**Technical assessment for**

***Macroalgae Restoration***

Sector: Oceans

Agency Level: Government

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# Executive Summary

Project Drawdown defines *Macroalgae Restoration* as processes or programs designed to return wild macroalgae forest ecosystems to a previous state from a degraded condition. Macroalgae forests are the major primary producers in coastal areas with a 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). Macroalgae forests include kelp forests as well as other stands of large, canopy forming macroalgae, which are abundant foundational species in much of the coastal ocean. Currently, global average abundance and extent of macroalgae forests is declining, although there is substantial regional and temporal variation. *Macroalgae Restoration* models the expansion of current efforts to actively restore these habitats. It is assumed that  *Macroalgae Restoration* primarily happens at the government level.

Out of a total ocean area available for the solution of 198 million hectares by 2050, the current solution adoption (2018) is assumed to be zero million hectares due to the lack of data. Five scenarios were developed based on a range of data from actual macroalgae restoration projects around the world. These scenarios were combined to produce *Plausible* (Average of All), *Ambitious* (High of All), and *Maximum* (single highest) scenarios.

Total adoption in the *Plausible Scenario* is 14 million hectares in 2050, representing 7 percent of the total suitable land. Total adoption in the *Ambitious Scenario* is 26 million hectares in 2050, representing 13 percent of the total suitable land. Total adoption in the *Maximum Scenario* is 34 million hectares in 2050, representing 17 percent of the total suitable land. Climate impact is 0.74, 1.45, and 1.95 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 Restoration* 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 (Melinda A. 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) (Melinda A. 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 (Melinda A. 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

Description automatically generated

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).

***Status and Trends in Macroalgae Restoration***

Ecosystem restoration is an important conservation approach, particularly in degraded ecosystems. Restoring marine ecosystems has the potential to restore biodiversity and ecosystem functioning (Kang et al., 2008; Layton et al., 2020), enhance ecosystem services, support UN Sustainable Development Goal 14, Life Below Water (Duarte et al., 2020). Specific objectives of restoration projects may range from returning the habitat to a previous state to building resilience into the habitat so it can better withstand projected changes in conditions (Coleman et al., 2020). Restoration of kelp and other macroalgae forests has generally been attempted in small-scale projects (A.M. Eger et al., 2019), proven challenging to scale and has been slower to develop and scale compared to restoration of other habitat types (Duarte et al., 2020); (Figure 1.3). Nevertheless, interest in active restoration programs in response to declines in kelp and other macroalgae forest ecosystems is increasing (Eger et al., 2020) with particularly active programs in Korea, Japan, and Australia (Fujita, 2011; Hwang et al., 2020; Jung et al., 2020; Kang et al., 2008; Kuwahara et al., 2006; Layton et al., 2020; Verdura et al., 2018; Vergés et al., 2020) and active restoration sites recently emerging in Europe, Chile, and the United States (Duarte et al., 2020) (Figure 1.4).

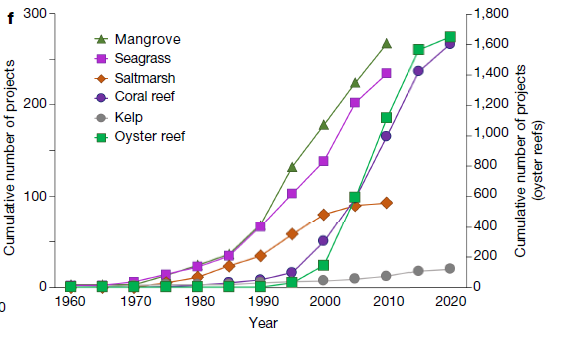


Figure 1.3. Trends in restoration projects in each ecosystem over time. Source: (Duarte et al., 2020)

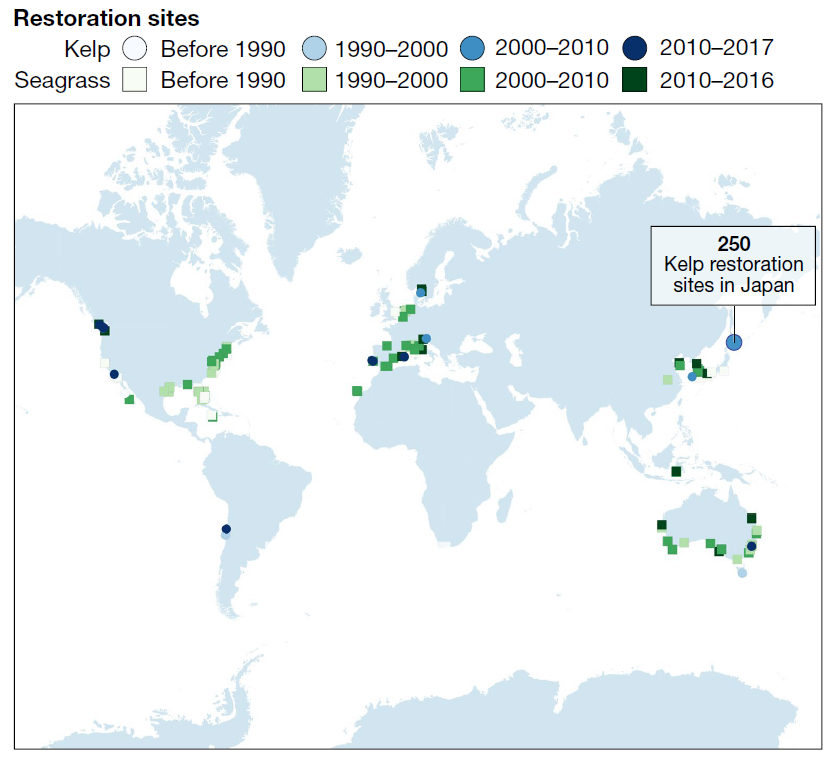


Figure .. Restoration sites by ecosystem. Duarte et al. 2020.

## Adoption Path

### Current Adoption

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

### Trends to Accelerate Adoption

Recent publications shed light on advances and approaches that may help accelerate adoption. A review by (Eger, Vergés, et al., 2020) demonstrated the role that strong financial and institutional support can play in supporting large scale restoration of kelp forests. As an example, Korea spent over USD 280 million between 2009 and 2019 in their successful restoration efforts (Hwang et al., 2020). Increasing awareness of the value of these ecosystems for the services they provide and as blue carbon, and growing pledges to conserve and restore large portions of the ocean, may help incentivize other countries to do similarly. Along those lines, the High Level Panel for Ocean Solutions released a report which highlighted ecosystem restoration, including macroalgae forest, as a priority and a potential climate solution (Hoegh-Guldberg et al., 2019; Lubchenco et al., 2020). In addition to Korea and the nations that are part of the Ocean Panel pledge, Japan has also incorporated prioritization of kelp and macroalgae forest restoration into national policy (Fujita, 2011). New approaches, such as incorporation of positive species interactions (Eger, Marzinelli, et al., 2020), advancement of seeding and recruitment enhancement techniques (Fredriksen et al., 2020; Jung et al., 2020; Terawaki et al., 2003; Verdura et al., 2018), and herbivore removal programs (Watanuki et al., 2010) may increase the success rate of restoration projects.

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

### Barriers to Adoption

Limited scientific publications on the subject, particularly on the long- term carbon sequestration potential of wild macroalgae, might delay setting up a policy agenda to create restoration schemes. When establishing restoration 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).

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 restoration projects 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).

Finally, macroalgae forest restoration projects are financially and logistically difficult to scale. While there are an increasing number of successful projects at a larger scale, the majority of work to date has been small-scale projects (A.M. Eger et al., 2019) and questions remain about the ability of restoration projects to keep pace with increasing degradation on a global scale (Fredriksen et al., 2020; Layton et al., 2020).

### Adoption Potential

Adoption potential can be extrapolated from consideration of trends in countries or regions that have had more aggressive restoration programs. At the high end of this range, Korea has implemented macroalgae restoration projects that have successfully restored 35 percent of deforested macroalgae forest area in Jeju Island and 51 percent of the barren macroalgae forest habitat in the East Sea region, for a total of 21,500 ha of active and successful seaweed forest restoration so far, and a goal of 54,000 ha restored by 2030 (Aaron M. Eger, Vergés, et al., 2020; Hwang et al., 2020). In Australia, the ongoing Operation Crayweed in the Sydney region has achieved ecological benefits beyond the scale of the original interventions (Layton et al., 2020). Eger et al. (2020) describe four relatively large kelp restoration projects in various countries, spanning the scales of tens to tens of thousands of hectares. Given that individual projects remain small for the most part, replication of successful models in a large number of locations must be part of the scaling up of adoption of this solution. Lessons from reviews such as Eger et al. (2020) and frameworks such as (Layton et al., 2020) can help provide a blueprint for such efforts, which are expected to increase in the coming years.

## Advantages and disadvantages of Macroalgae Restoration

### Similar Solutions

*Protection and restoration solutions*

This *Macroalgae Restoration* solution has been developed together with a related *Macroalgae Protection* solution, which estimates the climate benefits of protecting wild macroalgae forest area from degradation.

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

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, continued degradation of kelp forests extent or abundance would impact the provision of these ecosystem services (Krumhansl et al., 2016), and restoration efforts hold the potential to protect these services (Duarte et al., 2020; A.M. Eger et al., 2019).

### 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 Restoration 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 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. This meta-analysis is overwhelmingly based on data from brown algae and include only few data points from green algae. 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.

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).

Conservative custom adoption scenarios were developed by extrapolating the time series of area included in actual restoration projects from (Aaron M. Eger, Vergés, et al., 2020). More ambitious custom adoption scenarios were based on projections and assumption of more widespread adoption of Korea’s level of macroalgae forest restoration, as a percentage of degraded forest area, based on data in (Hwang et al., 2020).

## Total Ocean Area

A customized global TOA was built for this solution, beginning with a total undegraded macroalgae forest area based on Krause-Jensen and Duarte (2016) wild macroalgae area (355 Mha) and calculating the area subject to degradation each year using the data sources for ocean degradation rates listed above. The resulting total area of degraded macroalgae forest available for restoration increases is set to zero at the beginning of the model timeline (2018) and increases to 198 Mha by 2050. Because the adoption scenarios modeled here are relatively conservative and do not approach the total amount of degraded macroalgae forest area available for restoration, the TOA does not limit restoration adoption, even though the total area available begins as a small number and grows over time due to the ocean degradation growth rate. Therefore, the model incorporates a constant TOA of 198 Mha (the 2050 value) as a reference point to calculate the growth in percent of TOA adopted over time.

## 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.

Five custom adoption scenarios were developed for this solution using a combination of the more conservative and more ambitious approaches. Each growth scenario incorporated a maximum area of the Total Ocean Area available for restoration at that time (degraded TOA).

**Custom adoption scenario one:** This scenario is based on the projection of restoration area data from Korea, which had the largest proportional adoption of macroalgae forest restoration, assuming the same level of adoption by other regions with macroalgae forest habitat. This forms the most optimistic possible scenario, but was excluded from model averages.

**Custom adoption scenario two:** This scenario is based on an extrapolation of global restoration project data extracted from the review study by Eger et al. 2020 from 2017 to 2019, based on the cumulative size of large-scale kelp forest restoration projects, with growth projected into the future based on a best-fit 2nd order polynomial projection.

**Custom adoption scenario three:** Thisscenario assumes that countries or regions accounting for5 percent of the total available area for restoration achieve Korea’s level of adoption; it projects 5 percent of Korea’s restoration area applied to the full degraded TOA.

**Custom adoption scenario four:** Thisscenario assumes that countries or regions accounting for10 percent of the total available area for restoration achieve Korea’s level of adoption; it projects 10 percent of Korea’s restoration area applied to the full degraded TOA.

**Custom adoption scenario five:** Thisscenario assumes that countries or regions accounting for50 percent of the total available area for restoration achieve Korea’s level of adoption; it projects 50 percent of Korea’s restoration area applied to the full degraded TOA. This is the most optimistic scenario that was included in model averages.

### Reference Case / Current Adoption

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

### 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.

#### Ambitious Scenario – represented by the “high of all” custom adoption scenarios.

***Maximum Scenario*** *–* represented by the highest individual custom adoption scenario, i.e. Scenario 5 (Scenario 1 was excluded due to presumed infeasibility).

## Inputs

### Climate Inputs

The long-term sequestration rate is the crucial climate input for the *Macroalgae Restoration* 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 | 0.3-6 | 2.48 | 20 | 14 |

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 restoration 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 restoration 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 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.
5. It is assumed that the re-growth of the degraded macroalgae forest area will start within one year of restoration activities commencing, due to the fast growth of these species.

## 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 Restoration* 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, 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. *Improving 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 14 million hectares in 2050, representing 7 percent of the total suitable degraded ocean area.

Total adoption in the *Ambitious Scenario* is 26 million hectares in 2050, representing 13 percent of the total suitable degraded ocean area.

Total adoption in the *Maximum Scenario* is 35 million hectares in 2050, representing 18 percent of the total suitable degraded ocean area.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Solution** | **Units** | **Current Year (million hectare)** | **World Adoption by 2050** | | |
| **Plausible** | **Ambitious** | **Maximum** |
| Macroalgae Restoration | million hectare | 0.00 | 14.0 | 26.3 | 34.8 |
| *(% TOA)* | 0% | 7.1% | 13.3% | 17.6% |

Table 3‑1 World Adoption of the Solution

Figure 3.1 World Annual Adoption 2020-2050

Figure 3.2. World Annual Adoption, %TOA, 2020-2050

## 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 0.74, 1.45, and 1.95 gigatons of carbon-dioxide equivalent in the *Plausible, Ambitious* and *Maximum* scenarios respectively.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Scenario** | **Max Annual CO2 Sequestered** | **Total Additional CO2 Sequestered** | **Total Atmospheric CO2-eq Reduction** | **Emissions Reduction in 2030** | **Emissions Reduction 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*** | 0.05 | 0.74 | 0.74 | 0.02 | 0.05 |
| ***Ambitious*** | 0.09 | 1.45 | 1.45 | 0.03 | 0.09 |
| ***Maximum*** | 0.12 | 1.95 | 1.95 | 0.05 | 0.12 |

Table 3‑2 Climate Impacts

Figure 3.3. World Annual CO2 Reduction

|  |  |  |
| --- | --- | --- |
| **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*** | 0.06 | 0.0037 |
| ***Ambitious*** | 0.12 | 0.0068 |
| ***Maximum*** | 0.16 | 0.0090 |

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 and restoration.

## Macroalgae Restoration 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). 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 (Melinda A. 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). Active ecosystem restoration can help to increase the amount healthy macroalgae forest and will be an important approach to use in combination with ecosystem protection. However, even with the best efforts of local resource managers to restore 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.

## 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 and restore 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 Restoration* model includes only one estimate of the percent of NPP which is sequestered in the long- term based on Krause- Jensen and Duarte (2016). Moreover, there are generally a lack of data on the contribution of red and green algae to blue carbon export as well as data on restoration projects for these species. 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 restoration of 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. However, this estimate is more comparable to our analysis of Macroalgae Protection, a separate Drawdown model, because only a small fraction of total macroalgae forest area will be subject to active restoration.

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# 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)