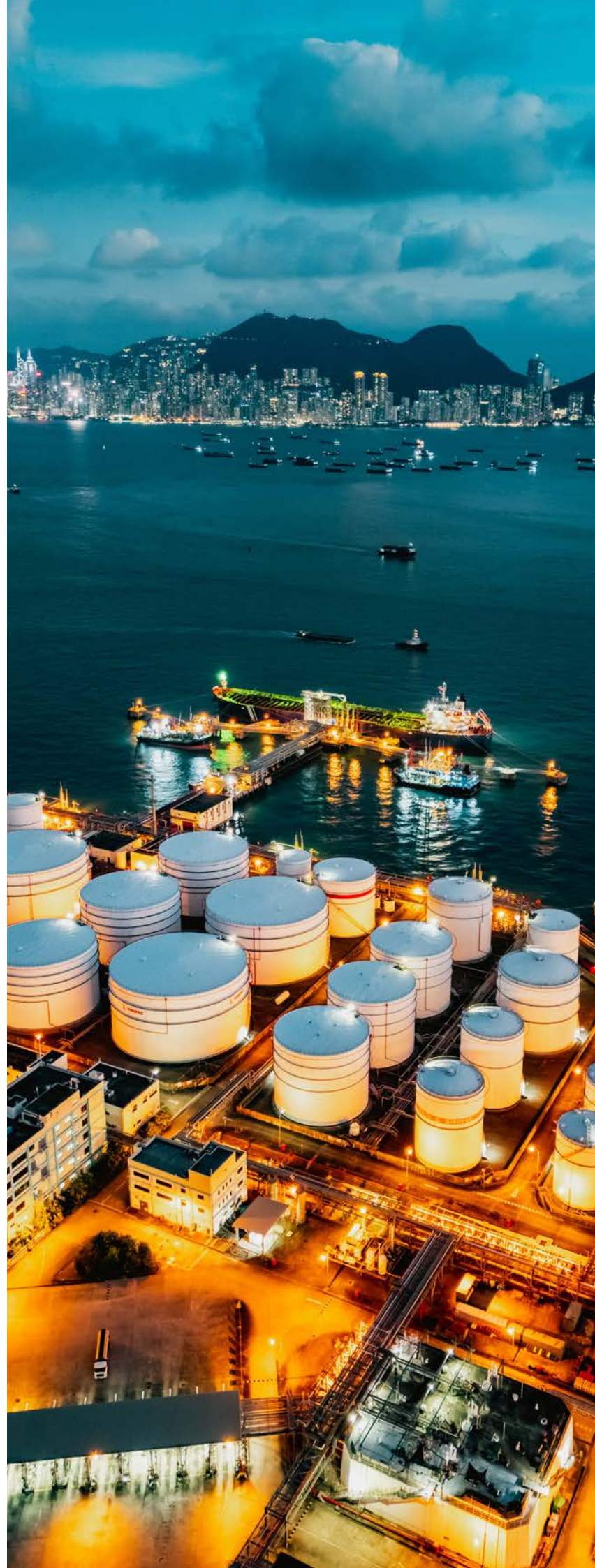
6. Conclusions

This report sets out a snapshot of the current ocean economy – its components, applications and impact on the natural environment, along with identification of influential actors and geopolitical hotspots.

We deliberately use the term ocean economy rather than the oft-used “blue economy” because many of the current activities in the oceans and coastal seas are unsustainable. With that context and the backdrop of global population growth from 8 bn to 9 bn and doubling of the world economy by 2050, projections for the ocean economy to the mid-21st century are proposed – considering shifting foci and drivers for change, effects of climate change, emerging & disruptive technologies, geopolitics & injustice, and governance.

It is clear that the ocean economy has major-power status with a current value equivalent to 2.5% of global GDP, which places it 7th in the list of largest national economies globally. The ocean economy is dominated by energy and food production and shipping, although more than 25 ocean economy sectors have been identified from the literature, including submarine cables that carry 97% of internet traffic globally or bring energy to shore from the increasing number of offshore wind farms, port activities, marine equipment and construction, hi-tech (robotics, autonomy & AI), biotechnology, cruise, leisure and coastal tourism, coastal protection, desalination, salt production and more (see Figure 1). The corporate sector, unsurprisingly, is the most influential actor in the ocean economy, and by association, the governments of countries that either own state-controlled dominant corporations or host the headquarters of privately owned or publicly listed dominant corporations. The so-called Ocean 100, the 100 largest corporations operating in the ocean economy, account for 60% of total revenues, with 9 of the top 10 largest companies in the ocean economy in the oil and gas industry.

Looking out to the mid-century, greater use of the ocean is inevitable to meet the needs (or demands) of an increasing and increasingly wealthy global population aspiring to western levels of resource consumption. The ocean economy of the mid-century will be determined by strategies developed and decisions made now. Here we consider alternative ocean economy futures through six scenarios of the projected, probable, plausible, possible, preposterous, and the preferable.



The projected future

Considering the projected future as the default extrapolated business-as-usual future, the ocean economy will continue to be dominated by hydrocarbon exploitation, over-fishing, unsustainable aquaculture practices, terrestrial pollution and shipping in its current form that is responsible for carbon emissions equivalent to that of Japan or Germany (see Section 2).

This future will be catastrophic for the environment and (continue to) perpetrate human rights abuses, supporting inequality and injustice. A business-as-usual future

ocean economy will continue to be based on unsustainable and extractive philosophies and practices borrowed or evolved from industrialised land agriculture, mining and urbanisation, driven by corporate and government desire for growth, and will be accompanied by environmental and social injustices witnessed currently in the ocean economy and across the rest of the global economy.

The business-as-usual future ocean economy will be controlled by the corporate sector with geographical centres of power in Saudi Arabia, Iran, China, South Korea, Brazil, Mexico and the US. The most influential corporate actors have been coined ‘keystone companies’ derived from

the term ‘keystone species’ in an ecosystem, which conceptualised in the age of the Anthropocene are those companies that are going to shape our future. Continued adoption of current practices to the mid-century will lead to catastrophic climate change and environmental tipping points that will ultimately destroy the natural capital on which the ocean economy - and humanity - depends. The projected default business-as-usual future is the choice of a tragic pathway leading to accelerated violation of planetary boundaries.



The probable future

The probable future is based on current trends, and that considered by forecasters as likely to happen.

This future is described in Section 3, and it is proposed that it will be shaped by (1) evolution and upscaling of established industries, with energy, food and shipping continuing to dominate; (2) emergence of new commercial-scale and globally significant industries, including offshore wind, marine biotech and biofuels, carbon storage, ocean monitoring, control & surveillance; and (3) emergence of demonstrator or fledging industries, such as seabed mining and BECCS.

Considering ‘the big 3’ of energy, food and shipping, offshore energy will continue to dominate the ocean economy although with a significant shift of investment to offshore wind, which may provide up to 13% of global electricity by 2050. While the oil and

gas sector is forecast to decline to mid-century – albeit only from 2035 onwards – it still remains a dominant component, providing > 70% of the offshore energy supply in 2050. Despite the acceleration of offshore wind, the Global Wind Energy Council has warned that the current rate of growth is insufficient to reach the Paris Agreement targets or net zero by 2050. Marine seafood production is forecast to grow by 25% to 2050, principally driven by aquaculture, which is forecast to double, to yield a similar volume to wild capture. Slight reductions in wild capture are forecast, driven by effects of climate change and overfishing on fish stocks, however, forecast catch sizes still exceed the maximum sustainable yield for capture fisheries. Shipping volume is forecast to increase 35% to the mid-century, although showing a marked slowing down after years of faster-than-GDP growth. Emissions reduction targets set by the IMO aim to

reduce the contribution of global shipping to climate change despite the continued growth in volume of shipping. Considering geographical shifts of power, China is forecast to become the dominant investor in the ocean economy in 2050, from a current share of 10% of global capex to > 25%; while capex from the Middle East and North Africa region falls from the currently dominating position of 25% to 7%. Europe will retain a relatively strong position, growing from 11% to 14% of share of global capex in the ocean economy (see Figure 5).

The probable future, based on current trends, will see some shifts in the dominant ocean sectors in an effort to move towards necessary decarbonisation targets, in conjunction with upscaling to meet increasing global demand. However, the **evidence suggests that the pace of change is insufficient to meet decarbonisation and broader sustainability targets by mid-century.**

The plausible future

A plausible future is defined by current knowledge and what could happen, and may result from responsible use of best current knowledge, or conversely irresponsible and unethical application of current technology for short term commercial gain of the most powerful actors.

Knowledge in this context is taken as scientific evidence, indigenous or lived experience, and knowledge embedded into current technology, economic and regulatory frameworks.

A plausible, sustainable and just future could be realised through the global transition of the ocean economy to a ‘blue’ economy, meaning one that is economically viable but also environmentally sustainable, culturally appropriate and focused on social equity and well-being. In contrast, the current ocean economy is ‘grey’, in which many activities, significantly the most dominant,

are based on unsustainable and unjust practices. A plausible blue ocean economy would see corporations and governments divert investment from unsustainable practices, such as oil and gas extraction and over fishing and instead make meaningful investment into sustainable sectors, such as renewable offshore energy production (e.g., wind, tidal, H₂ generation), responsible live-catch and aquaculture and future fuels for shipping. Within this scenario and shift of investment, it is necessary to ensure that decisions made about how we go to the oceans to meet our needs consider the needs of the ocean – that ultimately sustains those activities and much more. It is also essential to consider how these interventions at scale affect the traditional users of the ocean, for example fisher people, whether by displacing their activities due to exclusion zones around new developments or via marine protected areas created to offset environmental damage from a new development, that are defined without local consultation and knowledge.

An unsustainable and unjust future may equally be realised based on current knowledge and would include continued, or accelerated, oil and gas extraction, continued over-fishing and weak emissions reduction ambitions for global shipping. Poor oversight or enforcement of seafarer welfare, and continued blue crime, such as illegal fishing, trafficking and piracy. Fledging industries such as seabed mining would be permitted without the evidence base, regulation or protection for the environment, equitable distribution of royalties or onus on the licencees of mineral-rich seabeds to manage and restore the potential consequences.

It is noted that the concentration of power over the ocean economy in the hands of a limited number of mega-corporations and governments affords both threats and opportunities for achieving a sustainable and just future blue economy.

The possible future

A possible future is taken here as based on future knowledge and what might happen, and as with the plausible future could lead to positive or negative change and outcomes.

Considering a positive outlook, should the science and technology for increasingly efficient and effective design, installation, operation and intervention of offshore infrastructure at scale be developed, a reduction in cost of deployment and management would increase the rate of increase of capacity. For example, sustainable and responsible development of offshore wind or aquaculture will help achieve net zero targets and reduce overfishing. Convergence on a future liquid fuel and development of the processes, infrastructure (including the massive upscaling of renewable energy to manufacture green hydrogen) and regulations for manufacture, transport and storage at scale would enable shipping (and potentially aerospace and automotive

industries) to decarbonise. New science and technology to enable partnership with the oceans to absorb or store increasing amounts of waste, e.g. through carbon storage beneath the seabed or nature based solutions such as mangrove and seaweed forests or carbon dioxide reduction geoengineering approaches, could enable negative carbon emissions. Development of technology of sufficient reliability and endurance to monitor ocean health at scale and in near-real time would enable decisions about future ocean interventions to be informed by evidence of the effect of previous interventions enabling increasingly responsible decision making and solutions.

In contrast to the above, future knowledge may be mis-used for self interested, short-term financial gain of a few powerful actors at the expense of short and long term human and planetary wellbeing. New science and technology may be developed that could exploit the natural capital of the ocean more efficiently, increasing the economic incentive for operations, even if the

resulting actions were environmentally or socially detrimental, for example for greater hydrocarbon exploitation, seabed mining, or more efficient wild capture fisheries. A possible future where irresponsible strategies and decisions are enabled would lead to catastrophic climate change and environmental tipping points that will ultimately destroy the natural capital on which the ocean economy - and humanity – depends. An irresponsible possible future is equivalent to the dystopian business-as-usual projected future, potentially worse – accelerated to greater lows by more powerful future technology and misuse of future knowledge. As also outlined for the business-as-usual projected future, an irresponsible possible future would be a tragic pathway leading to accelerated violation of planetary boundaries, along with violation of human rights and perpetuating and amplifying existing inequality and injustice.

The preposterous future

The preposterous future is considered an impossible future, a situation that will never happen. Beyond the axiom to never say never it is perhaps easier to imagine a preposterously positive future – a nirvana rather than a nightmare scenario.

Global peace and justice for all, no poverty and abundance for all without negative impacts on the environment, a collaborative

co-existence of humanity and nature in which both thrive. An ocean economy supporting each of these ends, juxtaposed with a global economy working towards the same ends, would create such a nirvana scenario.

By contrast, residents and leaders of cities or countries suddenly thrown into turmoil of civil unrest or war, or struck down and isolated by a global pandemic could affirm that what may seem a preposterous nightmare scenario

can eventuate. Similarly in the oceans, acceleration of the bleakest views of the irresponsible possible future could lead to the nightmare scenario of multiple environmental tipping points, with catastrophic global warming, rapid sea level rise and collapse of the food chain within a human lifetime.

The preferable future

The preferable future is defined by value judgements of what should happen. While this may be subjective for a short-term outlook, with different actors having different priorities and preferences, for the long-term outlook the preferable future is unequivocal – and requires an ocean (and global) economy that enables a healthy ocean that can support us.

This must include the transition of the current ‘grey’ ocean economy to a truly blue economy – one that is economically viable, environmentally sustainable, culturally appropriate and focused on social equity and well-being.

The preferable future ocean economy will be driven by the imperative that growth is equitable, inclusive and just; the implementation of effective nature-based solutions that embrace the value of the natural capital of the ocean; that global demand is met while simultaneously safeguarding the global environment, biosphere, human life and property; and of sustainable use of resources, that provide opportunities for future generations. The preferable future ocean economy will be shaped and led by a community of thought leaders to deliver the oceans-based solutions we need to meet our collective mid-21st Century zero-carbon, zero-pollution commitments, in light of increasing resource demands on the oceans. A preferable future ocean economy will be based on principles that aspire to collaborative, fair and sustainable use of the ocean, and recognise the delicate balance between the ambitions to develop ocean infrastructure for energy and resources whilst nurturing and improving marine environments; rejuvenation of marine environments whilst ensuring food security and dependable work; encouraging the freedoms of peoples whilst devising enforceable ocean policy; and empowering communities to realise their role as custodians of future oceans.

The preferable future is a challenging route to sustainable use, and one that diverts us from a tragic pathway leading to accelerated violation of planetary boundaries and destruction of the natural capital on which the ocean economy and humanity depends. The science and evidence are plentiful (as demonstrated in this report) to know what strategies and decisions need to be made to realise a preferable ocean future. It is equally clear that strategies and decisions made now will determine the pathway of the actual realised future in the mid-century.



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In the preferable future global demand is met while simultaneously safeguarding the global environment, biosphere, human life and property; and of sustainable use of resources, that provide opportunities for future generations

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“From Grey to Blue: An Ocean Economy fit for the Future”

sets out a snapshot of the current ocean economy – its components, applications and impact on the natural environment, along with identification of influential actors and geopolitical hotspots. projections for the ocean economy to the mid-21st century are proposed – considering shifting foci and drivers for change, effects of climate change, emerging & disruptive technologies, geopolitics & injustice, and governance.

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