**Technical assessment for**

***Seaweed Farming***

Sector: Ocean

Agency Level: Farmer

Keywords: Macroalgae, Aquacultures, Sequestration, Aqueous Carbon

March 2021

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# Executive Summary

Seaweed farming has been developed for several decades primarily in Asia. 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 *seaweed farming*as: the culturing, cultivation and harvesting of different macroalgae species in the ocean area with the purpose of accounting for the long- term sequestration of the carbon exported to the deep sea and/ or stored in the ocean shelves. The solution is assumed to be developed in ocean areas which do not have alternative uses prior to the deployment of the solution. It is assumed that *seaweed farming* primarily happens at the farmer level.

Out of a total ocean area available for the solution of 240 million hectares, the current solution adoption (2018) is 0.19 million hectares (0.08%). Starting from this adoption value and based on different rates of macroalgae biomass production from FAO for 2006- 2016, projected growth rates of macroalgae farming by 2050 from the World Bank and projected growth from a report by Hoegh- Gudlberg et al. (2019), ten custom PDS adoption scenarios were developed for this solution which were combined to produce the *Plausible*, *Ambitious* and *Maximum* scenarios.

In the *Plausible* Scenario, the adoption area reaches 13.20 million hectares by 2050 totaling 5.58 % of total ocean area. Climate impact is 2.50 gigatons of carbon dioxide equivalent. Net profit margin is 2,736.69 Billion USD for 2020- 2050.

In the *Ambitious* Scenario, the adoption area reaches 24.96 million hectares by 2050 totaling 10.48 % of total ocean area. Climate impact is 4.72 gigatons of carbon dioxide equivalent. Net profit margin is 5,173.55 Billion USD for 2020- 2050.

In the *Maximum* Scenario, the adoption area reaches 33.60 million hectares by 2050 totaling 14.00 % of total ocean area. Climate impact is 6.32 gigatons of carbon dioxide equivalent. Net profit margin is 6,926.25 Billion USD for 2020- 2050.

# 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 (Nellemann *et al.*, 2009; McLeod *et al.*, 2011; Duarte *et al.*, 2013). Globally, over half (55%) of the carbon captured annually by photosynthetic activity is captured by marine organisms (Falkow­ski *et al.*, 2004; Arrigo, 2005; González, *et al.*, 2008; Bowler, 2009; Simon *et al.*, 2009). Seaweeds 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 and 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%) 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 and 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 (Ortega et al., 2019; Krause-Jensen & Duarte, 2016). These estimates exceed those 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 (Krause-Jensen and Duarte, 2016; Duarte et al., 2005).

***Seaweed Farming***

Macroalgae aquaculture comprises 27% of total marine aquaculture production and is valued at 5% of the total value of aquaculture crops (FAO, 2018). In 2005, global macroalgae production was estimated at 14.7 million metric tons, of which 13.5 million were cultured and 1.2 were wild harvests. By 2016, global yields more than doubled, reaching 31.2 million metric tons. This growth was seen exclusively in cultivated stocks, which soared to 30.1 million tons (96.5%), while wild harvest numbers fell to 1.1 million tons.



Figure 1-1: Global macroalgae production (1950- 2014). FAO (2015)

*Source: Cottier- Cook et al. (2016)*

From over 50 countries in which seaweed farming takes place, China, Indonesia, the Philippines and the Republic of Korea are the leading producers of cultivated macroalgae stocks totaling 91% and 95% of global production in 2005 and 2016 respectively (Ferdouse et al. 2018; FAO, 2018). The main contributor to the growth rate of 8% per year between 2005- 2016 was Indonesia which rose from less than 1 million tons in 2005 to 11 million tons in 2016 (FAO, 2018). Driven by a growing carageenan extraction industry, Indonesian production rose from 7% of total global production in 2005 to 39% in 2019, while China’s production fell from 70% in 2005 to 48% in 2016 (FAO, 2018). Chile, China, and Norway have been the largest harvesters of wild macroalgae (Ferdouse et al., 2018). The sharp increase in macroalgae farming between 2005 and 2016 is likely to continue with the leading producing nations focusing on ensuring the sector’s long- term sustainability (Ferdouse et al., 2018).

***Seaweed cultivation methods***

There are various methods of culturing and cultivating macroalgae. Although some macroalgae farming occurs on land – in ponds or tanks – this analysis focuses on utilizing ocean area. The stages of marine macroalgae farming include: the selection of cultivars, production of seedling, cultivation, harvesting and processing (Hwang et al., 2019).

Whilst some macroalgae can be cultivated vegetatively- in which small pieces of macroalgae are taken and placed in an environment that will sustain their growth, other species require their reproductive cycle to be monitored (Mc Hugh, 2003; Taelman et al., 2015). For the latter, the success of the farming process depends on the optimization of the hatchery production processes (Barbier et al., 2019). In addition to hatchery units, other land facilities are required to process the biomass (Barbier et al., 2019).

There are three near- shore cultivating methods which are widely used worldwide (Andersen, 2005; Taelman et al., 2015):

1. Off- bottom monoline method: approximately 10 m long ropes are held by stakes, usually made of wood (Sahoo et al., 2005; Valderrama et al., 2013) and small pieces – 50-100 g- of macroalgae are tied to the lines (Valderrama et al., 2015);
2. Floating longline method: generally implemented further away from the shore in deeper waters, buoys are used to provide stability to lines anchored to the sea bottom (figure 2);
3. Raft system: macroalgae culture ropes are attached to structures made of floating materials (plastic, bamboo) (figure 3)

**

Figure 1‑2: Schematic representation of a single longline system in Ireland

*Source: Taelman et al. (2015)*

**

Figure 1‑3: Schematic representation of a raft system in France

*Source: Taelman et al. (2015)*

Whilst the off- bottom monoline method provides easier access (at low tide farmers can walk around), the floating longline and raft system methods can be easily relocated if need be or removed from the water under bad weather conditions (McHugh, 2003; Valderrama et al., 2015).

Outside the scope of this solution is the integrated multi- trophic aquaculture (IMTA) process which combines the production of different species – macroalgae, fish, invertebrates- to benefit from the trophic relationships amongst them (Chopin, 2006, 2017; Barbier et al., 2019). In the IMTA process, which can be in both land- based and offshore systems, “the by-products from one species are recycled to become inputs for another” which results in increased productivity, profitability and sustainability (Ahmed et al., 2017).

***Seaweed uses***

Out of approximately 20,000 known seaweed species, 221 are commercially used and a little over 10 cultivated intensively (Critcheley and Ohno, 1998; Chung et al., 2010 and Ferdouse et al., 2018). Current uses include:

* Human consumption: Macroscopic marine algae (macroalgae) for human consumption, especially nori (Porphyra spp.), wakame (Undaria pinnatifida), and kombu (Laminaria japonica), are widely cultivated algal crops.
* Carrageenan, used in cosmetics and as a food additive.
* Feed: animal fodder, animal supplements, alginate, aquafeed, which is used as a binder in feeds for farm animals.
* Biofuel to directly replace fossil fuels, with a potential CO2 mitigation capacity, in terms of avoided emissions from fossil fuels. In addition, benefits over land crops derived biofuels include avoided competition for arable land and freshwater with food crops and avoided use of pesticides and fertilizers (Duarte et al., 2013).
* Bioremediation: wastewater treatment.

## Adoption Path

### Current Adoption

Current adoption of *seaweed farming* is 0.19 Mha resulting from the average of three data points: 0.19 Mha (Froehlich et al., 2019); 0.16 Mha (Duarte et al., 2017) and 0.21 Mha (Project Drawdown 2019 interpolated value using FAO 2005- 2015 data to get the current adoption for 2018). The literature review also resulted in four additional datapoints: 3 for China (0.13 Mha from Krause- Jensen et al. (2018); 0.14 Mha from Zhang et al. (2017) and 0.14 Mha from Hwang et al. (2019)) and one for Korea (0.07 Mha from Sondak and Chung (2015)).

### Trends to Accelerate Adoption

There are several trends which could accelerate the development of seaweed farming. These include:

1. R&D investments. Expanded investments in R&D and innovation are crucial to meet some of the industry’s expected challenges such as “disease risks, climate change and further introductions of nonindigenous marine species” (Hurtado et al. 2019). The MARINER program, a 22 US$ million initiative launched in 2018 by the US Department of Energy to develop technologies for offshore macroalgae farming, aims to bring the US at the forefront of the industry whilst improving energy security and economic competitiveness (Kim et al., 2019).
2. Microfinance. Further development and extent of microfinance schemes would contribute to reduce the sea farmers dependency on traders/ processors for farming materials, equipment and non- indigenous cultivars whilst also increasing their leverage to negotiate higher prices (Cottier- Cook et al., 2016; Valderrama et al., 2015).
3. National insurance programs. As a result of the devastating consequences of natural disasters on sea farms in Korea, the government launched the Aquaculture Disaster Insurance scheme in 2007. In the event of a natural disaster, the sea farmers receive “70-80% of the average-yearly production of the farm on the condition that the macroalgae farmers return their site to its prior state” (Cottier- Cook et al., 2016). The successful scheme was expanded from covering damages from natural disasters to other hazards such as disease epidemics and red tides (Cottier- Cook et al., 2016).
4. Development of accreditation system for long- term sequestration from macroalgae farming.
5. Rising number of coalitions e.g. Seaweed for Europe coalition was launched in 2020 to catalyze expansion of Europe seaweed sector.

Accounting for the long- term carbon storage potential of macroalgae farming is a new area of research. Krause- Jensen et al. (2018) highlight that macroalgae are already included in Blue Carbon schemes given their role as carbon donors. As an example, “assessments using stable isotopes showed that 50% of seagrass sediment C is contributed by other primary producers, including macroalgae” (Krause- Jensen et al., 2018; Kennedy et al., 2010 and Thormar et al., 2016). A study on an integrated multi-trophic aquaculture farm in China showed that the cultured scallop obtained between 14.1% and 42.8% of its carbon from the co- cultured kelp (Qiang et al., 2015). In another study on an IMTA system in China, Xu et al. (2016) concluded that between 14% and 42 % of carbon in scallop was sourced from kelp (Fernandez et al., 2019).

Chung et al. (2017) stress on the importance of establishing a measurement, reporting and verification (MRV) methodology so that macroalgae farming can be included in Nationally Appropriate Mitigation Actions (NAMA) and/ or Nationally Determined Contributions (NDC). 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

***Limitations***

The scope of expansion of seaweed farming expansion is limited by:

1. Availability of suitable areas, including nutrient (Forster and Radulovich, 2015) and temperature regimes.
2. Competition with other farming area uses.
3. Fragmented industry outside of Asia (UN Global Compact, Action Platform for Sustainable Ocean Business, 2020).
4. Volatility in market prices (Valderrama et al., 2015).
5. Engineering systems capable of coping with rough conditions offshore. Current technology can be deployed in relatively shallow areas.
6. Need for increased market demand.
7. Climate feedbacks on macroalgae cultivation are not clear (Callaway et al., 2012). Factors include ocean warming (Harley et al., 2012), increased storm energy and reduced nutrient supply (Callaway et al., 2012).
8. Increased CO2 may increase the yield of macroalgae aquaculture (Callaway et al., 2012).
9. Bureaucracy around the macroalgae farming permit process (Forster and Radulovich (2015); Kim et al., 2019), especially for near- shore farming areas.
10. Lastly, the expansion of macroalgae aquaculture needs to also consider potential impacts, such as the introduction of invasive species and proliferation of non – indigenous pathogens and pests (Barbier et al., 2019). However, assessments of the impacts of invasive macroalgae species, derived from aquaculture (e.g., *Undaria pinnatifida*), report both benefits and impacts, which are not severe in nature (McLaughlan et al., 2014).

***Future considerations***

Limited scientific publications on the subject, particularly on the long-term carbon sequestration potential of macroalgae, might delay setting up a policy agenda to create schemes and to incorporate macroalgae farming in existing Blue Carbon schemes. Even if this is surpassed and despite macroalgae high level of resilience, climate change and the resulting increasing frequency in warm water events present an ongoing threat to seaweeds, some of which remains outside the control of farmers (Krumhansl et al., 2016; Smale, 2020). Moreover, the productivity of seaweed farming could be affected by the consequences stemming from climate change such as ocean acidification, elevated CO2, elevated UVB, increased temperatures and an increase in storm activity (Chung et al., 2017). Future challenges also involve reducing the dependency from non- indigenous stock and develop tools to prevent and manage an outbreak if need be (Cottier- Cook et al., 2016).

### Adoption Potential

A recent study by Froehlich et al. (2019) found that an area of 48 million km2 (4,800 Mha) is ecologically suitable for seaweed farming after factoring in temperature and nutrients constraints. Lehahn et al. (2016), proposed that the global potential of offshore and shallow waters macroalgae farming for biorefineries is 10,000 million tons dry weight/ year occupying an area of 10,000 Mha (10 million km2).

## Advantages and disadvantages of Macroalgae Farming

### Similar Solutions

***Protection and restoration solutions***

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

The potential impact of near- shore seaweed farming on seagrass meadows is two- fold: on the one hand, it can counteract the negative impact from eutrophication and improve water quality; on the other hand, neighboring macroalgae farms could result in human disturbance leading to damages (Duarte et al., 2017).

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.

***Interaction with other Drawdown solutions***

As a solution to potential suitable space constraints, some marine spatial models propose the co- location of seaweed farms and *Wind Turbines (Offshore)* (Reith et al., 2005; Kraan et al., 2010; Gimpel et al., 2015; Duarte et al., 2017).

An increase in seaweed consumption as a food source through macroalgae farming development would be in line with the *Plant-rich Diet* solution. The potential production of biochar from macroalgae biomass for addition to soil would be aligned with the *Biochar* solution. It should be noted that research on macroalgae biochar is at early stages (Hill et al., 2015). Some part of produced macroalgae biomass can be also allocated to feed for livestock which have proven to reduce methane emissions from the ruminants (Morais et al., 2020) as well as to bioplastic (Vincent et al., 2020).

### Arguments for Adoption

***Seaweed farming benefits***

Commercial macroalgae aquaculture beds present the opportunity to vegetate areas of shallow coastal waters where natural vegetative cover is low or non-existent, thus creating new blue carbon sinks (Sondak et al., 2017). Duarte et al. (2017) estimated a sequestration potential from farmed macroalgae of 1,500 tonnes CO2 km-2 year-1 (Duarte et al., 2017). A recent study by Froehlich et al. (2019) factored in a reduction in the carbon sequestration by macroalgae by accounting for the emissions resulting from the macroalgae farms (16%) and the resulting mean sequestration potential is 1,110 tonnes of CO2 km-2 year-1. However, the carbon sequestration capacity depends on the fate of the farmed production (Chung et al. 2017; Krause- Jensen et al. 2018). Seaweed farming results in carbon fixation in four forms: carbon fixed in macroalgae through photosynthesis – ‘removable carbon’, dissolved organic carbon (DOC), particulate organic carbon (POC) stored in the seawater, and buried POC in sediments (Zhang et al., 2017). The extent to which the ‘removable carbon’ can be accounted as long- term sequestration depends entirely on the final use of the biomass: the carbon in macroalgae used for food quickly returns to the atmosphere whereas the macroalgae used for livestock feed (Machado et al., 2015) or for biofuel production results in avoided emissions from fossil fuels (Zhang et al., 2017).

Research indicates that macroalgae farming could play a role in coral reef management and conservation. Macroalgae’s capacity to take up carbon from surrounding water for storage in biomass may successfully raise reef-scale pH to combat the effects of ocean acidification, one of the leading threats to coral reef health. Although this strategy will be insufficient in countering the effects of future levels of acidification, its short-term effects can bolster other coral conservation efforts (Mongin et al., 2016).

Seaweed farming is playing an increasingly significant role in global social equity as well as climate stabilization. It can provide additional income to coastal communities in developing countries and is an especially important source of income for women. Because the technology is simple, requires low initial capital investment, and harvest is as soon as six weeks after planting (Valderrama et al., 2015), women are more easily able to begin macroalgal farming operations than traditional terrestrial farms, for example. Additionally, planting usually occurs in the intertidal, where women can safely bring young children in their care while men fish (Ferdouse et al., 2018; Shanmugam et al., 2017; Valderrama et al., 2013). There is evidence from the Philippines that macroalgae farming is correlated with increases in herbivorous fish catch (Hehre and Meeuwig, 2016).

Replacing food or feed land- production systems with intense CO2 emission footprints with macroalgae-based food systems, which have a much lower life-cycle of CO2 emissions (Fry et al. 2012), would also result in massive savings in freshwater consumption given that “4,000,000 L (one million gallons) of freshwater can be saved on land per ton of food produced at sea (Radulovich, 2011)” (Forster and Radulovich, 2015). Macroalgae farming could also play a significant role in food security. The European Commission estimated that macroalgae and microalgae cultivation could reach 56 million tons of protein production by 2054, totaling “18% of the global alternative protein market” (Buschmann et al., 2017).

Other benefits include: mitigation of wild macroalgae over- harvesting (Buschmann et al., 2017) as well as overfishing (Cottier- Cook et al., 2016) and the long- term CO2 sequestration potential from the production of macroalgal biochar (Hill et al., 2015). The latter is at early research stages (Lehman et al., 2006; Bird et al., 2011; Hill et al., 2015).

### Additional Benefits and Burdens

Here this solution is compared with other solutions in the ocean sector in terms of ecosystem, social and climate impact. Seaweed farming represents the highest climate impact within all ocean solutions with high adoption potential and intermediate 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 Fishery and Improve Aquacultures 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 Fishery | High | High | Middle | High (TAM 94 million tons landings) |
| Improve Aquacultures | n/a | Medium | Middle | High (TAM 126 million tons live weight) |
| **Seaweed Farming** | **Medium** | **Medium** | **High** | **High** |
| Macroalgae Forests Protection | High | High | Middle | Middle |
| Macroalgae Forests 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 template used for this solution was the Ocean model which accounts for sequestration of carbon dioxide from the atmosphere into plant biomass and soil, and reduction of emissions for a solution relative to a conventional practice. These practices are assumed to use ocean of a specific type that may be shared across several solutions. 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 constituted the results.

*Agency Level*

Farmer is selected as the agency level for this solution. Though certainly other agents can, do, and should play an important role in this solution, landowners/ managers are the most critical player in implementation.

## Data Sources

Key data sources include Krause- Jensen and Duarte (2016) as well as personal communications with Prof. Carlos Duarte and Megan Reilly Cayten from the Oceans 2050 team.

Krause- Jensen and Duarte (2016)’s seminal paper was used for estimating the % of exported POC/ DOC that results in long- term carbon sequestration. Discussions with Prof. Duarte and Megan Reilly Cayten from Oceans 2050 have been highly productive to validate our financial information and get first estimates on the % POC/ DOC export from macroalgae farms.

## Total Ocean Area

The Drawdown Ocean model defines the Total Ocean Area as the ocean area (in million hectares) suitable for a given solution.

A customized global TOA was built for this solution based on the Froehlich et al. (2019) analysis on the suitable area for seaweed farming considering nutrients and temperature constraints. According to this study, 48 million km2 (4,800 Mha) of the oceans are suitable for macroalgae farming.

The ocean area included in the model is 240 Mha, 5 percent of the Froehlich et al. (2019) value, which is smaller than the wild macroalgae area estimate of 355 Mha (Krause- Jensen et al. 2016) but in line with 221 Mha estimated as potential macroalgae farming expansion area (BFI, 2020). The rationale behind choosing 5 percent of 240 Mha was behind setting a conservative TOA.

## 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 focus on the change to the world relative to a baseline.

Ten custom adoption scenarios were created using FAO macroalgae production data from 2006-2016, projected annual growth rate given by World Bank Group (2016) and Hoegh- Guldberg et al. 2019. In the absence of actual data on trends in macroalgae area, the future area for this solution is projected based on the annual growth rate in production as estimated using the listed sources above. The details are given below:

**Custom adoption scenario one**: The FAO 2006-2016 data lists country level production of macroalgae. An annual rate of increase in production was calculated for each of the given countries. The maximum increase was reported in Indonesia (9.96%), followed by China (3.34%). This scenario projects the future growth of macroalgae area based on the annual rate of Indonesia, applying it to the current adoption.

**Custom adoption scenario two**: The FAO 2006-2016 data lists country level production of macroalgae. An annual rate of increase in production was calculated for each of the given countries. The maximum increase was reported in Indonesia (9.96%), followed by China (3.34%). This scenario projects the future growth of macroalgae area based on the annual rate of China applying it to the current adoption.

**Custom adoption scenario three**: The FAO 2006-2016 data lists country level production of macroalgae. An annual rate of increase in production was calculated for each of the given countries. The maximum increase was reported in Indonesia (9.96%), followed by China (3.34%). This scenario projects the future growth of macroalgae area based on the average global annual rate (5.57%) applying it to the current adoption.

**Custom adoption scenario four**: This scenario projects the future growth of macroalgae area based on the global average annual rate (14%) as reported by World Bank (2016) applying it to the current adoption.

**Custom adoption scenario five**: The FAO 2006-2016 data lists country level production of macroalgae. An annual rate of increase in production was calculated for each of the given countries. The maximum increase was reported in Indonesia (9.96%), followed by China (3.34%). This scenario projects the future growth of macroalgae area based on the annual rate of Indonesia applying it to the maximum TOA allocated for this solution.

**Custom adoption scenario six**: The FAO 2006-2016 data lists country level production of macroalgae. An annual rate of increase in production was calculated for each of the given countries. The maximum increase was reported in Indonesia (9.96%), followed by China (3.34%). This scenario projects the future growth of macroalgae area based on the annual rate of China applying it to the maximum TOA allocated for this solution.

**Custom adoption scenario seven**: The FAO 2006-2016 data lists country level production of macroalgae. An annual rate of increase in production was calculated for each of the given countries. The maximum increase was reported in Indonesia (9.96%), followed by China (3.34%). This scenario projects the future growth of macroalgae area based on the global average annual rate (5.57%) applying it to the maximum TOA allocated for this solution.

**Custom adoption scenario eight**: This scenario projects the future growth of macroalgae area based on the global average annual rate (14%) as reported by World Bank (2016)applying it to the maximum TOA allocated for this solution.

**Custom adoption scenario nine**: This scenario projects the future growth of macroalgae area based on the production estimates given by Hoegh-Guldberg et al. (2019), using the low estimates, i.e., 8.3% annual growth rate. The scenario assumes a linear projection to the 2050 adoption area of Hoegh-Guldberg et al. (2019) scenario 1.

**Custom adoption scenario ten**: This scenario projects the future growth of macroalgae area based on the production estimates given by Hoegh-Guldberg et al. (2019), using the high estimates, i.e., 14% annual growth rate. The scenario assumes a linear projection to the 2050 adoption area of Hoegh-Guldberg et al. (2019) scenario 2.

### Reference Case / Current Adoption

Current adoption of *seaweed farming* is 0.19 Mha resulting from the average of three data points: 0.19 Mha (Froehlich et al., 2019); 0.16 Mha (Duarte et al., 2017) and 0.21 Mha (Project Drawdown 2019 interpolated value).

### Project Drawdown Scenarios

Three 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 - This scenario presents a conservative growth, which is represented by the “average of all” custom adoption scenarios as listed above.

#### Ambitious Scenario – This scenario presents a high growth, which is represented by the “high of all” custom adoption scenarios as listed above.

#### Maximum Scenario – This scenario presents an optimistic growth, which is represented by the “custom adoption scenario eight”.

## Inputs

### Climate Inputs

The long-term sequestration rate is the crucial climate input for the *seaweed farming* model. The next subsection details the methodology used for its calculation.

Calculating long-term carbon sequestration for seaweed farming

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 with some experts’ estimates – albeit for wild macroalgae- exceeding the carbon sequestered in angiosperm-based habitats (mangroves, saltmarshes and seagrasses) (Krause-Jensen and Duarte, 2016).

The seminal work by 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% of NPP.

Duarte et al. (2017) and Froehlich et al. (2019) estimated a potential CO2 sequestration from macroalgae farming of 1,500- and 1,110-tons CO2/ km2/ year respectively (4.2 and 3 tC/ ha/ year). However, these also include the carbon in the harvested macroalgae which some authors denote “removable carbon” (Zhang et al., 2017). Given that the long-term sequestration potential of the harvested macroalgae depends on its final use and that -unlike wild macroalgae- macroalgae farms are not attached to the seabed, our analysis only includes DOC exported below the mixed layer and POC exported either buried in the shelves or exported to the deep sea.

In order to estimate the long-term sequestration from exported carbon in farms (DOC exported below the mixed layer and POC exported either buried in the shelves or exported to the deep sea), the following equation is used:

|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| Sequestration rate | tC/ ha/ yr | 1.12- 5.31 | 3.21 | 44 | 16 |
| Yield | tn dry weight/ ha/ yr | 8.6 – 41.0 | 24.8 | 44 | 16 |
| Farm biomass export | % | 48- 62 | 55 | 2 | 2 |
| Carbon content of algae biomass | % | 24- 33 | 28 | 30 | 16 |
| % long-term carbon sequestration from exported carbon in farms | % | 2- 55 | 37 | 2 | 2 |

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).

An input that is significant for climate impact calculations is yield. Yield data shows high variability and depends on farmed species, type of farm and location. Based on our metanalysis the average yield is 24.8 (± 8.6 – 41.0) t dry weight/ha/yr. The majority of data point currently available in published sources are coming from Asia where currently majority of the seaweed production occurs (FAO, 2018). The seaweed farming industry is growing and expanding to global north countries such as those located in north America or Europe. Based on personal communications, the farms in north America also experience high variability in yield but usually has lower yield than the ones reported in Asia (personal communication, GreenWave 2021). Current model would benefit if more data points coming from outside of Asia are publicly available. However, the average yield value calculated is in line with global seaweed production figures, with around 3.7 million tone of dry weight produced in 2015 in area of 0.18 Mha – by dividing production by area, we get global average yield of 20.1 t dry weight/ha/yr which is reasonable close to average estimated in our model.

### Financial Inputs

It is assumed that any costs for *seaweed farming* are borne at the landowner or manager level. The financial inputs are only for macroalgae farming -the solution- given that one of the assumptions in developing this solution is that it is deployed in ocean areas which are not allocated for other purposes (see section 2.6). Up to four sources are used for financial inputs which shows the data scarcity in this field. One of the source is a review of financials in 8 farms from 6 countries (Valderrama et al. 2015). The main conclusion of the review is that depending on the scale of farm (family size vs industrial) and country there is a high variability in costs.

|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| First cost | *US$2014/ ha/yr* | 3,387- 22,798 | 9,705 | 13 | 3 |
| Operating cost | *US$2014/ ha/yr* | 1,847- 25,019 | 11,585 | 14 | 4 |
| Net profit margin | *US$2014/ ha/yr* | 145- 25,640 | 12,892 | 12 | 2 |

Table 2.3 Financial Inputs for Solution

### Other Inputs

## Assumptions

Six overarching assumptions have been made for Project Drawdown models to enable the development and integration of individual model solutions. These are that the 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 other important assumptions made for the modeling of this specific solution. These are detailed below.

1. The scope of the solution is the farming of macroalgae excluding the harvest of wild macroalgae.
2. The TOA was estimated as 10% of the macroalgae farming suitable area from Froehlich et al. (2019) (4,800 Mha). The research on scaling up macroalgae farming is rather incipient which is why a conservative approach was chosen.
3. It is assumed that the adoption area used for macroalgae farming 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 macroalgae harvesting would be less than a year.
5. The solution’s expected lifetime -the years the implementation unit will last before replacement is required- is set at 30 years.
6. The carbon mitigation potential of the solution only includes the exported DOC/ POC that goes into the deep sea and/ or sediments. This carbon mitigation potential could be an underestimate if the harvested macroalgae were used as biofuel given the avoided fossil fuel emissions, feed for livestock and bioplastics. The effect of produced macroalgae biomass allocations on climate impact will be calculated further by other Drawdown sectors.

## 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.

*Seaweed farming* is part of Drawdown’s new Ocean sector. Integration of this sector with the other Drawdown sectors 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 2‑4 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 ocean-based solutions

Project Drawdown has investigated eight ocean-based solutions and their potential to avoid greenhouse gas 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 (Fig. 2-3). 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 aquacultures solution assumes shifting from fuel-based energy systems to hybrid systems partly based on renewables thus, include climate impact based on avoiding greenhouse gas 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 (Fig. 2-3). The agency-level for the two last solutions involve farmers.

Diagram

Description automatically generated

Figure 2.2 Schematic of all Drawdown ocean-based solutions.

## Limitations/Further Development

Although the harvesting of macroalgae has been developed in Asian countries for decades, scaling up this solution with carbon mitigation benefits at heart is a new area of research. As such, the long-term carbon sequestration potential from macroalgae farming is rather incipient. The *seaweed farming* model includes only two estimates for carbon exported as particulate organic carbon/ dissolved organic carbon and two for how much of that exported carbon can be classified as long-term carbon sequestration. Both variables include one data point for macroalgae farming and another for wild macroalgae given the constraint of data availability. Once research further progresses on this front, the model can be refined.

In addition, a potential increase in carbon dioxide concentration could result in a higher capacity of macroalgae to photosynthesize and grow in some cases which would result in higher harvesting yields.

# Results

## Adoption

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

Total adoption in the *Plausible* Scenario is 13.39 million hectares in 2050, representing 5.6 percent of the total suitable ocean area. Of this, 13.20 million hectares are adopted from 2020-2050.

Total adoption in the *Ambitious* Scenario is 25.14 million hectares in 2050, representing 10.1 percent of the total suitable land. Of this, 24.96 million hectares are adopted from 2020-2050.

Total adoption in the *Maximum* Scenario is 33.60 million hectares in 2050, representing 14 percent of the total suitable land. Of this, 33.41 million hectares are adopted from 2020-2050.

| **Solution** | **Units** | **Base Year (2018)** | **World Adoption by 2050** | | |
| --- | --- | --- | --- | --- | --- |
| **Plausible** | **Ambitious** | **Maximum** |
| Seaweed Farming | *Adoption (Mha)* | 0.19 | 13.39 | 25.14 | 33.60 |
| % Total Ocean Area available for this solution | 0.08 | 5.6 | 10.1 | 14 |

Table 3.1 World Adoption of the Solution

Figure 3‑1 World Annual Adoption 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 2.50, 4.72, and 6.32 gigatons of carbon-dioxide equivalent in the *Plausible, Ambitious,* and *Maximum* Scenarios respectively.

| **Scenario** | **Maximum Annual Emissions Reduction** | **Total Emissions Reduction** | **[Ocean] Max Annual CO2 Sequestered** | **[Ocean] Total Additional CO2 Sequestered** | **Total Atmospheric CO2-eq Reduction** | **CO2 sequestration in 2030** | **CO2 sequestration in 2050** |
| --- | --- | --- | --- | --- | --- | --- | --- |
| *(Gt CO2-eq/yr.)* | *Gt CO2-eq/yr. (2020-2050)* | *(Gt CO2-eq/yr.)* | *Gt CO2-eq/yr. (2020-2050)* | Gt CO2-eq (2020-2050) | (Gt CO2-eq/year) | *(Gt CO2-eq/year)* |
| ***Plausible*** | - | - | 0.15 | 2.50 | 2.50 | 0.06 | 0.15 |
| ***Ambitious*** | - | - | 0.29 | 4.72 | 4.27 | 0.11 | 0.29 |
| ***Maximum*** | - | - | 0.39 | 6.32 | 6.32 | 0.14 | 0.39 |

Table 3.2 Climate Impacts

The solution has not been integrated with all other Project Drawdown solutions which may have different emissions results from the models. This could be due to adjustments caused by interactions among solutions that limit full adoption (such as by feedstock or demand limits) or that limit the full benefit of some solutions (such as reduced individual solution impact when technologies are combined).

Figure 3‑2 World AnnualGreenhouse Gas Emissions 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** | 0.20 | 0.01 |
| **Ambitious** | 0.38 | 0.02 |
| **Maximum** | 0.50 | 0.03 |

Table 3.3 Impacts on Atmospheric Concentrations of CO2-eq

## Financial Impacts

Below are the financial results of the analysis for each scenario. For a detailed explanation of each result, please see the glossary.

For the *Plausible* Scenario, cumulative first cost is US$132.52 billion. Marginal first cost is almost the same as cumulative first cost. Net profit margin is US$2,736.69 billion, and lifetime profit margin is US$5,316.99 billion.

For the *Ambitious* Scenario, cumulative first cost is US$250.18 billion. Marginal first cost is almost the same as cumulative first cost. Net profit margin is US$5,173.55 billion, and lifetime profit margin is US$10,051.47 billion.

For the *Maximum* Scenario, cumulative first cost is US$334.81 billion. Marginal first cost is almost the same as cumulative first cost. Net profit margin is US$6,926.25 billion, and lifetime profit margin is US$13,456.72.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Scenario** | **Cumulative First Cost** | **Marginal First Cost** | **Net Profit Margine** | **Lifetime Profit Margine** |
| *2020-2050 Billion USD* | *2020-2050 Billion USD* | *2020-2050 Billion USD* | *2020-2050 Billion USD* |
| ***Plausible*** | 132.52 | 132.14 | 2 736.69 | 5 316.99 |
| ***Ambitious*** | 250.18 | 249.80 | 5 173.55 | 10 051.47 |
| ***Maximum*** | 334.81 | 334.42 | 6 926.25 | 13 456.72 |

Table 3.4 Financial Impacts

Figure 3‑3 Net Profit Margin /Operating Costs Over Time.

There is no conventional cost for this solution as it is assumed that seaweed farming occur on ocean area that previously had no use.

## Other Impacts

Other important impact that results by applying *seaweed farming* solution is global increase in seaweed yield. By expanding the seaweeds farming the global production in 2050 will amount 327 MMt, 620 MMt, and 794 MMt of dry seaweed biomass in *Plausible, Ambitious,* and *Maximum* scenarios respectively. The significant growth in produced biomass will have implications for food production, and industrial use of seaweeds.

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Plausible** | **Ambitious** | **Maximum** |
| *TOA adoption 2050 (Mha)* | 13 | 25 | 32 |
| *Seaweed production biomass 2050 (MMt)* | 327 | 620 | 794 |

Table 3.5 Global seaweeds production figures under three scenarios.

# Discussion

## Benchmarks

As mentioned in other sections of this report, research on the mitigation potential resulting from scaling up of seaweed farming is rather limited. Hoegh-Guldberg et al. (2019) developed two scenarios to investigate the mitigation potential of seaweed farming by 2030 and 2050:

* + - 1. Scenario 1: seaweed farming increases at 8.3%/ yr (following the 2000- 2017 harvesting evolution by FAO)
      2. Scenario 2: seaweed farming increases at 14%/ yr from 2013 onwards

In both scenarios, “100% production is assumed sequestered, and farming and processing are assumed CO2 neutral” and the average yield is set at 1,000 tonnes dry weight/ km2 based on Duarte et al. (2017). The resulting mitigation potential projected an “associated sequestration of nonseen production” of 0.0013 to 0.0027 Gt CO2 equiv./ year by 2030 and 0.0067 to 0.044 Gt CO2 equiv./ year by 2050.

These values are considerably lower than those resulting from Project Drawdown’s model. A thorough analysis was conducted to understand this difference.

| **Source and Scenario** | **(Ocean) Mitigation Impact (i.e. Gt CO2-eq in 2030)** | **(Ocean) Mitigation Impact (i.e. Gt CO2-eq in 2050)** |
| --- | --- | --- |
| Hoegh-Gudlberg et al. (2019)- Scenario 1 | 0.0013 | 0.0067 |
| Hoegh-Gudlberg et al. (2019)- Scenario 2 | 0.0027 | 0.044 |
| *Plausible* Scenario | 0.06 | 0.15 |
| *Ambitious* Scenario | 0.11 | 0.29 |
| *Maximum* Scenario | 0.14 | 0.39 |

Table 4.1 Benchmarks

Three adjustments were made to Hoegh-Guldberg et al. (2019) mitigation impact values for 2030 and 2050 in order to compare with Project Drawdown’s values:

1. Adjustment 1: In Hoegh-Guldberg et al. (2019) the long-term sequestration calculation includes a 24.5% carbon content in macroalgae, 60% export of DOC/ POC and 25% long-term sequestration of exported carbon vs. 28.5 % carbon content, 55% of export and 0.321 for sequestration of export for Project Drawdown.
2. Adjustment 2: Hoegh-Guldberg et al. (2019) used an average yield of 10 tn dry weight/ ha/ yr (not referenced to any particular source) vs. a resulting 24.8 tn dry weight/ ha/ yr from the meta-analysis of 44 data points from 16 sources in the seaweed farming model.
3. Adjustment 3: Hoegh-Guldberg et al. (2019)’s adoption areas reached 0.9 and 1.6 in 2030 and 4.9 and 32.4 Mha in 2050 for scenarios 1 and 2 respectively. Project Drawdown’s average values for the *Plausible*, *Ambitious* and *Maximum* scenarios resulted in 9.2 and 24.0 Mha in 2030 and 2050 respectively.

After applying these three adjustments to Hoegh-Guldberg et al. (2019) mitigation potential values the resulting values are: 0.05 and 0.06 Gt CO2 e/ yr in 2030 and 0.02 and 0.13 Gt CO2 e/ yr in 2050, in line with Project Drawdown’s *Plausible* scenario (0.06 and 0.15 Gt CO2 e/ yr in 2030 and 2050 respectively).

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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**.

**Seaweed** – is used interchangeably with ‘macroalgae’

**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)