TECHNICAL ASSESSMENT FOR IMPROVED RICE CULTIVATION

SECTOR: FOOD

AGENCY LEVEL: FARMER

KEYWORDS: METHANE REDUCTION, BIOSEQUESTRATION, RICE PRODUCTION

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*Note: For some of the technical reports, the result section is not yet updated. Kindly refer to the model for the latest results.

DRAWDOWN

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EXECUTIVE SUMMARY

Rice (*Oryza sativa*) is one the most important staple crops, cultivated on 163 million hectares. Smallholder farms with less than 5 hectares of land account for 80% of global rice production. However, rice fields are net sources of greenhouse gas emissions. Much rice is cultivated in a flooded environment that creates conditions for methane emissions, while nitrous oxide emissions result from nitrification and denitrification processes in cultivated soil. Recent research indicates that intermittent irrigation, a water management practice to lower the methane emissions, increases emissions for nitrous oxide emissions. Rice fields can function also as a temporal sink and take up a carbon, which may compensate for nitrous oxide and methane emissions.

Project Drawdown developed a statistical land use model to evaluate different rice cultivation practices that result in greenhouse gas emissions reduction and carbon sequestration. The improved rice cultivation practices considered are: water, nutrient and tillage management and new rice cultivars.

Total adoption of the improved rice cultivation practices in the *Plausible* Scenario is 93.58 million hectares in 2050, representing 84 percent of the total suitable land for rice cultivation. Of this, 62.3 million hectares are adopted from 2020-2050. The combined carbon sequestration and emissions reduction impact of this scenario is 12.14 gigatons of carbon dioxide-equivalent between 2020-2050. Net profit margin is $149.00 billion 2014 USD.

Total adoption in the *Drawdown* Scenario is 111 million hectares in 2050, representing 100 percent of the total suitable land. Of this, 79.72 million hectares are adopted from 2020-2050. The combined sequestration and emissions reduction impact of this scenario is 16.93 gigatons of carbon dioxide-equivalent between 2020-2050. Net profit margin is $219.46 billion 2014 USD.

Total adoption in the *Optimum* Scenario is 111 million hectares in 2050, representing 100 percent of the total suitable land. Of this, 79.72 million hectares are adopted from 2020-2050. The combined sequestration and emissions reduction impact of this scenario is 21.10 gigatons of carbon dioxide-equivalent between 2020-2050. Net profit margin is $325.89 billion 2014 USD.

Improved rice cultivation has one of the highest per-hectare impacts of any agricultural solution, when both emissions reduction and carbon sequestration are taken into account. However, there is a potential increase in nitrous oxide emissions from rice paddies, that calls for further research.

1 LITERATURE REVIEW

STATE OF THE PRACTICE

Rice cultivation is an important source of greenhouse gas emissions

Rice is cultivated on nearly 163 Million hectares of land, which is about 12% of world cropland (FAO, 2012, Figure 1). About 90 million hectares is irrigated rice land (Kritee et al., 2018). Total rice cultivated area increased by 16% since 1970 and it is projected to increase by another 5% in 2030 to meet the rice consumption demands of growing population. Rice production is a major source of livelihoods in Asia. Asia is also the largest producer and consumer of rice. About 80% of global rice production comes from small holder farms with five hectares or less (Samberg et al., 2016).

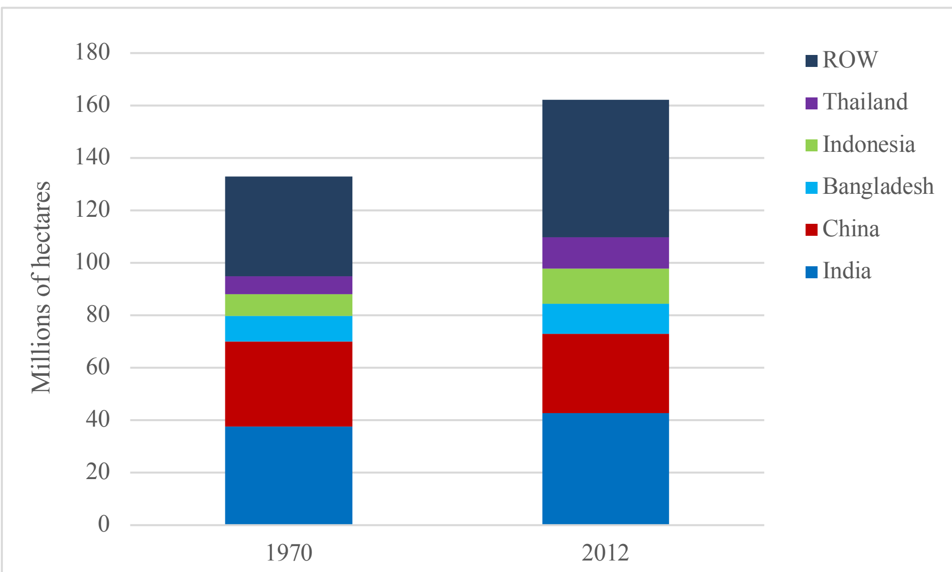

Figure 1.1:Rice cultivated area in 1970 and 2012. Data taken from International Rice Research Institute (IRRI)

Note that ROW means rest of the world (~ 117 countries)

Methane emissions

Rice cultivation is a major sources of methane emissions, accounting for 11% of the total agricultural greenhouse gas emissions (Adhya et al., 2014; Wassmann & Pathak, 2007; Xu et al., 2015, Towprayoon et al., 2005; Cai et al., 1997; Smith et al., 2008). Methane emissions results from the flooded ("paddy") environment that enables favorable anaerobic conditions for methanogenesis (Buendia et al., 1997;

Cicerone & Oremland, 1988; Wassmann et al., 2000; Xu et al., 2015). In contrast to carbon dioxide emissions, methane is a short-lived greenhouse gas. A short-lived greenhouse gas disappears much more rapidly. As long as their emissions remain constant, their concentration and warming effect remain roughly constant. The methane global warming potential over a 100-year time period is 28 times that of carbon dioxide (IPCC, 2011).

Methane emissions from rice cultivation were decreasing over the past 40 years (EDGAR, 2018). The reduction is mostly driven by changes in agriculture practices in China and India. One key practice that leads to reduction of methane emissions is better water management - draining rice paddy fields in the middle of the rice-growing season — a practice that most farmers have adopted since the 1980s. Around 80% of Chinese farmers routinely using this approach since 2000 (Li et al., 2002). This practice not only reduces methane emissions but also increases rice yields and saves water. In contrast, this practice is not fully adopted in other countries, such as Vietnam, Indonesia and Thailand, where methane emissions from rice cultivation are increasing (EPA, 2013; EDGAR, 2018).

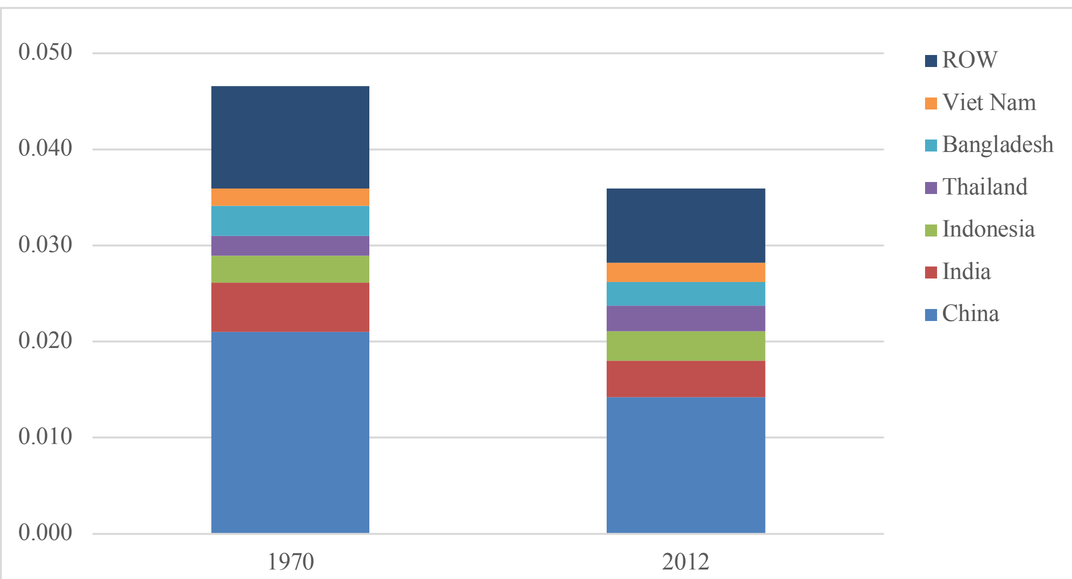

Figure 1.2:Methane emissions (CH4) in Gigatons (Gt) per year from rice cultivation in 1970 and 2012. Data are taken from the EDGAR database

Nitrous oxide emissions

Nitrous oxide is a long-lived greenhouse gas, that traps more heat compared to methane emissions. Rice paddies are considered to be less important source of nitrous oxide emissions. Nitrous oxide emissions are emitted primarily during microbial nitrification and denitrification process. Water management practices control the oxygen supply of the paddy rice soils by providing suitable conditions for microbial growth and activity and restricting oxygen supply to microsites by filling soil pores and creating anaerobic conditions. Recent research shows that intensive use of intermittent irrigation of rice fields increases per-hectare nitrous oxide emissions by three times in India (Kritee et al., 2018a, EPA, 2013). Globally nitrous oxide emissions from rice paddies may reach 1.42 million metric tons per year (Kritee et al., 2018b).

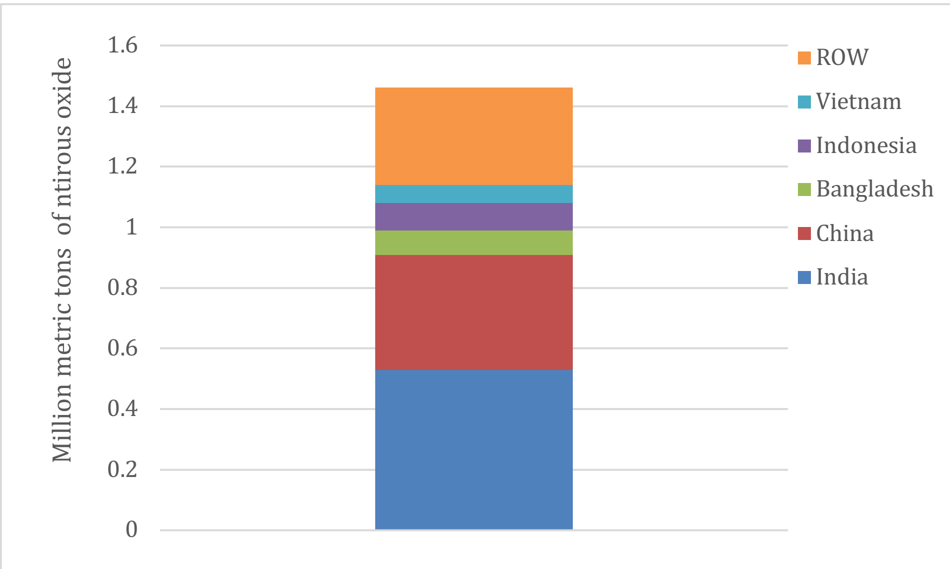

Figure 1.3:Potential N2O emissions in millions of metric tons (MMT). Modified from Kritee et al., 2018

Carbon sequestration

Rice fields can function also as a temporal sink and take up carbon, which may compensate for nitrous oxide and methane emissions. In general, every kilogram of soil organic carbon represents 3.7 kg of carbon dioxide removed from the atmosphere. Rice soils retain higher amount of carbon compared to other ecosystems. Jarecki and Lal (2003) reported that potential of soil organic carbon sequestration for rice is 401 kilogram of carbon per hectare per year. Carbon sequestration in rice soils can be improved for example by adopting integrated nutrient management practices that allows to conserve carbon or by using high yielding rice cultivars that have large biomass production. Both strategies are discussed into more details below.

Improved rice cultivation practices

Several strategies that reduce greenhouse gas emissions from rice cultivation exist. Project Drawdown consider four groups of improved rice cultivation practices: (1) water management, (2) nutrient use efficiency, (3) new rice cultivars and (4) tillage management. The detailed potential of each strategy is explained below. Please note that the System of Rice Intensification, an intensive smallholder technique, is featured as a separate Drawdown solution.

(1) Water Management practices

Rice being cultivated in flooded conditions provides a suitable environment (continuous flooding in puddle soils leading to anaerobic condition; a favorable one for methanogenesis) for emissions of greenhouse gases, particularly methane, which is a global concern (Li et al 2005). Research studies have shown that water management is one of the most effective greenhouse gas mitigation strategies in rice cultivation (Yagi et al., 1997; Wassmann et al., 2000; Aulakh et al., 2001, Wassmann & Pathak, 2007; Hussain et al., 2014; Xu et al., 2015). Thus, improving water-use efficiency is not only important from the perspective of greenhouse gas emission reduction, but also holds valid for replenishment of natural resources. Scientists across the globe have developed various water management techniques for reducing GHG emissions from rice fields. The major ones are listed below.

Mid-season drainage is a form of mild intermittent flooding that is used to reduce methane emissions from rice cultivation by allowing interrupted irrigation in the growth cycle. It requires removal of surface flood water from the rice crop for a period of minimum of 7 days towards the end of tillering (Yan et al., , 2009; Adhya et al., 2014; Hussain et al., 2014). Thus, mid-season drainage prevents the development of soil reductive conditions and leads to significant reduction in CH_4 emissions (Wang et al., 1999; Minamikawa & Sakai, 2006; Towprayoon et al., 2005) . Mid-season drainage has been found to reduce CH_4 emissions from rice cultivation by 35-70% (Mishra et al., 1997; Towprayoon et al., 2005; Zou et al., 2005; Yan et al., 2009; Corton et al., 2000). Most farmers in China, Japan, and South Korea already practice this technique to increase yields (Adhya et al., 2014). (Hussain et al., 2014) has proposed improving this technique further as there is a significant scope to experiment with the duration and timing of the drainage period. Studies have also shown that this technique may lead to an increase in nitrous oxide emissions, however the net effect is negligible when compared to the reduction in global warming potential (Cai et al., 1997; Wang et al., 1999; Zou et al., 2005; Smith et al., 2008; Yan et al., 2009; Zhang et al., 2012). To counter the challenges of N2O emissions using mid-season drainage, (Li et al., 2006) suggested changes in the timing and duration of midseason aeration. The mid-season drainage can be combined with early-season drainage, Isam et al. (2017) found that such combination can effectively reduce methane and nitrous oxide emissions from rice paddies without compromising yield by early.

Alternate Wetting and Drying (AWD) is also called intermittent flooding. It is a technique that exposes the rice field to alternate flooded and dry periods. In a typical experiment, 20 days after sowing rice fields are flooded to a depth of 5 centimeters and then allowed to dry out (roughly to a level of 15 cm at subsurface) and this exercise is repeated until 2 weeks before flowering (Cai et al., 1997; Kang & Zhang, 2004; Xue et al., 2008; Siopongco et al., 2013). Like mid-season drainage, water drainage and resulting aerobic soil conditions allow the oxidation of CH_4 and avoid CH_4 production; however it is bit difficult to shift from anaerobic to aerobic conditions in AWD because of short time intervals (Hussain et al., 2014; Wassmann et al., 2000). Moreover, there is flexibility in implementing AWD in terms of number of drying periods (more to less frequent) but that will have implications on CH_4 reductions (Adhya et al., 2014). Kritee et al., 2018 found that AWD practice increases nitrous oxide more (33 kg of nitrous oxide emissions per hectare) than previously reported. Further research is needed to understand the effects of AWD on both nitrous oxide emissions and methane. Some operational challenges are associated with this technique, as it is difficult for farmers to grasp the re-irrigation time and water amount when they practice AWD, because simple and visual irrigation indices for farmers have not yet been developed, and there may be a need for affordable technologies like soil moisture sensors to get maximum benefit of this technique (Xu et al., 2015). Overall, perfect water management can theoretically reduce emissions by up to 90% compared to full flooding (Adhya et al., 2014).

Ground Cover Rice Production Systems (GSPRS) is a practice during which soil is covered – typically with plastic film – to reduce evaporation, seepage losses and increase in soil temperatures. The soil is kept moist between irrigation periods which reduces irrigation water demand by 50–90 % (Tao et al., 2015). The actual reduction in irrigation water demand is dependent on soil type, precipitation, and cultivation duration (Tao et al., 2006; Liu et al., 2003). GCRPS has been already adopted in many provinces in China (~4 million hectares), it is also used in Korea, Japan, Africa and Middle-East. Compared to conventional paddy rice cultivation, ground cover rice production system reduces methane and nitrous oxide emissions by 50% (Yao et al., 2017) and increases rice yield, nitrogen stock and soil organic carbon in the soil (Liu et al., 2015).

(2) Nutrient Management

Like water management, nutrient management in rice cultivation also has promising results to show significant decline in greenhouse gas emissions. The different techniques available in organic and inorganic nutrient management are described below.

Inorganic nutrient management. One of the major limitations of the inorganic nutrient application in rice fields is it's poor uptake by roots, which leaves a wide scope for greenhouse gas emissions in the atmosphere (Fageria et al., 2010; Ladha et al., 2005; Galloway et al., 2003; Cassman et al.,2003). Reducing greenhouse gas emissions from inorganic nutrient management is thus critical for reducing environmental impacts of rice fields. Enhancing the inorganic nutrient use efficiency as resulted in decline in greenhouse gas emissions, directly and indirectly to nitrous oxide and carbon dioxide emissions respectively (Smith et al., 2008; Zhang et al., 2012; Ju et al., 2009).The many management practices leading to improved inorganic nutrient use efficiency and decreased greenhouse gas emissions include (i) crop specific inorganic nutrient application (Pittelkow et al., 2013; Zou et al., 2005; Shang et al., 2011), (ii) managing inorganic nutrient application timing (Cassman et al., 2003; Ali et al., 2012; Craswell et al., 1981), (iii) precise placement of inorganic nutrient into the soil (Zhang et al., 2012), and (iv) adoption of slow releasing inorganic nutrient or use of nitrification inhibitors (Ghosh et al., 2003; Linquist et al., 2015).

Organic nutrient management. Organic nutrients from rice cultivation have a significant impact on greenhouse gas emissions. However, the extent and intensity of greenhouse gas emissions from the organic nutrients depends largely on the quantity and quality of organic nutrients as well as their timing of application (Wang et al., 1999; Yao et al., 2012). Methane emissions rates are very sensitive to the rice straw (residue) management techniques. There are several ways by which greenhouse gas emissions can be reduced from organic nutrient management in rice cultivation. The prime one includes incorporation of rice straw in the dry period than in flooded periods (Xu et al., 2015). Incorporation of rice straw compost or producing biogas from rice straw for use as fuel are other greenhouse gas emissions-friendly residue management strategies (Wassmann et al., 2000; Wang & Shangguan, 1996)**.**

(3) Rice cultivar management

The plant breeders are working on developing rice cultivars that are able to grow in in water-scarce conditions instead of flooded conditions, these varieties category of rice is known as aerobic rice cultivars. There are also breeding strategies to increasing rice yield and enhancing biomass, these varieties of rice is now as high-yielding cultivars. Both anaerobic rice cultivars and high -yielding rice cultivars are important strategy to reduce greenhouse gas emission.

Aerobic rice cultivars. As anaerobic conditions are the prime cause of greenhouse emissions from rice fields, efforts have been laid to develop rice cultivars capable of growing well under aerobic conditions (Aulakh et al., 2001). These aerobic rice cultivars are different from the upland cultivars (which also grow without flooding), as the latter are low-yielding drought-resistant varieties which are grown under resource-constrained, naturally rainfed conditions. Aerobic rice cultivars, in contrast, are hybrids of upland (drought prone) and lowland (high yielding) cultivars and are suitable for both rainfed and irrigated conditions (IRRI). Development of water saving and drought-resistant rice (WDR) have emerged as a potential strategies to for cultivating rice in water-scarce conditions without much impact on yield loss (Bouman et al., 2006; Luo, 2010; Xue et al., 2008; Xiaoguang et al., 2005). Aerobic rice cultivars significantly affect the production, oxidation, and transport capacities of methane; thus reducing emissions from aerobic rice cultivation system (Aulakh et al., 2001, Luo, 2010). However, there is huge variability between various aerobic rice cultivars in terms of their water and methane reduction as well as yield capacity (Das & Baruah, 2008; Riya et al., 2012; Gutierrez et al., 2013; Jia et al., 2006). Unfortunately, quantitative data analysis on greenhouse gas emissions reduction from aerobic rice cultivars is still lacking. The studies that have been conducted are largely focused on assessment of yield and water savings. The yield-based studies concluded that variations in yield (especially on negative side) is one of the key reasons for lower adoption of this techniques despite of it significant potential for reduction of greenhouse gas emissions (Adhya et al., 2014).

High-yielding rice cultivars accounts for almost 50% of the recent yield growth in developing countries. Breeding strategies focus on enhancing biomass while maintaining the current harvest index (i.e., a measurement of crop yield the weight of harvested product as percentage of the total plant weight of a crop). Experimental research shows high-yielding cultivars increased root porosity and the abundance of methane-consuming microorganisms. Jiang et al. (2017) estimated that high-yielding cultivars decrease methane emissions from paddy soils with high organic carbon contents, on average increasing rice biomass by 10% can reduce methane emissions by 7% from Chinese agriculture.

(4) Tillage Management

Tilling the land to prepare the field bed for sowing is also one of the traditional practices, which is more intensive in rice cultivation (involving great degree of puddling of soil surface) than other principle crops in Asian region. Soil tillage practices emits greenhouse gas emissions significantly in rice fields; largely because of alteration in soil properties (soil porosity, soil temperature, soil moisture, etc.) and biochemical processes and use of fossil fuels to power tillage equipment (Ahmad et al., 2009; Li et al., 2006; Li et al., 2005; Jacinthe & Lal, 2005). Alteration in soil properties accelerates oxidation of soil organic carbon to carbon dioxide via soil aeration from tillage, interaction between crop residues and soil, and effect of microbial activities on soil organic matter (Khaliq et al., 2013). Hence, scientists have developed ways to cultivate in minimum disturbance to no-tillage conditions; the prime ones are described below.

No-tillage. No-tillage or minimum soil tillage is a form of cropping which does not use mechanical tillage for establishing the crops. Tillage practices involving minimum disturbances of soil properties have been popularized in last decades and reported to reduce greenhouse gas emissions through decreased use of fossil fuels in field preparation and by increasing carbon sequestration in soil (Ahmad et al., 2009; Ali et al., 2012; Feng et al., 2013; Xu et al., 2015; Petersen et al., 2008). The no-tillage system blocks or delays the entry of methane into the soil for oxidation, resulting in less availability of methane for uptake by soils (Omonode et al., 2007). Overall Global Warming Potential from no-tillage rice cultivation is significantly below than the conventional rice tillage practice and there is further need to explore this technique more for implementing it in wider geographies by the farming communities (Hussain et al., 2014). No-till rice probably now accounts for a quarter of all rice production in the United States (Kumar & Ladha, 2011). This technique is most suitable for rainfed and deep-water rice cultivation practices. These techniques have been trialed in experimental plots for several decades. These decade-long results are promising and in many places these have been also tested in the farmer's plots. In many regions these techniques have been adopted by the government programs and the area under these techniques are on continuous rise.

Dry Seeding Rice (DSR). Contrary to transplanting rice seedlings into the soil; rice can be grown by directly seeding the seeds into the soil; thus, saving water and reducing methane emissions by avoiding puddling and continuous flooding conditions, a key feature of traditional transplanted rice cultivation system. This technique also reduces labor requirements drastically by eliminating the steps of nursery raising, puddling, and transplanting. Direct seeding of rice is growing in Asia because of savings in water, while it is increasing in popularity in the United States on account of labor savings.

Co- Benefits

Water conservation: Adoption of water, nutrient, cultivar and tillage management practices saves water in rice cultivation. According to FAO estimates, adoption of improved water management practices will lead to 25% savings in water from the rice fields in future. According to (Parthasarathi et al., 2012), nearly 73% and 56% of irrigation water is saved during land preparation and crop growth respectively with the adoption of aerobic rice cultivars. Tillage management practices like DSR results in 25% savings in water; an estimate based on studies conducted in South Asia (Kumar & Ladha, 2011).

Savings on cost of cultivation: Some of the techniques discussed above also saved significantly on cost of cultivation. The savings varies from 2-16% (8–34 USD/ha) and 6-32% (29-125 USD/ ha) respectively in Wet-DSR and Dry-DSR (Kumar & Ladha, 2011).

Labor savings: (Kumar & Ladha, 2011) have also shown savings on labor that ranges from 0-46%, in Wet-DSR and 4-60% in Dry-DSR.

Increase in yield: Some of the techniques, like site-specific nutrient management in irrigated rice leads to yield gain compare to conventional practices (Dobermann, 2007). Similarly aerobic rice cultivars with a stronger root system, having more capacity to release oxygen into the soil, enhance resistance to environmental stresses, thereby resulting in yield gain (Mei et al., Li et al., 2005).

Trade-offs

Yield loss: GHG mitigation strategies in rice cultivation have both yield gain and loss evidences. Yield loss is one of the major limitations of these solutions. Despite of high potential for GHG emissions reduction and savings on water, a decline in yield leads de-motivates farmers to adopt these solutions. Analysis of studies from the South Asian region by (Kumar & Ladha, 2011) has shown significant decline in yield (10-30%) with the adoption of DSR. The negative trend in yield were also confirmed by studies conducted in Cambodia, Laos and Thailand (Rickman et al., 2001). The same is not true for Bangladesh and the Philippines, where practice of DSR leads to an increase in yield by 8.6–18.5%.

N_2O emissions: Recent scientific research recognizes that intermittently flooded rice fields are a source of nitrous oxide emissions (Choi et al., 2014; Jain et al., 2013, Oo et al., 2018). Until recently, the increase of nitrous oxide emissions was considered negligible or small and nullified with the much larger methane emission reductions. However, Kritee et al. (2018) shows that multiple aeration events leading to higher microbial activity, enhanced mineralization and nitrification-denitrification and more redox cycles, resulting in much higher nitrous oxide emissions than previously estimated (Figure 1.3.) More research on water management practices is needed to confirm negative effects of intensive intermittent flooding practice on nitrous oxide emissions across and within different countries.

Adoption Path

1.2.1 Current Adoption

Data on current adoption of improved rice cultivation is based on data points available for mid-season drainage in Asian countries and application of direct seeded rice method. See 2.4.1 below for details.

1.2.2 Trends to Accelerate Adoption

Some of the positive trends of these solutions are listed below, which highlights its high potential for wider up-scaling.

- Experimental studies conducted at China from 1980-2010 have shown a net reduction of nearly 5 Tg CH_4 yr^{-1} of GHG emissions from the rice fields operated under mid-season drainage techniques (Liu et al., 2011).
- Adoption of AWD technique by 40,688 farmers (~50,000 ha) in 2012 (Lampayan et al., 2015) is a result of proactive response by the Department of Plant Protection and the Department of Agriculture and Rural Development, An Giang Province, Vietnam towards this water saving and GHG emissions reduction technique. The technique results in 10–30% water savings and 15% yield increase, because of reduction in lodging, which often occurs in direct-seeded rice.
- Bangladesh Agricultural Development Cooperation, Barenda Multipurpose Development Authority, and Department of Agriculture Extension (DAE) are working with nearly 50,000 farmers on AWD. They are further planning to upscale it to 50 more districts with an estimated coverage of more than 12,000 ha of boro rice. The expected benefits are in terms of water saving by 15–30%, which translates into a reduction in pumping cost and fuel consumption, and increased income of US$67–97 per hectare.
- AWD technique has been promoted by National Rice Self-Sufficiency Program in Philippines. Secretary of the Department of Agriculture has directed all of the concerned agencies to adopt AWD and other water-saving technologies in all of their water management programs nationwide. With the serious efforts of government, AWD has been included in the official Rice Check (Palay Check), under the name “controlled irrigation”. AWD was adopted by 81,687 farmers (~93,000 ha) in 2012 (Lampayan et al., 2015).
- Global Rice Science Partnership has estimated the likely adoption of AWD technique globally for the period 2011 to 2035. According to their estimates, farmers practicing AWD will reach to nearly 5.11 million hectares by 2020 and 20.7 million hectares by 2035. This adoption will lead to a net reduction of GHG emissions by 48%; however this will be offset by 20% with increase

in N_2O emissions associated with AWD under imperfect nutrient management. Nevertheless, this leads to 1.92 tons of CO_2 equivalent emissions reduction per hectare of AWD adoption and a cumulative net reduction of 39.7 million tons annually with 2035 adoption levels.

- Regarding tillage management practice, it was observed that more than 90% of the area in the United States, Sri Lanka, and Malaysia are under direct seeding (Kumar & Ladha, 2011).
- According to a 2015 Cereal Systems Initiative for South Asia (CSISA) report, 16,424 farmers in India are practicing improved rice management techniques ranging from improved water management, nutrient management and tillage management.

1.2.3 Barriers to Adoption

Several factors influence the potential adoption of improved rice production.

- Technical limitations: There lies a wide gap between scientist's experimental trials performed under optimal conditions and the situation in farmers' fields. Hence, at many times, it has been observed that the required technical and systemic arrangement required to implement the strategies are not available at the farmer's end. Some of the examples are listed below.
    - Despite the water savings—and possibility of yield benefits—from reduced flooding in rice production, many farmers face important technical and practical constraints to implementing such improvements. In implementing AWD measures, farmers need reliable control over irrigation water as well as needing well-leveled fields to assure that water levels do not drop too far in parts of the field. While these facilities are quite available in developed countries like US, in developing countries, particularly in Asia, farmers have limited technical ability to drain their fields and also lack well-placed irrigation systems as they depend largely on the groundwater.
    - Farmers using surface irrigation are reluctant to interrupt irrigation when water is available because of uncertainty of water availability in future when needed to refill the field. In some of these locations, dry seeding may be an effective means of reducing CH_4 emissions, and in others, a single drawdown may still be feasible, but the technical opportunities remain generally unexplored (Adhya et al., 2014).
    - Efforts have not been made to upscale the experimental farm studies to wider level and for gaining a broader understanding.

- Mixed results of same techniques: It has been observed that impacts of water management techniques vary in different environments.

- Case studies have shown that, while farmers in China and Japan widely practice a single mid-season drainage and also attains yield gains, however the same is not true in US. There are many studies finding yield gains from AWD, but there are also studies showing losses; the reasons are not yet fully understood.

Thus, efforts (listed below) needs to be taken to implement these solutions globally:

- **Participatory trials**: Participatory trials on farmer's fields in order to bridge the gap between scientist field experiments based results and on-farm results.
- **Customized solutions**: Customizing solutions to different bio-physical and socio-economic settings in order to meet the location specific demands and for greater adaptability of the solutions on farmer's fields.
- **Awareness**: Awareness and wider demonstration of these solutions. These solutions are taking farming communities away from the centuries old traditional practices of rice cultivation. Hence it is really difficult for farmers to accept these changes. This necessitates efforts in awareness, communication, farmer field demonstrations, farmer to farmer success story sharing, learning from failures etc.
- **Incentives and motivation:** GHG mitigation solutions are not offering any direct incentives to farmers. They are largely concerned about their cost of cultivation, yield and returns from it. Water saving technologies lower the cost of cultivation, but considering the yield variation, it does not appears to be an impressive incentive to farming communities especially in regions where farmers are getting heavy subsidies for irrigation (eg India). Hence, thoughts should be given to some additional incentives that would motivate farmers to adopt these solutions.
- **Support**: Technical assistance to farmers has to be provided in order to sustain the solution for a longer period of time. It has been observed that in the absence of continuous feedback to farmers on the implemented solution, farmer's stop implementing those solutions. Thus, proper handholding to farmers is required, until they get trained and becomes the local entrepreneur of that solution in their region.
- **Integrated solutions**: There is a need for integrated GHG mitigation solutions in rice cultivation. GHG mitigation in the rice cultivation is researched a lot in last two decades, however there are very few studies where attempt was made to analyze integrated solutions (eg. water, nutrient, cultivar and tillage practices together as a package). This is important as farmer sees their crop in a holistic manner and looks for holistic solutions, also scientifically it is important to look for cumulative benefits of integrated solutions.

- **Policy advocacy**: It is equally important that these solutions gets mainstreamed into the policy framework of all nations; especially the key rice-producing countries, so that it can be implemented with a greater momentum in all geographies.

1.2.4 Adoption Potential

The adoption potential for improved rice cultivation is circa 108 million hectares by 2050. Based on available literature on water management practice in China, India, Vietnam, Indonesia and Japan, we estimated that about 32 million hectares of rice cultivated land is under mid-season water management and use direct seeding method in 2014.

Other studies, such as Griscom (2017) project a maximum potential adoption of 163 million hectares in 2030 which is current total area used for rice cultivation.

1.3 ADVANTAGES AND DISADVANTAGES OF IMPROVED RICE CULTIVATION

1.3.1 Similar Solutions

To a certain degree improved rice cultivation this solution is also similar to *conservation agriculture*, as it also incorporates no-till. This solution also incorporate *nutrient management*, also a Drawdown solution. However the solution to which is it most closely related is *System of Rice Intensification.* Both solutions are implemented on rice land, and both reduce methane emissions via practices including dry periods. There are several key differences. SRI is currently limited to smallholder operations only, while improved rice is scale-neutral. Another key difference is yields – SRI tends to dramatically increase yields, while improved rice tends to decrease them slightly. Other approaches to mitigation in rice production include agroforestry and development of perennial varieties of rice.

1.3.2 Arguments for Adoption

These solutions are based on scientific evidence and are tested in different geographies in both experimental plots and farms. They have huge greenhouse gas emissions reduction potential as well as saving on costs of cultivation and (sometimes) yield higher gains, thus proving to be more trustworthy for up scaling at a larger scale.

The other region of its adoption is its advocacy by globally leading scientific research institutes like; International Rice Research Institute (IRRI), International Rice Commission (IRC), Intergovernmental Panel on Climate Change (IPCC), United Nations Framework Convention on Climate Change (UNFCCC), Food and Agriculture Organization (FAO), Climate Change, Agriculture and Food Security (CCFAS), Global Rice Science Partnership (GRiSP) apart from national level institutions.

1.3.3 Additional Benefits and Burdens

Here this solution is compared with other solutions in the food production cluster for farm, ecosystem, and social impacts.

Table 1.1: Food Production Solutions Comparison: On-Farm Impacts

Yield Gains: loss of yield "loss", no impact "n/a", 1-9% low, 10-24% medium, 25%+ high. **First Cost**: Free is $0**,** Low is $1-100, Medium is $100-500, Expensive is $500+. **Net Profit Margin:** Low is $0-100/ha, Medium is $100-500, High is $500+. **Delayed Profit Period:** Short is 0-2, Mid is 3-6, Long is 6+

	Yield Gains	Startup Cost	Net Profit	Delayed Profit Period
Conventional cropping	n/a	n/a	Medium	n/a
Conventional grazing	n/a	n/a	Medium	n/a
Conservation agriculture	Low	Medium	High	Mid
Farmland restoration	High	Medium	Medium	Short
Farm water use efficiency	n/a	Expensive	Medium	Short
Improved rice	Loss	Free	High	Mid
Managed grazing	Medium	Medium	Medium	Mid
Multistrata agroforestry	n/a	Expensive	High	Long
Nutrient management	n/a	Free	Low	Short
Regenerative agriculture	Low	Medium	High	Mid
Silvopasture	Medium	Expensive	High	Long
System of Rice Intensification	High	Free	High	Mid
Tree intercropping	Low	Expensive	Medium	Long
Tropical staple tree crops	High	Expensive	High	Long
Women smallholders	high	Free	High	Short

Table 1.2 Food Production Solutions Comparison: On-Farm Impacts Social and Ecological Impacts

Ecosystem Services is subjective based on impacts on biodiversity, water quality, etc. **Social Justice Benefits:** Is solution Targeted to disadvantaged producers like smallholders and women, Relevant to them, or Not Applicable (n/a). **Climate Impacts per Hectare:** Low 0-3.7 t CO_2-eq/ha/yr (0-1tC), Medium 3.8-11.0 t CO_2-eq/yr (1-3 tC), High 11.1+ tCO_2-eq/yr (3+tC). **Global Adoption Potential:** Low 0-100Mha, Medium 101-500 Mha, High 500+ Mha

	Ecosystem Services	Social Justice Benefits	Climate Impact/ha	Global Adoption Potential
Conventional cropping	n/a	n/a	n/a	n/a
Conventional grazing	n/a	n/a	n/a	n/a
Conservation agriculture	Low	Relevant	Low	Medium
Farmland restoration	Medium	Relevant	Medium	Medium
Farm water use efficiency	Low	Relevant	Low	Medium
Improved rice	Medium	Relevant	high	Low-medium
Managed grazing	Low	Relevant	Low	Medium-high
Multistrata agroforestry	High	Relevant	High	Low
Nutrient management	Medium	Relevant	Low	High
Regenerative agriculture	Medium	Relevant	Low	Medium-high
Silvopasture	High	Relevant	High	Low-medium
System of Rice Intensification	Medium	Targeted	Medium	Low
Tree intercropping	High	Relevant	Medium	Medium
Tropical staple tree crops	Medium	Relevant	High	Low-medium
Women smallholders	n/a	Targeted	Low	Low

2 METHODOLOGY

2.1 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 Land 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 land of a specific type that may be shared across several solutions. The actual and maximum possible adoptions are therefore defined in terms of land 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 2014) and the comparison of these scenarios with a reference (for the 2020-2050 segment[1]) is what constituted the results.

Agency Level

The 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, the decision-maker on the ground is the most critical player in implementation.

2.2 DATA SOURCES

The FAO Statistical Service is a key dataset used in this study. A total of 28 peer-reviewed studies were used in the model.

2.3 TOTAL AVAILABLE LAND

Drawdown's agricultural production and land use model approach defines the Total Land Area as the area of land (in million hectares) suitable for adoption a given solution. Data on global land is acquired from Global Agro-Ecological Zones database, developed by the Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA). The Drawdown Land-Use Model categorizes and allocates land according to agro-ecological zones based on the following factors:

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[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 2015-2050.

thermal climate, moisture regimes, soil quality, slope, cover type, and degradation status. These characteristics influence the suitability of different practices, and solution adoption scenarios are restricted by one or more of these factors.

Determining the total available land for a solution is a two-part process. The technical potential is based on: current land cover or land use; the suitability of climate, soils, and slopes; and on degraded or non-degraded status. In the second stage, land is allocated using the Drawdown Agro-Ecological Zone model, based on priorities for each class of land. The total land allocated for each solution is capped at the solution's maximum adoption in the *Optimum* Scenario. Thus, in most cases the total available land is less than the technical potential.

Total available land for this solution is 111 million hectares, representing non-smallholder rice production. [2] Current adoption [3] of *improved rice cultivation* is estimated at 31.28 million hectares, based on historical data available on rice area under direct seeded rice practice and rice area under water management .

2.4 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.

2.4.1 Reference Case / Current Adoption[2]

Current adoption data is available for the mid-season drainage and direct seed practices for Asian countries, including China, India, Japan, Indonesia (Li et al., 2002, Yan et al., 2009). Both mid-season drainage and direct seed rice are sub-practices considered under improved rice cultivation in the Project Drawdown.

Averaged global values of adaption were used for both solutions, assuming that 40% of total rice irrigated land is applying mid-season drainage, and 30% of rice cultivated area apply direct seed practice. As a result, current adoption of mid-season drainage and direct seeding practices are estimated at 31.28 million hectares. Data on current adaption of the mid-season drainage are based on estimates from 1980 and 2000

[2] Current adoption is defined as the amount of land area adopted by the solution in 2018. This study uses 2014 as the base year due to the availability of global adoption data for all Project Drawdown solutions evaluated.

taken from (Li et al., 2002, Yan et al., 2009), while data on direct seed practice are adopted from Rao et al. (2007) and Sangera et al, (2018).

Project Drawdown Scenarios

Six custom adoption scenarios were developed based on the estimation of average and low, medium, and high adoption rates from 1736 data points (presenting the area under direct seeded rice in 13 Asian countries) from 3 sources. Some of these scenarios include early peak adoption (75%) of the solution by 2030, details as given below.

1. ***Custom adoption scenario one***: This scenario presents the results based on the average adoption growth rate. Thus, projecting 98 percent adoption of the solution by 2050.
2. ***Custom adoption scenario two***: This scenario presents the results based on the low adoption growth rate. Thus, projecting 63 percent adoption of the solution by 2050.
3. ***Custom adoption scenario three***: This scenario presents the results based on the high adoption growth rate. Thus, projecting 100 percent adoption of the solution by 2050.
4. ***Custom adoption scenario four***: This scenario presents the results based on the average adoption growth rate. Thus, projecting 98 percent adoption of the solution by 2050. In addition, it is also assumed that 75 percent adoption of the total projected adoption by 2050 will be achieved by 2030.
5. ***Custom adoption scenario five***: This scenario presents the results based on the low adoption growth rate. Thus, projecting 63 percent adoption of the solution by 2050. In addition, it is also assumed that 75 percent adoption of the total projected adoption by 2050 will be achieved by 2030.
6. ***Custom adoption scenario six***: This scenario presents the results based on the high adoption growth rate. Thus, projecting 100 percent adoption of the solution by 2050. In addition, it is also assumed that 75 percent adoption of the total projected adoption by 2050 will be achieved by 2030.

Impacts of increased adoption of *improved rice cultivation* from 2020-2050 were generated based on three growth scenarios, which were assessed in comparison to a *Reference* Scenario where the solution’s market share was fixed at the current levels.

Plausible Scenario - A conservative approach is adopted for the plausible scenario, and future growth of the solution is estimated based on the "average of all" custom adoption scenarios as listed above.

Drawdown Scenario – For the drawdown scenario, an ambitious approach is adopted, and future growth of the solution is estimated based on the "high of all" custom adoption scenarios as listed above.

Optimum Scenario - For the optimum scenario, custom adoption scenario that is giving maximum growth based on the existing prognostication is considered, which is represented by the "custom scenario 6" where future adoption is projected based on the high early growth rate.

2.5 INPUTS

2.5.1 Climate Inputs

Methane emissions reduction from *improved rice cultivation* is set at 5.26 tons of carbon dioxide-equivalent per hectare per year, based on 43 data points from 10 sources. Nitrous oxide emissions are calculated at -1.25 tons of carbon dioxide-equivalent per hectare per year, based on 7 data points from 2 sources. Sequestration rates are set at 1.45 tons of carbon per hectare per year, based on 25 data points from 3 sources.

Table 2.1:Climate Inputs

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Methane emissions reduction	*tCO2-eq/ha/yr*	-10.63 - 21.17	5.26	106	16
Nitrous oxide emissions reduction	*tCO2-eq/ha/yr*	-2.30 - -0.20	-1.25	47	4
Biosequestration	*tC/ha/yr*	-0.21 to 3.12	1.45	26	3

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[3].

Modeling Saturation

Biosequestration does not have limitless potential. In most cases, there is a maximum amount of carbon that can be stored in soils and aboveground perennial biomass before they become saturated. Biosequestration continues after saturation but is offset by more or less equal emissions. In most cases soils, and biomass can return to their approximate pre-agricultural or pre-degradation levels of carbon. This takes anywhere between 10-50 years in agricultural cases, and sometimes somewhat longer in the case of ecosystems like forests. Data about saturation time is very limited.

The Drawdown land model takes the conservative approach that all land units currently adopted for agricultural solutions (including multistrata agroforestry) have already achieved saturation, and will not be contributing additional sequestration. New adopted land is assumed to sequester for at least 30 years before achieving saturation.

Note that there are some important exceptions to saturation. Certain ecosystems continue to sequester soil carbon for centuries, notably peatlands and coastal wetlands. Some scientists argue that tropical forests can continue to sequester carbon at a slower rate after saturation. The addition of biochar to saturated soils may be able to overcome this constraint, as does the use of biomass from bamboo or afforestation in long-term products like buildings.

2.5.2 Financial Inputs

First costs of *improved rice cultivation* are US$0 per hectare, as the practices use existing equipment and infrastructure.[2] For all agricultural solutions, it is assumed that there is no conventional first cost, as agriculture is already in place on the land. Net profit is calculated at US$640.07 per hectare per year for the solution (based on meta-analysis of 16 data points from 5 sources), compared to US$450.84 per year for the conventional practice (based on 33 data points from 38 sources).

Farmers and ranchers transitioning to carbon-friendly practices face a period of reduced income. This reflects an individual learning curve, customization of the system to their farm or ranch, and time for the practice to begin to have in impact on productivity. Meta-analysis of 10 data points from 6 sources shows that in the case of implementation of improved annual cropping solutions, net profits per hectare do not

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[3] 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.

exceed business-as-usual for 3.4 years. To account for this delay in profitability, the Drawdown model assumes that net profit per hectare is 25% of the conventional rate until 4 years have elapsed.

Table 2.2:Financial Inputs for Conventional Technologies

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
First costs (Conventional)	*US$2014/ha*	n/a	n/a	n/a	n/a
Net profit (Conventional)	*US$2014/ha*	$206.73 - $694.96	$450.84	34	17
Operating Cost (Conventional)	*US$2014/ha*	$361.45 to $944.02	$652.74	27	13

Table 2.3: Financial Inputs for Solution

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
First costs (Solution)	*US$2014/ha*	$0.00	$0.00	n/a	n/a
Net profit (Solution)	*US$2014/ha*	$330.72 to $949.41	$640.07	16	6
Operating Cost (Solution)	*US$2014/ha*	$260.70 to $508.00	$384.35	12	5

2.5.3 Yield Inputs

Yield gain compared to business-as-usual annual cropping were set at 4.5 percent, based on meta-analysis of 33 data points from 11 sources.

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

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

Assumption 1: It is assumed that the land area for rice cultivation will remains same, based on the limited availability of new cropland area

Assumption 2: In the study only the **Irrigated Rice** conditions were considered because of the availability of maximum of greenhouse gas reduction solutions for the irrigated rice conditions. However, irrigated rice represents majority of the rice area worldwide.

Assumption 3: In this study, only those solutions were considered which have tested **integrated solutions** across water, nutrient, tillage and cultivars for improved rice management. Data points from studies featuring minimum two of the given four practices were used in meta-analysis.

Assumption 4: It is assumed that the solution will be largely adopted by the large farmers having required machinery available for implementing this solution. Thus, the maximum area allocated to this solution is calculated by applying the percentage of the large farmholders (based on meta-analysis) to the total rice area. The remaining area is assumed to be utilized by the small rice growing farmers, for which the SRI solution is allocated.

Assumption 5: the future adoption scenarios were built based on the data available for Asian countries, as rice is largely grown in those areas. So, it was assumed that similar trends will be followed at the global scale.

Assumption 6: nitrous oxide emissions are associated with this solution, recent estimate indicates that nitrous oxide emissions may be underestimated, especially in areas using intensive intermittent flooding methods.

Assumption 7: Due to use of high -yielding cultivars, the solution may increase yields by 4% per hectare per season.

2.7 INTEGRATION

The complete Project Drawdown integration documentation (will be available at 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.

Improved rice is part of Drawdown's Food sector, specifically the supply-side set that incorporate food production. Within agriculture it is part of a cluster of solutions based on annual crop production.

The Agroecological Zone model

Drawdown's approach seeks to model integration between and within sectors, and avoid double counting. Several tools were developed to assist in this effort. The Agroecological Zone (AEZ) model categorizes the world's land by: current cover (e.g. forest, grassland, cropland), thermal climate, moisture regime, soil quality, slope, and state of degradation. Both Food (supply-side) and Land Use solutions were assigned to AEZs based on suitability. Once current solution adoption was allocated for each zone (e.g. semi-arid cropland of minimal slopes), zone priorities were generated and available land was allocated for new adoption. Priorities were determined based on an evaluation of suitability, consideration of social and ecological co-benefits, mitigation impact, yield impact, etc. For example, *Indigenous peoples' land management* is given a higher priority than *forest protection* for AEZs with forest cover, in recognition of indigenous peoples' rights and livelihoods. *Multistrata agroforestry* is highly prioritized in tropical humid climates due to its high sequestration rate, food production, and highly limited climate constraints.

Each unit of land was allocated to a separate solution to avoid overlap between practices. The exception to this are *farmland irrigation*, *nutrient management*, and *women smallholders*, which can be implemented in addition to other practices. The constraint of limited available land meant that many solutions could not reach their technical adoption potential. The AEZ model thus prevents double-counting for adoption of agricultural and land use solutions.

Drawdown's agricultural production and land use model approach defines the Total Land Area as the area of land (in million hectares) suitable for adoption a given solution. Data on global land is acquired from Global Agro-Ecological Zones database, developed by the Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA). The Drawdown Land-Use Model categorizes and allocates land according to agro-ecological zones based on the following factors: thermal climate, moisture regimes, soil quality, slope, cover type, and degradation status. These characteristics influence the suitability of different practices, and solution adoption scenarios are restricted by one or more of these factors.

Determining the total available land for a solution is a two-part process. The technical potential is based on: current land cover or land use; the suitability of climate, soils, and slopes; and on degraded or non-degraded status. In the second stage, land is allocated using the Drawdown Agro-Ecological Zone model, based on priorities for each class of land. The total land allocated for each solution is capped at the solution's maximum adoption in the *Optimum* Scenario. Thus, in most cases the total available land is less than the technical potential.
Drawdown's Agro-Ecological Zone model allocates current and projected adoption of solutions to the planet's forest, grassland, rainfed cropland, and irrigated cropland areas. Adoption of *improved rice cultivation* was the second-highest priority for rice-growing cropland, following *System of Rice Intensification*.

The Yield model

Drawdown's yield model calculates total annual global supply of crops and livestock products based on their area of adoption in each of the three scenarios, and global yield impacts of each solution (including both gains due to increased productivity per hectare and losses due to reduction of productive area due to adoption of non-agricultural solutions, e.g., loss of grazing area due to afforestation of grasslands). Grain surpluses in the yield model were also used to set a ceiling for the amount of crops available for use as feedstock for the *bioplastic* Materials solution.

The yield model matches demand and supply as an integrated system. Both *Reference* Scenarios showed a food deficit in the high and medium population scenarios (see *family planning* and *educating girls* solutions). This would require the clearing of forest and grassland for food production, with associated emissions from land conversion.

All three Drawdown scenarios show agricultural production sufficient to meet food demand and provide a surplus that can be used in bio-based industry, for example as feedstock for *bioplastic* production. Due to this surplus, no land clearing is necessary, resulting in impressive emissions reduction from avoided deforestation. Because population change (resulting from *educating girls* and *family planning*), *plant-rich diet*, and *reduced food waste* are the principal drivers of this effect, Drawdown allocates the resulting reduction in emissions from land clearing to these solutions. However, as the impacts of population on yield and food demand are highly complex, we do not include avoided land conversion emissions associated with population change in the final emissions calculations for those solutions.

2.8 LIMITATIONS/FURTHER DEVELOPMENT

There are limited data availability for irrigated land, that is used for developing the future adoption scenario. Current dataset needs to be updated, based on new scientific knowledge, especially the area of rice irrigated land needs to be dived into different kinds of flooding regimes.

3 RESULTS

3.2 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.

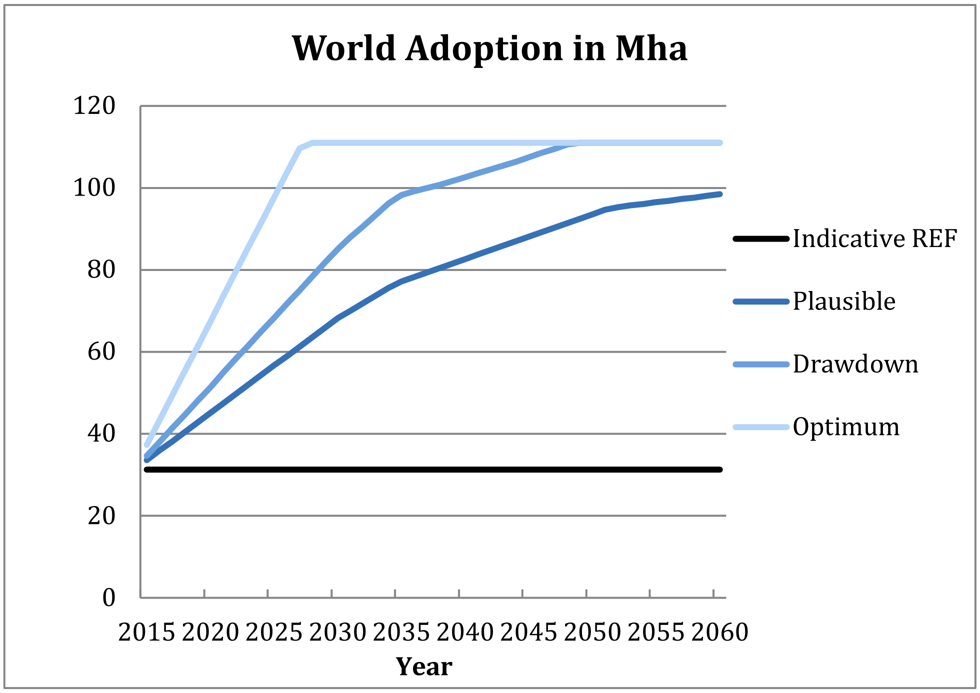
Total adoption in the *Plausible* Scenario is 93.58 million hectares in 2050, representing 86 percent of the total suitable land. Of this, 62.3 million hectares are adopted from 2020-2050.

Total adoption in the *Drawdown* Scenario is 110 million hectares in 2050, representing 100 percent of the total suitable land. Of this, 79.72 million hectares are adopted from 2020-2050.

Total adoption in the *Optimal* Scenario is 110 million hectares in 2050, representing 100 percent of the total suitable land. Of this, 79.72 million hectares are adopted from 2020-2050.

Table 3.1:World Adoption of the Solution

Solution	Units	Base Year (2014)	New Adoption by 2050		
			Plausible	Drawdown	Optimum
Improved Rice	Mha	31.28	62.30	79.72	79.72
	% Total Land Available	28.2%	84%	100%	100%



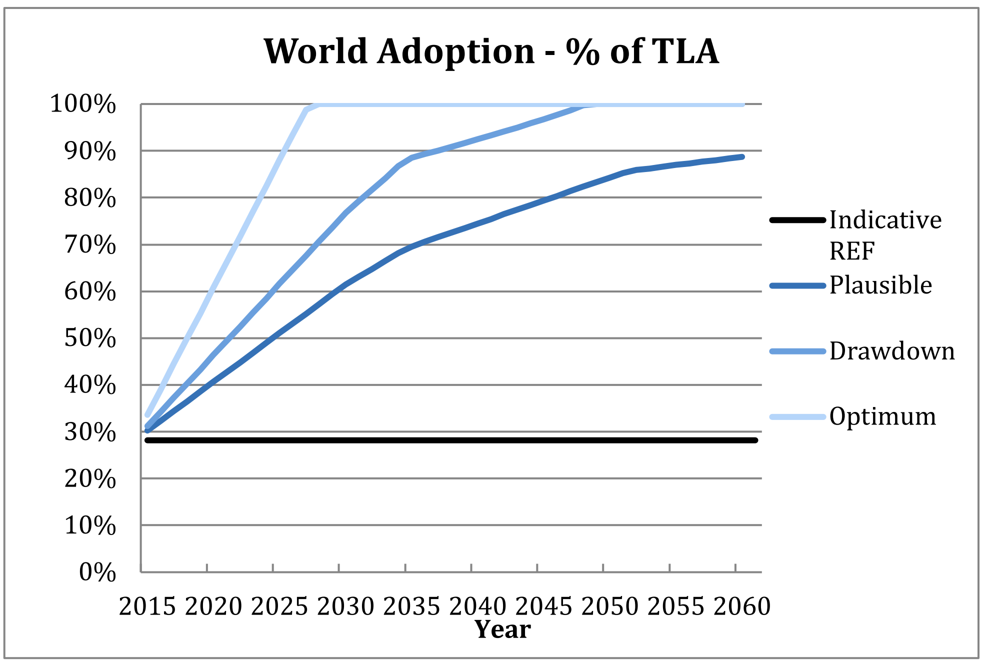


Figure 3.1 World Adoption between 2015-2060,

3.3 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).

Total impact is 12.07, 16.69, and 20.43 gigatons of carbon-dioxide equivalent in the *Plausible, Drawdown,* and *Optimum* Scenarios respectively.

Table 3.2: Climate Impacts

Scenario	Maximum Annual Emissions Reduction	Total Emissions Reduction	Max Annual CO_2 Sequestered	Total Additional CO_2 Sequestered	Total Atmospheric CO_2-eq Reduction	Emissions Reduction in 2030	Emissions Reduction in 2050
	(Gt CO_2-eq/yr.)	*Gt CO_2-eq/yr. (2020-2050)*	*(Gt CO_2-eq/yr.)*	*Gt CO_2-eq/yr. (2020-2050)*	Gt CO_2-eq (2020-2050)	(Gt CO_2-eq/year)	*(Gt CO_2-eq/year)*
Plausible	0.25	5.21	0.33	6.92	12.14	0.35	0.58
Drawdown	0.32	7.28	0.43	9.66	16.93	0.50	0.75
Optimum	0.32	9.07	0.43	12.03	21.10	0.75	0.75

The solution was integrated with all other Project Drawdown solutions and may have different emissions results from the models. This is 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).

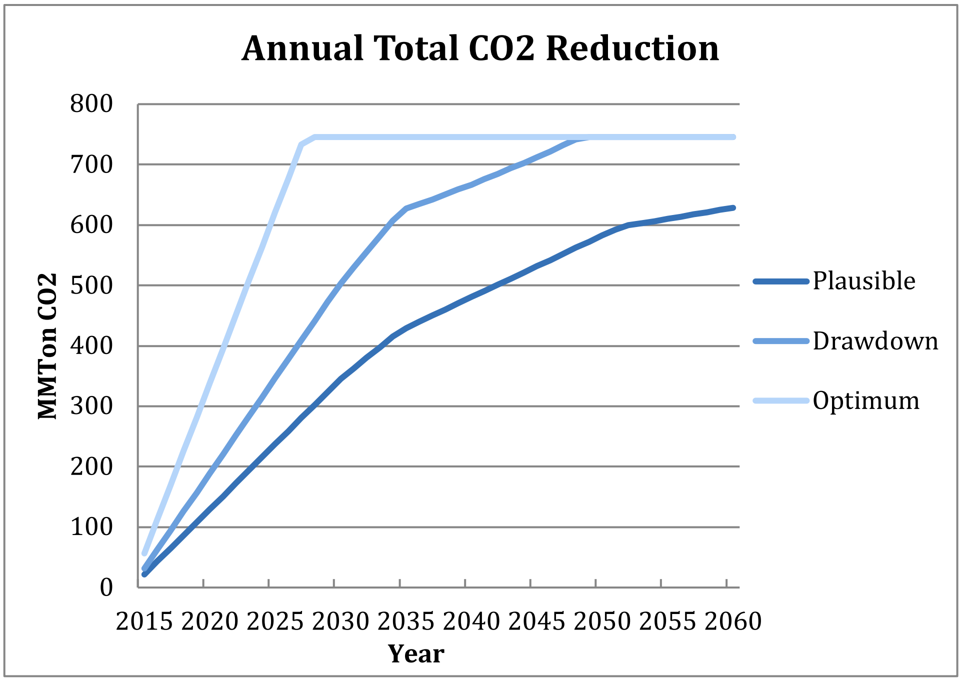


Figure 8. World Annual Greenhouse Gas Emissions Reduction

Table 3.3:Impacts on Atmospheric Concentrations of CO2-eq

Scenario	GHG Concentration Change in 2050	GHG Concentration Rate of Change in 2050
	PPM CO_2-eq (2050)	*PPM CO_2-eq change from 2049-2050*
Plausible	1.014	0.042
Drawdown	1.407	0.052
Optimum	1.724	0.048

3.4 Financial Impacts

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

Note that the financial results have changed from those published in the first edition of the *Drawdown* book.

Net profit margin is $344.95 billion 2014 USD, $476.78 billion 2014 USD, and $582.25 billion 2014 USD in the *Plausible, Drawdown,* and *Optimum* Scenarios respectively.

Table 3.4: Financial Impacts

Scenario	Cumulative First Cost	Marginal First Cost	Net Operating Savings	Net Profit Margin	Lifetime Profit Margin	Lifetime Cashflow Savings NPV (of All Implementation Units)
	2015-2050 Billion USD	*2015-2050 Billion USD*	*2020-2050 Billion USD*	*2020-2050 Billion USD*	*2020-2050 Billion USD*	*Billion USD*
Plausible	$0.00	$0.00	$ 348.28	$149.00	$312.62	$59.14
Drawdown	$0.00	$0.00	$ 485.91	$ 219.46	$414.18	$84.25
Optimum	$0.00	$0.00	$ 605.45	$ 325.89	$504.92	$124.39

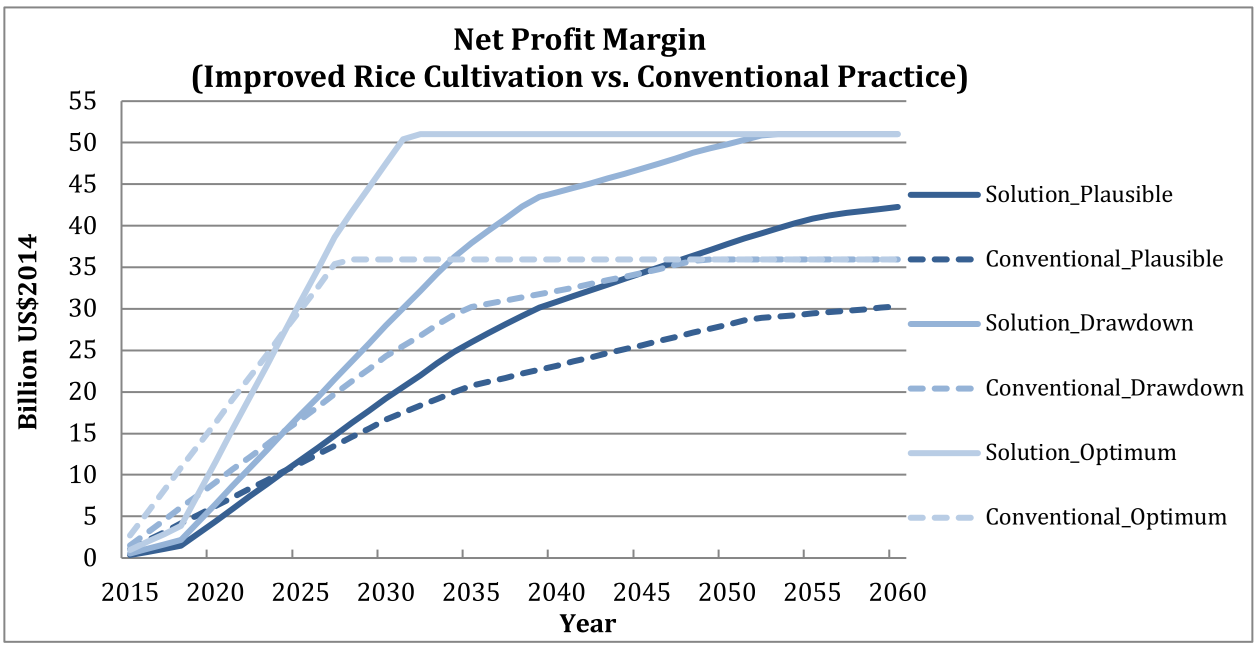


Figure 3.2 Net Profit Margin

3.5 Yield Impacts

This solution increase rice yields due to use of high yielding cultivars. The impact is an increase of 72.92, 101.79, and 127.45 million metric tons between 2020-2050.

4 Discussion

Rice is a staple crop of critical importance, particularly in Asia. Rice production is currently a major contributor of methane emissions. Fortunately, low-methane rice production systems are ready to be scaled up including water management. Wider adoption of improved rice cultivation practices that are well balanced (e.g. consider negative side effect on nitrous oxide emission) can have a significant impact on reduction of methane emissions and nitrous oxide emission.

4.2 Limitations

It would be useful to obtain more rice production financial data points for the conventional case. Additional data on current and projected adoption would be useful as well.

4.3 Benchmarks

The Intergovernmental Panel on Climate Change (Smith et al, 2007) estimates emissions reduction of 0.2 gigatons carbon dioxide-equivalent per year by 2030 for rice management. Griscolm et al (2017)'s "Natural climate solutions" calculate 0.08-0.26 gigatons of carbon dioxide equivalent per year in 2030. Between the three Scenarios, Drawdown's two rice solutions combined provide 0.45-0.92 gigatons carbon dioxide-equivalent per year by 2030. Drawdown's figures are likely higher due to the inclusion of carbon sequestration benefits (Table 10 shows that Drawdown's figures are much closer to the benchmarks when only emissions removal is considered).

Table 4.1 Benchmarks

Source and Scenario	Emissions Reduction Gt $CO_{2\text{-eq}}$ in 2030
Smith (2007)	0.20
EPA (2013)	0.20

Source and Scenario	Emissions Reduction Gt $CO_{2\text{-eq}}$ in 2030
Griscom (2017)	0.08-0.26
Project Drawdown (improved rice cultivation and system of rice intensification, only emission reduction)	0.22-0.44

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6 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 CO_2 (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 CO_2e/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 Drawdown 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