Prospects for Expanding the Use of Supplementary Cementitious Materials in California

Prepared For:
Coalition for Sustainable Cement Manufacturing & Environment

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The Coalition for Sustainable Cement Manufacturing & Environment is a coalition of all six cement manufacturers operating the 10 cement plants in the state of California. The Coalition includes California Portland Cement Company, Cemex, Inc., Lehigh Southwest Cement Company, Mitsubishi Cement Corporation, National Cement Company of California Inc., and Texas Industries, Inc.

EXECUTIVE SUMMARY

With the assistance of effective public policies, the cement industry can play a multi-faceted role in California's efforts to build an environmentally and economically sustainable future. Although cement manufacturing is an energy-intensive process that accounts for approximately 2.5% of California's greenhouse gas ("GHG") emissions, it is also an essential ingredient in concrete – a durable, indispensible building block of modern economies with many "green qualities" that directly contribute to reducing California's carbon footprint. Consequently, any successful program to regulate GHG emissions must not only incentivize cost-effective emissions reductions throughout the cement-concrete supply chain, but must also incentivize those reductions that result from the increased use of concrete products in California's buildings, roads, bridges, and other infrastructure.

The expanded use of supplementary cementitious materials ("SCMs") represents one pathway for achieving the twin objectives of reducing the GHG footprint associated with cement production while expanding the deployment of concrete products in California. SCMs include a wide range of industrial byproducts and mined materials (e.g., coal fly ash, steel blast furnace slag, silica fume, and pozzolonic materials), all of which have inherent cementitious properties or develop cementitious properties when hydrated in the presence of portland cement. When blended with cement in concrete, SCMs contribute important environmental, economic, and performance benefits.

Despite these potential benefits, however, a variety of technical, market, regulatory, legal, and policy barriers continue to limit the deployment of SCMs in the California marketplace beyond existing levels. In the short and medium terms, some of these barriers can be addressed through regulatory modifications and policy instruments that encourage all stakeholders within the cement-concrete supply chain – including environmental regulators, SCM suppliers, cement manufacturers, concrete manufacturers, architects, engineers, specifiers, and owners of the constructed environment – to optimize SCM usage.

In the long term, however, fundamental economic and policy trends are likely to create an environment of extreme uncertainty in SCM markets. For instance,

- The adoption of federal climate change policy is likely to simultaneously decrease the supply and increase the demand for fly ash and slag – resulting in exceedingly tight market conditions for the two most commonly used SCMs. Supplies would be particularly tight in the California market, given its distance from sources of key SCM supplies.
- Increasingly stringent mercury emissions controls at coal-fired power plants are likely to reduce the quantity of fly ash suitable for use in concrete.
- The development and deployment of cost-effective beneficiation technologies may provide an "upside surprise" for fly ash supplies in the long term, though beneficiation also requires greater costs and environmental burdens due to processing.

This environment of uncertainty has recently been compounded by a large-scale coal ash spill in Tennessee, which has prompted the U.S. EPA to consider labeling fly ash as a hazardous waste. Even if such a ruling does not legally, technically, or economically preclude the use of fly ash in concrete, the public stigma alone could effectively compromise the viability of fly ash substitution strategies.

Within this backdrop of uncertainty, California regulators must endeavor to design policies that remove impediments to increased SCM consumption and optimize SCM utilization in a manner that is equitable and consistent with evolving market conditions in the short, medium, and long terms. In the absence of a deliberate and coordinated effort to align policy instruments throughout the cement-concrete supply chain – including carbon price incentives, codes, standards, procurement guidelines, and consumer education – SCM utilization in California is likely to fall short of its full potential, regardless of prevailing market conditions. In the presence of supportive policies that remove barriers to deployment and leverage flexible market-based mechanisms to provide incentives throughout the cement-concrete supply chain, however, the environmentally and economically efficient use of SCMs in California is likely to be optimized in a manner consistent within highly dynamic, uncertain, and evolving market conditions.

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I. INTRODUCTION

With the assistance of effective public policies, the cement industry can play a multi-faceted role in California's efforts to build an environmentally and economically sustainable future. Although cement manufacturing is an energy-intensive process that accounts for approximately 2.5% of California's greenhouse gas ("GHG") emissions[1], it is also an essential ingredient in concrete – a durable, indispensible building block of modern economies with many "green qualities" that directly contribute to lowering California's GHG emissions through:

- **Enhanced Building Energy Efficiency:** Concrete's high thermal mass allows it to store heat better than other building materials, resulting in enhanced energy efficiency for buildings constructed with concrete walls.[2] As such, concrete structures require less energy to heat and cool than other building types with similar insulation levels, thus lowering energy-related CO_2 emissions.
- **Improved Fuel Efficiency:** Due to its rigidity, concrete pavement enhances fuel efficiency of vehicles when compared to more flexible and rough surface alternative pavement materials.[3] Improved vehicle highway mileage directly reduces CO_2 emissions.
- **Reduced Road Maintenance:** Concrete pavements are more durable than asphalt pavements, and require less energy intensive repair, maintenance, and refurbishment. Additional CO_2 emissions are reduced from a lower incidence of construction-related congestion and bottlenecks.
- **Reduced Electricity Demand:** Light-colored concrete reflects light better than dark materials, and evidence suggests that concrete sidewalks, parking lots, and streets need 36% less lighting at night than asphalt equivalents.[4]
- **Mitigated Urban Heat Island Effect:** Improved reflectivity also means that concrete reduces the absorption of solar energy and lowers ambient temperatures, particularly in urban environments.[5] According to the U.S. Environmental Protection Agency ("EPA"), concrete exhibits significantly more favorable "cooling" characteristics than any other material examined, including asphalt.[6]
- **GHG Absorption Upon Recycling:** Several studies indicate that 28%-39% of the volume of CO_2 emitted during the cement calcination process is reabsorbed by concrete during its service life, with this percentage increasing significantly if concrete is crushed prior to recycling.[7]

In short, environmental assessments that focus exclusively on the cement production process are likely to significantly overestimate the net GHG emissions associated with the full cement product lifecycle, including its use in concrete and its ultimate removal from service. Policy frameworks that fail to accurately account for these "cradle-to-grave" impacts are likely to incentivize the consumption of environmentally inferior alternatives to concrete. Simply put, an effective regulatory program must not only incentivize GHG reductions throughout the cement-concrete supply chain in a manner that is technically feasible, cost effective, and minimizes the risk of leakage, but must also incentivize reductions that result from the increased use of concrete products in California's buildings, roads, bridges, and other infrastructure.

The expanded use of supplementary cementitious materials ("SCMs") represents one pathway for achieving the twin objectives of reducing the GHG footprint associated with cement while expanding the deployment of concrete products in California. SCMs include a wide range of industrial byproducts and mined materials (e.g., coal fly ash, steel blast furnace slag, silica fume, and pozzolonic materials), all of which have inherent cementitious properties or develop cementitious properties when hydrated in the presence of portland cement. When blended with cement for use in concrete, SCMs contribute several important environmental, economic, and performance benefits, including:

- **Environmental Benefits:** SCMs can reduce requirements for cement clinker, the principle binding agent in concrete and the primary source of GHG emissions in the cement-concrete supply chain. Furthermore, SCMs can increase the quantity of cementitious material in the marketplace, which expands the potential supply chain for concrete. Finally, given that many SCMs are waste byproducts, SCM usage can reduce landfill requirements and the associated environmental impacts.[8]
- **Economic Benefits:** SCMs serve as "extenders" for locally produced cement, enabling cement manufacturers to cost-effectively meet consumers' needs during construction booms without undertaking expensive investments in new production facilities that may prove uneconomic as demand decreases.
- **Performance Benefits:** When used properly, SCMs can significantly augment concrete performance, improving finishability, workability, and pumpability of unhardened concrete, as well as enhancing the strength and durability of hardened concrete. Although not a "one-size-fits-all" solution, the performance benefits of SCM substitution are recognized within certain construction parameters.

The California cement industry is acutely aware of these benefits, and continues to be a proponent of the use of SCMs in concrete.

Despite its benefits, however, a variety of factors continue to limit the deployment of SCMs in the California marketplace beyond existing levels, including technical, market, regulatory, legal, and policy barriers. In the short and medium terms, many of these barriers can be addressed through regulatory modifications and policy instruments that encourage all stakeholders within the cement-concrete supply chain – including environmental regulators, SCM suppliers, cement manufacturers, concrete manufacturers, architects, engineers, specifiers, and owners of the constructed environment – to optimize SCM usage.

In the long term, however, fundamental economic and policy trends are likely to create new challenges that will strain SCM markets. For instance,

- Federal climate change legislation is likely to reduce conventional coal-fired electric power generation and integrated steel manufacturing – the two principal sources of commonly utilized SCMs, namely coal fly ash and blast furnace slag.
- Federal climate change legislation is also likely to increase the demand for SCMs due to their capacity to decrease GHG emissions and, therefore, reduce compliance costs.

- Similar supply and demand conditions are likely to materialize globally as the international community endeavors to stabilize GHG concentrations in the atmosphere.

The cumulative impact of these trends on the California cement and concrete industries will only be compounded by the state's distance from key sources of fly ash and slag, making the state a marginal consumer in both the domestic and international markets for SCMs.

With these issues and complexities in mind, the purpose of this study is to provide policymakers with information and analysis necessary to develop regulations and design instruments that have the greatest potential to remove impediments to increased SCM consumption in California and optimize SCM utilization in a manner that is consistent with evolving market conditions in the short, medium, and long terms. The study is organized as follows. Section II provides background information on the role of SCMs in the cement-concrete supply chain. Section III identifies key barriers to increased SCM utilization in California. Section IV examines the implications of environmental policy trends on the future supply of fly ash in the California market. Section V concludes with a discussion of the implications for designing policy instruments intended to increase SCM usage in California.

II. BACKGROUND: THE CEMENT-CONCRETE SUPPLY CHAIN

2.1 Cement

Cement manufacturing is a mature, complex, and highly refined technical process. Some 80 separate and continuous operations are required to generate complex chemical reactions of a closely controlled combination of multiple ingredients, including calcium, silicon, aluminum, iron, and gypsum. Such precision requires that each stage in the cement manufacturing process be closely monitored and frequently inspected, and that the finished product be routinely tested to ensure that it meets technical specifications.

In the most elementary sense, cement manufacturing involves a four-stage process:

- **Quarrying & Crushing:** Limestone (*i.e.*, calcium carbonate) and other raw materials are extracted from a quarry, crushed to more manageable sizes, and stockpiled for eventual use.
- **Raw Material Preparation:** Crushed limestone and other raw materials are recovered from stockpiles, ground into a fine powder, proportioned to achieve the correct chemical composition, and blended in a homogenization process to form a consistent raw meal.
- **Pyroprocessing:** The raw meal is heated at extreme temperatures -- separating limestone into calcium oxide and carbon dioxide, with the calcium oxide reacting with other components to form cement clinker and the carbon dioxide being emitted.
- **Finish Grinding:** The raw cement clinker is subjected to mechanical processes that grind it with a small proportion of limestone and gypsum, which controls the rate of hydration, to produce an ultra-fine powder known as portland cement (referred to hereafter as "cement").

The heart of the cement manufacturing process is the kiln – a slightly inclined, slowly rotating brick lined steel tube where the pyroprocessing stage takes place. Raw materials are fed into the upper end of the kiln and heated to temperatures of 2,700-2,800 degrees Fahrenheit. Fuel is supplied at the lower end of the kiln and the heated raw materials are transported downhill as the kiln rotates. Many fuels can be used in the pyroprocessing stage, but coal and petroleum coke (a byproduct of the petroleum refining process) have been the predominant fuels due to costs, availability, and superior performance characteristics in kiln operations.

Although this basic four-stage process is common to all cement production, critical differences in manufacturing technology exist. In the U.S., two distinct types of process technologies are used: (1) the "wet process" and (2) the "dry process."[9] The wet process consists of suspending raw materials in water to form slurry, which is then fed into the kiln. In contrast, the dry process consists of grinding dry raw materials into a manageable powder before being fed into the kiln.

The basic dry process technology, known as "long dry," is significantly more energy efficient than wet process technology. Moreover, a dry process plant can further improve efficiency by installing a series of preheaters, which recover thermal waste gases to heat the raw materials before entering the kiln, or diverting fuel to a calciner vessel at the base of the preheater tower. Some cement plants also use excess waste heat to generate electricity, which further improves plant efficiencies. Although the wet process is still used in the U.S. and throughout the world, all cement plants in California utilize dry process technology.

Cement production results in GHG emissions through three basic activities. Common to all cement production is the chemical reaction that occurs when the calcium carbonate ("$CaCO_3$") in limestone is heated and breaks down into lime ("CaO") and carbon dioxide ("CO_2") — a process known as "calcination." Calcination accounts for approximately 57% of CO_2 emissions in the California cement industry.[10] Emissions from non-calcination activities, which primarily result from the combustion of coal and other fuels in the pyroprocessing stage, account for 37% of CO_2 emissions in the California cement industry. Indirect emissions from the consumption of electricity, which are heavily dependent on the GHG emissions profile of the electric power generator, account for the remaining balance (6%) of CO_2 emissions.

The cement industry is well aware of the energy intensity of its manufacturing processes, and has worked diligently to innovate, invest in cutting edge technologies, and consume energy as efficiently and responsibly as possible. Between 1974 and 2008, the U.S. cement industry increased its use of dry process technology from 42% of total capacity to 84% of total capacity.[11] As a result of these capital investments and improved operational practices, average CO_2 emissions per ton of cement decreased by approximately 33% during the same period.[12] In 2006, the average U.S. cement plant emitted 0.89 metric tons of CO_2 per metric ton of cement produced, while the average California cement plant emitted 0.86 metric tons of CO_2 per metric ton of cement produced — making the California cement industry one of the most energy and environmentally efficient cement industries in the nation.[13]

2.2 Concrete

Concrete is the most widely used building material and the second most consumed substance on earth, after water.[14] In fact, global concrete consumption is estimated to be nearly twice that of all other building materials combined, including wood, steel, plastic, and aluminum.[15] The extensive use of concrete stems from its availability, versatility, effectiveness, performance, and economy as compared to alternative building materials.

Concrete is typically made up of 10-20% cement by weight, which functions primarily as the "glue" that binds the remaining aggregate materials together.[16] The remainder of concrete's content by weight consists of water, coarse and fine aggregates (e.g., sand), and air. Importantly, there is no "standard" concrete mix. Depending on a variety of constraints, such as the type of structure, soil conditions, weather, and material reactivity, concrete suppliers and mix designers use materials from numerous sources and in varying proportions. As a result, concrete mixes are not identical in composition, but are designed to meet certain regulatory and engineering specifications.

The GHG emissions embodied in concrete are primarily a function of its cement content, and the proportion of cement to aggregates in a particular concrete mix varies according to its intended use and performance needs, including strength and durability requirements.[17] As a result of such a highly prescriptive market, there are a wide variety of concrete mixes and there is significant variation in the emissions embodied in different concrete products. A given concrete manufacturer's ability to produce relatively low-carbon concrete is heavily dependent upon the technical specifications and performance needs of the end user. In this sense, concrete manufacturers do not directly control the GHG emissions of concrete products, but effectively serve as intermediaries between cement producers and end users.

2.3 Supplementary Cementitious Materials

Supplementary cementitious materials are used widely throughout the U.S. as additives to concrete, although regional discrepancies in utilization occur based on the availability and affordability of materials. SCMs can be introduced upstream at the cement facility to produce "blended cement" or downstream at the concrete manufacturer to produce concrete products. However, the point at which SCMs are introduced into the supply chain can vary substantially based on economics and market conditions.

In many parts of the U.S., including California, virtually all SCM blending occurs at the concrete facility. This practice provides California concrete suppliers with a high degree of flexibility in meeting the diverse needs of their customer base – enabling them to produce a variety of concrete designs, from the 16,000 psi concrete used in high-rise buildings to 4,000 psi concrete used for water treatment plants, and from high early strength concretes used for road repairs to very lean large aggregate concretes used in dams.

There are four primary types of SCMs: (1) coal fly ash, (2) blast furnace slag, (3) silica fume, and (4) natural pozzolans, such as metakaolin. For a variety of reasons, including availability and affordability of supply, SCM utilization varies greatly across material type. In a 1998 survey conducted by the National Ready Mixed Concrete Association ("NRMCA"), respondents reported using fly ash in a majority of the concrete produced (54%), with significantly less utilization of slag (9%), natural pozzolans (0.4%), and blended cement (0.3%).[18] The NRMCA study also showed that 94% of respondents used fly ash in at least some of their concrete and, on average, 15% of concrete consumed in the U.S. is comprised of SCMs.

The following sections provide an overview of the four primary types of SCMs used in concrete, including the unique benefits, challenges, and limitations associated with each.

2.3.1 Fly Ash

Fly ash, the most widely-used SCM in the U.S., is a fine mineral ash that is produced as a byproduct of coal-fired electric power generation. There are two main types of fly ash:

- "Class C" fly ash, which hardens when hydrated, typically consists of 10%-30% calcium oxide by content.
- "Class F" fly ash, which hardens only when hydrated in the presence of cement or lime, typically consists of less than 10% calcium oxide by content.[19]

When mixed with concrete, fly ash can actually improve the performance of the finished product – such as enhanced workability, strength, and durability – although characteristics may vary significantly depending on the coal source. Under certain conditions, however, fly ash may result in diminished performance, particularly when the replacement rate for cement exceeds the standard practice of 20–30%.[20] Furthermore, the addition of fly ash prolongs both the setting time of concrete and the rate at which it initially gains strength, although long-term strength gains can be greater. As a result, fast-track construction projects, which typically require greater levels of strength in the early stages of construction, use concretes with little or no fly ash.

The amount of fly ash produced as a byproduct of electric power generation depends heavily on the ash content of the coal combusted, which typically varies between 5-10%.[21] Generally speaking, approximately 80% of the ash content of coal is expelled in the exhaust gasses in the form of fly ash. In 2008, U.S. power plants generated approximately 65.7 MMT of fly ash.[22] Of this amount, approximately 17% (11.4 MMT) was used as an additive in concrete, roughly 24% (15.9 MMT) was beneficially used in other applications, and 58% (38.4 MMT) was disposed of in landfills.[23] In light of this high disposal rate, however, it must be noted that most fly ash deposited in landfills would not otherwise have been suitable for use in concrete.

Coal-fired electric power generation and, thus, supplies of fly ash are highly concentrated in regions east of the Mississippi River, including states such as Georgia, Illinois, Indiana, Ohio, North Carolina, and West Virginia. West of the Mississippi River, significant fly ash production occurs in Texas and New Mexico. Virtually no fly ash is produced in California, as there is no coal-fired electricity produced in California.

2.3.2 Slag Cement

Slag cement, also known as ground granulated blast furnace slag ("GGBFS"), is a byproduct of the steel refining process. As iron ore is melted in a blast furnace, molten slag rises to the top. The molten slag is then skimmed off and quenched with water to produce granulated blast furnace slag, which is finally ground into slag cement. Slag cement is classified by its reactivity, which is mainly a function of its fineness.

Slag is usually mixed with cement in larger amounts than fly ash, comprising 25-50% of concrete's cementitious material by weight, although in special limited cases (such as mass concrete manufacture) it can account for up to 70%.[24] Slag contributes additional beneficial properties to concrete in the form of enhanced workability and reduced permeability, which also slows the corrosive process on steel in reinforced concrete. Additionally, slag lightens the color of cement, which improves its light reflectivity and enhances energy efficiency. At elevated dosages, however, slag can retard the setting time of concrete and lessen its early strength, although slag-blended concretes typically gain greater strength over the long run than concretes containing only cement.[25]

Although approximately 16.5 MMT of slag are produced in the U.S. annually, only 15% of the blast furnaces possess the refining equipment necessary to generate the properties required for use in concrete.[26] It is estimated that approximately 4.0 MMT of slag cement was used in concrete in the U.S. in 2007, with 2.4 MMT originating from domestic blast furnaces and 1.6 MMT originating from foreign sources.[27]

Supplies of slag are concentrated in the eastern portion of the US, consistent with the location of the nation's remaining blast furnace steel mills. Due to prohibitively high costs of transporting slag cross-country, the majority of slag available on the West Coast must be imported from Asia, ground into slag cement in Seattle, then shipped to ready-mix concrete plants. Although there is no readily available data for slag use in California, based on the state's relatively low number of slag cement supply terminals and the high cost and regulatory burden to develop slag processing facilities in California, it does not appear to be a commonly used SCM.[28]

According to the Portland Cement Association ("PCA"), domestic slag supply conditions are likely to constrain its expanded use in the U.S. in the context of aging blast furnace facilities and disincentives to modernize or invest in refining equipment.[29] This suggests that an expansion of slag as a cement substitute will depend on imported slag. State, regional, or federal climate change legislation that results in the loss of domestic blast-furnace steel production is only likely to compound this trend.

2.3.3 Silica Fume

Silica fume, which consists of exceptionally fine silicon dioxide particles, is a byproduct of silicon metal manufacture. Silica fume typically comprises between 5-12% of cementitious materials in concrete by mass.[30] Approximately 50-60% of the silica fume produced in the U.S. in 2004 (100,000-120,000 MT) was used as an SCM additive in concrete.[31]

Silica fume's properties make it uniquely suited for creating high strength, high performance concrete for very specialized applications.[32] It strengthens finished concrete against compression, reduces permeability, and enhances durability.[33] It is occasionally used for construction projects exposed to seawater and high levels of deicing chemicals, such as bridge decks. Generally speaking, however, silica fume is rarely used in concrete due to its extremely high cost relative to portland cement and other available SCMs, and extremely limited market quantities. There are no known sources of silica fume in California.

2.3.4 Natural Pozzolans

Natural pozzolans are naturally-occurring SCMs, typically of volcanic origin. Commercially available pozzolans in the U.S. include calcined shale or clay and metakaolin, a popular variety of natural pozzolan. Metakaolin is produced by the low temperature calcination of high purity kaolin clay. Like silica fume, metakaolin is relatively expensive and used only for special applications where very low permeability or very high strength concretes are required. In such concretes, metakaolin typically makes up 5-15% by mass of total cementitious materials.[34] Metakaolin is used more as an additive to concrete rather than as a replacement of cement.[35]

To varying degrees, natural pozzolans require more mining and processing than alternative SCMs, and most currently available sources of commercial levels of natural pozzolans entail high energy consumption and CO_2 emissions from processing, relative to other SCMs. Also unlike other SCMs, natural pozzolans increase water demand in concrete processing, rendering the majority of pozzolans impractical for use in most general-use concretes. New products under development, however, are seeking to reduce the energy intensity and high water demand of natural pozzolans, which could potentially improve their performance and desirability as an alternative SCM.

Natural pozzolans are not as widely used as other SCMs. There are no current production sources of metakaolin in California, though there are over 900 known sources of mineral deposits in the state. To date, commercial production of natural pozzolans in the U.S. has been limited to less than ten locations.[36]

III. BARRIERS TO THE EXPANDED USE OF SCMS IN CALIFORNIA

As previously noted, the blending of SCMs in concrete can result in a varied and significant set of benefits, including improved performance, decreased energy consumption, and lower GHG emissions. Furthermore, some SCMs, such as fly ash, may cost less than cement – providing a financial incentive for concrete manufacturers to increase usage, especially during periods of high demand. Despite these advantages, evidence suggests that California’s SCM utilization rate remains below national averages. For instance, in a 2007 survey, the California Construction and Industrial Minerals Association (“CalCIMA”) found that SCMs represented approximately 9% of the cementitious material used in concrete produced in California, nearly all of which was fly ash (for a summary of the survey results, see Appendix A).[37]

Although just slightly lower than the U.S. average, California’s SCM utilization rate is surprising given that CalTrans, which represents just over one-third of the state’s concrete consumption[38], has mandated a minimum SCM content of 25% of cementitious material used in concretes. Given the apparent performance and economic advantages of SCMs, such data suggests that other factors may be inhibiting the deployment of SCMs in the California marketplace. The following section reviews several of the most significant barriers to more widespread SCM usage in California.

3.1 Technical Barriers: Consistency

A key barrier to expanding the use of SCMs in concrete is the intermittent availability of consistent materials that meet rigorous technical specifications for use. In particular, the properties of fly ash supplies are heavily influenced by a variety of factors that make it difficult to maintain consistency. The quality of fly ash product typically varies from one electric power plant to another, as power generators adjust plant operations (*e.g.*, the type of coal combusted) in order to achieve primary objectives (*e.g.*, generating electricity at appropriate times, minimizing fuel prices or meeting emissions standards), which are often met at the expense of producing a consistent quality and steady supply of fly ash.[39] Fly ash quality can also vary within a single plant, as plant operators adjust the configuration of burners and the source of the plant's coal, sometimes on an hourly or daily basis.

In the post-production phase, limited capacity at storage silos can require that fly ash be stored in less than ideal conditions, where it comingles with other materials and particles.[40] Recognizing the difficulty that suppliers have in maintaining fly ash in completely separate silos and also the potential physical implications of mixing intermingled fly ash with concrete, Caltrans permits intermingling but places significant restrictions on the practice.

The EPA has also acknowledged the difficulties inherent in maintaining a consistent supply of fly ash, as posed by storage capacity constraints. Citing Texas Department of Transportation as an example, an EPA review of coal combustion products ("CCPs") notes:

> *"The Texas CCP review notes that CCP generators and ash marketers each have stringent quality assurance/quality control (QA/QC) protocols, yet the Texas Department of Transportation (TX DOT) and ready-mix producers indicated that coal fly ash storage capacity is limited, affecting users' ability to store consistent supplies, and the quality of coal fly ash on a truck-by-truck basis is not consistent. If there is a change in combustion operations, there is a resulting change in ash quality, making it difficult to produce a consistent product."*[41]

The availability of consistent fly ash supplies is likely to become more challenging in future years, as suppliers face increasingly stringent environmental regulations on coal-fired power plants.

3.2 Market Barriers

3.2.1 Widespread Market Acceptance

A critical barrier to increased SCM utilization in concrete is market acceptance. Despite the many beneficial properties of SCMs, many specifiers commissioning or monitoring construction projects are still largely unfamiliar with or unwilling to use the many varieties. There is consistent bias in favor of using only well known SCMs, such as fly ash or slag, as well as for holding SCM substitution at low rates in concrete mixtures and limiting the number of different SCMs blended into a given batch of concrete.

In fact, some SCMs impart more beneficial properties to concrete when blended at higher rates than others. Slag cement, for example, achieves maximum performance levels when blended at rates of up to 50-80%, significantly higher than typical fly ash substitution rates. There is also evidence that ternary mixtures of SCMs (*i.e.*, mixtures comprised of three different cementitious materials) perform at a higher level than a single SCM blended with concrete, although specifiers are relatively unfamiliar with ternary mixtures and therefore reluctant to adopt them.

Although concretes with high SCM content have been used on many projects, convincing specifiers of the advantages of their use on each particular project typically involves a search for fully compatible materials, large amounts of pre-testing, and close oversight and attention by mix design experts and engineers. While such activities may be feasible for unique and larger scale undertakings, they are more likely to impose prohibitive costs and delays for the more standard and smaller scale projects.

3.2.2 Availability of Supply

In the long-term, the availability of supply is perhaps the greatest concern for increased SCM utilization in California. A significant number of new coal-fired power plants have already faced opposition and permitting difficulties, as local and state NIMBY ("not-in-my-back-yard") concerns have grown in recent years. This foreshadows a challenging environment for new plant construction even under business-as-usual conditions and existing environmental policies.

Furthermore, federal climate change legislation, if adopted, is almost certain to hinder the growth of conventional coal-fired power generation in the coming decades, precipitating a sharp decrease in fly ash production – the most widely used SCM in California.[42] At the same time, a federal carbon constraint is likely to increase the demand for fly ash and other SCMs in other regions of the nation, which may crowd out demand in incremental and relatively distant markets, such as California. A similar tightening of supply and demand conditions for blast furnace slag might be expected under a federal climate change program given existing slag supply limitations, the carbon intensity of the steel production process, and the distance between the California market and concentrations of slag supply.

Increasingly stringent regulation of mercury emissions from coal-fired power plants at both the state and federal level is likely to exacerbate supply conditions for fly ash in the medium and long terms. In October 2009, the U.S. EPA signed a settlement agreement that requires it to propose Maximum Achievable Control Technology ("MACT") emissions standards by March 2011, due to be finalized by November 2011.[43] Although there are a variety of mercury control technologies under development, the most advanced and commercially proven control technology is activated carbon injection ("ACI"), which involves the direct injection of carbon into the flue gas. The use of ACI can increase the carbon content and the air-entrainment agents in fly ash to levels that render it unsuitable for use in concrete.

Ultimately, existing supply constraints have led to shortages of fly ash in California. Furthermore, the state's dependence on fly ash imports tends to result in inconsistent fly ash qualities that, when coupled with the long transportation distances required to reach the California market, has lead to supply disruptions. Existing supply constraints in the fly ash market are likely to be compounded by environmental policy trends at the federal level, including the adoption of a national climate change policy, more stringent regulation of mercury emissions at coal-fired power plants, and (as discussed in Section 3.3.1) the potential regulation of fly ash as a hazardous waste.

3.2.3 Affordability of Supply

Even if the conventional coal-fired power plant industry continues to expand and manages to produce high-quality and consistent fly ash supplies, the extreme regional mismatch between fly ash production and consumption remains a concern. Geographic misalignment and consequential transportation costs can render SCMs uncompetitive and unattractive for concrete mixers in certain regions, such as California.

Given that most coal-fired generation and integrated steel manufacturing is located east of the Mississippi river, California concrete producers must typically bear relatively high transportation costs and price premiums in order to divert supplies away from consumers that are located closer to centers of SCM production.[44] For example, assuming an average rail shipping cost of 5 cents per ton-mile, the transportation of fly ash from Cincinnati to Los Angeles is estimated to exceed $100 per ton – that is, roughly the cost of a ton of portland cement.[45] In California, such cost differentials tend to advantage foreign imports, as it can be significantly less expensive to transport materials over water than land. However, foreign imports from emerging countries most likely have a GHG burden at least several times that of domestic SCMs. Although large-scale, high-volume construction projects may find it possible to overcome these affordability barriers to increased SCM usage, small-scale projects may find the incremental costs insurmountable.

3.3 Governmental Barriers

3.3.1 Regulatory Barriers

One of the most concerning government barriers to achieving increased SCM usage is inconsistent regulation at various government levels. National regulation lacks uniformity on the use of recovered supplementary materials in concrete, leaving states with no underlying framework by which to standardize their own regulation. The result is a disharmony between states on SCM and concrete standards, which is problematic for a market in which materials are often produced and stored across state lines from where they will ultimately be used.

Furthermore, many regulatory guidelines for power plants and other manufacturing processes, which routinely produce SCMs as a byproduct, may inhibit increased SCM production and use. Some states maintain stringent controls on power plant mercury and nitrogen oxide (“NO_X”) emissions, which decrease the quality and usability of fly ash.[46] Renewable portfolio standards, such as that being developed in California, are likely to incentivize the use of biomass co-firing at coal-fired power plants, which will further decrease the quantity of usable fly ash available to the California cement industry.[47] Regulatory mandates such as these not only adversely affect the availability of high quality SCMs for concrete manufacturers, they also impose an economic cost. High carbon fly ash is more difficult to sell than lower carbon fly ash, and power plant operators are forced to forgo revenue as larger proportions of their fly ash production become unmarketable.

While the future production of fly ash is uncertain, so is the future of its use in concrete. In recent months, public concerns regarding the safe handling, disposal, and beneficial use of fly ash, including its use in concrete, have emerged in the aftermath of a large-scale coal ash spill at the Tennessee Valley Authority’s Kingston power plant. As a result of this event and long-standing concerns about the fate of the mercury contained in coal ash, the EPA is actively considering labeling coal ash as a hazardous waste, with a decision expected to be announced in the first half of 2010. Although studies suggest that the leaching of mercury and other heavy metals from fly ash used in concrete does not occur at levels that pose environmental concern,[48] an EPA ruling that designates such ash as a hazardous waste is likely to substantially impair the continued use of fly ash in concrete, either directly through restrictions on use, indirectly through increased costs, or implicitly through adverse public perceptions.

As previously mentioned, recent environmental restrictions in some states, which are now being considered on the national level, mandate reduced mercury emissions from the electric power sector. Planned control technologies would use the same equipment to capture both mercury emissions and fly ash, intermingling the captured mercury with the fly ash, and green building advocates are increasingly calling for no mercury in building materials.[49] For instance, the U.S. Green Building Council's proposed *LEED for Healthcare* and California's *Collaborative for High-Performance Schools*, are setting limits on the mercury content of fly ash. Furthermore, the *Green Guide for Healthcare* allows credit only for fly ash usage with documentation proving that the coal plant was not co-fired with hazardous waste, medical waste, or tire-derived fuel.

3.3.2 Legal Barriers

Legal barriers in the form of contract rigidity effectively constrain the increased use of SCMs, as well as hinder the adoption of best practices and performance optimization. Typical construction contracts act to limit mid-project changes in cement-mix composition, which guarantees a consistent, but not necessarily more efficient or effective product. Due to general unfamiliarity with SCM usage, contractors commonly opt for portland-only concrete mixes or those with minimal SCM content to ensure that products maintain contractually required consistency.

3.3.3 Policy Barriers

Comprehensive procurement guidelines ("CPGs") determined by federal agencies outline preferential procurement standards for the use of recycled materials and SCMs in concretes, although in practice the implementation of these standards and guidelines is weak.

A flexible set of qualifications for SCM use allows agencies and contractors to opt out of more extensive SCM incorporation in concrete mixes for a variety of reasons, including:

- If SCMs are not made available in a timely manner (a requirement adversely affected by previously discussed geographic distributional disparities);
- If SCM blended concretes fail to meet performance standards set by procuring agencies (which are frequently affected by poor knowledge of SCM properties and best practices); or
- If SCMs are made available only at "unreasonable" prices, which may well continue to be the case if the distributional issues resulting in high transportation costs remain unresolved.

Although these exceptions have been built into pro-SCM policies to increase flexibility, they are often used inappropriately to enable avoidance of increased SCM usage.

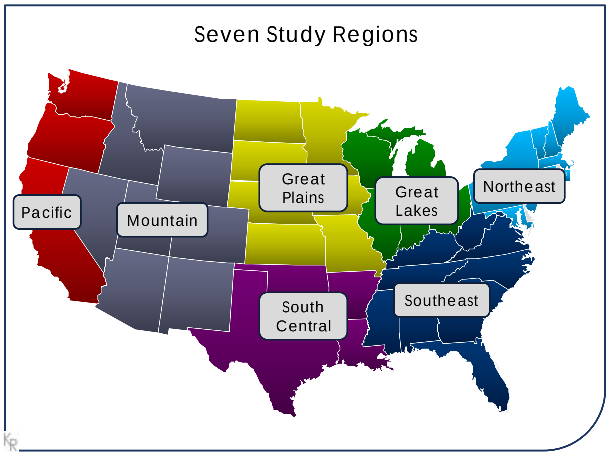
IV. QUANTIFYING LONG-TERM PROSPECTS & RISKS FOR FLY ASH UTILIZATION

Policies that seek to effectively and efficiently increase the use of SCMs should be rooted in a firm understanding of both the SCM market's current status and its potential evolution. Despite significant barriers, SCM substitution generally remains an environmentally and economically attractive strategy today. There are no assurances, however, that it will remain an attractive strategy in the longer term. It is critical that policymakers endeavor to identify, evaluate, and anticipate key long-term drivers in the SCM market with the goal of understanding the extent to which these drivers are likely to impact the prospects and risks associated with continued SCM substitution.

The challenges associated with expanding SCM utilization in the long term are perhaps best illustrated by the uncertainties that surround the U.S. fly ash market. As noted in previous sections, an array of environmental policy trends suggests that the long-term availability and affordability of concrete-quality fly ash supplies are likely to deteriorate, including:

- Policies that impose a price on GHG emissions (*e.g.*, a federal cap-and-trade program) are likely to discourage coal-fired electric power generation and, consequently, result in a sustained reduction in the supply of concrete-quality fly ash.
- Policies that impose a price on GHG emissions (*e.g.*, a federal cap-and-trade program) are likely to encourage widespread clinker substitution and, consequently, result in a sustained surge in the demand for concrete-quality fly ash.
- Policies that require coal-fired power plants to limit mercury emissions are likely to result in the adoption of ACI technologies, which tend to increase the carbon content of fly ash and decrease its suitability for use in concrete. Concerns about the mercury content of fly ash may result in environmental regulations or public perceptions that further impair or altogether eliminate its use in concrete.

With these challenges in mind, a set of plausible policy scenarios were developed to evaluate and illustrate the potential impact of environmental regulations on the supply of fly ash in the U.S. market. Utilizing both public and proprietary data, total production of concrete-quality fly ash is projected across seven U.S. regions under various policy assumptions. These fly ash supply forecasts are then integrated with long-term cement consumption forecasts to estimate the "sustainable substitution rate" for each U.S. region – that is, the level of substitution that could be achieved in a given region through the use of locally sourced fly ash. The results are interpreted and conclusions are drawn about the long-term prospects and risks associated with expanding fly ash substitution in the national market and the potential impact on geographically isolated markets, particularly California.



The objective of the exercise is not to predict the likely evolution of the U.S. fly ash market, which is currently beset with profound policy unknowns and market complexities. Rather, the objective is to develop a range of plausible scenarios that illustrate the significant uncertainty associated with supply-demand balances of concrete-quality fly ash in the U.S. market in the long term. It is this uncertainty that holds the key insights for policymakers interested in developing and implementing instruments best suited to encourage optimal fly ash utilization in the long term.

4.1 Analytical Framework

The modeling framework utilizes two key variables, which are derived from a variety of data sources, to drive the forecast throughout the 2010-2030 timeframe:

(1) **Total Fly Ash Production by Region:** Fly ash production by region is estimated using projections of coal consumption for coal-fired electric power generation. Energy quantities of coal consumption (*i.e.*, quadrillion Btu) for each region were converted into physical quantities (*i.e.*, tons of coal) using EIA historical data on the energy content of coal consumed by region (*i.e.*, quadrillion Btu per ton of coal consumed).[50] Physical quantities of coal consumption were then converted into estimates of total coal ash production using EIA historical data on the ash content of coal consumed by region.[51] Finally, total coal ash production is converted into estimates of fly ash production under the assumption that 80% of total coal ash is discharged as fly ash and 20% is discharged as bottom ash.

(2) **Concrete-Quality Fly Ash Ratios by Region:** Given that only a proportion of fly ash is suitable for use in concrete and considering that suitability can vary significantly across regions, estimates of concrete-quality fly ash ratios ("spec ash") were developed for each region. Estimates regarding the ratio of spec ash production to total fly ash production are based on proprietary data supplied by Minerals Resource Technologies ("MRT"), a wholly-owned subsidiary of CEMEX and a major supplier of fly ash in North America. Plant-level estimates of spec ash ratios were aggregated and applied to regional estimates of total fly ash production to calculate the annual quantity of spec ash generated in each region.

These two variables are forecasted under various assumptions to produce a range of plausible fly ash supply scenarios. In this analysis, four discrete scenarios are presented:

- **The "Business-as-Usual" scenario ("BAU")** reflects a world in which existing environmental policies and prevailing conditions in the fly ash market persist. It is based on detailed projections of coal-fired power generation as presented in the EIA's Reference Case scenario in the Annual Energy Outlook 2009. Given the direction of environmental policy at both the federal and state levels, the BAU scenario is not presented as a most likely scenario. Rather, it is presented as a useful benchmark by which to evaluate the direction and magnitude of impacts associated with more realistic policy and technology pathways.

- **The "Federal Climate Change Policy" scenario** assumes that federal climate change legislation is adopted, which is likely to reduce annual coal-fired electric power generation and, therefore, annual fly ash production. It is based on the Base Case scenario of the EIA's analysis of the American Clean Energy and Security Act of 2009 ("Waxman-Markey"), which includes projections of coal-fired electric power generation by region.

- **The "State Mercury Emissions Controls" scenario** assumes that more stringent mercury emissions standards for coal-fired generation plants are adopted in certain states, which is likely to increase the use of ACI technologies and reduce the supply of spec ash.[52] Assumptions about which states would adopt more stringent regulation and estimates regarding the impact of such regulation were based on an analysis performed by MRT. Specifically, MRT provided estimates of the spec ash to fly ash ratios for each region in the

2009-2013 timeframe, and these ratios were assumed to remain constant throughout the remainder of the forecast period.

- **The "Beneficiation Technology Deployment" scenario** assumes that technologies that enable the cost-effective beneficiation of impaired fly ash supplies are developed and deployed. Specifically, it assumes that the ratio of spec ash production to total fly ash production in each region increases to 60% by 2030. Given that the existing spec ash to fly ash ratio is estimated to be between 35-40%, such a scenario is considered optimistic but plausible. However, beneficiation has an associated GHG burden due to processing.

To isolate the impacts associated with each scenario, a consistent cement consumption forecast was used in all scenarios. The PCA produces state-by-state short-term forecasts (*i.e.*, five-year time horizon) on a quarterly basis and long-term forecasts (*i.e.*, 25-year time horizon) on an annual basis.[53] Keybridge blended PCA's latest short-term and long-term forecasts to construct consistent state-by-state projections.[54] State estimates were aggregated to produce regional estimates of total cement consumption during the 2010-2030 timeframe.

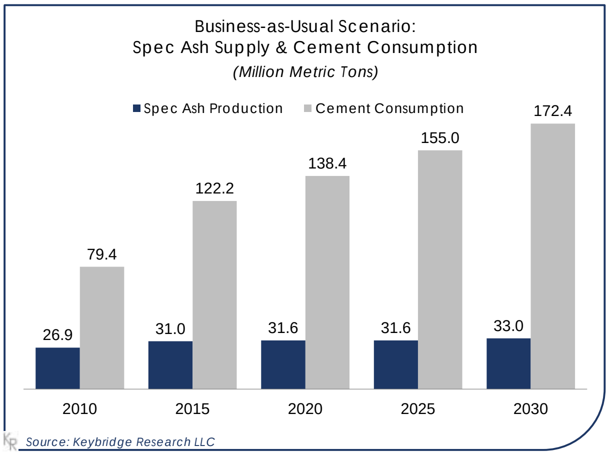
For each scenario, fly ash supply and cement consumption estimates are combined to estimate the "sustainable blending ratio" ("SBR") for each region, as calculated by dividing the total quantity of spec fly ash produced in a region by that region's cement consumption. Simply put, an SBR indicates a given region's maximum potential capacity to blend locally sourced fly ash to reduce its cement consumption requirements.[55] Regional data was also aggregated to calculate national SBRs.

4.2 Results

4.2.1 Business-as-Usual Scenario

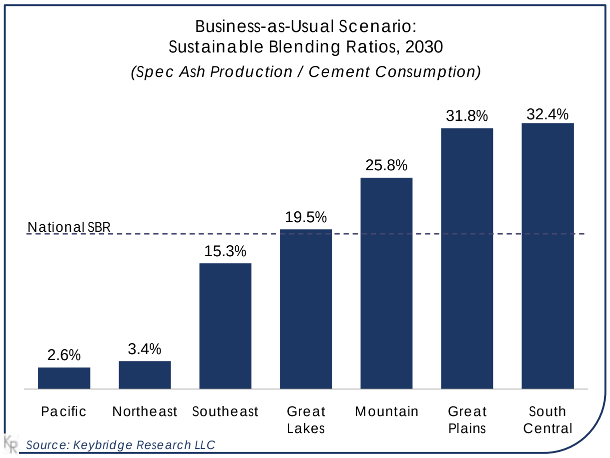
Under BAU assumptions, coal-fired electric power generation expands modestly in the absence of federal climate legislation or more stringent state mercury regulations. As a result, total spec ash supply increases from 27 MMT in 2010 to 33 MMT in 2030 – an increase of roughly 22%. However, cement consumption increases by more than 117% during the same period. Consistent with this backdrop of modest spec ash supply growth and robust cement consumption growth, the national SBR declines from 34% in 2010 to 19% in 2030.

Reflecting severe geographical mismatches between centers of fly ash supply and cement demand, regional SBRs vary greatly around this national average. Assuming that each region achieves the national SBR of 19% in 2030, significant excess supplies of fly ash are likely to materialize in the South Central region (4.6 MMT), with more modest surpluses accumulating in the Great Plains (1.7 MMT) and Mountain (1.5 MMT) regions. These would be offset by a severe deficit in the Pacific region (-4.0 MMT), with more modest deficits in the Northeast (-2.1 MMT) and Southeast (-1.8 MMT) regions.



Source: Keybridge Research LLC

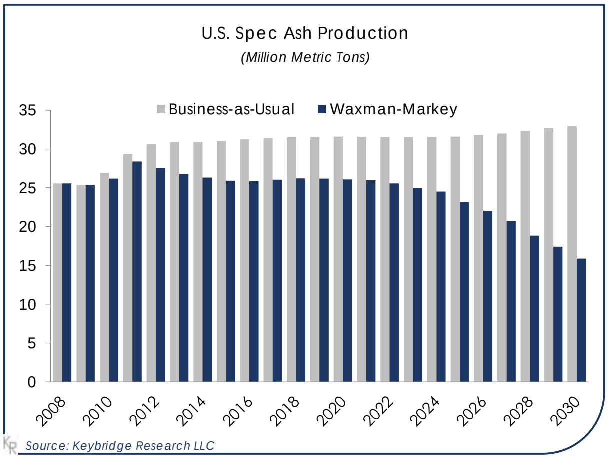
Thus, even under BAU assumptions, the results suggest that SCM supply conditions are likely to tighten rapidly throughout the forecast period and place downward pressure on sustainable blending ratios across every region. Furthermore, the reconciliation of vast regional discrepancies in spec ash supply and cement consumption would likely require significant long-distance transfers of SCM supplies across the country, which is likely to substantially increase acquisition costs and partially offset the GHG benefits of SCM utilization.



Source: Keybridge Research LLC

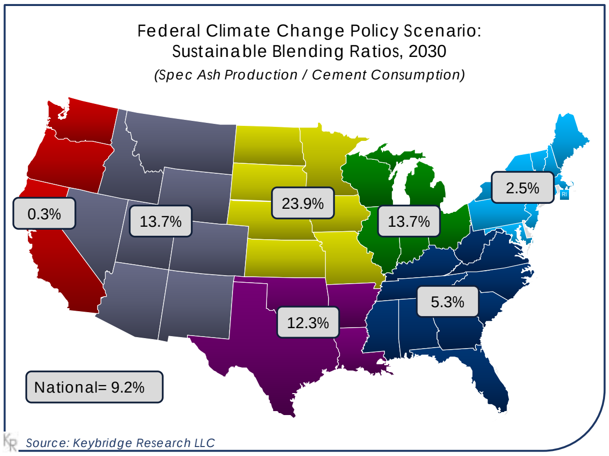
4.2.2 Federal Climate Change Policy Scenario

In the Federal Climate Change Policy scenario, the imposition of a federal cap-and-trade system decreases coal consumption for coal-fired generation by 47%, resulting in a similar decline in fly ash production. As a result, spec ash production is projected to decline from approximately 26 MMT in 2010 to less than 16 MMT in 2030 – resulting in a spec ash supply that is approximately half that observed in the BAU scenario. The precipitous decline in spec ash production coupled with increasing cement consumption results in a decline in the national SBR from 25% in 2007 to 9% in 2030.



Source: Keybridge Research LLC

Federal climate change policy is projected to have the greatest impact on spec ash supplies in the South Central and Southeast regions, both of which experience declines of more than 60% as compared to the BAU scenario. The reduction in spec ash supply between 2010-2030 in these two regions alone total more than 9 MMT – more than 50% of the quantity of all fly ash used in concrete in 2007.



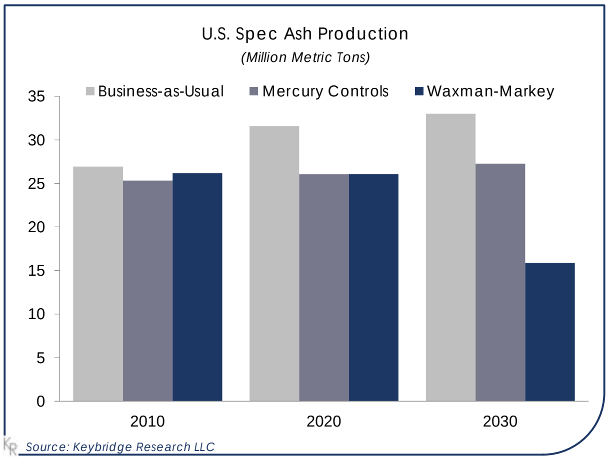
Source: Keybridge Research LLC

Assuming each region blends fly ash up to the national SBR, regional disparities are likely to persist as in the BAU scenario, though the absolute quantities of surpluses and deficits are reduced as the national SBR sharply declines. Modest surpluses are likely to materialize in the Great Plains (2.0 MMT), South Central (1.1 MMT), Mountain (1.0), and Great Lakes (0.8 MMT) regions, which are offset by similar deficits in the Pacific (-2.1 MMT), Southeast (-1.8 MMT), and Northeast (-0.9 MMT) regions.

Importantly, the SBR in the Pacific region is projected to decline from 5% in 2010 to 0% in 2030 – suggesting that the region will be fully dependent on imports to meet its fly ash needs. Fly ash demand in the region is likely to be highest in California, where PCA estimates that cement consumption will reach 19 MMT in 2030. Attaining the national SBR of 9%, which is generally consistent with the state's existing fly ash blending rate, would therefore require the importation of 1.7 MMT of fly ash. Given a sharp decline in national spec ash production and a likely increase in national spec ash consumption due to the imposition of a carbon price, chronic shortages of domestic supplies are likely to materialize throughout the nation. Consequently, California cement and concrete manufacturers will likely be forced to turn to foreign sources of supply, which may entail significant transportation emissions, especially if sourced from distant Asian nations.

4.2.3 State Mercury Emissions Controls Scenario

In the Mercury Controls scenario, the implementation of mercury emissions controls at the state level for coal-fired electric power generation results in a decrease in the ratio of spec ash to fly ash production. As a result, national spec ash supply is estimated to decline by 5.7 MMT, or 17% as compared to a BAU scenario. Specifically, spec ash production is projected to be 27.26 MMT in 2030 – roughly equal to the estimated supply in 2007. Due to relatively stagnant spec ash supply coupled with increasing cement consumption, the national SBR is expected to decline to 16% by 2030, as compared to 19% in the BAU scenario and 9% in the Federal Climate Change Policy scenario.



Source: Keybridge Research LLC

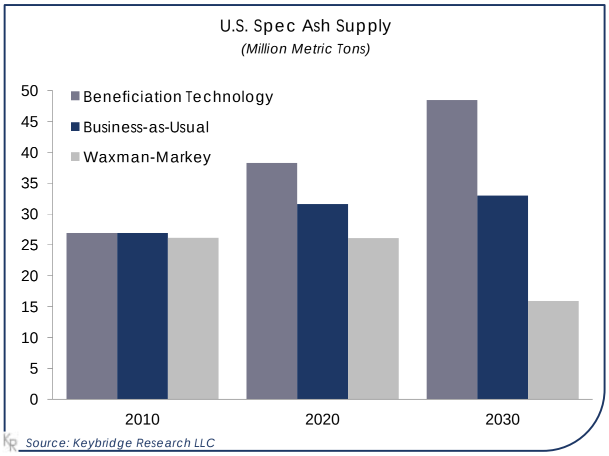
The state mercury emissions regulations are projected to have the greatest impact on spec ash in the South Central region, which experiences a decrease in supply from 9.49 MMT in 2010 to 7.30 MMT in 2030. All other regions are projected to experience minimal or modest increases in the absolute supply of spec ash compared to 2010 levels.

Assuming each region achieves the national SBR of 16%, a significant annual deficit of approximately 3 MMT of spec ash is expected to materialize in the Pacific region throughout the entire forecast period. By 2030, reconciling supply and demand in the Pacific region would likely require significant imports from the Mountain, Great Plains, and South Central regions, all three of which experience surpluses between 1.6-1.8 MMT.

4.2.4 Beneficiation Technology Deployment Scenario

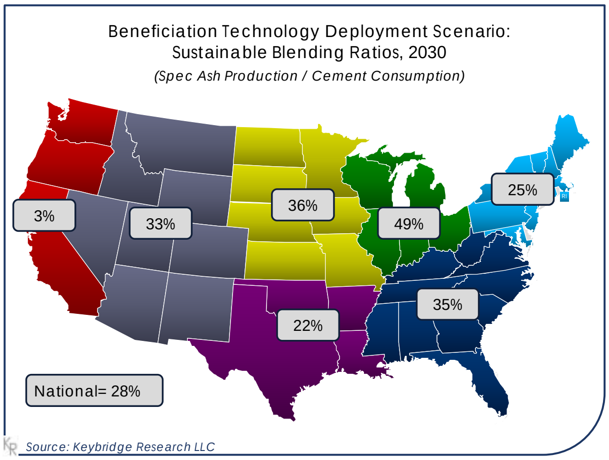
The third discrete scenario envisions that spec ash supplies experience an "upside surprise" in the form of the rapid development and widespread deployment of cost-effective beneficiation technologies. While estimating the expansion in SCM supplies due to the deployment of beneficiation technologies is difficult calculation, this scenario assumes the ratio of spec ash to fly ash production could increase by 50% during the forecast period, from slightly less than 40% today to approximately 60% in 2030.

Under these assumptions, the total supply of spec ash is projected to increase to 49 MMT by 2030, as compared to 33 MMT under the BAU scenario. This increase in spec ash supply increases the national SBR to 28%. The impact of beneficiation technology is likely to be greatest in the Southeast region, which currently has the highest amount of coal-fired power generation but one of the lowest spec ash to fly ash ratios.


U.S. Spec Ash Supply
(Million Metric Tons)

Source: Keybridge Research LLC

Assuming all regions attain the national SBR of 28%, spec ash supply surpluses are likely to materialize in all except the Pacific and Northeast regions, with the Pacific experiencing a particularly severe shortfall (-6.1 MMT) in the context of a high national average. Generally speaking, the results suggest that rapid development and widespread deployment of beneficiation technologies could effectively allow spec ash supply growth to keep pace with cement consumption – thereby maintaining the viability of existing substitution rates.


Beneficiation Technology Deployment Scenario:
Sustainable Blending Ratios, 2030
(Spec Ash Production / Cement Consumption)

Source: Keybridge Research LLC

4.3 Qualifications, Limitations, & Uncertainties

4.3.1 Integrated Scenarios

The preceding analysis is intended to illustrate the likely direction and magnitude of discrete policy and technological events, and it does not consider the combined impacts associated with the realization of multiple pathways. In reality, however, multiple events are likely to occur simultaneously, and the general direction of environmental policy at both the state and national levels suggest that the balance of risks to supply is likely to be on the downside.

Consequently, a series of "integrated scenarios" were simulated in which two or more events occur simultaneously. Although a small set of scenarios (*e.g.*, federal climate change policy with low international offsets availability or 100% beneficiation of all fly ash production) produced relatively extreme results, the vast majority of scenarios produced results that were generally consistent with those presented in the discrete scenarios. Consequently, the direction and magnitudes of the impacts illustrated by the discrete scenarios are believed to be a reasonable representation of the range of plausible scenarios that might materialize as existing policy and technological uncertainties are resolved.

Sample of Alternative Fly Ash Supply Simulations
Sustainable Blending Ratios, 2030

		Alternative Scenario			
Region	BAU	(A)	(B)	(C)	(D)
Great Plains	31.8%	20.9%	9.7%	27.1%	12.6%
Mountain	25.8%	12.6%	1.2%	17.3%	1.6%
Great Lakes	19.5%	11.1%	5.8%	34.7%	18.0%
Northeast	3.4%	2.5%	1.7%	18.4%	12.7%
Pacific	2.6%	0.3%	0.3%	0.4%	0.4%
South Central	32.4%	8.0%	1.8%	8.3%	1.9%
Southeast	15.3%	5.2%	1.1%	12.1%	2.6%
National	19.4%	7.7%	2.3%	14.4%	5.2%

Scenario A = W-M Base Case + State Mercury Regulations
Scenario B = W-M Base Case with Low Offsets Availability + State Mercury Regulations
Scenario C = W-M Base Case + Beneficiation Technology
Scenario D = W-M Base Case with Low Offsets Availability + Beneficiation Technology

4.3.2 Increases in Fly Ash Demand

The discrete scenarios primarily focus on how the supply of concrete-quality fly ash is likely to evolve over the coming decades. Importantly, it does not explicitly consider the potential for increased demand for fly ash. Although the impetus for increased demand under the Mercury Controls scenario is unclear, it is much more salient in the Federal Climate Change Policy scenario. To the extent that the imposition of a national carbon price increases the need to offset the costs of carbon-intensive clinker, overall demand for fly ash and regional substitution rates are likely to increase relative to what they would be in the absence of the policy.

Simply put, under a Federal Climate Change Policy Scenario, structural forces of supply and demand are working against SCM consumers. Although SCM supply is likely to fall in tandem with the decline of conventional coal-fired generation, SCM demand is likely to increase in response to the rise in carbon prices. As a result, SCM prices are likely to rise sharply in comparison to historical norms – presumably increasing to the point where they equalize with cement clinker costs on a carbon-adjusted basis. This is likely to enhance the competitive impacts of transportation cost differentials and intensify regional disparities.

4.3.3 Other Potential Sources of Fly Ash

The current analysis is principally concerned with the potential impact of changes in the ongoing flow of spec fly ash production within the U.S. market. It does not consider the potential impact of reclaiming fly ash supplies currently disposed in landfills. Although the existing stock of landfill fly ash is likely to be significant, it appears unlikely that such supplies could be cost-effectively extracted, sorted, processed, and beneficiated for use in concrete on a large-scale during the timeframe under consideration.[1]

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[1] Given that the majority of landfill fly ash was likely unsuitable for use in concrete at the time of disposal, the large-scale recovery of these supplies for use in concrete would be highly dependent on the emergence of cost-effective beneficiation technology which currently does not exist.

The current analysis also does not explicitly consider the potential impact of fly ash and slag imports. Federal climate change policy is likely to be implemented in the context of GHG reduction commitments by other nations, which would result in higher local use of fly ash and slag in concrete by other nations. Furthermore, the objective of the current analysis is to inform sound policy design, and policies that rely on the large-scale importation of fly ash supplies at the expense of local use are unlikely to generate the intended GHG reduction benefits.

V. CONCLUSIONS FOR POLICYMAKERS

The preceding sections offer illustrative scenarios about the potential evolution of fly ash supplies over the coming decades. Although the analysis focuses on three of the most consequential drivers of future fly ash supplies (*i.e.*, federal climate legislation, mercury emissions controls, and beneficiation technologies), it is not exhaustive or definitive. Indeed, there are likely to be a wide variety of factors that influence fly ash demand and supply over the coming decades, some of which may be overwhelmingly positive and some of which will be overwhelmingly negative from the perspective of SCM consumers. Forthcoming rulings by the U.S. EPA regarding coal ash's status as a hazardous waste, in particular, could have profoundly negative consequences for future SCM substitution.

While reasonable people may disagree about the balance of these countervailing forces, the above scenarios reveal a central and consistent conclusion: the future domestic, and potentially global, supply of fly ash is highly uncertain. Similar supply-side challenges exist for other key SCMs, especially slag. This high degree of uncertainty has important implications for policymakers interested in designing instruments to maximize SCM usage in a responsible manner. Rigid instruments, such as technology or performance mandates, are unlikely to be successful in such an environment. By their very nature, such instruments have high information and foresight requirements that are unlikely to be met in a marketplace beset by an extreme degree of uncertainty.

Rather, flexible instruments that leverage market incentives and price signals, such as emissions trading and credit programs, are likely to prove more effective in responding to rapidly evolving and unpredictable conditions. Indeed, the imposition of a carbon price will significantly increase the costs of cement and, under ideal conditions, this cost increase would be passed through to concrete manufacturers – thereby increasing the value of SCMs relative to cement and providing a consistent incentive to increase SCM substitution.

Unfortunately, the economics of the cement-concrete supply chain do not conform to these ideal conditions, especially in California. As a highly energy-intensive and trade-exposed industry, the California cement industry is unable to pass through the costs associated with an asymmetric carbon constraint, such as a state, regional, or federal cap-and-trade system. In the absence of a truly global system that places equivalent carbon costs on all cement, regardless of origin, regulated cement manufacturers are likely to lose market share to their unregulated competitors – thereby resulting in emissions leakage.

Targeted policy measures, such as the provision of output-based rebates or free allowance allocations, can be effective in preventing leakage. However, their effectiveness in preventing leakage is derived from their capacity to offset carbon cost increase, thereby also muting the price signal to downstream consumers. Consequently, any effective policy is likely to require the application of two different policy instruments – one that provides a carbon price signal to cement producers while mitigating the risk of leakage, and one that reestablishes a price signal for downstream consumers. In particular, a robust configuration of anti-leakage instruments combined with a credit program for SCM blenders has the potential to maximize SCM utilization in a manner that is consistent with environmental objectives, prevailing carbon prices, and rapidly evolving SCM market conditions.

Given the existing barriers to SCM utilization, however, other policies must underpin the goal of increasing SCM utilization in order to enhance the efficacy of carbon price incentives. This is likely to include initiatives to increase awareness and education among concrete manufacturers and end users regarding SCM utilization, as well as initiatives to update and harmonize codes, standards, and government procurement guidelines to reflect the latest science about both the benefits that SCMs hold for concrete and the positive contributions that concrete can make to building a more sustainable future.

Ultimately, in the absence of a deliberate and coordinated effort to remove barriers and leverage market-based mechanisms to provide incentives throughout the cement-concrete supply chain – including carbon price incentives, codes, standards, procurement guidelines, and consumer education – SCM utilization in California is likely to fall short of its full potential, regardless of prevailing market conditions. In the presence of such an effort, however, the environmentally and economically efficient use of SCMs in California is likely to be optimized in a manner consistent with highly dynamic, uncertain, and evolving market conditions.

APPENDIX A: CALCIMA SURVEY

CalCIMA
Summary of Ready-Mix Concrete, Cement Survey
July 9, 2008

CalCIMA conducted a survey of its ready-mix producers to assess current practices regarding the use of cement and supplemental cementitious materials (SCMs) in the production of concrete.

- Data was requested for statewide operations for the 2007 production year.
- 19 producers responded to the survey, representing 5.7 million metric tonnes (MMT) of cement usage and 0.5 MMT of SCM usage. (6.3 and 0.6 million short tons)
- The combined production of the survey respondents is estimated to represent 50% of the total cement usage by ready-mix producers in the state.
- Total cement consumption in California was estimated to be 15.5 MMT for 2007, per the October 23, 2007 report, titled "Minimizing Leakage Under Climate Change Proposals Affecting the Cement Industry", with approximately 30% coming from imports.
- The Portland Cement Association reports that approximately 73% of cement is shipped to ready-mix facilities for concrete production. This results in approximately 11.3 MMT of cement consumption for ready-mix concrete in 2007
- The average SCM usage based on the total response quantities is 8.8%. The highest and lowest usage rates were 23% and 2% respectively, while the typical usage ranged from 7% to 17%.

REFERENCES

Adrian, W., and R. Jobanputra (2005). "Influence of Pavement Reflectance on Lighting for Parking Lots." Portland Cement Association (SN2458).

American Coal Ash Association (2008). 2008 Coal Combustion Product (CCP) Production & Use Survey Results.

American Concrete Institute 232.1 R-00 (Reapproved 2006). *Use of Raw or Processed Natural Pozzolans in Concrete*.

Ashley, E. & L. Lemay (2008). "Concrete's Contribution to Sustainable Development." *The Journal of Green Building,* 3(4): 40.

ASTM International C595M – 09 Standard Specifications for Blended Hydraulic Cements.

ASTM International C618 – 08a Standard Specifications for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete.

CalCIMA (July 2008). *Summary of Ready-Mix Concrete Survey on SCM Utilization.*

Cambridge Systematics, Inc. (June 2005). "Cool Pavement Report." EPA *Cool Pavements Study*, Task 5: 14 (Figure 4.2).

Energy Information Administration (2005). Form-767: Annual Steam-Electric Plant Operation and Design Data. U.S. Department of Energy.

Engelsen, C.J., *et. al* (2005). "Carbon Dioxide Uptake in Demolished and Crushed Concrete." *Norwegian Building Research Institute.*

Gajda, J. (2001). "Absorption of Atmospheric Carbon Dioxide by Portland Cement." Portland Cement Association (SN2255a).

Marceau, M.L. and M. G. VanGeem (2006). "Modeling Energy Performance of Concrete Buildings for LEED-NC Version 2.2: Energy and Atmosphere Credit 1." Portland Cement Association (SN2880a).

Marceau, M. L., & M.G. VanGeem (2008). "Comparison of the Life Cycle Assessments of an Insulating Concrete Form House and a Wood Frame House*.*" Portland Cement Association (SN3041).

McLennan, J.F. *et. al* (August 2008). "The Living Building Challenge: In Pursuit of True Sustainability In the Built Environment." Cascadia Region Green Building Council.

National Ready Mix Concrete Association (2000). "Concrete in Practice: Supplementary Cementitious Materials", (30).

National Research Council of Canada (2005). Centre for Surface Transportation Technology.

Pade, C. *et. a* (September 2007). "The CO_2 Uptake of Concrete the Perspective of Life cycle Inventory." *Cement and Concrete Research*, (37) 9: 1348-1356.

Portland Cement Association (1998). Survey of Mineral Admixtures and Blended Cements in Ready Mixed Concrete.

Portland Cement Association (2002). *Design and Control of Concrete Mixture, 14th edition. (*EB001).

Portland Cement Association (2007). Lifecycle Inventory of Portland Cement Manufacture *(*PCA SN2095b).

Portland Cement Association (April 2008). Summary of California Portland Cement Plant Carbon Dioxide Emissions with Support Data.

Portland Cement Association (December 2008). *PCA Plant Information Summary.*

Portland Cement Association (Fall 2008). 2008 Apparent Use of Portland Cement by State & Market.

Portland Cement Association (July 2009). "Concrete Thinking: Stewardship."

Portland Cement Association (May 2009). Summary of National Portland Cement Plant Carbon Dioxide Emissions with Support Data.

Portland Cement Association (October 2009). "Long-Term Cement Consumption Outlook." *The Monitor: Forecast Report*.

Portland Cement Association (Summer 2009). State Construction and Cement Forecasts.

Pyle, T. (March 2009). "Reducing GHG Emissions with Cement Usage." California Climate Action Team.

Rosenfeld, A., *et. al* (July 2008). "Global Cooling: Increasing World-wide Albedos to Offset CO_2." *Climate Change*

Talley, Ian (2009). "Power Plants Face Potentially Costly New Air-Pollution Rules". *Wall Street Journal*, October 24, sec. A.

The Loreti Group (2008). Greenhouse Gas Emission Reductions from Blended Cement Production. Prepared for California Climate Action Registry.

The Loreti Group (2009). Cement Sector Greenhouse Gas Emissions Reduction Case Studies. Prepared for California Energy Commission.

U.S. Environmental Protection Agency (2008). "Study on Increasing the Usage of Recovered Mineral Components in Federally Funded Projects Involving Procurement of Cement or Concrete to Address the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users." Report to Congress. EPA530-R-08-007.

World Business Council for Sustainable Development. "Cement Sustainability Initiative: Sustainability Benefits of Concrete".

ENDNOTES

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[1] Pyle, T. (March 2009).

[2] Marceau, M. L., & M.G. VanGeem (2006) and Marceau, M. L., & M.G. VanGeem (2008) .

[3] Recent studies show that concrete roads increase truck fuel efficiency by 1%-6% as compared to asphalt, with faster moving and heavier trucks benefiting most. See: National Research Council of Canada, Centre for Surface Transportation Technology (2005).

[4] Adrian, W., and R, Jobanputra.

[5] As noted in a study co-authored by Arthur Rosenfeld of the California Energy Commission, "increasing the urban albedo can result in less absorption of incoming solar radiation by the surface-troposphere system, countering to some extent the global scale effects of increasing greenhouse gas emissions."

[6] Cambridge Systematics, Inc. (June 2005).

[7] See: Pade, C. *et. a* (September 2007); Gajda, J. (2001); Engelsen, C.J., *et. al* (2005).

[8] Note that fly ash, slag cement, and silica fume require minimal processing and therefore are a source of minimal GHG emissions. However, some other pozzolans are more intensely processed and have significant GHG emissions.

[9] We do not address vertical kilns which are not used in the U.S., a highly inefficient and polluting outdated manufacturing process, but which is still heavily relied upon in other countries, such as China.

[10] Lime is the key ingredient in cement, and CO_2 is released in a fixed ratio with the production of lime. In short, the majority of CO_2 emissions are a direct and unalterable consequence of the chemical reaction that is fundamental to the cement manufacturing process. These immutable "process emissions" distinguish the cement industry from many other carbon-intensive sectors, such as electric power or transportation.

[11] Portland Cement Association (December 2008).

[12] Portland Cement Association (July 2009).

[13] Portland Cement Association (April 2008 & May 2009). To standardize metrics and insure comparability, estimates of CO_2 emissions per ton of clinker were scaled to account for differences in mineral components usage in the California and national markets.

[14] Ashley, E. & L. Lemay (2008).

[15] World Business Council for Sustainable Development.

[16] Admixtures are also often added to enhance concrete's constructability or performance, but their content by weight or volume measures is not significant.

[17] Concrete manufacturing is a relatively low-emissions process, particularly when compared to the production of cement. The process of mining sand and gravel, crushing stone, manufacturing concrete, and transporting it to construction sites requires relatively little energy consumption and result in relatively few GHG emissions. Simply put, the manufacturing of concrete is only responsible for a small fraction of the GHG emissions released throughout the cement-concrete supply chain.

[18] Portland Cement Association (1998).

[19] The California Department of Transportation ("Caltrans") currently prohibits the use of Class C fly ash.

[20] Design and Control of Concrete Mixtures, Portland Cement Association.

[21] Calculations by Keybridge Research LLC based on plant-specific data for U.S. coal-fired electric power plants, as supplied by EIA Form 767.

[22] American Coal Ash Association (2008).

[23] *Ibid*.

[24] Design and Control of Concrete Mixtures, Portland Cement Association.

[25] To the extent that slag retards the setting time and early age strength of concrete, special extra consideration is needed to prevent shrinkage cracking in concrete for slabs and other flatwork. For this reason, contractors tend to use lower slag cement dosages unless the construction schedule allows for longer curing times or a high dosage of slag is specifically requested.

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[26] Portland Cement Association (October 2009).

[27] *Ibid.*

[28] One likely explanation for California's low incorporation of slag SCM is that the majority of Asian slag, the variety most readily available to the California concrete market, has a particularly high alumina content. Alumina is known to lower concrete's resistance to sulfates, which are prevalent in certain California soils.

[29] Portland Cement Association (October 2009).

[30] National Ready Mix Concrete Association (2000).

[31] The Silica Fume Association, www.silicafume.org

[32] Industry experts estimate that the cost of silica fume is approximately five times that of portland cement.

[33] Silica fume concrete can undergo single-pass finishing, where other concretes require a multi-step finishing process.

[34] National Ready Mix Concrete Association (2000).

[35] Portland Cement Association (2002), p. 61.

[36] Some of these are discussed in American Concrete Institute 232.1 R-00 (Reapproved 2006).

[37] CalCIMA (July 2008).

[38] Portland Cement Association (Fall 2008).

[39] Emission regulation requirements often change the daily, weekly, or monthly consistency and properties of fly ash. For example, Illinois coal-fired power plants' experience suggests that the carbon content of fly ash varies from the low single digits to as high as 15%, depending on how the boilers are run to comply with evolving environmental and emission regulation.

[40] At 15%-25% SCM replacement levels, intermingling does not pose a significant threat to the quality of the concrete, but intermingling at higher replacement levels is likely to have negative consequences. In addition, when the total amount of SCMs in concrete exceeds 25%, including that in blended cements and concrete, the interaction of the specific SCMs and cements must be considered to ensure durable concrete.

[41]U.S. EPA (2008).

[42] Although federal climate change legislation is likely to reduce conventional coal-fired power generation, the long-term impact on total coal-fired power generation is less certain. In particular, conventional coal-fired plants may be largely replaced by integrated gasification combined cycle ("IGCC") plants. IGCC coal plants do not produce a traditional coal ash byproduct, but a slag-like material that is not suitable for use in concrete.

[43] Talley, Ian (2009).

[44] California has no coal-fired power plants or blast furnaces in the state.

[45] Calculation also assumes a "straight-line" distance of 1900 miles from Cincinnati to Los Angeles and a circuity factor (which adjusts the straight-line distance for the curvature of the U.S. rail system) of 1.2 rail miles per straight-line mile – resulting in a transportation cost estimate of $114 per ton-mile.

[46] Additional activated carbon is added to the emissions capture process to trap more mercury, and low temperature boilers to mitigate NO_X emissions result in larger amounts of unburned carbon ash at power plants. Both measures increase the carbon content of fly ash, with the ultimate negative effect of decreasing its suitability as an SCM.

[47] RPS standards typically accelerate the practice of cofiring biomass with coal, which produces fly ash that does not meet specifications for use in cement. See: ASTM C618.

[48] For a comprehensive review of such studies, see: The Loreti Group (2009).

[49] McLennan, J.F. *et. al* (August 2008).

[50] EIA Form-767. The energy content of coal consumed by region is assumed to remain constant throughout the forecast period.

[51] EIA Form-767. The ash content of coal consumed by region is assumed to remain constant throughout the forecast period.

[52] It is important to note that this scenario considers the implementation of state-by-state regulation of mercury emissions, which was assessed by experts at MRT. It does not consider the potential impact of planed federal mercury control regulations that require the use of "maximum achievable control technology" at all U.S. coal-fired power plants, as announced by the U.S. EPA in October of 2009.

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[53] Portland Cement Association (October 2009) & Portland Cement Association (Summer 2009).

[54] Specifically, state cement consumption between 2009-2013 was assumed to equal the quantities specified in the PCA short-term forecast, while cement consumption between 2015-2030 was assumed to equal the quantities specified in the PCA's long-term forecast. Estimates for 2014 were assumed to equal the mid-point between 2013 and 2015 estimates. The blending of forecasts is necessary to reflect both the highly volatile short-term dynamics and the more structural long-term trends that are likely to drive cement consumption during the forecast period.

[55] There is reasonable evidence to suggest that actual SBRs may be lower than SBRs projected by this study. For example, concrete and SCM demand tends to weaken substantially during winter months, which results in prohibitively expensive storage costs for SCMs produced during this time. However, insufficient data makes seasonality and other factors affecting the economically efficient blending ratio difficult to estimate. Therefore, the calculated SBR is intended to signify a region's technical potential blending ratio, which is likely to exceed the economically efficient ratio.

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