Drawdown Reduction and Replacement Solutions (RRS) Model Framework and Guide

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Introduction

Project Drawdown is a living research and communications organization that assesses, maps, models, and describes the potential of the most substantive solutions to achieve drawdown by 2050. It is a collaborative effort of over 200 researchers, policymakers, businesses, thought leaders, and organizations developing a model to enable action and implementation throughout the world. Our common mission is to do our part in solving global warming, by enabling a new, regenerative 'business-as-usual' that has cascading benefits to human well-being in concert with nature, while training the next generation of global citizens and thought-leaders.

Project Drawdown defines and describes existing social, ecological, and technological solutions that reduce and sequester greenhouse gas (GHG) emissions in the atmosphere. It aims to provide a detailed, thoroughly researched description of solutions, their potential climate impact, and the financial returns they will have assuming vigorous increases in their adoption.

This guide will help you understand the methodology and the associated Excel model with the standardized greenhouse-gas (GHG) reductions by region for a particular action and the financial implications of those actions. Core models were developed to account for adoption pathways of different actions within constrained boundaries. The Reduction and Replacement (RRS) core model evaluates technologies and practices constrained by markets of functional demand; the Land Use (L-Use) core model by biophysical characteristics of different land types; and, the Food Systems (F-Sys) core model by estimated country-level per capita food consumption patterns. Sector-scale models are used to integrate solution-specific data within and across systems. See www.Drawdown.org for more details. Each model presents the difference in results between a reference (REF) scenario and a high growth Project Drawdown Scenario (PDS).

The model requires Microsoft Excel version 14 (2010) or later. You can see what Excel version you have by following these instructions: tinyurl.com/CheckOfficeVersion. The model has been tested in the Windows environment.

How to Use This Guide

This guide will provide information on use of the RRS Solution models which all use the same base model. The model has basic and advanced controls, so to allow basic and advanced users to get the information they need, each section requiring this distinction presents the information relevant for basic users first and then that for advanced users.

Feel free to use this guide as a reference only when necessary as the model was designed to be as self-explanatory as possible. Alternatively, you can read the Quick Start section alone, or that along with

The RRS Core Model section for an understanding of model operation. For detailed methodology, you can also review the Climate Calculations and Financial Calculations sections.

Quick Start

All Users

To get up and running with the models, you can follow the following steps:

1. Go to www.Drawdown.org and download the latest version of the solution model of interest. Open that model in Microsoft Excel. NOTE: models are currently unavailable online.
2. Enable Full model Operation:
    a. If the Software shows a message saying that the model was opened in 'Protected View', click on '**Enable Editing'**.

b. The model requires use of Excel Macros, so if the software asks you to enable macros, click '**Yes**'. If it says that 'active content has been disabled', click '**Enable Content**'.
c. Even if it doesn't, ensure that Macros are enabled. For help, see here: tinyurl.com/EnableMacros
d. Ensure Excel has Calculations automatically performed. For help, see tinyurl.com/TurnOnCalculation.

3. You will see a few tabs/sheets open. On the Welcome sheet you will see an introduction and a model as in Figure 1. Your next steps depend on whether you consider yourself a basic user who wants to adjust the most commonly-used variables, or an advanced user who wants access to all inputs and assumptions.

Basic Users

1. Click on Basic Controls.
2. On Basic Controls, you can
   a. Load a scenario by Selecting a saved scenario at the top left (Scenario to Customize) and clicking on "<<< Load Scenario Inputs"
   b. View key Scenario outputs at top right
   c. View and alter key Scenario inputs. Note the color scheme.

Advanced Users

1. Unhide Advanced Controls sheet
2. On Advanced Controls, you can
   a. View several model outputs
   b. View and alter several model inputs
   c. View statistical references values for model inputs
   d. Change adoption projections
   e. Change the years of analysis

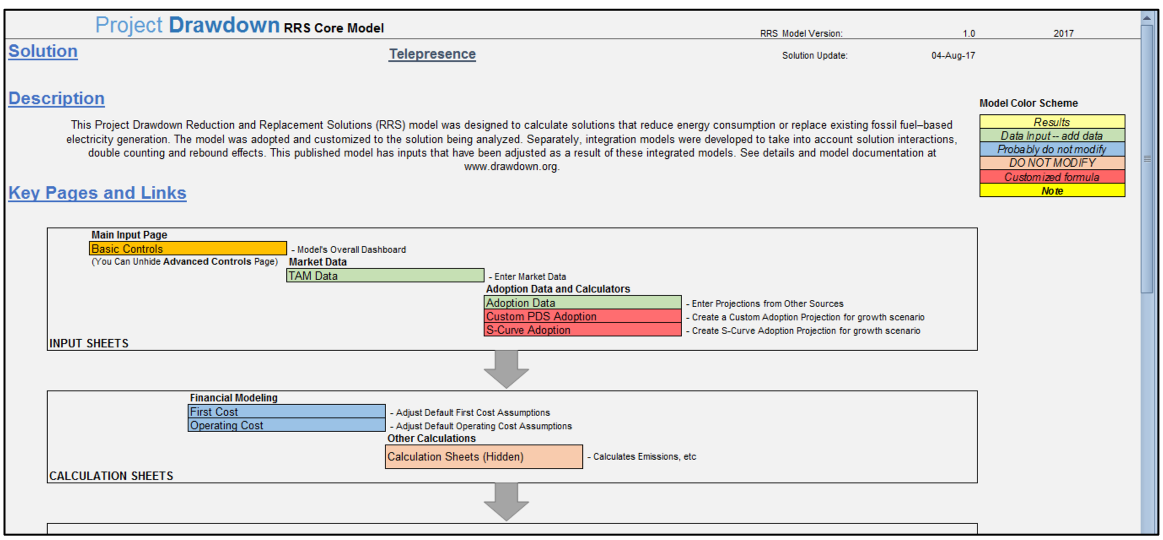

Figure 1 The Model Welcome Sheet

The RRS Core Model

The RRS core model is an Excel workbook that contains all of the data necessary to calculate the greenhouse-gas reductions and financial implications associated with a solution, and allows users to change important inputs and see how the results are impacted. The RRS core template model is a pre-designed framework to calculate results. Each model will have data for a specific solution filled in. As the model is a general model, you may see certain fields empty as they are irrelevant for that particular solution. The model presents for each solution key climate and financial outcomes such as:

1. Adoption Estimates
2. Total CO2-eq Emissions Reduction
3. Net First (implementation) Cost
4. Net Operating Cost Savings
5. Lifetime Cost/Savings

Basic Model Characteristics

Purpose: Provide a robust, defensible, scientifically-sound projection of the potential impact of optimistic global adoption of a climate-positive solution for global use
Model Target Scope: Global, but Regional Units as defined by Drawdown are accepted with lower priority
Base Year (Year 0): 2014
Model Unit: depend on solution, see section Units of Measure
Currency Unit: 2014 USD
Model Perspective: Agent Level, see section Units of Measure
Period of Analysis: 2015 – 2060
Unit System: Metric
Solutions Examined: See www.Drawdown.org

The core model specifies a color coded key to indicate which cells are editable and which cells have core, built-in calculations that should not be modified.

A. Light Yellow cells appear on the Main Controls Sheet and depict the RESULTS of the model	*Results*
B. Green cells indicate where data should be entered	*Data Input -- add data*
C. Blue cells indicate where data can be adjusted but probably doesn't need to be	*Probably do not modify*
D. Orange cells indicate results which should not be modified	*DO NOT MODIFY*
E. Researchers that customize cells should change the color to light red	*Customized formula*
F. Bright yellow cells with a message box provide more information	***Note***

Figure 2 Color Coding Used within Model

Model File Structure

Basic Sheets

The model will initially be presented with a simplified set of sheets for the basic user. By default, users will see at least the following tabs/sheets. :

- **Welcome** – this sheet presents the model, and the key sheets that basic users will be interested in.
- **Basic Controls** – A sheet where the most commonly used parameters of the model are available for editing, along with the overall Financial and GHG reduction results. This allows users of the model to easily change parameters and see their impact on results.
- **Detailed Results** – presents a full set of results from the model including all those presented on **Advanced Controls**, possibly a few more and several plots of the outputs.
- **Data Interpolator** – here users can interpolate and extrapolate data (TAM, Adoption) for missing years before entering into model.

- **Variable Summary** – shows the summary of the variables listed on **Variable Meta-Analysis** along with the values used in the model on **Advanced Controls**. This sheet is populated by pressing a button on the **Variable Meta-Analysis**, and although it comes filled with the summary of the data used by the Research Team, the user will only summarize the data on the sheet on which the button is pressed. Therefore, if the button on the empty public version of the **Variable Meta-analysis** sheet is pressed, no variables would be summarized.
- **Total Addressable Market (TAM) Data**— Provides an area for users to input various future market growth scenarios found in the literature. Automatically analyses the market growth scenarios provided and uses various regression fits (least squares, 2nd and 3rd degree polynomial, exponential) to estimate annual values for high, medium, and low market growth scenarios.
- **First Cost** – This sheet is used to calculate key assumptions and conversions to support the cost inputs related to acquisition, installation and implementation of the solution and conventional technologies/ practices. These assumptions include the learning rate, and the combined acquisition/ installation cost. This sheet also uses these assumptions to calculate the yearly (marginal) cost of installing new implementation units required to meet demand, the yearly (marginal) cost of installing replacement units, and a cumulative sum of all those costs for both the PDS scenario and the REF scenario. *For the most part, the user will not use this sheet; however, in cases where a customized first cost is required (i.e. when creating weighted average prices, accounting for regional deviations, etc.), users should use the placeholders on this sheet to perform requisite calculations.*
- **Operating Cost**– This sheet is used for calculating the comparative ongoing costs of the PDS scenario and the REF scenario. It provides placeholders for factoring and conversions for any data needed to determine the operating costs per functional unit of measure for both the solution and conventional technologies/ practices being replaced. *For the most part, the user will not use this sheet; however, in cases where a customized operating cost is required (i.e. when creating weighted average prices, accounting for regional deviations, etc.), users should use the placeholders on this sheet to perform requisite calculations.*
- **Net Profit Margin**– This sheet is used for calculating the comparative ongoing profit of the PDS scenario and the REF scenario. It provides placeholders for factoring and conversions for any data needed to determine the profit per functional unit of measure for the solution and conventional technologies/ practices being replaced. *For the most part, the user will not use this sheet; however, in cases where a customized profit is required users should use the placeholders on this sheet to perform requisite calculations.*

Advanced Sheets

Additionally, users can unhide and use the following sheets:

- **Advanced Controls** – A sheet where the major adjustable parameters of the model are prominently displayed, along with many Financial and GHG reduction results. This allows users of the model to easily change parameters and see their impact on results. These inputs represent the major assumptions used in the model, and can easily be over-written by users for using their own inputs or performing sensitivity analysis.
- **Adoption Data** – Provides an area for users to input various existing future adoption scenarios found in the literature. Generates a meta-analysis of the adoption scenarios provided and uses various regression fits (least squares, 2/3 degree polynomial, exponential) to estimate annual values for high, medium, and low adoption scenarios.
- **Carbon Price Analysis** – allows the user to simulate the change to the results shown on **Advanced Controls** when Carbon Prices are added to the economies represented by the results. Users can enter three cases of carbon prices than vary in simple or complex ways, and automatic calculators are added to calculate linear and fixed Carbon price curves. This sheet does not alter any other part of the model.
- **Custom PDS Adoption** — Contains placeholders to record customized PDS adoption scenarios based on the analysis of existing growth prognostications.

- **S-Curve Adoption** – provides tools for calculating several types of S-Curve to represent PDS adoption (including Logistic, Bass Diffusion Model and combinations of polynomials)
- **ScenarioRecord** – holds the inputs and outputs for each of the Project Drawdown Scenarios published in the Drawdown book and presented at www.drawdown.org. Advanced users can store and load their own scenarios.
- **Variable Meta-Analysis** – This sheet is used for collecting data on the various key assumptions that feed the controls used to calculate the key results. All variables used in the analysis are documented here. By entering data in the appropriate cells, a basic sensitivity analysis will be conducted based on standard deviations (S.D.) around the mean of all data collected. The results are reported as Mean, High, and Low, and appear on the **Advanced Controls** Sheet as reference values when deciding on the key inputs for the model. Models are presented with a hidden internal version where the raw data are expunged, and a public empty sheet where users can enter their own data. On **Advanced Controls**, users can select which sheet to use for statistics of each variable.
- **Custom REF Adoption** — Contains placeholders to construct customized REF adoption scenarios based on the analysis of existing reference prognostications.
- **Regions-Countries Sorting** – A tool to help sort country-level data by the Drawdown Regions.

Developer Sheets

Hidden in the model are the following calculation sheets which require a password to be shown (contact research@drawdown.org for details). These were hidden to protect the integrity of the model. With the password, developers can access these sheets by running the macro "showAllSheets".

- **Unit Adoption Calculations**– Contains all principal calculations related to the TAM and adoption of the solution in both the PDS and REF scenarios. As the principal calculations sheet, users will not be using this sheet directly. In some cases, users will benefit from the some of the data contained on this sheet, (e.g. the population and GDP projections used in the PDS and REF scenarios). *Changes should not be made here, and users should contact the Project Drawdown Research Team for more information on the calculations contained here.*
- **Variable Meta-analysis-DD**- this is the **Variable Meta-analysis** (as above) which has all variable data collected by the Project Drawdown team. The raw data are cleared from this sheet for legal reasons, but the summary statistics are maintained and are accessible from the **Advanced Controls** sheet.
- **Emissions Factors** – Contains the emission factors for the electric grid and primary fuel combustion. Emissions factors related to electricity generation (kg CO2 per kWh) for various regions and years for both CO2 and CO2-eq are derived from the projected energy generation mix and direct/indirect emissions factors by generation type taken from the Intergovernmental Panel on Climate Change (IPCC) AR5 Model Database, AMPERE v3 MESSAGE Base and 450 scenarios. Fuel emissions factors are calculated using the methodology recommended in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 2, Annex 1. *Changes should not be made here, and users should contact the Project Drawdown Research Team for more information on the calculations contained here.*
- **CO2 Calcs** – This sheet includes CO2 and other GHG metrics, including CO2 million metric tons (MMT) reduced by region and year, CO2-eq MMT by region and year, and parts per million (PPM) atmospheric CO2 avoided based on pulse-response functions that account for residence time of CO2. It combines CO2 and CH4 values provided into one ppm-CO2-eq value.
- **CH4 Calcs** – A sheet that includes CH4 metrics, including CH4 metric tons reduced by region and year and parts per billion atmospheric CH4 avoided based on pulse-response functions that account for residence time of CH4. This sheet is available, but is currently not used in the model calculations.
- **Helper Tables** – This sheet contains calculation summaries from several other sheets. *Changes should not be made here, and users should contact the Project Drawdown Research Team for more information on the calculations contained here.*

- **XLLANG** – This sheet stores Microsoft Office language codes which are used for storing and loading model scenarios which have formulae inputs. This is important since formulae are stored in the language of the Excel at the time of storage, and if opened in Excel with a different language, they may cause errors.

Additional Sheets

Some models may additional sheets containing solution-specific data from the literature or custom calculations that do not necessarily conform easily to the RRS Model structure. These are integrated into the relevant sections of the core template framework. These sheets are often used for unit conversions that are more complex than simple multiplication, or for collecting, combining or formatting raw data from several sources.

Units of Measure

To determine the impact potential of each solution requires a forecast of implementation based on estimated global functional demand for the period of study. Each model uses a **Functional Unit of Measure**, to best represent the outcome produced, or 'function' of the solution. This differs from the **Implementation Unit of Measure**, which best represents the number of acquisitions and installations, or 'implementations' of the solution. The two units are closely related: **the implementation unit produces the function that is in demand**. Here are some examples for each sector:

Table 1 Example Units Used for Selected Solutions

Sector	Solution	Functional Unit	Implementation Unit
Electricity Generation	Solar PV	Terawatt Hours (TWh) of electricity generated	Terawatts (TW) of capacity installed
Transportation	Electric Vehicles	Passenger kilometers (pkm) traveled	Number of vehicles in use
Waste & Material Reduction	Home Water Saving Measures	Cubic meters (m^3) of water demanded	Number of low flow fixtures installed
Buildings	LED Lighting	Petalumen-hours of LED Lighting	Petalumens of LED Lighting installed

Because of the diverse nature of the solutions there will be a particular *implementation unit* for each solution and the conventional technologies/ practices being replaced by the solution. In some cases, the *implementation unit* and *functional unit* will be the same, such as with million square meters of floor space adopted for smart glass/ glazing.

Functional units often overlap across a variety of solutions and conventional/technologies that produce the same function demanded. Solutions and conventional technologies/ practices that share the same functional unit are assumed to compete in the same market for functional demand. *For example, both solar photovoltaic (PV) farms and coal-fire plants generate electricity (in terawatt hours, or TWh) for the secondary energy market; therefore, the functional unit in question for both is TWh*.

Total Addressable Market

The total number of functional units demanded globally represents the **Total Addressable Market (TAM)**, which is composed of all technologies/practices (including the conventional mix and all possible solutions) that provide the same function. To continue with our example, the TAM for the secondary energy market consists of coal- and gas-fire plants, plus solar, wind, geothermal, biomass, nuclear, etc. Another example is LED Lighting, which exists in a global market for petalumen-hours of lighting supplied by multiple different technologies, including incandescent, halogen, HID, LFL, CFL, and LED lighting.

Estimated changes to the TAM are a function of population, economic conditions, policies and regulations, primary energy prices, infrastructural capacity, technologies costs and a host of other variables that impact individual and group preferences, such as culture, location, media, etc. Because many factors are difficult to model due to high variability across time and populations, population growth and economic conditions are the only factors considered to directly impact the size of the TAM in this study.

TAM is estimated for the period in question by entering data from the literature on the **TAM Data** sheet. Market prognostications from a variety of sources allow a meta-analysis to be conducted. There may need to be additional calculations required to derive the TAM in common functional units, in which case an additional sheet should be created and clearly explained with the results entered in **TAM Data**. Additionally, some sources used pre-2014 (or post-2014) projections of populations from the UN that were underestimates (or overestimates) compared to the newest UN estimates. For estimates of TAM (and Adoption, as discussed below) where the estimates are strongly correlated with population, the values are adjusted to harmonize with the 2014 UN population estimates assuming that the estimates were proportional to population.

TAM scenarios from external sources are classified as *Baseline*, *Conservative*, *Ambitious* or *Maximum* according to what they mean for the adoption of solutions and to how they compare with other projections. *Baseline* cases are typically considered "business-as-usual" scenarios with little to no adoption of solutions (e.g. IEA 6DS, or AMPERE RefPol scenarios). *Conservative* cases reflect scenarios with limited solution adoption (e.g. IEA 4DS, or the IPCC 550ppm scenarios). *Ambitious* cases are scenarios showing a vigorous, high-level of adoption (e.g. IEA 2DS, or IPCC 450ppm scenarios). *Maximum* cases are the highest plausible projections available in the literature reflecting massive global effort and focus on that specified technology or solution (e.g. IEA B2DS, or the Greenpeace Advanced Energy Revolution scenarios). *Note: the adoption of various actions may affect TAM size. E.g. adopting more reduction solutions, such as LED lighting and insulation, will reduce the electricity TAM; whereas more switch technologies, such as electric vehicles and heat pumps, will increase electricity demand. These effects are assumed to be accounted for in external market scenarios used.*

Each prognostication collected and incorporated into the model represents a future "possibility". There are a diversity of factors and assumptions used to create these scenarios, but no prognostication that can accurately predict any future global market. By collecting multiple prognostications from reliable sources representing a range of possibilities, we bound our assessment by using statistical analysis to create a reasonable facsimile of what the future may look like.

Users can select the desired PDS TAM from the **Basic Controls** and **Advanced Controls** sheets. Additionally, on **Advanced Controls** the user can select a different TAM for the historical and current adoption, and a different TAM for the REF case. If a group of TAMs is selected, then a curve fit of all the TAM's in that groups is used as input to the model. The type of curve fit (linear, 2nd order polynomial, etc.) is selected by the user on **TAM Data**.

Solution Adoption

To determine the impact potential of each solution requires a reasoned forecast of global adoption of said solution. Adoption is analyzed based on the functional demand for the solution at a global level and forecasted over the horizon from 2015 to 2060 using best available forecast data. Defining the adoption scenario requires walking a fine line between the projections of advocates of a particular technology who might provide projections that are implausibly optimistic, and others who are more plausible but not optimistic enough.

We used appropriate levels of adoption for each scenario where scenarios were defined as:

- **Plausible Scenario**: the case in which solutions on the Drawdown list are adopted at a realistically vigorous rate over the time period under investigation, adjusting for estimated economic and population growth.
- **Drawdown Scenario**: the case in which the adoption of solutions is optimized to achieve drawdown by 2050.

- **Optimum Scenario**: the case in which solutions achieve their maximum potential, fully replacing conventional technologies and practices within a limited, competitive market.

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

Base Year & Current Adoption

Adoption in functional units represents the proportion of the TAM 'captured' by the solution. *Base year adoption* represents the adoption of the solution in functional units in year 1 of the analysis, which is predetermined in this model to be 2014. It is an essential starting point required for the model to operate. Current adoption, on the other hand, represents the latest available adoption estimates of the solution based on the literature.

This value drives all of the global and regional adoption scenarios, and is added on the **Advanced Controls** sheet. Ideally reliable data for actual adoption will be available from the literature; however, where data was lacking, an extrapolation based on historic data or back-casting from projections was used to determine an assumed Current Adoption value.

Depending on the availability of data, the base year and current adoption value can be the same (i.e. if there is insufficient data on adoption after 2014); however, latest available data is preferred. Because the base year adoption is used to project the default REF adoption over each year of analysis using the assumption of fixed percent adoption of solution, when post-2014 data is introduced a custom REF scenario needs to be created.

Adoption Projections

PDS Adoption

The RRS model framework allows several different methods of inputting PDS adoption projections. The method most commonly used is by inputting *Existing Adoption Prognostications* from authoritative sources including peer-reviewed articles, public sector and multilateral agencies and other non-governmental organizations. These prognostications are interpolated/extrapolated[1] and converted to common units where necessary before being used in the model on **Adoption Data**.

When data were too sparse, adoption curves can be created based on published expectations of the growth of the solutions adoption. These curves can be linear (entered directly on **Advanced Controls**) or S-curves (entered on **S-Curve Adoption**), but in some cases, more complex curves can be customized for the solution and entered on the **Custom PDS Adoption** sheet. A custom adoption was also created if a source had an estimate of adoption that required many assumptions and calculations to convert to annual adoption values in functional units appropriate for input into the model. An example of this would be a source projecting that adoption would be "30% of the market" (TAM) by 2030 and "50% of the market" by 2050, thus requiring assumptions of the TAM in each year, and assumptions of adoption in the missing years.

Only the adoption sheets actually used in developing scenarios are shown on the **Welcome** sheet, and are unhidden in the downloaded model. Other adoption sheets are hidden by default.

Existing Adoption Prognostications

The **Adoption Data** sheet has annual projections from reputable sources of adoption of the solution, and they are classified as *Baseline*, *Conservative*, *Ambitious* or *Maximum* according to how they compare with other projections

[1] Annual projections were used when available, but in many cases only values in 5- or 10- year increments were published by sources. These were interpolated by curve fitting of the entire period under analysis on the Data Interpolator sheet. For projections with even less frequency, such as an adoption in 2014 and then values for 2030 and 2050, various approaches were used to estimate the missing years based on the type of growth expected in the literature. These approaches included linear connections between the published points, other types of curve fit between the points, and combination of projections from different sources when assumptions did not conflict.

and the market as a whole. *Baseline* cases are typically considered “business-as-usual” scenarios with little to no adoption of solutions (e.g. IEA 6DS, or AMPERE RefPol scenarios). *Conservative* cases reflect scenarios with limited solution adoption (e.g. IEA 4DS, or the IPCC 550ppm scenarios). *Ambitious* cases are scenarios showing a vigorous, high-level of adoption (e.g. IEA 2DS, or IPCC 450ppm scenarios). *Maximum* cases are the highest plausible projections available in the literature reflecting massive global effort and focus on that specified technology or solution (e.g. IEA B2DS, or the Greenpeace Advanced Energy Revolution scenarios). Users can select individual adoption cases or groups of cases (e.g. all *Baseline Cases*). If a group of cases is selected, then all the projections in that group are used to develop a curve fit or trendline of the type selected on **Adoption Data**, and based on analysis of the data (linear, 2nd degree polynomial, 3rd degree polynomial, or exponential). By default, the mean of the projections in the group each year are used, but by choosing ‘high growth’ or ‘low growth’, the values 1 standard deviation above or below the mean can be used instead. The global adoption can be defined on **Advanced Controls**, whereas each regional scenario must be manually entered at the top of **Adoption Data.**

Linear Projections

Linear projections are rarely true in real life, however, sometimes there is little information on the adoption of a solution other than a future percent estimate of adoption. In some cases, linear adoptions are used to represent the growth, but only when few other options exist. The user can see assumptions behind linear growth at the bottom of **Advanced Controls**, where curves can be specified at the global level, or for any of the Drawdown regions individually.

S-Curve Projections

S-curves are often the best choice to represent adoption for technologies as they start low, experience a period of high growth in the middle of the “S”, and slow down as market saturation is reached. Much research has illustrated the value of S-curves, and has analyzed the parameters best used for S-curve implementation. Several different types of S-curve are by default available in the model for each Drawdown region. On **S-curve Adoption**, the user can see the tools for calculating a *Logistic-based S-curve* at the top of the sheet, a *Bass-Diffusion S-curve* lower down, and an S-curve made of the *Combination of two Polynomial Curves* lower. Detailed explanations of the mathematics behind the S-curve modelling is available in the Appendices.

REF Adoption

For the default Reference (REF) scenario, adoption is typically fixed as the percent of base year or current adoption in the defined TAM. The percent of solution adoption remains constant throughout the study period. As the market grows, the total implementation units adopted grows proportionally to maintain the percent adoption at its starting value. It is acknowledged that this may not be a “business as usual” scenario considering changes taking place worldwide. However, as a counter-factual projection, it allows measurement of the full impact of the solution compared to a world where little to no efforts are made to adopt solutions.

For some cases where the literature strongly indicates a potential decline in the solution over time in a business-as-usual scenario, the default REF scenario would inaccurately represent the full impact of the solution. *For instance, there is a preponderance of literature indicating that Plant-rich Diets would decline in favor of higher meat consumption overall as a result of the increased wealth of hundreds of millions of low- and medium-income persons in China, India, and other developing countries. Assuming REF adoption as a fixed percent of TAM based on the current adoption of Plant-rich Diet would greatly misrepresent the impact of the solution.* In these cases, the REF scenario can be customized and justified in the technical reports for the solutions. Customized REF adoption is stored on the **Custom REF Adoption** sheet.

Sensitivity Analysis

Our goal is to present a robust scenario that is both optimistic and plausible. We endeavored to collect the best available information on adoption trends, inputting as many reliable data sources as possible. As adoption is a difficult thing to prognosticate, having more forecast data from reliable sources allows us to generate customized adoption cases that best reflects the data available.

On **Adoption Data**, users can automatically generate high, medium, and low scenarios based on a user-defined number of standard deviations (S.D.) above and below the mean. Users can change the sensitivity around the mean at the top of **Adoption Data**; currently, both the high and low scenarios default to 1 S.D. above/below the mean. This can be changed to fit tighter around the mean, or more loosely. This tool can be a useful in determining trends in regions where long-term prognostications are not known or reliable.

Variable Analysis

While the PDS Scenario is inherently optimistic, all other inputs that determine the climate and financial inputs are on the conservative side. One can think of our approach as "if adopted at this optimistically plausible level, the impacts would be *at least* x, y, and z."

To manage the collection and analysis of data on several variables and from several sources, the **Variable Meta-Analysis** sheet is used. The public sheet is by default, blank, and allows users to enter their own data which can be summarized on **Advanced Controls** by changing the Dataset for Statistics for the relevant variable to 'User-entered Data' as shown in Figure 3. The data collected by Project Drawdown uses hundreds of sources and includes some that are and others that are not open-source. These data points have been deleted from the model, but their statistical summaries along with source meta data have been saved on a sheet named **Variable Meta-Analysis-DD** which is available for developers who have the password to unlock the entire model. This password is available by contacting Project Drawdown at research@drawdown.org.

The Variable Meta-analysis tables will automatically calculate a low, mean/medium, and high estimate based on a range around the mean. This [low, high] range is a user-defined number of standard deviations above and below the mean of entered values. The default ranges are 1 standard deviation around the mean. Additionally, the tables exclude values falling outside 3 standard deviations of the mean by default.

Tables have a wealth of data for each variable, including the originator/author, link to the source, the Drawdown region and specific location in which the data point is derived, the source validation code (which represents the type of source), the license under which that source provides the data and, of course, the data point itself in the units originally reported. Data have been converted into the common units used throughout the model.

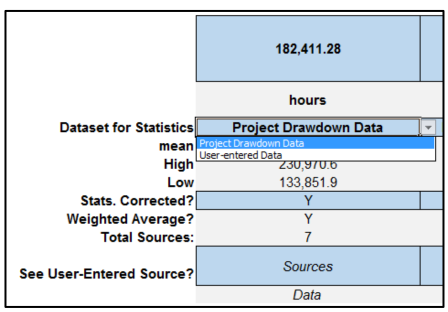

Figure 3 Changing the Source of Reference Data for a Variable using Tables on Advanced Controls

Model Integration

Integration is not performed directly in the RRS model due to the complexities involved and the uniqueness of each solution and each cluster or sector. Instead, integration is done manually with separate models, and is different for each sector. Integration was done to deal specifically with double counting, rebound effects and other dynamics among the systems modeled. This means that the impact of a cleaner grid on solution emissions or the impact of adoption of one solution on another are captured in individual RRS models but not in a way that allows tracing between models. Separate integration files were developed for that purpose. Integration was performed mainly at a sector level, particularly for clusters in the same sector (e.g. all urban passenger transport solutions were integrated separately from the other transportation solutions). But additional cross sectorial integration was performed for major interactions (e.g. as land use impacts of biomass and reduced food waste).

At the single model level, these integrations are virtually invisible since they are manifested as:

- Uniformity across solutions that share certain variables (e.g. all models use the same electricity emissions factors)
- Adjusted inputs where integration required it (e.g. reduced energy efficiency of some solutions as a direct result of other solutions partially causing some of the expected energy use reduction)
- Adjusted TAM or Adoptions (e.g. the TAM that is based on a feedstock may be adjusted if another solution affects that feedstock)

In most cases there was a prioritization process within each cluster according to the total benefit of adoption of solutions where tradeoffs were required. Within the materials sector, the priority was first to reduce waste, then recycle it, then use the remainder as best possible. For transportation, the priority was first active modes, then public transportation and other shared modes, then efficient vehicles. For the electricity generation, it was low cost non-regret solutions, then transition solutions and regret solutions. For buildings, the priority was based on low-cost and then building envelope inwards to appliances and building systems. The importance of this is that adoption of the higher priority solutions would increase to the maxima estimated from the literature, but that of lower priority solutions would likely decline at some time in the future, and this would be visible in the model's adoption graphs.

In a few cases, the solution models have labeled integration artifacts. Each model has space for several "Integrated Drawdown TAMs" which would be useful if the TAM's change as a result of adoption of other solutions. This is only used in some models. Additionally, some solutions have a text box explaining the variables on **Advanced Controls** that were adjusted as a result of integration. This would help explain the input choice made.

Updating the model inputs therefore should be done with the knowledge that there could be impacts on other solutions. The process is currently manual, and may be automated in the future.

Each sector has a description of its integration process. See www.Drawdown.org for more details.

Climate Calculations

Modelling considered emissions reductions due to more efficient fuel combustion, replacement of fuel use with electricity, more efficient electricity use, the replacement of fossil-fuel use with renewable sources of energy, and the prevention of GHG release. It covered emissions from the electric grid, fuel combustion, other direct sources and indirect sources. To allow for effective comparisons between different measures, we need a common set of outputs by region and year. The climate outputs of Drawdown RRS models are listed in Table 2.

Table 2 Summary of Climate Outputs of the Model

#	Name	Description	Unit
1	Total Emissions Reduction	Net greenhouse gas emissions difference between the REF scenario and any of the PDS scenarios	Gigatons of CO_2
2	Total Direct Emissions Reduction	The difference in greenhouse gas emissions from fuel, the electric grid, and other direct sources between the REF and PDS.	Gigatons of CO_2
3	Total Indirect Emissions Reduction	The difference in indirect greenhouse gas emissions between the REF and PDS.	Gigatons of CO_2
4	Annual Emissions Reduction: Maximum and in 2050	The maximum net greenhouse gas emissions difference between the REF and PDS in any year, and the difference in 2050 only respectively.	Gigatons of CO_2/year
5	Approximate PPM Equivalent in 2050	The change in CO2-eq atmospheric concentration in 2050 estimated as a result of the reduction in emissions due to solution adoption in the PDS compared to the REF.	Parts-per-million (PPM) CO_2-eq
6	Approximate PPM Rate of Change in 2050	The difference in PPM Equivalent in 2050 and 2049	Parts-per-million (PPM) CO_2-eq/year
7	Net Direct Energy Use Reduction	The reduction in direct energy use from the REF to the PDS and includes only grid energy and fuel energy use.	Exajoules

Climate Output Calculations

Below is described each climate output. Firstly, the notation used is defined in Table 3.

Notation

Table 3 lists the notation used for the climate math below.

Table 3 Variables Used in the Model Math

Variable	Description	Note
y, t, i	Years: y- year of emission, t- some time after emission, i-year of analysis	For analysis: $i = y + t$
$[y_1, y_{max}]$	The range of years of the analysis	[2020,2050] in the model
gas	Anyone of the set of all gases examined in the model,	$gas \in \{CO_2eq, CO_2, CH_4, N_2O\}$
R_y^{gas}	Total reduction in emissions of gas for year y	In Gt CO_2-eq
$Grid\Delta_y$	Reduction in CO_2eq grid emissions for year y	In Gt CO_2-eq
$Fuel\Delta_y$	Reduction in CO_2eq fuel emissions for year y	In Gt CO_2-eq
$ODirect\Delta_y$	Reduction in CO_2eq other direct emissions for year y (that is, not grid or fuel emissions)	In Gt CO_2-eq
$Indirect\Delta_y$	Reduction in CO_2eq indirect emissions for year y	In Gt CO_2-eq
$Grid\Omega_y$	Reduction in grid energy usage for year y	In Exajoules/ EJ
$Fuel\Omega_y$	Reduction in fuel energy usage for year y	In Exajoules/ EJ
$NAFU_y$	Net annual functional units, the solution adoption in the PDS minus the solution adoption in the REF in year y	In Functional Units
$NAIU_{con,y}$, $NAIU_{sol,y}$	Net annual implementation units of the conventional (or solution) is the conventional adoption in the REF minus the conventional adoption in the PDS in year y (or solution adoption in the PDS minus the solution adoption in the REF) in year y	In implementation Units
C_{con}^e	Electricity consumption of the conventional technology per functional unit, assumed constant	In TWh per Functional Unit
C_{sol}^e	Electricity consumption of the solution technology per functional unit, assumed constant	In TWh per Functional Unit
η_{sol}^e	Solution efficiency factor for electricity usage (compared to conventional) , assumed constant	In %
EF_y^g	Emissions factor of the grid in year y	In MMT CO_2-eq per TWh of electricity supplied
fc	The fuel used by the conventional technology	
fs	The fuel used by the solution	
C_{con}^{fc}	Consumption of fuel fc by conventional technology per functional unit, assumed constant	In Liters per Functional Unit or TJ per Functional Unit
η_{sol}^{fc}	Solution efficiency factor for fuel consumption (compared to conventional) in units of conventional fuel fc, assumed constant	In %
EF^{fc}	Emissions factor of the fuel used by the conventional technology, assumed constant	In t CO_2-eq / TJ or t CO_2-eq / liter
EF^{fs}	Emissions factor of the fuel used by the solution technology, assumed constant	In t CO_2-eq / TJ or t CO_2-eq / liter

Variable	Description	Note
CF_{fc}^{fs}	A conversion factor to convert fuel units of solution fs to units of fuel fc if they have different units, otherwise = 1.	In TJ/ liter or Liter/ TJ
$CFTJ^{fc}$	A conversion factor to convert fuel units of fuel fc to Terajoule if they are not.	In Liter/ TJ
EF_{con}^{OD}	Other direct emissions factor of the conventional technology besides grid and fuel emissions	In t CO_2-eq / functional unit
EF_{sol}^{OD}	Other direct emissions factor of the solution technology besides grid and fuel emissions	In t CO_2-eq / functional unit
EF_{con}^{Ind}	Indirect emissions factor of the conventional technology	In t CO_2-eq / functional unit or t CO_2-eq / Implementation Unit
EF_{sol}^{Ind}	Indirect emissions factor of the solution technology	In t CO_2-eq / functional unit or t CO_2-eq / Implementation Unit
$G_{gas}(y,t)$	A discrete pulse-response function representing the atmospheric impact of gas in t years after release in year y	In Million Metric tons (MMt)
$A_{gas}(i)$	Total atmospheric loading of gas in year i	In MMt
M_{gas}	Molar mass of gas	In gram per mole
P_{gas}	Atmospheric concentration of gas in base year	$P_{CO_2} = 400\ PPM$, $P_{CH_4} = 1800\ PPB$, $P_{N_2O} = 320\ PPB$
$\alpha_{gas}(y), \beta_{gas}(y)$	Increase in atmospheric concentrations of gas in year y as a result of additional emissions after base year	
ΔF_{gas}	Change to radiative forcing of gas	

Total Emissions Reduction

This is the most important climate result which is used to compare the impact of each solution. It is assumed that emissions reduction is linear in the number of functional units adopted, and that the emissions efficiency of the solution is a fixed value. We therefore exclude any potential improvements in the solution technology over time and use the emissions intensity at the time of data gathering.

Total emissions reduction is a linear sum of the emissions reduction from each modelled source: grid, fuel, other direct sources and indirect sources.

$$\sum_{y=y_1}^{y_{max}} R_y^{CO2e} = \sum_{y=y_1}^{y_{max}} \left[Grid\Delta_y + Fuel\Delta_y + ODirect\Delta_y + Indirect\Delta_y\right] \tag{1}$$

Grid Emissions Reduction

There are three methods for calculating the grid emissions reduction depending on the solution type and data availability. For clean energy solutions, such as Onshore Wind or Solar PV, where the current grid supply is replaced, the grid reduction is simply all the grid emissions that would have resulted on the conventional grid, but instead is not produced at all by the solution. This is shown below.

$$Grid\Delta_y = \frac{NAFU_y \cdot EF_y^g}{1000} \tag{2}$$

In other cases where the solution may be using some of the conventional grid electricity (such as Smart Glass which reduces electricity demand, or Electric Vehicles which increase it), there are two approaches. Firstly, we may use the electrical consumption of the conventional and the electrical efficiency of the solution versus the conventional.

$$Grid\Delta_y = \frac{NAFU_y \cdot C_{con}^{e} \cdot \eta_{sol}^{e} \cdot EF_y^{g}}{1000} \tag{3}$$

Alternatively, we may use the electricity consumption of both the conventional and solution.

$$Grid\Delta_y = \frac{NAFU_y \cdot (C_{con}^{e} - C_{sol}^{e}) \cdot EF_y^{g}}{1000} \tag{4}$$

Fuel Emissions Reduction

Fuel emissions reduction is calculated allowing for different fuel units in the model for ease of user understanding. Some fuels, particularly transport fuels were presented in liters, and others were in terajoules (TJ). This required a conversion when two fuels of different units were used together.

$$Fuel\Delta_y = \frac{NAFU_y \cdot C_{con}^{fc} \cdot \left\{EF^{fc} - EF^{fs} \cdot CF_{fc}^{fs} \cdot (1 - \eta_{sol}^{fc})\right\}}{10^9} \tag{5}$$

Other Direct Emissions Reduction

Besides, grid electricity and fuel usage changes, use of solutions may result in reductions of other direct emissions. If the solution directly limits or prevents emissions in some way other than from reduced electricity or fuel use (for example refrigerant management prevents the release of F-gases into the atmosphere) then this is included. Other direct emissions are input in the model as total emissions per functional unit for the conventional and solution approaches separately on **Advanced Controls**. This is illustrated below. Additional emissions reduction for CH_4 and N_2O only can be additionally input as a reduction per functional unit adopted. These are simply added to the expression below after applying user-selected global warming potential sources.

$$ODirect\Delta_y = \frac{NAFU_y \cdot \{EF_{con}^{OD} - EF_{sol}^{OD}\}}{10^9} \tag{6}$$

Indirect Emissions Reduction

This reflects the indirect emissions for the conventional technologies/practices and the solution. These include lifecycle emissions outside of the use-phase of the product (e.g. during manufacturing, transport, and disposal). We provide 2 approaches for calculation depending on whether the data are collected per functional unit or per implementation unit. Approach 1, for data entered per functional unit, is

$$\mathrm{Indirect}\Delta_y = \frac{NAFU_y \cdot \{EF_{con}^{Ind} - EF_{sol}^{Ind}\}}{10^9} \tag{7}$$

And approach 2 (data entered per implementation unit) is:

$$\mathrm{Indirect}\Delta_y = \frac{NAIU_y \cdot \{EF_{con}^{Ind} - EF_{sol}^{Ind}\}}{10^9} \tag{8}$$

Total Direct Emissions Reduction

Total direct emissions are calculated similarly to the total emissions reduction except that we only include the direct components of emissions reduction.

$$\sum_{y=y_1}^{y_{max}} \left[Grid\Delta_y + Fuel\Delta_y + ODirect\Delta_y \right] \tag{9}$$

Total Indirect Emissions Reduction

$$\sum_{y=y_1}^{y_{max}} Indirect\Delta_y \tag{10}$$

Annual Emissions Reduction

The max annual emissions reduction, and reduction in 2050 are taken directly from the calculations above for the relevant year.

Approximate PPM Equivalent

Reductions in greenhouse gases relative to the reference case for different measures need to be converted into changes in atmospheric concentrations of greenhouse gases. Here we will be using a simple metric of parts per million (ppm) CO_2-equivalent, which combines the warming effect of all GHGs into a single measure.

To translate emissions of different greenhouse gases (and changes in albedo forcings) into ppm CO_2-eq requires converting emissions into atmospheric concentrations, modeling the lifetime of these gasses in the atmosphere, converting atmospheric concentrations into radiative forcing, and converting radiative forcing into ppm CO2-eq.

CO_2, N_2O, and CH_4 have vastly different atmospheric lifetimes. For this discussion, the atmospheric lifetime functions from (Joos & Bruno, 1996; Joos, et al., 1996) are used for CO_2, CH_4, and N_2O. The results of these models can be fit to a set of mathematical equations, which model the response to a discrete one-time emissions pulse released in year y after t years (Myhrvold & Caldeira, 2012; Forster, et al., 2007):

$$G_{CO_2}(y,t) = 10^3 \cdot R_y^{CO_2} \cdot \left[0.217 + 0.259e^{-t/172.9} + 0.338e^{-t/18.51} + 0.186e^{-t/1.186}\right] \tag{11}$$

$$G_{CH_4}(y,t) = 10^3 \cdot R_y^{CH_4} \cdot e^{-t/12} \tag{12}$$

$$G_{N_2O}(y,t) = 10^3 \cdot R_y^{N_2O} \cdot e^{-t/114} \tag{13}$$

We have excluded, for simplicity, the requirement that $t > 0$. These discrete pulse-response functions are integrated to determine total atmospheric loading, A, in a year i after the emissions pulse of each gas based on specified emissions in each year y: [2]

$$A_{gas}(i) = \sum_{y=2015}^{i} G_{gas}(y, i-y) \tag{14}$$

These emissions are converted into atmospheric concentrations (in PPM) based on the ratio of moles of gas emitted to total moles in the atmosphere:

[2] Our analysis starts at year 2015, but the model focusses on results only between years 2020 and 2050 inclusive. In some cases though results for 2015 to 2050 are shown for reasons explained in the descriptions of relevant results.

$$\alpha_{gas}(i) = \frac{10^6 \cdot \left(\frac{10^{12} \cdot A_{gas}(i)}{M_{gas}}\right)}{(1.8 \cdot 10^{20})} \tag{15}$$

where M_{gas} is the molar mass of the gas in question in gram per mole.

For the purposes of this analysis the radiative forcing functions from the latest Intergovernmental Panel on Climate Change (IPCC) report are used (Myhre, et al., 2014). We drop the year parameter for simplicity. One simple model of the radiative forcing of an increase of CO_2 in the atmosphere (in parts per million – ppm):

$$\Delta F_{CO_2} = 5.35 \cdot \ln \frac{\left(P_{CO_2} + \alpha_{CO_2}\right)}{P_{CO_2}} \tag{16}$$

Here P_{CO_2}represents the initial concentration of CO_2 in the atmosphere in the base year, while α_{CO_2}represents the additional CO_2 added for any given scenario above the REF in ppm. For the purposes of this analysis, P_{CO_2} is set at 400 ppm, the approximate value in the base year.

According to the IPCC, the direct radiative forcing of a given increase of CH_4 in the atmosphere (in parts per billion – ppb) can be approximated by (Myhre, et al., 2014):

$$\Delta F_{CH_4,direct} = 0.036\left(\sqrt{P_{CH_4} + \beta_{CH_4}} - \sqrt{P_{CH_4}}\right) - f\left(P_{CH_4} + \beta_{CH_4},\ P_{N_2O}\right) + f\left(P_{CH_4}, P_{N_2O}\right) \tag{17}$$

$$\Delta F_{N_2O} = 0.12\left(\sqrt{P_{N_2O} + \beta_{N_2O}} - \sqrt{P_{N_2O}}\right) - f\left(P_{CH_4}, P_{N_2O} + \beta_{N_2O}\right) + f\left(P_{CH_4}, P_{N_2O}\right) \tag{18}$$

Where

$$f(M, N) = 0.47 \ln(1 + 2.01 \cdot 10^{-5}(MN)^{0.75} + 5.31 \cdot 10^{-15} M(MN)^{1.52}) \tag{19}$$

In this equation P_{CH_4} is the initial concentration of atmospheric CH_4, while β_{CH_4} is the addition being evaluated. P_{N_2O} is the initial concentration of nitrous oxide, which is also a component of the atmospheric chemistry of CH_4. For this analysis, P_{CH_4} is set to 1800 ppb and P_{N_2O} is set to 320 ppb, reflecting atmospheric concentrations at the base year.

CH_4 emissions are also responsible for indirect radiative forcing due to their secondary effects on tropospheric ozone formation and stratospheric water vapor concentrations (Myhre, et al., 2014). This is a complex process, but based on a recommendation by Drew Shindell (personal communication) we model these secondary effects as multiplying the radiative forcing from CH_4 by roughly 1.5, such that total radiative forcing equals:

$$\Delta F_{CH_4} = 1.5 \cdot \Delta F_{CH_4,direct} \tag{20}$$

Combined radiative forcing from all factors can be calculated as:

$$\Delta F_{total} = \Delta F_{CO_2} + \Delta F_{CH_4} + \Delta F_{N_2O} + \Delta F_{other} \tag{21}$$

where ΔF_{other} is radiative forcing from halocarbons, albedo, black carbon, aerosols, and other factors. Although it is included here, no model incorporates ΔF_{other}. Future forcing trajectories for non-CO_2 gasses in the REF scenario will be taken from the common forcing set for the RCP6 scenario CMIP5 model runs for the IPCC Fifth Assessment Report.

Finally, ΔF_{total} can be translated into an atmospheric CO_2 ppm equivalence (P_{co_2eq}) that combines both CO_2 and non-CO_2 forcings by estimating the equivalent amount of atmospheric CO_2 needed to result in the same net radiative forcing:

$$P_{CO_2eq} = P_{CO_2} e^{\Delta F_{total}/5.35} \tag{22}$$

Approximate PPM Rate of Change

The rate of change of the CO2 concentration is just the difference between the concentration in year y minus that of year $y-1$.

Net Direct Energy Use Reduction

$$\sum_{y=y_1}^{y_{max}} \left[Grid\Omega_y + Fuel\Omega_y \right] \tag{23}$$

Grid Energy Reduction

There were two methods for calculating the grid energy reduction depending on the data availability.

Approach 1 is

$$Grid\Omega_y = \frac{3600 \cdot NAFU_y \cdot C_{con}^{e} \cdot \eta_{sol}^{e}}{10^6} \tag{24}$$

Approach 2 is

$$Grid\Omega_y = \frac{3600 \cdot NAFU_y \cdot (C_{con}^{e} - C_{sol}^{e})}{10^6} \tag{25}$$

Fuel Energy Reduction

The fuel energy reduced is calculated taking into account the liters used as fuel for the conventional technology. The conversion factor, which is specific to each fuel type, converts the units to TJ as necessary.

$$Fuel\Omega_y = \frac{NAFU_y \cdot C_{con}^{fc} \cdot CFTJ^{fc} \cdot \eta_{sol}^{fc}}{10^6} \tag{26}$$

Financial Calculations

To effectively consider the factors that may drive or inhibit the adoption of the Project Drawdown solutions requires a standardized set of financial metrics to be assessed and presented for each solution. These key metrics produced by the models are shown in Table 4. Calculating and presenting these standardized output data will enable a more complete assessment of the potential for adopting and scaling each solution. This allows a more equivalent comparison of financial implications of adoption, and an ability to calculate a composite financial narrative of the implications of broad global adoption of all or any subset of the solutions.

Table 4 Summary of Financial Outputs of the Model

#	Name	Description	Unit
1	Cumulative First Cost	The total, undiscounted first cost of acquiring and installation of new and replacement solution units in the PDS implemented during the period of analysis	Billion 2014$US
2	Marginal First Cost	The total, undiscounted first cost of the solution in the PDS minus the total undiscounted first cost of the solution in the REF implemented during the period of analysis	Billion 2014$US
3	Net Operating Savings	The total undiscounted operating cost of both solution and conventional in the REF minus that in the PDS during the period of analysis	Billion 2014$US
4	Lifetime Operating Savings	The total undiscounted operating cost of both the solution and conventional in the REF minus that in the PDS for all years of life of implementation units purchased during the period of analysis	Billion 2014$US
5	Lifetime Cashflow Net Present Value (NPV)	The sum of all discounted cashflows (first and operating costs) in the PDS minus those in the REF for the entire implementation unit lifetime. Two different measures are provided: one counts the cashflows for a single unit, and the other looks at all units installed during the analysis period. In the RRS Core model, we additionally calculate profit cashflows not only cost savings.	Billion 2014$US
6	Average Abatement Cost	A measure of the relative cost of reducing emissions using this solution over its lifetime, which equals the ratio of the *Lifetime Cashflow NPV* to the *Total Emissions Reduction*.	2014$US/ tCO2-eq
7	Payback Period	The number of years that one solution implementation requires for the operative savings, relative to the conventional to cover the initial cost. Four different metrics are calculated depending on whether the marginal first cost is used and whether discounting is applied. Additionally, the RRS Core model calculates these four metrics using profit cash flows totaling 8 payback metrics.	Years

Financial Output Calculations

Each financial output is described below.

Notation

See in Table 5, the notation used for the financial calculations below.

Table 5 Summary of Variables used in Financial Calculations

Variable	Description	Note
y, t, i	Years: i- year of installation, t- some time after installation, y- year of analysis	For analysis: $y = i + t$
$[y_1, y_{max}]$	The range of years of the analysis,	[2020,2050] in the model
y_b	The base year or analysis	= 2014
CFC_y, MFC_y	Cumulative First Cost and Marginal First Cost in year y respectively.	In Billion 2014$US
$ADF_{sol,y}^{PDS}, ADF_{sol,y}^{REF}$	Total adoption in functional units of the solution in year y in the PDS and REF respectively.	In functional units
$ADF_{con,y}^{PDS}, ADF_{con,y}^{REF}$	Total adoption in functional units of the conventional technology in year y in the PDS and REF respectively.	In functional units
$NAFU_y$	Net annual functional units, the solution adoption in the PDS minus the solution adoption in the REF in year y	In functional Units
$NAIU_{con,y}$, $NAIU_{sol,y}$	Net annual implementation units of the conventional (or solution) is the conventional adoption in the REF minus the conventional adoption in the PDS in year y (or solution adoption in the PDS minus the solution adoption in the REF) in year y	In implementation Units
AU_{sol}, AU_{con}	Average annual use of the solution and conventional respectively, or the number of functional units provided by a single implementation unit in a year.	In functional units
$RU_{sol,y}^{PDS}, RU_{con,y}^{PDS}$	Implementation units installed in the PDS to replace previously installed units that have reached their end of life in year y for the solution and conventional respectively	In implementation units
$RU_{sol,y}^{REF}, RU_{con,y}^{REF}$	Implementation units installed in the REF to replace previously installed units that have reached their end of life in year y for the solution and conventional respectively	In implementation units
$FC_{sol,y}^{PDS}, FC_{sol,y}^{REF}$	The first costs of the solution in year y in the PDS and the REF scenarios respectively.	May be different in each year and in different scenarios depending on learning rates. In 2014$US/ implementation unit
$FC_{con,y}^{PDS}, FC_{con,y}^{REF}$	The first costs of the conventional technology in year y in the PDS and the REF scenarios respectively.	May be different in each year and in different scenarios depending on learning rates. In 2014$US/ implementation unit
$\theta_{i,t}, \pi_{i,t}$	Total operating costs of conventional and solution units respectively in the t^{th} year after installation of units initially in year i. We include replacements (assumed instantaneous at end of life) up to y_{max}, but the operating costs are independent of the replacement number.	In 2014$US.
$VOC_{sol,t}, VOC_{con,t}$	Variable operating costs of the solution and conventional technology respectively t years after initial installation of	In 2014$US/ functional unit

Variable	Description	Note
	the unit. Variable costs are realized per functional unit. In most cases, the costs are the same every year, and the t subscript falls away. Since we include (instantaneous) replacement units, these costs are defined to repeat for those units (so for a solution with 5 years lifetime $VOC_{sol,6} = VOC_{sol,1}$.	
$FOC_{sol,t}, FOC_{con,t}$	Fixed operating costs of the solution and conventional technology respectively t years after installation of the unit. Fixed costs are realized per implementation unit. In most cases, the costs are the same every year, and the t subscript falls away. Since we include (instantaneous) replacement units, these costs are defined to repeat for those units (so for a solution with 5 years lifetime $FOC_{sol,6} = FOC_{sol,1}$.	In 2014$US/ implementation unit
L_{sol}, L_{con}, L	Lifetime of the solution technology, conventional technology, and a generic technology respectively.	In years
r	Discount rate	In %

Cumulative First Cost

First Cost is the cumulative cost to the agent (the "consumer" based on agency level -> individual, community, buildings, companies, utilities, cities, etc.) of acquiring and installing the solution (see the Assumptions for more details on the costs). The model provides the option to define a learning curve for both the conventional and the solution if relevant. Details on how learning rates work and on how to use the built-in learning rate calculators can be found in the Appendices.

The total first cost of all solution implementation units in the PDS is calculated for this output without regard for discounting or for units that would have been purchased anyway in the REF. We therefore take the annual adoption increase in functional units and convert them to implementation units (by dividing by the average annual use) add on any replacement units in that year and multiply by the first cost of the solution in the PDS in that year.

Average annual use is used to determine the number of implementation units required to meet demand based on the adoption trajectory determined. This is only possible based on our simplified assumption that supply will always meet demand.

The Average Annual Use and the Lifetime Replacement have a direct impact on the first cost of the conventional technologies/practices and solution. The Average Annual Use determines how many implementation units are **required** on a year-to-year basis to meet changes in functional demand. Lifetime Replacement determines when a replacement implementation unit needs to be purchased. First cost results are presented as the total cost to achieve the emission reduction presented for 2020-2050, but since units installed in 2015 onwards contribute to those reductions, the results present 2015-2050 first costs. Hence $y_b + 1 = 2015$ and $y_{max} = 2050$.

$$\sum_{y=y_b+1}^{y_{max}} \left[CFC_y\right] = \sum_{y=y_b+1}^{y_{max}} \left[FC_{sol,y}^{PDS} \cdot \left\{\frac{ADF_{sol,y}^{PDS} - ADF_{sol,y-1}^{PDS}}{AU_{sol}} + RU_{sol,y}^{PDS}\right\}\right] \tag{27}$$

Marginal First Cost

The marginal first cost is total additional first cost of acquiring, adopting, installing and implementing the solution in the PDS scenario less the cost of (low) adoption of the solution and conventional technology growth under the

REF scenario, including replacement unit costs of units at end of life as appropriate. Note that the cost of the solution adoption that would have occurred anyway in the REF scenario is important to be included since the unit costs could be different if a learning rate is used. As learning rates reduced first costs according to production, the greater production in the PDS scenario can lead to lower first costs in the PDS for the solution technology.

$$\sum_{y=y_1}^{y_{max}}[MFC_y] = \sum_{y=y_1}^{y_{max}}\left[\left(FC_{sol,y}^{PDS} \cdot \left\{\frac{ADF_{sol,y}^{PDS} - ADF_{sol,y-1}^{PDS}}{AU_{sol}} + RU_{sol,y}^{PDS}\right\}\right) - \left(FC_{sol,y}^{REF} \cdot \left\{\frac{ADF_{sol,y}^{REF} - ADF_{sol,y-1}^{REF}}{AU_{sol}} + RU_{sol,y}^{REF}\right\} + FC_{con,y}^{REF} \cdot \left\{\frac{NAFU_y - NAFU_{y-1}}{AU_{con}} + RU_{con,y}^{REF}\right\}\right)\right] \tag{28}$$

Note that the expression above is based on the relation defined below.

$$\left(ADF_{sol,y}^{PDS} - ADF_{sol,y-1}^{PDS}\right) = \left(ADF_{sol,y}^{REF} - ADF_{sol,y-1}^{REF}\right) + \left(NAFU_y - NAFU_{y-1}\right) \tag{29}$$

This is based on the definition of the Net Annual Functional Unit (NAFU) as shown below. This assumes that there are only two technologies supplying the market: the solution and conventional technologies. This is appropriate if one defines the solution and conventional technologies to be mutually exclusive and exhaustive of the market options.

$$NAFU_y = \left(ADF_{sol,y}^{PDS} - ADF_{sol,y}^{REF}\right) = \left(ADF_{con,y}^{REF} - ADF_{con,y}^{PDS}\right) \tag{30}$$

Net Operating Savings

The case for adopting and scaling the Drawdown solutions will be influenced by a clear financial picture of the ongoing operational costs, both year over year and cumulative. Comparing the operational costs of adopting solutions under the PDS scenario with those of the REF scenario will indicate the potential return on investment, including the payback period. The cumulative difference in operating costs between the PDS scenario and the REF scenario is presented on **Advanced Controls** as **Net Operating Savings** (see the Assumptions for more details on the costs).

The operating costs for the conventional technologies/practices and the solution in question are associated with cost to derive the function demanded annually. In most cases, it is assumed that the operating cost per functional unit corresponds to the consumer price, usually the cost of the energy required to generate the function. *For example, the operating cost of rooftop solar PV is the adjusted price of electricity at the household level. This will be compared to the full price of electricity from the electric grid to produce the net cost/savings.*

In cases where the agent is the producer of the functional demand, i.e. a utility, the operating cost is also defined as the price to the consumer by using the simplified assumption of a perfect market. *For example, a utility-scale solar PV farm generates electricity for the secondary energy market and sells this electricity to consumers. The price paid by the consumer per TWh represents the total revenue generated and includes all operating and maintenance costs, as well as profit.*

In all cases, prices will be assumed constant throughout the period unless reliable and compelling data are discovered and documented, in which case a weighted average price can be calculated in the space provided on the sheet **Operating Cost**.

Other factors or variables of interest may be material to the calculation of the operating cost. If these inputs are material to the overall calculation, additional variables can be used on the **Variable Meta-Analysis** sheet and factored together in **Operating Cost** sheet. *For example, it is assumed the average maintenance costs for 'wear-and-tear' are roughly the same for the conventional technologies/practices and the solution in question. Since we are comparing the net cost-savings between the solution and the conventional technologies/practices maintenance* *costs net to zero; however, if the solution has a significantly higher or lower maintenance cost, then this may be important to factor along with the operational costs.*

Similar to First Cost, operating costs might vary from region to region. The core model only calculates costs based on global inputs. As costs will vary from region to region, operating costs for each region can be calculated separately. Totals from all regions can then be aggregated into a weighted average total based on each region's relative size compared to the world as a whole. If warranted, the **Operating Cost** sheet can be modified to accommodate a region-by-region calculation of operating cost. Similarly, this would require an Operating Cost PDS and Operating Cost REF dataset for each region.

For the calculation, we first define the conventional operating cost as a function of the year after initial installation t, and the year of initial installation, i. Here we include only the implementation units installed in that year and the increase in functional units in that year. Implementation units are calculated by dividing net annual functional units (NAFU) by the average annual use of the conventional. Costs continue only until the lifetime of the technology, L, (assuming instantaneous unit replacement) which may extend past the last year of analysis, y_{max} (after which no replacement occurs).

$$\theta_{i,t} = \begin{cases} VOC_{con,t} \cdot \{NAFU_i - NAFU_{i-1}\} + FOC_{con,t} \cdot \left\{\dfrac{NAFU_i - NAFU_{i-1}}{AU_{con}}\right\}, & if\ 0 < t <= L \cdot \left\lceil \frac{(y_{max}-i)}{L} \right\rceil \\ 0, & otherwise \end{cases} \tag{31}$$

Similarly, we define the solution operating cost for each year as a function of the year of installation:

$$\pi_{i,t} = \begin{cases} VOC_{sol,t} \cdot \{NAFU_i - NAFU_{i-1}\} + FOC_{sol,t} \cdot \left\{\dfrac{NAFU_i - NAFU_{i-1}}{AU_{sol}}\right\}, & if\ 0 < t <= L \cdot \left\lceil \frac{(y_{max}-i)}{L} \right\rceil \\ 0, & otherwise \end{cases} \tag{32}$$

Operating costs are dependent on year since they can be customized in the model, but for most solutions they are assumed constant each year. The difference between these expressions above in the same usage year t of units installed in the same year i is equal to savings from using the solution instead of the conventional for that usage year t. When we add these savings up across all years of usage and all years of installation (between y_1 and y_{max} inclusive), we get the Net Operating Savings:

$$\sum_{i=y_1}^{y_{max}} \sum_{t=1}^{y_{max}-i+1} [\theta_{i,t} - \pi_{i,t}] \tag{33}$$

Lifetime Operating Savings

The cumulative annual operating cost or savings of the solution from adoption to replacement time under the PDS scenario is the lifetime operating savings. We include only implementation units installed prior to the end of the analysis period, but we include all operational savings those units provide until their end of life, even if that falls outside of the analysis period. The calculation is only different from the Net Operating Savings in the number of years of usage summed (the inner summations). The number of years summed for the batch of implementation units installed in each year equals the total number of times those units or their replacements would be installed before the end of the analysis period multiplied by the lifetime used in years.

$$\sum_{i=y_1}^{y_{max}} \sum_{t=1}^{L_{sol} \cdot \left\lceil \frac{(y_{max}-i)}{L_{sol}} \right\rceil} [\theta_{i,t} - \pi_{i,t}] \tag{34}$$

Lifetime Cash Flow Net Present Value (NPV)

The lifetime cash flow NPV is determined by discounting and adding the first cost cash flow and the operating cost net cash flow for each of the years of the lifetime of the implementation unit. We present two different results: the lifetime cash flow NPV of a single implementation unit, (e.g. for a single hybrid vehicle), and the lifetime cash flow NPV of all solution implementation units adopted during the analysis period (e.g. for all TW of generating capacity installed globally). It is important to note that these calculations, though useful for decision-making, do not represent the actual cash flows that an investor would see since we are comparing two different scenarios, both of which cannot happen simultaneously[3]. We are comparing the operating costs in the PDS scenario (*if* adoption of the solution is high) to the operating costs in the REF scenario (*if* adoption of the solution is low). Since we assume that supply of the TAM is provided only by the solution technology or the conventional technology, then we are comparing the operating costs of the solution to those of the conventional only for those functional units that are supplied by a different technology in the PDS and the REF.

We use different discount rates depending on the agent of that solution and the typical discount rates that they would face for discounting the future net cash flows (rate which the capital needed for the project could return if invested in an alternative venture or the weighted average of global cost of capital) on the sheet **Advanced Controls**. The discount rate is the same for both solution and conventional though.

Here we need to include the lifetime operating savings but discount the savings from the year of use back to the base year, and then subtract the discounted marginal first costs (increased first costs are effectively negative cash flows of investment). For a single implementation unit, we can examine the NPV for different years of purchase/installation since the costs may change according to learning or customized operating costs. That will entail using the appropriate first and operating costs for the years of usage and discounting the cash flows back accordingly, but for the expression below, we will assume for simplicity, that the implementation unit is installed in the base year, y_b, and we are discounting to the base year so no discounting happens to the installation costs in the second part of the expression.

$$\left(\sum_{t=1}^{L_{sol}\cdot\left\lceil\frac{(y_{max}-i)}{L_{sol}}\right\rceil}\left[\frac{\theta_{y_b,t}-\pi_{y_b,t}}{(1+r)^t}\right]\right)-\left(FC_{sol,y_b}^{PDS}-FC_{con,y_b}^{REF}\right) \tag{35}$$

Note that for the lifetime cash flow NPV of all installed units, we include marginal first costs and operating costs of units installed from the base year, y_b since those units contribute to the emissions reductions measured particularly if we are considering the lifetime of implementation units. The lifetime cash flow NPV of all implemented units is shown below:

$$\sum_{i=y_b}^{y_{max}}\left(\sum_{t=1}^{L_{sol}\cdot\left\lceil\frac{(y_{max}-i)}{L_{sol}}\right\rceil}\left[\frac{\theta_{i,t}-\pi_{i,t}}{(1+r)^{t+i-y_b}}\right]-\frac{MFC_i}{(1+r)^{i-y_b}}\right) \tag{36}$$

Additionally, the RRS Core model calculates the lifetime cash flow NPV using net profit cash flow rather than operating cost savings to account for different potential revenues per functional unit for solution versus conventional implementation units (this is on the **Net Profit Margin** sheet). In most cases however, such as selling electricity (that is, for all solutions using the RRS ElectricityGeneration Solutions Model), the revenues per functional unit are equal between the solution and conventional.

[3] The real cash flows that the agent would experience would be negative first costs from installing the technology, and negative operating costs from running the technology (which are always included in the model) as well as positive revenues from the value that the technology provides (which are not always in the model).

Average Abatement Cost

The abatement costs calculated in the model is an average over the entire analysis period, which differs from the values normally published as the marginal abatement costs for a specific year. We did this to provide a metric that was more representative of the total analysis period, particularly as the abatement costs varied widely due to the assumption of instantaneous implementation costs[4]. We therefore take the negative of the discounted cash flows of the *analysis period* and divide them by the total emissions reduction of the analysis period. This is close to, but not exactly the same as, the ratio of the lifetime cash flow NPV of all adopted units divided by the total emissions reduction. The difference is that the average abatement cost does not include the operating savings of units installed prior to the start year in order to be more comparable to the published literature on abatement costs, and so the outer summation starts at y_1 not y_b. The expression is shown below.

$$\frac{-\left\{\sum_{i=y_1}^{y_{max}}\left(\sum_{t=1}^{L_{sol}\cdot\left\lceil\frac{(y_{max}-i)}{L_{sol}}\right\rceil}\left[\frac{\theta_{i,t}-\pi_{i,t}}{(1+r)^{t+i-y_b}}\right]-\frac{MFC_i}{(1+r)^{i-y_b}}\right)\right\}}{\sum_{y=y_1}^{y_{max}} R_y^{CO2e}} \tag{37}$$

Payback Period

The time to recover investment costs depends on which costs are included and how future cash flows are valued. The four main results include different combinations of cumulative first costs or marginal first costs and discounted or undiscounted cash flows. This can be represented as the sum of a series of binary variables X_y to infinity:

$$\sum_{y=1}^{\infty} X_y \tag{38}$$

These variables X_y differ according to the specific payback variable being calculated. We consider only a single implementation unit, and hence the term *cumulative* may be misleading, however it is used to distinguish it from *marginal*, or the additional first costs of the solution over the conventional. As we are considering a single implementation unit, we do need to understand how many functional units are provided by it (Average Annual Use, AU_{sol}) but we do not need the net annual functional units. We present the calculation of the simplest below: *cumulative undiscounted payback* period. Note that the condition is based on positive first costs and positive operations costs:

$$X_y = \begin{cases} 1, & if\ \sum_{t=0}^{y}\left(FOC_{con,t}-FOC_{sol,t}\right)+AU_{sol}\cdot\left(VOC_{con,t}-VOC_{sol,t}\right)<FC_{sol,y_b}^{PDS} \\ 0, & otherwise \end{cases} \tag{39}$$

For the case of *marginal undiscounted payback*, we have:

$$X_y = \begin{cases} 1, & if\ \sum_{t=0}^{y}\left(FOC_{con,t}-FOC_{sol,t}\right)+AU_{sol}\cdot\left(VOC_{con,t}-VOC_{sol,t}\right)<FC_{sol,y_b}^{PDS}-FC_{con,y_b}^{REF} \\ 0, & otherwise \end{cases} \tag{40}$$

For *cumulative discounted payback*:

$$X_y = \begin{cases} 1, & if\ \sum_{t=0}^{y}\frac{\left(FOC_{con,t}-FOC_{sol,t}\right)+AU_{sol}\cdot\left(VOC_{con,t}-VOC_{sol,t}\right)}{(1+r)^t}<FC_{sol,y_b}^{PDS} \\ 0, & otherwise \end{cases} \tag{41}$$

And for *marginal discounted payback*:

[4] Many marginal abatement costs results assume amortization of costs over say, the lifetime of the technology.

$$X_y = \begin{cases} 1, & if \ \sum_{t=0}^{y} \frac{(FOC_{con,t} - FOC_{sol,t}) + AU_{sol} \cdot (VOC_{con,t} - VOC_{sol,t})}{(1+r)^t} < FC_{sol,y_b}^{PDS} - FC_{con,y_b}^{REF} \\ 0, & otherwise \end{cases} \quad (42)$$

The RRS Core model also presents four similar payback period results using profit margins (when available) instead of operating costs. As before, the results would be exactly the same as those based on operating costs if there is no difference in revenue for conventional and solution functional units.

Background Financial Calculations and Notes

Lifetime Calculations

In the model, the lifetime of the conventional or solution technology is entered in functional units and converted to years automatically in the model as the ratio of the entered lifetime and the average annual use (also in functional units).

Implementation units and Functional units

The net annual implementation units (NAIU) and the net annual functional units (NAFU) are connected as shown below for the conventional technology. Note that the solution technology may not have the same NAIU as the conventional if the average annual use is different.

$$NAIU_{con,y} = \frac{NAFU_y}{AU_{con}} \quad (43)$$

Calculation of Replacement Units

The assumption of instantaneous replacement at the end of life of any unit means that for many analyses where the lifetime of the units is shorter than the analysis period, there will be replacements that incur additional first costs in the year of replacement. It is therefore important to estimate how many replacement units of each type would need to be installed each year for each technology. This can include several years' worth of initial installations. For instance, with a 5 year lifetime, at the start of year 25, replacement of the 20th, 15th, 10th and 5th year installations would need to take place. The calculation below accounts for this:

$$RU_{sol,y}^{PDS} = \sum_{i=y_0}^{y_{max}} \begin{cases} NAIU_{sol,i} - NAIU_{sol,i-1}, & if \ |i-y| \ mod \ L_{sol} = 0 \\ 0, & otherwise \end{cases} \quad (44)$$

Assumptions

In order to standardize the data to provide a meaningful basis for analysis, comparison and presentation, a number of assumptions were made. These are presented below.

Solution Adoption

- The solution will always replace the higher emitting conventional technology/practice (or mix of technologies/practices).
- The growth of the solution in the REF case will be set at the percent adoption in the base year (2014) and remain proportional to the growth of the TAM for *most* solutions. Some solutions have different REF case

adoption if this is deemed too optimistic or too pessimistic.

- Functional units that would be captured by the solution in the PDS Scenario instead represent the additional growth of the higher emitting conventional technology/practice (or mix of technologies/practices) in the REF Scenario.
- Replacement of implementation units occurs instantly at the end of life of units to maintain adoption in functional unit terms. Costs are accrued accordingly.

Market Dynamics

- The supply for functional units, and all that that entails (including costs), match the demand for those units, avoiding issues of market inefficiency and all that that entails.
- The infrastructure required to manufacture and scale each solution is already in place. This will eliminate the need for analysis of capital spending to enable or augment production.
- Manufacturing capacity and infrastructure will be sufficient to scale each technology.

Costs

- Operating costs for each solution include consumer costs to operate and associated maintenance costs. Operating costs can be calculated using the current operating cost through the entire 30-year period in the absence of reliable operational cost estimates.
- Operating costs and Savings can be calculated on an annual basis and then aggregated into one total at the end of the period, that is, there are no interdependencies of cash flows across years.
- First costs can be applied in the year of implementation, that is, no amortization is performed.
- Cost savings can be calculated per unit.

Need Help? Want to Share Your Data?

Questions on the methodology, or requests to include your data in the Project Drawdown models can be sent to the Project Drawdown Research Team at research@drawdown.org.

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Appendices

Appendix 1: Regions of Interest

While the world-wide remediation potential is the most important metric for the book, we also want to report results for regions and major countries, to the extent possible. To that end, we've adopted regions based on those used in the models created for the IPCC AR5 WG3. They include five major regions/groups that cover the whole world, as well as value for three distinct large countries and the European Union, as those four entities comprise a large portion of total global CO_2 emissions.

OECD90

Australia, Austria, Belgium, Canada, Denmark, Fiji, Finland, France, French Polynesia, Germany, Greece, Guam, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, New Caledonia, New Zealand, Norway, Portugal, Samoa, Solomon Islands, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States of America, Vanuatu

Eastern Europe

Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Georgia, Hungary, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Malta, Poland, Republic of Moldova, Romania, Russian Federation, Slovakia, Slovenia, Tajikistan, Macedonia, Turkmenistan, Ukraine, Uzbekistan, Yugoslavia

Asia (sans Japan)

Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, China, China Hong Kong SAR, China Macao SAR, Democratic People's Republic of Korea, East Timor, India, Indonesia, Lao People's Democratic Republic, Malaysia, Maldives, Mongolia, Myanmar, Nepal, Pakistan, Papua New Guinea, Philippines, Republic of Korea, Singapore, Sri Lanka, Taiwan, Thailand, Viet Nam

Middle East and Africa

Algeria, Angola, Bahrain, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Cote d'Ivoire, Democratic Republic of the Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Iran, Iraq, Israel, Jordan, Kenya, Kuwait, Lebanon, Lesotho, Liberia, Libyan Arab Jamahiriya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Oman, Qatar, Reunion, Rwanda, Saudi Arabia, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Syrian Arab Republic, Togo, Tunisia, Uganda, United Arab Emirates, United Republic of Tanzania, Western Sahara, Yemen, Zambia, Zimbabwe

Latin America (includes Caribbean)

Argentina, Bahamas, Barbados, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Suriname, Trinidad and Tobago, Uruguay, Venezuela

S**pecific Countries**

China
India
European Union (at 27 member countries)
United States of America

Appendix 2: Definitions

Adoption Scenario – the predicted shape of adoption growth over the period 2015 to 2060. We have a range of scenarios programmed in the model, but the user may enter her own. Note that the assumption behind all of these 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.

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**.

Direct Emissions – emissions caused by the operation or growth of the solution, and 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 economics but not the climate impacts of the solution).

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 economic 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 your solution. They should be in the units described below each variable entry cell.

Implementation Unit – a measurement unit that represents how the SOLUTION approach 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 phenomena: 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 mode has a tool for calculating how costs change due to learning, see Appendices for details on its use.

Lifetime Capacity – this is the total average functional units that one implementation unit of the SOLUTION or CONVENTIONAL technology 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 Savings–the savings (or additional costs if negative) of operations in the PDS versus the REF scenarios over the lifetime of the model period (2015-2060.

Lifetime Cost/Savings 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.

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 annual functional demand captured either by the solution in the PDS Adoption Scenario or the conventional technologies/practices in the REF Adoption Scenario.

Net Annual Implementation Units (NAIU) – the adoption in the PDS minus the adoption in the REF in each year of analysis divided by the average annual use. In the model, this represents the annual estimated number of implementation units needed above and beyond one scenario or the other (e.g. how many more solution units are needed in the PDS over the REF or how many more conventional units are needed in the REF over the PDS.

Operating Costs -the average cost to ensure operation of an activity (CONVENTIONAL or SOLUTION) is performed in $/functional unit. This is needed in order to make assumptions about 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.

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

PPM/ Parts per Million – a measure of concentration for atmospheric gases

REF/ Reference Scenario – this is the low growth scenario for adoption of the SOLUTION against which all PDS scenarios are compared.

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**.

TWh/ Terawatt-hour – A unit of energy equal to 1 billion kilowatt-hours

Appendix 3: Using Learning Rates/Curves for First Costs

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.

In many situations, this pattern of improvement follows a predictable pattern: for every doubling of (or some multiple of) production of units, the "cost" of production (measured in dollars, hours, or in terms of other inputs) declines to some fraction of previous costs. Note that a learning rate of 70% is 'better' than a learning rate of 90%. For purposes of the model, the learning rate input on **Advanced Controls** is defined as an experience curve labeled as an **efficiency rate** which is *1 – learning rate*. This seems more intuitive and enables the researcher to enter '0' for an experience curve if a conservative constant install cost is needed.

Mathematically the learning phenomena can be expressed as

$$K_n = K_m({}^{n}/{}_{m})^{\,b}$$

Where:

m is some number of units produced
n is some larger number of total units produced (n>m)
K_m is the "cost" of producing unit m (dollars, hours...)
K_n is the "cost" of producing unit n
b = log R / log 2 (if doubling)
R is the rate of learning

b and R can be calculated as:

b = [log K_n - log K_m] / [log n - log m] = log(K_n/K_m) / log(n/m)
R = 10b log 2 (if doubling)

A variety of data from a variety of sources can be input on the **Variable Meta-Analysis** sheet to input to arrive at a conservative estimate for a learning rate or efficiency rate and then copy the relevant results to the appropriate variable on **Advanced Controls**.

If the literature review shows a compelling case for adjusting the estimated install cost over time to something other than the install cost determined from 2014 data and the learning rate, then a factored install cost estimate can be calculated and shown on the First Cost sheet for both solution and conventional technologies/practices.

Appendix 4: S-Curve Math

Default S-Curve: Logistic Model

This section explains the default (basic) "S-curve" or logistic curve for estimating and forecasting adoption. Implicit in S-curve forecasting is the assumption of initial slow growth and then a period of rapid growth and then a declining rate of growth. The curve is represented by the following formulas and definitions.

Variables:

$\{y_b, y_0, y_{max}\}$ the base, initial and final years of analysis {2014, 2020, 2050}
$ADP_{sol,y}^{PDS}$ = percentage adoption of the solution in the PDS scenario at year y
$ADF_{sol,y}^{PDS}$ = adoption in functional units of the solution in the PDS scenario at year y
t, y = a year of analysis
Q = 1- ADP_{sol,y_b}^{PDS}, (1 minus the base year percentage adoption)
$TAM_{y_{max}}$ = TAM at final year of analysis

Steps:

1. the adoption values are transformed to H space

$$H_y = \ln\left(\frac{Q}{ADP_{sol,y}^{PDS}} - 1\right), \forall y \in \{y_0, y_{max}\}$$

2. standard linear regression is used to estimate α and β

$$\alpha + \beta t = H, \forall t \in \{y_0, y_{max}\}$$

3. a and b are calculated from α and β

$$a = e^{\alpha}$$
$$b = -\beta$$

4. We can calculate the unknown years using the expression

$$ADP_{sol,y}^{PDS} = \frac{Q}{[1 + a \cdot e^{-by}]}$$

5. For years y prior to the end year, y_{max}:

$$ADF_{sol,y}^{PDS} = \left(ADP_{sol,y}^{PDS} \cdot TAM_{y_{max}} + ADP_{sol,y_b}^{PDS} \cdot ADP_{sol,y_{max}}^{PDS} \cdot TAM_{y_{max}}\right) \cdot \frac{y - y_b}{y_{max} - y_b} + ADF_{sol,y_b}^{PDS} \cdot \frac{y_{max} - y}{y_{max} - y_b}$$

6. For years after end year, y_{max}:

$$ADF_{sol,y}^{PDS} = ADP_{sol,y}^{PDS} * TAM_{y_{max}} + \frac{ADF_{sol,y_b}^{PDS}}{ADP_{sol,y_{max}}^{PDS}}$$

Note:
Current Year Adoption is modified/adjusted in order to formulaically approach the already given variables of Base Year adoption and % of TAM at 2050. These adjustments can result in abnormal spikes in adoption outside of the 30 year period depending on the data.

As a result, we have also provided the Bass Diffusion S-Curve

Alternate Default S-Curve: Bass Diffusion Model

The Bass Diffusion model is commonly used for modeling adoption of a wide variety of products and is rather flexible since parameters can be tuned to adjust the shape of the S-Curve. Our implementation of the model is based on a technical note at the University of Washington available online[5].

The Bass Diffusion model uses the following parameters:

p, q = input parameters for calibration of model (innovation and imitation parameters respectively)

N_max = the maximum possible adoption in the ending year of analysis, which we define as TAM

$ADF_{sol,y}^{PDS}$ = cumulative adoption of the solution by year y in the PDS scenario in functional units

The Bass model adoption is calculated as:

$$ADF_{sol,y}^{PDS} = p * N\_max + (q - p) * ADF_{sol,y-1}^{PDS} - (q/N\_max) * \left(ADF_{sol,y-1}^{PDS}\right)^2$$

[5] See http://faculty.washington.edu/sundar/NPM/BASS-Forecasting%20Model/Bass%20Model%20Technical%20Note.pdf, Accessed 22 January, 2018

The innovation and imitation parameters are selected guided by recommended values found in web research[6]. Additionally, Excel's Solver/Goal Seek functions were used when needed to sequentially find parameters that maximized some key model result such as the total emissions impact.

Customized S-Curve

The customized S-Curve is yet another option for producing S-Curves in the model, and is based on automatically fitting 2nd order and 3rd order polynomial curves to different parts of available datasets in order to create an S-Curve. Since it was not used in any model, it will not be detailed here.

[6] See http://www3.nd.edu/~busiforc/handouts/Other%20Articles/Bass%20model.pdf, Accessed 22 January, 2018