A Sustainable Ocean Economy for 2050: Approximating Its Benefits and Costs

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Abbreviations

BAU	Business-as-usual
B-C	Benefit-cost
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
FCR	Feed conversion ratio
FOLU	Food and Land Use Coalition
GDP	Gross domestic product
GHG	Greenhouse gas
Gt	Gigatonne
GW	Gigawatt
IEA	International Energy Agency
IMO	International Maritime Organization
LCOE	Levelised cost of electricity
mmt	Million metric tonnes
Mt.	Megatonne
MW	Megawatt
MWh	Megawatt-hour
N_2O	Nitrous oxide
NREL	National Renewable Energy Laboratory
PV	Photovoltaic
R&D	Research and development
ROI	Return on investment
SCC	Social cost of carbon
SDG	Sustainable Development Goal
TWh	Terawatt hour
WACC	Weighted average of capital costs

1 Executive Summary

The ocean and its resources provide key ecosystem services and benefits that are crucial for human well-being and the prosperity of the global economy, but these services are at risk. The ocean's wide range of ecosystem services (including food, energy, recreational/ cultural services and trading/transport routes) is vital for the well-being of society. However, climate change, overfishing, pollution and a loss of biodiversity and coastal ecosystems are eroding the ability of the ocean to sustain livelihoods and prosperity.

Taking action to protect these ocean-based ecosystems and ensuring the environmental sustainability of ocean-based activities will produce health, environmental and ecological, and economic and social benefits to people and the planet. A key question for policymakers and funding agencies is how these benefits compare with the costs. This analysis aims to answer the question by building on several existing analyses and reports, including *The Ocean as a Solution to Climate Change: Five Opportunities for Action* (Hoegh-Guldberg et al. 2019) and *The Global Consultation Report of the Food and Land Use Coalition* (FOLU 2019).

Using both quantitative and qualitative methods, it demonstrates that ocean-based investments yield benefits to society in the long term, and these benefits substantially outweigh the costs.

This analysis is the first attempt to estimate the global net benefit and the B-C ratio over a 30-year time horizon (2020–2050) from implementing sustainable ocean-based interventions. It indicates the scale of benefits compared to the costs by focusing on four ocean-based policy interventions: conserving and restoring mangrove habitats, scaling up offshore wind production, decarbonising the international shipping sector and increasing the production of sustainably sourced ocean-based proteins (to ensure a healthy, balanced human diet by 2050). These interventions would contribute to global efforts to reduce greenhouse gas (GHG) emissions and move countries towards their Sustainable Development Goals and targets (Hoegh-Guldberg et al. 2019).

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For each intervention area, the impact to reach a sustainable transformation pathway by 2050 is measured relative to a business-as-usual scenario. A B-C ratio is developed by dividing the present value of benefits in 2050 by the present value of costs. The categories of benefits assessed include health (such as a reduction in mortality and morbidity), environmental and ecological (such as benefits from higher biodiversity, reduced water usage and land-based conflicts, and coastal protection) and economic and social (such as increased business revenues, household income, jobs and food security). The categories of costs include costs to business (such as capital investments and increases in operational costs), costs to government (such as costs of regulations, research and development [R&D] expenditures, enforcement and monitoring costs) and costs to households (such as opportunity costs of forgone activities)**.** The benefit and cost estimates are partial estimates; impacts are monetarily quantified where possible and are qualitatively described when quantifiable data are absent.

2 Key Findings

The overall rate of return on investment (ROI) can be very high, with sustainable ocean-based investments yielding benefits at least five times greater than the costs. When assessing individual interventions, the average economic B-C ratio range between 3-to-1 and 12-to-1, and in some cases even higher. The B-C ratios were similar to key health interventions in developed and developing countries.[1] Specifically, investing $2.0–3.7 trillion globally across the four areas from 2020 to 2050 would generate $8.2–22.8 trillion in net benefits (average $15.5 trillion), implying a rate of ROI of 400–615%. The B-C ratios vary across sectors and interventions (Table 18.1; Fig. 18.1) as follows:

Table 18.1 Summary of benefit-cost ratios for the four action areas in 2050

Action	Average benefit:cost ratio
Conserve and restore mangroves[a]	3:1
Decarbonise international shipping[b]	4:1
Increase production of sustainably sourced ocean-based proteins	10:1
Scale up offshore energy production[c]	12:1

Notes:

[a] *The ratio presented is the combined ratio for mangrove conservation and restoration. When assessing specific interventions, the benefit-cost ratio for conservation is estimated to be 88-to-1 and for restoration is 2-to-1*

[b] *The benefit-cost ratio estimated for decarbonising international shipping ranges from 2:1 to 5:1*

[c] *The benefit-cost ratio estimated for scaling up of global offshore wind production ranges from 2:1 to 17:1*

Source: Authors' calculations

- **Every $1 invested in mangrove conservation and restoration generates a benefit of $3.** When assessing specific interventions, the B-C ratio for conservation is 88-to-1 and for restoration is 2-to-1. Three factors drive the difference in the B-C ratios: the higher cost of mangrove restoration (due to seeding and replanting), low survival rates following restoration and the lag in accrual of benefits from restoration. The total value of net benefits for mangrove restoration over 30 years ($97–150 billion) is higher than for conservation ($48–96 billion) because we assume the area of mangroves restored is 10 times that of the area conserved.[2]
- **Every $1 invested in scaling up global offshore wind production generates a benefit estimated at $2–17**, depending on the cost of offshore energy production and transmission and the types of generation that would be displaced.[3] The value of the ROI will increase as the costs for offshore wind energy generation fall because of improvement in technologies and actions to reduce integration costs.
- **Every $1 invested in decarbonising international shipping and reducing emissions to net zero is estimated to generate a return of $2–5.** The analysis assumed the significant capital expenditure to switch to zero-carbon emissions will happen after 2030, and limiting the analy-

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[1] For example, the B-C ratio for double measles immunisation in Canada is estimated to be 2-to-1 to 4-to-1; for influenza vaccination in Italy, it is estimated at 4-to-1 to 12-to-1; for the meningitis prevention program in the Philippines, it is 8.4-to-1; and for the universal *Haemophilus influenzae* type B vaccination (starting at 2 months) in the United States, it is 3.4-to-1 to 5.4-to-1 (Bärnighausen et al. 2011; Colombo et al. 2006; Limcangco et al. 2001; Pelletier et al. 1998; Zhou et al. 2002).

[2] The conservation scenario assumes stopping the additional loss of mangroves whereas the restoration scenario assumes replanting large areas of mangroves already lost; that is we are doing more restoration in the scenarios analysed than conservation. The overall ratio of both conservation and restoration is calculated by adding the total present value benefits and costs of both measures. The very high restoration costs is the main factor driving the overall B-C ratio for both conservation and restoration.

[3] The return on investment for wind energy investments will vary depending on the specific generation technologies and costs in places where the offshore wind installations are located. On grids that have a high share of zero-carbon generation, including hydropower and nuclear energy, adding ocean energy will not decrease emissions significantly. Conversely, for grids with a high share of carbon-intensive generation, emission displacements could be significant.

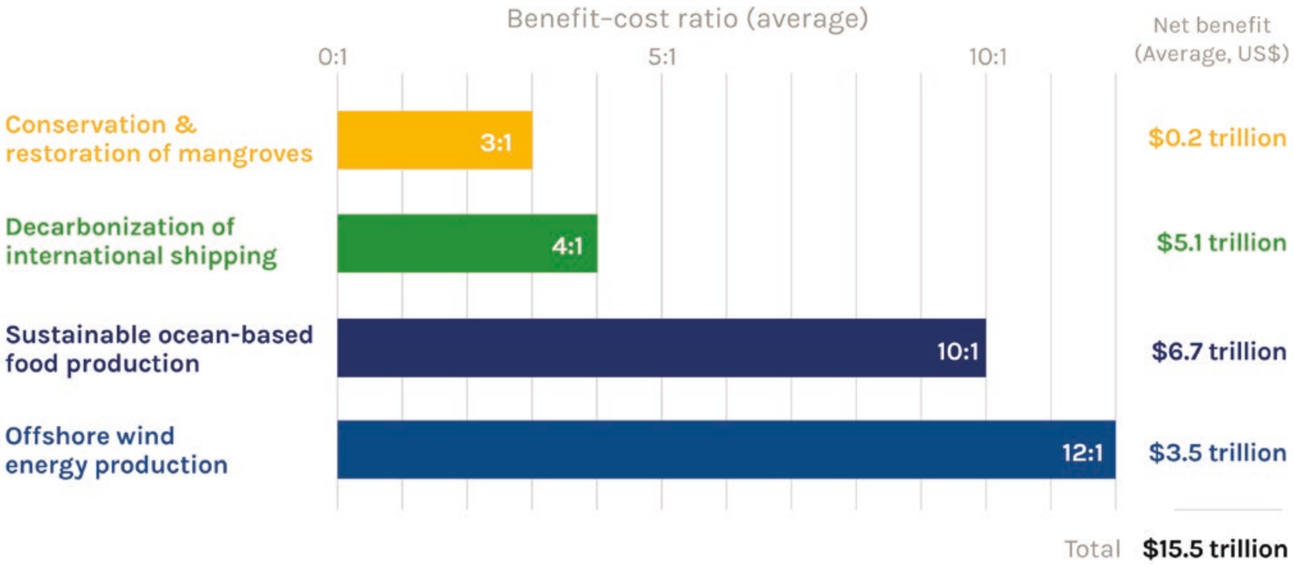

Fig. 18.1 Benefits significantly outweigh costs across sustainable ocean-based interventions, with average B-C ratio ranging between 3:1 and 12:1. *Note: Average benefit-cost (B-C) ratios have been rounded to the nearest integer and the net benefits value to the first decimal place. The B-C ratio for mangroves is the combined ratio for both conservation- and restoration-based interventions. The average net benefits represent the average net present value for investments and is calculated over a 30-year horizon (2020–2050). Source: Authors' calculations*

sis to 2050 captures only a portion of returns from these investments, which will continue beyond 2050.

- **Every $1 invested in increasing production of sustainably sourced ocean-based protein (to ensure a healthy, balanced diet by 2050) is estimated to yield $10 in benefits.** The increase in demand for ocean-based protein to provide a healthy diet for 9.7 billion people by 2050, which would replace a percentage of emission-intensive land-based protein sources, can be achieved by reforming wild-capture fisheries and by increasing the sustainable production of ocean-based aquaculture. Both measures will deliver benefits such as better health outcomes to consumers, higher revenues to fishers, lower GHG emissions mitigating the risks of climate damage, reduced land-based conflicts and lower water usage.

A number of impacts (both benefits and costs) have not yet been monetised, but they need to be considered by policymakers. These include the impact of GHG emissions on ocean acidification and the associated loss to biodiversity and commercial shellfish production; a potential increase in tourism revenues globally from restored mangroves; biodiversity benefits from healthier ecosystems; impacts on marine biodiversity from increasing the number of offshore wind farms; and distributional impacts of the benefits and costs on poorer communities. Given these nonmonetised impacts, the B-C ratios present a partial estimation of all benefits and costs that are likely to accrue as a result of such investments. These four examples are indicative of the relative scale of benefits compared to the costs. Further research and analysis to address these gaps will provide a more complete picture of the value of benefits versus costs.

Although data limitations prevented a full accounting of all benefits and costs, the results of the analyses suggest that taking actions to transform these sectors will generate a host of benefits that are much larger than the costs.[4] The results show that sustainable ocean-based investments yield benefits at least five times greater than the costs (Fig. 18.2), with minimum net returns of $8.2 trillion over 30 years. Better awareness of evidence of the possible ROI will help strengthen the economic case for action.

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[4] For example, this is particularly true for the majority of ecosystem service benefits for mangroves that are not privately owned or traded, and hence their "value" is not reflected in price signals. We refrained from monetising some of the benefits due to the uncertainty of nonmarket valuation techniques. Further information is available in Sect. 18.5.1.

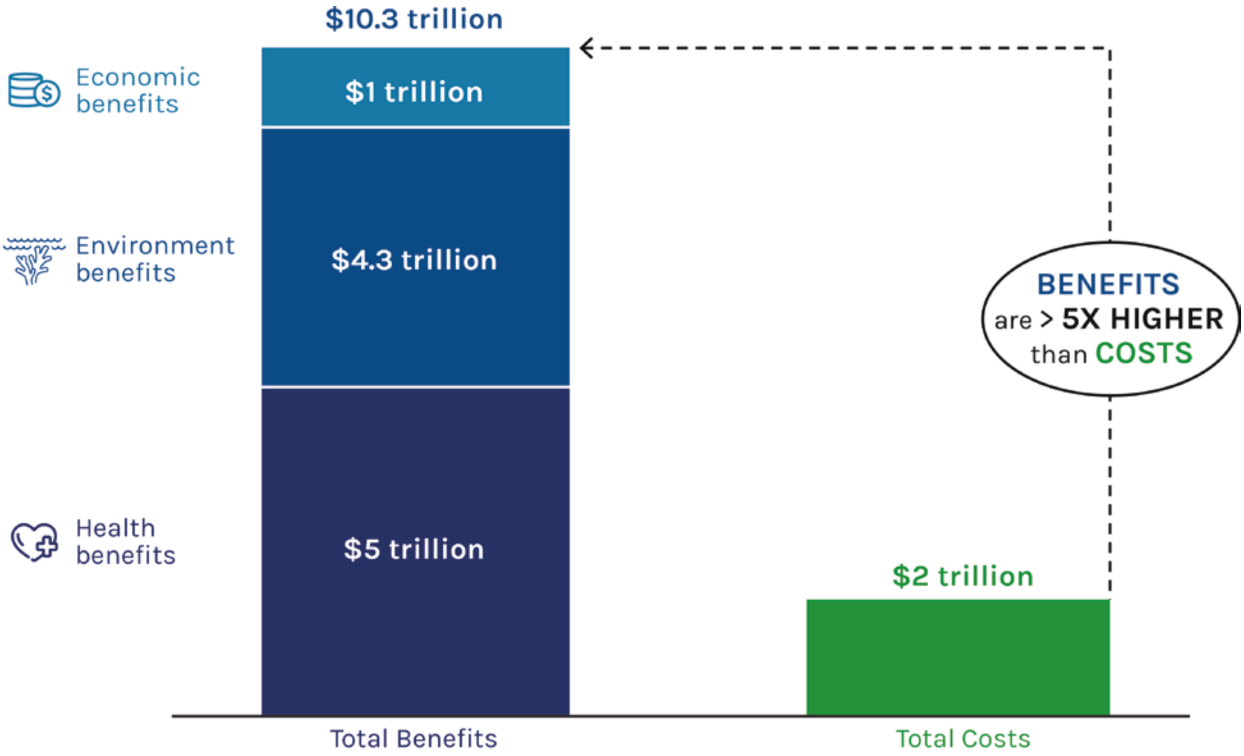

Fig. 18.2 Sustainable ocean investments yield benefits at least 5× higher than costs. *Note: The total benefits and costs in the figure present the lower-bound present value estimates to demonstrate the minimum scale of quantified net benefits. Source: Authors' calculations*

3 Introduction

The ocean's economic value is undisputed: it generates jobs that support millions of livelihoods, it supplies resources that have enabled decades of industrial growth, and its sea routes enable 90% of world trade (Fleming et al. 2014). The ocean's ecosystem services are vital for the well-being of society. For example, in some least-developed countries, fish protein accounts for more than 50% of animal protein intake (FAO 2018). Likewise, the ocean is reflected in many cultural practices, is manifest in inspirational art and provides recreational and aesthetic value to many (Fleming et al. 2014).

However, these services and benefits are at risk as the ocean faces pressures from enhanced economic activity, demands from a growing human population and uncertainty from a warmer, unstable climate.

Overfishing, pollution, climate change and loss of biodiversity are eroding the ability of the ocean to continue to sustain livelihoods and prosperity. The cumulative impact of human activities and climate change are likely to cause further ecosystem degradation or even collapse of ecosystems such as coral reefs, kelp forests and seagrasses (Halpern et al. 2019; IPCC 2019).

This analysis begins to estimate the benefits and costs of transitioning towards a sustainable ocean economy by focusing on four areas that represent key aspects of the ocean economy. It builds on *The Ocean as a Solution to Climate Change: Five Opportunities for Action* (Hoegh-Guldberg et al. 2019) and *The Global Consultation Report of the Food and Land Use Coalition* (FOLU 2019) and other analyses and reports to demonstrate that ocean-based investments can yield considerable economic benefits to society in the long term.

3.1 Scope of the Analysis

The High Level Panel for a Sustainable Ocean Economy (Ocean Panel) commissioned this benefit-cost analysis as an input to the deliberations of the Ocean Panel, serving to strengthen the evidence base of the forthcoming *Towards a Sustainable Ocean Economy* report and action agenda.

The Ocean Panel proposes that a sustainable ocean economy can simultaneously deliver on three dimensions. It can

- **Protect:** reduce greenhouse gas (GHG) emissions while safeguarding biodiversity;
- **Produce:** contribute to sustainably powering and feeding a planet of 9.7 billion people in 2050; and
- **Prosper:** create better jobs and support more equitable economic growth, household income and well-being.

To achieve this vision, it will be critical to take action to transform ocean-based sectors and ecosystems towards sustainability.

We indicate the scale of benefits compared to costs by focusing on specific policy interventions across one coastal ecosystem, mangroves, and the ocean-based sectors involved with offshore wind energy, international shipping and ocean-based protein from capture fisheries and mariculture (Table 18.2).

Although it was not possible to cover all potential interventions across these sectors, specific interventions were chosen to meet three criteria: achievement of the Ocean Panel's vision, contribution to the global efforts to reduce GHG emissions, and contribution to delivering countries' Sustainable Development Goals (SDGs) and targets (Hoegh-Guldberg et al. 2019).[5]

Table 18.2 The four ocean-based areas analysed

Ocean-based sectors/ ecosystems	Specific actions
Mangrove coastal habitats	Conserve and restore mangrove coastal habitats
Ocean-based renewable energy	Scale up the production of offshore wind energy (fixed and floating wind installations)[a]
Ocean-based transport	Reduce emissions from international shipping with a target to reach net-zero emissions in 2050[b]
Ocean-based food production	Achieve a healthier balanced diet for 9.7 billion people by 2050 by switching a share of protein from emission-intensive land-based sources of protein (notably beef and lamb) to low-carbon sustainably produced ocean-based sources of protein[c]

Notes:

[a] *Based on the scenarios analysed, offshore energy will likely continue to dominate the generation potential of the ocean energy sector in 2050, accounting for 65% of the sector's potential* (Hoegh-Guldberg et al. 2019)

[b] *The analysis excludes military and fishing vessels and domestic transport and includes bulk carriers, oil tankers and container ships, which account for the majority of the emissions (55%) in the shipping sector* (Olmer et al. 2017)

[c] *Sustainable production involves reforming fisheries by 2050 and increasing the production of sustainable ocean-based aquaculture (fed and nonfed)*

Source: Authors

These are the four interventions analysed:

- Conserving and restoring mangrove habitats
- Scaling up offshore wind energy production
- Decarbonising the international shipping sector
- Increasing production of sustainably sourced ocean-based protein (to ensure a healthy, balanced diet by 2050)

This analysis is the first attempt to measure the global net benefit and benefit-cost (B-C) ratio of implementing ocean-based interventions over a 30-year horizon (2020–2050). While in the past, significant efforts have been made to assess the net positive benefits from protecting marine ecosystems and transforming ocean-based activities, they focused on particular measures, ecosystems and investments in particular regions or referred to assessments over shorter time periods. Consequently, the overall global benefits and costs of transitioning to a sustainable ocean economy across these four areas have not been generated in an aggregate form or included in global discussions. Building on existing literature, this working paper aims to address the knowledge gap by focusing on sustainable transformation pathway scenarios and by using both quantitative and qualitative methods.

4 Methodology

This paper summarises the potential impact of investments in four ocean-based areas (see Table 18.2) over 30 years (2020–2050). By dividing the present value of benefits by the present value of costs, a B-C ratio for each sector is estimated (Box 18.1).

The assumptions used to derive the B-C ratio differ for each sector. They are discussed in detail in Sect. 18.5.

A generic analytical framework was applied to ensure consistency and comparability in analysing the impacts in each area:

- The ambition for each area was defined as the level of sustainability that would be achieved in 2050 with respect to an identified baseline scenario. The business-as-usual (BAU) and sustainable transformation pathway projections, based on scenarios modelled in *The Ocean as a Solution to Climate Change: Five Opportunities for Action* (Hoegh-Guldberg et al. 2019) and *The Global*

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[5] Although the interventions selected are key to achieving the 2050 sustainable ocean economy vision, they do not represent an exhaustive list of actions that will be required to make such a transition. For example, this analysis does not look at the impacts of moving towards a sustainable coastal tourism sector, of reducing marine pollution, or of expanding the network of marine protected areas.

Consultation Report of the Food and Land Use Coalition (FOLU 2019), are described in Sect. 18.4.1.

- A range of benefits and costs were identified that would achieve the target state over 30 years. These impacts were quantified monetarily where possible and were described qualitatively where a lack of data did not allow for such quantification.
- Future benefits and costs were discounted using a rate of 3.5%. The discounted benefits and costs were summed over 30 years (2020–2050) to arrive at a present value of benefits and costs for 2050 (Box 18.1). All values are based on 2019 prices.
- For each area, a B-C ratio was developed by dividing the present value of benefits in 2050 by the present value of costs.
- The present value of benefits and costs were aggregated across the areas to provide an aggregate B-C ratio for 2050.

Box 18.1 Estimating the Benefit-Cost Ratio

The benefit-cost (B-C) ratio indicates the return from ocean-based investments in the four areas in 2050. A B-C ratio greater than 1 demonstrates that the returns from an investment will be higher than the costs estimated over the chosen time period.

$$
\begin{aligned}
B/C &= \frac{\text{Present value of benefits}}{\text{Present value of costs}} \\
&= \frac{\text{Sum of discounted benefits over 30 years}}{\text{Sum of discounted costs over 30 years}} \\
&= \left[\frac{B_0}{(1+r)^0}+\ldots\frac{B_n}{(1+r)^n}\right] \div \left[\frac{C_0}{(1+r)^0}+\ldots\frac{C_n}{(1+r)^n}\right]
\end{aligned}
$$

where n = year; B = benefits; C = costs; r = discount rate.

Discounting is used to compare benefits and costs occurring over different periods of time by converting them into present values. This is based on the concept that people prefer to receive goods and services now rather than later.[a] The discount rate used in the Green Book, also known as the social time preference rate, is based on two components: the 'time preference', which is the rate at which consumption and spending are discounted over time, assuming no change in per capita consumption, and the 'wealth effect', which reflects the expected growth in per capita consumption over time, where future consumption will be higher relative to current consumption and is expected to have a lower utility.[b]

Source: a, b HMT (2018).

The time frame of 2020–2050 provides enough time for measures to be implemented and environmental benefits to result. In addition, the year 2050 aligns with long-term strategies to reduce emissions to net zero by midcentury (IPCC 2018) and meet the 2050 biodiversity vision where biodiversity is valued, conserved and restored to sustain a healthy planet (Cooper 2018). The time frame also overlaps with the United Nations Decade of Ocean Science and delivery of the 2030 SDG.

We used a constant social discount rate of 3.5% for the analysis (HMT 2018). Views vary on the correct discount rate for climate policies as well as the extent to which rates differ between developing and developed countries.[6] Some economists give more weight to environmental benefits that occur in distant years and recommend a lower discount rate for intergenerational decisions or a 'hyperbolic' discount rate that declines over time (Hausker 2011). For example, the *Stern Review* recommends a declining social discount rate, with rates lower than 3% for investments beyond 30 years (Stern 2007). The review states, 'If the ethical judgement is that future generations count very little regardless of their consumption level then investments with mainly long-run pay-offs would not be favoured. In other words, if you care little about future generations you will care little about climate change. As we have argued that is not a position which has much foundation in ethics and which many would find unacceptable'.[7] To reflect the intertemporal consideration of resource values, we selected a lower social discount rate. Given that the appraisal period is 30 years (and no longer), we decided on a constant 3.5% social discount rate.[8]

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[6] It is often argued that social discount rates are likely to be higher for developing countries because the social opportunity costs for capital is higher or the cost of borrowing capital tends to be higher. For example, the World Bank and the Asian Development Bank typically apply a real discount rate of 10–12% when evaluating projects in developing countries (Warusawitharana 2014).

[7] For example, the *Stern Review* recommends a declining social discount rate with rates lower than 3% for investments beyond 30 years (Stern 2007). The review states, 'If the ethical judgement is that future generations count very little regardless of their consumption level then investments with mainly long-run pay-offs would not be favoured. In other words, if you care little about future generations you will care little about climate change. As we have argued that is not a position which has much foundation in ethics and which many would find unacceptable'.

[8] Based on the recommendation of the *Stern Review*, the treasury for the United Kingdom recommends the use of a 3.5% discount rate for the first 30 years, followed by a declining rate until it reaches 1% for 301 years and beyond (Lowe 2008). It can be argued that a lower rate can be implemented in different ways if agreement to use a low rate is reached. For example, there could be two options: (1) a global agreement is reached so that investments on the ocean and coasts are evaluated with a low discount rate, but no country is required to act if its own internal discount rate is higher and the project does not pass its own internal return on investment criteria (unless international transfers change that balance), or (2) a global agreement is reached so that there are parallel evaluations—one with the low internationally agreed-upon discount rate and the other with the country's own rate for public investments.

Challenges related to carrying out a benefit-cost analysis of environmental measures include key benefit and cost omissions, ambiguity or uncertainty in assigning monetary benefits to nonmarket goods, difficulty in integrating distributional aspects,[9] and increased subjectivity for intangible benefits and costs. Although B-C ratio analyses or return on investment (ROI) studies at the global level are appealing, this approach has limitations. The biggest risk of global benefit-cost estimates is that they do not present the distribution of benefits and costs across developing and developed countries. Global B-C ratios do not reflect heterogeneity (due not only to the distribution of benefits and costs across the globe but also to differences in discount rates).

Consequently, the estimates should not be interpreted as giving an exact depiction of the flow of returns. They have been developed to indicate the scale of benefits relative to costs specific to the scenarios analysed for different activities. The analysis aims to stimulate timely discussion, influence ongoing debate on emerging sustainability issues and ensure that investments to obtain a sustainable ocean economy are not ignored in global discussions. The analysis does not attempt to show the regional variation of the benefits and costs. Conducting these assessments, which closely consider local factors, should be a key step when implementing ocean-based measures and regulations at local and national levels.

4.1 BAU and Sustainable Transformation Pathway Scenarios for 2050

The analysis aims to answer four key questions:

- If the rate of mangrove loss were halted and degraded mangrove areas were restored, what would be the benefits and costs to society?
- If the world decided to expand offshore wind energy generation (from 0.3% of total energy generation in 2020 to 2–7% of total future energy generation in 2050), what would be the benefits and costs to society?
- If the international shipping sector reduced its emissions to net zero, what would be the benefits and costs to society?
- If sustainable ocean-based food production increased (to meet the balanced diet requirements as advocated by the 2019 report by the EAT-*Lancet* Commission on Food, Planet, Health [Willett et al. 2019]), what would be the benefits and costs to society?

To answer these questions, we identified a sustainable transformation pathway scenario for 2050, then measured benefits and costs needed to achieve this pathway against a BAU scenario. The sustainable transformation pathway and BAU scenarios, taken from Hoegh-Guldberg et al. (2019) and the Food and Land Use Coalition (FOLU) report (2019), are summarised in Table 18.3. For most interventions, benefits are accrued over the long term but the investment costs occur up front.

4.2 Framework for Assessing Benefits

The four areas can yield three categories of benefits, which are discussed in more detail below:

- Health benefits from reducing environmental risks
- Environmental and ecological benefits from reduced environmental degradation (on land and in the ocean) and prevention of future temperature rise from climate change
- Economic and social benefits from stimulating economic activity and promoting sustainable development

Table 18.3 Business-as-usual and sustainable transformation pathway scenarios

Four actions	Business-as-usual (BAU) Scenario	Sustainable transformation pathway scenario
Conserve and restore mangroves	Blue carbon ecosystems continue to decline, but at decreasing rates. The rate of loss of mangroves globally is estimated at 0.11% per year.[a]	Mangrove conservation: The per year loss under BAU is halted completely.[b] Mangrove restoration: Two scenarios were considered: (1) a moderate restoration effort recovering 40% of the historical ecosystem cover by 2050 (consistent with global mangrove Alliance goals), and (2) an aggressive scenario of complete restoration of pre-1980s cover.[c]
Scale up offshore wind energy production	Worldwide installed offshore wind energy capacity in 2018 generated 77 terawatt hours (TWh) per year and accounted for less than 1% of world energy production.[d] The current energy technologies mix remains constant (and the share of offshore wind energy remains low) as energy production expands.	The total installation capacity for offshore wind energy is estimated to grow substantially by 2050. The offshore wind energy generation for 2050 is estimated at 650–3500 TWh per year.[e] Under this scenario, the energy mix will shift to a higher fraction of renewables to meet the future increase in energy demand.
Decarbonise international shipping	The total annual greenhouse gas (GHG) emissions from international shipping is estimated to grow from 800 megatonnes (Mt) in 2012, to 1100 Mt. in 2030 and to 1500 Mt. in 2050.[f]	Emissions in international shipping are reduced to net zero by 2050.[g]

(continued)

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[9] In addition, the benefit-cost analysis does not apply any 'equity weighting' when aggregating benefits across countries or regions that have very different levels of wealth, thus giving relatively greater weight to the impacts of rich people relative to poor people.

Table 18.3 (continued)

Four actions	Business-as-usual (BAU) Scenario	Sustainable transformation pathway scenario
Increase ocean-based food production	• Fisheries continue to be overfished and global annual marine capture production declines in 2050 by 25%.[h] • Fed aquaculture (finfish) production remains at the 2020 level (11.7 million metric tonnes, or mmt) due to fishmeal constraints.[i] • Nonfed aquaculture (bivalve) continues to grow slowly to 28.5 mmt in 2050 due to lack of investments.[j]	• To meet healthy diet requirements in 2050, we need to double the current amount of ocean-based protein.[k] Part of this can be achieved by fisheries reform and the rest by increasing sustainable marine aquaculture production. • With global fisheries reform, annual marine capture production increases by 40% compared with baseline projections.[l] Fed finfish mariculture production increases to 22.4 mmt by 2050.[m] Bivalve production grows to 65.2 mmt in 2050.[n]

Notes: Total energy generation in 2018 was estimated to be 27,000 TWh/year; offshore wind contributed 0.3%

Sources: [a–g]*Hoegh-Guldberg et al.* (2019); [h]*Costello et al.* (2019); [i, j]*FOLU* (2019); [k]*Willett et al.* (2019); [l]*Costello et al.* (2019); [m, n]*FOLU* (2019)

4.2.1 Health Benefits

These include interventions such as scaling up ocean-based renewable energy production and decarbonising shipping to reduce GHG emissions. Indirect health-related cobenefits of reducing air pollutants include reduced mortality rates, improvements in productivity from improved well-being of workers,[10] lower absenteeism from school/work caused by reduced childhood asthma,[11] and reduced morbidity.

Measures that induce even moderate shifts in diet from high meat consumption towards ocean-based protein have well-documented human health benefits (Blas et al. 2019; González Fischer and Garnett 2016; Hollander et al. 2018; Oita et al. 2018; Simões-Wüst and Dagnelie 2019; Tilman and Clark 2014). Finally, healthy mangroves directly provide nutrition to local communities via enhanced fisheries and indirectly via increases in other ecosystem services (such as coastal protection and improvements in water quality) and by income-generating activities (such as timber for fuelwood, nontimber forest products like honey and medicines, and income from tourism.)[12]

Some health benefits cannot be quantified; thus, they have been described qualitatively. The monetary value of these benefits could be significant, and additional research is required to quantify them. The benefit assessed across most interventions is avoided health damage from increased GHG emissions, and it focuses specifically on the impacts of criteria pollutants (Box 18.2).

4.2.2 Environmental and Ecological Benefits

Direct climate change mitigation would be achieved by reducing GHGs and limiting global temperature rise to 1.5 °C. These impacts include avoided losses in activities that are counted in a country's gross domestic product, or GDP (such as agriculture, fisheries productivity,[13] tourism, manufacturing and services); avoided property damages from increased coastal flooding; and avoided noneconomic impacts that do not appear in GDP measures (such as the loss of natural habitats from increased ocean acidification and increased risks to human health from extreme temperatures, including heat stress). We use the social cost of carbon method to measure the environmental externalities caused by an increase in GHG emissions (Box 18.3). Biodiversity-related cobenefits include an increased abundance of marine wildlife, reduced noise and other disturbances that negatively impact marine species, and the natural treatment of pollution and waste. These benefits have a direct positive impact on the marine ecosystem and its organisms and indirectly contribute to societal well-being.

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[10] Working in a highly polluted setting for a long period of time can affect your mood or disposition to work. Evidence shows statistically significant adverse output effects (resulting in lower productivity) from prolonged exposure to ambient particles (He et al. 2019).

[11] There is a link between shipping pollution and childhood asthma (Sofiev et al. 2018) that leads to children missing school and their parents missing work. The shipping sector analysis explores this in more detail.

[12] Tourism-based income can improve economic and social conditions in local communities; hence, it indirectly contributes to health benefits.

[13] Climate change can have a positive or negative impact on regional fisheries; overall, though, there will be a decline in fisheries productivity.

Box 18.2 A Description of Avoided Mortality Losses from Reduced Greenhouse Gas Emissions

The cobenefits of global greenhouse gas (GHG) reductions on air quality and human health are estimated using analysis from West et al. (2013), which found that the global average marginal cobenefits of avoided mortality were US $50–380 per tonne of carbon dioxide reduced ($65–490 in 2019 prices). The analysis used a global atmospheric model and consistent future scenarios via two mechanisms: reducing coemitted air pollutants and slowing climate change and its effect on air quality. The model accounts for the impacts of ozone as well as fine particulate matter ($PM_{2.5}$), international air pollution transport and changes in global ozone from methane, and the study evaluates future scenarios in which population susceptibility to air pollution and the economic 'value of statistical lives' grows.[a] The authors state that the cobenefits may be underestimated because they do not account for people younger than age 30 (including children and neonatal effects), and they do not account for the benefits of avoided morbidity outcomes (i.e., reduced output from lower productivity).

Note: [a] *The value of statistical life is based on the willingness (and ability) to pay for reducing the risk of death. Hence, the study estimates marginal cobenefits to be high in North America and Europe, reflecting higher incomes in the region. Overall, though, the marginal cobenefit is found to be highest in regions with largest population affected by air pollution.*

4.2.3 Economic and Social Benefits

Transitioning to a sustainable ocean economy can lead to higher productivity, efficiency gains and revenues. For example, reforming fisheries will lead to long-term revenues and profits from higher fisheries productivity (outweighing the short-term losses). Similar fisheries productivity benefits have been observed in restoring and maintaining healthy mangroves. Improving the productivity of resources will in turn help boost revenues to industry, contributing to a country's national income. In addition, driving innovation and technological advancement will increase efficiency gains and unleash unforeseen market opportunities (GCA 2019).

In addition, these investments will help countries meet their SDGs and targets (Hoegh-Guldberg et al. 2019).

This includes creating decent jobs (SDG 8.5), protecting vulnerable communities from climate-related disasters (SDG 1.5), reducing poverty by improving household income/livelihoods (SDGs 1.1 and 1.4) and helping countries achieve their food security targets (SDG 3.2).

Box 18.3 Measuring Climate Benefits Using the Social Cost of Carbon

Benefit-cost analysis assumes that society should reduce carbon dioxide (CO_2) emissions up to the point where the marginal cost of reducing a tonne of CO_2 is just equal to the marginal benefit of keeping that tonne out of the atmosphere. The social cost of carbon (SCC) measures the benefit of reducing carbon dioxide equivalent (CO_2e) emissions; that is, it represents the dollar value of the cost (i.e., damages) avoided by reducing CO_2e emissions by 1 tonne.[a]

The model used to deliver SCC values, the integrated assessment model, provides a range of estimates[b] because of the many factors (including the types of greenhouse gas emissions) analysed, the types of impacts (gross domestic product, or GDP, versus non-GDP) analysed,[c] the discount rates used and size of risk aversion of the population.[d]

The SCC value used in this analysis reflects the avoided costs from changes in net agricultural productivity, human health, loss from increased natural disasters and changes in energy system costs, such as reduced costs for heating and increased costs for air-conditioning.[e] To prevent double counting with estimated health benefits from a reduction in ozone and fine particulate matter ($PM_{2.5}$), we used the SCC value developed under the U.S. Environmental Protection Agency that focuses only on damage costs from increases in the level of carbon dioxide in the atmosphere. The damage costs for CO_2 was estimated, in 2007 prices, at US $42 in 2020 and rises to $69 in 2050. Because the SCC value used does not account for all the damage costs, the impacts quantified monetarily are underestimates.

Notes:

[a] *Hausker* (2011).

[b] *Based on a number of studies, SCC values range from $50 to $417 per tonne of CO_2e reduced* (BEIS 2019; ToI 2019).

[c] *Activities counted in a country's GDP, such as agriculture, fisheries productivity, tourism, manufacturing and services, would feature in a GDP measure whereas non-GDP measures would include noneconomic impacts, including the loss of natural habitats and increased risks to human health (from heat stress and other factors).*

[d] *Standard practice in benefit-cost analysis is to take a risk-neutral approach to uncertainties. In the real world, individuals and organisations of all types display risk aversion to catastrophic impacts* (Hausker 2011).

[e] *EPA* (2016).

4.3 Framework for Assessing Costs

The costs of transformation, relative to BAU, were assessed by examining a list of actions and measures that can be undertaken by the government and private sector to achieve targets such as restoring mangroves, reducing emissions, reforming fisheries and increasing sustainable ocean-based aquaculture production.

Examples of these types of costs are given below:

- **Costs to business** include capital investments; for example, building new offshore aquaculture farms, increasing offshore renewable energy, implementing technological improvements in shipping and increasing private research and development (R&D) expenditures.
- **Costs to government** include costs of regulations (on mangrove and fisheries conservation), public R&D expenditures and higher enforcement and monitoring costs (for mangroves and fisheries).
- **Costs to households** include temporary reductions in household income from fisheries reform and the forgone income from the alternative use of the mangrove area by shrimp farming and/or charcoal production if they are not protected (opportunity cost). The presence of positive private opportunity costs may be an economic barrier to the success of mangrove conservation because they represent a direct economic loss (or disincentive) to local communities that undertake mangrove conservation activities.

For some sectors, such as renewable energy production and ocean-based aquaculture, the private sector costs were estimated based on existing analytical projections of the state of the technology in 2030 and 2050, and we assumed reductions in future costs due to economies of scale and 'learning by doing' (Arrow 1962). If components of costs were not quantified—for example, the costs of implementing national regulations to ensure decarbonisation of the shipping sector have not been monetised—they are discussed qualitatively.

5 Assessing the Return on Investment for Four Sustainable Ocean Transformations: Scenarios, Assumptions, Methodology, Results

This section presents the scenarios, discusses the assumptions and methodology used to estimate the benefits and costs for each of the four areas examined and finally presents the net benefits and the B-C ratios.

5.1 Conserve and Restore Mangroves

5.1.1 Baseline, Sustainable Transformation Pathway and Target Scenarios

The assumptions about the BAU scenario and the sustainable transformation pathway needed to achieve the conservation and restoration targets by 2050 are informed by Hoegh-Guldberg et al. (2019).

5.1.2 The BAU Scenario

Although blue carbon ecosystems continue to decline, they do so at decreasing rates thanks to improved understanding, management and restoration (Lee et al. 2019). For instance, the rates of mangrove loss globally declined from 2.1% per year in the 1980s (Valiela et al. 2001) to 0.11% per year in the past decade (Bunting et al. 2018). The BAU scenario assumes the loss of mangroves continues at 0.11% per year until 2050. The sustainable transformation pathway builds from this base.

5.1.3 The Sustainable Transformation Pathway Scenario

The mitigation potential could be achieved via two pathways: conservation of ecosystems and restoration of ecosystems.

- **Conservation of mangroves.** The total area for mangroves conserved per year is estimated to be 15,000–30,000 hectares (ha) (see Table 18.4).[14] This scenario avoids emissions of carbon stored in soils and vegetation. The total potential GHG mitigation contribution is estimated to be 0.02–0.04 gigatonnes (Gt) of CO_2e per year (Hoegh-Guldberg et al. 2019).[15]
- **Restoration of mangroves.** Restoration sequesters and stores carbon as vegetation grows. In the Hoegh-Guldberg et al. (2019) study, the range of potential mitigation varied with the level of effort and investment. Two scenarios were considered: a moderate restoration effort recovering about 40% (184,000 ha per year) of the historical ecosystem cover by 2050 (consistent with Global Mangrove Alliance goals) and a more aggressivescenario of complete restoration (290,000 ha per year) of pre-1980s cover (Hoegh-Guldberg et al. 2019). The corresponding total GHG mitigation potential was estimated at 0.16 $GtCO_2$e per year to 0.25 $GtCO_2$e per year in 2050 (Hoegh-Guldberg et al. 2019). See Table 18.4.

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[14] This is based on avoiding the current loss of mangroves per year under BAU (Hoegh-Guldberg et al. 2019).

[15] The range of CO_2 sequestration potential per unit area for each ecosystem was calculated using default emission/removal factors from the IPCC (2013).

Table 18.4 Conservation and restoration pathways for mangroves by 2050

	Conservation		Restoration	
	Moderate	Aggressive	Moderate	Aggressive
Hectares conserved or restored per year	15,000	30,000	184,000	290,000
GHG mitigation potential (GtCO$_2$e per year)	0.02	0.04	0.16	0.25

Notes: GHG greenhouse gas, GtCO$_2$e gigatonnes of carbon dioxide equivalent
Source: Hoegh-Guldberg et al. (2019)

The GHG emission mitigation estimates are likely conservative because they do not account for avoided methane (CH_4) and high nitrous oxide (N_2O) emissions from alternative land uses such as aquaculture and rice production (Hoegh-Guldberg et al. 2019). These emissions can be significant due to mangrove conversions to aquaculture or rice farming; for example, 30% of mangrove ecosystems in Southeast Asia have been converted to aquaculture and 22% to rice cultivation (Richards and Friess 2016). These GHG estimates from land use changes are excluded from the present analysis due to the lack of global data.

5.1.4 Assessment of Costs

Conservation Costs

For conservation, we estimated the cost of monitoring and maintaining the mangroves and the opportunity costs of the forgone net income from alternative use of the mangrove area (Table 18.5). For enforcement and monitoring costs, a global average cost estimate of maintaining marine protected areas was used as a proxy. For the second component, we looked at the opportunity costs for returns from shrimp farming, crab catching and charcoal production (see Table 18.5). Because it was unknown which activities might exist at which sites, we used the sum of the three to represent the higher estimate of the opportunity costs.

We estimated the annual global costs of conservation to be $28.8–57.5 million based on the per-hectare estimates in Table 18.5 and the additional area conserved by 2050.

These numbers are indicative of global costs. In reality, the actual costs might be lower or higher depending on the location and sizes of the protected areas.

Table 18.5 Types of costs and data sources used to estimate the costs of mangrove conservation and restoration

Description of costs	Cost (US $/ha/year)	Adjusted 2019$	References
Monitoring and maintenance cost: Median cost covers the current marine protected area expenditure plus estimated shortfall[a]	27	40	Balmford et al. (2004)
Global restoration costs of mangroves	8961 (median)	9449	Bayraktarov et al. (2016)
Opportunity cost: Net economic returns from shrimp farming in Thailand	1078–1220	1873 (average)	Barbier (2007)
Opportunity cost: Net economic returns from charcoal production in northwestern Madagascar	4	5	Witt (2016)
Opportunity cost: Net economic returns from crab catching in northeastern Brazil[b]	12	16	Glaser and Diele (2004)

Notes: ha hectare

[a] *To assess the enforcement and monitoring costs, a global average cost estimate of marine protected areas was used as a proxy for the conservation costs for mangrove protection. Balmford et al. (2004) state that the total costs per unit area of running the marine protected areas in their sample varied enormously, with the sum of current expenditure plus estimated shortfall ranging from about $4 per square kilometre (km^2) per year to nearly $30 million/km^2/year (median, $2698/km^2/year or $27/ha). We use the median figure in our analysis. The costs of a protected-area system are divided into three categories: (1) recurrent management costs for existing areas, (2) systemwide expenses needed to support a network of protected areas and (3) costs of bringing new areas into the system*

[b] *At $13.50 per person/day × 4500 person days in a year over about 50 km^2 is about $12/ha/year*

Restoration Costs

Restoration is often needed when ecosystem degradation is reaching its ecological threshold and significant efforts are required for seeding and replanting mangrove species to restore it. The analysis uses the global restoration cost estimates reported in the Bayraktarov et al. (2016) study that conducted a meta-analysis and systematically reviewed 235 studies (with 954 observations), including projects that restored and rehabilitated mangroves and other vegetated coastal habitats in different world regions. They suggested a median cost per hectare of $8961 per year (2010 prices, converted to $9449 in 2019 prices). We assume the costs are two times higher ($18,997) if both operating and capital costs are included (Bayraktarov et al. 2016).

The opportunity cost for restoration is assumed to be the same as that of conservation, but the forgone benefits can occur only 5 years after the restoration efforts have been completed, assuming that once the coastal ecosystems have improved, these areas are again under the risk of being disturbed. The annual restoration costs are estimated to be $3.5–5.5 billion between 2020 and 2050.[16]

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[16] The range is obtained by multiplying the median cost (point estimate) with the area of restoration (range).

Assessment of Benefits

Mangroves extend over 150,000 square kilometres (km^2), distributed across 123 countries (Beck et al. 2018).

They provide a wide array of market and nonmarket benefits, which are categorised below according to health, environmental and economic/social benefits. The range of benefits quantified includes coastal protection benefits, sequestration benefits and fisheries productivity benefits. Conserving and restoring mangroves will also increase other ecosystem services, which, in turn, will increase societal well-being, which we have discussed qualitatively.

In this study, we assumed that the benefits generated through mangrove restoration (such as coastal protection and fisheries productivity) will not accrue immediately following the restoration effort but rather after there has been improvement in the condition of the ecosystem. We assume this to be 5 years after the restoration/rehabilitation work begins (Burke and Ding 2016).[17] In addition, the probability of success for mangrove restoration is very low. Bayraktarov et al. (2016) estimate the median survival of restored mangroves, assessed only within the first 1–2 years after restoration, to be 51.3%. For the restoration scenarios, we multiply the benefits by the probability of success of restoration or the median survival rate.

5.2 Health Benefits

Mangroves are a direct source of food, fuelwood, fiber and traditional medicine for local inhabitants (Bandaranayake 1998; Chaigneau et al. 2019). They provide important opportunities for communities to generate incomes from tourism associated with recreational fishing and bird-watching that generate recreational and aesthetic value to visitors (Carnell et al. 2019). These livelihood, cultural and recreational benefits, while important to the physical and mental health and well-being of local communities as well as visitors (de Souza Queiroz et al. 2017; Pearson et al. 2019), have not yet been quantified. In some developing countries such as Kenya and Mozambique, mangrove medicine was used by coastal communities to cure stomach pains or headaches but did not have direct commercial value (Chaigneau et al. 2019).

5.3 Environmental Benefits

5.3.1 Protection from Storm Surges

The biggest benefits of mangroves are that they form a natural breakwater that limits the damage to property, economic disruption and loss of life caused by coastal flooding and storm surges, which become stronger and more frequent with climate change. The aerial roots, trunks and canopy of mangrove forests provide a strong protective barrier against winds, swell waves, storm surges, cyclones and tsunamis.

Studies indicate that incoming wave heights are reduced by 13–66% by a 100-m-wide mangrove belt, and by 50–100% by a 500-m-wide belt (World Bank 2016).

Protecting and restoring coastal and marine ecosystems can reduce the impacts of cyclones on an estimated 208 million individuals in 23 major mangrove-holding countries (Hochard et al. 2019).[18] A meta-analysis of 44 studies found a median value of $3604 per hectare per year for the coastal protection services (avoided property damage) provided by mangroves (Salem and Mercer 2012), which, when updated to 2019 prices, yield annual benefits of $60–120 million for conservation scenarios analysed, and $375–592 million for restoration scenarios analysed (Table 18.6).

5.3.2 Mitigation of Climate Change and Carbon Sequestration Benefits

Mangroves play an important role in sequestering carbon; hence, they can contribute towards mitigation solutions aimed at limiting temperature rise to 1.5 °C. The discounted climate benefits (calculated based on annual GHG emissions in Table 18.4) from reducing CO_2 emissions are estimated at $42–83 billion for conservation and $137–214 billion for restoration over 30 years.

5.3.3 Other Ecosystem Services

Mangroves also provide many ecosystem services, such as regulating water quality and reducing coastal erosion, that we have not been able to quantify (see Appendix 1).

5.4 Economic and Social Benefits

5.4.1 Commercial Fisheries

Although some estimates have been much higher [e.g., Aburto-Oropeza et al. (2008) estimated that protecting 1 ha of mangroves in California was associated with increased fish yields valued at $37,500 per year], we conservatively used $18,000 per hectare per year (de Groot et al. 2012), based on global meta-analysis, to assess the commercial value of fish yields associated with conserved or restored mangroves (Table 18.6). We estimate the global economic benefit from increased productivity of commercial fish spe-

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[17] The time frame for generating these benefits will vary, and in some extreme cases, full development of the aboveground biomass will not be achieved for 20–30 years (Osland et al. 2012; Salmo et al. 2013).

[18] Countries receiving the largest benefits in avoided flood damage in absolute dollar terms include China, India, Mexico, the United States and Vietnam. The largest beneficiaries relative to the size of their economies include many low-income countries, such as Guinea, Mozambique and Sierra Leone (Beck et al. 2018).

Table 18.6 Benefits of mangrove conservation and restoration in avoided property damage and fisheries productivity

Type of benefit	Benefit (US $/ha/year)	Adjusted 2019$	References
Avoided property damage	3604	4000	Salem and Mercer (2012)
Fisheries productivity	18,000	19,980	de Groot et al. (2012)

Note: ha = hectare
Source: Authors' calculations

cies to be $300–600 million per year for the conservation scenarios and $1.9–3.0 billion per year for restoration scenarios.

5.4.2 Tourism

Although we have not been able to provide a global estimate on increases in tourism arising from the scenarios analysed, these are likely to be significant for some countries. Mangrove tourism and recreation is a multibillion-dollar industry (Spalding and Parrett 2019). For example, tourism associated with coral reefs and mangroves in Belize contributed an estimated $150–196 million (12–15% of GDP) to the national economy in 2007 (Cooper et al. 2009). These benefits are also further discussed in Appendix 1. While there will be a short-term dip in coastal tourism following the COVID-19 lockdown, this assessment focuses on benefits over a 30-year period. Over the longer term, we estimate these benefits will pick up as the global economy emerges out of the pandemic and economic crisis.

There is also a strong social angle in terms of the distribution of the benefits. For example, low-income communities are most reliant on mangroves for key ecosystem services (Box 18.4).

5.4.3 Estimated Benefits and Costs

We estimated the B-C ratio under two approaches. In the first approach, we estimated the ratio over 30 years (2020–2050) using present value benefits and costs. In the second approach, we calculated the B-C ratio per hectare.

B-C Ratio Using Present Value Approach

For every $1 invested in mangrove conservation and restoration, we get a return of $3. Net benefits for mangrove conservation are estimated at $48–96 billion and for restoration at $97–150 billion over 30 years (2020–2050). The value of net benefits for mangrove restoration is higher than conservation because we assumed the area of mangroves restored would be 10 times the area conserved (Table 18.7).

However, we find that conservation of mangroves yields significantly more returns per dollar invested than restoration. For every $1 invested in mangrove conservation, we get a return of $88 dollars for conservation, versus $2 for restoration.

Table 18.7 Net present value and benefit-cost ratios for mangrove conservation and restoration

Transformation areas	Net present value (US $, billions, 2019$, 2020–2050)	Benefit-cost ratio
Conservation of mangroves[a]	48–96	88:1
Restoration of mangroves[b]	97–150	2:1
Total	145–246	3:1

Notes:
[a] *Conservation of 15,000–30,000 ha per year based on halting annual loss of mangroves*
[b] *Based on 184,000 ha per year for a moderate effort to 290,000 ha per year for an aggressive estimate*
Source: Authors' calculations

B-C Ratio for a Hectare of Mangrove Restored/Conserved

We estimated the benefits for restoring 1 ha of mangrove to be $30,080 and for conservation $79,980. Based on the per hectare conservation and restoration costs in Table 18.5, we estimate the B-C ratio per hectare to be 2:1 for restoration and 48:1 for conservation.

Box 18.4 Mangroves Protect the Poorest Populations

Low-income communities rely heavily on mangroves for key ecosystem services. Over nearly 98 million people from 10 low- or lower-middle-income countries with major mangrove areas and a gross national income per capita less than US $4036 annually have suffered from cyclones.[a] This accounts for 50% of the global cyclone-affected population from 18 mangrove-holding countries. Poor coastal families are most vulnerable to natural disasters; hence, building ecosystem resilience to protect them from coastal flooding and cyclones will not only safeguard their valuable assets but also generate tremendous social benefits (e.g., feeling safe) that cannot be easily quantified monetarily.

Note: [a] *Hochard et al.* (2019).

For both of the approaches, the ROI for restoration is lower, first, because the cost of mangrove restoration is much higher than conservation due to the high costs of seeding and replanting; second, it takes time to accrue benefits from restoration since the plants need to regrow and restoration requires the right conditions to ensure a high survival rate (see caveats in Appendix 1).

The monetised benefits presented under both of the approaches exclude a number of ecosystem services provided by mangroves. Major ecosystem benefits such as erosion control, water management, nutritional benefits from fisheries supported by mangroves[19] and health benefits are excluded from the current assessment. This is mainly because our assessment relies on previous valuation studies or meta-analyses that either do not attribute a value to these particular services or provide a total value across a range of services but do not address double-counting issues. Other social benefits that are not accounted for include employment and the potential for livelihoods associated with sustainably harvesting timber and nontimber forest products. Taking into account these benefits will likely result in a higher ROI.

The results from both of the approaches show that both types of interventions yield significant benefits and are important to ensure a high ROI. To reverse the current trend of marine and coastal resource depletion and further halt the release of CO_2 emissions from marine resource degradation, significant investment will need to be made to transform the way coastal and marine ecosystems are being managed. They would need more reliable funding for management/enforcement and greater participation/diversification of opportunities dependent on these ecosystems, in addition to strong ‘political will’ to involve measures that alter the fundamental attributes of a system (including value systems; regulatory, legislative or bureaucratic regimes; financial institutions; and technological or biological systems) (Ellis and Tschakert 2019). These social and political investments are important and have not been valued in the analysis.

5.4.4 Data Limitations and Caveats

Data limitations prevented us from assessing other coastal ecosystems: salt marsh and seagrass beds. Some caveats are that the value of mangrove conservation or restoration varies by locality, the costs are higher in developed countries, and coastal development pressure is a big influence. See Appendix 1 for important caveats.

5.5 Scale Up Offshore Wind Energy Production

Currently, global electricity generation from all ocean-based energy sources is less than 0.3% of the total (IEA 2019a). The ocean energy sector has seen a dramatic increase in investments over the past decade and is expected to grow (European Commission 2018; Hoegh-Guldberg et al. 2019; WBG et al. 2018). Currently, most offshore installations are in Europe, but a significant increase is expected in Asia, especially China (Hoegh-Guldberg et al. 2019).

In assessing the impacts of expanding offshore wind energy generation, we do not advocate one renewable energy technology over another. Rather, we focus on the impact (positive and negative) of expanding offshore wind energy against a baseline where fossil fuel sources of electricity generation continue to dominate. We looked at how much it would cost to increase production of offshore wind energy to meet the energy generation potential proposed in Hoegh-Guldberg et al. (2019) and estimate the benefits to society from reductions in GHGs and water usage.

5.5.1 Baseline, Sustainable Transformation Pathway and Target Scenarios

Between 2000 and 2017, the cumulative installed capacity of offshore wind energy rose from 67 megawatts (MW) to 20 gigawatts (GW) (IRENA 2018a, b). In 2018, the total global capacity of wind energy was 564 GW, of which 23 GW were offshore. Offshore wind energy produced 77 terawatt hours (TWh) of electricity annually.[20]

By 2050, gross global electricity generation is projected to be between 42,000 and 47,000 (TWh) (IEA 2019a).

In reviewing 15 energy scenarios for 2050 that considered ocean renewable energy, Hoegh-Guldberg et al. (2019) concluded that the annual energy generation from offshore wind technologies would increase between 650 and 3500 TWh per year.[21] To assess the impact of this increase on GHG emissions, the authors made assumptions about what technologies offshore wind would displace. They looked at the impact on GHG emissions if

- Offshore wind technologies displaced coal; and
- Offshore wind technologies displaced the current (2018) energy-generation mix.

We used the second scenario, which projected that scaling up offshore wind energy could reduce GHG emissions by between 0.3 and 1.61 $GtCO_2e$ per year in 2050 (Hoegh-Guldberg et al. 2019). Hoegh-Guldberg et al. (2019) acknowledge that this is a simplistic approach and, in reality, the substitution effect of ocean-based energy will mainly impact certain grids with given energy mixes, which, in turn, depends on global trends, including technology costs.

5.5.2 Assessment of Costs

Offshore Wind Energy Generation Costs

We use the levelised cost of electricity (LCOE) to estimate the cost of additional offshore wind energy generation. The LCOE includes capital costs, fuel costs, fixed and variable

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[19] It can be argued that the value of nutritional benefits is already embedded in the value of fish sold.

[20] Within offshore wind energy technologies, bottom-fixed water technologies dominate the current capacity of offshore wind energy.

[21] The authors based their estimation on several studies that have included offshore wind in scenarios projecting future energy mix. These include International Energy Agency scenarios, Bahar et al. (2019) and Teske et al. (2011). We assume a linear increase in energy generation from 2020 to 2050.

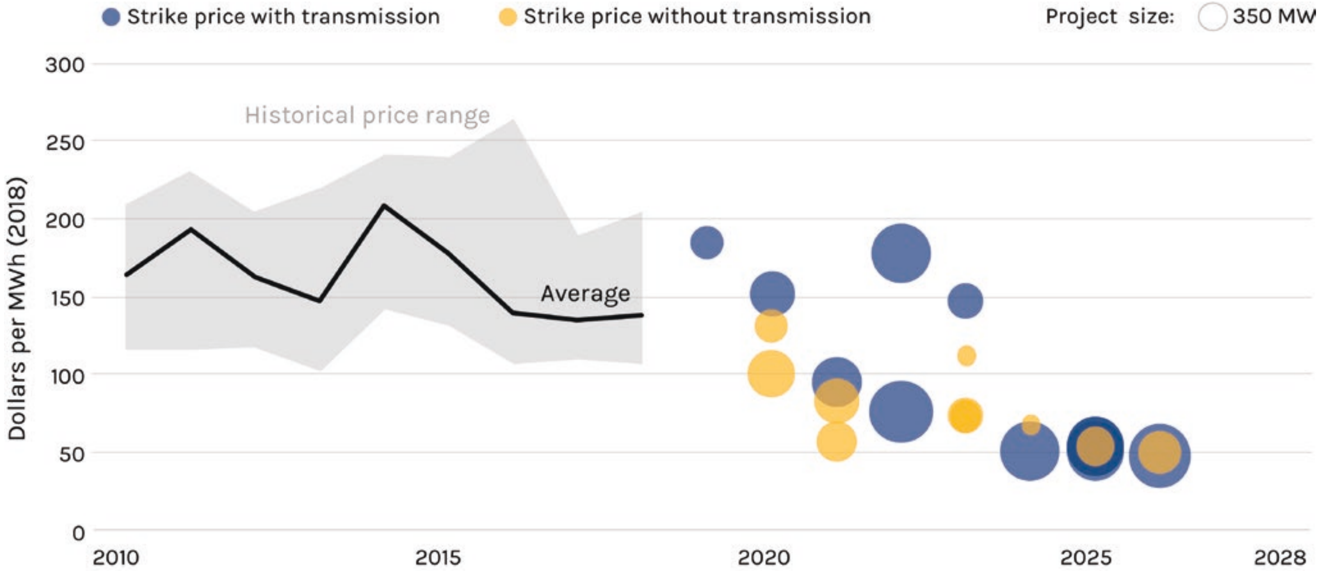

Fig. 18.3 Historical levelised cost of electricity generation of offshore wind and strike prices in recent auctions in Europe. Note: *MWh* megawatt-hour. Source: IEA (2019b)

operations and maintenance costs, financing cost and an assumed utilisation rate for each plant type (IEA 2015).

The LCOE for offshore wind power has declined since 2010 due to factors such as increased capacity from new installations (the ratio between realised energy output and theoretical maximum output), declining operational and maintenance costs due to improved turbine design (as they are made more robust for the offshore environment), improved capacity factors (linked to an increase in turbine size and hub height) and reduced transmission costs (Hoegh-Guldberg et al. 2019).

The global weighted-average LCOE of offshore wind projects commissioned in 2018 was estimated at $127–140 per megawatt-hour (MWh) based on the standard cost of capital representing full market risk (7% for developing countries and 7.5–8% for developed countries) (IEA 2019a; IRENA 2019). Improved financing terms could reduce the LCOE of offshore wind (IEA 2019a).

For example, applying a 4% weighted average of capital costs (WACC) to 2018 costs and performance parameters yields an offshore wind LCOE of about $100/MWh, which is 30% less than the LCOE derived from the standard WACC (7–8%) (IEA 2019b).

Declining recent strike prices[22] of offshore wind projects provide strong market signals of future cost reductions, indicating increased confidence from investors and setting the stage for low-cost financing opportunities for upcoming projects (Fig. 18.3). Analysis by the International Energy Agency (IEA) of auction strike prices shows costs could fall as low as $50/MWh (in some cases including transmission) for delivery in the mid-2020s (for example, a UK strike price of $51/MWh was seen in the September 2019 auction) (IEA 2019b).[23] Overall, evidence shows that with an economy of scale and learning curve effects, significant additional reductions in generation costs of offshore wind can be anticipated in subsequent years (IEA 2019b).

For floating offshore wind energy platforms, the LCOE may be higher because this is a less mature technology compared with the predominate bottom-fixed technology; it represents only 0.03 GW of the total of 23 GW of offshore power capacity. While cost reductions in the sector are expected due to rapidly advancing technology and market conditions enabling deployment to compete globally,[24] given the current low installation capacity of floating offshore wind facilities, it is difficult

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[22] The strike price is a guaranteed price to be paid to wholesale generators of electricity.

[23] There is a risk that, depending on how auctions are designed, low bids may be associated with no delivery and/or renegotiations. For example, Welisch and Poudineh (2019) state that one-shot auctions and the lack of a nondelivery penalty clause increase the probability of speculative bidding and prevent bidders from learning and from utilising information efficiently.

[24] In 2015 the costs of floating offshore energy were estimated to range between $187/MWh and $316/MWh (IEA and NEA 2015), with predictions that costs would fall by 40% by 2030 due to rapidly advancing technology and market conditions that enable offshore wind deployment to compete globally. These cost declines are also reflected in recent studies. Previous National Renewable Energy Laboratory (NREL) studies estimated the LCOE for an offshore wind project in the Massachusetts wind energy area to be $77/MWh (Moné et al. 2016). Later NREL studies revised the LCOEs downward to $74/MWh by 2027 and $57/MWh by 2032 for floating offshore technologies in Maine (Musial et al. 2020). The recent technological and commercial improvements in the global industry are applicable to the turbine design, turbine scaling effects on the balance of station, lower financing terms and lower costs for the floating platform, array and export cables. Commercial-scale plant costs (in terms of dollars per kilowatt) modelled for the Aqua Ventus technology were found to be approximately five times lower than the pilot-scale demonstration project cost that was originally estimated at $300/MWh.

to predict its future global costs. That said, while the relative importance of floating wind power platforms will increase, we assume that within the next 30 years the majority of offshore wind installations will be bottom fixed; thus, for an overall cost estimate, we assume the LCOE figures will be close to that of the bottom-fixed installations.

For this analysis, we looked at two scenarios based on IEA cost projections (IEA 2019b):

- A **moderate scenario** based on a standard cost of capital financing representing full market risk (WACC is 7–8%). In this scenario, the global LCOE falls from $140/MWh in 2018 to less than $90/MWh in 2030 and close to $60/MWh in 2040.
- An **aggressive scenario** based on the same underlying technology costs and performance parameters as the moderate scenario, but which assumes low-cost financing (WACC of 4%). The global LCOE of offshore wind declines from $100/MWh in 2018 to $60/MWh in 2030 and to $45/MWh in 2040).

5.5.3 Offshore Wind System Integration Costs

The costs of integrating offshore power generation into the land-based electricity system include infrastructure costs (for expanding and adjusting the existing electricity infrastructure to feed in electricity production) and balancing costs (for handling deviations from planned production and extra costs for investments in reserves for handling power plant or transmission facility outages).

Offshore wind power requires an offshore grid as well as expanding the onshore transmission grid. The transmission or grid costs are closely tied to the regional regulations for connecting the project to the onshore grid (IEA 2019b). In 2015, the grid and balancing costs of integrating 50% of offshore wind power into the system were estimated at $43/MWh in 2019 prices (or €37/MWh) for offshore projects in Germany (Agora Energywiende 2015). These estimates were higher than the integration costs for photovoltaic (PV) solar and onshore wind ($5–20/MWh) because it costs more to connect with an offshore generation source. However, these costs are expected to decline as offshore wind projects increase and technologies improve. The average up-front cost to build an offshore wind project, including transmission costs, will drop by more than 40% over the next decade, according to the IEA. Such a drop would be due to innovation, economies of scale and supportive action to reduce costs by grid operators.[25]

Table 18.8 Levelised cost of electricity for conventional sources of energy, 2019

Type of energy source[a]	US $/MWH, 2019$ (3% discount factor)	US $/MWH, 2019$ (7% discount factor)
Conventional coal	71–103	72–152
Natural gas	67–146	83–110
Nuclear	28–70	41–111
Hydropower (seasonal)[b]	74	74

Notes: MWh megawatt-hour

[a] *Levelised cost of electricity generation (LCOE) estimates for coal, natural gas and nuclear are based on NEA and IEA (2015) country-level analysis of LCOE for the various technologies. The ranges show that the LCOEs will vary by location as each technology and each country faces a different set of risk profiles. Original estimates are converted from 2013 prices to 2019 prices using the Consumer Price Index inflation calculator*

[b] *LCOE estimates for hydropower are based on analysis of plants based in the United States (see Stacey and Taylor 2019). They calculate LCOE for new plants using EIA data (which used WACC of about 4%). They state that new plants have higher fixed costs and LCOE (than existing resources) as they begin their operational lives with a full burden of construction cost to recover*

Source: IEA and NEA (2015), Stacey and Taylor (2019)

For this analysis, we take a conservative approach and assume the grid and balancing cost is $43/MWh in 2020 and declines by 20% ($34/MWh) over 2030–2050.

5.5.4 Baseline Energy Generation Costs

In 2018, coal, gas, nuclear and hydropower accounted for 90% of the total electricity generation (IEA 2019a). We assume that, under the baseline scenario, demand for electricity will increase over 30 years (2020–2050) and additional investments in conventional sources of energy (mainly fossil fuels) will be made to meet the demand.

We analysed the LCOE of conventional sources of energy to estimate the current costs of energy generation in the baseline based on two discount factors (Table 18.8).

Based on the current energy mix and the discount factor, we estimate the global weighted average of LCOE in the baseline to be $86–94/MWh. We assume that by 2040 the LCOE will fall by 20% based on learning effects.

6 Additional Costs of Energy Generation from Offshore Wind

The following equation is used to calculate the additional costs of scaling up offshore wind production:

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[25] Wind corridors for onshore wind have helped to streamline the siting of transmission for multiple projects that allow multiple developers to share the cost. These innovations could help bring down costs.

$$\text{Costs of offshore wind energy generation} = \text{offshore wind generation costs} + \text{offshore wind integration costs} - \text{baseline energy generation costs}$$

The total costs of scaling up offshore wind power are shown in Table 18.9, with the moderate scenario costing \$250–884 billion and the aggressive scenario costing \$97–420 billion.

Table 18.9 Total costs of scaling up offshore wind production, 2020–2050

Scenarios	Description	Costs (US \$, billions, 2019\$)
Moderate	• Global LCOE falls from \$140/MWh in 2018 to less than \$90/MWh in 2030 and close to \$60/MWh in 2040 • Integration costs: Grid and balancing costs are \$43/MWh in 2020, declines by 20% over 2030–2050	250–884
Aggressive	• Global LCOE of offshore wind declines from \$100/MWh to \$60/MWh in 2030 and to \$45/MWh in 2050 • Integration costs: Grid and balancing costs are \$43/MWh in 2020, declines by 20% over 2030–2050	97–420

Source: Authors' calculations

6.1 Assessment of Benefits

Offshore wind energy can deliver a suite of health, environmental and ecological, and economic and social benefits.

6.1.1 Health Benefits

Due to its very low CO_2 emissions and negligible emissions of mercury, nitrogen dioxide and sulphur dioxide, as well as its 0 generation of solid or liquid waste, offshore wind energy production could have a positive impact on human health depending on what energy sources it displaces. Observational and modelling studies indicate that three million premature deaths are attributable to ambient air pollution and another 4.3 million to household pollution (WHO 2016). By multiplying the annual CO_2e emissions mitigation potential by the marginal cobenefits of avoided mortality (see Box 18.2), we estimate the total avoided damage costs (or discounted health benefits) from transitioning to offshore renewable energy at \$0.15–4.4 trillion over 30 years (2020–2050).[26]

6.1.2 Environmental and Ecological Benefits

Water Consumption Impacts

When estimating the impact of water usage for energy generation, we looked at water withdrawal and water consumption. Water withdrawal is the volume of water removed from a source, including water that is eventually returned to the same source; by definition, withdrawals are always greater than or equal to consumption (IEA 2016).[27] The type of cooling technology used mainly determines how much freshwater is withdrawn and ultimately consumed, although fuel mix, the power plant's role in the electricity system, turbine design and weather also influence the amount of water required (IEA 2016). Thermal power plants (coal, natural gas, oil, nuclear and geothermal) demand considerable amounts of water for cooling (IEA 2016) (Table 18.10). In contrast, studies show that wind systems require near zero water for energy generation and cooling (Macknick et al. 2011).

We estimate the water consumption to be 860–1315 gallons/MWh under the baseline. Using the true cost of water in terms of avoided damage to the environment, we estimate a range from \$0.10 per cubic metre (m^3) in water-abundant

Table 18.10 Water consumption factors for nonrenewable technologies

Fuel type	Cooling type[a,b]	Water consumption (Gallons/MWH)
Nuclear	Tower, once-through, pond	269–672
Natural gas	Tower, once-through, pond, inlet	198–826
Coal	Tower, once-through, pond	103–942
PV solar	n/a	26
Offshore wind	n/a	0

Notes: MWh megawatt-hour, PV photovoltaic

[a] *Dry cooling is also an option that is not discussed here as it is expensive and has limited application*

[b] *Once-through cooling involves lower water consumption but higher water withdrawal than circulating cooling systems. In some jurisdictions (typically arid), once- through cooling is no longer permitted. However, we provide estimates of this technology to demonstrate a conservative water consumption scenario*

Source: Macknick et al. (2011)

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[26] This is due to reduced criteria pollutants such as ozone and particulate matter (that are indirectly displaced).

[27] This analysis does not account for the impact of returning the water because it often gets returned at a different temperature, leading to thermal pollution.

areas to \$15/m^3 in extremely water-scarce areas (Trucost 2013). We estimate the benefits (discounted) of achieving offshore energy transformation through water savings alone to be \$1.3 billion to \$1.4 trillion over 2020–2050.

Climate Impacts

We used the social cost of carbon method (see Box 18.3) to estimate the value of reductions in GHG emissions attributable to offshore wind at \$344 billion to \$1.4 trillion over 30 years.

Impacts on Biodiversity

Building more offshore wind farms could have both positive and negative impacts on biodiversity. The net impacts have not been quantified monetarily, and they would vary depending on the location of the offshore wind farm and the policies and measures to address negative impacts. Effective marine spatial planning, combined with emerging ocean energy technologies, can be effective in mitigating biodiversity loss from ocean energy technologies and reinforcing biodiversity cobenefits (Hoegh-Guldberg et al. 2019).

The risks of installing wind farms in the marine environment include biological invasions, noise and disturbing vibrations to marine species, collisions between birds and wind turbine rotors and the presence of electromagnetic fields that can disrupt marine life and benthic habitats (Langhamer 2012; Sotta 2012). However, studies have shown a gap between perceived risks and actual risks, and the former arise from uncertainty or lack of data about the real impacts (Copping et al. 2016). While it is important to acknowledge possible impacts, some of the actual risks are likely to be small and can be avoided or mitigated (Copping et al. 2016). For example, spatial planning appears to reduce risks, such as collisions with seabirds and impacts on migratory cetaceans, to manageable levels (Best and Halpin 2019). However, as wind energy expands into new areas, it could become more difficult to mitigate impacts.

Wind farms can have positive environmental impacts by serving as artificial reefs for many organisms (Hammar et al. 2016). In addition, the prohibition of bottom trawling near offshore wind farms for safety reasons eliminates the disturbance of fish, benthos and benthic habitats.

Evidence from Belgium and Norway suggests that in areas with a homogeneous seabed, wind farms may enhance diversity (Buhl-Mortensen et al. 2012; Degraer et al. 2012).

6.1.3 Economic and Social Benefits

This analysis does not monetise the impacts on jobs and livelihoods to the wider community, but it acknowledges them qualitatively. Offshore wind energy can create jobs: German and UK case studies state that offshore wind development is more labour-intensive than onshore wind development because of the greater challenges inherent in building and operating offshore farms in marine environments (BMWi 2018; IRENA 2018a). In Germany, the offshore segment accounted for 17% of total German wind employment in 2016, even though it represents no more than about 10% of the country's current total wind capacity. Estimates predict that direct full-time employment in offshore wind will be around 435,000 globally by 2030 (OECD 2016).[28] Similar analysis by Ocean Energy Systems shows that deployment of other forms of ocean energy (tidal range, wave power and ocean thermal energy) can also provide new jobs and additional investments (Huckerby et al. 2016).

However, the net global impact of the growth of the ocean-based energy on net jobs across the whole of the energy sector are less certain because the entire energy sector will transition to cleaner energy sources. Moving to cleaner energy will lead to job losses in the fossil fuel sector, though ocean-based renewable energy has the potential to benefit workers transitioning from declining offshore fossil fuel industries (IRENA 2018a; Poulsen and Lema 2017; Scottish Enterprise 2016), minimising the costs of transition and the risks of structural unemployment.

6.2 Estimated Benefits and Costs

We estimated the B-C ratio under two approaches.

In the first approach, we estimated the ratio over 30 years (2020–2050), where additional energy production is calculated for each year against the BAU scenario, using present value benefits and costs. In the second approach, we calculated the B-C ratio for one unit of energy produced.

6.2.1 B-C Ratio Using Present Value Approach

Table 18.11 shows the high and low benefit-cost ratios for the first approach—calculating additional energy production for each year against the BAU using present values benefits and costs.

On average, there is a net positive benefit from expanding offshore wind production. The net present value of benefits was estimated to be \$253 billion to \$6.8 trillion over 30 years.

Table 18.11 Net benefits from scaling up offshore wind energy and benefit-cost ratio

Action	Net present value; net benefit (US \$, billions, 2020–2050)	Benefit-cost ratio (low)	Benefit-cost ratio (high)
Scale up offshore wind production	253–6849	2:1	17:1

Source: Authors' calculations

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[28] This is an estimate of direct jobs, not including indirect or induced jobs, derived from the economic activity of an offshore wind farm.

Table 18.12 Benefit-cost ratio for offshore wind production under varying LCOE levels

Scenario	Benefit-cost ratio
Scenario 1: LCOE is US $140/MWh; integration costs are $43/MWh; baseline costs are $86–94/MWh	0.9:1–3:1
Scenario 2: LCOE is $60/MWh; integration costs are $43/MWh; baseline costs are $86–94/MWh	4:1–16:1
Scenario 3: LCOE is $45/MWh; integration costs are $30/MWh; baseline costs are $68–75/MWh	7:1–28:1

Note: LCOE levelised cost of electricity; MWh megawatt-hour
Source: Authors' calculations

The ROI in 2050 can be high, as shown by the B-C ratio of 2-to-1 to 17-to-1 in 2050.

6.2.2 B-C Ratio for a Unit of Energy Generation and Transmission

We estimated the benefits for production of one additional unit of energy to be $75–300/MWh. The B-C ratio varies mainly depending on the LCOE of offshore wind assumed. We examined three scenarios with different LCOE values and found B-C ratios between 0.9-to-1 and 28-to-1 (Table 18.12).

Both approaches show that the value of the ROI will increase as the costs of energy generation for offshore wind fall with improved technologies and as actions are taken to reduce integration costs. The estimates should be treated as partial because they do not include key impacts that are discussed qualitatively, such as impacts (positive and negative) on biodiversity and on jobs and livelihoods in coastal communities.

Data Limitations and Caveats

Data limitations and caveats are described in Appendix 2. They include potential risks to biodiversity, variations in GHG mitigation depending on the fuel mix in the local grid, variations in LCOE depending on local market conditions, and omitting financial benefits from water savings.

6.3 Decarbonise the International Shipping Sector

Shipping is a significant source of emissions with identifiable reduction pathways (Hoegh-Guldberg et al. 2019). The sector is responsible for approximately 1 $GtCO_2e$ per year and represents around 3% of global anthropogenic CO_2 emissions (Smith et al. 2015). Based on current trends, GHG emissions will double by 2050 to roughly 2 $GtCO_2e$, compared with 2010 (Hoegh-Guldberg et al. 2019). In 2018, the United Nations International Maritime Organization (IMO) adopted a resolution[29] to reduce GHG emissions from shipping by at least 50% by 2050, relative to 2008 emission levels. However, greater ambition is needed to keep global temperature rise under 2 °C to 1.5 °C (Hoegh-Guldberg et al. 2019; UNFCCC 2015).

6.3.1 Baseline, Sustainable Transformation Pathway and Target Scenarios

The sustainable transformation pathway focuses on decarbonising only the international shipping sector. Although there is potential to reduce emissions in both domestic and international shipping, we focused on international shipping, which accounts for 55% of the total emissions in the sector (Olmer et al. 2017). The following scenarios were considered from Hoegh-Guldberg et al. (2019).

Under the BAU scenario, it is estimated that total annual GHG emissions from international shipping will grow from 800 megatonnes (Mt) in 2012 to 1100 Mt. in 2030 to 1500 Mt. in 2050. The mitigation potential assumes a 20–39% emissions reduction in 2030 from a 2008 baseline, and in 2050, a 50–100% emissions reduction from the 2008 baseline emissions (Table 18.13).

The upper-bound emissions reduction for 2050 assumes that all vessels move to full use of nonfossil fuels from renewable feedstock. The lower bound is set at 50%, taken as the minimum interpretation of the IMO's objectives in the initial GHG reduction strategy (Hoegh-Guldberg et al. 2019).

6.3.2 Assessment of Costs

Because only a small subset of the fleet is likely to be 'zero-carbon-fuels ready' by 2030, we assume the mitigation potential for 2030 to be mainly driven by maximising energy efficiency (Hoegh-Guldberg et al. 2019). This includes technological measures that increase the energy efficiency of a ship, such as altering its weight (using lighter materials) or design (such as hull coatings and air lubrication to reduce friction), and other ways to reduce or recover energy (such as via propeller upgrades and heat recovery). These measures could result in fuel savings of up to 25% (ITF 2018). In addition, energy could be saved by changes in how ships—and, more broadly, maritime transport systems—are operated, such as changes in speed, ship-port interface and onshore power. Over the last few years, both slower speeds and larger ship sizes have contributed to a decrease in shipping emissions (ITF 2018).

Table 18.13 Greenhouse gas mitigation potential from decarbonising international shipping, 2030 and 2050

Action	2030 Mitigation potential ($GtCO_2e$/year)	2050 Mitigation potential ($GtCO_2e$/year)
Reduce emissions from international shipping	0.2–0.4	0.75–1.50

Note: $GtCO_2e$ gigatonnes of carbon dioxide equivalent
Source: Hoegh-Guldberg et al. (2019)

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[29] See IMO (2018).

However, efficiency measures are ultimately limited by factors such as the efficiency of a propeller or an internal combustion engine that are impossible to improve beyond a certain point (IMarEST 2018). As those limits are approached, improvements have increasingly diminishing returns and become less cost-effective (IMarEST 2018). Hence, the cost of decarbonising international shipping is ultimately capped by the cost of switching to zero CO_2 emissions fuels and technologies (IMarEST 2018).

We refer to the IMarEST (2018) study to estimate the cost of GHG reduction in international shipping. The study assumes that significant absolute emissions reductions are achieved even at low marginal cost of carbon ($50/tonne) (IMarEST 2018).[30] The results from the same IMarEST (2018) model state that, depending on how prices evolve for renewable electricity in coming decades and other assumptions in the scenarios, a 70–100% absolute reduction in GHG emissions by 2050 can be achievable for a marginal abatement cost of $100–500/t$CO_2$e. By multiplying the cost per tCO_2e abated with the mitigation potential estimated in the Hoegh-Guldberg et al. (2019) study, we estimate the total costs (capital and operational) over 30 years to be $2.3 trillion to decarbonise shipping by 100%.[31]

6.3.3 Assessment of Benefits

The health, environmental and ecological, and economic and social benefits from the international shipping sector reducing its GHG emissions are summarised below.

Health Benefits

Reduced $PM_{2.5}$ from marine engine combustion mitigates ship-related premature mortality and morbidity (Sofiev et al. 2018). The annual avoided health damage cost to adults is calculated by multiplying the CO_2e emission mitigation potential by the average marginal cobenefits of avoided mortality (see Box 18.2). In addition to the impact on adult mortality, evidence shows that reducing shipping emissions will positively impact childhood morbidity by reducing childhood asthma (Sofiev et al. 2018). Based on the methodology outlined above for reducing adult mortality and for childhood asthma (see Appendix 3), we estimate the discounted cumulative health benefits from reducing emissions to be $1.3–9.8 trillion over 30 years (2020–2050).

Environmental and Ecological Benefits

Strong acids formed from shipping emissions can produce seasonal 'hot spots' of ocean acidification in areas close to busy shipping lanes. Hot spots harm local marine ecology and commercially farmed seafood species (Hassellöv et al. 2013). Reducing global GHG emissions, including shipping emissions, is critical to mitigating local and global ocean acidification.

A recent study found that lower trophic species such as bivalves were affected disproportionately due to the compounding effects of shifts in temperature, chlorophyll and ocean acidification. The commercial mollusc industry is estimated to lose over $100 billion by 2100 due to ocean acidification alone (Narita et al. 2012).

In addition, reducing ship speeds could positively impact marine mammals and other species. A 10% reduction in ship speed could reduce the total sound energy generated underwater by 40% and reduce the overall whale strike rate by 50% (Leaper 2019). Such measures would benefit marine species (including the whale population) globally, resulting in higher ecosystem service values (both recreational and nonuse values[32]) that will, in turn, improve human wellbeing. Because of uncertainty about the exact impact that measures to reduce GHG emissions would have on ocean acidification and noise, we have not been able to monetarily quantify these key impacts.

Reducing emissions in shipping will help avoid the most catastrophic impacts of climate change. We estimate the climate benefits (see Box 18.3) from reducing carbon emissions to be $0.8–1.6 trillion over 30 years.

Economic and Social Benefits

Estimates suggest that improved hull shape and materials, larger ships, drag reductions, hotel-load savings and better engines and propulsors, together with routing improvements, can deliver overall efficiency improvements of 30–55% (ETC 2018). The analysis indicates that reducing

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[30] This is because of the assumption about the availability of bioenergy; in these scenarios, it is significant relative to international shipping's total demand for energy. In this modelling, bioenergy is assumed to enter the fuel mix as a substitute for fossil fuels and, therefore, is at the same price as the fossil fuel equivalent and is not dependent on additional carbon price to stimulate its take-up. For example, the study assumes that bioenergy enters the fuel mix as a substitute for fossil fuels at the same price as the fossil fuel equivalent (and is not dependent on additional carbon price to stimulate its take-up), the supply of bioenergy is 4.7 exajoules and there is a low price/capital cost of moving to future shipping energy sources, particularly electricity, biofuel, hydrogen and ammonia. The costs of investments increase (and, consequently, the B-C ratio decreases) if we assume a scenario where the cost of alternative fuel is higher.

[31] Our estimates reflect both operational costs and capital investments. It is, hence, higher than the cost estimate provided in the recent analysis by the University Maritime Advisory Services (UMAS) and the Energy Transitions Commission for the Getting to Zero Coalition (2019), which states that approximately up to $1.6 trillion 'capital investments' is needed between 2030 and 2050 to achieve the IMO target of reducing carbon emissions from shipping by 100% by 2050.

[32] Nonuse values (e.g., existence, bequest and option values) are the benefit values assigned to environmental goods that people have not used or do not intend to use. For example, the current generation can place a value on ensuring the availability of biodiversity and ecosystem functioning to future generations (bequest value).

a vessel's speed by 10% (e.g., from 20 knots to 18 knots) results in a 19% reduction in cargo-hauling fuel consumption after accounting for the reduced shipping speed and the associated loss in shipping time (Faber et al. 2012). These savings are already included in the cost calculations for 2030.

Estimated Benefits and Costs

Based on the methodology outlined above, we estimated that there are net benefits from making investments to decarbonise the shipping sector. The net discounted benefit (average) over 30 years (2020–2050) is estimated to be $1.2–9.1 trillion. The B-C ratio is estimated to be 2-to-1 to 5-to-1 in 2050 (Table 18.14).

6.3.4 Data Limitations and Caveats

Data limitations and caveats include a lack of consideration of the secondary impact on commodity prices and the impact of all cost reductions (technology change) in the future. For details, see Appendix 3.

6.4 Increase the Production of Sustainably Sourced Ocean-Based Proteins

The analysis for this section builds on the estimates provided in *The Global Consultation Report of the Food and Land Use Coalition* (FOLU 2019), the analysis of Costello et al. (2016) that looks at the return from global fisheries under contrasting management regimes, the analysis of Sumaila et al. (2012) that measures the net present value of rebuilding fish stocks over 50 years, and the analysis of Mangin et al. (2018) that compares the benefits from fisheries management against the costs for individual countries.

To determine the level of ocean-based protein production required to ensure a healthy, balanced human diet by 2050, we refer to the EAT-*Lancet* Commission report (Appendix 4; Willett et al. 2019), which states that the ocean will be required to produce 85–90 million metric tonnes (mmt) of edible-weight ocean protein annually by 2050. It is estimated that the world (freshwater and ocean) currently produces only half that amount (FOLU 2019; Willett et al. 2019).

Table 18.14 Net benefit from decarbonising international shipping and benefit-cost ratio

Action	Net benefit by 2050 (US $, billions, 2019$)	Benefit-cost ratio (low)	Benefit-cost ratio (high)
Decarbonise international shipping	1152–9050	2:1	5:1

Source: Authors' calculations

6.4.1 Baseline, Sustainable Transformation Pathway and Target Scenarios

The 2019 FOLU report looks at ocean-based production across three sectors: wild marine capture fisheries, ocean-based fed aquaculture (finfish) and ocean-based nonfed aquaculture (bivalves). The production scenarios under BAU and the sustainable transformation pathways are shown in Table 18.15. Production is measured in million metric tonnes live-weight equivalent. Broadly, the transformation scenarios for the sectors were modelled in terms of possibilities of expanded production.

- **Wild-capture fisheries.** Costello et al. (2016) and Sumaila et al. (2012) estimate fisheries management that aims to maximise long-term catch (maximum sustainable yield) could increase fisheries production up to 96–99 mmt. This is higher than the current catch (80 mmt) and the projected BAU catch in 2050 (67 mmt) (Costello et al. 2019).
- **Fed mariculture production.** In the BAU scenario, fishmeal and fish oil feed requirements remain at current levels due to the absence of large investments into improving feed efficiency, limiting the growth of fed aquaculture (FOLU 2019). Under the sustainable transformation pathway scenario, aquaculture fishmeal and fish oil feed requirements decrease by 50% by 2050, allowing increased production in fed aquaculture to be achieved via measures such as feed efficiency and alternative feed replacement (FOLU 2019).
- **Nonfed mariculture production.** In the sustainable transformation pathway scenario, policy incentives to boost the eating of low-carbon food increase bivalve/mol-

Table 18.15 The business-as-usual and sustainable transformation pathways

Type of ocean-based food production	Business-as-usual scenario	Sustainable transformation pathway scenario
Wild-capture fisheries (marine)	Global annual marine capture production will decline from 80 mmt in 2020 to 67 mmt in 2050[a]	Global annual marine capture production stabilises at 96–99 mmt[b] by 2050
Fed mariculture (finfish)	Fed mariculture production remains at the 2020 level of 11.2 mmt[c]	Fed mariculture production increases to 22.4 mmt by 2050[c]
Nonfed mariculture (bivalves)	Bivalve mariculture grows to 28.5 mmt in 2050 from 16.3 mmt in 2020[c]	Bivalve mariculture grows to 65.2 mmt in 2050[c]

Notes: mmt million metric tonnes

[a] *Costello et al.* (2019)

[b] *Costello et al.* (2016, 2019); *Sumaila et al.* (2012); *this refers to the higher estimates of the Sumaila et al. optimal catch range under reform*

[c] *FOLU* (2019)

lusc production and consumption to 4% per annum as opposed to the BAU average annual growth rate of 3.1% over the last 10 years (FOLU 2019).

6.4.2 Assessment of Costs

The analysis in this paper builds on the investment cost estimates and assumptions in *The Global Consultation Report of the Food and Land Use Coalition* (FOLU 2019), Sumaila et al. (2012) and Mangin et al. (2018).

Capture Fisheries Reform

Analysis by Mangin et al. (2018) estimates that under a fisheries reform scenario, annual global fisheries management costs would be $13–15 billion, whereas under BAU, the costs are estimated at $8 billion.[33] Sumaila et al. (2012) estimate that the amount governments need to invest to rebuild world fisheries is between $130 billion and $292 billion in present value over 50 years, with a mean of $203 billion.[34]

Nonfed and Fed Mariculture Production

- Additional bivalve production (compared with BAU) is estimated at an average cost of $605 per tonne (FOLU 2019).
- In the sustainable transformation pathway scenario, the capital costs for setting up fed mariculture farms are estimated at $157 million for offshore mariculture and $60 million for nearshore mariculture for 2020–2030 (FOLU 2019; O'Shea et al. 2019).[35] Between 2020 and 2030, it is assumed that 25% of the additional production will come from new capital expenditures to build these farms (FOLU 2019). After 2030, we assume that the cost of investment will fall by 15%. The capital costs will fall from $157 million to $133 million over 2031–2050. All increases in production beyond 2030 come from new farms.
- Because mariculture expansion is limited by shortages and the rising costs of fishmeal made from forage fish, we assume that fed mariculture expansion is possible over 30 years (2020–50) because of a 50% reduction in traditional fishmeal, with the gap filled by novel feed ingredients such as insects or algae.[36] Although these alternatives currently cost more than fishmeal,[37] we assume prices will decline with innovation and scaled-up production.
- Increasing the scale of fed mariculture and replacing fishmeal and fish oil with alternative fish feed will lead to a change in the variable costs of mariculture farms. To calculate the impact on variable costs, we assumed that, until 2030, the price of alternative feed would be twice the price of fishmeal and then, because of innovations, it would fall to equal the price of fishmeal in 2030–2050.
- Public and private R&D spending across food and land-use systems was assumed to grow from 0.07% GDP (2018) to 0.1% of GDP by 2030. FOLU analysis assumes 20% of the additional R&D spending on food and land-use systems ($197 billion over 2018–2030) is allocated to alternative fish feed, intensification impacts and the scaling up of innovative production methods such as multi-trophic mariculture and offshore mariculture. After 2030, we assumed the R&D expenditure in the food and land-use systems would continue to grow at the same rate[38] (reaching 0.13% of GDP in 2040 and 0.17% in 2050), and the proportion spent on ocean-based proteins would remain the same.
- Under the Organisation for Economic Co-operation and Development 2030 scenario, mariculture would employ

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[33] The paper estimates a country-level B-C ratio for management improvements for 30 countries. It categorises landings in each country into three broad management categories: catch share, where managers and regulators set a scientifically determined catch limit on the amount of fish that can be caught using measures (e.g., community-based allocation, individual quotas, individual vessel quotas, individual transferable quotas, and territorial use rights for fisheries); strong catch controls, which include a broad range of management that can be classified as strong biological management without catch shares; and a broad 'other' category that consists of the rest of the fisheries referred to as open access. It focuses on three types of fisheries management costs: administration (or management), research and surveillance, and enforcement (Mangin et al. 2018).

[34] The estimated transition costs include the costs to society of reducing the current fishing effort to levels consistent with the maximum sustainable yield and the payments governments may decide to employ to adjust capital and labour to uses outside the fisheries sector (such as vessel buyback programs and alternative employment training initiatives for fishers).

[35] This is based on estimates that the average capital expenditure for a large-scale, high-tech farm is $6.50–20.00 per kg (O'Shea et al. 2019). The average production per farm is estimated to be 3000 tonnes/year (FOLU 2019).

[36] We estimated the increase in fishmeal and alternatives required under the sustainable transformation pathway scenario where mariculture increases to 22.4 t by 2050. The gap filled by novel alternatives and associated costs is calculated via the following steps. (1) We calculated the existing fishmeal requirements in the BAU using the feed conversion ratio (FCR) and fishmeal inclusion rate for salmon production. We use an FCR of 1.5 and a fishmeal inclusion rate of 25% (Konar et al. 2019). We assume the fishmeal inclusion rate decreases by 50% (to 13%) in the sustainable transformation pathway scenario. (2) We assumed that under the sustainable transformation pathway scenario, 50% of the fishmeal production (100 million t) will be replaced by alternative ingredients by 2050. (3) Finally, we used the current capital cost to produce feed ($1426/t) as a proxy to calculate the additional capital investment required to expand alternative feed (Suleiman and Rosentrater 2018). Using these steps, we estimated $145 billion in additional investments will be required in alternative feed to expand production to meet the gap caused by reducing traditional fishmeal usage.

[37] The fishmeal price in 2018 was approximately $1600/t.

[38] This reflects the gradual growth of R&D expenditure observed for the world over 2000–2010. For all countries within the Organisation for Economic Co-operation and Development, R&D expenditure grew from 2.1 to 2.4% in 2017.

three million farmers (OECD 2016). We assumed all mariculture farmers would receive training for sustainable production and improving feed efficiency ($450 per farmer [FOLU 2019]) over 2020–2050.

Based on these estimates and assumptions, the discounted costs are estimated to be $656 billion over 30 years (2020–2050).

6.4.3 Assessment of Benefits

Health Benefits

The real gain in health benefits is the potential to increase sustainable protein supplies by encouraging more fish consumption (produced via sustainable means) over other protein sources. This would reduce human mortality and morbidity from reduced GHG emissions (see below for the link between GHG emissions and animal-based proteins), increase healthier diets and reduce health costs from reduced pesticide and antimicrobial exposure. This is estimated to be approximately $170 billion in 2030 and $390 billion in 2050 (FOLU 2019).

Sustainable sourcing of ocean protein and micronutrients also helps diversify nutritious food supplies, particularly for poorer coastal communities that depend disproportionately on fish for their protein and micronutrient consumption. The distributional health benefits to poorer communities have not been analysed or quantified here.

Environmental and Ecological Benefits

Livestock production has high GHG emissions and requires extensive land use. The demand for animal- based protein is projected to increase even more quickly than overall food demand by 2050 due to increases in the world population and in incomes across the developing world (Searchinger et al. 2019). Since foods vary widely in their embedded land use and GHG emissions per unit of protein (Poore and Nemecek 2018), changes in the composition of future diets could greatly affect the emissions consequences of growth in protein demand (González Fischer and Garnett 2016). It is estimated that CH_4 and N_2O emissions in the BAU food system scenario will grow from 5.2 $GtCO_2e$ in 2010 to 9.7 $GtCO_2e$ in 2050 (Springmann et al. 2018). Of that projected growth, over 75% will come from projected growth in animal products (Hoegh-Guldberg et al. 2019).

Ocean-based proteins are substantially less carbon intensive than land-based animal proteins (especially beef and lamb), with farmed bivalves being particularly climate friendly (Hoegh-Guldberg et al. 2019).[39] Therefore, actions that shift diets towards ocean-based proteins can reduce pressure on land and also reduce emissions. Moving to diets that are less dependent on terrestrial animal products, especially beef and lamb, would also slow the growth in demand for freshwater to support livestock agriculture (Hoegh-Guldberg et al. 2019). The transition, if properly managed, could yield benefits of $330 billion in 2050 (FOLU 2019).

In addition, such diet shifts will reduce deforestation, the majority of which will be driven by clearing forests for future meat production and consumption. Searchinger et al. (2019) estimated that animal-based foods accounted for roughly two-thirds of agricultural production emissions in 2010 and more than three-quarters of agricultural land use. Under BAU, the analysis estimated that agriculture would expand by nearly 600 million ha (an area nearly twice the size of India), including the expansion of 400 million ha of pasturelands (Searchinger et al. 2019). The additional reduction in emissions from preventing deforestation has not been included in the estimated benefits.

6.4.4 Economic and Social Benefits

Reforming fisheries will result in an increase in revenues and profits to fishers in the long term. Costello et al. (2016) state that after all fisheries are optimally managed, it will take 10 years for stocks to recover and will result in $53 billion in fisheries profits against the BAU scenario. Sumaila et al. (2012) estimate that rebuilding world fisheries could increase profits from the current negative $13 billion to a positive $77 billion per year. Comparing these benefits to the cost of management, Sumaila et al. (2012) and Mangin et al. (2018) show that the cumulative benefits of sustainable management of fish stocks exceed the management costs. Sumaila et al. (2012) state that rebuilding fisheries stock will deliver a net gain (net present value) of between $600 billion and $1.4 trillion over 50 years, versus transition costs of $130–292 billion.[40]

Estimated Benefits and Costs

Based on key reports and papers, the benefits from increasing the share of sustainably produced ocean-based proteins in diets is estimated to be 10 times the costs (Table 18.16). Evidence indicates that while the global B-C ratio for fisheries management reform is about 9.2-to-1, the ratio is higher than 200 for some countries (Mangin et al. 2018). Sumaila

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[39] This does not include farmed shrimp, which can be quite high in GHGs. However, salmon/marine fish and bivalves score well in terms of lower GHG emissions.

[40] The lower bound corresponds to 82 t of catch and the upper bound, 99 t, which is closer to the Costello et al. (2016) estimates. To be consistent, we used both cumulative benefit and cost estimates from Sumaila et al. (2012), which offer a scenario in which the optimal fish landings increase to 99 t when calculating the total net present value for increasing consumption of sustainably produced ocean based protein from capture fisheries, fed aquaculture and nonfed aquaculture. The net gains are present value estimates calculated using a 3% discount rate (Table 18.17).

Table 18.16 Net benefits from increasing the production of sustainably sourced ocean-based proteins and benefit-cost ratio

Action	Net benefit by 2050 (US $, billions, 2019$)	Benefit-cost ratio
Increase production of sustainably sourced ocean-based protein in diets	6678	10:1

Source: Authors' calculations based on estimates from FOLU (2019)*, Mangin et al.* (2018)*, Sumaila et al.* (2012)

et al. (2012) estimate the B-C ratio for rebuilding global fisheries to be as high as 7:1. The value of net benefits is estimated to be $6.7 trillion over 30 years; the total benefits are $7.4 trillion versus $769 billion total costs.[41]

Data Limitations and Caveats

The estimates do not fully take into account the effects of climate change and ocean acidification. We recognise that there are regional differences and that there are barriers to shifting diets. See Appendix 4 for more details.

7 Conclusion

The overall rate of ROI can be high, with the average B-C ratio ranging from 3-to-1 to 12-to-1 (Table 18.17), and in some cases, such as conservation of mangroves and fisheries reform (for particular countries), it can be much higher. Our research found that investing $2.0–3.7 trillion globally across the four areas from 2020 to 2050 could generate $8.2–22.8 trillion in net benefits.

Actions to transform these four areas will bring multiple benefits. The total monetised and discounted benefits are estimated at $10.3–26.5 trillion over 2020–2050.

Monetised benefits include health benefits, such as reduced mortality from improved air quality, reduced childhood asthma and improved health outcomes from dietary shifts towards sustainably produced ocean-based protein; environmental benefits, such as avoided property losses from coastal flooding, the prevention of land degradation and reduced water usage; and economic benefits, such as reduced production costs due to technological improvements and increased profits from higher fisheries productivity.

The total monetised and discounted costs are estimated to be $2.0–3.7 trillion over 2020–2050. The costs assessed include costs to business (capital costs to set up new infrastructure, R&D costs and increases in variable costs), costs to government (regulatory costs, monitoring costs and research costs) and costs to households (loss of forgone income).

Table 18.17 Summary of benefit-cost ratios for the four action areas in 2050

Action	Average benefit-cost ratio
Conserve and restore mangroves[a]	3:1
Decarbonise international shipping[b]	4:1
Increase production of sustainably sourced ocean-based proteins	10:1
Scale up offshore energy production[c]	12:1

Notes:
[a] *The ratio presented is the combined ratio for mangrove conservation and restoration. When assessing specific interventions, the benefit-cost ratio for conservation is estimated to be 88:1 and for restoration 2:1*
[b] *The benefit-cost ratio estimated for decarbonising international shipping ranges from 2:1 to 5:1*
[c] *The benefit-cost ratio estimated for scaling up of global offshore wind energy production ranges from 2:1 to 17:1*
Source: Authors' calculations

A number of impacts (both benefits and costs) have not been monetised but are important and must be considered during the policy decision-making process. These include the following considerations:

- Reduced GHG emissions have a positive correlation with the reduced risk of ocean acidification. The measures assessed can positively impact lower trophic species such as bivalves, which are affected disproportionately due to the compounding effects of shifts in temperature, chlorophyll and ocean acidification.
- The tourism value of mangroves (and other coastal ecosystems) may increase over time as biomass and diversity increase within the protected areas.
- A number of ecosystem services from mangrove protection and restoration have not been quantified.

  For example, vegetated coastal habitats are used by a remarkable number of marine and terrestrial animals. Dense mangroves buffer ocean acidification and are becoming recognised as valuable natural systems that can help treat wastewater (Ouyang and Guo 2016).
- Measures to reduce emissions in shipping that involve lowering ship speeds reduce the total sound energy generated and overall whale strike rate and, hence, positively impact marine mammals and other species.
- The distributional impacts of the benefits and costs have not been measured. For example, poor coastal families are the most vulnerable in natural disasters, so building ecosystem resilience to protect them from coastal flooding and cyclones will not only safeguard their valuable assets but also generate tremendous social benefits (e.g., feeling safe) that cannot be easily monetised. The estimates also do not take into account the additional nutritional benefits to human health in terms of micronutrients, particularly in low- and middle-income countries.
- The analysis does not account for changes to the B-C ratio based on changes in the global physical risk profile associ-

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[41] The B-C ratios vary across the countries and range from 1.7 up to 268, with a median of about 14 for catch share management (Mangin et al. 2018).

ated with climate change. Often, the costs of climate change–related risks are underestimated, including the potential damage of weather-related shocks and sea level rise. If 'resilience' (e.g., through the integration of natural flood defences) is built into investments, then the benefits (e.g., of protective mangroves) could include a reduction in the cost of capital (due to improved risk-adjusted performance metrics) and/or reduced long-term operational expenses (e.g., through avoided losses and reduced maintenance costs).

Given that the B-C ratios in Table 18.17 are a partial estimate of all benefits and costs likely to accrue as a result of the specified investments, they should be treated as indicative to provide the relative scale of benefits from sustainable ocean-based investments compared with the costs. Further research and analysis to address gaps in quantifying benefits will help provide a more complete picture of their value versus their costs. The analysis does not attempt to show the regional variation of the costs and benefits, nor does it show the distribution of benefits and cost across society (especially focusing on the impact on vulnerable groups). Conducting these assessments should be a key step when implementing ocean-based policies and regulations.

Although data limitations prevented a full accounting of all benefits and costs, the results of the analyses suggest that taking the following actions to transform the ocean economy will generate a host of benefits that are larger in magnitude than the costs:

- **Conserving and restoring mangroves.** While the B-C ratio for restoration is lower than for conservation, both types of interventions yield significant benefits and, hence, are both important to ensure a high ROI. Protection measures to conserve these ecosystems should be enhanced along with measures that provide incentives for restoration (e.g., payment for ecosystem services schemes) (Hoegh-Guldberg et al. 2019).
- **Scaling up offshore wind energy production.** Scaling up offshore wind energy to replace fossil fuel–based sources of power generation will help deliver better local health outcomes, reduce risks of damages from climate change, create jobs and deliver immediate environmental benefits such as reduced water usage. Measures such as marine spatial planning is key to ensuring offshore wind technologies amplify these benefits as well as mitigate any environmental risks to habitats and marine species (Hoegh-Guldberg et al. 2019).
- **Decarbonising the international shipping sector.** Transitioning international shipping to net-zero emissions by 2050 will be costly, but these measures will be key to realising the estimated scale of benefits (health outcomes and environmental benefits), which substantially outweigh the costs.
- **Increasing the production of sustainably sourced ocean-based proteins**. Substantial gains in fisheries productivity can be achieved through better management of fish stocks, which eliminates overfishing, illegal and unregulated fishing and discards of nonmarketable fish. Sustainable marine aquaculture practices will also help meet the growing food demand. Technological innovation and adoption in breeding, production systems, disease control and environmental management will help improve mariculture's productivity and environmental performance (Waite et al. 2014). Encouraging innovation can make valuable contributions to the future scalability and lower prices of substitutes as forage fish resources become scarce (Konar et al. 2019). Incentives are required to shift diets towards low-carbon ocean-based proteins and away from high-carbon land-based sources of protein (Hoegh-Guldberg et al. 2019).

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Appendix 1. Conservation and Restoration of Mangrove Habitats

Increasing Ecosystem Services from Mangrove Conservation and Restoration

Vegetated coastal habitats are used by a remarkable number of marine and terrestrial animals (Li et al. 2018; Rog et al. 2017). Dense mangroves trap and stabilise sediments that buffer the effects of floodwaters and tidal movements. They are becoming recognised as valuable natural systems that can play an important role in wastewater treatment systems (Ouyang and Guo 2016). The values of these ecosystem services can be significant, as demonstrated in Box 18.5, which provides a local example of the scale of these values for mangroves in Myanmar. While global value estimates of ecosystem services exist (i.e., Costanza et al. 1997, 2014; de Groot et al. 2012), many of these estimates are resulting from meta-analysis (i.e., analysis of analyses) rather than primary valuation studies. Hence, there have been concerns around the validity of using these values for simple benefit transfer without accounting for specific characteristics of the sites where ecosystem service value needs to be estimated (Himes-Cornell et al. 2018). We thus excluded them from the current B-C ratio analysis. However, as new primary valuation data become available, incorporating such benefits will improve marine decision-making.

Data Limitations and Caveats

- We excluded salt marshes and seagrasses from the calculation due to limited global data availability for both in terms of benefit assessment. During the literature review, only one study (Carnell et al. 2019) was found to assess the improvement in fisheries productivity through seagrass conservation, but the estimate is very local, pertaining only to Australia. Restoring salt marshes and seagrasses is found to be more expensive than restoring mangroves because most salt marsh and seagrass restoration efforts did not reach economy of scale.
- The actual conservation and restoration costs for mangroves might be lower or higher depending on the specific location, the sizes of the targeted areas and the measures used. Total restoration costs are up to 30 times cheaper in countries with developing economies (compared to Australia, European countries and the United States) (Bayraktarov et al. 2016).
- The analysis assumes a survival rate of 51.3% for the restored area, based on median survival rates provided by Bayraktarov et al. (2016). In reality, however, survival rates vary significantly between sites due to a few factors in play. First, the survival rate of mangroves is highly species-specific (Mitra et al. 2017). Second, a lack of incentives to engage local residents in the long-term management of restored areas is another reason for low survival rates (Hai et al. 2020). Addressing these factors will be key to improving restoration survival rates and achieving the scale of the benefits described in this study. Restoration efforts should follow a protocol that includes diagnosing the causes of the deterioration or deforestation of the mangroves, setting a baseline, planning restoration activities and long-term monitoring of the restoration project (Hai et al. 2020). Strong community participation in managing the ecosystem, including in the planning, implementation, management and monitoring, will be essential to ensure the success of restoration efforts.
- It is not yet understood how climate change will affect the productivity and resilience of coastal mangroves. In marine ecosystems, rising atmospheric CO_2 and climate change are associated with concurrent shifts in temperature, circulation, stratification, nutrient input, oxygen content and ocean acidification, with potentially wide-ranging biological effects (Doney et al. 2012). However, there is less confidence regarding the influence temperature will have on interactions among organisms, which is important for ecosystem productivities (Kennedy et al. 2002).
- The analysis does not account for the opportunity costs of coastal developments. The economic value of protecting and restoring coastal habitats, even when the necessary legal framework is in place, often loses out to the economic value of coastal development—even when sea level rise, storm surge and other risks are clearly present. To mitigate these risks, a better understanding of the drivers of degradation is needed, as are measures (policy and educational) that aim to change consumer/human behaviour and raise awareness of the benefits derived from nature-based solutions.
- Marine and coastal ecosystem conservation may result in short-term economic losses due to the forgone economic gains from any prohibited or reduced commercial fishing activities (opportunity costs). However, in the long term, this will help increase the productivity of fisheries in nearby fishing grounds through fish migration and reduce the risk of ecosystem collapse due to overfishing. The conservation benefits estimated are highly dependent on the annual carbon mitigation potential estimated by Hoegh-Guldberg et al. (2019) and the avoided risk of climate damages estimated using the social cost of carbon.

Box 18.5 The Economic Value of Key Mangrove Benefits in Myanmar

The values for ecosystem services of mangroves in Myanmar, as estimated by Estoque et al. (2018), illustrate the scale of the benefits that accrue to society from various ecosystem services.

In Myanmar, a mangrove's most valuable service is as a fish nursery (US $9122 per hectare [ha] per year) and as coastal protection from storm surges ($1369/ha/year). Recreational benefits are estimated at $476/ha/year. Mangroves also regulate water flow ($275/ ha/year) and water quality ($61/ha/year) (see Table 18.18).

Table 18.18 Value of mangroves in Myanmar

Ecosystem service	Valuation method	Value (2018US $/ha/year)
Wood-based energy and timber	Value of marketed and nonmarketed production	7.22
Coastal protection	Avoided expenditures on physical reclamation and replenishment	1369.28
Hazard mitigation	Costs of equivalent engineered storm protection defences	349.01
Regulation of water flow	Expenditures saved on alternative freshwater sources (alternative deep well and borehole drilling, piping)	275.25
Regulation of water quality	Reduced costs of wastewater treatment and sediment trapping	617.13
Mitigation of climate change	Potential value of carbon emissions reductions offsets sales	304.64
Maintenance of fisheries nursery populations and habitat	Contribution to on-site and off-site capture fisheries	9112.45
Recreation and experiential	Tourism expenditures and earnings	475.97
Cultural, amenity and aesthetics	Domestic and international visitor willingness to pay	28.46

8 Appendix 2. Scaling Up Offshore Wind Energy Production

Data Limitations and Caveats

Potential risks to biodiversity could arise or increase with the expansion of wind energy, especially as it moves farther from the coast. In such cases, it could be more difficult or costly to mitigate impacts on habitats and wider biodiversity.

- The types of generation displaced by ocean energy will depend on the specific generation technologies and costs in places where ocean energy is located. On grids that have a high share of zero-carbon generation, including hydropower and nuclear energy, adding ocean energy will not decrease emissions significantly. Conversely, for grids with a high share of carbon-intensive generation, emission displacements could be significant.
- The cost of building more offshore wind generation will vary depending on the supply chain and infrastructure available in each market. The investment required will be much higher for developing nations than for countries like Denmark that already have a wind power market.
- The analysis focuses solely on offshore wind energy generation because the projected future costs of other ocean renewable energy installations are subject to high uncertainty because energy development is still immature. Further analysis in this area will help provide a more holistic picture on the ROI for the ocean energy sector overall.
- Water-saving benefits are estimated based on the opportunity costs of water. Direct financial benefits are also associated with water savings, but we excluded them from the benefit assessment because local water prices vary greatly across countries.

Appendix 3. Decarbonising International Shipping

Estimating the Avoided Costs of Childhood Asthma

In schoolchildren, asthma leads to lost school days, which limits academic performance and has consequent psychological effects. Therefore, children with asthma have more indirect costs than older asthmatics, as the direct cost to parents is limited to missed workdays and other expenses. The total avoided costs from childhood asthma are estimated by summing the health care costs, the cost of school absenteeism and adult missed workdays. The following assumptions are made to derive the avoided costs from childhood asthma:

- Globally, 86 million children could suffer from asthma, based on the fact that 334 million people in the world have asthma and 26% of the world population is 14 years or younger (Global Asthma Network 2018).[42] Evidence-based regression analysis shows that 16% of these cases could be attributed to shipping (Sofiev et al. 2018), accounting for 14 million childhood asthma cases.
- Sofiev et al. (2018) states that childhood asthma morbidity due to shipping declines by 54%, from 14 million children affected in the BAU case to 6.4 million children in the 2020 Action case.[43] We assume these benefits are delivered in 2030 (i.e., when 54% of children suffering from asthma are asthma free). We assume a 100% reduction of GHG emissions in shipping will reduce childhood morbidity cases (attributable to shipping) by 100% (14 million).
- The average missed days is estimated to be 6.4 days per child (Nunes et al. 2017; Ojeda and Sanz de Burgoa 2013), and we assume at least one adult loses that many days of work per year to care for the child. The value of additional days lost attributable to asthma per year was $301 for each worker and $93 for each student (Nunes et al. 2017).

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[42] Without adjusting for the higher prevalence for asthma among young and old persons.

[43] The 2020 Action assumes on-time implementation of the IMO’s 0.5% low-sulphur fuel standard.

- The average annual health financial costs to government for treating pediatric asthma is estimated to range from $3076 to $13,612 per child in the United States (Perry et al. 2019). We take this as a proxy of the global health care cost to treat the illness.

Data Limitations and Caveats

- The analysis does not incorporate all potential cost reductions from innovation and increased R&D efforts. In this respect, the model is conservative because these factors would be expected to reduce technology capital costs. The analysis does not account for additional infrastructure investments such as safe storage and handling of hydrogen/ammonia at the ship-to-shore interface.
- The costs of investments increase (and consequently B-C ratio decreases) if we assume a scenario where the cost of alternative fuel is higher.
- The analysis does not compare the carbon impact of ship transportation versus air transportation. Investment in cleaner ships to meet demands from a growing economy will lead to a lower carbon footprint solution for global trade and travel (versus ground or air transport of goods and people).
- The analysis is static and does not analyse the secondary or indirect impacts following the shipping sector transitioning to a low-fuel economy. Although switching to cleaner fuel will impose costs to the shipping industry, the overall impacts on the economy will depend on how the firms absorb the increase in costs and, thus, are relatively uncertain. Being faced with higher cost, the industry could transfer part of the impacts to the price of final commodities (more likely if they are price inelastic), produce more local product, or reduce profit margins, which would lead to lower future capital investment until the industry's market equilibrium returns. The overall impact on consumers and households will depend on which of these impacts dominate, and by what extent. In most developed economies, impacts are expected to be negligible, and there are policy options for managing impacts in especially vulnerable and/or disproportionately impacted countries.

Appendix 4. Increasing the Production of Sustainably Sourced Ocean-Based Proteins

Data Limitations and Caveats

- The report by the EAT-*Lancet* Commission has set out scientific targets for healthy diets that will optimise human health (Willett et al. 2019). By its own admission, the report did not have the scope to fully analyse fishing and mariculture systems globally. Therefore, while some estimates were included on recommended fish intake, more detailed analysis is needed. EAT, along with other partners,[44] is supporting further work to expand scientific understanding of the role of ocean-based protein for planetary health and human well-being. This research, referred to as the Blue Food Assessment, aims to outline pathways for a transformation to sustainable and healthy blue food for all people on the planet, now and into the future. Analysis has focused on marine food production, but a greater understanding of aquatic food production as a whole (including freshwater fisheries and aquaculture)[45] is needed to evaluate the benefits and costs of aquatic food to human health and the environment. Those working on the Blue Food Assessment have recognised this and aim to incorporate it into the analysis.
- The fisheries reform scenarios are optimistic and assume optimal fisheries management everywhere, which may not be achievable in reality. In addition, the impacts of climate change, such as warming sea temperatures, on fish stocks and their movements have not been fully taken into account in this paper because they are difficult to model and cost. The authors recognise that impacts on production could be significant in some regions.
- The projections do not incorporate the potential impacts of ocean acidification on fish and fisheries. There is a lack of sufficient understanding of the capacity for marine organisms to adapt through acclimation as well as transgenerational and evolutionary adaptation (Gaylord et al. 2015; Munday 2014; Munday et al. 2013) to reliably predict ocean acidification impacts on marine populations and ecosystems (FAO 2018).
- The FOLU (2019) analysis states that the benefits are the difference between the global hidden costs under the better future and current trends scenarios. It provides an indicative estimate of the potential benefits accruing to the global economy from following the better future development path relative to remaining on the current trajectory. For the aquaculture sector the FOLU does not estimate the increase in revenues from production or direct benefit in terms of value added to GDP (which is accounted for under the fisheries reform scenario); rather, it is a reduction in the size of the externalities currently stemming from food and land use.

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[44] Partners include the Food and Agriculture Organization, Friends of Ocean Action, Stanford Center for Ocean Solutions, Stockholm Resilience Centre, World Economic Forum and World Resources Institute.

[45] Currently, the majority of aquaculture production is inland or freshwater, which constitutes 64% of the total global aquaculture production, and the proportion is likely to be higher in Asia (FAO 2018).

- There are many barriers to shifting diets away from emission-intensive land-based sources of protein such as beef and lamb.[46] Consumer purchases are typically based on habit and unconscious mental processing rather than on rational, informed decisions (Ranganathan et al. 2016). Factors such as price, taste and quality tend to be more important than sustainability in purchasing decisions (Ranganathan et al. 2016). The costs of policy measures and business practices—such as private/public procurement, marketing and campaigning costs or sending clear market signals via carbon taxes or changes in subsidies—to enable a change in diet have not been estimated in this analysis. Several assumptions have been used to estimate the costs; hence, these should be treated with caution.
- The estimates do not take into account the additional nutritional benefits to human health in terms of micronutrients, not just protein, particularly in low- and middle-income countries. Ocean-based food production provides food security during extreme events (e.g., heavy rainfall and hurricanes) when the supply of land-based food sources is affected and limited.
- The average B-C ratio calculated here hides the regional and local variances that will occur in aquatic food production. These variances are likely to impact the livelihoods of smaller-scale fishers and farmers the most, and they often have the lowest resilience to changes in capture/farming levels.

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We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.

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[46] Reducing consumption of animal-based foods should not be a goal for people who are underconsuming. Animal-based foods provide a concentrated source of some vitamins and minerals that are particularly valuable to young children in developing countries whose diets are otherwise poor (Ranganathan et al. 2016).

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