**Technical assessment for**

**Recycled Metals**

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# Solution Definition

The solution is defined as metal goods produced from recycled materials, replacing the conventional technology, where metals are produced out of virgin materials extracted from ores, a non-renewable resource. The system consider is bulk production of metals, not the manufacturing of end-use goods.

# Executive Summary

Materials production is a significant contributor to greenhouse gas (GHG) emissions, and as consumption of commodities and resources continues to increase, so does the environmental footprint of extraction per unit of material. Primary production of metals has been progressing with decreasing ore grades, which results in higher energy requirements for extraction and processing of larger ore volumes bearing lower metal concentrations. Secondary production from recycled material stocks requires less energy than primary production and thereby has a lower GHG footprint. An LCA-based assessment of potential future adoption scenarios (Plausible, Ambitious, Maximum) of secondary production in the total global metals market was conducted to identify the GHG emissions reductions possible from increased metal recycling and secondary production. The Plausible and Ambitious future scenarios result in 4.5 to 12 Gt of GHG emissions reduction globally, and a maximum future scenario results in over 42 Gt of GHG emissions reductions. The results of the analyses of the Plausible and Ambitious scenarios, though not close to maximizing total scrap availability, clearly indicate that even small increments of improved metal recovery for secondary production have significant potential for GHG emission reductions. Financial analysis of material feedstock costs was also performed to assess the cost to producers of switching from virgin to recycled materials. As recycled materials generally cost less than virgin ores, the operating savings on feedstock costs are significant with increased secondary production of metals.

# Literature Review

## State of Metal Recycling

Greenhouse gas (GHG) emissions associated with the primary production of metals produced from extracted virgin material feedstocks have been studied in depth and are now well understood, and recognized to represent significant contributions to global GHG emissions (1,2,3). With demand for metals continuing to grow in many parts of the world (4,5), and concern about the climate impacts of GHG emissions also growing, there is increasing interest in reducing the GHG emissions associated with metal production. An approach often advocated for reducing GHG emissions associated with metal production is to increase recovery and reuse of metals, i.e., to increase the secondary production of metals and thus the circularity of metals.

Circularity and the circular economy are at the forefront of sustainability research, as reducing consumption and using waste are significant factors in mitigating climate change as well as limiting a variety of other negative environmental impacts (2, 4). Indeed, Sustainable Consumption and Production is identified as one of the UN Sustainable Development Goals (SDG12) recognizing the unsustainable nature of natural resource consumption, most embodied in Target 12.5: “Substantially reduce waste generation through prevention, reduction, recycling, and reuse” (6). Adopting solutions related to improving circularity, improving material reuse, and reducing waste have a direct impact on achieving SDG12, and also have substantial impacts on SDGs 6, 8, 9, 11, 14, and 15, as demonstrated in a previous assessment of the impacts of achieving Drawdown Materials and Waste solutions on the SDGs (7). The linkages of the Waste sector solutions with the SDGs can be seen in Figure 1.

Diagram

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Figure ‑: Links Between Materials & Waste and Circular Economy Solutions and SDGs from Drawdown ‘System of Solution’ Analysis (7)

Improving circularity of metals in commerce by increasing secondary production from recycled materials and limiting primary production with virgin material feedstocks is recognized as important to the environmental sustainability of the metals industry (2, 8, 9). When a product is made with less material or with recycled content, less energy is needed to extract, transport, and process raw or virgin materials (2, 8). These lower energy requirements translate to lower GHG emissions. Furthermore the secondary production of end-use goods from recycled materials generally involves significantly less energy consumption since the feedstocks are already refined and at relatively high purity.

The objective of this work was to determine the potential GHG emission reduction and financial implications of increasing adoption of secondary production of metals and related displacement of demand for virgin metals. Significant limitations to circularity exist, resulting in hibernating stocks and thus potential for increased recovery of metals (3, 10). A high-resolution examination of the GHG implications of the production stage of the metal life cycle was performed, building on previous work examining circularity and opportunities for improvement of circularity in metals (11) as well as the environmental and circularity footprint of metals in the future (12). A general representation of the anthropogenic metal life cycle is represented in Figure 2, with material flows shown in green and life cycle phases in blue. There are very limited data on the degree to which metal recycling occurs globally. In this work, relevant global data for the stocks and flows in Figure 2 were compiled from existing sources and analysis was performed to obtain insight into the GHG emission reductions and financial implications of potential adoption of increased production of metals from recycled materials.

Diagram

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Figure ‑: Anthropogenic Metal Life Cycle and Flows of Materials.

The analysis included evaluation of the conventional system, metal production from virgin feedstocks, and a solution technology, metal production from recycled feedstocks, and the impact of replacing the primary production with secondary production. Recycled feedstocks include old scrap recovered from end-of-life management as well as new and home scrap from the manufacturing phase of metals production (8, 11). These feedstocks can serve as drop-ins or direct replacement for mined, virgin ores. The direct replacement makes possible the direct comparison of the GHG footprint for both types of production, and thus identification of GHG emissions reductions associated with replacement of one feedstock for the other. Similarly, the cost of raw materials for both production types can be identified and compared to estimate the financial implications of increased global adoption of secondary metal production replacing primary metal production. Scenarios for increased adoption of metals recycling from 2014-2050 were evaluated within the identified and projected market for metals, and used to identify the potential GHG emission reductions and financial impact of increased metal recycling.

## 

# Methodology

## 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) is what constituted the results.

The GHG emission reductions and financial impacts of greater adoption of recycled metals use in metal production globally from 2014-2050 were estimated using the Project Drawdown modeling framework (13). The basic unit of analysis is the Functional Unit of Measure (FU), defined in this case to be Million Metric Tons of metal produced. In the Project Drawdown parlance, the “conventional” technology was defined as primary production, so the conventional FU was one million metric tons of primary metals production, weighted by mass produced. The “solution” technology was defined as secondary production from recycled materials, so the solution FU was one million metric tons of metals produced from recycled materials. The GHG emissions impact and financial requirements for producing one Primary Production FU as well as Secondary Production FU were estimated for global scale for a selected group of metals. The basis of this analysis is replacement of Primary Production FUs with Secondary Production FUs in the context of the total global metals market.

The Total Addressable Market (TAM) in Functional Units was investigated for the period 2014 to 2050 for all practices involved with metals production. The TAM reflects the projected demand for metals and is a time series that represents the potential growth of both the primary and secondary production to meet the projected demand. The percent of the TAM that is met by secondary production in the year 2018 was designated as current adoption.

Three adoption scenarios were developed with different levels of increased adoption of secondary production compared to a reference case in which the relative proportion of overall production attributable to secondary production is at the level of current (2018) adoption. Though the analysis was for the complete time period of 2014 to 2050, historical data were used where possible. The most recent year with available complete adoption and TAM data is 2018, so this was considered the “current year” in the analysis. Between the base year (2014), where the analysis begins, and current year (2018), primary or historical data were used for analysis. After the current year, analysis of the metals system was done using projections. The GHG emission and financial impacts of each adoption scenario were evaluated and compared.

## Data Sources

Analysis of the global metals market was performed with focus on the metals produced and used in the largest quantities: iron and steel, aluminum, copper zinc, nickel, and manganese (5). This group of metals accounts for over 99% of the total annual global production of metals (5); complete percentages by global production quantity are included in the Supplemental Information. Iron and steel comprise the majority of global metals production, with raw steel production of 1.8 billion tonnes in 2018 and 1.9 billion tonnes in 2019 (5). The next largest production material is aluminum, with production of 63.6 and 64 million metric tonnes in 2018 and 2019, respectively (5).

For the analysis of the GHG emission and financial implications of increased adoption of recycled materials in global metals production, the key variables used were material feedstock costs, direct GHG emissions, and current adoption of secondary production. Data for these variables were obtained from various sources as documented below and in Supplemental Information. For the analyses conducted with the data, a weighting scheme was employed and data ranges were considered. The weighting was based on global production of metal types. Based on relative production amounts in 2018, the life-cycle assessment (LCA) data for the GHG emissions footprint of iron and steel production in the Primary Production FU were given approximately 95% of the weight, and emissions data for other metals were also weighted according to the remaining 5% distribution by production quantity. The same approach was used in the weighting scheme for the Secondary Production FU, as global secondary production of metals is not linearly proportional to total production: only 80% of secondary production is steel, 4% is aluminum, 1% is copper, and 15% are other metals. To provide for a level of sensitivity analysis, metals production estimates for low, mean/medium, and high scenarios were developed based on a range around the mean. In the model, the low-to-high range is a user-defined number of standard deviations above and below the mean of entered values (in this case one standard deviation), which allows for identification and elimination of outlier data points.

A literature review was performed to identify relevant LCAs that have been carried out for metals with an appropriate system boundary (cradle-to-gate production), from which the global warming potential or carbon emissions footprint data were compiled into Direct Emissions Factors for both the Primary and Secondary Production FUs. A weighted average was used to develop the Emissions Factors: all data sources indicating production GHG emissions for primary production of steel, for example, were averaged, and then assigned a 95% weight. All data with production emissions for primary aluminum were averaged and then assigned a total 3% weight, etc. for all metals. These were then summed across all metals to determine the direct emissions for one functional unit of primary production. The table of weights can be found in the Supporting Information Table SI-2, and raw data for emissions are in Tables SI-3 and SI-4.

The financial variables considered for this analysis were the costs of the raw materials, i.e. virgin or recycled materials per functional unit.Material feedstock costs are only one aspect of the total cost of production. Other relevant costs include, for example, end-of-life collection, sorting, processing, and transportation. Such costs were excluded from this analysis to avoid double counting of end-of-life management costs in scenarios with different levels of primary and secondary production, and to avoid comparison of functional units with dissimilar system boundaries. The cost data, therefore, represent costs for only one part of the metal production system. The costs of raw materials were obtained from market analysis sources (eg: Fastmarkets AMM) and again weighted by production quantity, using the same weighting methodology as emissions factors. The weights can be found in the Supporting Information Table SI-2, and raw data for costs are in Tables SI-5 and SI-6.

The variables employed, the mean and standard deviation values used for each in the meta-analysis, and the number of data points used are shown in Tables 1-3. Data used in the variable analysis as well as for the development of the TAM and adoption scenarios were identified by a literature review process considering authoritative sources including peer-reviewed articles, public sector and multilateral agencies and other non-governmental organizations. Sources of the estimates listed in Tables 1-3 are provided in Supplemental Information.

Table ‑: Current Adoption of Secondary Metals Production

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Variable Name** | **Unit** | **Mean/Value Used** | **Standard Deviation (SD)** | **Number of Estimates** |
| Current Adoption | MMt Metal Production | 1277 | 104.3 | 3 |

Table ‑: Material Feedstock Costs

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Variable Name** | **Unit** | **Weighted Average** | **Standard Deviation (SD)** | **Number of Estimates** |
| Virgin Material Feedstock Cost | US $/MMt Metal Production | 208.9 Million | 19.4 Million | 14 |
| Recycled Material Feedstock Cost | US $/MMt Metal Production | 660.4 Million | 21.8 Million | 17 |

Table ‑: Emissions Factors

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Variable Name** | **Unit** | **Weighted Average** | **Standard Deviation (SD)** | **Number of Estimates** |
| Primary Production Emissions Factor | Million t CO2-eq/MMt Metal Production | 2.140 | 0.185 | 18 |
| Secondary Production Emissions Factor | Million t CO2-eq/MMt Metal Production | 0.665 | 0.091 | 13 |

## Total Addressable Market / TLA

The total number of functional units of metals demanded globally represents the TAM, which includes all technologies and practices that provide the same function, in this case production of metals both primary and secondary. Market projections for global metal demand from a variety of sources were used for the analyses conducted.

TAM scenarios for metals production and recycling in future years were collected from external sources and incorporated into the model as possible futures. By collecting multiple projections from reliable sources representing a range of possibilities, the analysis was bounded by using statistical analysis to create an envelope of possible futures.

Historical TAM data were taken from global production reports in the USGS Mineral Yearbook Table 9 (14). Future TAM growth scenarios were developed using a linear regression analysis of the historical data, an S-Curve scenario, in which increased consumption accelerates due to economic growth and then saturates; and also using projections of metal production from growth rates from Elshkaki et al., (15), Van der Voet (3), and a Materials Economics (10) assessment of circular economy scenarios of various materials, including metals.

## 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.

### Project Drawdown Scenarios

Adoption scenarios were developed in terms of functional demand for the secondary production of metals at a global level from 2014 to 2050 using the best available data and forecast information. Defining an adoption scenario requires balancing projections of advocates for a particular technology who might provide projections that are implausibly optimistic, and projections of others that are more feasible but closely linked to the status quo and perhaps not optimistic enough. The current (2018) level of adoption of secondary production was defined as the *Reference Scenario*, which is discussed and defined in more detail below.The levels of adoption for three other scenarios were defined as follows:

* *Plausible Scenario*: metal production from recycled feedstocks is adopted at a realistically vigorous rate, derived from global metal market projections.
* *Ambitious Scenario*: adoption of metal production from recycled feedstocks is increased above conservative estimates to achieve a significantly more circular life cycle for metals
* *Maximum Scenario:* metal production from recycled feedstocks reaches maximum potential, fully replacing as much virgin feedstocks as possible based on availability of recycled feedstocks and market growth. This scenario is based on technical potential and is not necessarily representative of a realistic adoption without significant incentives or behavioral changes.

Inherent in this approach is the core assumption that all policy and financial levers, infrastructure development, and consumer behavior required to reach the specified levels of adoption will be implemented.

The specific features of the adoption scenarios were developed from review and analysis of current literature on forecasting of metal demand and production. Forecasted increases in demand and production per metal type from a recent investigation of the metals system to 2050 (15) were aggregated to represent the *Plausible Scenario.*  Two slightly more aggressive forecasts of adoption of secondary metal production from studies focused on optimizing circularity (3, 10) were averaged to represent the *Ambitious* *Scenario*, and the *Maximum Scenario* was based on forecasted scrap availability(10), so it is a technical feasibility scenario more than a realistic adoption scenario.

### Reference Case / Current Adoption

For the *Reference* (REF) scenario, adoption was fixed at the percent adoption of secondary production in the specified current year (2018). The percent of solution adoption was kept constant throughout the study period for the REF. As the market grows, the total implementation units adopted were considered to grow proportionally to maintain the percent adoption at its starting value. This serves as the baseline for comparison that the *Plausible, Ambitious*, and *Maximum* scenarios are compared against. A complete analysis is performed for the *Plausible* scenario, where the GHG emissions of both Primary and Secondary production for the TAM are calculated, as well as financial costs from the current year 2018 to 2050. These results are compared to the REF over the same time period, 2018-2050, and the difference between them is the cumulative GHG emissions reduction and net material feedstock cost (presented in 3. Results). The same approach is taken for the *Ambitious* and *Maximum* cases, which are compared to the same REF to estimate the impact of adoption of secondary production at increasing rates compared to the current level. The results are analyzed for 2018 to 2050 as the primary interest is the impact of varying levels of future adoption increases, so the focus is on using the adoption forecasts, not the historical data collected from 2014-2018, which is only an estimate of the current system.

## 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](http://www.drawdown.org)

## Integration

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

The global metals production system is one sub-system being considered within the broader Project Drawdown framework (13, 21); Project Drawdown’s approach and assessment of dozens of solutions across varying sectors has been a significant contribution to leading thought on how to analyze GHG emissions and climate change mitigation (22, 23, 24, 25). The GHG emission and cost implications of expanded adoption of secondary metals production with recycled feedstocks will be integrated into the larger waste system and complete Drawdown ‘System of Solutions’ (7, 13, 21).The results of this study reflect the impact of recycled metals as a standalone solution; however, the results may change when the solution is modeled as a component of the broader integrated, cross-sectoral system. Evaluating the impact of the accelerated adoption of solutions, like increased recycling of metals, in an integrated system provides a more balanced, complete assessment by taking into account system dynamics, such stock and flows, interaction effects, and avoiding possible double counting within system boundaries that have multiple technologies and practices being implemented in parallel. This is the aim of the Drawdown modeling approach and this study will be incorporated in future work. This standalone assessment nonetheless highlights the substantial potential impact of secondary metals production as an important Drawdown solution with direct implications on future atmospheric GHG concentrations.

# Results

## Adoption

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

Table ‑ World Adoption of the Solution

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Solution** | **Units** | **Current Year (2018)** | **World Adoption by 2050** | | |
| **Plausible Scenario** | **Ambitious Scenario** | **Maximum Scenario** |
| Recycled Metals | MMt Metal Secondary Production | 1,276 | 2,158 | 2,436 | 3,556 |
| *(% Market)* | 39.3% | 41.6% | 47.0% | 68.6% |

Figure ‑ World Annual Adoption 2020-2050

## Climate Impacts

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

Table ‑ Climate Impacts

|  |  |  |  |
| --- | --- | --- | --- |
| **Scenario** | **Cumulative Emissions Reduction** | **Emissions Reduction in 2030** | **Emissions Reduction in 2050\*** |
| *Gt CO2-eq. (2018-2050)* | *(Gt CO2-eq/year)* | *(Gt CO2-eq/year)* |
| ***Plausible*** | 4.57 | 0.13 | 0.18 |
| ***Ambitious*** | 12.10 | 0.31 | 0.59 |
| ***Maximum*** | 42.37 | 1.04 | 2.24 |

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).

## 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 ‑ Financial Impacts

|  |  |  |
| --- | --- | --- |
| **Scenario** | **Net Materials Cost\*** | **Lifetime Materials Cost\*\*** |
| *2018-2050 Trillion USD* | *2018-2050 Trillion USD* |
| ***Plausible*** | 1.53 | 1.841 |
| ***Ambitious*** | 4.092 | 4.731 |
| ***Maximum*** | 14.38 | 16.34 |

# Discussion

Some key limitations to achieving the *Maximum* scenario and going beyond the *Plausible* or *Ambitious* adoption scenarios for secondary production include limitations of the recycling process and infrastructure. Metals, though theoretically infinitely recyclable, have technical recycling limits due to introduction of impurities, dissipation, quality degradation, and other factors (2, 18) . Recycling of many metals is also limited by technical and financial obstacles to end-of-life collection (19). Collection is a major obstacle to increased adoption of secondary production, and there are various challenges to expanding metals collection. Not only is end-of-life collection expensive and difficult to implement well, even if collection increased the separation of raw materials is often design-limited. For many materials, such as e-waste, separation is expensive and often incomplete, resulting in impurities in recycling streams preventing valorization (19). Also, metal producers are not evenly geographically distributed, which means that there are additional transportation and shipping costs associated with increased collection to get materials to places where they can be processed for reuse (5, 19, 20).

Opportunities for meeting some of these challenges to metal recovery and reuse may exist in the form of producer take-back programs, shown to be successful in improving end-of-life collection or more regulation of end-of-life management (2). New technologies to valorize scrap are also an important opportunity to improve circularity. Many of these challenges might be addressed by design for disassembly or design for recovery, or by a transition from a focus on materials centric recycling to product centric recycling where entire products or components may be recycled without shredding and separation steps (1, 2). A focus on quantification and analysis of metal cycles would also allow for improved systems to address challenges in metal circularity (18).

Despite these limitations, the results of the analyses of the *Plausible* and *Ambitious* scenarios, though not close to maximizing total scrap availability, clearly indicate that even small increments of improved metal recovery for secondary production using recycled feedstocks have significant potential for GHG emission reductions. For example, increasing secondary production from 39% of the total metal production market to 42% over the next 30 years, which seems quite feasible given more widespread recycling programs globally, results in projection of over 4 Gt of CO2 emissions reduction from the metal industry. A further 5% increase in secondary production over the same time period increases the GHG reductions to over 12 Gt These potential GHG emissions savings represent an opportunity to make a significant contribution to meeting global warming control goals.

Beyond reduction of GHG emissions, reusing metal materials has other significant environmental benefits. Metal recycling reduces the amount of land disruption, soil and water pollution, and ecosystem impacts of mining (9).

The environmental benefits associated with an accelerated transition to recycled metals should not be outweighed by the increased feedstock costs. Though increased global adoption would cost between 1.5 and 4 trillion USD in the *Plausible* and *Ambitious* scenarios, where adoption increases to 42 and 47% of the TAM, they are only one component of the cost structure of metals production. Secondary production requires less energy, water and chemicals than primary production, all of which would result in financial savings. Additionally, there is less waste production, another avoided cost for producers. These costs, however, are highly variable by time and region, and so while they were not included in this analysis, would be a valuable subject for future analysis.

Analysis of the metals system and identification of opportunities for improving the circularity of metals through increased recycling is a first step and suggests paths for future work. The framework developed and identified in this analysis can be applied to analysis of smaller systems for a higher resolution look at specific materials (limiting the system boundary to only one type of metal), particular use phases like metals in buildings, or smaller geographical regions. Primary data availability may limit some of these efforts, emphasizing the need for more resources and studies to be focused on the metal life cycle to identify databases of global metal production from various feedstocks and identification of specific flows of materials.

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# Glossary

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

**PDS/ Project 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