TECHNICAL ASSESSMENT FOR BIOPLASTICS

SECTOR: MATERIALS

AGENCY LEVEL: PRIMARY CONSUMER/PRODUCT MANUFACTURER

KEYWORDS: BIOPOLYMER, PLASTIC

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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.

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info@drawdown.org www.drawdown.org

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EXECUTIVE SUMMARY

Bioplastics, also referred to as biopolymers, are plastics which are derived from biological feedstocks rather than fossil resources. Bioplastics represent a broad array of technologies to produce many different types of materials such as packaging, textiles, durable goods, and disposable products. The many different types of bioplastics can and are made using a wide variety of feedstocks with a significant portion of the current research being dedicated to identifying and expanding available feedstocks. Some bioplastics, such as thermoplastic starch (TPS), require little processing while others such as polylactic acid (PLA) are the result of a fairly intensive process of fermentation, distillation, and polymerization. This report addresses bioplastics collectively, assessing current pricing and production as well as forecasting a possible future given current trends and an optimistic outlook on future adoption.

Currently the most visible bioplastics are disposable, and often compostable, products that are advertised as 'green' and 'plant-based,' however, the most growth in the market is characterized by "drop-in" products like Coke-a-Cola's PlantBottle which is a hybrid polyethylene terephthalate (PET) with biobased ethylene while the rest of the plastic is generated from fossil resources. Bioplastics exist as both mature and nascent technologies with some being drop in replacements (chemical equivalents) for traditional plastics and others that differ in performance and material characteristics. For example, PLA has become a favored plastic in 3D printing due to its favorable thermal properties and the current printer technologies.

There are environmental tradeoffs as a result of shifting from fossil extraction and refining to an agriculture-based system. With regards to carbon, the fossil system is characterized by extraction hydrocarbons from the earth then the fossil resource itself is used as a raw material to create different plastic products. Through the agriculture process, carbon dioxide is taken in by plants which are then harvested and used to create bioplastics so the carbon in these materials is referred to as biogenic carbon.

In 2015 there were 2.03 MMT of biopolymers produced throughout the world, with a current maximum replacement potential of 90% of the market. Average prices of bioplastics ranging around \$2.70 per kilogram for resin, but the range of prices can be between \$1.00 and \$6.00, depending on the material. Given the past growth in bioplastics and a high level of continued gains in market share, this report includes three likely scenarios of growth, a baseline of 13% TAM penetration in 2050, a drawdown scenario with 51% market replacement in 2050, and finally an optimum scenario where complete replacement is achieved by 2050 within technological limits, at 90%.

Based upon the anticipated rate of adoption there will be an equivalent of around 0.96 , 3.8 and 5.77 GT of CO2 emissions avoided in the three scenarios, respectively, during the thirty year period between 2020 and 2050. This analysis suggests that the bioplastics market can grow to replace a significant portion of traditional plastics while reducing climate emissions, but growth is highly variable. To date, growth of the bioplastics market has been slower than some of the more aggressive projections. Factors such as feedstock development and end of life treatment, whether recycling, composting, or landfilling, will play important roles in minimizing emissions throughout the life cycle of these products. Furthermore the reduction of demand for traditional plastics will decouple plastic markets from fossil fuel markets and will also make more fossil resources available for other uses.

1 Literature Review

1.1. State of Bioplastics

Bioplastics, simply put, are plastics made from plants or other biological sources. The concept of commercial production of bioplastics began in earnest in the 1990's with the introduction of Green Chemistry and increasing fossil fuel prices[1]. Since then bioplastics have been developed to and marketed as replacements for traditional plastics. The primary advantage of bioplastics over traditional fossil-based plastics is that using a plant feedstock allows for carbon sequestration in the raw material through carbon fixing. Beyond this, some bioplastics additionally have material characteristics which may make them more attractive than the commodity fossil plastics that dominate the market. Examples of these characteristics are biodegradability or compostability (reducing landfilling and recycling demand), good thermal properties (for 3D printing), and stiffness to density ratio (important for packaging)[2,3].

There are several categories of materials that encompass bioplastics. Some plastics are bio-based, or part bio-based and part fossil-based, but not biodegradable, such as Bio-PET (polyethlylene terephthalate) which contains plant-derived ethylene, this is used in Coca-Cola's PlantBottle[4]. In this particular case the PET is the exact same polymer as a completely fossil based version, which makes it a 'drop-in' technology for extruding and forming products and recycling streams during end of life treatment for the material. Other plastics that are bio-based but not biodegradable are bio polyethylene, bio polypropylene, polyamides, and more. There are additionally bio-based and biodegradable plastics, of which some examples are polylactic acid (PLA) and polyhydroxyalkanoates (PHA). The final category are other biodegradable plastics, such as polybutylene adipate terephthalate (PBAT).

Beyond types of plastics, there exist three methods for production of bio-based plastics: starch pastics, which make use of natural polymers largely remaining intact, production of monomers and then polymerization (PLA), and production of biopolymers directly in microorganisms or GMO crops.

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[1] Iles, A., & Martin, A. N. (2013). Expanding bioplastics production: sustainable business innovation in the chemical industry. *Journal of Cleaner Production*, *45*, 38–49. http://doi.org/10.1016/j.jclepro.2012.05.008

[2] Braasch, G. (2015, March 9). RE: research question PLA pricepoints.

[3] Patel, M., Crank, M., Dornburg, V., Hermann, B., Roes, L., Husing, B., … Elena, R. (2006). *Medium and long-term opportunities and risks of the biotechnological production of bulk chemicals from renewable resources - The BREW Project*. European Commissions's GROWTH Programme. Retrieved from http://brew.geo.uu.nl/BREW_Final_Report_September_2006.pdf

[4] Tabone, M. D., Cregg, J. J., Beckman, E. J., & Landis, A. E. (2010). Sustainability Metrics: Life Cycle Assessment and Green Design in Polymers. *Environmental Science & Technology*, *44*(21), 8264–8269. http://doi.org/10.1021/es101640n

There are a wide variety of bioplastics with different feedstocks and different underlying technologies used to refine the raw materials into formable plastics but generally the process starts with simple carbohydrates from root or grain crops. The production of biopolymers can be as simple as isolating starches from grain and thermoforming the starch along with a few additives. Conversely some biopolymers must go through complex fermentation and polymerization processes to create high value products[5]. For unique bioplastics, new facilities must be constructed, such as the NatureWorks PLA production facility in Blair, Nebraska[6]. For 'drop-in' materials, biopolymers may be processed and produced at existing facilities, reducing the capital costs and time required to scale up the production of bioplastic materials. Another trend in biopolymer technology is feedstock improvement to create crops that minimize processing while maximizing useful biomass enabling more efficient and consistent production of biopolymers[7].

While bioplastics have the potential to be implemented across many different markets but the technologies, as they currently stand, tend to favor growth in packaging applications. Figure 1 depicts the type and amount of bioplastics that are produced for different markets[8]. While there are some bioplastics available to individual consumers, they are largely purchased through wholesalers for packaging other products or use on the commercial scale. As investments in bioplastics continue to increase, the industry will find new uses and markets for the products just as the fossil plastic industry did in the last century. The development of new feedstocks and polymer types will enable more diverse applications[9].

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[5] De Jong, E., Higson, A., Walsh, P., & Wellisch, M. (2012). Product developments in the bio-based chemicals arena. *Biofuels, Bioproducts and Biorefining*, *6*(6), 606–624. http://doi.org/10.1002/bbb.1360

[6] Vink, E. T. H., Davies, S., & Kolstad, J. J. (2010). ORIGINAL RESEARCH: The eco-profile for current Ingeo® polylactide production. *Industrial Biotechnology*, *6*(4), 212–224. http://doi.org/10.1089/ind.2010.6.212

[7] Babu, R. P., O'Connor, K., & Seeram, R. (2013). Current progress on bio-based polymers and their future trends. *Progress in Biomaterials*, *2*(1), 8. http://doi.org/10.1186/2194-0517-2-8

[8] European Bioplastics. (2018). *Bioplastics facts and figures*.

[9] Snell, K. D., Singh, V., & Brumbley, S. M. (2015). Production of novel biopolymers in plants: recent technological advances and future prospects. *Current Opinion in Biotechnology*, *32*, 68–75. http://doi.org/10.1016/j.copbio.2014.11.005

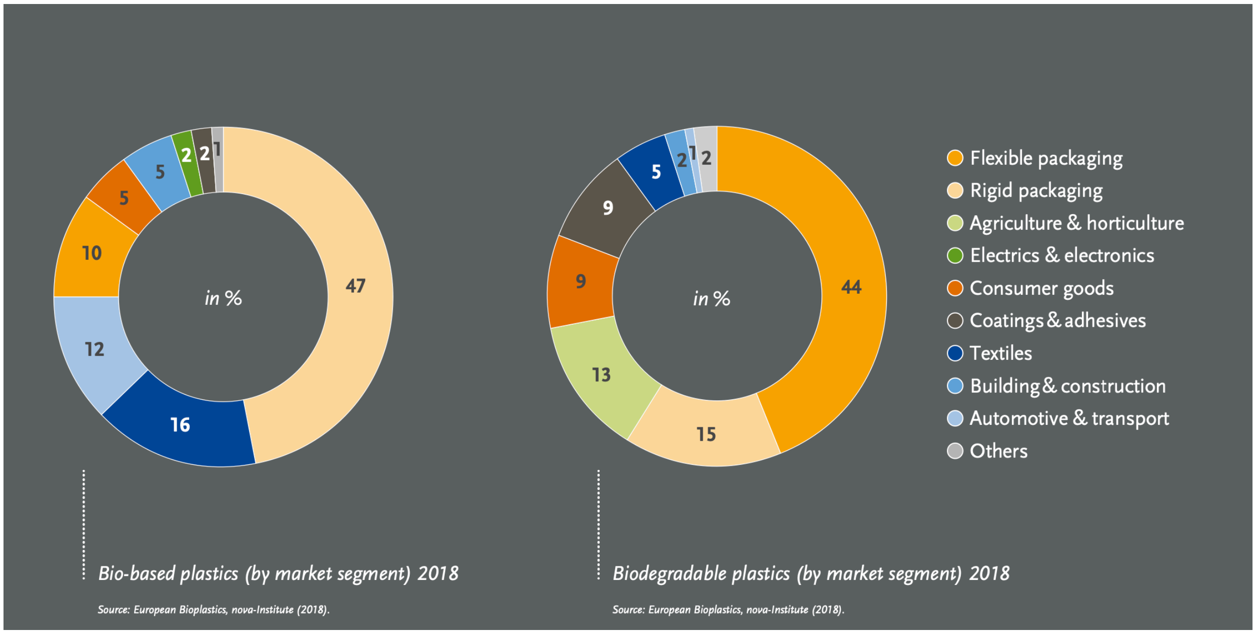

Figure 1. Production capacities and bioplastic types by market segment. This graph was published in a report by European Bioplastics[8].

1.2. Adoption Path

1.2.1 Current Adoption

Many bioplastics have been developed by large, international chemical companies and already have global representation as seen in Figure 2. With names like DuPont, Cargill, Dow, BASF, and Mitsubishi Chemicals in addition to many other companies investing in bioplastics development these technologies have a strong platform to expand on the global scale; just since 2013, global production of bioplastics has increased over 30% from 1.62 million tons to 2.11 million tons in 2018[8]. However, this is still less than 1% of the total global plastics market. Bioplastics are promising similar breakthroughs in feedstock development as biofuels with higher output and fewer environmental impacts from cellulosic and algal sources. Because bioplastics are a replacement technology there is already demand for plastic materials worldwide and outlets for these materials. This suggests that bioplastics may be able to transition from research and development to products in the market relatively quickly.

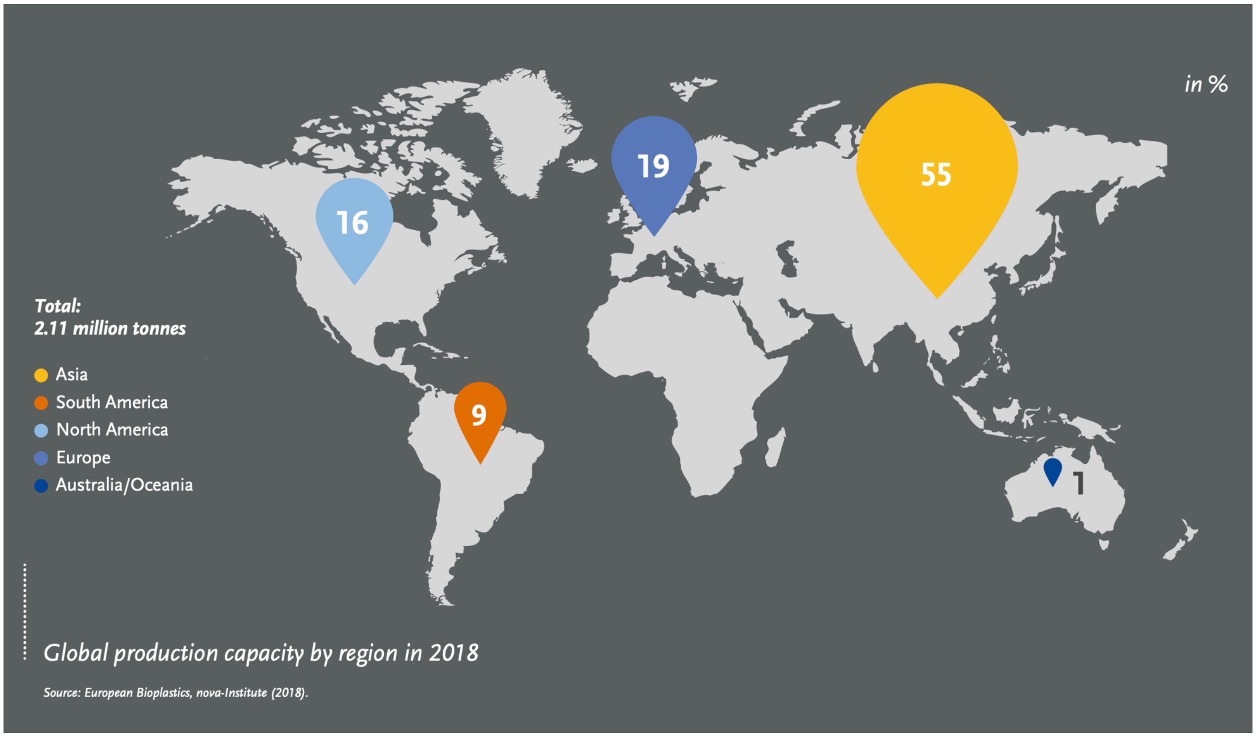

Figure 2. Global production rate for bioplastics by region. This graph was published in a report by European Bioplastics[8].

There are a few specific factors in the development of bioplastics which may influence the global rate of adoption some which favor bioplastics and others which may dampen their growth in the market. Factors favoring the development of bioplastics include the availability and uncertainty regarding fossil resources, the increasingly viable economics of production, environmental performance, and investments in bioplastics development. Conversely, low performance of some bioplastics, high processing costs, land use factors, and environmental impacts from agricultural are factors that will need to be addressed as bioplastics continue to gain an increasing market share[10,11,7]. Fossil resources are a double-edged sword which with volatile or high prices can encourage rapid bioplastics development but consistently low fossil prices may limit bioplastics to the niche markets they already occupy. Policy is another avenue by which biopolymers may make inroads into the fossil plastics market as bio-preferred programs, carbon markets (or taxes), and plastic bans may make bioplastics the favorable alternative to fossil plastics even if they have slightly higher prices.

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[10] Philip, J. C., & Ritchie, R. J. (2013). Biobased plastics in a bioeconomy. *Trends in Biotechnology*, *31*(2), 65–67.

[11] Shen, L., Worrell, E., & Patel, M. (2010). Present and future development in plastics from biomass. *Biofuels, Bioproducts and Biorefining*, *4*(1), 25–40. http://doi.org/10.1002/bbb.189

1.2.2 Barriers to Adoption

There are several barriers to adoption which affect different phases of the bioplastic life cycle, some of which are technical barriers, and others of which are market barriers.

The main barriers to market entry and continued growth are competition from the mature fossil plastics industries, pricing, and feedstock availability [1,8,12]. One feedstock related issue is proximity of production facilities to raw materials. Agricultural products have extremely low density when compared to fossil resources and cannot be moved through pipelines or tankers, making transportation logistics one of the more challenging aspects of production which cannot be as centralized as fossil based plastic production. Bioplastic facilities must be located near feedstock production in order to realize any benefits that agricultural based production may have over fossil plastics[7]. Another market barrier is cost of bioplastics – not only are bioplastics currently more expensive than fossil plastics, but since the market is currently small, scaling up the production of new products is challenging. Furthermore current market standards are based on fossil plastics, not bioplastics, which can be a limit to direct competition[12].

Technical barriers to adoption are varied. While cellulosic plastics from trees have several advantages, effective and scalable methods for separation and depolymerization of lignin – which is necessary for the valorization of this material – is still very much in development[12]. Even for starch-based plastics, in which production is happening at a larger scale than cellulosics, improvements in conversion methodology as well as fermentation methods could be achieved[12]. Another consideration is the use of starch feedstocks to produce bioplastics. Increased demand could result in allocation of food crops for production, or major land use change. Land use for bioplastics in 2017 was 672,000 ha and is projected to grow to 1,038,000 ha by 2022[13].

1.2.3 Trends to Accelerate Adoption

The foremost trend to accelerate adoption of bioplastics over fossil plastics is perception. As concerns over the impact of continued use of fossil resources grows, interest in alternatives grows. Bioplastics have several advantages over fossil resources which can be leveraged to increase adoption. One such advantage is that bioplastics are "energy carriers," even after use, they could be incinerated or processed for energy, reducing the necessity for direct incineration of biomass[13]. As energy production from biomass is a growing field of interest as well, emphasizing that these two uses of biomass (energy and

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[12] US DOE. (2020). *The Technology Roadmap for Plant/Crop-Based Renewable Resources 2020*. 44.

[13] IfBB. (2018). *Biopolymers facts and statistics: 2018 production capacities, processing routes, feedstock, land and water use*. Retrieved from Institute for Bioplastics and Biocomposites, Hochschule Hannover website: https://www.ifbb-hannover.de/files/IfBB/downloads/faltblaetter_broschueren/Biopolymers-Facts-Statistics-2018.pdf

plastic production) do not need to be in direct competition for raw materials in the form of feedstocks and land use is a notable advantage. Another perception of bioplastics, and more generally, "green" materials generally is that performance may be compromised when compared to conventional goods. However, recent research and advances have shown that thermal and mechanical properties of bioplastics have been developed and improved significantly in recent years, and in many areas are comparable to fossil plastics[14]. PLA, for example, has an extremely high tensile strength, but production results in 40% less GHG emissions than its conventional counterpart[14].

1.2.4 Adoption Potential

Despite some cost and technological hurdles to overcome in the near future, the direct parallels of bioplastics to conventional plastics, means that there is high adoption potential as markets for these products already exist. The US DOE, in 1999, set goals for growth of bio-based chemicals to 10% of market by 2020, and 50% of market by 2050[12] – global plastics production has been over 300 million tons since 2014. In the near term, several projections show that meeting this adoption potential is possible. The European Bioplastics 2018 report is one of the most conservative projections available, forecasting 2020 consumption to be 2.2 MMT[8] (down significantly from the 2013 report, which projected almost 8 MMT by 2019). The Institute for Bioplastics and Biocomposites has a more aggressive projection, with adoption 82% higher[13] than European Bioplastics, and the USDA also has a higher projection, with expected 18% market growth through 2025 resulting in 3.4 MMT in 2020[15]. A 2010 study by Shen et al., has three adoption scenarios – Low, Business as Usual, and High – with projections of the bioplastic market growing to 1.47, 3.45, and 4.40 MMT, respectively [16]. Since current consumption has already exceeded the low scenario, it is safe to conclude that the adoption of bioplastics will continue to grow to meet or exceed expectations.

1.3. Advantages and Disadvantages of Bioplastics

Bioplastics are the only real way to transition away from the incumbent fossil based plastics. The beginning of the 20th century marked what is now known as the Polymer Age, a leap in materials science revolutionizing the ability humans have to shape the world around them just as the Bronze Age and Iron

[14] Chen, G.-Q., & Patel, M. K. (2012). Plastics Derived from Biological Sources: Present and Future: A Technical and Environmental Review. *Chemical Reviews*, *112*(4), 2082–2099. https://doi.org/10.1021/cr200162d

[15] Lewis, K. (2018). A New Industrial Revolution for Plastics. *USDA Biopreferred.* Retrieved from https://www.usda.gov/media/blog/2018/09/19/new-industrial-revolution-plastics

[16] Shen, L., Worrell, E., & Patel, M. (2010). Present and future development in plastics from biomass. *Biofuels, Bioproducts and Biorefining*, *4*(1), 25–40. https://doi.org/10.1002/bbb.189

Age had before. Plastics at the most fundamental level enable us to create products of various sizes and shapes with high durability and low weight in a way that no material had ever been able to previously. The transition from fossil plastics to bioplastics is not a transition away from these materials but a shift towards biologically based raw materials that are not directly tied to energy costs and are renewable. The other method of reducing impacts from plastics comes from the USEPA's Waste Management Hierarchy[17] which characterizes the ubiquitous mantra Reduce, Reuse, Recycle. However, this ranking of waste avoidance can exist under either paradigm of plastic production and should be viewed as a both/and situation rather than an either/or competition.

If for no other reason, bioplastics should continue to be developed simply to diversify the feedstocks available to continue to supply plastic materials in order to maintain and raise the standard living for people and improve our environment. Many of the LCAs conducted on biopolymers also suggest that they may have improved performance with regards to climate impacts[18,19,20]. Further there are already niche markets for compostable and biodegradable products that will continue to grow, fostering the continued development of these technologies so bioplastics can become fully competitive on the global scale. Compostable products can also provide knock-on effects, enabling the composting of other organics including food and yard wastes which may otherwise go to landfill and create methane, which has a higher global warming potential than the CO_2 generated through composting.

There are some potential drawbacks to bioplastics as previously mentioned in the Adoption Path section. The drawbacks include low performance of some bioplastics, high processing costs, land use concerns, and environmental impacts from agricultural. Any climate benefits from biopolymers must be seen in the context of environmental tradeoffs specifically from agricultural processes[4, 21,22,23]. Localized

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[17] US EPA, O. (n.d.). Solid Waste Management Hierarchy [Overviews & Factsheets]. Retrieved March 25, 2015, from http://www.epa.gov/waste/nonhaz/municipal/hierarchy.htm

[18] Weiss, M., Haufe, J., Carus, M., Brandão, M., Bringezu, S., Hermann, B., & Patel, M. K. (2012). A Review of the Environmental Impacts of Biobased Materials. *Journal of Industrial Ecology*, *16*, S169–S181. http://doi.org/10.1111/j.1530-9290.2012.00468.x

[19] Joshi, S. (2008). Can Nanotechnology Improve the Sustainability of Biobased Products? *Journal of Industrial Ecology*, *12*(3), 474–489. http://doi.org/10.1111/j.1530-9290.2008.00039.x

[20] Karpušenkaitė, A., & Varžinskas, V. (2014). Bioplastics: Development, Possibilities and Difficulties. *Environmental Research, Engineering and Management*, *68*(2). http://doi.org/10.5755/j01.erem.68.2.6777

[21] Yates, M. R., & Barlow, C. Y. (2013). Life cycle assessments of biodegradable, commercial biopolymers—A critical review. *Resources, Conservation and Recycling*, *78*, 54–66. http://doi.org/10.1016/j.resconrec.2013.06.010

[22] Groot, W. J., & Borén, T. (2010). Life cycle assessment of the manufacture of lactide and PLA biopolymers from sugarcane in Thailand. *The International Journal of Life Cycle Assessment*, *15*(9), 970–984. http://doi.org/10.1007/s11367-010-0225-y

[23] Hottle, T. A., Bilec, M. M., & Landis, A. E. (2013). Sustainability assessments of bio-based polymers. *Polymer Degradation and Stability*, *98*(9), 1898–1907. http://doi.org/10.1016/j.polymdegradstab.2013.06.016

impacts such as eutrophication, acidification, and ecotoxicity are examples of harmful effects caused by annual agricultural feedstock production compared to drilling a well that can provide resources for many years. Additionally, the variability of annual cropping can be unpredictable and may be strongly influenced by any severe weather impacts from climate change in the coming years.

The most significant disadvantage to bioplastics, however, is the high variability and uncertainty in the impact of these materials. Because this is a burgeoning field, methods for production are in development and highly variable. Directly tied to this disadvantage, conversely, is a significant advantage: a new and exciting research area results in significant interest and resources in exploring these uncertainties to allow for more informed decisions. One example of variability of impact, is in the type of feedstock used for production. Though many LCAs show reduction in greenhouse gas emissions from the production of bioplastics as opposed to conventional fossil plastics, a closer look at feedstocks show a more interesting picture: cradle-to-gate impacts of PLA and PHB from corn do not, in all scenarios, result in lower GHG emissions than fossil plastics, where cradle-to-gate impacts of the same materials from switchgrass show significant reductions in GHG emissions[24]. Another critical factor that contributes to uncertainty is end of life management. Where composability and biodegradation are marketed as advantages of bioplastics, in reality composting bioplastics leads to the release of much of the sequestered carbon. Greenhouse gas emissions of PLA from both corn and switchgrass, when landfilled, are only 0.04 kg CO_2/kg plastic, but when composted this increases dramatically to 1.7 kg CO_2/kg plastic[24]. This same study finds that recycling of bioplastics is the most effective EoL management method for reduction of GHGs, but methods for recycling bioplastics are still very much in development. A look at this, and similar studies that compare the impacts of feedstocks, plastic types, and end of life management highlight the huge variability in the benefits of bioplastics, and the fact that in some cases the benefits may in fact be minimal. Despite this, perhaps the most critical take away from this uncertainty is that there is huge potential in certain types of plastics, and these studies provide a framework for decision makers to focus R&D and production efforts into low impact feedstocks and plastics, and to bolster improvement for end of life management of these resources.

[24] Posen, I. D., Jaramillo, P., & Griffin, W. M. (2016). Uncertainty in the Life Cycle Greenhouse Gas Emissions from U.S. Production of Three Biobased Polymer Families. *Environmental Science & Technology*, *50*(6), 2846–2858. https://doi.org/10.1021/acs.est.5b05589

2 METHODOLOGY

2.1 INTRODUCTION

Project Drawdown's models are developed in Microsoft Excel using standard templates that allow easier integration since integration is critical to the bottom-up approach used. The template used for this solution was the Reduction and Replacement Solutions (RRS) which accounts for reductions in energy consumption and emissions generation for a solution relative to a conventional technology. These technologies are assumed to compete in markets to supply the final functional demand which is exogenous to the model, but may be shared across several solution models. The adoption and markets are therefore defined in terms of functional units, and for investment costing, adoptions are also converted to implementation units. The adoptions of both conventional and solution were projected for each of several scenarios from 2015 to 2060 (from a base year of 2014) and the comparison of these scenarios (for the 2020-2050 segment[1]) is what constituted the results.

2.2 DATA SOURCES

Key sources of data for this model include both peer-reviewed journal articles as well as publications from industry organizations, as well as some government or non-profit sources. The majority of data collected and used falls into three categories: environmental impact data, market data, and cost data.

Environmental impact, as quantified by $CO_{2,eq}$ emissions, was collected for both the conventional functional unit [MMt of fossil plastics] and also the solution functional unit [MMt of bioplastics]. Emissions from production of plastics were collected primarily from peer-reviewed LCA studies. Some key sources include Akiyama et al. (2003), Dornburg et al. (2003), Groot and Boren (2010), Chen and Patel (2012), Shen et al. (2012), Yates and Barlow (2013), Hottle et al. (2013). Additional sources include LCAs or data published by bioplastics producers, such as Natureworks (PE Americas, 2009).

Market data, used to produce adoption cases as well as calculate the TAM, are primarily from industry organizations. Critical data of historical bioplastics production and short term projections are available from European Bioplastics (2018), as well as IfBB, the Institute for Bioplastics and Biocomposites (2018). Data about plastics generally, was collected from Plastics Europe (2019). Additional sources for bioplastics production projections include the Ellen Macarthur Foundation (2016) and the USDA (Lewis, 2018), as well as PRO-BIP, a peer-reviewed product overview of bioplastics supported by European Bioplastics (Shen et al., 2009).

Cost data were available also from PRO-BIP (Shen et al., 2009) as well as several other peer-reviewed articles, including Guzman (2012), Rorrer et al. (2017), Ashok et al. (2018) as well as a book (Biron, 2012).

2.3 Total Addressable Market

The total addressable market is calculated based on several estimates for total plastic demand. Baseline cases are developed based on historical global plastics consumption from PlasticsEurope, and a World Economic Forum projection of consumption in 2050 (also used by the Ellen Macarthur Foundation in the New Plastics Economy report). A more conservative case is based on a Mosko (2012) publication which uses a PlasticsEurope market projection based on the same per capita plastics production in 2010 as in 2050, where only population drives increased demand, and people, on average, do not consume more plastic.

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.

Bioplastics are a replacement technology for fossil based plastics. This report and the corresponding model are based on an increasing market share for bioplastics of the total, still growing, plastics market. The main assumption here is that bioplastics grow into the plastics market but do not expand independent of the current plastics market. There is, however, a possibility that there are certain applications in which bioplastics will experience growth not captured in projections for traditional plastics, especially as biopolymers continue to improve with technological development (feedstocks and processing) and scale into the market. This report includes a REF scenario based on the current adoption percentage of bioplastics remaining static from 2020 and 2050 and an PDS scenario based on aggressive growth adoption between 2020 and 2050.

2.4.1 Reference Case / Current Adoption

The REF scenario for bioplastics is characterized by a static share of the total plastics market over the next thirty years. In 2014, the base year, the plastics market was around 311 MMt with only 1,670 kT of biopolymers going to market. In 2018, total plastics market was 359 MMt, and bioplastics were 2.1 MMt resulting in a REF adoption value set at 0.6% of the total market. This approach assumes only enough growth for biopolymers to maintain the 0.6% market share from 2020 to 2050.

2.4.2 Project Drawdown Scenarios

The PDS scenarios are based on a combination of projections in the literature and an interpolation based on the total market growth mentioned above as well as a projection of bioplastic market share development in the 30 year timeframe. For the years ranging from 2014 to 2018 real, historical data were used. Bioplastics production was then estimated for the following years using a “maximum technical substitution potential” of traditional plastics with bioplastics of 90%[11,25], and growth to various percentages of the TAM.

PDS1, the plausible scenario, in which solutions are adopted at a realistically vigorous rate over the time, follows a modest growth rate to 2023, from European Bioplastics[8], and then a polynomial fit to 13% of the replaceable market in 2050, based on baseline projections.

PDS2, the drawdown scenario, in which solutions are optimized to achieve drawdown by 2050, follows a modest growth rate to 2023, from European Bioplastics[8], and then a polynomial fit to 51% of the replaceable market in 2050, based on aggressive projections.

PDS3, the optimum scenario, in which solutions achieve their maximum potential, follows a more aggressive growth rate to 2025, and then a polynomial fit to complete adoption of the replaceable market by 2050.

2.5 Inputs

2.5.1 Climate Inputs

Climate reductions from bioplastics are achieved through a combination of the atmospheric origin of the carbon within the materials themselves and by keeping production impacts low enough to realize the benefits of the biogenic carbon. The LCAs used to assess the climate impacts of bioplastics and fossil plastics are cradle-to-gate include raw material acquisition and production energy. Bioplastics, being consumable materials, do not incur operational impacts and were assed solely on annual production. There is, however, uncertainty around the end of life treatment of biopolymers which may impact climate emissions when compared to traditional plastics, especially over such a long time frame. However, cradle-to-grave studies, or end of life impacts are not currently within the scope of this model, as they will be included in the larger waste integration model, where quantity of bioplastics landfilled, recycled, or composted are included.

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[25] Shen, L., Haufe, J., & Patel, M. K. (2009). *Product overview and market projection of emerging bio-based plastics PRO-BIP 2009* (No. 243). European Polysaccharide Network of Exxcellence (EPNOE) and European Bioplastics.

Within the general category of bioplastics, there are multiple subcategories of solution technologies and types that have different climate impacts. Bioplastics can be categorized by feedstock, generation, biodegradability, or even chemical compound, all of which have different environmental impacts, and are growing at different rates within the larger plastics market. For this reason, climate impacts are weighted based on time-based market growth. The subcategories used to develop these time-based market weights are biodegradability, because of better data availability, as well as the fact that these are the most general of the categories, and can be sub-divided even further based on feedstock or chemical compound, if more data becomes available.

The market share of biodegradable and non-biodegradable plastics was determined for years until 2018, and then modeled based on projections, to 2050. The percent of market in each year can then be multiplied by the adoption scenario to estimate total adoption of each sub-solution in MMt of plastic (the functional unit) and summed for the entire time frame considered. The cumulative market share is then used to weight the sub-solution variables to determine the total direct emission per solution functional unit.

2.5.2 Financial Inputs

Forecasting prices is particularly difficult for this assessment comparing traditional plastics, which are sold as commodities on a global market, and bioplastics, which are still, largely, niche products just starting to make significant progress in global markets. Fossil based plastics track the price and availability of natural gas and petroleum and energy futures so plastic prices tend to be volatile with many markets providing daily price points. Bioplastics, however, are sold on such limited scales that it is difficult to find any data on material pricing. This model relies upon available literature and direct email inquiry with bioplastic producers (there are some paid market reports that may provide more insight into the bioplastics market but they remain inaccessible at the time of writing this report[26,27]).

Price points within the model for both traditional plastics and bioplastics are based on the most currently available price data and a projection for prices in 2020 from the literature[26, 28]. The data found within the literature, via email, and in online market reports from 2011 to 2015 was averaged to estimate current market prices and was combined with future estimates for polypropylene and bioplastics in the book by Biron[28] (see ‘prices’ sheet in the model) in an attempt to accommodate both historical prices and future trends within the model. Uncertainty in fossil resources was addressed by Biron by modeling based first on

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[26] Kline-Group. (2014). *Biopolymers: Global Market Brief*. Retrieved from http://www.klinegroup.com/reports/biopolymers.asp

[27] Smithers-Pira. (n.d.). *The Future of Bioplastics for Packaging to 2023*. Smithers Pira.

[28] Biron, M. (n.d.). Thermoplastics and Thermoplastic Composites - Michel Biron - Google Books. Retrieved February 26, 2015.

historical prices and then based on two different prices for a barrel of oil; \$150/barrel and \$300/barrel. Pricing data, however, is limited in availability, due to the discretion of producers to set prices based on quantity or other variables. As the bioplastics market grows, more data and set prices may become available.

This data aggregation method includes scenario assessments and multiple price points from several sources which were averaged for inclusion, and the Drawdown standard 4.7% first cost learning rate is assumed for bioplastics. Conventional plastics do not have a learning rate, as the technology is fully developed, and in fact, raw materials prices (oil) are rising. The adoption scenarios are then valuated by multiplying this average price per unit by the market volume for traditional plastics and bioplastics and then summing them to get a total scenario cost for both REF and PDS scenarios. The uncertainty concerning these markets is high and any results should be seen as general trends and relationships rather than accurate predictors of future prices.

2.6 Assumptions

2.7 Integration

2.8 Limitations/Further Development

Within each sub-solution emissions variable, as mentioned in 2.5.1 Climate Inputs, further resolution of data is possible. Currently, there is not sufficient emissions data for each type of plastic within the biodegradable and non-biodegradable categories, to use a weighted average. However, as more LCA studies are done or more data becomes available, this would be possible. It is also possible to weight by feedstock type, if the percent of bioplastics from different feedstocks is determined.

Further, the same time-based weighting scheme could be applied to cost to determine a more accurate estimation of cost. Two variables, first cost for biodegradable plastics and first cost for non-biodegradable plastics, would need to be included, and then weighted in the same way as emissions. However, current price and cost data is lacking in both quantity of sources as well as accuracy for this to be implemented in this version.

3 Results

The total growth of the plastics market is represented by a five year period of strong growth followed by a more gradual development for the following twenty-five year period. These two linear trends combined in a way suggesting the typical 'S' shape of a logistical curve which is used to chart the growth of technologies (**Error! Reference source not found.**). Bioplastics in the REF scenario, given the anticipated growth in the total market, would increase from about 1.7 MMT in 2014 to around 4.8 MMT by 2050, to remain at 0.6% of the cumulative plastic production. For the PDS scenarios, bioplastics production was estimated using predictions from the literature.

In the PDS 1 scenario, where 44% of the replaceable market is substituted with bioplastics over conventional plastics, in 2050, of adoption bioplastics is 310 MMt in the final year. Given the rate of adoption in the PDS1 scenario there will be 3.3 GT of CO_2 equivalent emissions avoided during the thirty year period between 2020 and 2050 when compared to the REF scenario, or 0.29 PPM. In the final year biopolymers contribute a 0.03 ppm CO_2 eq. reduction when compared to the REF scenario.

Biopolymers are expected to average $2.77/kg between 2015 and 2050 compared with $1.7/kg for fossil based plastics. Since the model for the plastics market assumes no operational costs, the initial price and market share of bioplastics dictates the relative financial performance between the REF and PDS scenarios. Because bioplastics are a developing technology, the costs are expected to come down as production grows in scale, but not below conventional plastics in the near future.

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.

Table 3.1 World Adoption of the Solution

Solution	Units	Base Year (2014)	Current Year (2018)	World Adoption in 2050		
				Plausible	Drawdown	Optimum
Solution Name	*MMt of Plastic Produced Annually*	1.67	2.11	92.19	356.8	705.2
	(% market)	0.54%	0.67%	12%	46%	90%

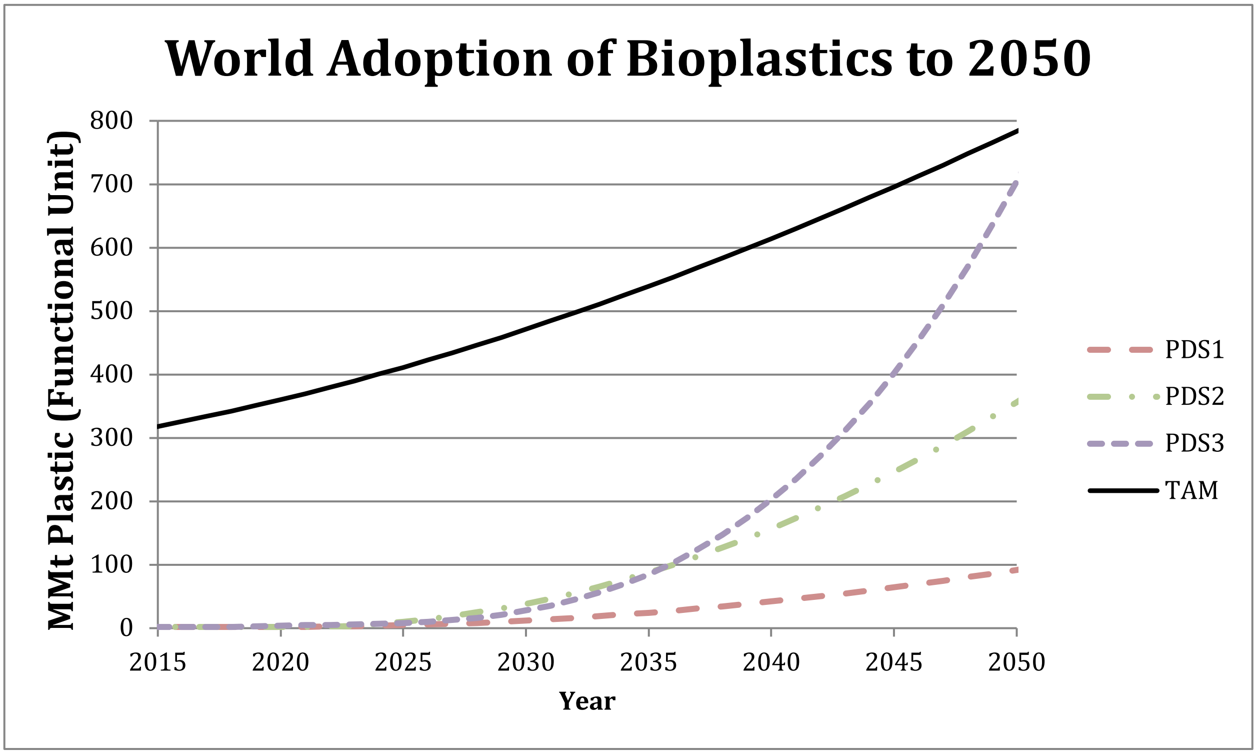


Figure 3-1 World Annual Adoption 2015-2050

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).

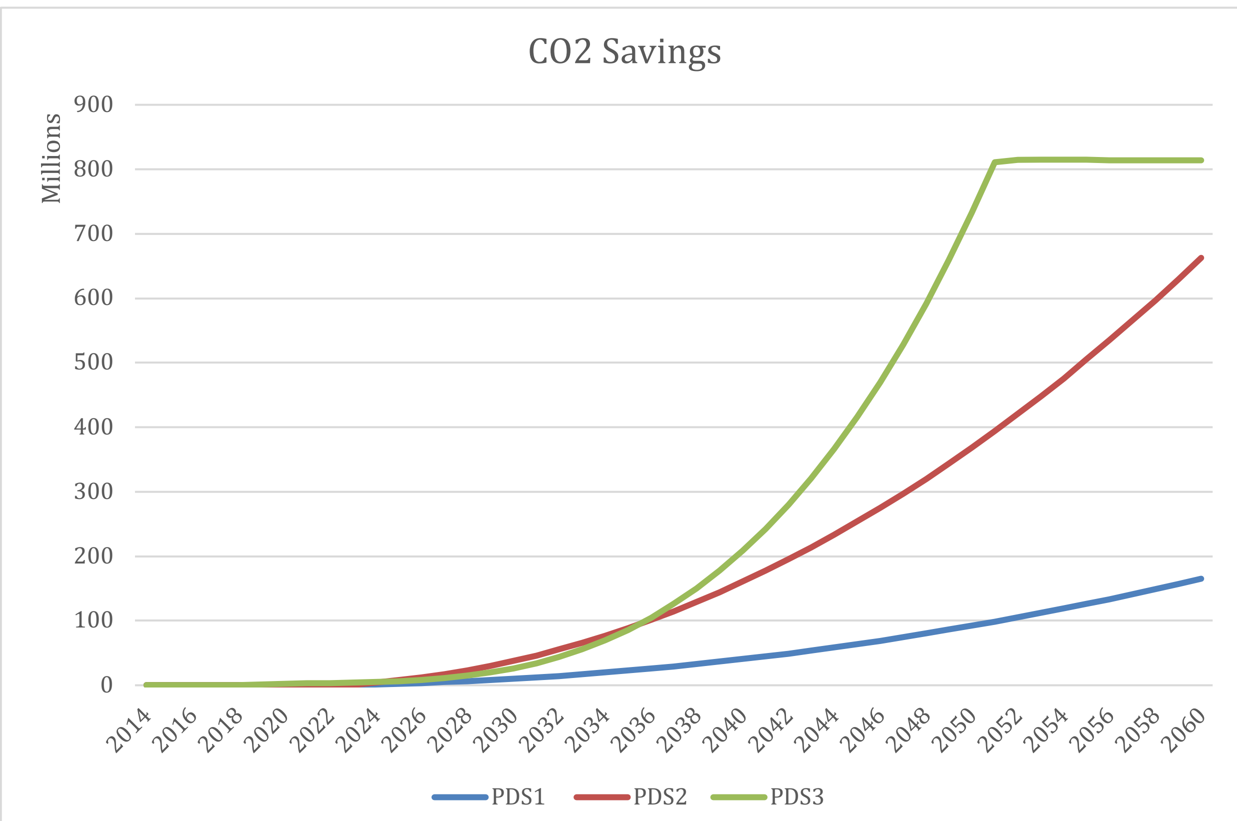
Table 3.2 Climate Impacts

Scenario	Maximum Annual Emissions Reduction	Total Emissions Reduction
	(Gt CO_2-eq/yr.)	*Gt CO_2-eq/yr. (2020-2050)*
Plausible	0.09	0.96
Drawdown	0.37	3.80
Optimum	0.73	5.77

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).

Table 3.3 Impacts on Atmospheric Concentrations of CO_2-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	0.09	0.01
Drawdown	0.34	0.03
Optimum	0.53	0.07



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.

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	$2,065	$88.15	-	-	-	-
Drawdown	$7,135	$25.47	-	-	-	-
Optimum	$10,698	$25.23	-	-	-	-

4 Discussion

Though the REF scenario is based on current adoption rates, it does not correlate to the trends of growth within the market. The PDS scenarios better represents the rate of growth in the production of bioplastics and continued investment from the producers of bioplastics, this growth is likely to continue. The high levels of market adoption in the later years of the PDS scenarios may require favorable policies in addition to higher prices for fossil resources but are conceivable given adequate feedstocks and production infrastructure. Plastics are not going away anytime soon and the volatility in the fossil fuel market suggests diversification into biological production would be a logical investment.

Bioplastics are nascent technologies and will continue to develop. As such, there are some areas of uncertainty regarding the model and room for improvement in future iterations. While there was quite a bit of literature dedicated to measuring the climate impacts of fossil plastics and bioplastics, there are many different types of bioplastics each with different feedstocks and production techniques. The current model considers different polymer type and categorizes the solution based on projected growth of biodegradable and non-biodegradable plastics. An interesting finding of this analysis is that as the biodegradable portion of the bioplastics market is projected to grow and eventually surpass non-biodegradable and "drop in" technologies such as BioPET, BioPP, etc., the biodegradable plastics on average actually have a higher carbon footprint, and additionally when end of life is considered, composting and degradation of these materials releases significant amounts of the carbon that was fixed in the material during feedstock growth. As these technologies continue to develop, therefore, it is important to continue to update carbon emissions estimates, as the growing sector of bioplastics seems to currently be the sector with more carbon emissions, but this may not continue to be the case as production scales and grows in efficiency.

Additional work could also be done on a robust financial breakdown of plastic commodities and feedstock availability including a techno-economic analysis of bioplastics. Production models could also include more nuanced data regarding geographical production rates, recycling rates, and source reductions, even if they are already accounted for in the aggregate in this version of the model.

In conclusion, this analysis suggests that the bioplastics market can grow to replace a significant portion of traditional plastics while reducing climate emissions. Other factors such as feedstock development and end of life treatment, whether recycling, composting, energy generation, or landfilling, will play important roles in minimizing emissions throughout the life cycle of these products. Furthermore the reduction of demand for traditional plastics will decouple plastic markets from fossil fuel markets and will also make more fossil resources available for other uses. Tradeoffs must be considered as bioplastics grow to ensure an effort for marginal improvement in climate impacts does not result more significant localized impacts.

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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