TECHNICAL ASSESSMENT FOR ALTERNATIVE CEMENTS

SECTOR: MATERIALS

AGENCY LEVEL: BUSINESS

KEYWORDS: ALTERNATIVE CONCRETES, SUSTAINABLE CONCRETE, SUPPLEMENTARY CEMENTITIOUS MATERIALS, FLY ASH

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

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Acronyms and Symbols Used

- **AAC** – alkali activated cement
- **BYF** – belite clinkers with ye'elimite
- **IEA** – International Energy Agency
- **CACS** – carbonation of calcium silicates
- **CEM** – cement
- **CH** – calcium hydroxide
- **C-S-H** – calcium silicate hydrate
- **CSAB** – calcium sulphoaluminate belite
- **EN** – European standard
- **IEA** – International Energy Agency
- **GJ** – gigajoules
- **LC3** – limestone calcined clay cement
- **MOMs** – magnesium oxide derived from magnesium silicates
- **OPC** – ordinary portland cement
- **PDS** – Project Drawdown Scenario
- **REF** – Reference
- **SCM** – supplementary cementitious material
- **TAM** – total addressable market

EXECUTIVE SUMMARY

Alternative cement is a Drawdown Solution that has significant potential to reduce carbon emissions of the cement industry, which is responsible for 6% of global carbon emissions. Cement is a material ubiquitous in the construction industry and is the primary material used in concrete and mortar. Alternative cements are a suite of solutions that include reducing the electricity and thermal intensity of clinker production, in addition to the reduction of clinker demand through the use of alternative clinker materials. To reduce the electricity and thermal intensity of clinker, manufacturers should adopt more efficient kilns (e.g., dry kilns rather than wet kilns). Additionally, many alternative clinker materials exist and have the ability to reduce the carbon emissions of cement. Examples include waste materials such as fly ash and slag which can replace between 20% and 80% of clinker in cement, depending upon the intended application.

The Solution is modeled by evaluating the global clinker to cement ratio and how alternative cements can replace clinker, resulting in a reduction to the average clinker to cement ratio. The adoption prognostication model constructs four scenarios for future adoption of alternative cements. A reference (REF) growth scenario is constructed which fixes the current clinker to cement ratio. Three Project Drawdown Scenarios (PDSs) were built upon a reduction in the clinker intensity of cement which align to existing international cement standards.

Comparing each of the PDS scenarios to the REF scenario yields the climate and financial impacts of Alternative Cement adoption. The least aggressive PDS (the Plausible Scenario) utilized a clinker to cement ratio of 0.60 in 2050, and the most aggressive PDS (the Optimum Scenario) utilized a clinker to cement ratio of 0.27 in 2050.

The climate and financial impacts for this accelerated adoption of Alternative Cements is promising. The Plausible Scenario avoids a total of 7.95 gigatons (Gt) of CO_2-equivalent greenhouse gas (GHG) emissions, the approximate parts per million (PPM) equivalent of which is 0.484 (ppm CO_2-eq). The marginal capital cost of PDS adoption compared to the REF scenario is US$63.46 billion. Increased adoption of Alternative Cements can assist the materials sector contribute to Drawdown.

1 LITERATURE REVIEW

1.1 STATE OF ALTERNATIVE CEMENTS

Today, cement is the second most consumed material in the world after water. Cement is used ubiquitously across the construction industry to make mortar and concrete which comprises the structure of buildings. In 2016, global emissions due to the production of cement were estimated to be 1.45 ± 0.20 Gt CO_2, or 4-6% of global carbon dioxide emissions (Andrew, 2018). The demand for buildings is expected to double by 2050 (IEA & UN Environment Programme, 2018) driven by increases in population, urbanization, and economic development. In turn, the global demand for cement is expected to increase between 12% and 23% relative to consumption in 2014 (IEA, 2018).

1.1.1 Manufacturing Process

The production of hydraulic cement (e.g., ordinary portland cement, OPC) involves three main stages. First, the raw materials are prepared, next the clinker is produced, and lastly, the clinker is ground and mixed with other components. These three stages can be seen in Figure 1.1. Carbon emissions are associated with each step, yet, the vast majority is associated with the burning of fossil fuels to produce clinker. The production of clinker involves the calcination of limestone ($CaCO_3$) which results in direct, or process emissions, of about 60-70% of total cement emissions. For this calcination reaction to occur, the limestone is heated to temperatures of up to 1450°C which requires the combustion of fuels (typically non-renewable) and electricity, accounting for the other 30-40% of emissions. Two primary kiln technologies exist for clinker production, “wet” and “dry”. Wet kilns require more energy and thus release more CO_2 than dry kilns since the raw material used has a higher moisture content. Two types of energy are consumed throughout the clinker manufacturing process: electricity and thermal energy. A variety of manufacturing technologies have been developed to improve both the thermal and electricity efficiency of clinker production, such as the use of preheating and precalcining stages. After the clinker is produced, it is blended with other materials, such as gypsum to form OPC which is then used to produce concrete or mortar. For a succinct overview of the details of cement production, the reader is referred to Section 2 of the IEA Technology Roadmap for Cement (IEA, 2018, pp. 12–14).

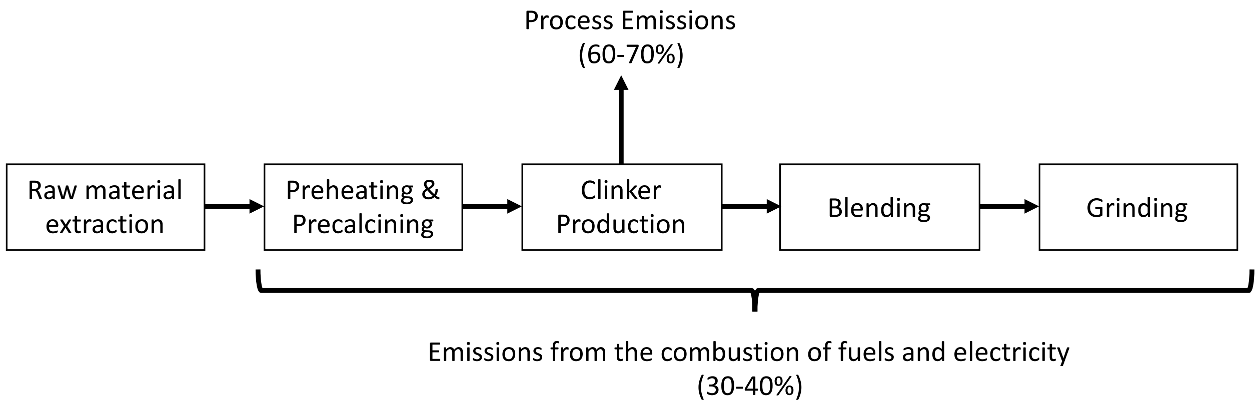

Figure 1.1. Cement manufacturing process overview.

1.1.2 Manufacturing Efficiencies

Reducing the thermal and electricity intensity of clinker has been a focus of the cement manufacturing industry for a number of years. A wet kiln uses between 5.85 and 6.28 GJ of thermal energy per ton of clinker produced, whereas a 4-stage cyclone preheater with a precalciner consumes only 3.141 GJ/clinker (Damtoft et al., 2008). The minimum theoretical limit for clinker production from a thermodynamics perspective is between 1.85 and 2.80 GJ/ton of clinker, depending upon the moisture content required for the drying raw materials. Electricity is primarily used in cement manufacturing to grind raw materials, produce clinker, and grind cement to the appropriate fineness. Globally, between 2000 and 2012, the average electrical efficiency of cement production reduced nearly 10 kWh/ton (to an average of 104 kWh/ton) of cement due to the adoption of technological updates of cement plants. The most efficient cement manufacturers in 2014 showed electricity intensities of 85 kWh/ton of cement are achievable (Cement Sustainability Initiative & European Cement Research Academy, 2017). To adopt more efficient manufacturing methods, the retrofit of existing kilns, a capital-intensive project, must occur. Because cement plants have relatively short lifespans in comparison to other industrial processes, intervention and adoption of thermal and electricity efficient technologies can occur in new cement plants.

1.1.3 Clinker Reduction

Two of the primary mineral phases of clinker that make cement a useful construction material are alite and belite, composed of silicates and calcium oxides. In the presence of water, alite and belite hydrate to form calcium hydroxide (CH) and calcium silicate hydrate (C-S-H), which are the "glue" that holds together aggregates, such as sand and gravel, to form concrete and mortar. Depending upon the intended application of cement, its exact clinker mineral composition can be modified. Standard OPC mineral compositions are summarized by national and international standards such as ASTM C150.

Alternative methods to produce CH and C-S-H in hydraulic cements have been in existence for many years. Supplementary cementitious materials (SCMs) can replace clinker to form a cement that performs equally, if not better, than traditional high clinker content OPC. SCMs can be industrial by- or co-products or be found naturally. Examples include fly ash, a by-product of the combustion of coal; ground granulated blast furnace slag, a by-product of pig iron manufacturing; metakaolin, a naturally occurring clay mineral; agricultural waste products, such as rice husk ash, and limestone. SCMs typically have lower emissions than clinker since they are waste products or naturally occurring, therefore when they replace carbon-intensive clinker, some of the emissions associated with cement can be avoided. Blended cements are a variety of cement that utilize multiple SCMs. For example, CEM V/A designation cement consists of 52% clinker, 28% ground granulated blast furnace slag, 10% pozzolana (a silica sand), and 10% fly ash (García-Gusano et al., 2015). Another type of blended cement, limestone calcined clay cement (LC^3), uses a clinker substitution of 45% composed of limestone (15%) and calcined clays, such as metakaolin (30%), which has been shown to outperform a 100% clinker counterpart in compressive strength (Antoni et al., 2012). The agency level at which alternative cements are typically adopted are at the building designer or contractor. Building designers specify the type of concrete or mortar that is used and have the ability to specify target reductions in clinker, yet builders often have control over the mix design used.

1.1.4 Solution Definition

The conventional technology as defined as the use of Type I/CEM I cement (i.e., high clinker cement), while the solution technology of Alternative Cements is defined as the suite of other cement standard designations (see Table 1.1) in conjunction with reductions to manufacturing emissions. The chemical compositions of both ordinary portland cement and alternative cements are described by various standards (i.e., ASTM C150, ASTM C595 and EN 197). The ASTM standards are most commonly used in the United States building code, while the EN standards are referred to by building codes throughout the world. Table 1.1 summarizes the CEM and ASTM designations for cement. Note that there are similarities between the two standards and some types of cement are grouped together.

Table 1.1. Designations of ASTM and CEM cement standards and common applications.

Designation	Description and Purpose	Clinker Content	Clinker Substitute
EN: CEM II / ASTM: Type I	General purpose OPC	>0.95	Gypsum
ASTM: Type II	Moderate sulfate resistance OPC	>0.95	Gypsum
ASTM: Type III	High early strength OPC	>0.95	Gypsum
ASTM: Type IV	Low heat portland cement	>0.95	Gypsum
ASTM: Type V	Sulfate resistant portland cement	>0.95	Gypsum
EN: CEM III / ASTM Type IS	Portland blast-furnace slag cement	0.05-0.64	Blast-furnace slag
ASTM Type IL	Limestone cement	0.85-0.95	Limestone
EN CEM IV / ASTM Type IP	Portland pozzolan cement	0.45-0.89	Pozzolans
EN CEM V / ASTM Type IT	Ternary blended cement	0.20-0.64	Slag or fly ash with a pozzolan
EN: CEM II	Portland-composite cement	0.65-0.94	Any cementitious constituent

1.1.5 Effect of Carbonation

While cement manufacturing releases direct carbon-dioxide emissions due to the chemical process that occurs, this chemical reaction reverses when the concrete is exposed to carbon-dioxide. Up to 17% of initial carbon dioxide emissions can be recovered through this carbonation reaction throughout the lifetime of the concrete (Souto-Martinez et al., 2017). The global scale is estimated to be 0.92 Gt CO_2 in 2014 due to the historical pervasiveness of concrete construction (Xi et al., 2016). Accelerated carbonation is another technology which injects compressed CO_2 into fresh state concrete to accelerate the carbonation reaction. Modest reductions of ~5% cement content have been achieved, reducing net carbon emissions, yet this technology has not widely adopted.

1.2 Adoption Path

1.2.1 Current Adoption

In 2014, the average global clinker content of cement was 0.65, thermal intensity of clinker production 3.5 GJ/ton clinker, and the electricity intensity was 91 kWh/ton cement (IEA, 2018). Typical OPC has a clinker content of 0.95. Experts agree that clinker will always be a component of the future cement industry, yet no agreed upon minimum clinker content has been arrived at. Very low clinker cements (e.g., CEM III), which use 0.34 clinker to cement ratios do not have high rates of adoption (3.8% of the Spanish cement market (García-Gusano et al., 2015)) due to their specialty application to provide resistance to sulfate and chloride attack. The distribution of the Spanish cement market in 2010 and the potential applications of various types of cement can be seen in Table 1.2.

Table 1.2. Distribution and application of CEM cement types in Spain in 2010.

Designation	Typical Application	Share of Spanish cement market in 2010 (García-Gusano et al., 2015)
CEM I	General purpose	25.4%
CEM II	General purpose	66.1%
CEM III	Sulfate and chloride resistance	3.8%
CEM IV	General purpose	3.3%
CEM V	General purpose	0.9%

1.2.2 Trends to Accelerate Adoption

To encourage adoption, the retrofit of cement plants can be incentivized. Imposing regulations on the construction of new cement plants to only allow efficient manufacturing technologies will ensure that CO_2 savings are realized. Likewise, educating building designers on the environmental impacts of the concrete they specify will also accelerate adoption. Furthermore a shift in codes and standards to be performance-based, rather than prescriptive, can help accelerate adoption.

1.2.3 Barriers to Adoption

A primary barrier to the adoption of low-clinker cement is that its use is limited to specific applications and not transferable to all construction applications. The type of cement chosen is typically driven upon the constructability requirements (e.g., as high early strength gain) or durability requirements (e.g., high exposure to sulfates). Cement is typically not selected based upon its carbon emissions, but rather its performance which is a barrier to adoption low clinker cements. Since codes and designers are comfortable specifying high clinker cement, a key barrier to adoption is education surrounding the potential applications and performance of low-clinker cements. A barrier to the adoption of manufacturing efficiency measures is the capital intensity of improving cement plants. Due to their short lifespans, cement plants are typically not retrofitted, but improvements are made in their design. As cement plants are decommissioned, and new, efficient, plants built, the manufacturing efficiency measures will become adopted, since they are also more economical. The price of cement is closely tied to the cost of energy, therefore the more energy-efficient the production of cement is, the less costly the cement will be. The supply of some SCMs, such as fly ash and slag, will decrease in the future due to the reduction of coal combustion and steel manufacturing. Other SCMs, such as calcined clays, will need to take the place of fly ash and slag in the future, which may create a barrier for adoption. The availability of SCMs is region dependent and their transport is expensive in terms of both cost and emissions. Thus, region-specific solutions are needed, which may cause a barrier to adoption.

1.2.4 Adoption Potential

The future cement industry will continue to rely, to some extent, on the use of clinker. However, the potential for every cement application to use less than 95% clinker has already been achieved. In 2014, the IEA estimated the average clinker intensity of cement to be 0.65 (IEA, 2018). In 2050, the IEA estimates only a minor reduction in the clinker-to-cement ratio to 0.64, yet lower clinker intensities can be realized with higher levels of adoption of blended cements.

1.3 ADVANTAGES AND DISADVANTAGES OF ALTERNATIVE CEMENTS

1.3.1 Similar Solutions

There are a variety of other cement systems which can also be used to produce concrete and mortar (Gevaudan et al., 2019). Belite-rich clinkers require a lower temperature to produce and can achieve around a 10% reduction in CO_2 as compared to traditional OPC. Belite-rich clinkers do not gain strength as quickly as traditional OPC, which is why they have not gained widespread use. Similarly, belitic clinkers with ye'elimite (BYF) are a lower carbon cement technology that has been used in China since the 1970s which can achieve CO_2 savings of more than 20% (Scrivener et al., 2018). Alkali activated cements (AACs), or geo-polymers, are another class of low-carbon cement technologies that are considered more durable than traditional OPC. AACs are technically feasible as a technology and there are commercial scale operations in many developed and developing countries. The lack of adoption of AACs is attributed to the lack of supply chains (Provis, 2018). Additional cement systems such as carbonation of calcium silicates (CACS), and magnesium oxide derived from magnesium silicates (MOMS) are in development as low-carbon alternatives, but do not currently have a substantial portion of the global cement market.

Other solutions that are similar to Alternative Cements include the substitution of concrete for other structural materials. For example, the use of steel or mass timber for building construction can reduce the demand (i.e., the total addressable market) for cement, and also reduce the carbon emissions of the construction sector. While the built environment will continue to utilize concrete as a structural system to some extent, the partial replacement of concrete structure with mass timber ones (Drawdown coming attraction "Building with Wood") is a similar solution.

1.3.2 Arguments for Adoption

In addition to having reduced climate impacts, low-clinker cements are typically more durable than traditional OPC systems. More durable materials result in lower replacement rates and reduced lifecycle costs for infrastructure management. This additional benefit is an argument for adoption of alternative cements.

1.3.3 Additional Benefits and Burdens

Additional benefits and burdens of related technologies of alternative cements are explored in Table 1.3. Each metric is rated on a scale of “high”, “medium”, and “low”. Note that technologies with a star (*) are included in the solution definition for Alternative Cements (see Section 1.1.4).

Table 1.3 Comparison of Technologies Related to Alternative Cements.

	Climate Impacts	Durability	Adoption Potential
Traditional OPC (95% clinker content)	High	Medium	High
Cement manufacturing efficiency (electric and thermal)*	Low	N/A	High
Low clinker cement*	Low	High	High
Very-low clinker cement*	Very Low	High	Low
Alternative fuel use for clinker production (e.g., biomass)	Low	N/A	Medium
Alternative cement systems (e.g., alkali-activated cements)	Very Low	High	Medium
Alternative structural materials (e.g., steel or timber)	Very Low - Medium	Medium	High

2 METHODOLOGY

2.1 INTRODUCTION

To model the potential impact the adoption of alternative cements may have as a carbon emissions reduction strategy, a scenario analysis is performed. Alternative cements as a Drawdown Solution is defined for this model as the reduction of clinker to cement ratio, in addition to the adoption of more efficient clinker production manufacturing processes.

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

2.2 DATA SOURCES

Key data sources used in the modeling process include ASTM C595 and EN 197 standards which specify the mineral content (and thus clinker content) required for different types of alternative cements. These standards are leveraged to define the rate of adoption of the solution technology for each Project Drawdown scenario. Additionally, details on the indirect emissions associated with alternative cements utilized the global scale analysis performed by Miller et al.

[1] For most results, only the differences between scenarios, summed over 2020-2050 were presented, but for the net first cost, the position was taken that to achieve the adoptions in 2020, growth must first happen from 2015 to 2020, and that growth comes at a cost which should be accounted for, hence net first cost results represent the period 2015-2050.

(2018). To evaluate the supply of non-clinker binder and filler materials, a global estimate of precursor availability is utilized (Scrivener et al., 2018).

2.3 Total Addressable Market

The total addressable market (TAM) is derived from both peer-reviewed and global trade organizations to predict the future demand for cement in millions of metric tons (MMt). The IEA has a low- and high-variability scenario which provides a global estimate for the cement market through 2050 (IEA, 2018). Two recent peer reviewed studies (Farfan et al., 2019; van Ruijven et al., 2016) use historical data and forecasted economic and population data to develop a TAM. The average of each of the TAMs identified in the literature are used in the present analysis.

2.4 Levels of Adoption

The magnitude of adoption of alternative cements is modeled by using already existing standards for cement (ASTM and CEM). For each type of cement (e.g., CEM II), there is a range of clinker-to-cement ratios that are acceptable. The present model considers three different adoption levels (described by each scenario) which are informed by a weighted average of clinker-to-cement ratios and assumed market share of each type of cement, see Table 2.1. These market sharers are derived from historical CEMBUREAU data.

Table 2.1. Model inputs for market share distribution of cement.

Cement Type	Market share in 2020	Market share in 2050	Notes on assumed market share in 2050
CEM I	29.70%	0.00%	No CEM I is produced in any scenario.
CEM II	57.20%	44.35%	50% split of remaining share to CEM II and CEM V.
CEM III	5.60%	5.60%	Same percentage of CEM III used.
CEM IV	5.70%	5.70%	Same percentage of CEM IV used.
CEM V	1.80%	44.35%	50% split of remaining share to CEM II and CEM V.

2.5 Adoption Scenarios

Two different types of adoption scenarios were developed: a Reference (REF) Case which was considered the baseline, where not much changes in the world, and a set of Project Drawdown Scenarios (PDS) with varying levels of ambitious adoption of the solution. Published results show the comparison of one PDS to the REF, and therefore focus on the change to the world relative to a baseline.

2.5.1 Reference Case / Current Adoption

The reference case assumes that current adoption of alternative cements remains constant with a clinker to cement ratio of 0.69. No adoption of more efficient kilns is included, and no further reductions to the clinker to cement ratio is made. The REF case uses the same TAM as each PDS.

2.5.2 Project Drawdown Scenarios

Three Project Drawdown scenarios (PDS) were developed for each solution, to compare the impact of an increased adoption of the solution to a reference case scenario. The magnitude of adoption of alternative cements is in each scenario is modeled through a shift in the clinker to cement ratio from higher use of low-clinker cements. CEM III and CEM IV cements are primarily used for specialty construction applications and are not expected to be used in general construction applications, thus their market share is fixed to the percentage of adoption in 2020. For all PDSs, it is assumed that market share of CEM I is 0% in 2050, with the remaining market share, depending upon the scenario, split evenly between CEM II and CEM V. Table 2.1 summarizes the market share of each type of cement in 2020 and 2050.

Each CEM designation has a range of acceptable clinker to cement ratios. For example, CEM V can have a clinker to cement ratio between 20% and 64%. Thus, the lower, middle, or upper limit within each CEM designation can inform the total cement market clinker-to-cement ratio.

Plausible Scenario

In the Plausible Scenario, alternative cements are adopted at an aggressive rate between 2020 and 2050. Clinker to cement ratios decrease from 0.69 in 2020 to 0.60 in 2050 and full adoption of electricity and thermal efficiencies (to their theoretical minimums) are realized by 2050. The

2050 clinker ratio assumes that the statistically high value of the middle value of the clinker intensities is used. Furthermore, adoption is assumed to be linear.

Drawdown Scenario

In the Drawdown Scenario, alternative cements are adopted at a "realistically vigorous" rate between 2020 and 2050. Clinker to cement ratios decrease from 0.69 in 2020 to 0.46 in 2050 and full adoption of electricity and thermal efficiencies (to their theoretical minimums) are realized by 2050. The 2050 clinker ratio assumes that the mean statistical value of the middle range of clinker intensities is used. Furthermore, adoption is assumed to be linear.

Optimum Scenario

In the Optimum Scenario, alternative cements are adopted at an optimistic, but achievable, rate between 2020 and 2050. Clinker to cement ratios decrease from 0.69 in 2020 to 0.27 in 2050 and full adoption of electricity and thermal efficiencies (to their theoretical minimums) are realized by 2050. The 2050 clinker ratio uses the statistical low of the middle range of clinker intensities. Furthermore, adoption is assumed to be linear.

2.6 INPUTS

2.6.1 Climate Inputs

Direct Emissions Factor

The adoption of alternative cements results in the reduction of direct carbon dioxide emissions. The climate analysis portion of this model separates the emissions associated with cement production into three categories: (1) the reduction of the clinker intensity of cement, (2) reduction in the fuel required to produce clinker, and (3) the reduction in electricity required to produce clinker. The reduction of fuel and electricity consumption are converted to direct emissions reductions using reported emissions factors, and the clinker related emissions reductions (i.e. from calcination of limestone) are modeled as reductions to direct emissions.

Emissions factors for electricity generation are derived from the projected energy generation mix from three AMPERE RefPol scenarios in IPCC AR5 model Database (GEM3, IMAGE, MESSAGE) and the IEA's ETP 6DS scenario, and direct/indirect emissions factors by generation type taken from the IPCC AR5 Model Database, AMPERE3-MESSAGE Base scenario. The reader should note that since this combined reference projection includes a shift away from coal and oil to natural gas, the reference emissions factors decline slowly over the analysis period. Fuel emissions factors are calculated using the methodology recommended in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 2, Annex 1. The values used are shown in Table 2.2.

To calculate the climate impacts of alternative cement adoption in the PDS scenarios, estimations were made of the annual reduction in both electricity and fuel consumption for clinker production per MMt of cement demanded. Emissions factors for grid electricity and fuel are applied to calculate emissions reductions by applying the following equation for each year:

$$CO_2reduced = (Reduction\theta_{PDS}) \cdot (G_{ef}) + \sum_{each\,fuel} (Reduction\delta_{PDS}) \cdot (\mathrm{F}_{ef})$$

where:

- $CO_2reduced$ is the CO_2-eq emissions reduction associated with the reduction in energy consumption in each PDS scenario.
- $Reduction\theta_{PDS}$ is the reduction in electricity consumption (TWh).
- G_{ef} is the emissions factor (in $t$$CO_2$-eq / TWh) of grid electricity globally for each year.
- $Reduction\delta_{PDS}$ is the reduction in fuel consumption (TJ) in each PDS scenario for each fuel.
- F_{ef} is the fuel emissions factor (in $t$$CO_2$-eq / TJ) for each fuel.

Updating of Grid Emissions Factors

As electricity sector Drawdown solutions are adopted, the grid becomes cleaner, and the high emissions factor shown in Table 2.2 will decline. This is not calculated directly in the model as it is considered an integration issue and covered in separate Project Drawdown reports. This is discussed further in the Integration section of the report.

Indirect Emissions Factor

The model defines indirect emissions with those emissions associated with the production of clinker-alternatives (i.e., embodied emissions). Note that this definition differs from how indirect emissions are modeled in other Drawdown solutions and other modeling efforts. The reduction of cement clinker intensity requires other cementitious, pozzolanic, or filler materials to be used in place to produce a unit of cement. The production of these clinker-alternatives is not emission-free and are captured as indirect emissions inputs to the model.

Other Factors

Other factors that contribute to reductions in greenhouse gas emission are the thermal and electricity intensities of clinker production which depend upon the manufacturing technology used. The climate impacts of these variables are captured in the direct emissions reduction factor but are informed by efficiency factors presented in Table 2.2.

Table 2.2 Climate Inputs

Variable	Unit	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Global average REF Grid Emissions Factor	g CO_2e/kWh	503-593	Depends on year. Starts at High Input in 2020 declines to Low Input in 2050 to represent the decarbonization of the grid in the reference.	12 each year	4
Combined REF Coal Fuel Emissions Factor	t CO_2e/TJ of fuel	N/A	95	1	1
Direct Emissions Factor	t CO_2/tonne clinker	N/A	0.507	1 (derived from stoichiometry of chemical reaction)	1
Indirect Emissions Factor	kg CO_2e/kg material	2,156 – 30,025	30,025	5	2
Electricity Consumed (Conventional)	kWh/t cement	91-103	97.0	2	1
Electricity Consumed (Solution)	kWh/t cement	79-95	88.0	3	2

Fuel Use Efficiency Factor	--	0.646 – 0.656	0.651	2	2

Sources: IEA (2016) ETP, AMPERE Public Database (Version 1.0.0) https://secure.iiasa.ac.at/web-apps/ene/AMPEREDB for Models: GEM-E3, IMAGE and MESSAGE. Note: Project Drawdown data set range is defined by the low and high boundaries which are respectively 1 standard deviation below and above the mean of the collected data points[2].

2.6.2 Financial Inputs

First Cost Factor

The conventional first cost is estimated using data about the average price of cement before the start of the base year. The solution first cost includes data in the form of both cost reduction (in percent form) and the cost of alternative cement technologies with low clinker ratios. Data for the price of CEM II – CEM V (solution technology) is difficult to find for the world, so data for the US is used for the price reduction of cement with SCMs relative to the price of CEM I/Type I OPC (conventional technology). No learning rate factor is applied to cost data since the price of clinker and clinker alternatives is highly variable in today's market. A summary of all cost variables used in the model are included in Table 2.3.

Operational Cost

There is no operational cost associated with cement or alternative cements. Repair and maintenance costs are ignored in this analysis since they are expected to be equivalent between the conventional and solution technologies.

Table 2.3 Financial Inputs for Conventional Technologies

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
First costs (Conventional)	*US$2014/MMt*	$47,525,165 - $102,056,834	$74,790,999	7	6
First costs (Solution)	US$2014/MMt	$69,527,880 - $78,199,302	$73,863,591	5	4

[2] In some cases, the low boundary is negative for a variable that can only be positive, and in these cases the lowest collected data point is used as the "low" boundary.

2.6.3 Technical Inputs

Besides only climate- and financial-oriented variables, some variables have been defined which apply to both climate and financial results. These are called Technical inputs and are described below.

Lifetime Capacity

The lifetime of cement, when used in concrete, is highly dependent upon the application. For example, cement used to make reinforced concrete use in a building may last 50-100 years, depending upon the lifespan of the building. Yet if the cement is used to make concrete used for a road, the lifespan may be less than 40 years. The lifetime capacity of both the conventional and solution technologies are assumed to be the same, since the type of cement typically does not have a significant impact on the design length of concrete.

Average Annual Use

The conventional and solution technologies have a ratio of 1 between the functional unit (1MMt cement) and implementation unit (1 MMt cement), thus the average annual use variable is set to 1 for the analysis.

Table 2.4 Technical Inputs

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Lifetime Capacity (Conventional)	*years*	30 – 60	30	2	1
Lifetime Capacity (Solution)	*years*	30 – 60	30	2	1
Clinker to Cement Ratio (Conventional)	--	0.62 – 0.76	Variable based upon scenario	13	3
Clinker to Cement Ratio (Solution)	--	0.27 – 0.71	Variable based upon scenario	27	10

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Average Annual Use	*MMt cement*	1	1	1	1

2.7 Assumptions

Six overarching assumptions have been made for Project Drawdown models to enable the development and integration of individual model solutions. These are that infrastructure required for solution is available and in-place, policies required are already in-place, no carbon price is modeled, all costs accrue at the level of agency modeled, improvements in technology are not modeled, and that first costs may change according to learning. Full details of core assumptions and methodology will be available at www.drawdown.org. Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution. These are detailed below:

Assumption 1: This model does not specify the exact type of non-clinker material that is used to produce cement. Global supplies of many commonly used supplementary cementitious materials (e.g., fly ash and slag) may not be readily available in the future. Additional low-CO_2 technology, such as limestone-calcined clay cement systems exist, although they are not currently adopted widely. This model assumes that there is sufficient supply of non-clinker materials in all regions of the world, and only models a reduction of clinker content.

Assumption 2: Carbonation is a well-studied phenomenon in cement sustainability (Souto-Martinez et al., 2017) and has been shown to sequester a non-trivial amount of carbon dioxide at the global scale (Xi et al., 2016). This analysis excludes carbonation from its scope since the extent of concrete carbonation is difficult to model at the global scale.

Assumption 3: Alternative fuels, such as biomass, are not considered by the model. The model assumes that coal will continue to be the primary fuel type used by the cement industry because of the high temperatures required to calcine limestone.

Assumption 4: Only low-clinker cements are considered in the analysis; alternative cement systems (e.g., belite cements and alkali-activated cements) are ignored. Although alternative cement systems have been shown to be viable as a technology, they do not have large market shares and therefore are not included in the analysis. However, they do have significant potential to reduce carbon dioxide emissions.

2.8 Integration

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

2.9 Limitations/Further Development

This analysis does not robustly evaluate the potential limitations of the supply of non-clinker materials used in cement. Regionally, certain precursor materials may have larger supplies than others, and thus different indirect emissions. This model averages across all indirect emissions for the solution technology and does not take into account the increased adoption of any particular clinker alternative. This limitation serves as an opportunity to develop regional models to evaluate the potential to use local clinker-alternatives to create cement. Additionally, no end-of-life climate impacts from cement were modeled. It is assumed that only the "cradle-to-gate" emissions profiles of the conventional and solution technologies vary. Inclusion of end-of-life impacts may change the extent to which alternative cements can reduce carbon dioxide emissions but due to a lack of data, these life cycle stages were ignored.

3 Results

3.1 Adoption

Below are shown the world adoptions of the solution in some key years of analysis in functional units and percent for the three Project Drawdown scenarios. Adoption of Alternative Cements is modeled through the clinker-to-cement ratio. Thus, the total adoption of the TAM is 100%, with the clinker-to-cement ratio in 2050 being variable for each PDS. Furthermore, the adoption is assumed to be linear between 2020 and 2050.

Table 3.1 World Adoption of the Solution

Solution	Units	Base Year (2020)	World Adoption by 2050		
			Plausible	Drawdown	Optimum
Alternative Cements	*clinker-to-cement ratio*	0.69	0.60	0.46	0.27
	% of TAM	100%	100%	100%	100%

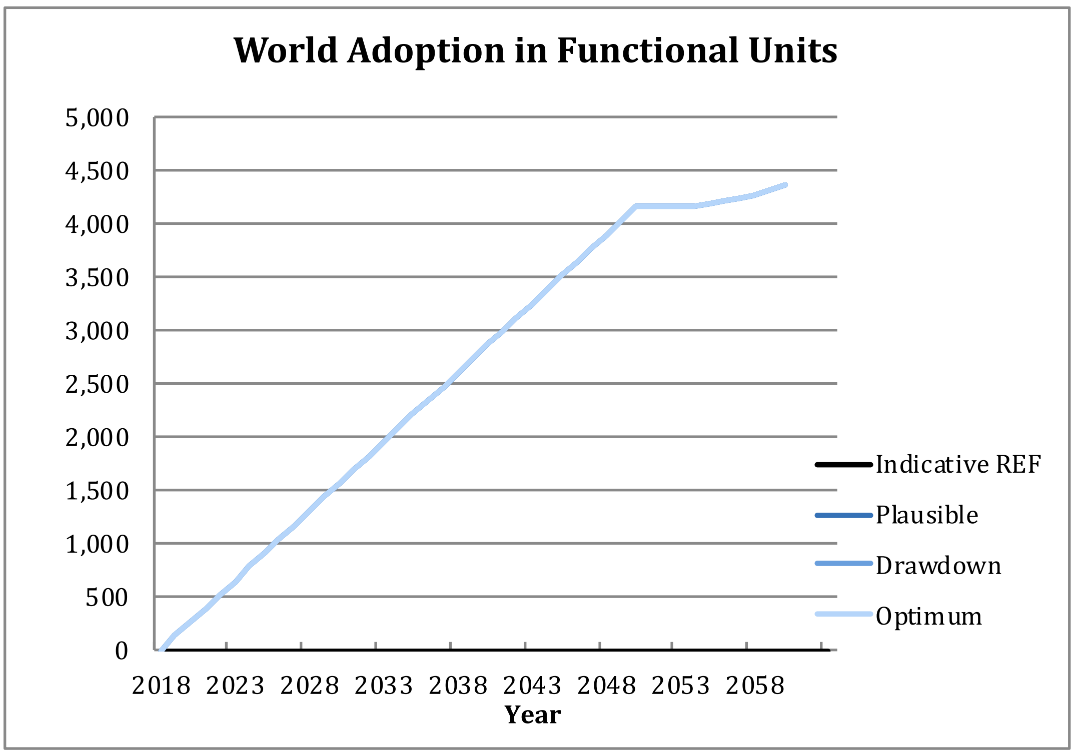

Figure 3.1 World Annual Adoption 2020-2050

3.2 Climate Impacts

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

Table 3.2 Climate Impacts

Scenario	Maximum Annual Emissions Reduction	Total Atmospheric CO_2-eq Reduction	Emissions Reduction in 2050
	(Gt CO_2-eq/yr.)	Gt CO_2-eq (2020-2050)	*(Gt CO_2-eq/year)*
Plausible	0.484	7.98	0.484
Drawdown	0.978	16.10	0.978
Optimum	1.654	27.09	1.654

The solution was integrated with all other Project Drawdown solutions and may have different emissions results from the models. This is due to adjustments caused by interactions among solutions that limit full adoption (such as by feedstock or demand limits) or that limit the full benefit of some solutions (such as reduced individual solution impact when technologies are combined).

Table 3.3 Impacts on Atmospheric Concentrations of CO_2-eq

Scenario	GHG Concentration Change in 2050	GHG Concentration Rate of Change in 2050
	PPM CO_2-eq (2050)	*PPM CO_2-eq change from 2049-2050*
Plausible	0.671	0.038
Drawdown	1.355	0.076
Optimum	2.279	0.127

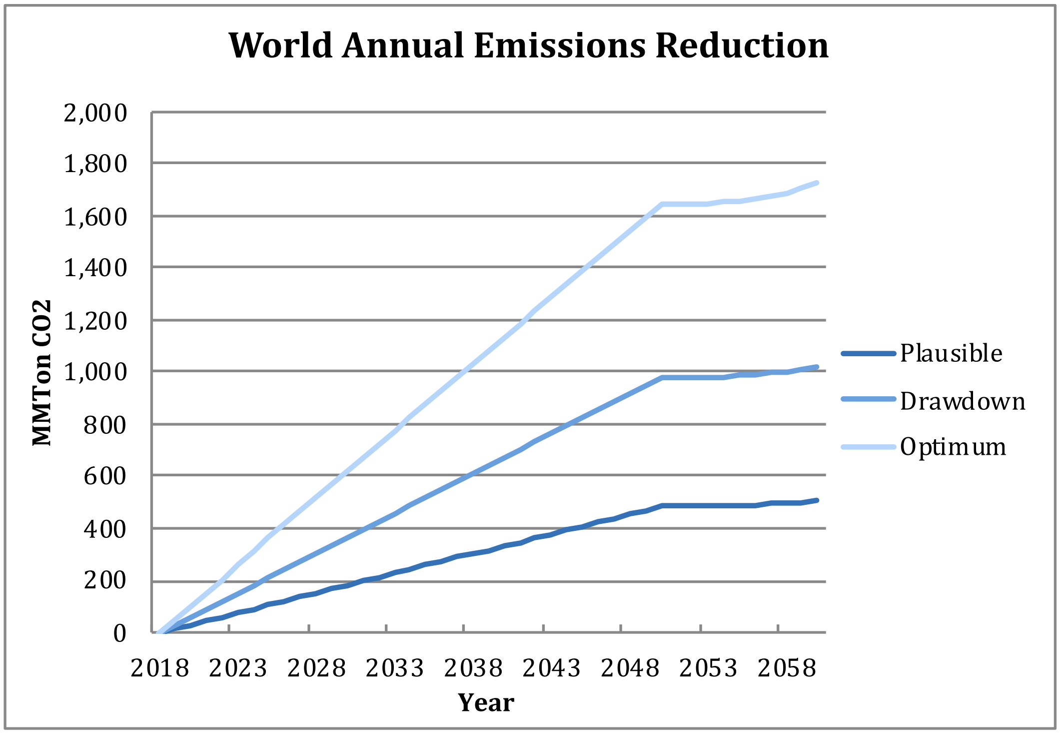

Figure 3.2 World Annual Greenhouse Gas Emissions Reduction

3.3 Financial Impacts

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

Table 3.4 Financial Impacts

Scenario	Cumulative First Cost	Marginal First Cost	Net Operating Savings	Lifetime Cashflow Savings NPV (of All Implementation Units)
	2015-2050 Billion USD	*2015-2050 Billion USD*	*2020-2050 Billion USD*	*Billion USD*
Plausible	5045.66	63.46	--	8.46
Drawdown	5045.66	63.46	--	8.46

Scenario	Cumulative First Cost	Marginal First Cost	Net Operating Savings	Lifetime Cashflow Savings NPV (of All Implementation Units)
	2015-2050 Billion USD	*2015-2050 Billion USD*	*2020-2050 Billion USD*	*Billion USD*
Optimum	5045.66	63.46	--	8.46

4 Discussion

By adopting alternative cements, significant reductions in global carbon dioxide emissions can be achieved between 2020 and 2050. Both PDS1 and PDS2 highlight pathways for the global cement community to achieve a low-carbon future. Since the cement manufacturing industry in present day is relatively efficient, the opportunities for emissions reductions primarily lie in reducing the quantity of clinker produced. Manufacturing efficiencies only account for about 10% of potential carbon savings, whereas reduction in the average clinker to cement ratio account for upwards of 90% of the potential carbon savings. Data for the market share of each cement type is limited, or out of date, thus the inclusion of more up to date details of the market can inform a more precise level of future adoption. Additionally, the model can be improved through the inclusion of additional financial data for both the conventional and solution technologies. Due to the high variability of cement cost data, it may be difficult to come by at the global scale.

4.1 Limitations

The results of this model show that significant reductions in carbon emissions can be achieved through the adoption of alternative cement technologies, yet, the interpretation of these results requires a discussion of the limitations. This model does not account for any differences in the end-of-life emissions profiles for either the conventional or solution technology. The technologies each have different potentials for carbon sequestration at end-of-life based upon each's carbonation mechanics. Due to the complexity and uncertainty associated with modeling the end-of-life carbonation, it was not included in this analysis.

Additionally, the supply of clinker alternative materials was not modeled, and thus adoption of alternative cements was not bounded by any constraints to supply. In reality, not all regions of the world may have access to the appropriate precursor materials required to produce alternative cements. For example, if a region does not have high steel production, it will not have large quantities of slag. These differences, and additional climate impacts associated with further transportation of materials were not considered.

Finally, the model currently uses a single cost for all low clinker cements, therefore the financial analysis does not differ for each scenario. As more data is collected in future on clinker material, the costs for the different clinker ratios and the costs associated with different CEM standards locational variability can be incorporated into the model.

4.2 BENCHMARKS

The results of the Project Drawdown analysis were compared against two other studies which have modeled emissions reductions as a result of the adoption of alternative cements. Miller et al. (2018) modeled LC3 cements to have a global clinker-to-cement ratio of 0.5. With 100% adoption of LC3, about 10.4 Gt CO_2e could be avoided between 2014 and 2050. This scenario, in contrast to the PDS scenarios, does not take into account the adoption of more efficient manufacturing processes. Additionally, the IEA 2DS Low Variability scenario estimates that with modest reductions to the clinker to cement ratio and adoption of efficient manufacturing technologies, 7.7 Gt CO_2e could be avoided between 2014 and 2050. The PDS1 scenario aligns closely with the IEA 2DS Low Variability scenario, with the difference attributed to different TAMs being used. The PDS2 scenario tracks higher, closer to Miller and colleague's (2018) estimates as a result of increased adoption (lower clinker to cement ratios). The PDS 3 is the optimum scenario where the cement community transitions significantly away from clinker to produce cements, which accounts for it being ambitious when compared to other benchmarks.

Table 4.1 Benchmarks

Source and Scenario	Emissions reduction in 2050 (Gt CO_2e)	Clinker-to-cement ratio
Miller et al. 2018 (LC3)	10.4	0.5
IEA 2DS Low Variability	7.7	0.64

Source and Scenario	Emissions reduction in 2050 (Gt CO_2e)	Clinker-to-cement ratio
Project Drawdown – Plausible Scenario (PDS1)	7.98	0.60
Project Drawdown – Drawdown Scenario (PDS2)	16.10	0.46
Project Drawdown – Optimum Scenario (PDS3)	27.09	0.27

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6 GLOSSARY

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

Approximate PPM Equivalent – the reduction in atmospheric concentration of CO_2 (in **PPM**) that is expected to result if the **PDS Scenario** occurs. This assumes a discrete avoided pulse model based on the Bern Carbon Cycle model.

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

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

Carbonation – a chemical process in which carbon dioxide reacts with the calcium oxide present in concrete to form calcium carbonate. This process takes decades to occur and decreases the pH of concrete. If not controlled for, carbonation can induce the corrosion of reinforcing stel.

Cement – a substance, in the form of a powder, that is produces from the calcining of lime and clay. It is used mixed with water and aggregate (such as sand and/or gravel) to produce **mortar** and **concrete**. Ordinary portland cement (OPC) is the most common type of cement produces from portland limestone.

Clinker – a solid material produced from the heating of limestone, iron, silica, and alumina during the manufacturing of ordinary portland cement. It is an intermediary product that contains the necessary minerals for cement hydration.

Concrete – a construction material consisting of gravel, sand, **cement**, and water, which are mixed together and placed into forms. In a building, concrete elements can include columns, beams, floors, roofs, and foundations. Concrete is also used in infrastructure applications such as dams, bridges, and roads.

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

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

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

Emissions Factor– the average normalized emissions resulting from consumption of a unit of electricity across the global grid. Typical units are kg CO_2e/kWh.

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

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

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

Ground Granulated Blast-Furnace Slag (GGBFS) – a byproduct of iron and steel making. It is produced from the quenching of molten iron in water. The slag is then ground into a fine powder and used as a cementitious material due to its chemical properties.

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

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

Kiln – a high temperature furnace used to calcinate limestone and clay. Common types of cement kilns include wet-kilns and dry-kilns.

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

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

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

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

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

Mortar – a mixture of **cement**, lime, sand, and water used to secure masonry units (i.e., bricks or stones) to one another.

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

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

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

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

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

PDS/ Project Drawdown Scenario – this is the high growth scenario for adoption of the solution

Pozzolan – a class of siliceous and aluminous materials that react with calcium hydroxide (a hydration product of cement hydration) which form cementitious compounds. Pozzolans can occur naturally, such as many clays, can be industrial by-products such as fly ash or silica fume, or be agricultural by-products such as rice husk ash.

PPB/ Parts per Billion – a measure of concentration for atmospheric gases. 10 million PPB = 1%.

PPM/ Parts per Million – a measure of concentration for atmospheric gases. 10 thousand PPM = 1%.

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

Regrets solution has a positive impact on overall carbon emissions being therefore considered in some scenarios; however, the social and environmental costs could be harmful and high.

Replacement Time- the length of time in years, from installation/acquisition/setup of the solution through usage until a new installation/acquisition/setup is required to replace the earlier one. This is calculated as the ratio of **Lifetime Capacity** and the **Average Annual Use**.

TAM/ Total Addressable Market – represents the total potential market of functional demand provided by the technologies and practices under investigation, adjusting for estimated economic and population growth. For this solutions sector, it represents world and regional total addressable markets for electricity generation technologies in which the solutions are considered.

Total Emissions Reduction – the sum of grid, fuel, indirect, and other direct emissions reductions over the analysis period. The emissions reduction of each of these is the difference between the emissions that would have resulted in the **REF Scenario** (from both solution and conventional) and the emissions that would result in the **PDS Scenario**. These may also be considered as "emissions avoided" as they may have occurred in the REF Scenario, but not in the PDS Scenario.

Transition solutions are considered till better technologies and less impactful are more cost effective and mature.

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