**Technical assessment for**

***Macroalgae Protection***

Sector: Oceans

Agency Level: Government

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# Executive Summary

Macroalgae have been excluded from Blue Carbon schemes despite being the primary producers in coastal areas. Recent findings have quantified the long- term carbon sequestration potential of macroalgae at 173 TgC yr-1, exceeding the carbon buried in coastal angiosperm environments, such as mangroves, saltmarshes, and seagrass beds (111-131 TgC yr-1).

Project Drawdown defines *Macroalgae Protection*as the legal protection of wild macroalgae forest ecosystems. The solution is assumed to be developed in ocean areas which do not have alternative uses prior to the deployment of the solution. Related solutions include *Seaweed Farming,* which is the culturing, cultivation and harvesting of different macroalgae species in the ocean, and *Macroalgae Restoration,* defined as processes or programs designed to return wild macroalgae forest ecosystems to a previous state from a degraded condition. It is assumed that  *Macroalgae Protection* primarily happens at the government level.

Out of a total ocean area available for the solution of 355 million hectares, the current solution adoption (2018) is assumed to be zero million hectares due to the lack of data. Four custom adoption scenarios were developed based on a variety of assumptions regarding total percentage of ocean area in Marine Protected Areas (MPAs) by 2050 and annual growth rate of MPAs. These scenarios were combined to produce *Plausible* (Average of All), *Ambitious* (High of All), and *Maximum* (highest individual) scenarios.

Total adoption in the *Plausible Scenario* is 160 million hectares in 2050, representing 45 percent of the total suitable area. Total adoption in the *Ambitious Scenario* is 199 million hectares in 2050, representing 56 percent of the total suitable ocean area. Total adoption in the *Maximum Scenario* is 265 million hectares in 2050, representing 75 percent of the total suitable ocean area. Climate impact is 1.84, 2.28, and 4.02 gigatons of carbon-dioxide equivalent in the *Plausible, Ambitious* and *Maximum* scenarios respectively.

# Literature Review

## State of practice

A great deal of focus in the scientific community has recently been directed on the concept of “Blue Carbon”, referring to the capacity of marine plants to bind CO2 and draw down greenhouse gases from the atmosphere (Duarte et al., 2013; Mcleod et al., 2011; Nellemann & GRID Arendal, 2009). Globally, over half (55 percent) of the carbon captured annually by photosynthetic activity is captured by marine organisms (Arrigo, 2005; Bowler et al., 2009; Falkowski, 2004; Simon et al., 2009). While coastal ecosystems (seagrasses, mangroves, and wetlands) have received the majority of attention in Blue Carbon discussions, the abundance of macroalgae in the ocean suggests it also is an important potential Blue Carbon system.

Macroalgae alone take up 1.5 Pg C per year in net primary production and are an important part of the global autotrophic community (Krause-Jensen & Duarte, 2016). Land and ocean systems cycle nearly equivalent amounts of carbon every year, despite ocean plant biomass representing a small fraction (just 0.05 percent) of that in terrestrial environments (Bouillon et al., 2008; Houghton, 2007). This difference between standing biomass on land and in the ocean is attributable to the lifecycle and growth forms of marine algae, including phytoplankton and marine macroalgae. These organisms fix an enormous amount of carbon and recycle carbon quickly. The fate of such carbon has been of interest and consideration, to better understand the role which algal fixation plays in long-term sequestration of carbon by the oceanic biological pump. Recent findings indicate that global macroalgae facilitates the export of 679 Tg C yr-1 (Krause-Jensen & Duarte, 2016). Of this, an estimated 14 Tg C yr-1 is sequestered in sediments and another 152 Tg C yr-1 in the deep ocean. Total carbon sequestration by macroalgae is estimated at 173 TgC yr-1 with a range of 61– 268 Tg C yr-1 (Krause-Jensen & Duarte, 2016; Ortega et al., 2019). These estimates exceed that for carbon buried in coastal angiosperm environments, such as mangroves, saltmarshes, and seagrass beds (111-131 TgC yr-1) and underscore the importance of biological CO2 sequestration by macroalgae (Duarte et al., 2005; Krause-Jensen & Duarte, 2016).

***Biogeography of Macroalgae Forests***

The *Macroalgae Protection* solution focuses on macroalgae forests, or dense assemblages of large, canopy-forming macroalgae. Macroalgae forests are broadly distributed throughout the global ocean, especially in temperate subtidal ecosystems (Figure 1.1), and create habitats for several fish and invertebrate species (Christie et al., 2009; Filbee-Dexter et al., 2019; Kjell M. Norderhaug & Christie, 2011). The most well-known macroalgae forests are those created by true kelps, or large brown algae that are common in temperate subtidal ecosystem (Bennett et al., 2016; Bolton, 2010; Krumhansl et al., 2016; Steneck & Johnson, 2013; Wernberg et al., 2019). Kelp are large (up to 40 meters or longer), very fast-growing macroalgae that extend from the shoreline down to depths exceeding 60 meters in some regions (Bennett et al., 2016; Graham et al., 2007, n.d.; Layton et al., 2020) and, depending on the species, can have a lifetime of up to 25 years (Layton et al., 2020; Steneck & Johnson, 2013). Due to their fast growth rates, kelp forests are extremely productive (Bennett et al., 2016; Mann, 1973), with productivity driven by temperature and availability of light and nutrients (Bearham et al., 2013; Gagné et al., 1982; Gattuso et al., 2006; Steneck et al., 2002).

True kelps (order Laminariales) include the genera *Macrocystis, Nereocystis, Laminaria, Saccharina, Ecklonia, Lessonia, and Eualaria,* and are most dominant in the northern hemisphere. Specifically, kelps of the genus *Laminaria* are most dominant in the Atlantic ocean and coastal China and Japan, and *Macrocystis* and *Nereocystis* dominate the west coast of North America. Though kelps are less dominant in the southern hemisphere compared to the northern hemisphere, *Ecklonia* is common in some areas of Australia, New Zealand, and South Africa, and there are *Macrocystis* forests off the coasts of Chile, New Zealand, and other southern locations (Dayton, 1985).

While kelp forests are the most widely studied macroalgae forest, in many parts of the world macroalgae forests are dominated by other species, including fucoid algae (Coleman & Wernberg, 2017). Temperate fucoid (order Fucales) genera include *Durvillaea* and *Phyllospora*, and are more dominant in the southern hemisphere, especially the temperate coasts of Australia (also called the Great Southern Reef) (Coleman & Wernberg, 2017). *Sargassum* seaweeds, which are also in the order Fucales, exist in both benthic and free-floating forms and are abundant in the tropical and subtropical Atlantic Ocean (Coleman & Wernberg, 2017; Gouvêa et al., 2020).

Map

Description automatically generated

Figure 1.1. Distribution of kelp forests. Source: Wernberg and Filbee-Dexter 2019.

***Carbon Sequestration in Macroalgae Forests***

Macroalgae forests contribute an estimated 1.5 Pg C year-1 to global net primary production, yet have historically not been included in blue carbon accounting. Initially, their reliance on rocky habitat led to the assumption that the carbon in macroalgae was not subject to long-term sequestration via burial in soft sediments. However, nearly half of the carbon in macroalgae forests is exported, and some of this exported carbon is sequestered in deep sea sediments (Figure 1.2). Primarily through the mechanism of export to the deep sea, Krause-Jensen and Duarte (2016) estimated that macroalgae forests sequester about 173 TgC yr-1. Currently, it is well understood that macroalgae carbon is exported to the deep sea, but it is difficult to estimate the proportion that is exported due to particular protection or restoration activities, which poses a challenge for incorporation in Blue Carbon schemes.

Diagram

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Figure 1.2. Schematic of carbon export and sequestration. Adapted from Krause-Jensen and Duarte, 2016.

***Status and Trends of Macroalgae Forest Ecosystems***

Abundance and distribution of macroalgae forests are determined by a variety of physical and biological factors, and declines can be induced by temperature changes, over-grazing by herbivores, pollution, eutrophication, invasive species, and overharvest, among other causes (Filbee-Dexter et al., 2016; Filbee-Dexter & Scheibling, 2014; Filbee-Dexter & Wernberg, 2018; Rogers-Bennett & Catton, 2019; Smale, 2020). Kelp forests declines are often caused by ocean heating and are expected to worsen with global warming (Carnell & Keough, 2019; Filbee-Dexter et al., 2016; Filbee-Dexter & Scheibling, 2014; Rogers-Bennett & Catton, 2019; Smale, 2020; Wernberg et al., 2011, 2016). While fluctuations in macroalgae forest abundance occur in response to environmental conditions, of particular concern is the increasing phenomenon of regime shifts to alternative stable states, e.g. shifts from kelp forest to urchin barren or algal turf communities, which are not readily reversed when environmental conditions become favorable for kelp (Carnell & Keough, 2019; Filbee-Dexter et al., 2016; Filbee-Dexter & Scheibling, 2014; Filbee-Dexter & Wernberg, 2018; Moy & Christie, 2012; O’Brien & Scheibling, 2018; Rogers-Bennett & Catton, 2019; Wernberg et al., 2019). Such regime shifts are frequently triggered by multiple drivers (Christie et al., 2019a; Filbee-Dexter et al., 2016; Filbee-Dexter & Scheibling, 2014; Filbee-Dexter & Wernberg, 2018; Rogers-Bennett & Catton, 2019; Wernberg et al., 2019), such as warm-water events co-occurring with pollution and eutrophication (Christie et al., 2019b; Moy & Christie, 2012) or declines in predator populations driven by overfishing (Atwood & Hammill, 2018; Estes et al., 1998; Filbee-Dexter & Scheibling, 2014; Kjell Magnus Norderhaug et al., 2021; Steneck et al., 2002) (Figure 1.3).

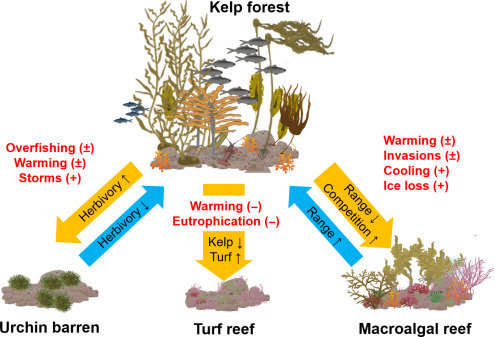


Figure 1.3. Replacement of kelp forests by three alternative ecosystem states: urchin barrens, turf reefs, and macroalgal reefs. Source: Wernberg et al. 2019.

In these cases, the loss of ecosystem functioning due to pollution or predator declines reduces the resilience of the ecosystem to recover back to macroalgae forest stands when the warm-water event ends. Likely due to this role of multiple factors driving macroalgae forest collapse, including a combination of factors largely outside of resource managers’ control (e.g. water temperature) and those that can be controlled or mitigated (e.g. harvest of urchin predators, eutrophication or other pollution), there is evidence that Marine Protected Areas and management actions such as protecting predators, minimizing kelp harvest, and reducing nutrification due to runoff can improve macroalgae forests’ resistance and resilience to regime shifts exacerbated by climate change (Babcock et al., 1999; Eisaguirre et al., 2020; Filbee-Dexter & Scheibling, 2014; Ling & Johnson, 2012). Therefore, there is a role for government protection of macroalgae forest habitat to reduce their degradation.

Overall, kelp and other macroalgae forests have experienced rapid and dramatic declines in some regions while abundance remains stable or even increasing in other areas (Krumhansl et al., 2016). Krumhansl et al. (2016) compiled a global database with data from 34 out of 99 ecoregions in which kelp forests exist and concluded that the rate of decrease totaled -1.8 percent per year, although results were variable by region, with 38 percent of regions with data showing declines, 27 percent showing increases, and 35 percent with no changes detected (Krumhansl et al., 2016). In many cases the declines appear to be driven by climatic factors; however, many regions exhibited declines that were attributed to other factors, such as harvesting, eutrophication, and pollution (Filbee-Dexter & Wernberg, 2018; Krumhansl et al., 2016) (Figure 1.4). While Krumhansl et al.’s meta-analysis focuses on trends in stands of true kelp (Order Laminariales), other studies have found declining trends of a similar magnitude in other types of macroalgae forest, including fucoid forests (Casado-Amezúa et al., 2019; Gorman et al., 2020; Middelboe & Sand-Jensen, 2000)*.*

Map

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Figure 1.4. Drivers of kelp forest decline. Source: Filbee-Dexter and Wernberg 2018).

## Adoption Path

### Current Adoption

Current adoption of *Macroalgae Protection* is assumed to be zero given the lack of data on protected wild macroalgae forests.

### Trends to Accelerate Adoption

Recognition of the importance of protecting the marine environment is growing. In 2000, Marine Protected Areas (MPAs) covered around 2 million km2, which increased to 9.1 million km2 in 2010 and over 27 million km2 in 2020 (UNEP-WCMC, 2020). The 10-fold increase between 2000 and 2020 would be equivalent to a 13.7 percent annual growth rate in the past two decades. However, the average annual growth rate has fluctuated over time and this large overall rate of growth appears to have been driven by a rapid expansion of MPAs in the mid-2010s, and has leveled out in more recent years. In the last decade, the growth rate has averaged about 9 percent per year (Duarte et al., 2020). At the more optimistic end of the range of potential adoption, assuming a continuation of the linear trend of 13.7 percent annual growth rate in the last twenty years, or even the 9 percent growth rate over the last ten years, would result in reaching protection of more than 50 percent of the world’s ocean before 2050 (Duarte et al., 2020).

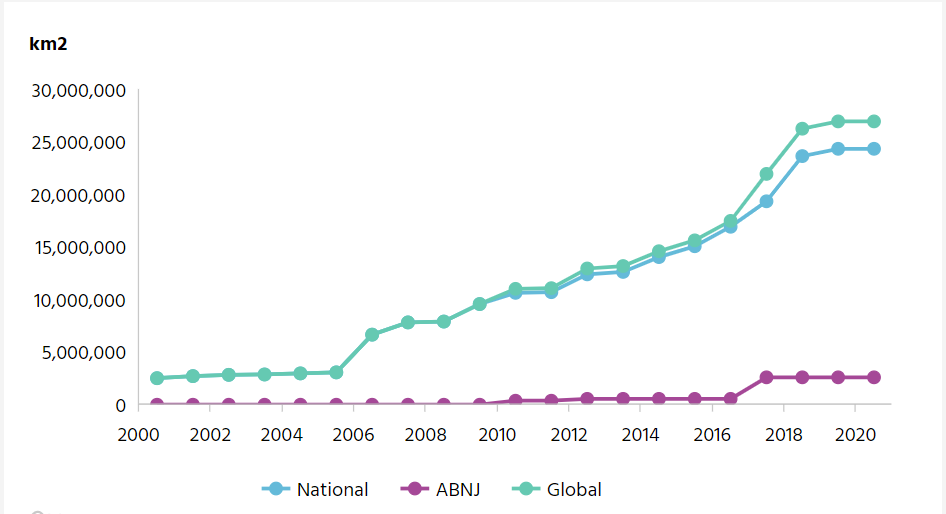


Figure 1.5. Growth in marine protected area coverage. Source: https://www.protectedplanet.net/en/thematic-areas/marine-protected-areas

In the past year, efforts and commitments to protect 30 percent of the world’s ocean area have become increasingly common. In December 2020, the High Level Panel for a Sustainable Ocean Economy (Ocean Panel) published a report proposing that 30 percent of the ocean should be protected in order to deliver carbon drawdown, food security, and economic benefits (Lubchenco et al., 2020; Stuchtey et al., 2020). This report is endorsed by leaders from 14 nations, which collectively represent 40 percent of the world’s coastal area and almost 30 percent of the ocean area in Exclusive Economic Zones (EEZs). The nations represented in the Ocean Panel committed to this ocean protection goal and called upon other world leaders to do the same (National Geographic, 2020). In January 2021, U.S. President Biden committed via Executive Order to protect 30 percent of U.S. land and coastal ocean by 2030 (National Geographic, 2021).

In addition to increasing the percent of the ocean in MPAs, another key trend which would accelerate the protection of wild macroalgae entails the development of an accreditation system for long-term carbon sequestration from wild macroalgae to formally include them in Blue Carbon schemes as independent ecosystems.

Krause-Jensen et al. (2018) highlight that macroalgae are already included in Blue Carbon schemes given their role as carbon donors. As an example, studies have found up to 50 percent of carbon sequestered in sediments of seagrass ecosystems originated from other primary producers, with macroalgae playing a significant role (Kennedy et al., 2010; Krause-Jensen et al., 2018; Macreadie et al., 2019; Ortega et al., 2019). As another example, a study on an integrated multi-trophic aquaculture farm in China showed that the cultured scallop obtained between 14.1 percent and 42.8 percent of its carbon from the co- cultured kelp (Xu et al., 2016).

Krause- Jensen and Duarte (2018) developed both a science and a management/ policy agenda to account for macroalgae in Blue Carbon mechanisms:

“The science agenda:

1. Development of reliable tools to fingerprint the contribution of macroalgae to oceanic C sink sites beyond the habitats.
2. Field evidence, derived with the tools above, of macroalgal burial rates and stocks in oceanic C sink sites beyond the habitats.
3. Improved estimates of the global area and production of macroalgae, resolved to the level of major functional groups.
4. Case studies providing evidence of effects of management practices, in terms of protection and enhancement of macroalgal area and production, for C sequestration beyond the habitat, to meet the additional requirement.

The management/ policy agenda:

1. A certification system of the CO2 emissions avoided and/or of enhanced sequestration through protection and restoration of habitats and through seaweed farming.
2. Revising crediting schemes to incorporate macroalgal C sequestered beyond these habitats.
3. Establishing fair mechanisms apportioning macroalgal C sequestered in shared deep sinks among the participating nations.” P. 4

Because kelp forests and most macroalgae forests (excepting free floating *Sargassum*) require rocky substrate and good water quality, protection practices must aim to preserve and maintain habitat quality in rocky substrate habitats (Laffoley & Grimsditch, 2009). In addition, management actions should include protection of key predators (e.g. lobsters or sea otters), which maintain herbivore (e.g. urchin) populations at reduced levels that prevent macroalgae deforestation, thus preventing trophic cascades that have had negative impacts on macroalgae forests (Estes et al., 1998; Wilmers et al., 2012).

### Barriers to Adoption

Limited scientific publications on the subject, particularly on the long-term carbon sequestration potential of macroalgae forests, might delay setting up a policy agenda to create protection schemes and to incorporate macroalgae forests in existing Blue Carbon schemes. Even if this is surpassed and despite macroalgae forests’ high level of resilience, climate change and the resulting increasing frequency in warm water events present an ongoing threat to macroalgae forests, some of which remains outside the control of resource managers (Krumhansl et al., 2016; Smale, 2020).

When establishing protection areas, several practices which jeopardize the health of macroalgae forests ecosystems should be closely monitored, including runoff and discharge of waste waters leading to water pollution and eutrophication; overfishing of predators; and direct harvesting of kelp (Christie et al., 2019a; Connell et al., 2008; Filbee-Dexter & Scheibling, 2014; Filbee-Dexter & Wernberg, 2018; Laffoley & Grimsditch, 2009; Moy & Christie, 2012; Smale et al., 2013; Steneck et al., 2002; Steneck & Johnson, 2013).

MPAs strongly rely on the effectiveness of human behavioral change therefore, it is often underlined that community support for management is essential. The fishery related benefits from applying MPAs are likely to be observed after several years and this is a long time for community members to have to wait especially in areas where MPA designation has resulted in prohibition in fishery practices. Therefore, some community push-back has been already noted and the lack of support from local communities in establishing MPAs is a great barrier for this solution (Savage et al., 2020).

### Adoption Potential

Given the lack of data on protected wild macroalgae, a proxy for analyzing its adoption potential could result from the protection of marine protected areas (MPAs) over the past decades. According to the Marine Protection Atlas, 6.4 percent of the ocean is currently in implemented MPAs, with another 1.4 percent of the ocean in areas of proposed or planned MPAs, though only 2.7 percent of the ocean is in fully or highly protected areas (Marine Conservation Institute, 2019). The recent commitments of the countries represented by the Ocean Panel as well as the United States to demonstrate a potential to protect 30 percent of ocean area by 2030, while an extrapolation of the last two decades’ growth rates in MPAs suggest that protection of up to 50 percent or more of certain ecosystems may be achievable if trends continue (UNEP-WCMC, 2020).

## Advantages and disadvantages of Macroalgae Protection

### Similar Solutions

*Ocean protection and restoration solutions*

This *Macroalgae Protection* solution has been developed together with a related *Macroalgae Restoration* solution, which estimates the climate benefits of actively restoring degraded macroalgae forest area.

There are other ocean protection solutions from the which contribute to maintaining carbon stocks in the ocean or creating new ones through ecosystem restoration efforts. These include: *Coastal Wetlands Protection*, *Coastal Wetlands Restoration*, and *Seafloor Protection*.

Sustainable *Seaweed Farming* could also result in a reduction of wild macroalgae harvesting (Hoegh- Guldberg et al., 2019) which would further reinforce the *Macroalgae Protection* solution.

A deeper understanding on the role of wild macroalgae as a carbon donor to coastal wetland ecosystems is required to analyze potential interactions with the *Coastal Wetlands Protection* and *Restoration* solutions.

### Arguments for Adoption

*Benefits of Macroalgae Forests*

Macroalgae forests provide numerous important ecosystem services throughout their distribution (Bennett et al., 2016; Filbee-Dexter et al., 2019; Filbee-Dexter & Scheibling, 2014; Filbee-Dexter & Wernberg, 2018, p.; Graham et al., 2007, n.d.; Krause-Jensen et al., 2018; Krause-Jensen & Duarte, 2016; Krumhansl et al., 2016; Laffoley & Grimsditch, 2009; Layton et al., 2020; Smale et al., 2013; Wernberg et al., 2019), including

* food (direct provisioning services);
* habitat and shelter providers to several species;
* food sources to marine communities as detritus and dissolved organic carbon export;
* nutrient cycling;
* shoreline protection;
* improvement in water quality;
* commercial fisheries;
* carbon storage and sequestration;
* recreation and ecotourism; and
* cultural services.

As a consequence, changes in kelp forests extent or abundance would impact the provision of these ecosystem services (Krumhansl et al., 2016).

### Additional Benefits and Burdens

Here this solution is compared with other solutions in the ocean sector in terms of ecosystem, social and climate impact. While the climate impact of Macroalgae Protection is intermediate within this sector, it has high environmental and social benefits.

Table 1‑1 Ocean Solutions Comparison.

**Ecosystem Services** is subjective based on impacts on biodiversity, habitat restoration, protection from extreme weather events etc. **Social Justice Benefits:** If solution is causing positive impact on local societies. **Climate Impact:** GHG reduction potentialin GT CO2 eq, 2020-2050:low >1, middle between 1 and3, high <3. **Global Adoption Potential:** TOA in Mha: low > 100, middle between 100 and 400, high < 400; TAM is applicable for only two solutions Improve Fisheries and Improve Aquaculture therefore direct comparison with other ocean solutions is not possible, however, both solutions represents high total adoption potential. n/a – not applicable.

|  | **Ecosystem Services** | **Social Justice Benefits** | **Climate Impact** | **Global Adoption Potential** |
| --- | --- | --- | --- | --- |
| Conventional fishery | Low | Low | n/a | n/a |
| Conventional aquacultures | n/a | Medium | n/a | n/a |
| Conventional seaweed farming | Medium | Medium | Low | n/a |
| Improve Fisheries | High | High | Middle | High (TAM 94 million tons landings) |
| Improve Aquaculture | n/a | Medium | Middle | High (TAM 126 million tons live weight) |
| Seaweed Farming | Medium | Medium | High | High |
| **Macroalgae Protection** | **High** | **High** | **Middle** | **Middle** |
| Macroalgae Restoration | High | High | Middle | Middle |
| Coastal Wetlands Protection | High | High | Middle | Low |
| Coastal Wetlands Restoration | High | High | Middle | Low |
| Seafloor Protection | High | Medium | High | High |

# Methodology

## Introduction

Project Drawdown’s models are developed in Microsoft Excel using standard templates that allow easier integration with each other since integration is critical to the bottom-up approach used. The analysis of this solution was done using the Ocean\_Protect model. This model accounts for sequestration of carbon dioxide from the atmosphere into biomass that is long- term sequestered to the deep ocean and sediments, and a reduction of emissions for a solution relative to a conventional practice. The actual and maximum possible adoptions are therefore defined in terms of ocean area (million hectares). The adoptions of both conventional and solution were projected for each of several Drawdown scenarios from 2015 to 2060 (from a base year of 2018) and the comparison of these scenarios with a reference (for the 2020-2050 segment[[1]](#footnote-1)) is what constitutes the results.

*Agency Level*

Government is selected as the agency level for this solution. Though certainly other agents can, do, and should play an important role in this solution, the governments are the most critical players in implementation.

## Data Sources

Krause-Jensen and Duarte (2016)’s seminal paper was used for estimating the percent of Net Primary Production (NPP) that results in long-term carbon sequestration as well as the global extent of wild macroalgae and NPP values. Sources for wild macroalgae NPP values were compiled from (Chemodanov et al., 2017; Duarte, 2017; Duarte et al., 2013; Kraan, 2013; Krause-Jensen & Duarte, 2016), and the average value was multiplied by the percent sequestered from (Krause-Jensen & Duarte, 2016) to calculate C sequestration rates Krause-Jensen and Duarte’s (2016) estimate was used for total ocean area for wild macroalgae forest.

Adoption scenarios for Protection are informed by the Seafloor Protection solution, and references include (Lubchenco et al., 2020; Marine Conservation Institute, 2019; National Geographic, 2020, 2021; Stuchtey et al., 2020; UNEP-WCMC, 2020).

Ocean degradation rates for macroalgae forest are based on the meta-analysis by Krumhansl et al (2016). Because the Krumhansl meta-analysis focused on true kelps (Order Laminariales) and was published in 2016, we expanded the analysis to include studies of the rate of change of macroalgae forests outside of the order Laminariales (e.g. fucoids), as well as studies published after 2016 (Carnell & Keough, 2019; Casado-Amezúa et al., 2019; Connell et al., 2008, 2008; Eriksson et al., 2002; Filbee-Dexter et al., 2016; Friedlander et al., 2020; Hamilton et al., 2020; Johnson et al., 2011; Middelboe & Sand-Jensen, 2000; Rogers-Bennett & Catton, 2019; Voerman et al., 2013; Vogt & Schramm, 1991; Wernberg et al., 2016).

Data for long-term storage of carbon in protected macroalgae forests were derived from (Aller-Rojas et al., 2020; Bayley et al., 2017; Filbee-Dexter & Wernberg, 2020; Gouvêa et al., 2020; Pessarrodona et al., 2018; Smale, 2020).

## Total Ocean Area

A customized global TOA was built for this solution based on Krause-Jensen and Duarte (2016) wild macroalgae area (355 Mha) excluding an estimate of the wild macroalgae harvested area (0.007 Mha/ yr) up to 2060.

## Adoption Scenarios

Two different types of adoption scenarios were developed:

A Reference (REF) Case which was considered the baseline, where not much changes in the world, and a set of Project Drawdown Scenarios (PDS) with varying levels of ambitious adoption of the solution. Published results show the comparison of one PDS to the REF, and therefore focuses on the change to the world relative to a baseline.

Four custom adoption scenarios were developed for this solution based on projections based on historical growth in Marine Protected Areas, as well as recent international attention and commitment to the goal to protect 30 percent of the ocean by 2030. Each growth scenario incorporated a maximum area of the Total Ocean Area minus the degraded ocean area (Constrained TOA).

**Custom adoption scenario 1:** 30 percent TOA protected by 2030; an optimistic scenario based on full adoption of the international target toward committing to protect 30 percent of the ocean by 2030.

**Custom adoption scenario 2:** 30 percent TOA protected by 2050: This scenario assumes 30 percent TOA protected by 2050 following the less optimistic assumption of the IUCN (that recommends 30 percent highly protected MPA coverage by 2030).

**Custom adoption scenario 3:** 50 percent TOA protected by 2044: This scenario assumes 50 percent of TOA is protected by 2044, following projected growth rates as described in (Duarte et al., 2020).

**Custom adoption scenario 4:** 100 percent protection of TOA by 2050 following Drawdown assumptions for the optimum scenario, excluding the percent of area subject to natural degradation.

### Reference Case / Current Adoption

Current adoption of *Macroalgae Protection* is zero considering the lack of data availability. This is in line with many other protection solutions.

### Project Drawdown Scenarios

Two Project Drawdown scenarios (PDS) were developed for each solution, to compare the impact of an increased adoption of the solution to a reference case scenario, being:

#### Plausible Scenario – represented by the “average of all” custom adoption scenarios, excluding the 100 percent adoption scenario.

#### Ambitious Scenario – represented by the “high of all” custom adoption scenarios, excluding the 100 percent adoption scenario.

***Optimum Scenario*** *–* represented by the highest individual custom adoption scenario, 100 percent protection of TOA by 2050, excluding the percent of area subject to natural degradation

## Inputs

### Climate Inputs

The long-term sequestration rate is the crucial climate input for the *Macroalgae Protection* model. The role of macroalgae in long-term sequestration is contested with some authors claiming it cannot be accounted as long-term carbon sinks (Howard et al., 2017). On the other hand, most of the literature reviewed argues otherwise (e.g.: (Smale et al., 2018)) with some experts’ estimates exceeding the carbon sequestered in angiosperm- based habitats (mangroves, saltmarshes and seagrasses) (Krause-Jensen & Duarte, 2016).

Krause- Jensen and Duarte (2016) synthesized the role of wild macroalgae in marine carbon sequestration as follows:



Figure 2.1“Pathways for the sequestration of macroalgal carbon in the ocean” [TgC/ yr]

*Source: Krause- Jensen and Duarte (2016)*

Using the net primary production (NPP) from wild macroalgae, the figure above identifies four pathways of long-term carbon sequestration: macroalgae buried in the algal bed, dissolved organic carbon (DOC) exported below the mixed layer, particulate organic carbon (POC) buried in the shelves and exported to the deep sea. The combined total long- term carbon sequestration estimate is 173 TgC/ yr, 11 percent of NPP.

In order to estimate the long- term sequestration, the following equation is used:

|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| Sequestration rate | tC/ ha/ yr | 0.29- 1.65 | 0.97 | 14 | 6 |
| NPP | tC/ ha/ yr | 2.5- 14.5 | 8.49 | 14 | 6 |
| % long- term carbon sequestration from NPP | % | NA | 0.11 | 1 | 1 |
| Growth rate of ocean degradation | % annual | 0.3-0.6 | 2.48 | 20 | 14 |
| tons C storage in protected landscape | tC/ ha | 0.83-8.4 | 4.6 | 13 | 6 |

Table 2‑1 Climate Inputs

Note: Project Drawdown data set range is defined by the low and high boundaries which are respectively 1 standard deviation below and above the mean of the collected data points[[2]](#footnote-2).

### Financial Inputs

No financials are modeled here because the agency and likely costs for macroalgae protection occur at the government level.

### Other Inputs

There are no other inputs used in the model.

## Assumptions

Six overarching assumptions have been made for Project Drawdown models to enable the development and integration of individual model solutions. These are that infrastructure required for the solution is available and in-place, policies required are already in-place, no carbon price is modeled, all costs accrue at the level of agency modeled, improvements in technology are not modeled, and that first costs may change according to learning. Full details of core assumptions and methodology will be available at [www.drawdown.org](http://www.drawdown.org).

Beyond these core assumptions, there are five other important assumptions made for the modeling of this specific solution. These are detailed below.

1. The scope of the solution excludes the wild macroalgae that is harvested.
2. The TOA was estimated based on Krause-Jensen and Duarte (2016) estimate despite other available estimates. The reason for this is that the other available estimates resulted from older sources, e.g.: (Duarte et al., 2013).
3. It is assumed that the adoption area used for wild macroalgae protection had no previous use. Hence there are no climate or financial benefits and/ or costs perceived from a conventional use of that ocean area.
4. The solution assumes that the delay in obtaining permits for establishing the protection areas would be less than a year.
5. The carbon mitigation potential of the solution includes the carbon buried in the algal bed and the exported DOC/ POC that goes into the deep sea and/ or sediments.

## Integration

The complete Project Drawdown integration documentation (will be available at [www.drawdown.org](http://www.drawdown.org)) details how all solution models in each sector are integrated, and how sectors are integrated to form a complete system. Those general notes are excluded from this document but should be referenced for a complete understanding of the integration process. Only key elements of the integration process that are needed to understand how this solution fits into the entire system are described here.

*Macroalgae protection* is part of Drawdown’s new Ocean sector. Integration of this sector with the other Drawdown sector will be developed after all the Ocean solutions are complete.

### The Ocean model

The Drawdown Ocean model classifies the ocean into 42 possible ocean zones using three dimensions:

* + - 1. “Cover and climate” dimension: a primarily physical climate- and bathymetry- and cover- based classification of the ocean into the following regions, 4 zones for the deep ocean (biological desserts, equatorial waters, bloom waters and transition waters), 2 zones for shallow and slope waters (shallow waters and slope waters), and 1 ice-covered zone (sea ice covered waters).
      2. “Access” dimension: there are political instruments in place that can limit how large parts of the ocean are used, the most common are Exclusive Economic Zones (EEZ) and Marine Protected Areas (MPA). EEZs are broadly defined by a 200 nautical mile offset from the seacoast of a country and as such collectively represent a significant fraction of the total ocean area. EEZs also coincide with the most accessible waters because of their definition; EEZ waters are closest to shore. And while EEZs tend to be shallow waters, they are not always shallow and can cross slope waters and extend into the deep ocean. The access dimension classifies whether waters are in or out of a national jurisdiction as defined by an EEZ.
      3. “Depth” dimension: the open ocean can be broadly subdivided into three layers, the epipelagic (0 to 200 m), the mesopelagic (200 to 1000 m), and bathypelagic (1000 m to bottom). Since the bottom of the epipelagic zone corresponds to the maximum depth of the coastal or shallow waters, these two ocean zones are by definition excluded from the mesopelagic and bathypegic layers.



Table 2‑2. Project Drawdown Ocean model zones

This ocean classification has about one third the number of zones in the Drawdown Land Model in large part because the large-scale cover and climate of the oceans are not independent while cover and climate are independent on land.

### The Ocean Sector and solutions

Project Drawdown has investigated eight ocean-based solutions and their potential to avoid GHG emissions or sequester carbon. The ocean-based solutions form two main groups: a group of protection and restoration solutions and a group of approaches to improving fisheries and aquaculture operation.

The protection and restoration solutions focus on blue carbon sinks, and their potential to sequester carbon. They include protection and restoration of coastal wetlands and macroalgae ecosystems, as well as seafloor protection from bottom trawling activities (Figure 2.2). The adoption of protection solutions involves the expansion of marine protected areas and other conservation tools such as bottom trawling bans. The adoption of solutions focusing on restoration additionally requires active restoration programs. The climate impact of solutions from this sector, include avoiding carbon emissions or enhanced carbon sequestration and are designated for the government agency level.

The second group of solutions explores the potential of improving fishery, improving aquacultures and seaweed farming. The fishery can be improved by reducing fishing effort and restoring large fish biomass. The climate impact of *Improve fishery*, therefore, includes avoiding carbon emissions from fuel usage and enhanced carbon sequestration in sunken large fish biomass and the implementation of this solution involve governments. *Improve aquaculture* solution assumes shifting from fuel-based energy systems to hybrid systems partly based on renewables thus, include climate impact based on avoiding GHG emissions. The *Seaweed farming* solution explores the potential of expanding seaweed production and its climate effect on the enhancement of carbon sequestration in the deep sea together with unharvested biomass (Figure 2.2). The agency-level for the two last solutions involve farmers.

Diagram

Description automatically generated

Figure 2.2. Schematic of all Drawdown ocean-based solutions.

# Results

## Adoption

Below are shown the world adoptions of the solution in some key years of analysis in functional units and percentages for the two Project Drawdown scenarios.

Total adoption in the *Plausible Scenario* is 160 million hectares in 2050, representing 45.1 percent of the total suitable ocean area.

Total adoption in the *Ambitious Scenario* is 199 million hectares in 2050, representing 56.1 percent of the total suitable ocean area.

Total adoption in the *Optimum Scenario* is 265 million hectares in 2050, representing 74.7 percent of the total suitable ocean area.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Solution** | **Units** | **Current Year (million hectare)** | **World Adoption by 2050** | | |
| **Plausible** | **Ambitious** | **Optimum** |
| Macroalgae protection | million hectare | 0.00 | 160.00 | 199.13 | 265.00 |
| *(% TOA)* | 0.0% | 45.1% | 56.1% | 74.7% |

Table 3‑1 World Adoption of the Solution

Figure 3.1 World Annual Adoption 2020-2050

Figure 3.2. World Annual Adoption 2020-2050, as percentage of Total Ocean Area.

## Climate Impacts

Below are the emissions results of the analysis for each scenario which include total emissions reduction, atmospheric concentration changes, and sequestration where relevant. For a detailed explanation of each result, please see the glossary (Section 6).

Climate impact is 1.84, 2.28, and 4.02 gigatons of carbon-dioxide equivalent in the *Plausible, Ambitious* and *Optimum* scenarios respectively.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Scenario** | **Max Annual CO2 Sequestered** | **Total Additional CO2 Sequestered** | **Total Atmospheric CO2-eq Reduction** | **CO2 Sequestered in 2030** | **CO2 Sequestered in 2050** |
| *(Gt CO2-eq/year)* | *Gt CO2-eq/yr. (2020-2050)* | *Gt CO2-eq (2020-2050)* | *(Gt CO2-eq/year)* | *(Gt CO2-eq/year)* |
| ***Plausible*** | 0.16 | 1.84 | 1.84 | 0.02 | 0.16 |
| ***Ambitious*** | 0.20 | 2.28 | 2.28 | 0.03 | 0.19 |
| ***Optimum*** | 0.34 | 4.02 | 4.02 | 0.05 | 0.33 |

Table 3‑2 Climate Impacts

Figure 3.3. Annual total reduction in CO2, 2020-2050

|  |  |  |
| --- | --- | --- |
| **Scenario** | **GHG Concentration Change in 2050** | **GHG Concentration Rate of Change in 2050** |
| *PPM CO2-eq (2050)* | *PPM CO2-eq change from 2049-2050* |
| ***Plausible*** | 0.15 | 0.01 |
| ***Ambitious*** | 0.18 | 0.02 |
| ***Optimum*** | 0.33 | 0.03 |

Table 3‑3 Impacts on Atmospheric Concentrations of CO2-eq

## Financial Impacts

Currently, the financial impacts are not modeled.

## Other Impacts

There are no other impacts modeled.

# Discussion

Macroalgae forests play a key role in carbon cycling in the ocean as well as providing numerous additional ecosystem services. It is estimated that macroalgae forests may sequester as much carbon as coastal vegetated ecosystems (salt marshes, mangroves, and seagrasses), yet these important ecosystems are typically left out of blue carbon schemes and discussions. Reasons for the exclusion of macroalgae forests from such initiatives include the belief that long-term sequestration is minimal due to their rocky substrate habitat, uncertainty about the amount of carbon exported to and sequestered in deep sea sediments, and the complexity involved in parsing macroalgae forest carbon exported to and sequestered in tidal marsh, mangrove, and seagrass ecosystems, where they are potentially already counted as blue carbon (Filbee-Dexter & Wernberg, 2020; Krause-Jensen & Duarte, 2016). However, despite only rudimentary estimates of the percentage of macroalgae forest carbon that is sequestered, the importance of these ecosystems both as a carbon sink and as foundational species, and their current trends of declining abundance, suggest an urgency in advocating for their protection.

## Macroalgae Protection and Climate Change

A global meta-analysis found that kelp forests are declining an average of 1.8 percent per year, but with high regional variability, including increases in several regions (Krumhansl et al., 2016). Our study, accounting for more recent studies and those that focus on other macroalgae forest species outside of the Laminariales calculated an estimated average of 2.6 percent degradation per year. In areas where kelp or other macroalgae forests are declining, numerous drivers have been identified, including warming, overfishing of predators, direct harvest of kelp, and eutrophication (Carnell & Keough, 2019; Christie et al., 2019b; Estes et al., 1998; Filbee-Dexter et al., 2016; Filbee-Dexter & Scheibling, 2014; Filbee-Dexter & Wernberg, 2018; Krause-Jensen et al., 2018; Krumhansl et al., 2016; Ling et al., 2009; Moy & Christie, 2012; Kjell Magnus Norderhaug et al., 2021; Rogers-Bennett & Catton, 2019; Smale, 2020; Steneck et al., 2002; Wernberg et al., 2016).

Many of these anthropogenic drivers, such as eutrophication, algae harvesting, and fishing, can be addressed by local resources managers and may be ameliorated in part via protection of macroalgae forests in MPAs (Coleman & Wernberg, 2017; Krause-Jensen et al., 2018; Wernberg et al., 2019). Even in areas which experience declines due to warming, protection in MPAs is likely to increase the resilience of the ecosystem to withstand warming events and recover following warming-induced declines, rather than shift to alternative stable states (Babcock et al., 1999; Eisaguirre et al., 2020; Filbee-Dexter & Scheibling, 2014; Ling & Johnson, 2012). However, even with the best efforts of local resource managers to conserve these ecosystems, some continued decline due to climate change is likely inevitable (Filbee-Dexter & Wernberg, 2020; Wernberg et al., 2019). Unfortunately, the expected declines in macroalgae forest area will reduce the amount of carbon sequestered in these habitats (Filbee-Dexter & Wernberg, 2020), which in turn reduces the ability to combat climate change. The potential losses of macroalgae forests which may occur despite protection of these habitats in MPAs, underscores the importance of also incorporating active habitat restoration, which is considered as a part of one solution.

## Limitations

One of the limitations is the data constraint on how much of the wild macroalgae area is currently being degraded which would shed light on the need to protect these ecosystems. Krumhansl et al. (2016) compiled a global database with data from 34 out of 99 ecoregions in which kelp forests exist and concluded that the rate of decrease totaled -1.8 percent per year. However, the results show a significant spread of regional variability with “declines in 38 percent of ecoregions for which there are data (-0.015 to - 0.18 y-1), increases in 27 percent of ecoregions (0.015 to 0.11 y-1), and no detectable change in 35 percent of ecoregions” (Krumhansl et al., 2016).

The long-term carbon mitigation potential stemming from wild macroalgae is a rather new area of research. As a result, the *Macroalgae Protection* model includes only one estimate of the percent of NPP which is sequestered in the long- term based on Krause- Jensen and Duarte (2016). Once research progresses further on this front, the model can be refined.

In addition, a potential increase in CO2 concentration could result in a higher capacity of macroalgae to photosynthesize and grow in some cases which would result in higher NPP values.

Another limitation is the lack of financial data.

## Benchmarks

No study was found which estimated the potential carbon benefits of protecting macroalgae forests. Krause-Jensen and Duarte (2016) estimated that macroalgae forests sequester up to 173 Tg (range: 61-268 Tg C/yr) of carbon per year. Converted to Gigatons of CO2-eq, this is equivalent to approximately 0.635 Gt CO2-eq sequestered per year. This represents total current macroalgae forest carbon sequestration, and they did not estimate the proportion of this sequestration that would result from macroalgae forest protection scenarios. Considering that the Drawdown model estimates the climate benefit of protection of some proportion of this macroalgae forest, relative to a reference scenario in which a larger proportion is degraded but some still survives, it is expected that about 25 to 50 percent of this total sequestration could be attributed to a climate benefit of the protection scenarios, depending on the specific protection scenario.

Our model estimated that, relative to a reference, protection of macroalgae forests could annually sequester, depending on the level of adoption, 0.15 Gt CO2-eq (for the *Plausible* scenario) to 0.33 Gt CO2-eq (for the *Optimum* scenario). Adjusting for the proportion of the total carbon sequestration potential that might be attributed to macroalgae forest protection (about 25 to 50 percent), the comparison of our values with those in Krause-Jensen and Duarte (2016) are in line with expectations.

| **Source and Scenario** | **Max (Ocean) Mitigation Impact (i.e. Gt CO2-eq sequestered per year)** |
| --- | --- |
| (Krause-Jensen & Duarte, 2016) | 0.635 |
| *Plausible* Scenario | 0.15 |
| *Ambitious* Scenario | 0.18 |
| *Optimum* Scenario | 0.33 |

# References

Aller-Rojas, O., Moreno, B., Aponte, H., & Zavala, J. (2020). Carbon storage estimation of *Lessonia trabeculata* kelp beds in Southern Peru: An analysis from the San Juan de Marcona region. *Carbon Management*, *11*(5), 525–532. https://doi.org/10.1080/17583004.2020.1808765

Arrigo, K. R. (2005). Marine microorganisms and global nutrient cycles. *Nature*, *437*(7057), 349–355. https://doi.org/10.1038/nature04159

Atwood, T. B., & Hammill, E. (2018). The Importance of Marine Predators in the Provisioning of Ecosystem Services by Coastal Plant Communities. *Frontiers in Plant Science*, *9*. https://doi.org/10.3389/fpls.2018.01289

Babcock, R. C., Kelly, S., Shears, N. T., Walker, J. W., & Willis, T. J. (1999). Changes in community structure in temperate marine reserves. *Marine Ecology Progress Series*, *189*, 125–134. https://doi.org/10.3354/meps189125

Bayley, D. T. I., Marengo, I., & Pelembe, T. (2017). *Giant kelp ‘Blue carbon’ storage and sequestration value in the Falkland Islands.* (p. 25). South Atlantic Environment Research Institute. https://www.south-atlantic-research.org/wp-content/uploads/2018/04/Valuing-Ecosystem-services-in-the-Falkland-Islands\_05062017.pdf

Bearham, D., Vanderklift, M. A., & Gunson, J. R. (2013). Temperature and light explain spatial variation in growth and productivity of the kelp Ecklonia radiata. *Marine Ecology Progress Series*, *476*, 59–70. https://doi.org/10.3354/meps10148

Bennett, S., Wernberg, T., Connell, S. D., Hobday, A. J., Johnson, C. R., & Poloczanska, E. S. (2016). The ‘Great Southern Reef’: Social, ecological and economic value of Australia’s neglected kelp forests. *Marine and Freshwater Research*, *67*(1), 47–56. https://doi.org/10.1071/MF15232

Bolton, J. J. (2010). The biogeography of kelps (Laminariales, Phaeophyceae): A global analysis with new insights from recent advances in molecular phylogenetics. *Helgoland Marine Research*, *64*(4), 263–279. https://doi.org/10.1007/s10152-010-0211-6

Bouillon, S., Borges, A. V., Castañeda‐Moya, E., Diele, K., Dittmar, T., Duke, N. C., Kristensen, E., Lee, S. Y., Marchand, C., Middelburg, J. J., Rivera‐Monroy, V. H., Smith, T. J., & Twilley, R. R. (2008). Mangrove production and carbon sinks: A revision of global budget estimates. *Global Biogeochemical Cycles*, *22*(2). https://doi.org/10.1029/2007GB003052

Bowler, C., Karl, D. M., & Colwell, R. R. (2009). Microbial oceanography in a sea of opportunity. *Nature*, *459*(7244), 180–184. https://doi.org/10.1038/nature08056

Carnell, P. E., & Keough, M. J. (2019). Reconstructing Historical Marine Populations Reveals Major Decline of a Kelp Forest Ecosystem in Australia. *Estuaries and Coasts*, *42*(3), 765–778. https://doi.org/10.1007/s12237-019-00525-1

Casado-Amezúa, P., Araújo, R., Bárbara, I., Bermejo, R., Borja, Á., Díez, I., Fernández, C., Gorostiaga, J. M., Guinda, X., Hernández, I., Juanes, J. A., Peña, V., Peteiro, C., Puente, A., Quintana, I., Tuya, F., Viejo, R. M., Altamirano, M., Gallardo, T., & Martínez, B. (2019). Distributional shifts of canopy-forming seaweeds from the Atlantic coast of Southern Europe. *Biodiversity and Conservation*, *28*(5), 1151–1172. https://doi.org/10.1007/s10531-019-01716-9

Chemodanov, A., Jinjikhashvily, G., Habiby, O., Liberzon, A., Israel, A., Yakhini, Z., & Golberg, A. (2017). Net primary productivity, biofuel production and CO2 emissions reduction potential of Ulva sp. (Chlorophyta) biomass in a coastal area of the Eastern Mediterranean. *Energy Conversion and Management*, *148*, 1497–1507. https://doi.org/10.1016/j.enconman.2017.06.066

Christie, H., Andersen, G. S., Bekkby, T., Fagerli, C. W., Gitmark, J. K., Gundersen, H., & Rinde, E. (2019a). Shifts Between Sugar Kelp and Turf Algae in Norway: Regime Shifts or Fluctuations Between Different Opportunistic Seaweed Species? *Frontiers in Marine Science*, *6*. https://doi.org/10.3389/fmars.2019.00072

Christie, H., Andersen, G. S., Bekkby, T., Fagerli, C. W., Gitmark, J. K., Gundersen, H., & Rinde, E. (2019b). Shifts Between Sugar Kelp and Turf Algae in Norway: Regime Shifts or Fluctuations Between Different Opportunistic Seaweed Species? *Frontiers in Marine Science*, *6*. https://doi.org/10.3389/fmars.2019.00072

Christie, H., Norderhaug, K., & Fredriksen, S. (2009). Macrophytes as habitat for fauna. *Marine Ecology Progress Series*, *396*, 221–233. https://doi.org/10.3354/meps08351

Coleman, M. A., & Wernberg, T. (2017). Forgotten underwater forests: The key role of fucoids on Australian temperate reefs. *Ecology and Evolution*, *7*(20), 8406–8418. https://doi.org/10.1002/ece3.3279

Connell, S., Russell, B., Turner, D., Shepherd, S., Kildea, T., Miller, D., Airoldi, L., & Cheshire, A. (2008). Recovering a lost baseline: Missing kelp forests from a metropolitan coast. *Marine Ecology Progress Series*, *360*, 63–72. https://doi.org/10.3354/meps07526

Dayton, P. K. (1985). Ecology of Kelp Communities. *Annual Review of Ecology and Systematics*, *16*, 215–245.

Duarte, C. M. (2017). Reviews and syntheses: Hidden forests, the role of vegetated coastal habitats in the ocean carbon budget. *Biogeosciences*, *14*(2), 301–310. https://doi.org/10.5194/bg-14-301-2017

Duarte, C. M., Agusti, S., Barbier, E., Britten, G. L., Castilla, J. C., Gattuso, J.-P., Fulweiler, R. W., Hughes, T. P., Knowlton, N., Lovelock, C. E., Lotze, H. K., Predragovic, M., Poloczanska, E., Roberts, C., & Worm, B. (2020). Rebuilding marine life. *Nature*, *580*(7801), 39–51. https://doi.org/10.1038/s41586-020-2146-7

Duarte, C. M., Losada, I. J., Hendriks, I. E., Mazarrasa, I., & Marbà, N. (2013). The role of coastal plant communities for climate change mitigation and adaptation. *Nature Climate Change*, *3*(11), 961–968. https://doi.org/10.1038/nclimate1970

Duarte, C. M., Middelburg, J. J., & Caraco, N. (2005). Major role of marine vegetation on the oceanic carbon cycle. *Biogeosciences*, *2*(1), 1–8. https://doi.org/10.5194/bg-2-1-2005

Eisaguirre, J. H., Eisaguirre, J. M., Davis, K., Carlson, P. M., Gaines, S. D., & Caselle, J. E. (2020). Trophic redundancy and predator size class structure drive differences in kelp forest ecosystem dynamics. *Ecology*, *101*(5), e02993. https://doi.org/10.1002/ecy.2993

Eriksson, B. K., Johansson, G., & Snoeijs, P. (2002). Long-Term Changes in the Macroalgal Vegetation of the Inner Gullmar Fjord, Swedish Skagerrak Coast1. *Journal of Phycology*, *38*(2), 284–296. https://doi.org/10.1046/j.1529-8817.2002.00170.x

Estes, J. A., Tinker, M. T., Williams, T. M., & Doak, D. F. (1998). Killer Whale Predation on Sea Otters Linking Oceanic and Nearshore Ecosystems. *Science*, *282*(5388), 473–476.

Falkowski, P. G. (2004). The Evolution of Modern Eukaryotic Phytoplankton. *Science*, *305*(5682), 354–360. https://doi.org/10.1126/science.1095964

Filbee-Dexter, K., Feehan, C., & Scheibling, R. (2016). Large-scale degradation of a kelp ecosystem in an ocean warming hotspot. *Marine Ecology Progress Series*, *543*. https://doi.org/10.3354/meps11554

Filbee-Dexter, K., & Scheibling, R. E. (2014). *Sea urchin barrens as alternative stable states of collapsed kelp ecosystems*. https://doi.org/10.3354/MEPS10573

Filbee-Dexter, K., & Wernberg, T. (2018). Rise of Turfs: A New Battlefront for Globally Declining Kelp Forests. *BioScience*, *68*(2), 64–76. https://doi.org/10.1093/biosci/bix147

Filbee-Dexter, K., & Wernberg, T. (2020). Substantial blue carbon in overlooked Australian kelp forests. *Scientific Reports*, *10*(1), 12341. https://doi.org/10.1038/s41598-020-69258-7

Filbee-Dexter, K., Wernberg, T., Fredriksen, S., Norderhaug, K. M., & Pedersen, M. F. (2019). Arctic kelp forests: Diversity, resilience and future. *Global and Planetary Change*, *172*, 1–14. https://doi.org/10.1016/j.gloplacha.2018.09.005

Friedlander, A. M., Ballesteros, E., Bell, T. W., Caselle, J. E., Campagna, C., Goodell, W., Hüne, M., Muñoz, A., Salinas-de-León, P., Sala, E., & Dayton, P. K. (2020). Kelp forests at the end of the earth: 45 years later. *PLOS ONE*, *15*(3), e0229259. https://doi.org/10.1371/journal.pone.0229259

Gagné, J. A., Mann, K. H., & Chapman, A. R. O. (1982). Seasonal patterns of growth and storage in Laminaria longicruris in relation to differing patterns of availability of nitrogen in the water. *Marine Biology*, *69*(1), 91–101. https://doi.org/10.1007/BF00396965

Gattuso, J.-P., B, G., Duarte, C., Kleypas, J., Middelburg, J., & Antoine, D. (2006). Light availability in the coastal ocean: Impact on the distribution of benthic photosynthetic organisms and their contribution to primary production. *Biogeosciences*, *3*. https://doi.org/10.5194/bg-3-489-2006

Gorman, D., Horta, P., Flores, A. A. V., Turra, A., Berchez, F. A. de S., Batista, M. B., Filho, E. S. L., Melo, M. S., Ignacio, B. L., Carneiro, I. M., Villaça, R. C., & Széchy, M. T. M. (2020). Decadal losses of canopy-forming algae along the warm temperate coastline of Brazil. *Global Change Biology*, *26*(3), 1446–1457. https://doi.org/10.1111/gcb.14956

Gouvêa, L. P., Assis, J., Gurgel, C. F. D., Serrão, E. A., Silveira, T. C. L., Santos, R., Duarte, C. M., Peres, L. M. C., Carvalho, V. F., Batista, M., Bastos, E., Sissini, M. N., & Horta, P. A. (2020). Golden carbon of Sargassum forests revealed as an opportunity for climate change mitigation. *Science of The Total Environment*, *729*, 138745. https://doi.org/10.1016/j.scitotenv.2020.138745

Graham et al., 2007. (n.d.). *Deep-water kelp refugia as potential hotspots of tropical marine diversity and productivity*.

Hamilton, S. L., Bell, T. W., Watson, J. R., Grorud‐Colvert, K. A., & Menge, B. A. (2020). Remote sensing: Generation of long-term kelp bed data sets for evaluation of impacts of climatic variation. *Ecology*, *101*(7), e03031. https://doi.org/10.1002/ecy.3031

Houghton, R. a. (2007). Balancing the Global Carbon Budget. *Annual Review of Earth and Planetary Sciences*, *35*(1), 313–347. https://doi.org/10.1146/annurev.earth.35.031306.140057

Howard, J., McLeod, E., Thomas, S., Eastwood, E., Fox, M., Wenzel, L., & Pidgeon, E. (2017). The potential to integrate blue carbon into MPA design and management. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *27*(S1), 100–115. https://doi.org/10.1002/aqc.2809

Johnson, C. R., Banks, S. C., Barrett, N. S., Cazassus, F., Dunstan, P. K., Edgar, G. J., Frusher, S. D., Gardner, C., Haddon, M., Helidoniotis, F., Hill, K. L., Holbrook, N. J., Hosie, G. W., Last, P. R., Ling, S. D., Melbourne-Thomas, J., Miller, K., Pecl, G. T., Richardson, A. J., … Taw, N. (2011). Climate change cascades: Shifts in oceanography, species’ ranges and subtidal marine community dynamics in eastern Tasmania. *Journal of Experimental Marine Biology and Ecology*, *400*(1), 17–32. https://doi.org/10.1016/j.jembe.2011.02.032

Kennedy, H., Beggins, J., Duarte, C. M., Fourqurean, J. W., Holmer, M., Marbà, N., & Middelburg, J. J. (2010). Seagrass sediments as a global carbon sink: Isotopic constraints. *Global Biogeochemical Cycles*, *24*(4). https://doi.org/10.1029/2010GB003848

Kraan, S. (2013). Mass-cultivation of carbohydrate rich macroalgae, a possible solution for sustainable biofuel production. *Mitigation and Adaptation Strategies for Global Change*, *18*(1), 27–46. https://doi.org/10.1007/s11027-010-9275-5

Krause-Jensen, D., & Duarte, C. M. (2016). Substantial role of macroalgae in marine carbon sequestration. *Nature Geoscience*, *9*(10), 737–742.

Krause-Jensen, D., Lavery, P., Serrano, O., Marbà, N., Masque, P., & Duarte, C. M. (2018). Sequestration of macroalgal carbon: The elephant in the Blue Carbon room. *Biology Letters*, *14*(6), 20180236. https://doi.org/10.1098/rsbl.2018.0236

Krumhansl, K. A., Okamoto, D. K., Rassweiler, A., Novak, M., Bolton, J. J., Cavanaugh, K. C., Connell, S. D., Johnson, C. R., Konar, B., Ling, S. D., Micheli, F., Norderhaug, K. M., Pérez-Matus, A., Sousa-Pinto, I., Reed, D. C., Salomon, A. K., Shears, N. T., Wernberg, T., Anderson, R. J., … Byrnes, J. E. K. (2016). Global patterns of kelp forest change over the past half-century. *Proceedings of the National Academy of Sciences*, *113*(48), 13785–13790. https://doi.org/10.1073/pnas.1606102113

Laffoley, D., & Grimsditch, G. D. (2009). *The management of natural coastal carbon sinks*. Iucn. https://books.google.com/books?hl=en&lr=&id=NZzlOHYvvO4C&oi=fnd&pg=PR5&dq=The+management+of+natural+coastal+carbon+sinks.&ots=8dA\_kKqnlx&sig=UsMrrz\_Ads95wwGu6vFiIU1qMh0

Layton, C., Coleman, M. A., Marzinelli, E. M., Steinberg, P. D., Swearer, S. E., Vergés, A., Wernberg, T., & Johnson, C. R. (2020). Kelp Forest Restoration in Australia. *Frontiers in Marine Science*, *7*. https://doi.org/10.3389/fmars.2020.00074

Ling, S. D., & Johnson, C. R. (2012). Marine reserves reduce risk of climate-driven phase shift by reinstating size- and habitat-specific trophic interactions. *Ecological Applications*, *22*(4), 1232–1245. https://doi.org/10.1890/11-1587.1

Ling, S. D., Johnson, C. R., Frusher, S. D., & Ridgway, K. R. (2009). Overfishing reduces resilience of kelp beds to climate-driven catastrophic phase shift. *Proceedings of the National Academy of Sciences*, *106*(52), 22341–22345. https://doi.org/10.1073/pnas.0907529106

Lubchenco, J., Haugan, P. M., & Pangestu, M. E. (2020). Five priorities for a sustainable ocean economy. *Nature*, *588*(7836), 30–32. https://doi.org/10.1038/d41586-020-03303-3

Macreadie, P. I., Anton, A., Raven, J. A., Beaumont, N., Connolly, R. M., Friess, D. A., Kelleway, J. J., Kennedy, H., Kuwae, T., Lavery, P. S., Lovelock, C. E., Smale, D. A., Apostolaki, E. T., Atwood, T. B., Baldock, J., Bianchi, T. S., Chmura, G. L., Eyre, B. D., Fourqurean, J. W., … Duarte, C. M. (2019). The future of Blue Carbon science. *Nature Communications*, *10*(1), 3998. https://doi.org/10.1038/s41467-019-11693-w

Mann, K. H. (1973). Seaweeds: Their Productivity and Strategy for Growth: The role of large marine algae in coastal productivity is far more important than has been suspected. *Science*, *182*(4116), 975–981. https://doi.org/10.1126/science.182.4116.975

Marine Conservation Institute. (2019). *MPAtlas*. MPAtlas [On-Line]. Seattle, WA. http://www.mpatlas.org/map/mpas/

Mcleod, E., Chmura, G. L., Bouillon, S., Salm, R., Björk, M., Duarte, C. M., Lovelock, C. E., Schlesinger, W. H., & Silliman, B. R. (2011). A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. *Frontiers in Ecology and the Environment*, *9*(10), 552–560.

Middelboe, A., & Sand-Jensen, K. (2000). Long-term changes in macroalgal communities in a Danish estuary. *Phycologia*, *39*, 245–257. https://doi.org/10.2216/i0031-8884-39-3-245.1

Moy, F. E., & Christie, H. (2012). Large-scale shift from sugar kelp (Saccharina latissima) to ephemeral algae along the south and west coast of Norway. *Marine Biology Research*, *8*(4), 309–321. https://doi.org/10.1080/17451000.2011.637561

National Geographic. (2020, December 2). *Key Fishing Nations Endorse the Protection of 30% of the Ocean*. National Geographic Society Newsroom. https://blog.nationalgeographic.org/2020/12/02/key-fishing-nations-endorse-the-protection-of-30-of-the-ocean/

National Geographic. (2021). *Biden commits to ambitious 30x30 conservation target*. https://www.nationalgeographic.com/environment/2021/01/biden-commits-to-30-by-2030-conservation-executive-orders/

Nellemann, C., & GRID--Arendal (Eds.). (2009). *Blue carbon: The role of healthy oceans in binding carbon: a rapid response assessment*. GRID-Arendal.

Norderhaug, Kjell M., & Christie, H. (2011). Secondary production in a Laminaria hyperborea kelp forest and variation according to wave exposure. *Estuarine, Coastal and Shelf Science*, *95*(1), 135–144. https://doi.org/10.1016/j.ecss.2011.08.028

Norderhaug, Kjell Magnus, Nedreaas, K., Huserbråten, M., & Moland, E. (2021). Depletion of coastal predatory fish sub-stocks coincided with the largest sea urchin grazing event observed in the NE Atlantic. *Ambio*, *50*(1), 163–173. https://doi.org/10.1007/s13280-020-01362-4

O’Brien, J. M., & Scheibling, R. E. (2018). Turf wars: Competition between foundation and turf-forming species on temperate and tropical reefs and its role in regime shifts. *Marine Ecology Progress Series*, *590*, 1–17. https://doi.org/10.3354/meps12530

Ortega, A., Geraldi, N., Alam, I., Kamau, A., Acinas, S., Logares, R., Gasol, J., Massana, R., Krause-Jensen, D., & Duarte, C. (2019). Important contribution of macroalgae to oceanic carbon sequestration. *Nature Geoscience*, *12*. https://doi.org/10.1038/s41561-019-0421-8

Pessarrodona, A., Moore, P. J., Sayer, M. D. J., & Smale, D. A. (2018). Carbon assimilation and transfer through kelp forests in the NE Atlantic is diminished under a warmer ocean climate. *Global Change Biology*, *24*(9), 4386–4398. https://doi.org/10.1111/gcb.14303

Rogers-Bennett, L., & Catton, C. A. (2019). Marine heat wave and multiple stressors tip bull kelp forest to sea urchin barrens. *Scientific Reports*, *9*(1), 15050. https://doi.org/10.1038/s41598-019-51114-y

Savage, J. M., Hudson, M. D., & Osborne, P. E. (2020). Chapter 18—The challenges of establishing marine protected areas in South East Asia. In J. Humphreys & R. W. E. Clark (Eds.), *Marine Protected Areas* (pp. 343–359). Elsevier. https://doi.org/10.1016/B978-0-08-102698-4.00018-6

Simon, N., Cras, A.-L., Foulon, E., & Lemée, R. (2009). Diversity and evolution of marine phytoplankton. *Comptes Rendus Biologies*, *332*(2), 159–170. https://doi.org/10.1016/j.crvi.2008.09.009

Smale, D. A. (2020). Impacts of ocean warming on kelp forest ecosystems. *New Phytologist*, *225*(4), 1447–1454. https://doi.org/10.1111/nph.16107

Smale, D. A., Burrows, M. T., Moore, P., O’Connor, N., & Hawkins, S. J. (2013). Threats and knowledge gaps for ecosystem services provided by kelp forests: A northeast Atlantic perspective. *Ecology and Evolution*, *3*(11), 4016–4038. https://doi.org/10.1002/ece3.774

Smale, D. A., Moore, P. J., Queirós, A. M., Higgs, N. D., & Burrows, M. T. (2018). Appreciating interconnectivity between habitats is key to blue carbon management. *Frontiers in Ecology and the Environment*, *16*(2), 71–73. https://doi.org/10.1002/fee.1765

Steneck, R. S., Graham, M., Bourque, B., Corbett, D., Erlandson, J., & Estes, J. (2002). Kelp Forest Ecosystems: Biodiversity, Stability, Resilience and Future. *Environmental Conservation*, *29*, 436–459. https://doi.org/10.1017/S0376892902000322

Steneck, R. S., & Johnson, C. (2013). Kelp forests: Dynamic patterns, processes, and feedbacks. *Marine Community Ecology and Conservation*, 315–336.

Stuchtey, M. R., Vincent, A., Merkl, A., Bucher, M., Haugan, P. M., Lubchenco, J., & Pangestu, M. E. (2020). *Ocean Solutions That Benefit People, Nature and the Economy* (A Report Commissioned by the High Level Panel for a Sustainable Ocean Economy., p. 148).

UNEP-WCMC. (2020). *Explore the World’s Marine Protected Areas*. Protected Planet. https://protectedplanet.net/marine

Voerman, S. E., Llera, E., & Rico, J. M. (2013). Climate driven changes in subtidal kelp forest communities in NW Spain. *Marine Environmental Research*, *90*, 119–127. https://doi.org/10.1016/j.marenvres.2013.06.006

Vogt, H., & Schramm, W. (1991). Conspicuous decline of Fucus in Kiel Bay (Western Baltic): What are the causes? *Marine Ecology Progress Series*, *69*(1/2), 189–194.

Wernberg, T., Bennett, S., Babcock, R. C., Bettignies, T. de, Cure, K., Depczynski, M., Dufois, F., Fromont, J., Fulton, C. J., Hovey, R. K., Harvey, E. S., Holmes, T. H., Kendrick, G. A., Radford, B., Santana-Garcon, J., Saunders, B. J., Smale, D. A., Thomsen, M. S., Tuckett, C. A., … Wilson, S. (2016). Climate-driven regime shift of a temperate marine ecosystem. *Science*, *353*(6295), 169–172. https://doi.org/10.1126/science.aad8745

Wernberg, T., Krumhansl, K., Filbee-dexter, K., & Pedersen, M. (2019). *Status and Trends for the World’s Kelp Forests* (pp. 57–78). https://doi.org/10.1016/B978-0-12-805052-1.00003-6

Wernberg, T., Russell, B. D., Moore, P. J., Ling, S. D., Smale, D. A., Campbell, A., Coleman, M. A., Steinberg, P. D., Kendrick, G. A., & Connell, S. D. (2011). Impacts of climate change in a global hotspot for temperate marine biodiversity and ocean warming. *Journal of Experimental Marine Biology and Ecology*, *400*(1), 7–16. https://doi.org/10.1016/j.jembe.2011.02.021

Wilmers, C. C., Estes, J. A., Edwards, M., Laidre, K. L., & Konar, B. (2012). Do trophic cascades affect the storage and flux of atmospheric carbon? An analysis of sea otters and kelp forests. *Frontiers in Ecology and the Environment*, *10*(8), 409–415. https://doi.org/10.1890/110176

Xu, Q., Gao, F., & Yang, H. (2016). Importance of kelp-derived organic carbon to the scallop Chlamys farreri in an integrated multi-trophic aquaculture system. *Chinese Journal of Oceanology and Limnology*, *34*(2), 322–329. https://doi.org/10.1007/s00343-015-4332-2

# Glossary

**Adoption Scenario** – the predicted annual adoption over the period 2015 to 2060, which is usually measured in **Functional Units**. A range of scenarios is programmed in the model, but the user may enter her own. Note that the assumption behind most scenarios is one of growth. If for instance a solution is one of reduced heating energy usage due to better insulation, then the solution adoption is translated into an increase in use of insulation. There are two types of adoption scenarios in use: **Reference (REF)** where global adoption remains mostly constant, and **Project Drawdown Scenarios (PDS)** which illustrate high growth of the solution.

**Approximate PPM Equivalent** – the reduction in atmospheric concentration of CO2 (in **PPM**) that is expected to result if the **PDS Scenario** occurs. This assumes a discrete avoided pulse model based on the Bern Carbon Cycle model.

**Average Abatement Cost** – the ratio of the present value of the solution (**Net** **Operating Savings** minus **Marginal First Costs**) and the **Total Emissions Reduction**. This is a single value for each solution for each **PDS Scenario**, and is used to build the characteristic “*Marginal Abatement Cost*” curves when Average Abatement Cost values for each solution are ordered and graphed.

**Average Annual Use** – the average number of functional units that a single implementation unit typically provides in one year. This is usually a weighted average for all users according to the data available. For instance, total number of passenger-km driven by a hybrid vehicle in a year depends on country and typical number of occupants. We take global weighted averages for this input. This is used to estimate the **Replacement Time**.

**Cumulative First Cost** – the total **First Cost** of solution **Implementation Units** purchased in the **PDS Scenario** in the analysis period. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

**Direct Emissions** – emissions caused by the operation of the solution, which are typically caused over the lifetime of the solution. They should be entered into the model normalized per functional unit.

**Discount Rate**- the interest rate used in discounted cash flow (DCF) analysis to determine the present value of future cash flows. The discount rate in DCF analysis takes into account not just the time value of money, but also the risk or uncertainty of future cash flows; the greater the uncertainty of future cash flows, the higher the discount rate. Most importantly, the greater the discount rate, the more the future savings are devalued (which impacts the financial but not the climate impacts of the solution).

**Emissions** **Factor**– the average normalized emissions resulting from consumption of a unit of electricity across the global grid. Typical units are kg CO2e/kWh.

**First Cost**- the investment cost per **Implementation Unit** which is essentially the full cost of establishing or implementing the solution. This value, measured in 2014$US, is only accurate to the extent that the cost-based analysis is accurate. The financial model assumes that the first cost is made entirely in the first year of establishment and none thereafter (that is, no amortization is included). Thus, both the first cost and operating cost are factored in the financial model for the first year of implementation, all years thereafter simply reflect the operating cost until replacement of the solution at its end of life.

**Functional Unit** – a measurement unit that represents the value, provided to the world, of the function that the solution performs. This depends on the solution. Therefore, LED Lighting provides petalumen-hours of light, Biomass provides tera-watt-hours of electricity and high speed rail provides billions of passenger-km of mobility.

**Grid Emissions** – emissions caused by use of the electricity grid in supplying power to any operation associated with a solution. They should be in the units described below each variable entry cell. Drawdown models assume that the global electric grid, even in a Reference Scenario, is slowly getting cleaner, and that emissions factors fall over time resulting in lower grid emissions for the same electricity demand.

**Implementation Unit** – a measurement unit that represents how the solution practice or technology will be installed/setup and priced. The implementation unit depends on the solution. For instance, implementing electric vehicles (EV) is measured according to the number of actual EV’s in use, and adoption of Onshore Wind power is measured according to the total terawatts (TW) of capacity installed worldwide.

**Indirect Emissions** – emissions caused by the production or delivery or setup or establishment of the solution in a specified area. These are NOT caused by day to day operations or growth over time, but they should be entered into the model normalized on a per functional unit or per implementation unit basis.

**Learning Rate/Learning Curve** - Learning curves (sometimes called experience curves) are used to analyze a well-known and easily observed phenomenon: humans become increasingly efficient with experience. The first time a product is manufactured, or a service provided, costs are high, work is inefficient, quality is marginal, and time is wasted. As experienced is acquired, costs decline, efficiency and quality improve, and waste is reduced. The model has a tool for calculating how costs change due to learning. A 2% learning rate means that the cost of producing a *good* drops by 2% every time total production doubles.

**Lifetime Capacity** – this is the total average functional units that one implementation unit of the solution or conventional technology or practice can provide before replacement is needed. All technologies have an average lifetime usage potential, even considering regular maintenance. This is used to estimate the **Replacement Time**. and has a direct impact on the cost to install/acquire technologies/practices over time. E.g. solar panels generate, on average, a limited amount of electricity (in TWh) per installed capacity (in TW) before a new solar panel must be purchased. Electric vehicles can travel a limited number of passenger kilometers over its lifetime before needing to be replaced.

**Lifetime Operating Savings**–the operating cost in the PDS versus the REF scenarios over the lifetime of the implementation units purchased during the model period regardless of when their useful life ends.

**Lifetime Cashflow NPV**-the present value (PV) of the net cash flows (PDS versus REF) in each year of the model period (2015-2060). The net cash flows include net operating costs and first costs. There are two results in the model: Lifetime Cashflow NPV for a Single **Implementation Unit**, which refers to the installation of one **Implementation Unit**, and Lifetime Cashflow NPV of All Units, which refers to all **Implementation Units** installed in a particular scenario. These calculations are also available using profit inputs instead of operating costs.

**Marginal First Cost** – the difference between the **First Cost** of all units (solution and conventional) installed in the **PDS Scenario** and the **First Cost** of all units installed in the **REF Scenario** during the analysis period. No discounting is performed. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

**Net Annual Functional Units (NAFU)** – the adoption in the PDS minus the adoption in the REF in each year of analysis. In the model, this represents the additional annual functional demand captured either by the solution in the **PDS Scenario** or the conventional in the **REF Scenario**.

**Net Annual Implementation Units (NAIU)** – the number of **Implementation Units** of the solution that are needed in the PDS to supply the **Net Annual Functional Units (NAFU).** This equals the adoption in the PDS minus the adoption in the REF in each year of analysis divided by the average annual use.

**Net Operating Savings** – The undiscounted difference between the operating cost of all units (solution and conventional) in the **PDS Scenario** minus that of all units in the **REF Scenario**.

**Operating Costs** – the average cost to ensure operation of an activity (conventional or solution) which is measured in 2014$US/**Functional Unit**. This is needed to estimate how much it would cost to achieve the adoption projected when compared to the **REF Case**. Note that this excludes **First Costs** for implementing the solution.

**Payback Period** – the number of years required to pay all the **First Costs** of the solution using **Net Operating Savings**. There are four specific metrics each with one of **Marginal First Costs** or **First Costs** of the solution only combined with either discounted or non-discounted values. All four are in the model. Additionally, the four outputs are calculated using the increased profit estimation instead of **Net Operating Savings**.

**PDS/ Project Ambitious Scenario** – this is the high growth scenario for adoption of the solution

**PPB/ Parts per Billion** – a measure of concentration for atmospheric gases. 10 million PPB = 1%.

**PPM/ Parts per Million** – a measure of concentration for atmospheric gases. 10 thousand PPM = 1%.

**REF/ Reference Scenario** – this is the low growth scenario for adoption of the solution against which all **PDS scenarios** are compared.

**Regrets solution** has a positive impact on overall carbon emissions being therefore considered in some scenarios; however, the social and environmental costs could be harmful and high.

**Replacement Time**- the length of time in years, from installation/acquisition/setup of the solution through usage until a new installation/acquisition/setup is required to replace the earlier one. This is calculated as the ratio of **Lifetime Capacity** and the **Average Annual Use**.

**TAM/ Total Addressable Market** – represents the total potential market of functional demand provided by the technologies and practices under investigation, adjusting for estimated economic and population growth. For this solutions sector, it represents world and regional total addressable markets for electricity generation technologies in which the solutions are considered.

**Total Emissions Reduction** – the sum of grid, fuel, indirect, and other direct emissions reductions over the analysis period. The emissions reduction of each of these is the difference between the emissions that would have resulted in the **REF Scenario** (from both solution and conventional) and the emissions that would result in the **PDS Scenario**. These may also be considered as “emissions avoided” as they may have occurred in the REF Scenario, but not in the PDS Scenario.

**Transition solutions** are considered till better technologies and less impactful are more cost effective and mature.

**TWh/ Terawatt-hour** – A unit of energy equal to 1 billion kilowatt-hours

1. For most results, only the differences between scenarios, summed over 2020-2050 were presented, but for the net first cost, the position was taken that to achieve the adoptions in 2020, growth must first happen from 2015 to 2020, and that growth comes at a cost which should be accounted for, hence net first cost results represent the period 2019-2050. [↑](#footnote-ref-1)
2. In some cases, the low boundary is negative for a variable that can only be positive, and in these cases the lowest collected data point is used as the “low” boundary. [↑](#footnote-ref-2)