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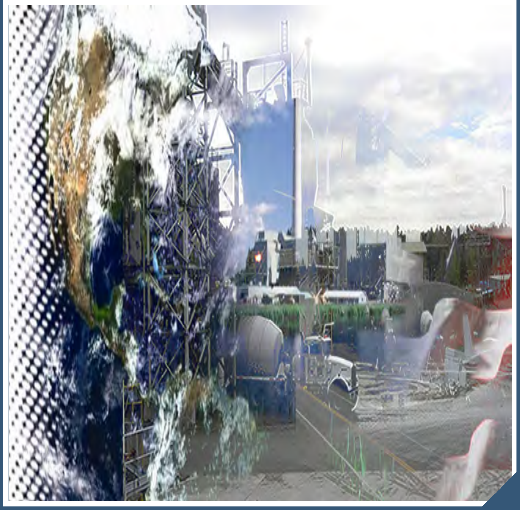
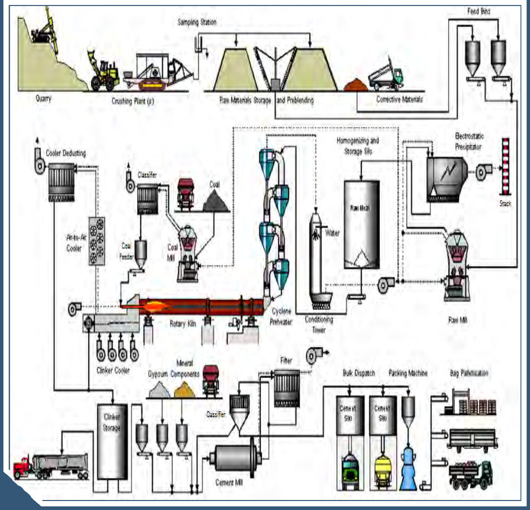
Universal Industrial Sectors Integrated Solutions (U-ISIS) Model for the Portland Cement Manufacturing Industry





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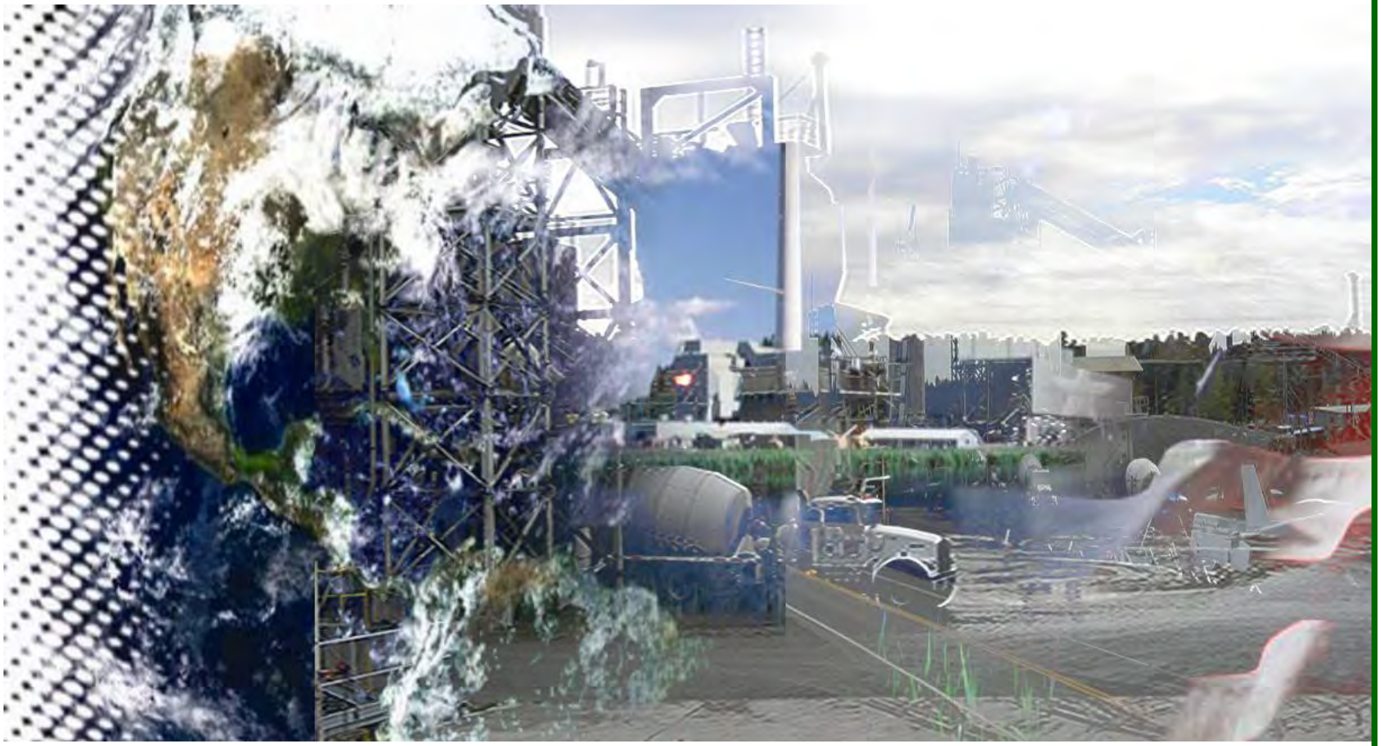

Universal Industrial Sectors Integrated Solutions (U-ISIS) Model for the Portland Cement Manufacturing Industry

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Version 3.0
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U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

Office of Research and Development
Air Pollution Prevention and Control Division
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Acronyms, Initializations, and Abbreviations

ACI	Activated Carbon Injection
AEO	Annual Energy Outlook
APCA	American Portland Cement Alliance
APPCD	Air Pollution Prevention and Control Division
ASD	Adjustable Speed Drives
ASTM	American Society for Testing and Materials
AVC	Average Variable Cost
AZ	Arizona
BACT	Best Available Control Technology
BAU	Business As Usual
BFS	Blast Furnace Slag
BLS	Bureau of Labor Statistics
BTS	Bureau of Transportation Statistics
CA	California
CCS	Carbon Capture and Sequestration
CEMBUREAU	European Cement Association based in Brussels
CGC	Convert to Reciprocating Grate Cooler
CKD	Cement Kiln Dust
CO	Colorado (in state listings only)
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CSI	Combustion System Improvement
DE	Delaware
EGFW	Exhaust Gas Flow Rate (wet)
EIA	Energy Information Administration
EMCS	Energy Management and Control System
EMD	Efficient Mill Drives
EMPC	Energy Management and Process Control
EPA	U.S. Environmental Protection Agency
ETS	Efficient Transport System
FL	Florida
FOM	Fixed Operation and Maintenance
GA	Georgia
GAMS	General Algebraic Modeling System
GDP	Gross Domestic Product
GHG	Greenhouse Gas
H_2O	Water
HAP(s)	Hazardous Air Pollutant(s)
HCl	Hydrochloric Acid
HEC	High-Efficiency Classifiers
HEM	High Efficiency Motors
HERM	High Efficiency Roller Mill
Hg	Mercury
HPRP	High-Pressure Roller Press
HRPG	Heat Recovery for Power Generation
ID	Idaho
IF	Indirect Firing

IGMBM	Improved Grinding Media (Ball Mills)
IL	Illinois
ISIS	Industrial Sectors Integrated Solutions
LNB	Low NO_X Burner
MI	Michigan
MMBtu	Million British Thermal Units
MO	Missouri
MYB	Minerals Yearbook (USGS)
N/A	Not Available
NAA	Nonattainment Area
NACT	North American Cement Transportation
NAS	National Academy of Science
NATA	National Air Toxics Assessment
NC	North Carolina
NEI	National Emission Inventory
NESCAUM	Northeast States for Coordinated Air Use Management
NESHAP	National Emission Standards for Hazardous Air Pollutants
NG	Natural Gas
NM	New Mexico
NO_X	Oxides of Nitrogen (also Nitrogen Oxides)
NRC	National Research Council
NSPS	New Source Performance Standards
NV	Nevada
O_3	Ozone
O&M	Operations and Maintenance
OAQPS	Office of Air Quality Planning and Standards
OCAS	Optimization of Compressed Air Systems
OGR	Optimize Grate Cooler
OK	Oklahoma
OMB	U.S. Office of Management and Budget
OR	Oregon
ORD	Office of Research and Development
PA	Pennsylvania
PCA	Portland Cement Association
PCVM	Process Control Vertical Mill
PM	Particulate Matter
PRB	Powder River Basin
PSD	Prevention of Significant Deterioration
QAPP	Quality Assurance Project Plan
RMB	Raw Materials Blending
RMTHEC	Raw Materials Transport High Energy Classifiers
ROW	Rest of the World
RTO	Regenerative Thermal Oxidizer
SBH	Slurry Blending and Homogenization
SC	South Carolina
SCR	Selective Catalytic Reduction
SFC	Specific Fuel Consumption
SHLR	Shell Heat Loss Reduction
SNCR	Selective Non-Catalytic Reduction

SO_2	Sulfur Dioxide
SO_3	Sulfur Trioxide
SPE	Spatial Price Equilibrium
SR	Seal Replacement
TDF	Tire Derived Fuel
THC	Total Hydrocarbons
TRAGIS	Transportation Routing Analysis Geographic Information System
U-ISIS	Universal ISIS
USGS	United States Geological Survey
UT	Utah
WA	Washington
WDOT	Washington State Department of Transportation
WMCCC	Wash Mills with Closed Circuit Classifier
WV BIT	West Virginia Bituminous Coal

Conversion Table – English Units to SI Units

To Obtain	From	Multiply by
M	ft	0.3048
m^2	ft^2	9.29×10^{-2}
m^3	ft^3	2.83×10^{-2}
°C	°F	5/9 × (°F – 32)
kg	lb	0.454
J/kg	Btu/lb	1.33×10^{-4}
m^3/s	cfm	4.72×10^{-4}
m^3/s	gpm	6.31×10^{-5}
J/kWh	Btu/kWh	1055.056
Mills	$	0.001
kg/m^2	in. Hg	345.31
metric ton	short ton	0.907

PLEASE NOTE: for the purpose of this document, short tons will be referred to as "tons." Short ton (ton) equals 2000 lbs. Metric tons will be referred to in this document as "metric tons." Metric ton equals 1000 kg.

Chapter 1
Introduction

In the National Academy of Science's 2004 report, "Air Quality Management in the United States," the National Research Council (NRC) recommended to the U.S. Environmental Protection Agency (EPA) that standard setting, planning, and control strategy development should be based on integrated assessments that consider multiple pollutants, and that these integrated assessments should be conducted in a comprehensive and coordinated manner (NAS, 2004). With these recommendations, EPA began to move toward establishing multipollutant and sector-based approaches to manage air quality and environmental protection. The benefits of multipollutant and sector-based analyses and approaches include the ability to identify optimum strategies (considering feasibility, costs, and benefits across all pollutant types such as criteria, toxics, and others), while streamlining administrative and compliance complexities and reducing conflicting and redundant requirements.

The development of policy options for managing emissions and air quality can be made more effective and efficient through sophisticated analyses of relevant technical and economic factors. Such analyses are greatly enhanced by the use of an appropriate modeling framework. Accordingly, the Universal Industrial Sectors Integrated Solutions (U-ISIS) model has been developed at EPA (ARCADIS, 2010). Currently, the U-ISIS model is populated with U.S. cement manufacturing data. This module has undergone external peer review and comments have been addressed. Efforts are underway to build representations of the U.S. pulp and paper sector and the U.S. iron and steel sector. This document describes the framework of EPA's U-ISIS model and its application to the U.S. cement manufacturing industry.

1.1 The U.S. Cement Industry

1.1.1 Cement Types and Categories

Cement is a finely ground powder which, when mixed with water, forms a hardening paste of calcium silicate hydrates and calcium aluminate hydrates. Cement is used in mortar (to bind together bricks or stones) and concrete (bulk rock-like building material made from cement, aggregate, sand, and water). Concrete production uses the majority of cement produced.

Portland cement and blended cement are used in concrete production, but Portland cement is by far the most common type of cement used for concrete production. By modifying the raw material mix and, to some degree, the temperatures utilized in manufacturing, slight compositional variations can be achieved to produce Portland cements with slightly different properties. In the U.S., the different varieties of Portland cement are denoted per the American Society for Testing and Materials (ASTM)

Specification C-150. The ASTM standard C-150 recognizes eight types of Portland cement:

- Type I is for use in general construction (e.g., buildings, bridges, floors, etc.).
- Type IA is similar to Type I with the addition of an air-entraining agent.
- Type II generates less heat at a slower rate and has a moderate sulfate-attack resistance.
- Type IIA is similar to Type II with the addition of an air-entraining agent.
- Type III is used when concrete must set and gain strength rapidly.
- Type IIIA is similar to Type III with the addition of an air-entraining agent.
- Type IV has low heat of hydration and slow strength development.
- Type V is used when concrete must resist high sulfate concentration in soil and groundwater.

Portland cements are usually gray, but a more expensive white Portland cement (generally within the Type I or II designations) can be obtained by processing only raw materials with very low iron and transition-elements content.

Blended hydraulic cements are produced by intimately blending two or more types of cementitious material. Primary blending materials are Portland cement, ground granulated blast-furnace slag, fly ash, natural pozzolans, and silica fume. These cements are commonly used in the same manner as Portland cements. Blended hydraulic cements conform to the requirements of ASTM C-595. ASTM C-595 cements are as follows: Type IS-Portland blast-furnace slag cement, Type IP and Type P-Portland-pozzolan cement, Type S-slag cement, Type I (PM)-pozzolan modified Portland cement, and Type I (SM)-slag modified Portland cement. The blast-furnace slag content of Type IS is between 25 percent and 70 percent by mass. The pozzolan content of Types IP and P is between 15 percent and 40 percent by mass of the blended cement. Type I (PM) contains less than 15 percent pozzolan. Type S contains at least 70 percent slag by mass. Type I (SM) contains less than 25 percent slag by mass. These blended cements may also be designated as air-entraining, moderate sulfate resistant, or with moderate or low heat of hydration. The most common blended cements available are Types IP and IS. The United States uses a relatively small amount of blended cement compared to countries in Europe or Asia. However, this may change with consumer demands for products with specific properties, along with environmental and energy concerns.

Expansive cements are hydraulic cements that expand slightly during the early hardening period after setting. They meet the requirements of ASTM C-845 in which it is designated as Type E-1. Although three varieties of expansive cement are designated in the standard as K, M, and S, only K is available in the United States. Type E-1 (K) contains Portland cement, anhydrous tetracalcium trialuminosulfate, calcium sulfate, and uncombined calcium oxide (lime). Expansive cement is used to make shrinkage-compensating concrete that is used (1) to compensate for volume decrease due to drying shrinkage, (2) to induce tensile stress in reinforcement, and (3) to stabilize long-term dimensions of post-tensioned concrete structures. One of the major advantages of using expansive cement is in the control and reduction of drying-shrinkage cracks. In recent years, shrinkage-compensating concrete has been of particular interest in bridge deck construction, where crack development must be minimized.

Natural cement is an hydraulic cement produced by calcining argillaceous limestone below sintering temperatures. Natural cement may be specified by ASTM C-10. It was used primarily during the 19th century and early 20th century, but largely disappeared after about 1910, as Portland cement became more popular and began dominating the market.

Aluminous cement or calcium aluminate cements are hydraulic cements made from limestone and Bauxite. These cements are principally used in refractory applications. These cements are produced in tiny quantities with just a few manufacturers worldwide (USGS, 2005).

Cements can also be specified by performance per ASTM C-1157 and include the following: Type GU hydraulic cement for general construction, Type HE-high-early-strength cement, Type MS-moderate sulfate resistant cement, Type HS-high sulfate resistant cement, Type MH-moderate heat of hydration cement, and Type LH-low heat of hydration cement. These cements can also be designated for low reactivity (option R) with alkali-reactive aggregates. Performance based standards are not prescriptive with respect to composition as in ASTM C-1157 or ASTM C-595, but are inclusive of cements falling within these standards.

The common industry practice, and that of the U.S. Geological Survey (USGS), includes, within the Portland cement designation, a number of other cements not within ASTM C-150, which are composed largely of Portland cement and are used for similar applications (e.g., concrete) (USGS, 2005). These include blended cement, block cement, expansive cement, oil well cement, regulated fast setting cement, and waterproof cement. Plastic cements and Portland-lime cements are grouped within masonry cement, hydraulic cements for use in mortars for masonry construction. Because Portland cement accounts for approximately 95 percent of the cement industry's total production (van Oss, 2008), and because the costs and trends of this industry sector can be adequately captured by describing the market processes associated with the production, distribution, and use of Portland cement, in this work the focus is on Portland cement. In 2006, Portland cement's market share in the U.S. was 94 percent, while masonry cement's market share comprised the remaining 6 percent (USGS, 2007a).

1.1.2 Overview of the Cement Manufacturing Process

Portland cement is produced from raw materials such as limestone, chalk, shale, clay, and sand. These raw materials are quarried, crushed, finely ground, and blended to the correct chemical composition. Small quantities of iron ore, alumina, and other minerals may be added to adjust the raw material composition. The fine raw material is fed into a large rotary kiln (cylindrical furnace) where it is heated to extremely high temperatures (about 2640 °F [about 1450 °C]). The high temperature causes the raw material to react and form a hard nodular material called "clinker". Clinker is cooled and ground with approximately 5-percent gypsum and other minor additives to produce Portland cement. The main steps in the cement manufacturing process are illustrated in Figures 1-1 and 1-2, which show the wet process and the dry process with cyclone preheater, respectively. The schematic for a precalciner kiln would be very similar to that shown in Figure 1-2, with the addition of a calciner vessel.

The heart of the clinker production process is the kiln, which can be rotary or vertical shaft designs. Rotary kilns are commonly used in the U.S. and elsewhere. These kilns are 6-8 m in diameter and 60 m to well over 100 m long. The kilns are set at a slight incline and rotate at 1 to 3 revolutions per minute. The kiln is fired at the lower end and the feed materials move toward the flame as the kiln rotates. The materials reach temperatures between 1400-1500 °C in the kiln. Three steps occur with the raw material mixture during pyroprocessing. First, all moisture is driven off from the materials. Then the calcium carbonate in limestone decomposes into carbon dioxide (CO_2) and calcium oxide (free lime) during calcination. Finally, the lime and other minerals in the raw materials react to form calcium silicates and calcium aluminates, the main components of clinker.

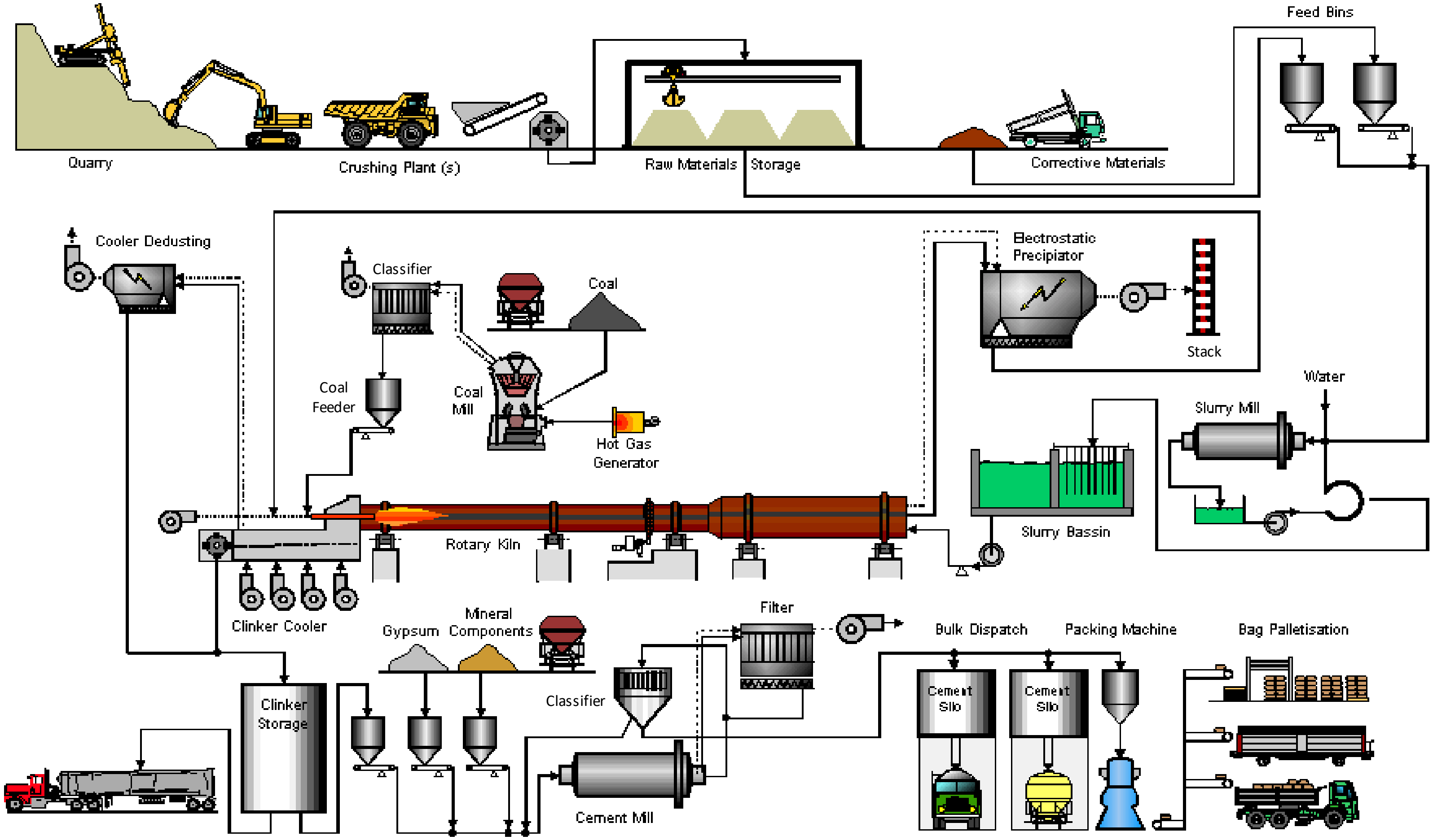

Figure 1-1. Schematic of the Wet Cement Process

Source: CEMBUREAU, 1999

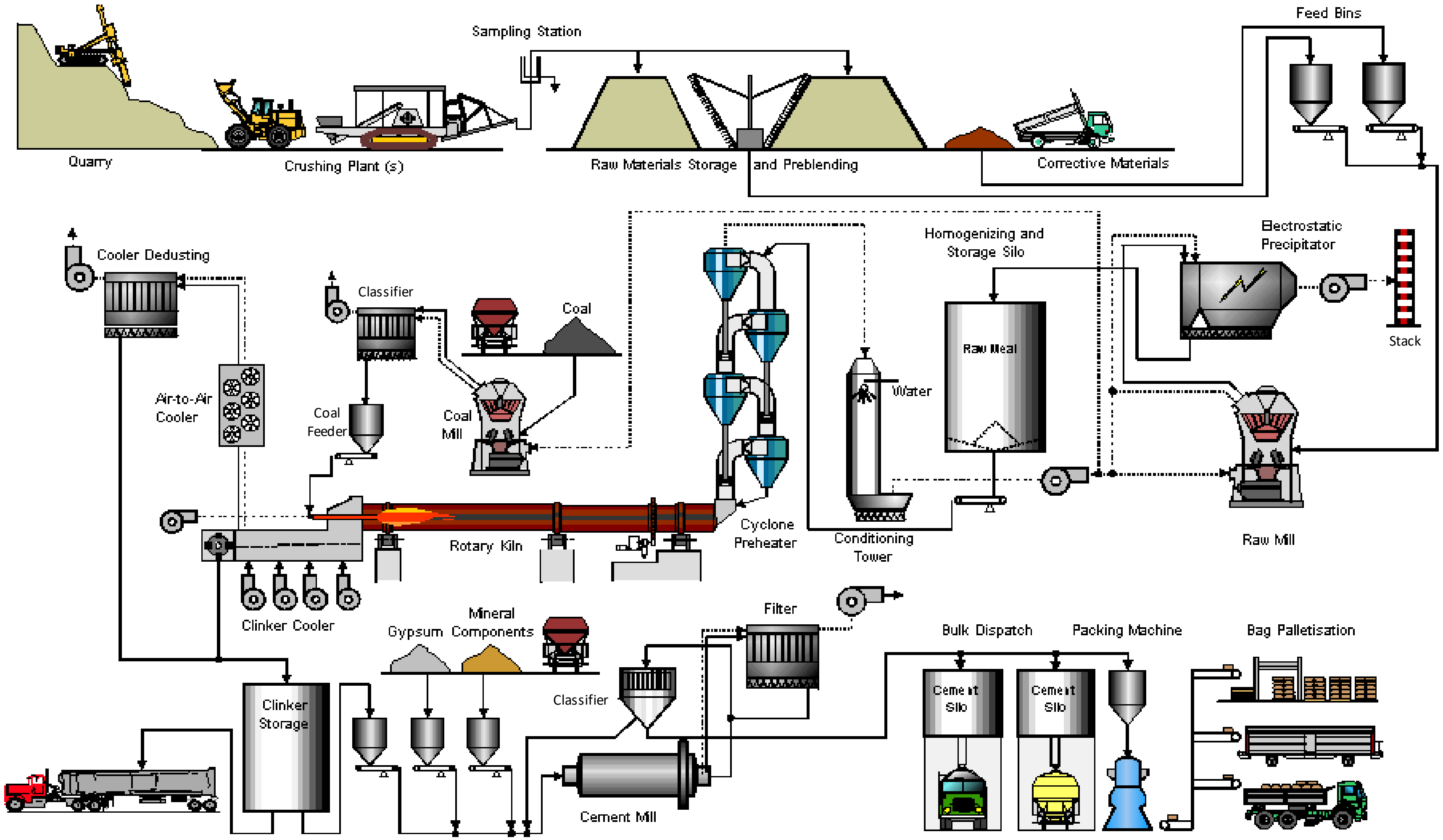

Figure 1-2. Schematic of the Dry Cement Process with Cyclone Preheater

Source: CEMBUREAU, 1999

1.1.3 Kiln Types and Their Use

Rotary kilns are broadly categorized as dry- and wet-process kilns, depending on how the raw materials are prepared. Wet-process kilns are fed raw material slurry with moisture content ranging between 30 and 40 percent. A wet-process kiln needs additional length to evaporate the water contained in the raw material feed. Nearly 33 percent additional kiln energy is consumed in evaporating the water in the slurry.

In dry-process kilns, raw material is fed as dry powder. There are three major variations of dry-process kilns in operation in the U.S.: long dry kilns, preheater kilns, and preheater/precalciner kilns. In preheater kilns and preheater/precalciner kilns, the early stages of pyroprocessing occur before the materials enter the rotary kiln. Preheater and preheater/precalciner kilns have higher production capacities and greater fuel efficiency compared to other types of cement kilns. Table 1-1 shows heat input in terms of millions of British Thermal Units (MMBtu)/ton[1] of clinker for various types of kilns. As the data clearly demonstrate, preheater/precalciner kilns provide greater fuel efficiency. The replacement of wet and (certain) dry process kiln capacity with modern kiln processes can yield, theoretically, substantial reductions in fuel use due to fuel efficiency gains. As the industry moves toward more efficient processes, replacement of wet and long dry process capacity with more efficient kiln process technologies is expected.

Table 1-1. Typical Average Heat Input by Cement Kiln Type

Kiln Type	Heat Input, MMBtu/ton of clinker
Wet	6.0
Long Dry	4.5
Preheater	3.8
Preheater/Precalciner	3.3

Source: EPA, 2007 (Table 3-3)

As expected, a recent trend in the cement sector has shown the replacement of lower capacity, inefficient wet and long dry kilns with bigger and more efficient kilns. This trend is expected to continue. In the U.S., the overall number of kilns decreased by 11 percent from 1995 to 2004. During the same period, total clinker production capacity increased by 18.6 percent. Portland Cement Association (PCA) data show that average kiln capacity also increased by 27 percent, from 405,000 to 556,000 tons per year between 1995 and 2004. The number of kilns operating in the U.S. in 2005 compared with the number of kilns in operation in 2009 is shown in Table 1-2. The trend in kiln design and average kiln capacity is shown in Figure 1-3.

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[1] *PLEASE NOTE: for the purposes of this document, short tons will be referred to simply as "tons" and represents 2000 lbs. A unit conversion table is provided in the front matter of this document.*

Table 1-2. Number of Kilns by Kiln Type in the U.S. in 2005 and 2009

Kiln Type	Number of Kilns (2005)	Number of Kilns (2009)
Wet	50	42
Dry	48	32
Preheater	36	29
Precalciner	47	58

Source: PCA, 2006 and PCA, 2009a

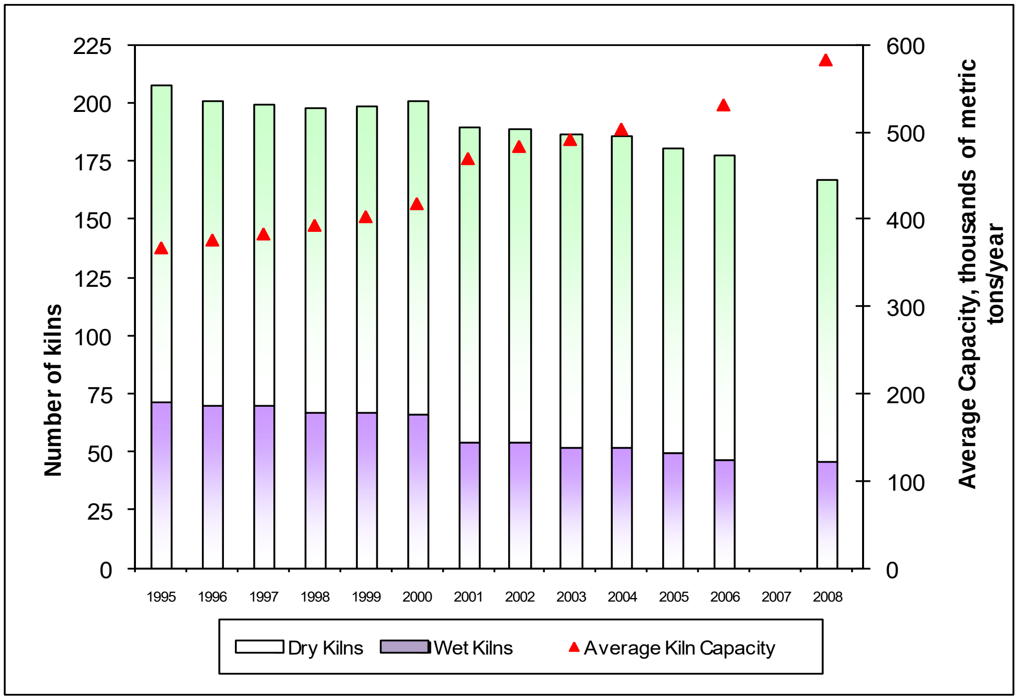


Figure 1-3. Trends in Cement Kiln Type and Capacity in the U.S. (1995 to 2008)

Note: The PCA Plant Information Summary became biennial in 2004. The 2005 data were obtained by personal communications between EPA and the PCA.

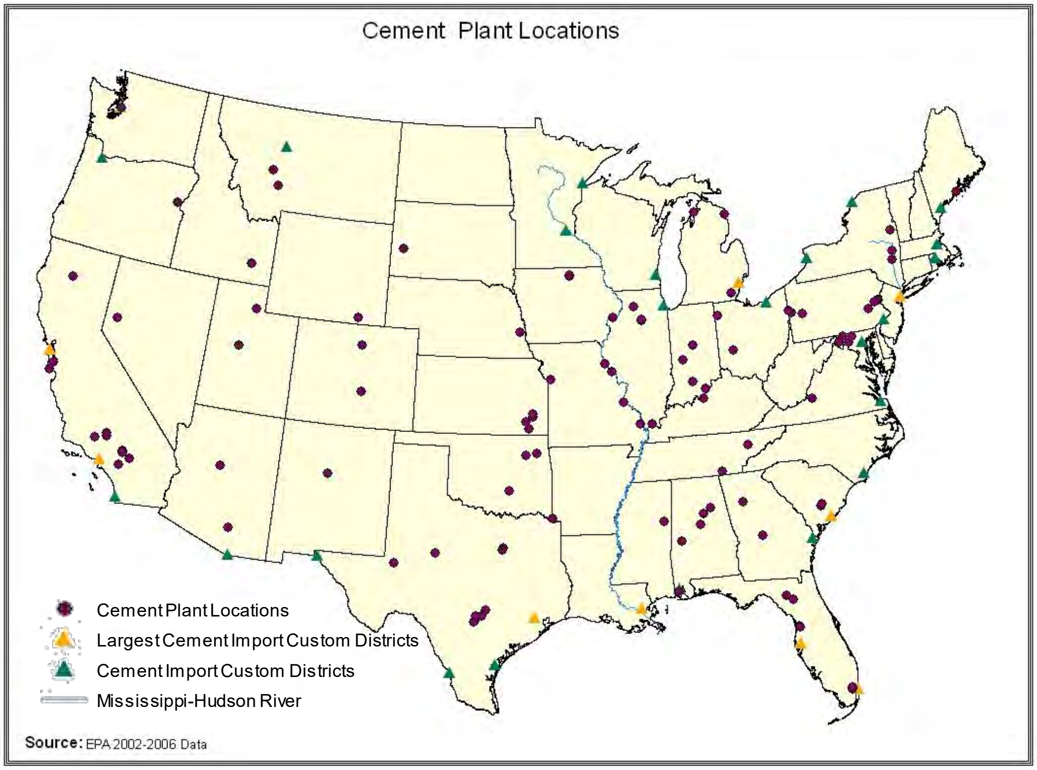
As reported by the USGS, in 2005, the U.S. Portland cement industry produced approximately 87 million metric tons of clinker, of which 13.5 percent was produced by plants with wet process kiln systems, while 81 percent was produced by plants operating only dry kilns of all three types (long-dry, preheater and preheater/precalciner). The remaining 5.5 percent was produced by plants that operate both wet and dry kilns (USGS, 2007b: Table 7).

1.1.4 Portland Cement Production in the U.S.

The cement industry remains a vital industry in the U.S. and throughout the world. In the U.S., Portland cement is a $12 billion industry (van Oss, 2008). In 2005, the U.S. consumed a record 128 million metric tons of Portland cement (USGS, 2007b: Table 1).

In 2005, Portland cement was produced at 107 plants in the U.S., including 37 states and Puerto Rico. The locations of the clinker-producing Portland cement plant facilities in 2005 are shown in Figure 1-4. The cement manufacturing sector in the U.S. is concentrated among a relatively small number of companies, many of which are owned by or are subsidiaries of foreign companies (USGS, 2007b). Together, ten companies accounted for about 80 percent of the total cement production in U.S. for 2005 (USGS, 2007b). California, Texas, Pennsylvania, Florida, and Alabama are the five leading cement-producing states, which accounted for about 43 percent of the total production in 2005 (USGS, 2007b: Table 3).

In 2009, PCA projected a capacity expansion of 27 million tons between 2008 and 2013, an 18-percent increase in existing capacity from 2006. PCA's projected capacity expansions are to come from 23 kilns; five came on-line in 2008 and 18 more are expected to come on-line between 2009 and 2013 (PCA, 2009b). The investment in these projected capacity expansions is projected at $6.9 billion. Note that a typical project for a new facility (greenfield) from ground breaking to startup has a timeframe of about 2 to 3 years. Building a new kiln in an existing facility (brownfield) can take approximately 1 year (EPA, 2007). If permitting for mining and (re)construction is accounted, a typical project can take as long as 4 to 6 years for a greenfield facility and up to 3 years for a brownfield facility (Andover Technology Partners, 2009a).



Source: EPA 2002-2006 Data

Figure 1-4. Portland Cement Plant Locations

1.1.5 Imports of Portland Cement in the U.S.

Portland cement is not only produced and consumed domestically, but it is also traded internationally. In 2005, the U.S. (not including Puerto Rico) produced 94 million metric tons of cement (USGS, 2007b: Table 3) and imported 34 million metric tons of hydraulic cement and clinker (USGS, 2007b: Tables 3 and 18). The level of imports to the U.S. is highly cyclical, with domestic producers importing primarily when domestic plants are at full capacity and cannot meet excess demand. Generally, imported cement and clinker make up 20 to 27 percent of domestic cement consumption. In 2005, total imports of cement and clinker (especially clinker) increased, owing to continued high demand; imported cement accounted for about 24 percent of the total cement sales in the U.S. (USGS, 2007b).

In 2005, the ten leading international cement and clinker suppliers to the U.S. were, in descending order, Canada, China, Thailand, Greece, the Republic of Korea, Venezuela, Mexico, Colombia, Taiwan, and Sweden. The ten busiest ports of entry within customs districts existing in 2005 were, in descending order, New Orleans, Tampa, Los Angeles, Houston-Galveston, San Francisco, Miami, Seattle, Detroit, New York, and Charleston (South Carolina) (USGS, 2007b). Table 1-3 shows the major customs districts for hydraulic cement and clinker imports in the U.S. Figure 1-5 shows the imports of clinker and cement from 1998 to 2008.

Table 1-3. Largest Hydraulic Cement and Clinker Import Custom Districts in the U.S. in 2005

Custom District	Import of Hydraulic Cement and Clinker		Percentage of Total U.S. Imports
	thousands of metric tons	thousands of tons	
New Orleans, LA	4,095	4,514	12.31
Tampa, FL	3,478	3,834	10.46
Los Angeles, CA	3,053	3,365	9.18
Houston-Galveston, TX	2,619	2,887	7.87
San Francisco, CA	2,363	2,605	7.10
Miami, FL	2,265	2,497	6.81
Seattle, WA	1,489	1,641	4.48
Detroit, MI	1,317	1,452	3.96
New York, NY	1,264	1,394	3.80
Charleston, SC	1,102	1,215	3.31
Total	**23,046**	**25,404***	**69.29%**

* rounding, original data in metric tons

(Source: USGS, 2007b (Table 18)

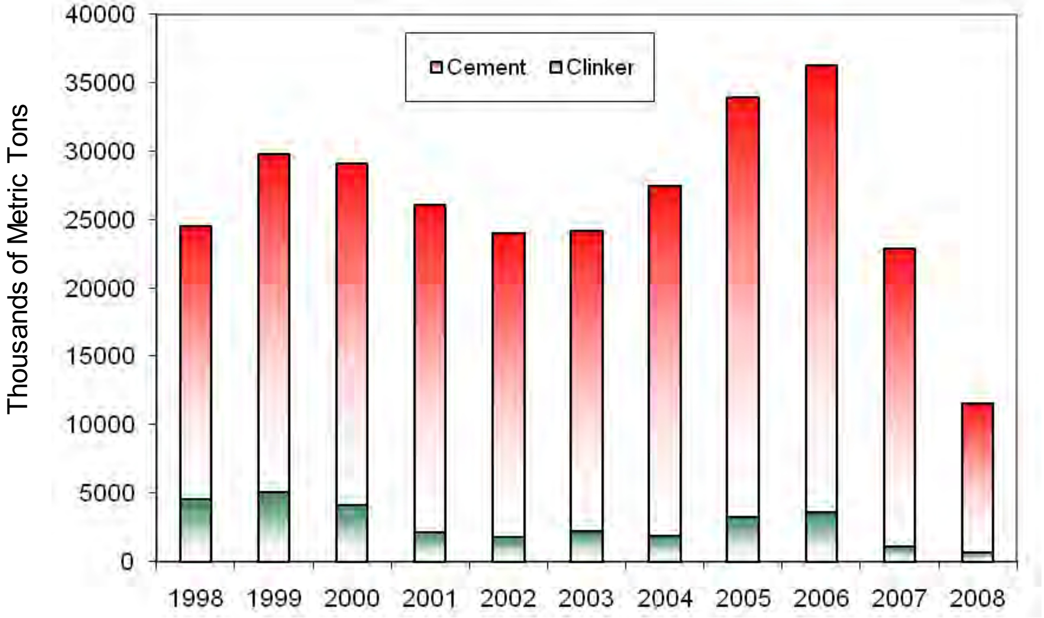


Figure 1-5. Imports of Clinker and Cement from 1998 to 2008 (PCA, 2009a)

1.1.6 Cement Demand Centers

Because of the relatively high transportation costs, the U.S. cement industry is structured around state-specific cement demand centers. PCA reports that the vast majority of cement produced in the U.S. is being transported less than 300 miles by truck due to cement's low value by weight and high cost of transport (PCA, 2005). However, cement may be transported over longer distances, especially when the less expensive rail and water transportation modes are available (APCA, 1997).

1.2 Emissions from the U.S. Cement Industry and Applicable Regulations

Criteria pollutants, hazardous air pollutants (HAPs), and CO_2 are released during cement manufacturing. Nitrogen oxides (NO_X) emissions from cement kilns result primarily from the combustion process: oxidation of fuel nitrogen (fuel NO_X) and the oxidation of nitrogen in the combustion air (thermal NO_X). EPA's 2005 National Air Toxics Assessment (NATA) Inventory reports that cement kilns released 181,000 metric tons (200,000 tons) of NO_X emissions from the combustion of fuels (EPA, 2009).

Sulfur dioxide (SO_2) emissions[2] from cement kilns result from the combustion of sulfur-bearing compounds in coal, oil, and petroleum coke, as well as sulfur compounds in raw materials. Sulfur in the fuel will oxidize to SO_2 during pyroprocessing and a significant amount is likely to be captured in the form of sulfates as the flue gas passes through the calcination zone. Compared to long dry and wet kilns, preheater and precalciner kilns tend to be more effective at capturing fuel-generated SO_2. Accordingly,

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[2] Small amounts of sulfur trioxide (SO_3) may be released in addition to bulk SO_2 but the SO_3 emissions are treated as SO_2 for computational purposes.

oxidation of sulfur in the feed materials is likely to be the major component of total SO_2 emissions. The 2005 NATA Inventory reflects that cement kilns released 133,000 metric tons (147,000 tons) of SO_2 emissions in 2005.

Particulate matter (PM) emissions result from quarrying operations (the crushing and grinding of raw materials and clinker) as well as kiln line operations. The 2005 NATA Inventory estimates show that, in 2005, cement kilns released 10,000 tons of PM_{10} emissions. The cement industry is also a source of HAPs (e.g., hydrochloric acid vapor and chlorine), as well as metals including but not limited to mercury, antimony, cadmium, and lead (EPA, 2008).

The cement manufacturing process is also a source of CO_2 emissions. CO_2 emissions are a product of the combustion of fuel as well as the calcination of the limestone in the raw meal. The CO_2 from fuel combustion can be calculated from heat input and fuel characteristics combined with clinker production. The CO_2 from calcination can be calculated taking into account the amount of limestone used as a source of clinker calcium. Limestone currently is the predominant source of calcium for the clinker. Pure limestone would produce 0.44 tons of CO_2 for every ton of limestone completely calcined to calcium oxide. Substitute materials may be used in lieu of limestone with the effect of reducing the CO_2 emissions from clinker production. The CO_2 emissions reduction would be proportional to the amount of substitute materials added. Detailed discussion of CO_2 emissions from cement kilns can be found in Appendix A.

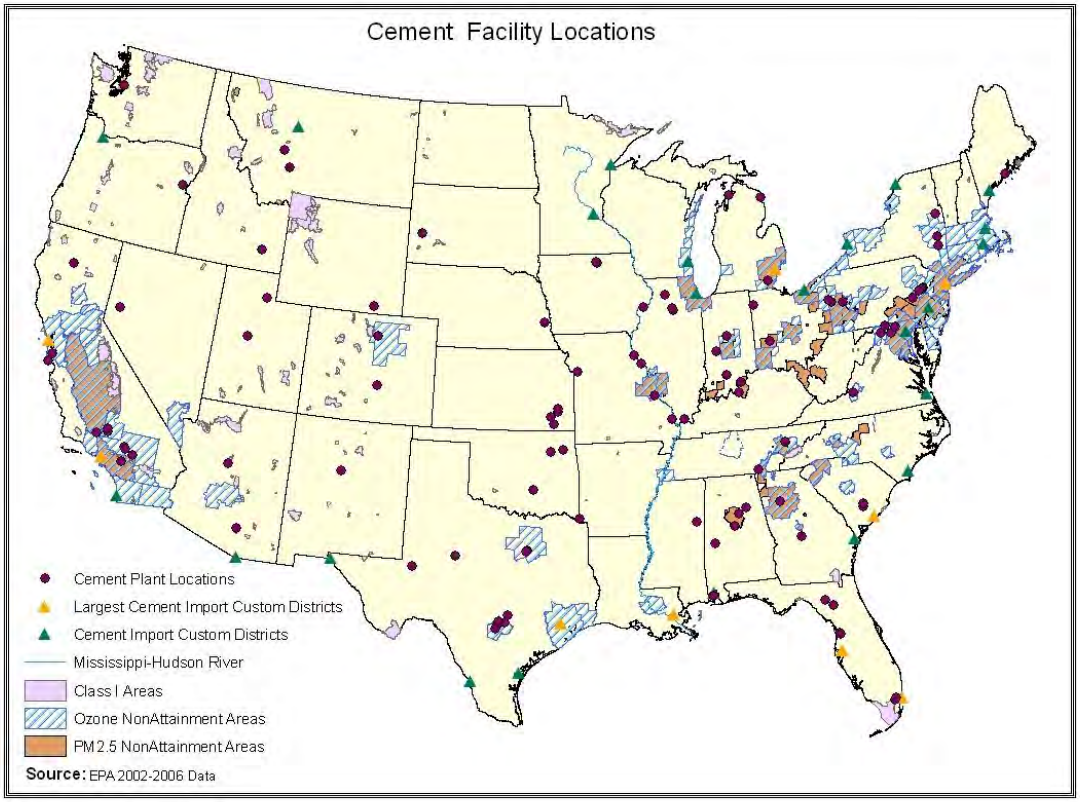
Multiple regulatory requirements to reduce criteria air pollutants and HAPs emissions currently apply to the cement industry sector. The New Source Performance Standards (NSPS) and the National Emissions Standards for Hazardous Air Pollutants (NESHAPs) are two of the federal requirements that apply to cement facilities. Additionally, state and local regulatory requirements might apply to individual cement facilities depending on their locations. In 2008, 44 cement facilities were located within ozone (O_3) nonattainment areas (NAA), while 20 facilities were within $PM_{2.5}$ nonattainment areas. Seventeen facilities were found to be located in (or within 30 miles of) Class 1 areas, as shown in Figure 1-6. Class 1 areas are areas of special natural, scenic, recreational, or historic (national or regional) value for which the Prevention of Significant Deterioration (PSD) regulations provide special protection.

1.3 Overview of U-ISIS

U-ISIS, a sector-based dynamic programming model, will facilitate the analyses of emission reduction strategies for multiple pollutants while taking into account plant-level economic and technical factors such as the type of emission units (for cement – kiln), associated capacity, location, cost of production, applicable controls, and their costs. For each of the emission reduction strategies under consideration, the model is able to provide information on the following:

- Optimal (least cost) industry operation
- Cost-effective controls to meet the demand for cement
- Emission reduction requirements over the time period of interest

U-ISIS incorporates multiple industries within a multi-market, multi-product, multipollutant, and multi-region emissions trading framework. The objective function in U-ISIS maximizes total surplus and uses an elastic formulation of the demand function to estimate area under the demand curve.



Source: EPA 2002-2006 Data

Figure 1-6. Portland Cement Facilities and O_3 NAA, $PM_{2.5}$ NAA, and Class 1 Areas

The U-ISIS code is written in the General Algebraic Modeling System (GAMS) language. Input data, organized in various spreadsheets of a Microsoft Excel workbook, are passed on to the GAMS files. These input data consist of an industry database, which provides unit-level production, capacity, production cost, and emissions information. The controls database provides information regarding applicable air pollution control technologies and their cost and emission control characteristics. A policy module is used to specify various parameters of interest to the policy analyst, such as emissions cap, emission reduction scenarios, and discount rate. The input data, control data, and policy parameters are then transmitted to the optimization part of the U-ISIS model, where they are used to solve the selected base and policy cases. After solving, the results are post-processed to calculate values of various outputs of interest. The output data are exported to Excel spreadsheets for further analyses and graphical representation of selected results.

Within an industrial sector, generally emissions arise from four pathways: (1) on-site emissions due to combustion of fossil fuels for energy at plants, (2) on-site emissions due to processing of certain raw materials (e.g., limestone calcination in cement plants, non-energy uses of fossil fuels in chemical processing and metal smelting), (3) off-site emissions due to combustion of fossil fuels at power plants to generate the electricity needed by the industrial sector, and (4) overseas emissions associated with imports. These pathways are depicted in Figure 1-7.

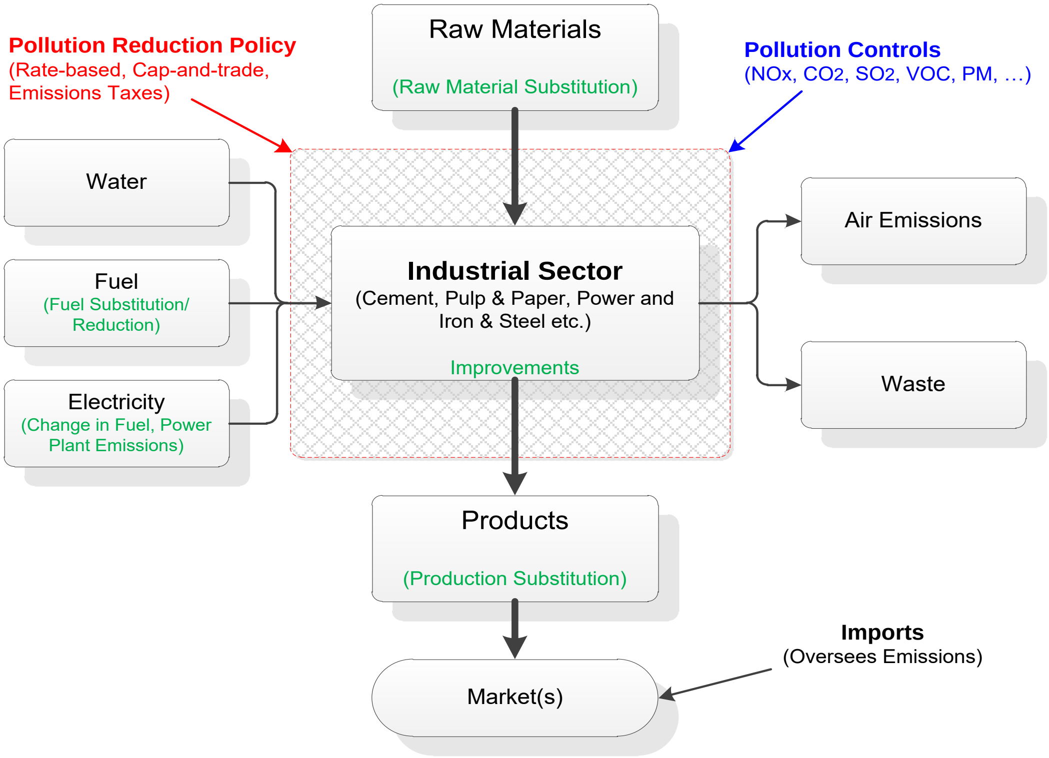


Figure 1-7. An Integrated View of Pollution Generation Pathways, Emissions Abatement Approaches, and Multimedia Impacts for an Industrial Sector

Also shown in Figure 1-7 are the potential options for abating emissions from industrial sectors and multimedia impacts. The options shown in green are pollution prevention measures and the ones in red are mitigation measures. Clearly, the integrated picture presented in Figure 1-7 makes a compelling case for considering commodity production/supply activities along with emissions while developing holistic emission reduction strategies. While developing the U-ISIS framework, care has been taken to build the emission pathways and abatement options shown in Figure 1-7. Example emission reduction policies that can be evaluated using U-ISIS are:

- Criteria pollutants (NO_X, SO_2, PM, carbon monoxide (CO)) –emission limits and/or cap-and-trade
- HAPs (e.g., mercury (Hg), hydrochloric acid (HCl)) – emission limits
- CO_2 – cap-and-trade and/or emission taxes
- Long and short time horizons: CO_2 (decades), criteria pollutants (annual)
- Regional or national requirements

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Chapter 2
U-ISIS Framework

U-ISIS is a sector-based *linear programming* model that can help analyze optimal sector operations for meeting demand and pollution reduction requirements over specified time periods. The objective in U-ISIS simulation is to maximize *total surplus* (see Figure 2-1) over a time horizon of interest for an industry. The total surplus concept has long been a mainstay of social welfare economics because it takes into account the interests of both consumers and of producers (Samuelson and Nordhaus, 1977).

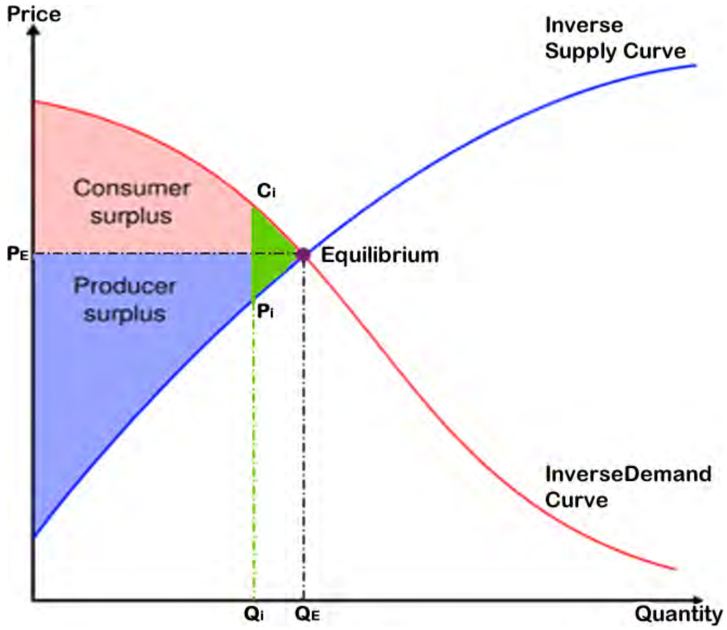


Figure 2-1. Total Surplus in a Market

In a market at competitive equilibrium, without exogenous factors, the total surplus can be thought of as composed of producer surplus and consumer surplus. Using Figure 2-1, the producer surplus corresponding to a quantity Q of a commodity is the difference between the gross revenue and the inverse supply curve. Gross revenue is simply the product of the price and the quantity consumed. Similarly, the consumer surplus corresponding to a quantity Q is given by the area under the inverse demand curve up to that quantity minus the gross revenue. The consumer surplus is the cumulative opportunity gain of all consumers who purchase the commodity at a price lower than the price they would have been willing to pay. It is evident from Figure 2-1 that the total surplus is maximized exactly when Q is equal to the equilibrium quantity Q_E. This result allows determination of the demand quantity at equilibrium, where total surplus is maximized, as the cost of production meets the inverse demand curve.

When the quantity consumed is less than the optimum Q_E (e.g., Q_i) due to some market disturbance such as a policy or regulation change, the consumer pays a higher price C_i resulting in a reduction in consumer surplus. The inverse supply curve shifts as a result of this disturbance. At a new equilibrium the marginal total cost will increase from P_i of the base case to C_i at the lower quantity Q_i. The total surplus shrinks resulting in a welfare loss, represented by the lighter shaded area in Figure 2-1. The producer surplus changes from the base case as a proportion of total surplus, but some of this surplus may be diverted from the producer by the form of the policy or regulation change. The framework of the U-ISIS model does not proportion the total surplus into consumer and producer surplus, but calculates the total surplus from the total benefit, i.e., the total area under the inverse demand curve less the area under the inverse supply curve for the quantity of interest.

The general concept of *spatial price equilibrium* (SPE) in a network, where the mutual influences of production, transportation, and consumption patterns are given full consideration, has been developed over the past 6 decades. In SPE network models, interregional economies are simulated by finding the balance of demand, supply, and trade that will result in competitive market equilibrium among the regions. Enke (1951) first demonstrated how the cost of transportation might be included in an equilibrium analysis of spatially separated markets by means of analogy with resistance to the flow of current in an electric circuit. Shortly after Enke, Samuelson (1952) analyzed interregional flows of commodities and market equilibrium using a linear programming formulation. In this type of formulation, the equilibrium for each market of a sector is equivalent to the quantities and prices that result while maximizing the sum of consumer and producer surpluses for each market of the sector. This sum is referred to as the total surplus or net social payoff of the sector; McCarl and Spreen (1980) provide interpretation and justification. The linear programming formulation of the SPE problem was developed by Duloy and Norton (1975).

Figure 2-2. Modular Architecture of U-ISIS

The *Industry* inputs part of U-ISIS allows users to enter industrial sector data including the number of production facilities, distance from production facilities to demand center, production capacity, associated costs (material costs, operations and maintenance costs, etc.), fuel types and costs, emissions sources and intensities, etc. The *Market* inputs part of the model includes historical and projected nationwide commodity consumption, commodity imports and exports. The *Others* inputs allows users to define discounts rates, electricity parameters, escalation rates, economic life, and technologies and emissions abetments factors. The *Policy* inputs allows users to define policy related parameters such as the amount of control required and the total quantity of emissions allowed. The user can specify the policy horizon (time period) to be used for the model runs. Policies may be simulated over long and short time horizons, such as a CO_2 policy that occurs over a decadal time-frame, and a criteria pollutant policy that occurs on an annual-time frame. The U-ISIS model is also capable of evaluating requirements at a regional or national-scale.

2.1 Objective Function

The objective function of the model is to maximize the net present value total surplus (by the equivalent function, minimizing the negative of the total surplus) for the given sector of interest over a selected time horizon. The total costs, as calculated by the algorithm, approximate the area under the inverse supply curve. Components of total costs include production cost, transportation cost, import cost, control cost, energy efficiency cost, and emission charge. The total benefit − which includes total costs, producer surplus, and consumer surplus − is calculated from the total area under the inverse demand curve. Each element is corrected to net present value by applying a discount factor for each year within the time horizon based on a user supplied discount rate. The negative of the total surplus is calculated by subtracting the total benefit from the total costs.

Elements of total costs include:

1) **Production cost** - obtained for each cement production unit. Each unit's production cost takes into account the factor input costs of raw material, labor, energy, and other cost components.

2) **Transportation cost** - cost of transporting from supply center to the demand center. Production from each supply center may be transported to any demand center. Distance from each supply center to each demand center is incorporated in the industry inputs.

3) **Import cost** - calculated by multiplying the quantity of imported goods by the import price for each country of origin and adding any handling and other associated costs. All imports arrive at the import terminals and incur transportation costs to reach each demand center; distances from import terminals to each demand center are incorporated in the industry inputs module.

4) **Control and energy efficiency costs** - includes the capital and variable cost of installing controls and energy efficiency options, to achieve any emission reduction targets governed by the constraints.

5) **Emission charge** - added if any allowance price is given for the pollutants.

The objective function is:

$$\begin{aligned}
\text{Minimize}\quad z = & \sum_{t,i,n} \text{discount factor(time)} \bullet \text{production cost(time, production unit, final product)} + \\
& \sum_{t,dc,n} \text{discount factor(time)} \bullet \text{transportation cost(time, demand center, final product)} + \\
& \sum_{t,id,n} \text{discount factor(time)} \bullet \text{import cost(time, import district, final product)} + \\
& \sum_{t,i,k} \text{discount factor(time)} \bullet \text{control cost(time, production unit, control option)} + \\
& \sum_{t,i,ee} \text{discount factor(time)} \bullet \text{energy efficiency cost(time, production unit, efficiency option)} + \\
& \sum_{\text{t,j}} \text{discount factor(time)} \bullet \text{allowance price(time, pollutant)} \bullet \text{total emissions(time, pollutant)} - \\
& \sum_{t,dc,n} \left[\text{discount factor(time)} \bullet \text{total benefit(time, demand center, final product)}\right]
\end{aligned}$$

Where the quantities appearing in the equation above are defined as:

- discount factor(time) is the factor to correct costs from year **t** to net present value,
- production cost(time, production unit, final product) is the production cost in year **t** for production unit **i** of final product **n**,
- transportation cost(time, demand center, final product) is the cost for year **t** of transporting the product **n** to demand center **dc**,
- import cost(time, import district, final product) is the cost for year **t** of importing foreign product **n** in import district **id**,
- control cost(time, production unit, control option) is cost for year **t** to control production unit **i** using control technology **k**,
- energy efficiency cost(time, production unit, efficiency option) is the cost for year **t** for production unit **i** to use the energy efficiency measures **ee**,
- allowance price(time, pollutant) is the user defined allowance price for pollutant **j** in year **t**
- total emissions(time, pollutant)is the total emissions of pollutant **j** during year **t** from the sector, and
- total benefit(time, demand center, final product) is the area under the demand-price curves for product **n** for all markets **dc**.

Total costs, as calculated by the algorithm, approximates the inverse supply curve by filling demand from the lowest cost product incorporating production or import costs, transportation, and policy measures through consecutively higher cost product until demand is satisfied. Demand is satisfied when the demand price no longer exceeds the supply cost. The user chooses a range of interest centered on the expected demand for demand center and production year; model default is 0.5 to 1.5 times the expected demand. Demand in this range is divided into a user defined number of steps or intervals; the model default is 100 steps. The inverse demand curve is used to determine the demand price at the midpoint of each demand step user supplied data (e.g., elasticity) in each demand region using a constant elasticity of demand:

$$P(D) = \mathrm{P0}\left(\frac{D}{\mathrm{D0}}\right)^{\frac{1}{\sigma}} \tag{2-1}$$

Where:

D is the demand for the commodity with corresponding price $P(D)$,

σ is the elasticity of demand relative to price, and

D0 and **P0** are the initially-specified demand quantity and price, respectively.

The total benefit is calculated based on a constant elasticity of demand model in the same stepwise fashion as illustrated in Figure 2.3. The benefit within the demand range considered by the user, from D_{min} to the final demand quantity, is estimated by the product of price at the midpoint of each step and the width of the step. The benefit associated with demand from zero to D_{min} is estimated by the product of D_{min} and the demand price of the first step of the range.

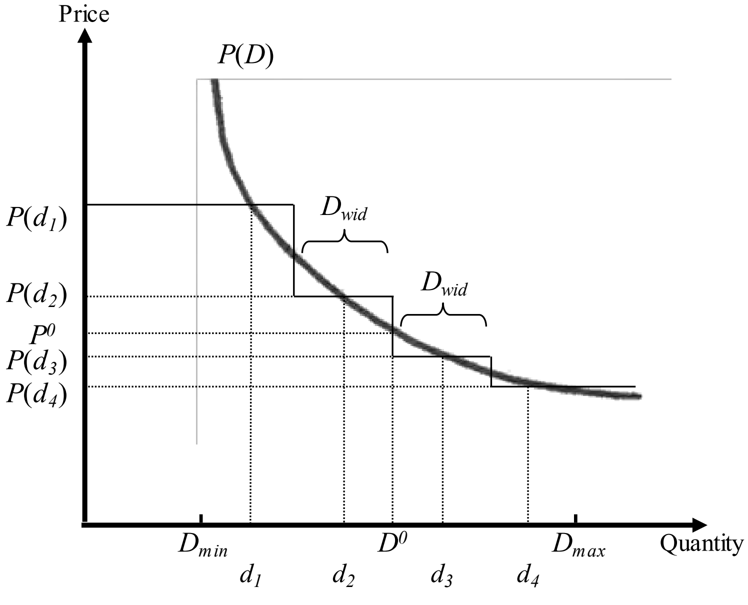


Figure 2-3. Stepwise Integration of the Inverse Demand Curve

Production costs are a combination of fixed cost, in the form of capital recovery costs, and variable costs. Capital recovery usually depreciates the cost of new production capacity over the economic life of the additional capacity using a user-defined interest rate for capital expenses. However, the user will have the option to add fixed costs, if any, for an existing production unit.

The U-ISIS model includes constraints for ensuring that production capacity changes occur in a realistic way. Production is modeled for five types of units: existing production units, expansion units, replacement units, projected units and new production units. Existing production units are units currently installed and capable of producing product. Expansion units are the units associated with increasing production capacity at an existing production unit. Replacement units are production units built to retire existing production units and replace with new production units. New production and projected units represent entirely new production capacity.

Variable production costs include raw material costs, operations and maintenance costs (O&M), labor costs and electricity costs provided by the user on a unit of production basis. The model adds fuel cost, water cost and solid waste cost. Fuel cost is calculated as the product of energy intensity of production and fuel cost for each type of fuel used. Similarly, water cost is the product of the water used in production and the price of water per unit volume. Solid waste cost is the product of the amount of solid waste produced and the price of solid waste disposal.

Transportation costs are the costs associated with moving production from factories to the demand center and the costs of moving imports from the import district to the demand center. The variable cost of transporting each unit of supply from the factory or import district to the demand center is supplied by the user. The transportation cost is the sum of the product of variable transportation costs for each factory or import district and the supply from that factory or import district.

Imports cost to each import district is the product of imported quantity and the cost of importing product. The imported quantity to each import district is iteratively determined from the marginal cost of domestic production, at the high cost production facility, and the total cost associated with the imports inclusive of transportation. Costs of imports is the sum of the import price to the import district, insurance and freight to the import district, and handling costs at each import district. The import price is determined from a constant elasticity of supply curve for each import district based on user-supplied information.

Similar to the added production, costs for both controls and energy efficiency measures consist of both capital recovery costs and variable costs. Both further modify the energy intensity of production, and therefore, the fuel cost as well. Both measures are amortized over the expected lifetime of the modification.

The cost of emissions is determined for each pollutant as the product of the emission and allowance price for the respective emission. No emissions costs are associated with imports. These costs are consistent with a user-supplied emission tax.

2.2 Constraints

The objective function is minimized with regard to the constraints described in the following sections to arrive at the optimal solutions.

Consumption & Supply for each demand center; the total supply has to be greater than or equal to consumption in the given time period. Supply can be comprised of local production, import from other regions, and foreign import. U-ISIS provides full flexibility to determine demand centers, imports/exports terminals, commodities quantity and price, and associated transportation costs. Total domestic consumption for a commodity can be satisfied by domestic production and foreign imports as follows:

$$\sum \text{Production Quantity} + \sum \text{Imports Quantity} - \sum \text{Exports Quantity} \geq \sum \text{Consumption (Demand)} \qquad (2\text{-}2)$$

where import/export quantity is limited to terminal capacity. Production of a commodity is limited to cement plants' availability. Plant availability can be restricted by resources availability such as fuel and raw materials availability and capacity. For instance, energy consumption by a plant can only be picked from the fuels available at the location of production. While in reality switching of fuels, e.g., from coal to natural gas, can be complicated requiring capital investment in the infrastructure. For the purpose of this model, the fuels are assumed to be perfectly substitutable without any additional cost of switching.

$$\text{Production} \begin{cases} \leq \text{Capacity} \\ \leq \text{Fuel availability} \end{cases} \qquad (2\text{-}3)$$

Emissions pathways are included in the U-ISIS framework. The U-ISIS framework includes algorithms to account for tracking multiple pollutant streams associated with uncontrolled emissions, controlled emissions, pollution prevention from process modifications and energy efficiency measures, and any controls-related effects. For a given pollutant, total emissions have to be limited to emission limits specified by the exogenous policy constraints on emissions. If the policy being analyzed allows for banking of emissions, then the banking equation enables banking of allowances for future use.

Transportation of goods and commodities from a production unit is limited by the lower of the two - the production capacity of the unit or the transportation capacity from a production unit to all demand centers, if specified. Certain other constraints on transportation can limit the transportation network based on empirical studies.

Imports and Exports quantity on each terminal is limited by the terminal capacity, but U-ISIS provides full flexibility to customize assumptions including changes in quantity, imports/exports prices and terminal locations.

Emissions Abatement Approaches in U-ISIS are categorized in three abatement approaches: process modifications and upgrades, raw material and/or fuel substitution, and mitigation technologies. For each emission abatement approach, where possible, information is included in the U-ISIS model on capital cost, fixed operating cost, variable operating cost, emission reduction performance for all of the pollutants, impacts on fuel and/or raw material use, impact on electricity consumption, byproduct generation and cost, and impact on water use parameters.

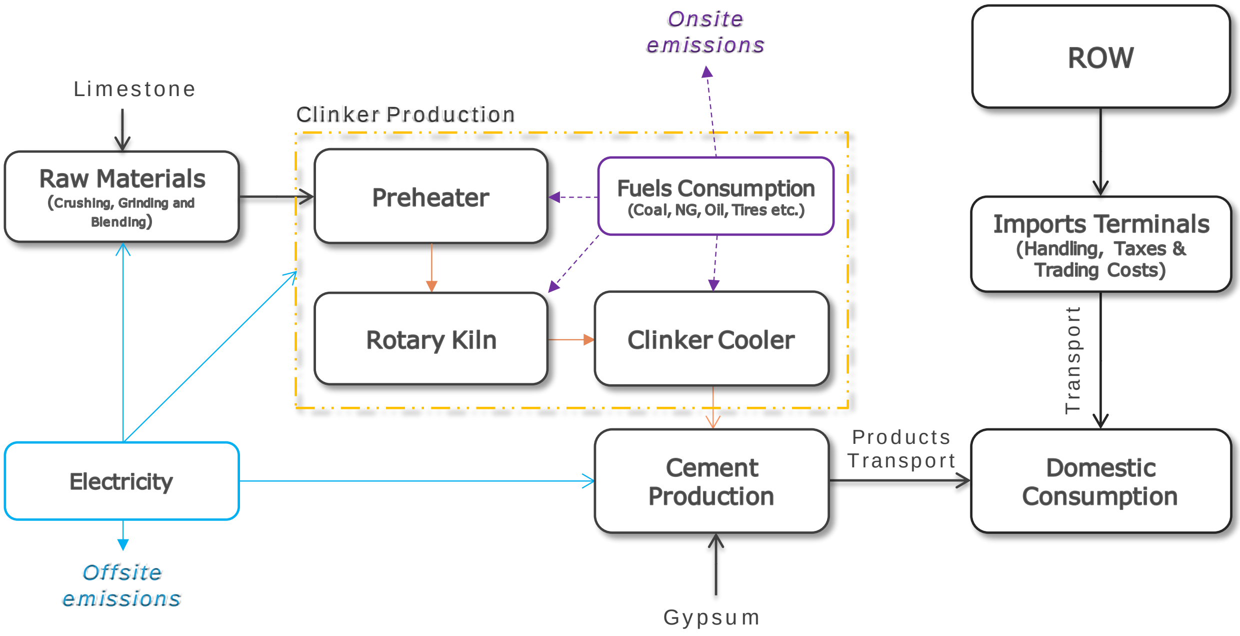
Policy Parameters in the U-ISIS Framework allows the user to select a variety of potential policy options for evaluation. The user can select from cap-and-trade policy, emissions charge policy, or rate-based policies. In a cap-and-trade policy scenario, separate caps on pollutants of interest can be specified. The user has the option to run a cap-and-trade policy scenario with or without banking of emissions. Further, a cap-and-trade policy scenario can include *de minimus* requirements, where the user defines a minimum level of emission reduction required for each emission unit. It is also possible for the user to input an emission charge for pollutants of interest. Furthermore, traditional policy scenarios (rate-based policies) with unit-specific emission reduction requirements specified by the user can be modeled in U-ISIS.

2.3 Optimization and Post Processing

In U-ISIS, the input data are pre-processed to arrive at suitable input parameters for use in the model equations explained in this chapter. Once the data have been pre-processed, U-ISIS solves for the appropriate levels of production, imports and controls required to meet the constraints associated with commodity demand and emissions, while maximizing total surplus. Once the surplus maximization problem has been solved, the results are post-processed to obtain parameters and level values of the variables of interest. The key variables of interest are production level of each production unit to meet regional demand, level of imports in each region, installation of various controls, emissions, and various costs. Output data are written in appropriate worksheets in an Excel workbook and further linked to various plots to enable visual presentation and analyses of the results.

2.4 U-ISIS Interface

The U-ISIS interface is a single PC-based executable tool with a multi-sector (modular) approach that provides a user-friendly interface for exploring and comparing various scenarios of meeting product demand and pollution reduction requirements for an industrial sector of interest over specified time periods. The U-ISIS interface allows the user to develop, edit, or delete scenarios for an industrial sector of interest. Both the web application and the downloadable tool are being developed by EPA's Air Pollution Prevention and Control Division (APPCD) within ORD. A beta version of the web application is being developed. Data collection (from published data and from well-developed existing technologies) is underway to produce and populate data for the web application to help ensure it will become a robust, production-ready application. Figure 2-4 shows the modeling framework for the cement industry and the types and interaction between the various parameters involved.



NG = Natural Gas
ROW = Rest of the World

Figure 2-4. Cement Modeling Framework

The ultimate goal of the web application is to provide a database for users, both internal and external of EPA, to explore emissions and least-cost scenarios for supply, supply costs, and emission control costs under various policy options for the industrial sectors covered in the modules. This web application will link to the database, developed and maintained by ORD/APPCD. This database, once available to EPA and the public will need updating on a regular basis to include new and updated information as they become available. The user will have the option of querying the database, through the web application, and populating data and information based on their scenario of interest. With this, the user will have the capability to export the data from the web application to Excel or in PDF format.

2.4.1 Interface Features

The features of the user interface will include pull-down menus, mouse support and “point-and-click” activation of many of the features and will be tested using “internal best test” procedure. The U-ISIS database will be fully protected, such that each user scenario option will be evaluated individually. Step-by-step instructions for using each module of the U-ISIS model will be provided to all external users and will be updated as needed. Any user will be expected to have read the U-ISIS Quality Assurance Project Plan (QAPP) and industry-specific module appendix as well as be familiar with the model, how it works, and the types of outputs to be generated.

2.4.2 Interface Data Structure

As shown in Figure 2-2, U-ISIS has a modular architecture and emission, fuel, and policy parameters relate to each industry-specific module. Input data are organized in various spreadsheets of a Microsoft Excel workbook to run as a standalone (single module without interface) version of the U-ISIS model. U-ISIS data are organized in a Microsoft sql database. U-ISIS code is written in the General Algebraic Modeling System (GAMS) language. The U-ISIS interface is being programmed in C# and web development programming software in a graphical and web-based layout. The interface plays an intermediate role between the U-ISIS model (developed in GAMS) and as an interface to exchange data. Furthermore, the interface retrieves data from the U-ISIS model and allows the user to generate tables and graphs of interest.

All data are organized in a Microsoft Access database and in Excel. The U-ISIS interface communicates with the Microsoft Access database, generates input data sheets, and transmits to the U-ISIS model for the optimization. Selected data are then pre-processed in the U-ISIS model to arrive at suitable input parameters for use in the model equations. After pre-processing the data, U-ISIS solves for the appropriate levels of production, imports, and controls required meeting the constraints associated with commodity demand and emissions, while maximizing total surplus. Once the surplus maximization problem has been solved, the results are post-processed to obtain parameters and level values of the variables of interest. After solving, the output results are transferred into a Microsoft Access database. The U-ISIS interface then helps the user to interpret these outputs in the desired format (tables, graphs, etc.). The systematic diagram of the interface and U-ISIS engine is shown in Figure 2-5.

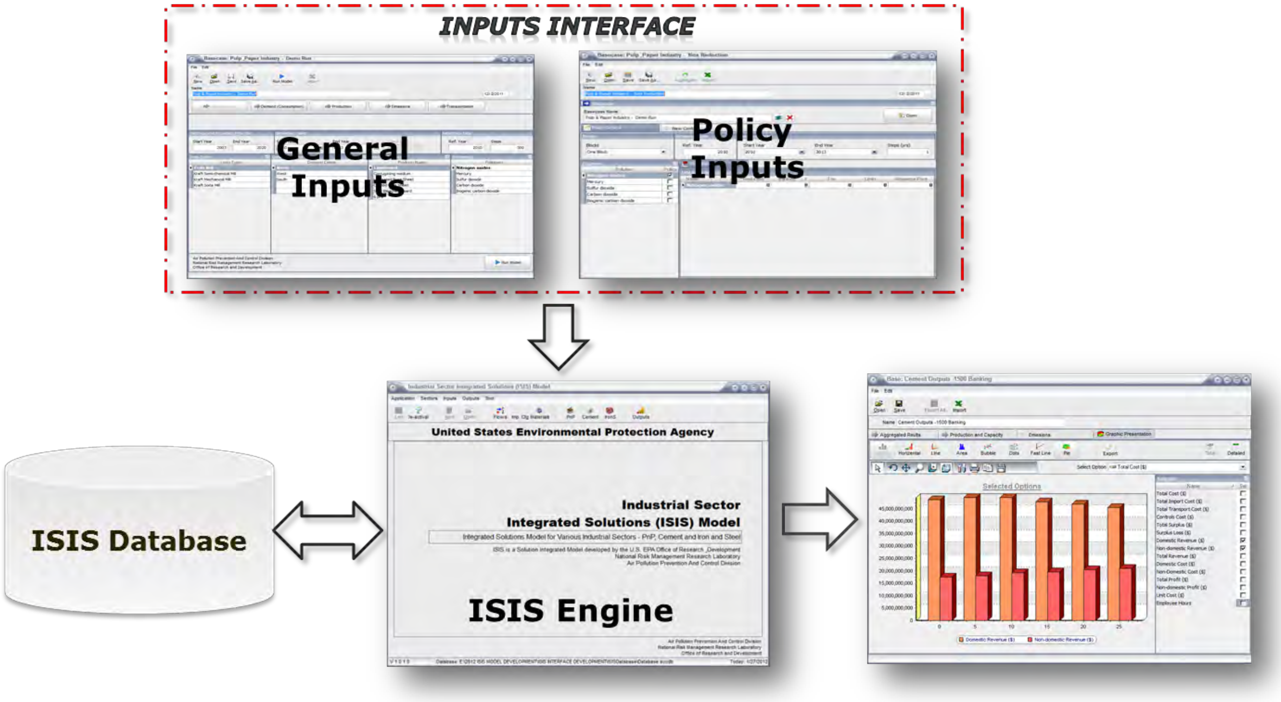


Figure 2-5. Interface of the U-ISIS

The general input interface of U-ISIS helps the user to develop the required modeling framework of the industrial sector of interest which includes time horizon (simulation period) to be used for the model runs, reference year, discount rate, time blocks, commodity characteristics , emissions types, fuels types, plants types, etc. The general input interface allows the users to enter three sets (market, facility based and other data) of Business-As-Usual (BAU) industrial sector data which include historical and projected nationwide commodity consumption, commodity imports and exports, the number of production facilities, distance from production facilities to demand center, production capacity, associated costs (material costs, operations and maintenance costs, etc.), fuel types and costs, emissions sources and intensities, etc., that the Market (Inputs) module includes.

The Policy (Inputs) module allows users to define policy related parameters such as the amount of control required and the total quantity of emissions allowed. The user can specify the emission reduction percentage of interest, allowance, banking or non-banking, taxes, minimum reduction levels and policy horizon (time period) to be used for the model runs. Policies may be simulated over long- and short-time horizons, such as a CO_2 policy that occurs over a decadal time-frame, and a criteria pollutant policy that occurs on an annual time-frame. The U-ISIS model is also capable of evaluating requirements on a regional or national-scale.

The goal of the PC-based executable application is to provide data entry and modeling flexibilities and easy access to U-ISIS modules (multi-sectors) for its users, both internal and external to EPA, to explore emissions and least-cost scenarios for supply, supply costs, and emission control costs under various policy options for the industrial sectors covered in the U-ISIS modules. The user will have the capability to export the outputs from the interface to Excel, or to text, graphic or PDF format.

The functionality of the interface will ensure that users will be allowed to use individually chosen general inputs as well as policy inputs and will be able to access the EPA-hosted database and U-ISIS engine to produce output for the desired type of analysis for the industrial sectors of interest. The U-ISIS database will be fully secured and protected, so that each user's scenario option will be evaluated individually.

2.5 References for Chapter 2

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Chapter 3
Cement Data

3.1 Data Requirements

Data requirements for U-ISIS module include sector-specific (in this case, cement-specific) data as well as policy and economic parameters. The cement-specific data requirements for U-ISIS cement module are discussed below.

As shown in Figure 3-1, the inputs are transmitted to the optimization part of the U-ISIS model, where they are used to solve the selected BAU and policy cases. Potential policy options may include cap-and-trade, emissions taxes, or emissions limits as emission reduction mechanisms. After solving, the results are post-processed to calculate values of various outputs of interest.

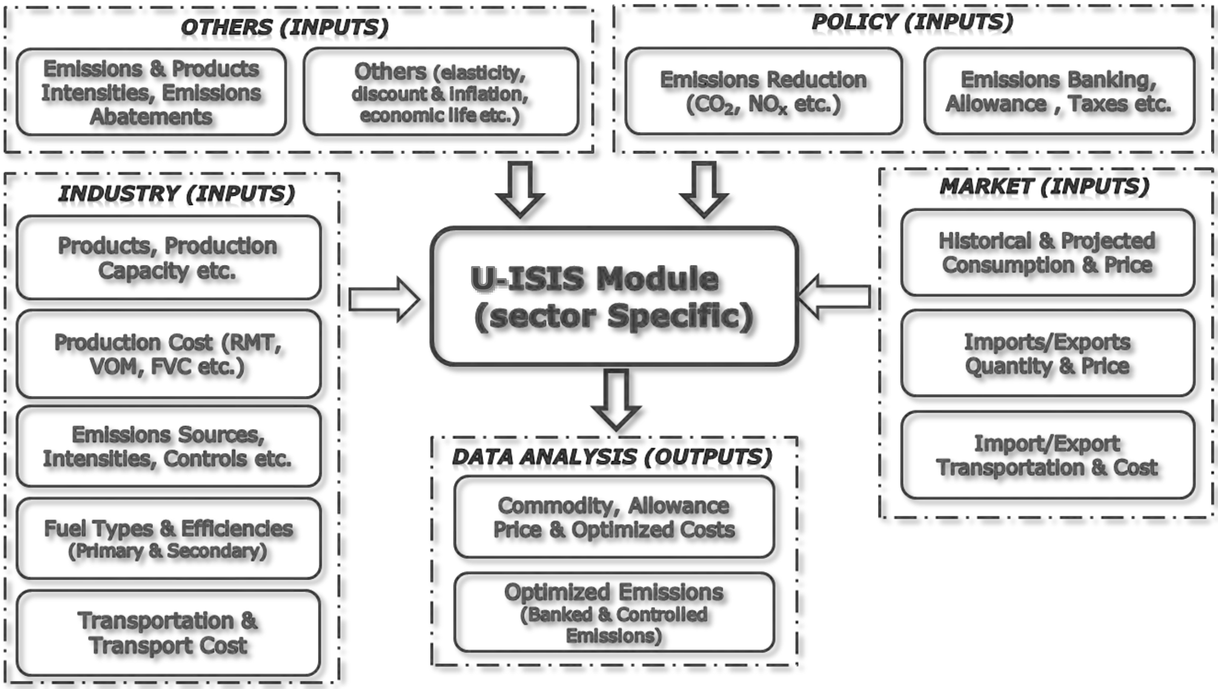

Figure 3-1. Modules and Associated Information Flows Utilized in the U-ISIS Framework

Input data consist of the industry sector database, which provides unit-level production, capacity, production cost, and emissions information. The controls database provides information regarding applicable air pollution control technologies and their cost and emission control characteristics. A policy module is used to specify various parameters of interest to the policy analyst such as emissions cap, emission reduction scenarios, and discount rate. The input data, control data, and policy parameters are then transmitted to the optimization part of the U-ISIS model, where they are used to solve the selected base and policy cases. After solving, the results are post-processed to calculate values of various outputs of interest. The output data are exported to Excel spreadsheets for further analyses and graphical representation of selected results.

The U-ISIS model allows the user to select the policy case to be evaluated. In a cap-and-trade policy scenario, separate caps on pollutants of interest can be specified based on emissions from a selected reference year. The cap-and-trade policy scenario can be run with or without banking of emissions and can include *de minimis* requirements. Traditional rate-based policy scenarios with unit-specific emission reduction requirements specified by the user can also be modeled in the U-ISIS model.

3.2 Cement-Specific Data

The inputs to the U-ISIS cement module can be broadly categorized into three main components:

- Industry production, fuel, and emissions
- Control technologies, and emission abatement approaches
- Policy and economic parameters

3.2.1 Industry, Fuel, and Emissions

3.2.1.1 Existing, Planned/Committed, and Potential Units

The U-ISIS cement module contains information on 110 cement plants that were in existence in 2010 (USGS, 2012). Additionally, the model also includes potential kiln representations that may come on line as a result of endogenous capacity addition (i.e., new production capacity [by state] and replacements [by kilns]).

Some cement plants have multiple kilns. For example, in 2009 there were 189 kilns in 114 plants. Each kiln modeled in U-ISIS cement module is characterized by its location, design (i.e., wet, dry, preheater, or precalciner), daily and annual clinker capacity[3], vintage, and retirement information when available (PCA, 2006). In addition, each kiln is characterized by its average variable costs components (AVC).

3.2.1.2 Average Variable Costs

In previous economic analyses, five input variables in cement production have been identified to determine the kiln-level AVC functions: raw materials, repair and maintenance, labor, electricity, and fuel (Depro et al., 2007; Depro, 2010; Depro and Lentz, 2010). Raw materials serve as the kiln feed, and repair and maintenance are required for periodic upkeep of the kiln. Labor is used in the quarry, in the operation of the kiln, and for packing. Electricity is consumed mainly by the auxiliary equipment and fuel is largely consumed in the kilns. The AVC for raw materials, labor, repair and

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[3] Annual clinker capacity as reported by PCA refers to the kiln daily capacity multiplied by 365 less normal downtime days, where daily capacity is the normal clinker output a kiln can produce per day given a realistic work pattern and normal downtime days are number of days of downtime required for maintenance, repair or cleanup.

maintenance, and electricity was determined following the methodology in the EPA regulatory impact analysis of the cement kiln dust rulemaking (EPA, 1998).

3.2.1.3 Cement Demand Centers

The U.S. cement markets are organized in state-specific demand centers. Figure 3-2 shows the distribution of Portland cement kilns operating in 2009. Each state containing at least one kiln is shaded. The U-ISIS-cement module simulates each cement plant's ability to compete in each of the demand centers as a function of the plant's production cost and transportation cost associated with supply to each demand center.

3.2.1.4 Portland Cement Demand

One of the key data inputs for the U-ISIS-cement module is the demand projection for each demand center. In general, this demand is a function of gross domestic product (GDP) growth, interest rates, special construction projects (e.g., highways), and public sector construction spending. Portland cement demand was 128 million metric tons in 2005 but only 71 million metric tons in 2010. PCA expects cement demand will reach 180 million metric tons by 2035. Should this happen it would reflect an increase of nearly 110 million metric tons with a compound annual growth rate of 3.85 percent. Cement demand through year 2035 is reported in the PCA Long-Term Cement Consumption Outlook (PCA, 2009b). PCA projections of cement demand (in million metric tons) by state through 2035, in 5-year increments, are shown in Table 3-2 (2005 data is given for comparison).

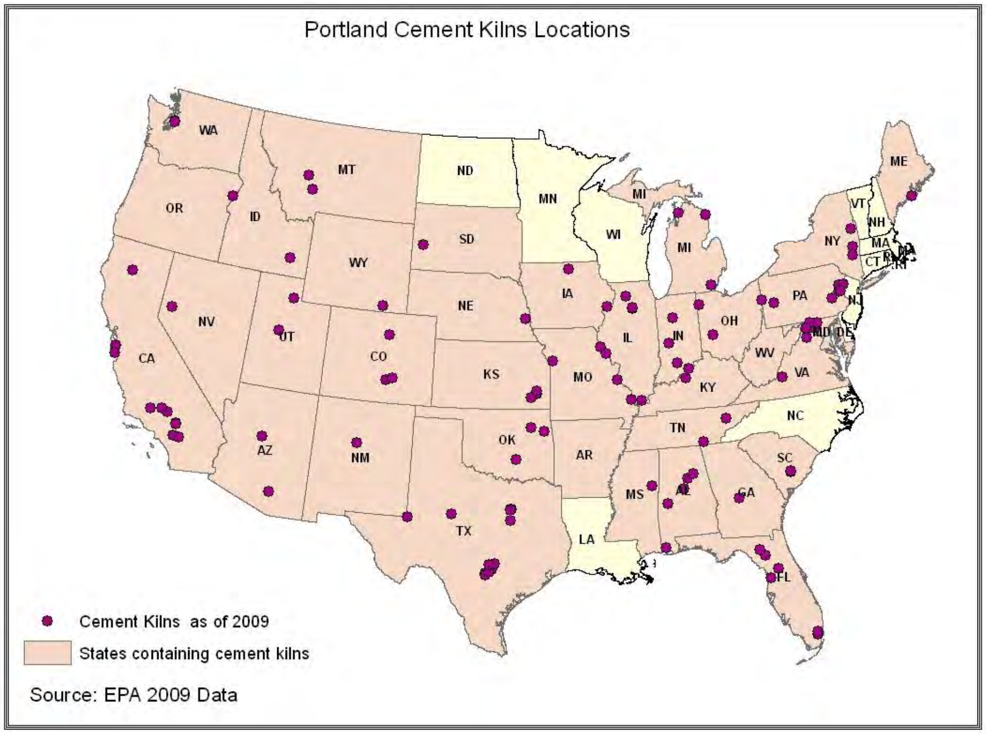

Figure 3-2. Distribution of Cement Kilns in the United States as of 2009

Table 3-2. Portland Cement Demand in Millions of Metric Tons (2009 projections)

State Demand Center	2005	2015	2020	2025	2030	2035
Alabama	1.92	2.02	2.16	2.32	2.49	2.67
Arizona	4.77	3.85	5.16	6.55	7.95	9.59
Arkansas	1.30	1.29	1.41	1.54	1.67	1.81
California	16.01	13.88	15.43	17.11	18.95	20.96
Colorado	2.55	2.76	3.08	3.47	3.90	4.33
Connecticut	0.82	0.77	0.83	0.88	0.94	0.98
Delaware	0.22	0.26	0.28	0.29	0.31	0.32
District of Columbia	0.21	0.18	0.18	0.17	0.18	0.18
Florida	12.28	8.99	11.05	13.47	16.33	19.67
Georgia	4.75	3.95	4.96	5.67	6.17	6.65
Hawaii	0.44	0.47	0.49	0.52	0.55	0.57
Idaho	0.70	0.70	0.82	0.92	1.03	1.15
Illinois	4.64	4.29	4.62	4.99	5.44	5.98
Indiana	2.27	2.30	2.49	2.73	2.98	3.25
Iowa	1.94	1.98	2.04	2.10	2.15	2.20
Kansas	1.55	1.65	1.71	1.78	1.85	1.91
Kentucky	1.60	1.48	1.59	1.71	1.84	1.97
Louisiana	2.23	2.91	3.15	3.29	3.42	3.52
Maine	0.35	0.29	0.31	0.32	0.34	0.35
Maryland	1.66	1.63	1.78	1.94	2.12	2.31
Massachusetts	1.26	1.11	1.21	1.31	1.43	1.56
Michigan	3.06	2.05	2.19	2.44	2.68	2.75
Minnesota	2.06	1.86	2.09	2.34	2.57	2.80
Mississippi	1.14	1.50	1.58	1.66	1.76	1.85
Missouri	2.87	2.71	3.18	3.58	3.90	4.29
Montana	0.38	0.42	0.45	0.48	0.51	0.53
Nebraska	1.37	1.46	1.55	1.66	1.76	1.87
Nevada	2.63	2.33	3.26	4.27	5.14	6.16
New Hampshire	0.37	0.33	0.36	0.39	0.42	0.45
New Jersey	2.06	1.89	1.99	2.09	2.18	2.28
New Mexico	0.91	0.94	1.00	1.07	1.12	1.15
New York	3.29	3.60	3.73	3.87	3.98	4.08
North Carolina	3.25	3.43	3.92	4.50	5.16	5.88
North Dakota	0.36	0.47	0.47	0.46	0.44	0.42
Ohio	4.06	3.61	3.75	3.90	4.02	4.12
Oklahoma	1.67	1.68	1.76	1.87	1.98	2.11

State Demand Center	2005	2015	2020	2025	2030	2035
Oregon	1.24	1.22	1.40	1.61	1.86	2.15
Pennsylvania	3.44	3.49	3.64	3.78	3.89	3.97
Rhode Island	0.19	0.17	0.18	0.19	0.19	0.20
South Carolina	1.94	1.81	1.99	2.19	2.38	2.56
South Dakota	0.48	0.55	0.57	0.61	0.64	0.67
Tennessee	2.52	2.38	2.61	2.89	3.19	3.53
Texas	15.09	17.51	21.03	24.10	27.48	30.58
Utah	1.53	1.82	2.08	2.40	2.78	3.23
Vermont	0.16	0.16	0.17	0.18	0.20	0.21
Virginia	2.87	2.84	3.13	3.45	3.80	4.17
Washington	2.24	2.50	2.75	3.04	3.36	3.73
West Virginia	0.54	0.59	0.60	0.60	0.59	0.58
Wisconsin	2.37	2.18	2.32	2.45	2.59	2.74
Wyoming	0.47	0.55	0.55	0.55	0.55	0.54
Total	**128.03**	**122.81**	**139.06**	**155.70**	**173.14**	**191.51**

3.2.1.5 Transportation-Interregional Trade

In U-ISIS-cement module, a transportation matrix is used to describe the costs for transporting cement from kiln and import district locations to demand centers. To develop these costs, information on distances between supply and demand points and costs of transportation modes (truck, rail, or water transport) was obtained. In particular, the Transportation Routing Analysis Geographic Information System (TRAGIS) model (TRAGIS, 2003) was used to develop the origin-destination distances as described below. Also, in the matrix, the applicable lowest cost transportation option is used to connect a supply point with a destination. While the cement demand centers are interlinked through a transportation matrix, the competition is generally maintained on a regional level because the cost of transporting cement is relatively high.

As mentioned above, the TRAGIS model was used to calculate transportation distances associated with delivery of Portland cement from domestic U.S. manufacturing sites and import terminals to each of the demand centers. Operation of the TRAGIS program requires the identification of a shipment's origin and destinations, as well as the selection of mode of transportation (highway, rail, or water) for each origin-destination pair. The TRAGIS program does not use actual addresses or coordinates as origins or destinations. Instead, the program uses a fixed set of pre-determined locations within the model corresponding to locations in a number of U.S. cities and towns. The locations of domestic Portland cement manufacturers used correspond to the lists of manufacturing plants published in the Cement Americas (Penton Media Inc.), North American Cement Directory (Cement Americas 2008); and the PCA, U.S. and Canadian Portland Cement Industry Plant Information Summary December 31, 2006 (2007).

The cost of transportation for interregional trade takes into account the impact of terminals and the frequent use of modes other than truck. According to the USGS (2007a), nearly half of cement shipments reach customers via terminals rather than direct. Shipments to terminals are more than 80 percent by rail or water, rather than by truck. Table 3-3 provides information on cost per ton mile for bulk shipping via truck, rail, and barge. In U-ISIS-cement, transportation costs for each mode of transportation (truck, rail, and barge) are calculated from each kiln and import district to each demand center. For a given origin-destination pair, the dominant mode (lowest cost of shipment) is used to determine the transportation cost for that route. The TRAGIS model was used to arrive at the origin-destination distances and feasible routes for rail and barge; Google Maps was used for truck transportation. The shipment costs shown in Table 3-3 were used to determine the transportation costs for the routes in U-ISIS cement module.

Table 3-3. Bulk Shipment Costs (Cents per Metric Ton per Mile)

Mode	BTS[1]	WDOT[2]	NACT[3]	AU[4]	Average Used in U-ISIS
Truck	33.06	7.64	11.02	7.18	14.73
Rail	2.78	3.32	5.51	N/A	3.87
Barge	0.89	1.05	2.20	N/A	1.38

1. BTS=Bureau of Transportation Statistics
2. WDOT=Washington State Department of Transportation
3. NACT= North American Cement Transportation
4. AU=American University

3.2.1.6 Imports

U.S. cement markets receive imported quantities of cement and clinker from a number of countries, and these imports arrive at more than 30 import districts (USGS, 2007b). In U-ISIS-cement module, international supplies from exporting countries to U.S. import districts are modeled using supply elasticity and then these imports are transported to the demand centers.

The five largest international suppliers of cement and clinker to the U.S. in 2005 were China, Thailand, Venezuela, South Korea, and Greece. In 2010, the five largest international suppliers were Canada, Korea, China, Mexico, and Colombia (USGS, 2012). However, an econometric study was conducted to provide an estimate of international supply elasticity for supplies the top five international suppliers in 2005 and the rest of the world. The results of this study (Burtraw, 2010) reflected that the best estimate of the international supply elasticity of cement and clinker from China, Thailand, Venezuela, South Korea, Greece, and the rest of the world into the U.S. is 3.94. This value indicates that if the price of cement were to increase by 1 percent within any import district in the U.S., then, *ceteris paribus*, the quantity of cement imported from each of these five supply countries into that district would increase by 3.94 percent.

Table 3-4 shows the import levels by major USGS Customs District for 2010, estimated by using USGS data (USGS, 2012).

Table 3-4. Portland Cement and Clinker Imports in Million Metric Tons, by Major USGS Customs District in 2010

USGS Customs District	Quantity, million metric tons
Alaska, Anchorage	0.11
California, Los Angeles	0.03
California, San Francisco	0.20
Florida, Miami	0.14
Georgia, Savannah	0.15
Hawaii, Honolulu	0.27
Louisiana, New Orleans	0.07
Maine, Portland	0.05
Massachusetts, Boston	0.02
Michigan, Detroit	0.93
Minnesota, Minneapolis;	0.01
Missouri, St. Louis	0.05
New York, New York	0.21
New York, Ogdensburg	0.16
North Carolina, Wilmington	0.11
Ohio, Cleveland	0.55
Oregon, Columbia-Snake	0.33
Pennsylvania, Philadelphia	0.14
Texas, El Paso	0.26
Texas, Houston-Galveston	0.64
U.S. Virgin Islands	0.02
Vermont, St. Albans	0.07
Virginia, Norfolk	0.11
Washington, Seattle	0.91
Total	6.62

Source: USGS, 2012 Table 18

3.2.1.7 Capacity Changes

Cement plants have a relatively long lifespan, typically 50 years or more (FLSmidth, 2007). Various factors, including (but not limited to) raw material availability in the quarry, technology changes, productivity, efficiency, longevity, reliability, maintenance, and long-term costs can affect the lifespan of a cement kiln/plant. In U-ISIS cement module, retirements and projected retirements of existing kilns were based on information from PCA on capacity expansion estimates. These estimates were supplemented with information from individual cement companies on their plans for shut-downs, new construction, and kiln consolidation (PCA, 2004). Further, as mentioned earlier, U-ISIS-cement includes algorithms for endogenous capacity growth and retirement of kilns. To determine capital recovery factor for capital costs associated with kiln capacity changes, an economic life of 25 years and an interest rate of 15 percent are used. Capital costs in 2005 $ per ton of clinker for new, replacement of wet, and replacement of dry capacity are 208, 296, and 238, respectively (PCA, 2009b).

3.2.1.8 Fuel Intensity

The Annual Energy Outlook energy use profile for 2005 (EIA, 2008) is shown in Figure 3-3. In 2005, the cement sector consumed 451.2 trillion Btu (476.0 trillion kJ) of energy (EIA, 2008). As shown in Figure 3-3, the primary fuel being burned in kilns is coal. Coal is projected to remain the dominant fuel used by the U.S. cement industry. However, there has been an increasing trend towards using other fuels, particularly alternative fuels, such as coke,[4] waste tires, and other wastes, especially oily wastes.

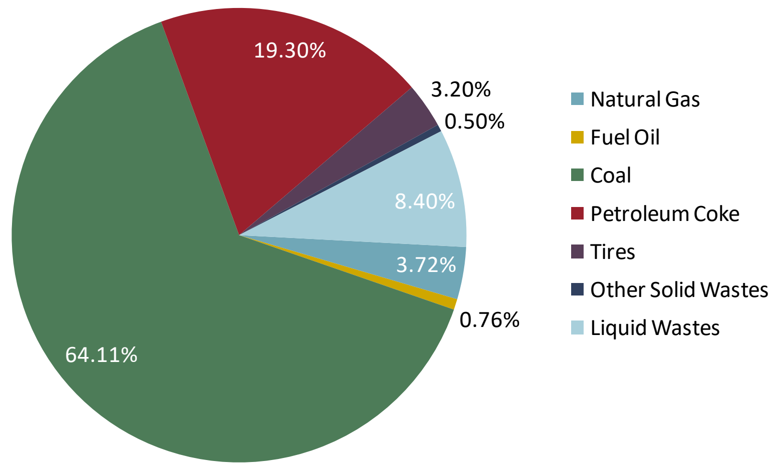

Figure 3-3. Commercial Fuel Use Profile by U.S. Cement Industry in 2005.

Source: EIA, 2008

In the U-ISIS-cement module, to determine the fuel intensity of each kiln, correlations of kiln type to heat input and/or gas flow were developed (see Appendix A). Once determined, the kiln's specific fuel intensity is used to calculate fuel cost for each kiln. PCA's data on heat input to various kilns by type were used to develop kilns' fuel intensities. The data, expressed in heat input per unit of clinker (specific fuel consumption [SFC]) and exhaust gas flow rate (wet) (EGFW) per unit of clinker, are summarized in Table 3-5.

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[4] PCA does not specify if "coke" is metallurgical coke or petroleum coke. Authors believe it is the latter.

Table 3-5. Specific Fuel Consumption and Total Exhaust Gas Flow Rate (wet) for Various Kiln Types

Kiln Type	SFC[a]	EGFW
	MMBtu/short ton	Nm^3/kg
Wet	6.0	3.4
Dry	4.5	1.8
Preheater	3.8	1.5
Preheater/Precalciner	3.3	1.4

a. SFC=specific fuel consumption; (Source: EPA, 2007 (Table 3-3)

b. EGFW=exhaust gas flow rate (wet): (Source: PCA, 2004; original data in metric units)

For each individual kiln, the U-ISIS model determines the optimal fuel type(s) based on the regional cost of the chosen fuel and the kiln's specific fuel intensity.

3.2.1.9 Emission Intensities

The design of the U-ISIS model can accommodate any number of pollutants of interest. In U-ISIS-cement, each kiln is characterized by its NO_X, SO_2, PM, HCl, Hg, total hydrocarbon (THC), and CO_2 emission intensities. These emission intensities were developed using available data (Andover Technology Partners, 2009a).

NO_X emissions from cement kilns result primarily from the following combustion process: oxidation of fuel nitrogen (fuel NO_X) and the oxidation of nitrogen in the combustion air (thermal NO_X). Oxidation of nitrogen in the feed materials (feed NO_X) can also influence total NO_X emissions. Table 3-6 shows NO_X emission intensities for cement kilns in lb/ton of clinker and in lb/MMBtu (EPA, 2007).

Table 3-6. Estimated Uncontrolled NO_X Emission Intensities for Cement Kilns

Kiln Type	Heat Input, MMBtu/ton of clinker	Uncontrolled NO_X Emissions	
		lb/ton of clinker *	lb/MMBtu
Wet	6.0	9.7	1.62
Long Dry	4.5	8.6	1.91
Preheater	3.8	5.9	1.55
Preheater/Precalciner	3.3	3.8	1.15

* Average

Source: EPA, 2007 (Table 3-3 and Table 6-1)

SO_2 emissions from cement kilns are the product of sulfur in the fuel as well as sulfur in the feed materials. Sulfur in the fuel will oxidize to SO_2 during pyroprocessing, and a significant amount is likely to be captured in the form of sulfates as the gas passes through the calcination zone. Compared to long dry and wet kilns, preheater and preheater/precalciner kilns tend to be more effective at capturing fuel-generated SO_2. Accordingly, oxidation of sulfur in the feed materials is likely to be a major component of total SO_2 emissions. Table 3-7 shows average SO_2 emissions for each kiln type for each state (Andover Technology Partners, 2009a). State-specific emission intensities of

SO_2 were determined from emissions reported for the kilns in that state. For any state where the emission intensity was not available for a kiln-type, the national average emission intensity was assigned to kilns in that state.

CO_2 emissions from cement kilns result from limestone calcination and fuel combustion. Appendix A explains how CO_2 emission intensities from calcination and combustion are calculated in the U-ISIS model. Calcination releases 0.52 tons of CO_2 per ton of clinker produced, while fuel-based CO_2 emission factors range from 199.52 lb CO_2/MMBtu for coal to 105.02 lb CO_2/MMBtu for natural gas (Andover Technology Partners, 2009b, 2010a, and 2010b). Table 3-8 shows approximate CO_2 and water (H_2O) produced from combustion for the most important fuels for cement kilns.

Table 3-7. Average SO_2 Emissions for Each Kiln Type in Each State

State	SO_2 (lb/ton clinker)			
	Precalciner	Preheater	Dry	Wet
AL	0.09	0.61	9.02	13.99
AZ	1.30	0.07	8.51	7.81
AR	2.94	2.32	3.45	7.59
CA	0.33	1.12	0.81	0.00
CO	0.32	0.10	1.07	4.24
CT	1.15	2.32	9.02	7.81
DE	1.15	2.32	9.02	7.81
FL	0.45	0.02	9.02	7.81
GA	0.95	2.73	11.42	12.25
ID	0.13	2.32	9.02	0.70
IL	5.58	5.77	5.88	9.50
IN	1.15	2.32	9.02	7.81
IA	1.15	2.32	9.02	7.81
KS	1.25	5.88	24.85	8.61
KY	0.19	5.04	12.53	7.81
LA	1.15	2.32	9.03	7.81
ME	0.30	0.30	N/A	11.98
MD	3.14	3.95	7.31	7.49
MA	1.15	2.32	9.03	7.81
MI	5.23	2.32	5.31	18.00
MN	1.15	2.32	9.03	7.81
MS	0.09	0.61	9.02	13.99
MO	2.18	2.32	1.51	7.02
MT	0.13	2.32	9.02	0.70
NE	1.25	5.88	24.85	8.61
NV	0.49	0.05	1.51	7.81
NH	1.15	2.32	9.02	7.81
NJ	1.15	2.32	9.02	7.81
NM	1.30	0.07	8.51	7.81

State	SO$_2$ (lb/ton clinker)			
	Precalciner	Preheater	Dry	Wet
NY	0.30	0.30	9.02	11.98
NC	1.15	2.32	9.02	7.81
ND	1.15	2.32	9.02	7.81
OH	0.19	5.04	12.53	7.81
OK	1.25	5.88	24.85	8.61
OR	0.13	2.32	9.02	0.70
PA	1.15	2.32	9.02	7.81
RI	1.15	2.32	9.02	7.81
SC	0.95	2.73	11.42	12.25
SD	0.32	0.10	1.07	4.24
TN	0.95	2.73	11.42	12.25
TX	1.15	2.32	9.02	7.81
UT	0.13	2.32	9.02	0.70
VT	1.15	2.32	9.02	7.81
VA	0.95	2.73	11.42	12.25
WA	0.53	2.32	9.02	3.80
WV	3.14	3.95	7.31	7.49
WI	1.15	2.32	9.02	7.81
WY	0.32	0.10	1.07	4.24
National Average	**1.15**	**2.32**	**9.02**	**7.81**

N/A = Not available.

Table 3-8. Approximate CO$_2$ and H$_2$O Produced from Combustion of Fuels

Variable Name	Flue Gas (per MMBtu)	Tires	Petroleum Cokes	Heavy Fuel Oil	Rosemont PRB[a]	Logan, WV BIT[b]	Natural Gas
LBMCO2MMBTU	lb moles CO$_2$	4.26	4.83	3.85	4.25	4.53	2.39
LBCO2MMBTU	lb CO$_2$	187.44	212.56	169.32	186.83	199.52	105.02
LBMH2OMMBTU	lb moles H$_2$O	2.76	2.76	2.23	3.23	4.14	2.77
LBH2OMMBTU	lbs H$_2$O	49.71	49.73	40.26	58.21	74.64	49.92

[a] PRB = Powder River Basin coal

[b] WV BIT = West Virginia bituminous coal

3.2.2 Control Technologies and Emission Abatement Approaches

U-ISIS-cement contains information on abatement approaches for NO_X, SO_2, PM, HCl, Hg, THC, and CO_2 emissions described above. The three categories of abatement approaches included are: process modifications and upgrades, raw material and/or fuel substitution, and mitigation technologies. For each emission abatement approach, where possible, information on the following parameters was developed (Andover Technology Partners, 2009b and 2009c) and included in the model: capital cost, fixed operating cost, variable operating cost, emission reduction performance for all of the pollutants, impacts on fuel and/or raw material use, impact on electricity consumption, byproduct generation and cost, and impact on water use.

To estimate capital recovery factors for capital costs associated with control technologies, economic life values of 15 years and an interest rate of 7 percent are generally used, but different values can be selected by the user. Payback periods and technical life for the energy efficiency measures shown in Tables 3-14 through 3-17 (at the end of this chapter) are given in Worrell and Galitsky (2004). Economic life for each of these measures can be taken to be the average of the technical life and the payback period. Again, an interest rate of 7 percent can be used for capital recovery in the absence of more specific information.

Tables 3-9 through 3-12 show the NO_X, SO_2, CO_2, HCl, Hg, and THC emissions control technologies being used in the U-ISIS-cement module. Tables also reflect the impacts of these technologies on pollution reduction, electricity use, and water use. Multimedia impacts of changes to the capacity of cement kilns are listed in Table 3-13. Tables 3-14 through 3-17 show the electricity consumption and heat input changes accomplished as a result of implementation of energy efficiency measures for raw materials preparation, clinker making, finish grinding, and plant-wide measures, respectively.

More details on cost, efficiency, and co-impacts for each of the above control technologies or process modifications are given in Appendix A.

3.2.3 Policy and Economic Parameters

3.2.3.1 Policy Parameters

The U-ISIS model framework allows the user to select a variety of potential policy options for evaluation. The user can select from cap-and-trade policy (with or without *de minimis* requirements), emissions charge policy, or rate-based policies. In a cap-and-trade policy scenario, separate caps on pollutants of interest can be specified. The user has the option to run a cap-and-trade policy scenario with or without banking of emissions. Further, a cap-and-trade policy scenario can include *de minimis* requirements, where the user defines a minimum level of emission reduction required for each emission unit. As mentioned before, it is also possible for the user to input an emission charge for pollutants of interest. Furthermore, traditional policy scenarios (rate-based policies) with unit-specific emission reduction requirements specified by the user can be modeled in U-ISIS.

The user can specify the policy horizon (time period) to be used for the model runs. Since climate-related simulation horizons can be long (e.g., 40 years), the user may choose to run U-ISIS with blocks of years (e.g., 5-year blocks). The simulation horizon and blocks of years can be chosen by the user subject to availability of data.

3.2.3.2 Additional Economic Parameters

In the U-ISIS framework, the following additional economic parameters are used: discount rate, escalation rates, and demand elasticity. For the U-ISIS-cement module, the default discount rate has been chosen as 7-percent, as recommended by the U.S. Office of Management and Budget (OMB) for project evaluation (OMB, 1992). Escalation rates used can be found in the "ISIS_Inputs.xls" workbook. Escalation rates for labor are based on historical data from Bureau of Labor and Statistics (BLS) (BLS, 2008). Raw materials escalation factors are calculated from historical price data of crushed sandstone and gypsum from USGS. The escalation factors for variable operating and maintenance costs are based on Chemical Engineering Index. Escalation factors for various fuels and electricity are estimated based on data from the EIA's Annual Energy Outlook 2008 (RTI, 2010). Demand for cement is relatively inelastic and an elasticity value of -0.88 is used in the model (EPA, 1998).

Table 3-9. NO$_X$ Control Technologies for Cement Kilns

Control Type	Impact on Emissions, ±% change					Electricity Consumption, kWh/ton of cement		Water Consumption, gal/ton of cement
	NO$_X$	SO$_2$	PM	Hg	Other	Grinding	Kiln Operation	
Low NO$_X$ Burners – Indirect Firing	-20% to -30%[1]	No impact[2]				0[3]	-1.2[4]	0[3]
Mid Kiln Firing-Tires	-20% to -40%[1]	May vary[5]				0[3]	0[6]	0[3]
Low NO$_X$ Burner + Mid Kiln Firing- Tires	-20% to -40%[1]	May vary[5]				0[3]	-1.2[4,6]	0[3]
Low NO$_X$ Burners + Tire Derived Fuel	-20% to -40%[7]	May vary[5]				0[3]	-1.2[4,6]	0[3]
Low NO$_X$ Burner + Selective Non Catalytic Reduction	-50%[2]	No data[5]	No data[8]	No data[8]	No data[8]	0	-1.2[4,9]	+1.25[9]
Low NO$_X$ Burner + Selective Catalytic Reduction	-90%[2]	Oxidation [10]	No data[8]	Oxidation [10]	No data[8]	0	-1.2[4,9]	+1.25[9]
Low NO$_X$ Burners + CemStar[a]	-30%[11]					-1.3 (wet process); -1.9 (dry process) [12]	-1.2[4,12] from LNB and -1.5 (wet process) or -2.2 (dry process) from CemStar[13]	0
CemStar/Fly Ash Injection	-20%[14]					-1.3 (wet process); -1.9 (dry process) [13]	-1.5 (wet process) or -2.2 (dry process) from CemStar [13]	0

Notes to Table 3-9 on following pages

1. See EPA (2004), Table 5-1.
2. See Andover Technology Partners 2009b memo.
3. These technologies do not use and do not affect the consumption of water in raw mix preparation or significantly affect electric power consumption in cement manufacturing processes.
4. Conversion from direct firing systems typical of wet and dry process kilns and older preheater kilns to indirect firing systems, required to implement low NO_X burner (LNB) technology, could result in reductions in primary air fan and kiln-induced draft fan power requirements and concomitant slight increases in coal conveying power requirements. A reduction in fan/blower power on the order of 100 hp might be anticipated for a moderately sized (300,000 – 500,000 clinker tons per year) kiln converted from direct firing to indirect firing. No power savings on adding an LNB would be anticipated if the kiln system is already indirect-fired.
5. SO_2 emissions from cement kilns are strongly related to fuel and raw materials sulfur content and to method of kiln operation. Sulfur content of tire-derived fuel (TDF) (typically, 1.24% by weight, dry) may be higher or lower than the sulfur content of other fuels commonly used in cement kilns, such as coal or coke. Therefore it is not practical to relate SO_2 emissions to the use of these NO_X control methods. With respect to use of an SO_2 wet scrubber using ground limestone, it is assumed that, for wet process kiln systems, uncontrolled SO_2 emissions of 8.2 lb per ton of clinker (8.9 lb/ton of cement) (EPA, 1995: Table 11.6-8) are treated by use of a stoichiometric amount (with respect to uncontrolled SO_2) of limestone of 90-percent purity in a 15-percent limestone slurry. Limestone and water consumption are 15.5 lb and 87.7 lb, respectively, per ton of cement produced. For a precalciner kiln, it is assumed that uncontrolled SO_2 emissions of 1.1 lb per ton of clinker (1.2 lb/ton of cement) (EPA, 1995: Table 11.6-8) are treated similarly (stoichiometric amount limestone of 90% purity in a 15% limestone slurry). Limestone and water consumption are 2.1 lb and 11.8 lb per ton of cement produced.
6. Kiln system and raw materials grinding electric power consumption would not be significantly affected by introduction of tires or tire-derived fuel.
7. Combined effect will vary. Low NO_X 20 to 40 percent, mid kiln firing 20 to 40 percent.
8. While there may be theoretical or limited experimental bases to assume increases or decreases in emissions of various pollutants in connection with NO_X emission controls, statistics on such effects are not available. See, generally, EPA (2007a), Chapter 11.
9. Assumes selective non-catalytic reduction (SNCR) or selective catalytic reduction (SCR) both with stoichiometric addition of NH_3 in 20-percent solution, typical precalciner NO_X emissions of 4.2 lb/ton clinker before treatment (EPA 1995, Table 11.6-8), and 0.92 tons of clinker being used in each ton of cement. It should also be noted that SNCR is not applicable to wet process, long dry process, and many preheater kilns because the kiln gas exit temperatures are too low from those units for the necessary reactions to take place. See EPA (2007). SNCR is assumed to achieve 63-percent reduction in NO_X emissions from applicable kiln systems. See EPA (2007), Chapter 8. There may be an attendant small increase in kiln system electric power in connection with injection of water into the kiln system due to an increase in gas volume handled by the kiln's fan system. The increase is not considered in the calculation.
10. Typically, up to about 1 percent of SO_2 can be oxidized to SO_3. Elemental form of Hg oxidized across SCR provided there is sufficient concentration of halogens in flue gas.
11. On a lb/ton of clinker basis.
12. Use of the CemStar process may have multiple effects on electric power consumption, including reduced raw mix preparation costs in the event that unground CemStar material is fed to the rotary kiln, and reduced fan power requirements resulting from

reduced kiln gas volumes in connection with both combustion gases and raw mix calcination. Assuming a 5-percent replacement of raw mix with carbonate-free CemStar material, a concomitant 5-percent reduction in raw mix preparation energy is also assumed. An approximate 5-percent reduction in kiln electrical energy consumption is assumed based on a roughly 5-percent reduction in kiln exit gases from both calcination and combustion.

13. CemStar and fly ash injection are expected to have similar effects on raw mix preparation and kiln process electrical energy requirements.
14. See NESCAUM (2000) for effect of CemStar on NO_X reductions from cement kilns. Investigation of the combined effects of multiple technologies on pollutant emissions was not carried out for this summary.

General Notes

A. Cement kiln processes do not use steam.

B. Cement kiln dust (CKD) disposal rates as functions of NO_X or SO_2 emissions control technology has not been reported. Typical CKD disposal rates range from 0.042 to 0.115 tons CKD/ton clinker (0.046 to 0.125 tons CKD/ton cement assuming 0.92 tons clinker per ton of cement).

C. CKD disposal costs vary widely by region, CKD characteristics, CKD volumes, and location of disposal site (on-site or off-site). In addition, disposal costs are expected to be of comparable cost to transportation costs in connection with off-site disposal. For example, prices at three northern California landfills range from $26/ton to $69/ton of CKD plus transportation, which may range from approximately $500 to $1,200 per truck load. Pers. Comm., E. Leamer (ARCADIS) Feb. 26, 2009. CKD disposal prices would be expected to be generally unaffected by the type of cement kiln pollution controls employed.

References for Table 3-9 (references called out in the above notes can be found at the end of the chapter)

Air Pollution Controls and Efficiency Improvement Measures for Cement Kilns, Prepared by ARCADIS Under Contract No. EP-C-04-023, March 31, 2008.

Srivastava et al., ES&T, March 2006, pp.1385-1393.

Theoretical Approach for Enhanced Mass Transfer Effects in-Duct Flue Gas Desulfurization Processes. Final Report. 1992.

Table 3-10.SO_2 Control Technologies for Cement Kilns

Control Type	Impact on Emissions, ±% change					Electricity Consumption, kWh/ton of cement		Water Consumption, gal/ton of cement
	NO_X	SO_2	PM	Hg	Other	Grinding	Kiln Operation	
Wet Scrubber		-90% to -95%[1]		-80%	-50% for THC -99.9% for HCl	+0.2 (wet process kilns)[2]	+5[2]	+12 (wet process); +1.5 (dry process)[3]
Dry Lime Injection		-50%[4]			-75% for HCl	[5]	[5]	[5]

Notes to Table 3-10

1. See Andover Technology Partners 2009b memo.
2. Electric power consumption in connection with wet scrubbing is assumed to be primarily a result of: 1) grinding of limestone to below 45 to 74 micrometers in particle size and pumping limestone slurry; and 2) increased kiln exhaust gas fan power requirements. The latter energy increase is caused by increased pressure drop demand on kiln ID fans due to conveying kiln exit gases across the scrubber spray tower plus increased gas volume demand on kiln ID fans due to the addition of water in the limestone slurry. Slurry preparation and pumping is assumed to require 20 kWh per ton of limestone. The spray tower pressure drop is assumed to add 500 hp to ID fan requirements on a 300,000 to 500,000 ton per year cement kiln process.
3. SO_2 emissions from cement kilns are strongly related to fuel and raw materials sulfur content and to method of kiln operation. Sulfur content of TDF (typically 1.24% by weight, dry) may be higher or lower than the sulfur content of other fuels commonly used in cement kilns, such as coal or coke. Therefore it is not practical to relate SO_2 emissions to the use of these NO_X control methods. With respect to use of an SO_2 wet scrubber using ground limestone, it is assumed that, for wet process kiln systems, uncontrolled SO_2 emissions of 8.2 lb per ton of clinker (8.9 lb/ton of cement) (EPA, 1995: Table 11.6-8) are treated by use of a stoichiometric amount (with respect to uncontrolled SO_2) of limestone of 90-percent purity in a 15-percent limestone slurry. Limestone and water consumption are 15.5 lb and 87.7 lb, respectively, per ton of cement produced. For a precalciner kiln, it is assumed that uncontrolled SO_2 emissions of 1.1 lb per ton of clinker (1.2 lb/ton of cement) (EPA, 1995: Table 11.6-8) are treated similarly (stoichiometric amount limestone of 90% purity in a 15% limestone slurry). Limestone and water consumption are 2.1 lb and 11.8 lb per ton of cement produced.
4. 20 percent at Ca:S stoichiometry of 2:1 to 5:1. See Dry Sorbent Injection report (ARCADIS, 1992).
5. Dry lime injection technology is not well developed for the cement industry and no statistics are available.

References for Table 3-10 (references called out in the above notes can be found at the end of the chapter)

Andover Technology Partners, Cost and Performance of Controls, March 10, 2009.

Srivastava et al., ES&T, March 2006, pp.1385-1393.

Theoretical Approach for Enhanced Mass Transfer Effects in-Duct Flue Gas Desulfurization Processes. Final Report. ARCADIS, 1992.

EPA (1995). Compilation of Air Pollution Emission Factors - Volume 1: Stationary Point and Area Sources. Fifth Edition, Supplements A-F, AP-42. U.S. Environmental Protection Agency, Research Triangle Park, North Carolina.

Table 3-11. CO_2 Control Technologies for Cement Kilns

Control Type	Impact on Emissions, +/- % change						Electricity Consumption, MWh/ton of clinker	Process Water Consumption, ton/ton of clinker	Cooling Water Consumption, ton/ton of clinker
	NO_X	SO_2	PM	Hg	CO_2	Other			
Solvent CCS[1] New	-99%	-99%			-85%		-0.022	0.429	4.82
Solvent CCS[1] Retrofit	-99%	-99%			-85%		-0.103	0.160	4.82
Oxy-combustion	-99%	-99%			-85%		0.174		14.3

Notes to Table 3-11

1. CCS = carbon capture and sequestration.

References for Table 3-11

Andover Technology Partners, Cost and Performance of Controls, March 10, 2009.

EPA, Report to Congress on Cement Kiln Dust, Chapter 3: CKD Generation and Characteristics; U.S. Environmental Protection Agency: 1993.

Table 3-12.HCl, Hg, and THC Control Technologies for Cement Kilns

Control Type[1]	Impact on Emissions, ± % change				
	NO_X	SO_2	PM	Hg	Other
ACI[2]			-99.9%	-90%	-50% for THC
Membrane Bag			-99.9%		
RTO[3]					-98% for THC
Dry Lime Injection		-50%			-75% for HCl
Wet Scrubber		-90% to -95%		-80%	

Notes to Table 3-12

1. Feasible combinations of the above control technologies may be utilized as necessary.
2. ACI = activated carbon injection.
3. RTO = regenerative thermal oxidizer

Table 3-13.Multimedia Impacts of Process Capacity Replacement on Cement Kiln Operation[1]

Kiln Type	Water Consumption, gal/ton of cement[2]	Electricity Consumption, kWh/ton of cement		Waste	
		Grinding[3]	Kiln Operation[4]	Generation Rate, ton/ton of cement[5]	Disposal Cost, $/ton of cement
Wet to Precalciner	-214[2,6]	-12[8]	-7[8]	-0.072	see notes 9,10
Long Dry to Precalciner	No change[2]	Not available[7]	Not available[7]	-0.062	see notes 9,10
Preheater to Precalciner	No change[2]	Not available[7]	Not available[7]	0[11]	see notes 9,10

Notes to Table 3-13.

1. Unless specifically noted otherwise, impacts are presented on a per-short-ton-of-cement basis and generally make use of published data reported on a per-short-ton-of-clinker basis. These values are converted to a per-ton-of-cement basis by assuming that cement consists of 92-percent clinker. All weight units in this table are short tons.
2. Water is not normally consumed in dry process cement kiln processes, except on an emergency basis to prevent damage to process equipment by hot gas or solid process streams. Water is used in non-contact cooling processes that are common in both wet process and dry process cement plants, some of which may or may not use closed circuit cooling systems with no evaporation losses. Water is consumed in direct contact cooling processes such as cement grinding in both wet process and dry process plants. However, the nature and amount of such water consumption is not intrinsically different between wet process and dry process plants.
3. Power data reported in Worrell and Galitsky (2004) are used for raw mix preparation and kiln process electrical energy consumption for wet and all dry processes.

4. Air pollution control device contributions to electric power consumption data on cement kiln process systems are assumed to include only existing particulate matter control devices and not scrubbers for SO_2 or other criteria pollutants.
5. Solid waste from all process types is assumed to be CKD. Data used here are as reported in EPA (1993).
6. Cement is assumed to consist of 92-percent clinker. Clinker is assumed to require 1.42 tons of raw kiln feed (dry) per ton of clinker. Kiln feed loss on ignition is assumed to be 35 percent. Kiln feed slurry is assumed to contain 36-percent water.
7. Industry-wide statistics on electrical energy use do not distinguish among the various cement processing stages between the various dry processes – all dry process plants are averaged together. Published data that distinguish between various process types combine all process phases without indicating energy use for individual process phases. Therefore, electrical energy use is reported here to be the same for all dry process plants. See Worrell and Galitsky (2004).
8. As stated in note 7, industry data on electric power use in raw materials preparation and kiln processing are not available for every dry process. Data are for all dry processes are combined.
9. Data reported in EPA (1993) on CKG generation by cement plants doe not distinguish between preheater and precalciner kilns with respect to net CKD generation rates.
10. CKD disposal prices vary widely by location. Transportation of CKD is a significant component of the cost of disposal if disposal is off-site. For example, an estimated off-site disposal cost ranging from $26 to $69 per ton of CKD for disposal, plus transportation costs ranging from $500 - $1,500 per truck load for one northern California location, depending on the landfill chosen. (ARCADIS, 2009) On-site disposal costs would include costs of transportation, dust control, and landfill operation. These costs have not been determined and would most certainly vary widely by location based on terrain, site geology, landfill operating requirements, and permit and future closure costs.
11. Modern preheater cement kilns and precalciner cement kilns generate similar volumes of CKD. Older preheater cement kilns are similar in CKD generation to long dry process cement kilns.

Table 3-14.Energy Efficiency Measures for Raw Materials Preparation

Energy Efficiency Improvement Method	**Electricity Consumption Change, kWh/ton clinker**			
	Dry	**Wet**	**Pre-heater**	**Pre-calciner**
ETS (Efficient Transport System)	-3.20		-3.20	-3.20
RMB (Raw Materials Blending)	-2.70		-2.70	-2.70
PCVM (Process Control Vertical Mill)	-0.90		-0.90	-0.90
HERM (High Efficiency Roller Mill)	-11.05		-11.05	-11.05
SBH (Slurry Blending and Homogenization)		-0.35		
WMCCC (Wash Mills with Closed Circuit Classifier)		-12.00		
RMTHEC (Raw Materials Transport High-Efficiency Classifiers)	-5.05	-5.05	-5.05	-5.05

Table 3-15.Energy Efficiency Clinker Making Measures

Energy Efficiency Improvement Method	Electricity Consumption Change, kWh/ton clinker				Heat Input Change, MMBtu/ton of clinker			
	Dry	Wet	Pre-heater	Pre-calciner	Dry	Wet	Pre-heater	Pre-calciner
EMCS (Energy Management and Control System)	-1.90	-1.50	-1.90	-1.90	-0.15	-0.21	-0.15	-0.15
SR (Seal Replacement)					-0.02	-0.02	-0.02	-0.02
CSI (Combustion System Improvement)					-0.25	-0.35	-0.25	-0.25
IF (Indirect Firing)					-0.16	-0.16	-0.16	-0.16
SHLR (Shell Heat Loss Reduction)					-0.20	-0.20	-0.20	-0.20
OGR (Optimize Grate Cooler)	0.90		0.90	0.90	-0.09	-0.10	-0.09	-0.09
CGC (Convert to reciprocating grate cooler)	2.40	2.40	2.40	2.40	-0.23	-0.24	-0.23	-0.23
HRPG (Heat Recovery for Power Generation)	-18.0							
EMD (Efficient Mill Drives)	-2.00	-1.70	-2.00	-2.00				

Table 3-16.Energy Efficiency Measures for Finish Grinding

Energy Efficiency Improvement Method	Electricity Consumption Change, kWh/ton clinker			
	Dry	Wet	Preheater	Precalciner
EMPC (Energy Management and Process Control)	-1.60	-1.60	-1.60	-1.60
IGMBM (Improved Grinding Media [Ball Mills])	-1.80	-1.80	-1.80	-1.80
HPRP (High-Pressure Roller Press)	-16.00	-16.00	-16.00	-16.00
HEC (High-Efficiency Classifiers)	-3.85	-3.55	-3.85	-3.85

Table 3-17.Energy Efficiency Plant-wide Measures

Energy Efficiency Improvement Method	Electricity Consumption Change, kWh/ton clinker			
	Dry	Wet	Preheater	Precalciner
PM* (Preventive Maintenance)	-2.50	-2.50	-2.50	-2.50
HEM (High Efficiency Motors)	-2.50	-2.50	-2.50	-2.50
ASD (Adjustable Speed Drives)	-6.25	-6.00	-6.25	-6.25
OCAS (Optimization of Compressed Air Systems)	-1.00	-2.50	-1.00	-1.00

*This is the only occurrence wherein “PM” does not stand for “particulate matter”

3.3 References for Chapter 3

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Chapter 4
Model Calibration

Large techno-economic models of U-ISIS framework size require model calibration as they utilize an extensive amount of data which comes from different sources. This chapter outlines calibration methodology that was used, discusses data used for calibration, presents calibration results, and gives further recommendations.

4.1 Calibration Methodology

Calibration methodology utilizes the concept of a calibration constant. The calibration constant has been developed to account for possible errors in costs. The value of the calibration constant, *calconst(i)*, is set by trial and error during calibration. The objective of the trial and error approach is to minimize the absolute difference in the reported and module-predicted prices (which are marginal values of the supply equation) for each USGS district.

In the first step of calibration, the module is set to run for 2005-2007 by making appropriate changes in the input "Policy" worksheet, and GAMS input files. The import quantities are then adjusted equal to reported import quantity for each of the import district, except for those of Mexico and Canada.

In the next step, the impact of changing the calibration constant is monitored. This impact of the calibration constant is assessed on estimated production quantities to keep the difference between reported and module predicted production values within reasonable limits[5]. The calibration constant modifies each kiln's variable cost of production. The "Calibration" worksheet within the Inputs workbook has values of calibration constant assigned for each USGS district. Finally, in the input GAMS file, the values are assigned for a given USGS district to each of the kilns located in that USGS district.

The module is first calibrated for year 2005, to obtain values of the calibration parameter *calconst(i)* for the year. Next, *calconst(i)* values for 2005 are used as a starting point to obtain values for the same parameter for 2006. Similarly, the process is repeated to obtain the values for 2007. Then, an average of the *calconst(i)* values over the three years is taken and used for the future module runs. Current values of the parameter *Calconst(i)* being used in the module runs can be found in the worksheet "Calibration" of the "ISIS_Inputs.xls" workbook.

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[5] There is no standard method to guide the user in determining an acceptable level of "error" in the reported and predicted values for the purpose of calibration. In this works, we have set an acceptable level for the absolute gap between the individual reported and predicted values to ±15%, although effort has been made to keep this level below 10% for most of the quantities. However, due to discontinuities in the transportation matrix, error in the reported data, or other unknowns, the gap in the estimated and reported values may be higher in certain markets.

Calibration is a dynamic process, and it is recommended that module calibration be performed periodically. In this fashion, any available new production, imports, or price data could be utilized in the module.

4.2 Data for Calibration

Production quantities in various USGS production districts, import levels in the import districts and reported cement prices for USGS districts are the key quantities used for calibration of the module. Reported data for years 2005, 2006 and 2007 were used to calibrate the module and obtain values of appropriate calibration parameters.

4.2.1 Cement Prices in USGS Districts

Reported cement prices in various USGS districts are shown in Table 4-1 for years 2005 through 2007. For a given year, the reported cement price shows significant variation across USGS districts. For most districts the cement price has increased over the three year period. USGS districts assignation is the location of the reporting production facilities.

Table 4-1. Cement Prices ($/ton) for USGS Districts

USGS District	2005	2006	2007
Alabama	74.61	81.74	87.09
Illinois	80.29	89.81	91.17
Indiana	72.03	80.04	79.99
Kansas	76.58	86.50	92.87
Maryland	74.76	81.19	80.18
Missouri	78.92	86.61	89.36
Ohio	82.08	90.24	91.47
South Carolina	68.57	80.46	87.54
Maine and New York	80.74	92.53	96.62
Pennsylvania	79.73	89.99	90.85
Michigan and Wisconsin	79.83	84.82	90.12
Iowa, Nebraska and South Dakota	78.72	89.83	93.08
Florida	77.56	90.44	95.55
Georgia, Virginia and West Virginia	84.49	95.93	93.60
Kentucky, Mississippi and Tennessee	84.37	89.81	88.90
Arkansas and Oklahoma	89.00	96.99	97.74
Texas	74.72	85.10	88.33
Arizona and New Mexico	75.76	84.16	86.64
Colorado and Wyoming	82.24	92.90	92.73
Idaho, Montana, Nevada and Utah	83.61	90.26	95.25
California	88.20	99.09	100.24
Oregon and Washington	79.38	90.72	90.72

4.2.2 Cement Production in USGS Districts

Reported cement production in various USGS districts is shown in Table 4-2 for years 2005 through 2007. For a given year, the reported cement production shows significant variation across USGS districts. Generally production dropped from 2005 to 2007, due to a decrease in demand resulting from the economic downturn.

Table 4-2. Cement Production (tons) for Various USGS Districts

USGS District	2005	2006	2007
Alabama	5,647,141	5,733,121	5,578,650
Illinois	3,568,182	3,425,984	3,434,254
Indiana	3,370,868	3,334,492	3,285,999
Kansas	3,182,373	3,310,241	3,039,164
Maryland	2,813,098	2,922,227	3,305,160
Missouri	5,877,524	5,776,111	5,763,479
Ohio	1,086,879	1,064,833	1,010,077
South Carolina	3,601,251	3,654,162	4,057,414
Maine and New York	3,572,591	3,699,357	3,471,388
Pennsylvania	6,931,334	6,631,505	6,239,551
Michigan and Wisconsin	6,171,841	5,993,267	6,047,588
Iowa, Nebraska and South Dakota	4,962,606	5,024,335	4,889,607
Florida	6,311,835	6,477,181	6,076,137
Georgia, Virginia and West Virginia	2,612,478	2,696,253	2,528,648
Kentucky, Mississippi and Tennessee	3,649,753	3,849,271	3,770,250
Arkansas and Oklahoma	3,097,495	2,979,547	2,879,982
Texas	12,737,207	12,510,131	12,038,919
Arizona and New Mexico	3,073,244	2,809,792	2,902,131
Colorado and Wyoming	2,918,920	2,842,861	2,797,240
Idaho, Montana, Nevada and Utah	3,400,630	3,354,333	3,308,645
California	12,747,128	12,069,207	11,941,198
Oregon and Washington	2,175,963	2,101,005	2,103,481

4.2.3 Cement Imports by Import Districts

Reported cement import quantity in various import districts is shown in Table 4-3 for years 2005 through 2007. For a given year, the reported cement imports show a significant variation across import districts. Generally imports dropped from 2005 to 2007, due to a decrease in demand resulting from the economic downturn. New Orleans (LA), San Francisco (CA) and Tampa (FL) suffered large drops in the quantities of cement imported in 2007 compared to that in 2005.

Table 4-3. Cement Imports (except from Canada and Mexico) for Import Districts (tons)

Import District	2005	2006	2007
Baltimore, MD	146,300	203,500	18,700
Boston, MA	145,200	50,600	3,300
Buffalo, NY	6,600	4,400	0
Charleston, SC	1,212,200	1,100,000	363,000
Chicago, IL	1,100	1,100	0
Cleveland, OH	0	1,100	0
Columbia-Snake, ID-OR-WA	831,600	1,115,400	1,180,300
Detroit, MI	59,400	0	0
Duluth, MN	0	0	0
El Paso, TX	0	0	0
Great Falls, MT	0	0	0
Houston-Galveston, TX	2,880,900	3,705,900	3,641,000
Laredo, TX	0	0	0
Los Angeles, CA	3,357,200	3,759,800	2,029,500
Miami, FL	2,395,800	2,311,100	980,100
Minneapolis, MN	0	0	0
Mobile, AL	565,400	573,100	0
New Orleans, LA	4,503,400	5,090,800	1,171,500
New York, NY	1,390,400	1,327,700	810,700
Nogales, AZ	0	0	0
Norfolk, VA	767,800	793,100	447,700
Ogdensburg, NY	0	0	0
Pembina, ND	0	0	0
Philadelphia, PA	544,500	665,500	342,100
Portland, ME	0	0	0
Providence, RI	814,000	680,900	509,300
San Diego, CA	620,400	708,400	427,900
San Francisco, CA	2,599,300	3,081,100	1,524,600
Savannah, GA	88,000	204,600	376,200
Seattle, WA	368,500	733,700	644,600
St. Albans, VT	0	0	0
St. Louis, MO	0	0	3,300
Tampa, FL	3,825,800	3,791,700	1,523,500
Wilmington, NC	427,900	416,900	284,900

4.3 Results of Calibration

Reported and calculated values of cement prices by USGS district are shown for years 2005, 2006, and 2007 in Table 4-4, Table 4-5, and Table 4-6, respectively. As can be seen from these tables, in most of the districts reported and calculated cement prices are within 10 percent range, whereas in a few they are higher. It should be noted that in general the price differentials are smaller in the year 2005 and have increased in 2007. In some USGS districts the reported and calculated prices are different than the module predicted prices due to several factors, including error in reported prices, discontinuities in the transportation matrix, and/or unique factors for some specific markets.

Table 4-4. Reported and Calculated Cement Prices in USGS Districts (2005)

USGS District	Reported	Calculated	%Δ
Alabama	74.61	78	5
Illinois	80.29	83	3
Indiana	72.03	84	16
Kansas	76.58	81	6
Maryland	74.76	74	-1
Missouri	78.92	82	4
Ohio	82.08	83	1
South Carolina	68.57	76	10
Maine and New York	80.74	73	-9
Pennsylvania	79.73	77	-3
Michigan and Wisconsin	79.83	81	2
Iowa, Nebraska and South Dakota	78.72	81	3
Florida	77.56	75	-3
Georgia, Virginia and West Virginia	84.49	80	-6
Kentucky, Mississippi and Tennessee	84.37	81	-4
Arkansas and Oklahoma	89.00	87	-2
Texas	74.72	78	4
Arizona and New Mexico	75.76	105	39
Colorado and Wyoming	82.24	98	20
Idaho, Montana, Nevada and Utah	83.61	70	-16
California	88.20	85	-4
Oregon and Washington	79.38	69	-13

Table 4-5. Reported and Calculated Cement Prices in USGS Districts (2006)

USGS District	Reported	Calculated	%Δ
Alabama	81.74	85	4
Illinois	89.81	83	-8
Indiana	80.04	85	6
Kansas	86.50	83	-4
Maryland	81.19	80	-1
Missouri	86.61	81	-6
Ohio	90.24	83	-8
South Carolina	80.46	85	6
Maine and New York	92.53	78	-16
Pennsylvania	89.99	80	-11
Michigan and Wisconsin	84.82	80	-6
Iowa, Nebraska and South Dakota	89.83	81	-10
Florida	90.44	82	-10
Georgia, Virginia and West Virginia	95.93	86	-10
Kentucky, Mississippi and Tennessee	89.81	84	-6
Arkansas and Oklahoma	96.99	91	-6
Texas	85.10	81	-4
Arizona and New Mexico	84.16	105	25
Colorado and Wyoming	92.90	100	8
Idaho, Montana, Nevada and Utah	90.26	83	-8
California	99.09	85	-14
Oregon and Washington	90.72	74	-18

Table 4-6. Reported and Calculated Cement Prices in USGS Districts (2007)

USGS District	Reported	Calculated	%Δ
Alabama	87.09	73	-17
Illinois	91.17	72	-21
Indiana	79.99	75	-7
Kansas	92.87	71	-24
Maryland	80.18	74	-8
Missouri	89.36	71	-21
Ohio	91.47	76	-17
South Carolina	87.54	69	-21
Maine and New York	96.62	74	-24
Pennsylvania	90.85	75	-17
Michigan and Wisconsin	90.12	76	-15
Iowa, Nebraska and South Dakota	93.08	71	-23
Florida	95.55	66	-31
Georgia, Virginia and West Virginia	93.60	74	-20
Kentucky, Mississippi and Tennessee	88.90	71	-20
Arkansas and Oklahoma	97.74	88	-10
Texas	88.33	80	-10
Arizona and New Mexico	86.64	101	17
Colorado and Wyoming	92.73	89	-4
Idaho, Montana, Nevada and Utah	95.25	83	-13
California	100.24	81	-20
Oregon and Washington	90.72	75	-18

Specifically, the Arizona and New Mexico USGS district has a price differential due to capacity constraints in New Mexico. New Mexico has only two small, very old kilns with a capacity half than the demand in New Mexico. The balance demand is met by kilns in Texas, and imports, which incur a significant transportation cost, resulting in a high price for cement in this market. Similarly, Oregon and Washington USGS District is dependent on supplies from other states. While demand in Washington is met by domestic production and imports from Canada, Oregon relies on imports from Canada and other nearby states, resulting in higher cost.

Generally, individual market prices are within the criteria specified in the QAPP document, the deviations are explained by the demand-supply gap and transportation cost. Moreover, root-mean-square values of the price difference for 2005 and 2006 are about 12 percent and 10 percent respectively, and 18 percent for 2007.

Further while calibrating for price, aggregate production level is also tracked to make sure that it is within reasonable limits. The reported and predicted aggregate production levels for 2005-2007 are shown in Table 4-7.

Table 4-7. Aggregate production (reported and modeled) for 2005-2007

Year	Reported Production (million tons)	Calculated Production (million tons)	%Δ
2005	111.84	112.54	0.63
2006	110.30	111.23	0.84
2007	108.17	101.95	-5.75

The current set of calibration constant values are averaged over the years of calibration, and are available in the "Calibration" worksheet in the "ISIS_Inputs.xls" workbook.

4.4 Recommendations

If any of the key input parameters, specifically those relating to production quantities and costs, are refined or otherwise modified or additional observed data becomes available, the calibration of the module should be repeated. Transportation matrix, modes, and cost of transportation also have significant impact on the behavior of production distribution across the districts and production prices. Therefore, if any further modifications or refinements are made to the transportation matrix, the module needs to be re-calibrated.

At the time of calibration of the current version of the module, production, import and price values were used. As discussed above, when the new values become available, the module needs to be calibrated again. Calibration of the module should be repeated as soon as new information or new observed data becomes available. Due to practical limitations it is recommended that the calibration of the module be repeated every two years. Further, since the calibration data is available only for three years, equal weight was given to the parameters obtained for each year. Once a larger data-set is available, a modified weighing system can be adopted to give highest weight to the most-recent year data.

Appendix A

Andover Technology Partners and RTI International Memos

Andover Technology Partners

May 7, 2010	Electrical Load for Wet Scrubbers
February 26, 2010	Wet Scrubber Cost Algorithms
July 10, 2009	GHG Mitigation Methods for Cement
March 10, 2009	Costs and Performance of Controls – revised from comments
March 10, 2009	NO_X, SO_2 and CO_2 Emissions from Cement Kilns (Emissions Memo) – revised from comments

RTI

March 31, 2010	ISIS Cement Production Costs
August 31, 2007	Documentation for Portland Cement Kiln Cost Functions (2005)

Appendix B

ISIS Mathematical Framework

Appendix B
ISIS Mathematical Framework

U-ISIS is a sector-based *dynamic linear programming* model that can determine optimal sector operation for meeting demand and pollution reduction requirements over specified time periods. The objective in U-ISIS simulation is to maximize *total surplus* (see Figure B-1) over a horizon of interest for an industry, which, in general, can be a multi-product one.

The general concept of *spatial price equilibrium* (SPE) in a network, where the mutual influences of production, transportation, and consumption patterns are given full consideration, has been developed over the past 6 decades. In SPE network models, interregional economies are simulated by finding the balance of demand, supply, and trade that will result in competitive market equilibrium among the regions. Enke (1951) first demonstrated how the cost of transportation might be included in an equilibrium analysis of spatially separated markets by means of analogy with resistance to the flow of current in an electric circuit. Shortly after Enke, Samuelson (1952) analyzed interregional flows of commodities and market equilibrium using a linear programming formulation. In this type of formulation, the equilibrium for each market of a sector is equivalent to the quantities and prices that result while maximizing the sum of consumer and producer surpluses for each market of the sector. This sum is referred to as the total surplus or net social payoff of the sector; McCarl and Spreen (1980) provide interpretation and justification. The linear programming formulation of the SPE problem was developed by Duloy and Norton (1975).

Using Figure B-1, the definition of the suppliers' surplus corresponding to a quantity Q of a commodity is the difference between the total revenue and the total cost of supplying the commodity. This surplus (gross profit) is given by the area under the horizontal line P1-P minus the area under the inverse supply curve up to point P. Similarly, the consumers' surplus corresponding to a quantity Q is given by the area under the inverse demand curve up to point C minus the area under the horizontal line C1-C. This area is the cumulative opportunity gain of all consumers who purchase the commodity at a price lower than the price they would have been willing to pay. It is evident from Figure B-1 that the total surplus is maximized exactly when Q is equal to the equilibrium quantity QE. This is a very useful result, as it provides a method for computing the equilibrium.

The total surplus concept has long been a mainstay of social welfare economics because it takes in to account the interests of both consumers and of producers (Samuelson and Nordhaus, 1977).

The broad modules and associated information flows utilized in the U-ISIS framework are shown in Figure B-2. While the U-ISIS structure permits accounting for multiple products, the description below is provided relative to one product to bring out the important elements of the formulation and not burden the reader with many details. Also, to make the description more readable and understandable, the input data (i.e., those supplied by the user, or derived from user-supplied data) are shown in **bold** and the variables, whose values are determined in the optimization process, are shown in *italics*. This scheme helps in organizing the numerous data elements and variables, and hopefully makes it easier for the reader to relate the data element to descriptions in the previous chapters. Finally, the names of variables and data elements have been chosen to be self-explanatory as far as possible.

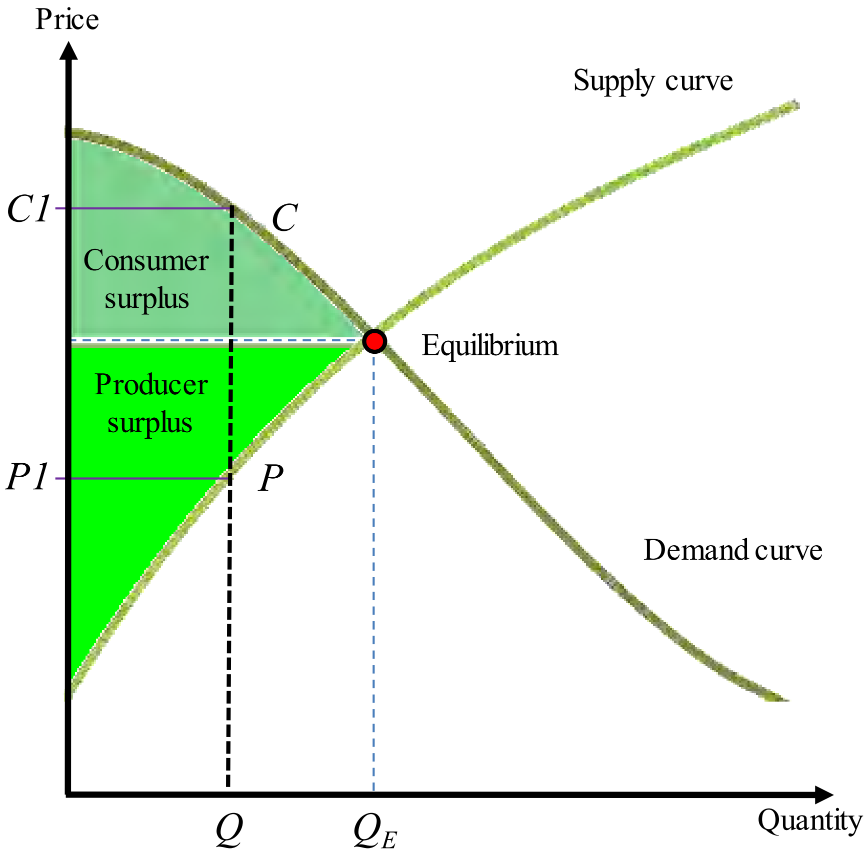

Figure B-1. Consumer and Producer Surplus in a Market

B.1 Indexes and Mappings

Before we start the description of the mathematical structure of U-ISIS, it is helpful to define the sets of relevant entities and mappings describing the relationships among various entities.

Indexes (one-dimensional sets)

U-ISIS data structures (sets and parameters), variables, and equations use the following indexes:

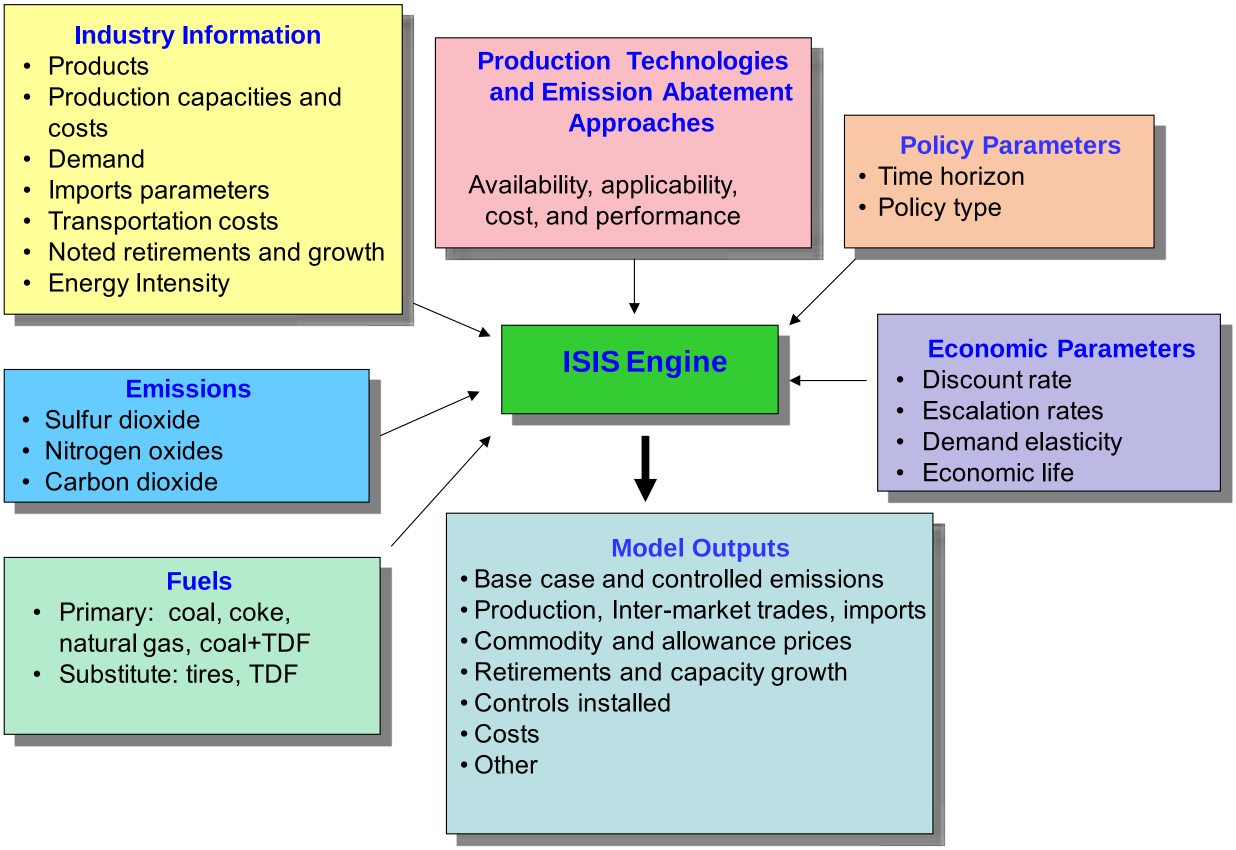

Figure B-2. Broad Modules and Associated Information Flows Utilized in the ISIS Framework

- **byprod** is the set of byproducts generated by controls;
- **cat** is the set of catalysts used with controls;
- **dc** is the set of demand centers across the United States;
- **dsteps** is the set of a series of steps defined for a demand curve;
- **ee** is the set of energy efficiency measures;
- **EEmeasures** is the set of energy efficiency measures not including “NOEE”;
- **eekk** is the set of aliased with **ee**;
- **Emutex** is the set of energy efficiency compatibility;
- **f** is the set of fuels applicable to the sector;
- **i** is the set of all units, including existing, replacement, expansion, and new units. Subsets of **i** described below define more-specific populations of units;
- **iE(i)** is the set of existing units;
- **iii** is the set of all units aliased with **i**;
- **iP(i)** represents the set of projected units;
- **iEP(i)** is the set of existing and projected units ;
- **irepl(i)** is the set of replacement units;
- **iExpCap(i)** represents the set of expansion units;
- **iNewCap(i)** represents the set of new units;
- **ipol(i)** represents the set of units included in the policy run ;
- **id** is the set of import districts for a sector;

- **isteps** is a set of a series of steps defined for an import curve;
- **j** is the set of sector-specific pollutants of interest;
- **jpol(j)** represents the set of pollutants included in policy;
- **jj** is the set of sector-specific pollutants aliased with **j**;
- **k** is the set of sector-specific controls relevant to the emission reduction policy of interest;
- **kk** is the set of sector-specific controls relevant to the emission reduction policy of interest aliased with **k**;
- **m** is the set of raw materials specific to the sector;
- **n** is the set of all products for a sector;
- **oi** is the set of origin of imports for a sector;
- **r** is the set of geographic regions where units are located;
- **t** is the set of years in the time horizon of interest;
- **tpolc(t)** is the set of policy years; and
- **v** is the set of vintage years for added capacity.

<u>Mappings</u>

The mappings used in U-ISIS are:

- **fi(i,f)** is the mapping relating a unit **i** to fuels **f**;
- **iirepl(i,irepl)** is the mapping between an unit **i** and its replacement **irepl**;
- **kf(k,f)** is the mapping relating the control **k** to its fuel used **f;**
- **ri(i,r)** is the mapping relating a unit **i** to its geographic location **r**;
- **poltikjee(t,i,k,j,ee)** is the mapping relating availability, applicability, and the ability to change emissions of controls **k** and energy efficiency measures **ee** to unit **i,** pollutant **j**, and year **t**;
- **poltik(t,i,k)** is the mapping relating availability and applicability of controls **k** to unit **i** and year **t**;
- **poltiee(t,i,ee)** is the mapping relating availability and applicability of energy efficiency measures **ee** to unit **i** and year **t**;
- **poltirk(t, ri(i,r),k)** is the mapping relating availability and applicability of controls **k** to unit **i** located in geographic region **r** and year **t**; and
- **poltiree(t, ri(i,r),ee)** is the mapping relating availability and applicability of energy efficiency measures **ee** to unit **i** located in geographic region **r** and year **t**.

B.2 Objective Function

As mentioned above, the objective function solved in the U-ISIS model corresponds to maximizing the total surplus (or minimizing the negative of the total surplus) for the sector of interest over the selected time horizon. This objective function is:

$$
\begin{aligned}
\text{Minimize } z = & \sum_{t,i,n} \mathbf{dis(t)} \cdot tannualprodncost(t,i,n) \\
& + \sum_{t,dc,n} \mathbf{dis(t)} \cdot ttranscost(t,dc,n) \\
& + \sum_{t,id,n} \mathbf{dis(t)} \cdot timportscost(t,id,n) \\
& + \sum_{t,i,k} \mathbf{dis(t)} \cdot tcontrolcost(t,i,k) \\
& + \sum_{t,i,ee} \mathbf{dis(t)} \cdot teemeasurescost(t,i,ee) \\
& + \sum_{t,j} \mathbf{dis(t)} \cdot \mathbf{alprice(t,j)} \cdot totalemissions(t,j) \\
& - \sum_{t,n} \left[\mathbf{dis(t)} \cdot \int_{dc} price(t,dc,n) \cdot ddemand(t,dc,n) \right]
\end{aligned}
\tag{B.2.1}
$$

where the quantities appearing in the equation above are defined for year **t** as follows,

dis(t) is the discount factor,
tannualprodncost(t,i,n) is the annual production cost ($) for production unit **i** of final product **n**,
ttranscost(t,dc,n) is the cost ($) of transporting the product **n** to demand center **dc**,
timportscost(t,id,n) is the cost ($) of importing foreign product **n** in import district **id**,
tcontrolcost(t,i k) is each unit's total control cost ($) using control technology **k**,
teemeasurescost(t, i, ee) is each unit's total cost ($) using the energy efficiency measures **ee**,
alprice(t,j) is the allowance price input by the user,
totalemissions(t,j) is emission of pollutant *j* from the sector, and
$\int_{dc} price(t,dc,n) \cdot ddemand(t,dc,n)$ is the area under the demand-price curves for product **n** for all markets **dc**.

Note that in the objective function the term with **alprice(t,j)** comes into effect only if the user provides values for **alprice(t,j)**. If these values are specified, the model runs as described under the "Allowance Price Inputs" in a later section.

A stepwise approximation of the demand curves (FPL-PELPS, 2003) is used in U-ISIS so that relevant area can be computed in a linear programming scheme. This approximation is explained below.

Stepwise Approximation of Demand Curves in U-ISIS

For clarity, the subscripts **t** and **dc** corresponding to time and demand center are dropped in the following explanation.

The relationship between demand and price in a market **dc** is expressed as:

$$P(D) = \mathrm{P0}\left(\frac{D}{\mathrm{D0}}\right)^{\frac{1}{\sigma}} \qquad \text{(B.2.2)}$$

where

D is the demand for the commodity with corresponding price $P(demand)$,
σ is the elasticity of demand relative to price, and
D0 and **P0** are the initially-specified demand quantity and price, respectively.

Figure B-3 shows a representation of the above equation and also reflects how a stepwise approximation of the price-demand curve can be created.

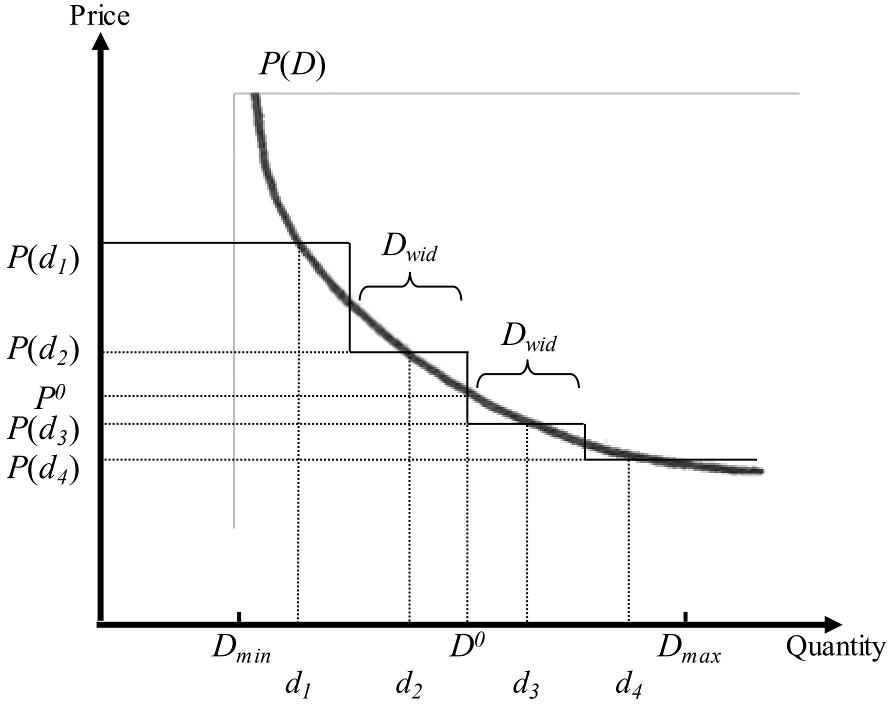

Figure B-3. Stepwise Calculation of the Demand Curve

First the range of the demand-price curve is defined using:

$$\mathbf{D_{min} = D0 \cdot (1 - range)} \qquad \text{(B.2.3)}$$

$$\mathbf{D_{max} = D0 \cdot (1 + range)} \qquad \text{(B.2.4)}$$

where

range is a user-supplied parameter with value between 0 and 1. This parameter defines the interval $\mathbf{D_{min}}$ **-** $\mathbf{D_{max}}$ within which the new equilibrium demand quantity is expected to be found. Note **range** should be large enough to ensure that the solution does fall in the interval $\mathbf{D_{min}}$ **-** $\mathbf{D_{max}}$. On the other hand a smaller value of

range can increase precision of the stepwise approximation. In U-ISIS a value of 0.5 is used for **range**.

Next, a series of steps is defined within the interval $\mathbf{D_{min}}$ **-** $\mathbf{D_{max}}$ with the width of each step given by:

$$\mathbf{dwidth} = \frac{\mathbf{D_{max} - D_{min}}}{\mathbf{Number\ of\ steps}} \tag{B.2.5}$$

where

Number of steps is another user-supplied parameter. Increasing the value of this parameter will increase precision of the stepwise approximation, but will increase the model size. In U-ISIS, a value of 100 is used for **Number of steps**.

Now the demand quantity at the center of the slice **dstep** inside the interval is:

$$\mathbf{D^{dstep}} = \mathbf{D_{min}} + \frac{\mathbf{dwidth \cdot (2 \cdot dstep - 1)}}{\mathbf{2}} \tag{B.2.6}$$

Using the above information, the price-demand curve is determined by:

$$\mathbf{P(D^{dstep})} = \mathbf{P0}\left(\frac{\mathbf{D^{dstep}}}{\mathbf{D0}}\right)^{\frac{1}{\sigma}} \tag{B.2.7}$$

Finally, the approximated area under the price-demand curve is:

$$\sum_{\mathbf{dsteps=1}}^{\mathbf{Number\ of\ steps}} D^{dstep} \cdot \mathbf{P}(D^{dstep}) \tag{B.2.8}$$

Substituting (B.2.8) in (B.2.1), the objective function becomes:

$$\begin{aligned}
\text{Minimize } z = & \sum_{t,i} \mathbf{dis(t)} \cdot \mathit{tannualprodncost(t,i)} \\
& + \sum_{t,dc} \mathbf{dis(t)} \cdot \mathit{ttranscost(t,dc)} \\
& + \sum_{t,id} \mathbf{dis(t)} \cdot \mathit{timportscost(t,id)} \\
& + \sum_{t,i,k} \mathbf{dis(t)} \cdot \mathit{tcontrolcost(t,i,k)} \\
& + \sum_{t,i,ee} \mathbf{dis(t)} \cdot \mathit{teemeasurescost(t,i,ee)} \\
& + \sum_{t,j} \mathbf{dis(t)} \cdot \mathbf{alprice(t,j)} \cdot \mathit{totalemissions(t,j)} \\
& - \sum_{t} \left[\mathbf{dis(t)} \cdot \sum_{dc,dstep} ElasticDemand(t,dc,dstep) \cdot \mathbf{dprice(demand(t,dc,dstep)} \right]
\end{aligned} \tag{B.2.9}$$

where

demand(t, dc,dstep) is the demand for the commodity at the dstepth level of the price-demand curve for the demand center **dc** in year **t**. The construction of the price-demand curves has been explained above.

dprice(demand(t,dc,dstep) is the price for the commodity at the dstepth level pf the price-demand curve for the demand center **dc** in year **t**.

The above objective function is minimized with the constraints and related equations described in the following sections to arrive at the relevant optimum solution.

Equation (B.2.7) is used to generate the price-demand curves for all time periods and demand centers. However, this equation needs specifications of one point on each demand function in each time period (i.e., **[P0(t, dc), D0(t, dc)])**. To determine such points, a single run of the inelastic version of the U-ISIS model (with exogenous **D0(t, dc))** is made and then the resulting shadow prices **P0(t, dc)** are used in Equation (B.2.7) to generate price-demand curves for all time periods and demand centers. These curves are used in the last term of the objective function and in the supply constraint, Equation (B.3.1), presented in the next section.

B.3 Supply

The demand for a commodity in a market can be satisfied by domestic production and foreign imports as follows:

$$\sum_{i} prodnquantity(t,i,dc) + \sum_{id} importedquantity(t,id,dc) \geq \sum_{dstep} ElasticDemand(t,dc,dstep). \tag{B.3.1}$$

where

prodnquantity(t,i,dc) is the quantity supplied from the domestic production unit **i** to demand center **dc** in year **t**, and

importedquantity(t,id,dc) is the quantity of commodity received from the origin (country) of imports **oi** at the domestic import district **id** and supplied from that district to demand center **dc** in year **t**.

Note that transportation of quantity from production units and import districts to demand centers is implicit in the above equation.

The sum of all quantities in year **t** supplied from a kiln **i** to various demand centers **dc** must equal the production level of unit **i** in that year. Then,

$$\sum_{dc} prodnquantity(t,i,dc) = prodn(t,i). \qquad \text{(B.3.2)}$$

where

prodn(t, i) is the production level (tons/year) of manufacturing unit **i** in year **t**.

Note that, in general, production can be from existing units, units added at a plant (i.e., expansion units), newer units replacing units at a plant (i.e., replacement units), and new kilns. Treatment of these is explained in a subsequent section.

Production of a unit is constrained by its capacity. So,

$$prodn(t,i) \leq \cdot \mathbf{capacity(t,i)} \qquad \text{(B.3.3)}$$

where

capacity(t, i) is the capacity (tons product/year) of manufacturing unit **i** in year **t**.

The sum of all imported quantities supplied from an import district **id** to various demand centers **dc** in year **t** must equal the imports available at that import district in that year. Then,

$$\sum_{dc} importedquantity(t,id,dc) = \sum_{oi,istep} Imports(t,oi,id,istep) \qquad \text{(B.3.4)}$$

where

Importedquantity(t,id,dc) is the imported quantity supplied from import district **id** to demand center **dc** in year **t,** and
Imports(t,oi,id,istep) is the imported quantity available at the import district **id** in year **t** at the istepth level of the imports curve for country **oi**. Construction of the country (or region) and import district specific imports-cost curves is explained below.

<u>Stepwise Approximation of Imports Curves in ISIS</u>

The treatment of imports is similar to the treatment for elastic demand curves. Again, for clarity, the subscripts **t, oi,** and **id** corresponding to time, origin of imports, and import district are dropped in the following explanation.

The relationship between imports arriving from **oi** at **id** and their price is expressed as:

$$Iprice(Imports) = \mathbf{Iprice0}\left(\frac{Imports}{\mathbf{Imports0}}\right)^{\frac{\mathbf{1}}{\alpha}} \qquad \text{(B.3.5)}$$

where

Imports is the imports of the commodity arriving from **oi** at **id** with corresponding imports price (value) *Iprice*,
α is the elasticity of imports relative to imports price, and
(Imports0, Iprice0) is a point on the applicable quantity-price curve.

First the range of the imports-price curve is defined using:

$$\mathbf{I_{min} = Imports0 \cdot (1 - range)} \qquad \text{(B.3.6)}$$

$$\mathbf{I_{max} = Imports0 \cdot (1 + range)} \qquad \text{(B.3.7)}$$

where

range is a user-supplied parameter with value between 0 and 1. This parameter defines the interval **I_{min}**

Using the above information, the imports-price curve is determined by:

$$\mathbf{Iprice}(\mathbf{Imports}^{\mathbf{istep}}) = \mathbf{Iprice0}\left(\frac{\mathbf{Imports}^{\mathbf{istep}}}{\mathbf{Imports0}}\right)^{\frac{1}{\alpha}} \tag{B.3.10}$$

Equation (B.3.10) is used to generate the imports-cost curves for all time periods, origins of imports, and import districts. However, this equation needs specifications of one point on each import function in each time period (i.e., **[Iprice0(t, oi, id), Imports0(t, oi, id)]**). To determine such points, a single run of the inelastic version of the U-ISIS model (with exogenous **Imports0(t, oi, id)** corresponding to capacities of import districts) is made and then the resulting **Iprice0(t, oi, id)** are used in Equation (B.3.10) to generate the imports-cost curves for all time periods, origins of imports, and import districts.

B.4 Production Capacity and Supply Costs

The U-ISIS model includes constraints for ensuring that endogenous production capacity changes occur in a realistic way. This section describes how the capacity changes take place in the U-ISIS framework and the treatment of related costs. Note that various cost elements (e.g., capital cost of a unit [$/ton clinker] in the cement sector) are escalated appropriately to reflect values in years of interest.

Production Capacity Related Constraints

Added capacity in year **t** is given by:

When **t** = 1,

$$\begin{gathered} addcap(t,i) = \sum_{v} tcap(t,i,v) \cdot \mathbf{capacity(t,i)}; \\ \mathbf{vyear(v)} \le \mathbf{tyear(t)} < (\mathbf{vyear(v)} + \mathbf{techlifeplants}); \\ \mathrm{i} \in [\mathrm{irepl(i)} \cup \mathrm{iExpCap(i)} \cup \mathrm{iNewCap(i)}] \end{gathered} \tag{B.4.1a}$$

For **t** > 1,

$$\begin{gathered} addcap(t,i) = addcap(t-timeblock,i) + \sum_{v} tcap(t,i,v) \cdot \mathbf{capacity(t,i)}; \\ \mathbf{vyear(v)} \le \mathbf{tyear(t)} < (\mathbf{vyear(v)} + \mathbf{techlifeplants}); \\ \mathrm{i} \in [\mathrm{irepl(i)} \cup \mathrm{iExpCap(i)} \cup \mathrm{iNewCap(i)}] \end{gathered} \tag{B.4.1b}$$

where

v is the set of vintages of an unit **I**,
AddCap (t,i) is the added capacity of an unit **i** in year **t**,
tcap(t,i,v) is a binary variable that can bring **vth** vintage of unit **i** online in year **t,**
vyear(v) and **tyear(t)** are parameters with values corresponding to years in the selected time horizon,
timeblock is the block of years used in simulation, and

techlifeplants is the technical life of a unit.

Only one vintage of a unit is possible for the period starting when the vintage comes on line and ending with its technical life.

$$\sum_{t,v} tcap(t,i,v) \le 1;$$
$$\mathbf{vyear(v)} \le \mathbf{tyear(t)} < [\mathbf{vyear(v)} + \mathbf{techlifeplants}];$$
$$\mathrm{i} \in [\mathrm{irepl(i)} \cup \mathrm{iExpCap(i)} \cup \mathrm{iNewCap(i)}] \qquad \text{(B.4.2)}$$

The annual costs associated with meeting the demand for the commodity include: (1) annualized capital costs associated with capacity growth (i.e., replacement units, expansion units, and new capacity) and projected units, (2) annual fixed operation and maintenance (FOM) costs, (3) annual variable costs associated with use of labor, raw material, fuel, electricity, and operation and maintenance, (4) annual transportation costs, and (5) annual cost of imports. These costs are described below.

Capital Recovery

If the existing units are paid for and do not have capital recovery costs, then:

$$plantcapcost(t,i) = 0;\ \ \mathbf{i} \in \{\mathbf{iE(i)}\}. \qquad \text{(B.4.3)}$$

where

plantcapcost(t,i) is the annual capital cost of a unit.

For projected units, for which startup date is known, annual capital cost is given by:

$$plantcapcost(t,i) = \mathbf{CRFplant} \cdot \mathbf{capacity(t,i)} \cdot \mathbf{pcapcostt(t,i)};$$
$$\mathrm{tstart(i)} \le \mathrm{tyear(t)} \le (\mathrm{tstart(i)} + \mathbf{ecolifeplants});\ \mathrm{i} \in [\mathrm{iP(i)}]. \qquad \text{(B.4.4)}$$

where

pcapcostt(t,i) is the capital cost (e.g., $/ton of clinker for the cement sector) of **i**$^{\mathbf{th}}$ unit in year **t,** and
CRFplant is the capital recovery factor calculated using an appropriate interest rate and time period, **ecolifeplants**, for capital recovery.

Annual capital costs for all populations except existing and projected is:

$$plantcapcost(t,i) = AddCap(t,i) \cdot \mathbf{capcostt(t,i)} \cdot \mathbf{CRFplant} \qquad \text{(B.4.5)}$$

where

capcostt(t,i) is the capital cost (e.g., $/ton of clinker for the cement sector) for the **i**$^{\mathbf{th}}$ unit**.**

Variable Costs

The annual variable cost at a unit is calculated using:

$$\begin{aligned} \mathit{varcost(t,i)} = {} & \left[\mathbf{RMTt(t,i)} + \mathbf{VOMt(t,i)} + \mathbf{LBRt(t,i)} + \mathbf{ELCostt(t,i)}\right] \cdot \mathit{prodn}(t,i) + \\ & \mathit{fc}(t,i) + \mathit{H2Oconsumptncost(t,i)} + \sum_{sw} \mathit{SWdispcost(t,i,SW)}. \end{aligned} \tag{B.4.6}$$

where

RMTt(t,i) is the raw material cost ($/ton product) at unit **i** in year **t**,
VOMt(t,i) is the cost of operation and maintenance ($/ton product) at unit **i** in year **t**,
LBRt(t,i) is the cost of labor ($/ton product) at unit **i** in year **t**,
ELCostt(t,i) is the cost of electricity use ($/ton product) at unit **i** in year **t**,
fc(t, i) is the cost of fuel ($) at unit **i** in year **t**,
varcost(t,i) is the annual variable cost ($) at unit **i** in year **t**,
sWdispcost(t,i,SW) is the annual variable cost ($) of solid waste disposal at unit **i** in year **t**, and
H2Oconsumptncost(t,i) is the annual variable cost ($) of water consumption at unit **i** in year **t**.

The fuel cost for a unit is calculated as follows:

$$\begin{aligned} \mathit{fc(t,i)} = {} & \sum_{\mathrm{f}} [\mathbf{eintensity(i)} \cdot \mathbf{fuelcostt(t,i,f)} \cdot \\ & \sum_{\mathrm{m,poltikjee(t,i,k,j,ee)}} \mathit{varprodn(t,i,f,m,j,k,ee)}] \cdot \frac{1}{\text{Number of pollutants}}. \end{aligned} \tag{B.4.7}$$

where

eintensity(i) is the energy intensity (MMBtu/ton product) for unit **i**,
fuelcostt(t,i, f) is the cost of fuel **f** ($/MMBtu) at unit **i** in year **t**, and
varprodn(t,i,f,m,j,k,ee) is a production coefficient described in the next section.

Annual water consumption related cost is given by:

$$\mathit{H2Oconsumptncost(t,i)} = \mathit{H2Oconsumptn(t,i)} \cdot \mathbf{H2Ocostt(t)} / 1000 \tag{B.4.8}$$

With annual water consumption given by:

$$\mathit{H2Oconsumptn(t,i)} = \mathbf{H2Ointensity(i)} \cdot \mathit{prodn}(t,i). \tag{B.4.9}$$

where

H2Ocostt(t) is the cost of water ($/1000 gallon) in year **t**, and
H2Ointensity(i) is the gallons of water needed to produce a ton of product at unit **i**.

Annual solids discharge related cost is given by:

$$SWdispcost(t,i,sw) = SWgen(t,i,sw) \cdot \mathbf{SWdisposalcostt(t,sw)} \qquad \text{(B.4.10)}$$

With annual solids discharges given by:

$$SWgen(t,i,sw) = \mathbf{SWgeneration(i,sw)} \cdot prodn(t,i). \qquad \text{(B.4.11)}$$

where

sWgen(t,i,sw) is the annual variable of solid waste generation rate (tons/year) at unit **i** in year **t**,
sWdisposalcostt(t,sw) is the cost of disposing of a solid discharge **sw** in year **t**, and
sWgeneration(i,sw) is the discharge of a solid **sw** (tons) in the process of producing a ton of product at unit **i**.

Note that **sWdisposalcostt(t,sw)** value can be positive (disposal cost) or negative (sale price).

Total Annual Cost of Production

Using the above information, the total annual cost of production at unit **i** in year **t** is:

$$tannualprodncost(t,i) = plantcapcost(t,i) + varcost(t,i). \qquad \text{(B.4.12)}$$

Annual Cost of Imported Commodity

The cost of imports of commodity at import district **id** in year **t** is calculated using the following equation:

$$timportscost(t,id) = \sum_{oi,isteps} [(\mathbf{Iprice(t,oi,id,isteps)} + \mathbf{InsFreight(id)} + \mathbf{imphandlingt(id)}) \cdot Imports(t,oi,id,isteps)]. \qquad \text{(B.4.13)}$$

where

Iprice(t,oi,id,isteps) is the price (value) of importing commodity from origin **oi** (foreign country) at the import district **dc**, at the istepth level of the relevant price-import curve,
InsFreight(id) is the insurance and freight at the import district, and
imphandlingt(id) is the handling cost at the import district.

Total Annual Transportation Cost

The cost of transporting the commodity from unit **i** and import district **id** to demand center **dc** is calculated using:

$$\mathit{ttranscost}(t,dc) = \sum_{i}[\mathbf{prodntransportcostt(t,i,dc)} \cdot \mathit{prodnquantity}(t,i,dc)] + \sum_{id}[\mathbf{imprttransportcostt(t,id,dc)} \cdot \mathit{Importedquantity}(t,id,dc)]. \qquad \text{(B.4.14)}$$

where

prodntransportcostt(t,i,dc) is the cost of transporting one ton of commodity ($/ton) from unit **i** to demand center **dc**, and
imprttransportcostt(t,id,dc) is the cost of transporting one ton of commodity ($/ton) from import district **id** to demand center **dc**.

B.5 Emissions

As discussed in the previous chapter, emissions can be generated from fuel firing and also from use of raw materials (e.g., CO_2 emissions from calcination of limestone in cement kiln). As such, both of these emission generation pathways are included in U-ISIS. Further, the U-ISIS framework includes algorithms to account for tracking multiple pollutant streams associated with uncontrolled emissions, controlled emissions, pollution prevention from process modifications and energy efficiency measures, and any controls-related effects (e.g., generation of CO_2 in a wet SO_2 scrubber). These algorithms are described below.

$$\mathbf{polfuel(t,i,f,j,k,ee)} = \mathbf{emintensityfuel(i,f,j) \cdot modeintensity(i,k,ee) \cdot [1 - cp(i,j,k)/100].} \qquad \text{(B.5.1)}$$

$$\mathbf{modeintensity(i,k,ee)} = \mathbf{eintensity(i) + primaryHIchange(i,k) + secondaryHIchange(i,k) + eHIdispi(i,ee)} \qquad \text{(B.5.2)}$$

where

polfuel(t,i,f,j,k,ee) is emission (tons pollutant per ton product) of pollutant **j** resulting from processing (firing) fuel **f** and application of any control **k** and/or energy efficiency measure **ee** at unit **i** in year **t,** taking into account whether a unit is available for operation in that year;
emintensityfuel(i,f,j) is the emission intensity (tons pollutant per ton product) of pollutant **j** resulting from processing (firing) fuel **f** at unit **i,** taking in to account whether any controls (e.g., Best Available Control Technology [BACT]) are already installed on the unit;
modeintensity(i,k,ee) is the modified energy intensity (MMBtu per ton product) needed to produce 1 ton of product at unit **i**. This energy intensity takes into account any heat input changes accompanying a control **k** and/or an energy efficiency measure **ee**;
eintensity(i) is the energy intensity (MMBtu per ton product) needed to produce 1 ton of product at unit **i**;
primaryHIchange(i,k) is the change in primary heat input (MMBtu per ton product) due to application of control **k** at unit **i**;

secondaryHIchange(i,k) is the change in heat input (MMBtu per ton product) due to any secondary fuel addition resulting from application of control **k** at unit **i**;
eHIdispi(i,ee) is the amount of heat input (MMBtu per ton product) displaced (reduced) due to application of energy efficiency measure **ee** at unit **i**; and
cp(i,j,k) is the reduction efficiency for pollutant **j** using control **k** at unit **i**.

Similarly,

$$\mathbf{polrmt(t,\ i, m, j, k)} = \mathbf{emintensityrmt(i,\ m,\ j)} \cdot \begin{bmatrix} 1 + \mathbf{primaryRMTchangepercent(i,k)}/100 + \\ \mathbf{secondaryRMTchangepercent(i,k)}/100 \end{bmatrix} \cdot [1 - \mathbf{cp(i,\ j,\ k)}/100]. \tag{B.5.3}$$

where

polrmt(t,i,m,j,k,) is emission (tons pollutant per ton product) of pollutant **j** resulting from processing raw material **m** and application of any control **k** and/or energy efficiency measure **ee** at unit **i** in year **t,** taking into account whether a unit is available for operation in that year;
emintensityrmt(i,m,j) is the emission intensity (tons pollutant per ton product) of pollutant **j** resulting from processing raw material **m** at unit **i,** taking into account whether any controls (e.g., BACT) are already installed on the unit;
primaryRMTchangepercent(i,k) is the percent change in primary raw material input (tons raw material per ton product) due to application of control **k** at unit **i**; and
secondaryRMTchangepercent (i,k) is the percent change in raw material input (tons raw material per ton product) due to any secondary raw material addition resulting from application of control **k** at unit **i**.

Finally,

$$\mathbf{pol(t,i,f,m,j,k,ee)} = \mathbf{polfuel(t,i,f,j,k,ee)} + \mathbf{polrmt(t,i,m,j,k)}. \tag{B.5.4}$$

where

pol(t,i,f,m,j,k,ee) is emission (tons pollutant per ton product) of pollutant **j** resulting from processing fuel **f** and raw material **m,** and application of any control **k** and/or energy efficiency measure **ee,** at unit **i** in year **t,** taking into account whether a unit is available for operation in that year.

Emissions of pollutant *j* at unit *i* in year *t* are given by:

$$emissions(t,i,j) = \sum_{\mathrm{f,m,poltikjee(t,i,k,j,ee)}} \mathbf{pol(t,i,f,m,j,k,ee)} \cdot varprodn(t,i,f,m,j,k,ee). \tag{B.5.5}$$

where

varprodn(t,i,f,m,j,k,ee) is the production variable associated with use of **kth** control and/or **eeth** energy efficiency measure for **jth** pollutant at unit **i** using fuel **f** and raw material **m** in year **t**;
emissions(t,i,j) are the emissions (tons of pollutant per ton of clinker) of pollutant **j** at unit **i**; and
poltikjee(t,i,k,j,ee) is the mapping described above.

Now total emissions from all units are:

$$totalemissions(t,j) = \sum_i emissions(t,i,j). \tag{B.5.6}$$

where

totalemissions(t,,j) are total emissions (tons of pollutant per ton of clinker) of pollutant *j* resulting from production activity in the entire sector.

Note that production associated with each pollutant is the same and therefore:

$$prodnpol(t,i,f,m,j) = prodnpol(t,i,f,m,jj); \quad j \neq jj; \tag{B.5.7}$$

with

$$prodnpol(t,i,f,m,j) = \sum_{poltikjee(t,i,k,j,ee)} varprodn(t,i,f,m,j,k,ee). \tag{B.5.8}$$

where

prodnpol(t,i,f,m,j,) production variable associated with pollutant **j**.

B.6 Controls and Costs

The U-ISIS framework includes constraints to ensure that endogenous applications of sector-based controls and energy efficiency options occur in a realistic manner. A description of these constraints and costs for controls is presented in this section. The treatment of energy efficiency measures is described in a subsequent section.

Controls Related Constraints

Only one vintage of a control on a unit is possible for the period starting when the vintage comes on line and ending with its technical life. After the technical life of the vintage, it cannot be used.

$$\sum_{t,v} ts\_c(poltik(t,i,k),v) \leq \mathbf{1};$$

$$\mathbf{vyear(v) \leq tyear(t) < [(vyear(v) + techlifecontrols(k)].} \tag{B.6.1}$$

where

v is the set of vintages of a control for unit **i**,
vyear(v) and **tyear(t)** are parameters with values corresponding to years in the selected time horizon,
ts_c(t,i,k,v) is a binary variable that can bring **vth** vintage of control **k** for unit **i** online in year **t,** and
techlifecontrols(k) is the technical life of control **k.**

Control capacity is given by the following equations.

For **t** = 1,

$$ControlCap(t,i,k) = \sum_{v} ts\_c(t,i,k,v) \cdot \mathbf{capacity(t,i)}; \quad \text{(B.6.2a)}$$
$$\mathbf{vyear(v)} \le \mathbf{tyear(t)} < (\mathbf{vyear(v)} + \mathbf{techlifecontrols(k)}).$$

For **t** > 1,

$$ControlCap(t,i,k) = ControlCap(t - timeblock,i,k) + \sum_{v} ts\_c(t,i,k,v) \cdot \mathbf{capacity(t,i)}; \quad \text{(B.6.2b)}$$
$$\mathbf{vyear(v)} \le \mathbf{tyear(t)} < (\mathbf{vyear(v)} + \mathbf{techlifecontrols(k)}).$$

In any year, no two incompatible controls can coexist on a unit,

$$ControlCap(t,i,k) + ControlCap(t,i,kk) \le \mathbf{capacity(t,i)} \quad \text{(B.6.2c)}$$

where

k and **kk** are incompatible controls.

Finally, the production coefficient associated with a control is less than the capacity of the unit the control is installed on,

$$\frac{\sum_{f,m,poltikjee(t,i,k,j,ee)} varprodn(t,i,f,m,j,k,ee)}{\text{Number of pollutants}} \le \sum_{v} ts\_c(t,i,k,v) \cdot \mathbf{capacity(t,i)};$$
$$\mathbf{vyear(v)} \le \mathbf{tyear(t)} \quad \text{(B.6.3)}$$

where

capacity(t,i) is the capacity of unit **i** in year **t**.

In general, the costs associated with controls comprise the following components: (1) capital and fixed operation and maintenance costs, (2) costs associated with any reagent and/or catalyst consumption, (3) costs associated with any reduction in fuel and/or raw material use, (4) cost associated with electricity consumption, (5) cost associated with byproduct(s), and (6) costs associated with water use. The calculations of these costs are described below. Note that various cost elements (e.g., capital cost of a control [$/ton clinker] for the cement sector) are escalated appropriately to use values in years of interest.

Capital Recovery and Fixed Cost

Annual recovery of capital cost of control *k* is given by:

$$\begin{aligned} &\mathit{capcost\_c(poltik(t,i,k))} = \\ &\qquad \mathit{ControlCap(t,i,k)} \cdot \mathbf{cntrlcapitalcostt(t,i,k)} \cdot \mathbf{CRFcontrol(k)}; \\ &\mathbf{CRFcontrol(k)} \cdot \sum \left[\mathbf{vyear(v)} \le \mathbf{tyear(t)} < [\mathbf{vyear(v)} + \mathbf{ecolifecontrols(k)}].\right] \end{aligned} \qquad (B.6.4)$$

Similarly, annual FOM cost is given by:

$$\begin{aligned} &\mathit{FOMcost\_c(poltik(t,i,k))} = \mathit{ControlCap(t,i,k)} \cdot \mathbf{cntrlfixedcostt(t,i,k)}; \\ &\sum \begin{bmatrix} \mathbf{vyear(v)} \le \mathbf{tyear(t)} < [\mathbf{vyear(v)} + \mathbf{techlifecontrols(k)}], \mathrm{vcntrlfixedcostt(v,i,k)} \cdot \\ \mathrm{ts\_c(t,i,k,v)} \cdot \sum \mathit{capacity}(t,i) \end{bmatrix}. \end{aligned} \qquad (B.6.5)$$

where

cntrlcapitalcostt(t,i,k) is the capital cost ($/ton of clinker) of application of control **k** on **ith** unit,
cntrlfixedcostt(t,i,k) is the annual fixed operation and maintenance (FOM) cost ($/ton of clinker) of application of control **k** on **ith** unit,
capcost_c(t,i,k) is the annualized capital cost ($) of **kth** control application on **ith** unit,
FOMcost_c(t,i,k) is the annual fixed operation and maintenance cost ($) of **kth** control application on **ith** unit, and
CRFcontrol(k) is the capital recovery factor calculated using an appropriate interest rate and time period, **ecolifecontrols(k)**, for capital recovery.

Variable Costs

Change in fuel cost associated with application of controls is given by:

$$\begin{aligned} &\mathit{fuelcostchange\_c(poltirk(t,ri(i,r),k))} = \\ &\frac{\begin{aligned}&[\mathbf{primaryHIchange(i,k)} \cdot \sum_{fi(i,f),m,poltikjee(t,i,k,j,ee)} \mathit{varprodn(t,i,f,m,j,k,ee)} \cdot \mathbf{fuelcostt(t,r,f)} \\ &+ \mathbf{secondaryHIchange(i,k)} \cdot \sum_{kf(k,f),m,poltikjee(t,i,k,j,ee)} \mathit{varprodn(t,i,f,m,j,k,ee)} \cdot \mathbf{fuelcostt(t,r,f)}]\end{aligned}}{\mathbf{Number\ of\ pollutants}}. \end{aligned} \qquad (B.6.6)$$

where

primaryHIchange(i,k) is the primary heat input change (MMBtu per ton clinker) with use of **kth** technology,
secondaryHIchange(i,k) is the primary heat input change (MMBtu per ton clinker) with use of **kth** technology,
fuelcostt(t,r,f) is the regional cost of fuel ($/MMBtu) in year t,

ri(i,r) is a set with elements corresponding to mapping between kiln and their geographic locations,
kf(k,f) is a set with elements corresponding to mapping between fuels and technologies, and
poltirk(t, ri(i,r),k) is a mapping described above.

Change in raw material cost associated with application of controls is given by:

$$\begin{aligned}&\mathit{RMTcostchange\_c(poltirk(t,ri(i,r),k))} = \\ &\frac{\begin{aligned}&[\mathbf{primaryRMTchangepercent}/100 \cdot \sum_{fi(i,f),m,poltikjee(t,i,k,j,ee)} \mathit{varprodn(t,i,f,m,j,k,ee)} \cdot \mathbf{RMTt(t,i)} \\ &+ \mathbf{secondaryRMTchangepercent}/100 \cdot \sum_{fi(i,f),m,poltikjee(t,i,k,j,ee)} \mathit{varprodn(t,i,f,m,j,k,ee)} \cdot \mathbf{RMTt(t,i)}]\end{aligned}}{\textbf{Number of pollutants}}.\end{aligned} \qquad \text{(B.6.7)}$$

where

primaryRMTchangepercent is the percent change in primary raw material with use of **kth** technology,
secondaryRMTchange(i,k) is the percent change raw material input corresponding to any secondary raw material addition with use of **kth** technology, and
RMTt(t,i) is the unit-specific cost of raw material ($/ton clinker) in year t.

Annual reagent consumption costs are:

$$\begin{aligned}&\mathit{rgntconsumptcost\_c}(\mathit{poltik}(t,i,k)) = \\ &\sum_{rgnt} \mathit{rgntconsumpt\_c}(t,i,k,rgnt) \cdot \mathbf{reagentpricet(t,rgnt).}\end{aligned} \qquad \text{(B.6.8)}$$

The annual consumption of a reagent given by:

$$\begin{aligned}&\mathit{rgntconsumpt\_c(poltik}(t,i,k)\mathit{,rgnt)} = \\ &\frac{\sum_{fi(i,f),j} [\mathbf{reagentconsumptfuel(i, f, k, j, rgnt)} \cdot \sum_{m,poltikjee(t,i,k,j,ee)} \mathit{varprodn(t,i,f,m,j,k,ee)}]}{\textbf{Number of pollutants}} \\ &+ \\ &\frac{\sum_{m,j} [\mathbf{reagentconsumptrmt(i, m, k, j, rgnt)} \cdot \sum_{fi(i,f),poltikjee(t,i,k,j,ee)} \mathit{varprodn(t,i,f,m,j,k,ee)}]}{\textbf{Number of pollutants}}.\end{aligned} \qquad \text{(B.6.9)}$$

where

reagentconsumptfuel(i,f,k,j,rgnt) is the reagent consumption due to control (tons reagent/tons clinker) associated with fuel-based emission intensity,

reagentconsumptrmt(i,m,k,j,rgnt) is the reagent consumption due to control (tons reagent/tons clinker) associated with raw material-based emission intensity,
reagentpricet(t,rgnt) is the price of reagent **rgnt** ($/ton of reagent) in year **t**, and
rgntconsumpt_c(t,i,k,rgnt) is the annual reagent consumption due to control (tons reagent/year), and
Rgntconsumptcost_c(t,i,k) is the annual reagent consumption cost ($/year) due to control **k** at unit **i** in year **t**.

Catalyst consumption cost is:

$$catconsumptcost\_c(poltik(t,i,k)) = \sum_{cat} catconsumpt\_c(t,i,k,cat) \cdot \mathbf{catalystpricet(t,cat)}; \qquad \text{(B.6.10)}$$

with

$$catconsumpt\_c(poltik(t,i,k),cat) = \frac{\displaystyle\sum_{j} \frac{\mathbf{catalystconsumpt(i,\ k,j,\ cat)}}{10000} \cdot \mathbf{EGFW(i)} \cdot \sum_{fi(i,f),m,poltikjee(t,i,k,j,ee)} varprodn(t,i,f,m,j,k,ee)}{\mathbf{Number\ of\ pollutants}}. \qquad \text{(B.6.11)}$$

where

catalystconsumpt(i,k,j,cat) is the catalyst consumption rate (ft^3 catalyst/10000 ft^3 flue gas),
EGFW(i) is the exhaust gas flow rate (scf/ton clinker),
catalystpricet(t,cat) is the price of the catalyst ($/ft^3) in year **t**,
catconsumpt_c(t,i,k,cat) is the catalyst consumption rate (ft^3/year), and
catconsumptcost_c(t,i,k) is the catalyst cost ($/year).

Annual cash flow associated with byproduct generation disposal/sale is:

$$byproductcost\_c(poltik(t,i,k)) = \sum_{byprod} byproductgen\_c(t,i,k,byprod) \cdot \mathbf{byproductpricet(t,byprod)}; \qquad \text{(B.6.12)}$$

with annual generation of a byproduct given by:

$$byproductgen\_c(poltik(t,i,k),byprod) =$$

$$\frac{\sum_{fi(i,f),j} [\mathbf{byproductprodnfuel(i,f,k,j,byprod)} \cdot \sum_{m,poltikjee(t,i,k,j,ee)} varprodn(t,i,f,m,j,k,ee)]}{\textbf{Number of pollutants}}$$

$$+$$

$$\frac{\sum_{m,j} [\mathbf{byproductprodnrmt(i,\ m,k,j,byprod)} \cdot \sum_{fi(i,f),poltikjee(t,i,k,j,ee)} varprodn(t,i,f,m,j,k,ee)]}{\textbf{Number of pollutants}}. \quad (B.6.13)$$

where

byproductprodnfuel(i,f,k,j,byprod) is the byproduct generation due to control (tons reagent/tons clinker) associated with fuel-based emission intensity,
byproductprodnrmt(i,m,k,j,byprod) is the byproduct generation due to control (tons reagent/tons clinker) associated with raw material-based emission intensity,
byproductpricet(t, byprod) is the price of disposing or selling the byproduct **byprod** ($/ton of reagent) in year **t**,
byproductgen_c(t,i,k,byprod) is the annual byproduct generation due to control (tons reagent/year), and
byproductcost_c(t,i,k) is the annual cash flow associated with byproduct generation/sale due to control **k** at unit **i** in year **t**.

Note that **byproductpricet** value can be positive (disposal cost) or negative (sale price).

Annual electricity consumption (kWh/yr) due to control is:

$$kwh\_c(poltik(t,i,k)) = \frac{\sum_{fi(i,f)} [\mathrm{kWhperton(i,f,k)} \cdot \sum_{m,poltikjee(t,i,k,j,ee)} varprodn(t,i,f,m,j,k,ee)]}{\text{Number of pollutants}}. \quad (B.6.14)$$

The cost of electricity consumption is:

$$kwhcost\_c(poltik(t,i,k)) = kwh\_c(t,i,k) \cdot \mathbf{electricitycostt(t,i).} \quad (B.6.15)$$

where

kwh_c(t,i,k) is the annual electricity consumption (kWh/year) due to control **k** at unit **i** in year **t**,
kwhcost_c(t,i,k) is the annual electricity consumption cost ($) due to control **k** at unit **i** in year **t**,
KWhperton(i,f,k) is the electrical requirement (kWh per ton of clinker) for technology **k**, and
electricitycostt(t,r) is the electricity price ($/kWh) in year **t** at unit **i.**

Annual water consumption associated with control *k* is:

$$
\begin{aligned}
&H2Oconsumpt\_c(poltik(t,i,k)) = \\
&\frac{\sum_{fi(i,f),j}[\mathbf{H2Ousefuel(i,f,k)} \cdot \sum_{m,poltikjee(t,i,k,j,ee)} varprodn(t,i,f,m,j,k,ee)]}{\textbf{Number of pollutants}} \\
&+ \\
&\frac{\sum_{m,j}[\mathbf{H2Ousermt(i,m,k)} \cdot \sum_{fi(i,f),poltikjee(t,i,k,j,ee)} varprodn(t,i,f,m,j,k,ee)]}{\textbf{Number of pollutants}}.
\end{aligned}
\qquad \text{(B.6.16)}
$$

The cost of water consumption is:

$$
H2Ocost\_c(poltik(t,i,k)) = H2Oconsumpt\_c(t,i,k) \cdot \mathbf{H2Ocostt(t)} / 1000 . \qquad \text{(B.6.17)}
$$

where

H2Ousefuel(i,f,k) is the water use due to control (tons reagent/tons clinker) associated with fuel-based emission intensity,
H2Ousermt(i,m,k) is the water use due to control (tons reagent/tons clinker) associated with raw material-based emission intensity,
H2Ocostt(t) is the price of water ($/1000 gallons) in year **t**,
H2Oconsumpt_c(t,i,k) is the annual water use due to control (gallons/year), and
H2Ocost_c(t,i,k) is the annual cost of water consumption ($) due to control at unit **i** in year **t**.

Total Annual Cost

Using the above costs, the total annual cost of controls is:

$$
\begin{aligned}
&tcontrolcost(t,i,k) = capcost\_c(t,i,k) + FOMcost\_c(t,i,k) \\
&+ fuelcostchange\_c(t,i,k) + RMTcostchange\_c(t,i,k) \\
&+ rgntconsumptcost\_c(t,i,k) + catconsumptcost\_c(t,i,k) + byproductcost\_c(t,i,k) \\
&+ kWhcost\_c(t,i,k) + H2Ocost\_c(t,i,k)
\end{aligned}
\qquad \text{(B.6.18)}
$$

B.7 Costs of Energy Efficiency Measures

As described below, the treatment of energy efficiency measures in U-ISIS is similar to that for control.

Energy Efficiency Measures Related Constraints

As for controls, constraints are needed to ensure realistic applications of energy efficiency measures. These constraints are described below.

Only one vintage of an energy efficiency measure on a unit is possible for the period starting when the vintage comes on line and ending with its technical life.

$$\sum_{t,v} ts\_ee(poltiee(t,i,ee),v) \;\leq\; 1;$$
$$\mathbf{vyear(v) \leq tyear(t) < [(vyear(v) + etechlife(ee)]}. \tag{B.7.1}$$

where

v is the set of vintages of measure **ee**,
poltiee(tpolc(t) is the mapping described before,
vyear(v) and **tyear(t)** are parameters with values corresponding to years in the selected time horizon,
ts_ee(t,i,ee,v) is a binary variable that can bring **vth** vintage of measure **ee** online on unit **i** in year **t,** and
etechlife (ee) is the technical life of measure **ee.**

Energy efficiency measure capacity is given by the following equations.

For **t** = 1,

$$EECap(t,i,ee) = \sum_{v} ts\_ee(poltiee(t,i,ee),v) \cdot \mathbf{capacity(t,i)};$$
$$\mathbf{vyear(v) \leq tyear(t) < (vyear(v) + eetechlife(ee))}. \tag{B.7.2a}$$

For **t** > 1,

$$EECap(t,i,ee) = EECap(t - timeblock,i,ee) + \sum_{v} ts\_ee(poltiee(t,i,ee),v) \cdot \mathbf{capacity(t,i)};$$
$$\mathbf{vyear(v) \leq tyear(t) < (vyear(v) + eetechlife(ee))}. \tag{B.7.2b}$$

In any year, no two incompatible measures can coexist on a unit,

$$\sum_{v} \left[ts\_ee(poltiee(t,i,ee),v) \;+ ts\_ee(poltiee(t,i,eee),v) \right] \leq \;\mathbf{1}; \tag{B.7.2c}$$

where

ee and **eee** are incompatible measures.
Finally, production coefficient associated with an energy efficiency measure is less than the capacity of the unit the measure is installed on,

$$\frac{\sum_{f,m,poltikjee(t,i,k,j,ee)} varprodn(t,i,f,m,j,k,ee)}{\text{Number of pollutants}} \leq \sum_{v} ts\_ee(t,i,ee,v) \cdot \mathbf{capacity(t,i)};$$
$$\mathbf{vyear(v) \leq tyear(t)} \tag{B.7.3}$$

where

capacity(t,i) is the capacity of unit **i** in year **t.**

Capital Recovery and Fixed Cost

For an energy efficiency measure **ee**, annual recovery of capital and annual FOM cost are given by Equations B.7.4 and B.7.5, respectively.

$$\begin{aligned} & capcost\_ee(poltiee(t,i,ee)) = \\ & EECap(t,i,ee) \cdot \mathbf{ecapitalcostt(t,i,ee)} \cdot \mathbf{CRFEE(ee)}; \\ & \mathbf{vyear(v)} \leq \mathbf{tyear(t)} < [\mathbf{vyear(v)} + \mathbf{ecolifeee(ee)}]. \end{aligned} \qquad (B.7.4)$$

$$\begin{aligned} & FOMcost\_ee(poltiee(t,i,ee)) = \\ & EECap(t,i,ee) \cdot \mathbf{efixedcostt(t,i,ee)}; \\ & \mathbf{vyear(v)} \leq \mathbf{tyear(t)} < [\mathbf{vyear(v)} + \mathbf{eetechlife(ee)}]. \end{aligned} \qquad (B.7.5)$$

where

ecapitalcostt(t,i,ee) is the capital cost ($/ton of clinker) of **eeth** energy efficiency measure application on **ith** unit,
efixedcostt(t,i,ee) is the annual fixed operation and maintenance (FOM) cost ($/ton of clinker) of **eeth** energy efficiency measure application on **ith** unit,
ts_ee(t,i,ee,v) is a binary variable that can bring **vth** vintage of measure **ee** online on unit **i** in year **t**,
capcost_ee(t,i,ee) is the annualized capital cost ($) of **ee** application on **ith** unit, and
FOMcost_ee(t,i,ee) is the annual fixed operation and maintenance cost ($) of **ee** application on **ith** unit, and
CRFEE(ee) is the capital recovery factor calculated using an appropriate interest rate and time period, **ecolifeee(ee)**, for capital recovery.

Variable Costs

Change in fuel cost associated with application of **ee** measures is given by:

$$fuelcostchange\_ee(poltiree(t,ri(i,r),ee)) = \frac{\mathbf{eHIdispi(i,ee)} \cdot \sum_{f,m,poltikjee(t,i,k,j,ee)} varprodn(t,i,f,m,j,k,ee) \cdot \mathbf{fuelcostt(t,r,f)}}{\mathbf{Number\ of\ pollutants}} \qquad (B.7.6)$$

where

eHIdispi(i,ee) is the displacement of primary heat input (MMBtu per ton clinker) with use of **eeth** energy efficiency measure,
fuelcostt(t,r,f) is the regional cost of fuel ($/MMBtu) in year t,
ri(i,r) is a set with elements corresponding to mapping between kiln and their geographic locations, and
poltiree(t, ri(i,r),ee) is a mapping described above.

Annual electricity consumption (kWh/yr) due to an energy efficiency measure is:

$$kwh\_ee(poltiee(t,i,ee)) = \frac{e\mathbf{kWhperton(i,ee)} \cdot \sum_{f,m,poltikjee(t,i,k,j,ee)} varprodn(t,i,f,m,j,k,ee)}{\textbf{Number of pollutants}} \tag{B.7.7}$$

The cost of electricity consumption is:

$$kwhcost\_ee(poltiee(t,i,ee)) = kwh\_ee(t,i,ee) \cdot \mathbf{electricitycostt(t,i)} \tag{B.7.8}$$

where

eKWhperton(i,f,ee) is the electrical requirement (kWh per ton of clinker) for ee, and **electricitycostt(t,i)** is the electricity price ($/kWh) in year **t** at unit **i.**

Total Annual Cost

Using the above costs, the total annual cost of energy efficiency measures is:

$$\begin{aligned} &teemeasurescost(t,i,ee) = \\ &capcost\_ee(t,i,ee) + FOMcost\_ee(t,i,ee) + \\ &fuelcostchange\_ee(t,i,ee) + kWhcost\_ee(t,i,ee) \end{aligned} \tag{B.7.9}$$

B.8 Policy Options

U-ISIS can help design and evaluate a number of emissions reduction policy options including cap-and-trade, emissions taxes, and emissions limits. Additionally, appropriate combinations of these options can also be evaluated. The policy options included in U-ISIS are described below.

Cap-and-Trade

Under this option, an emissions cap is set on the amount of a pollutant that can be emitted. Sources, companies, or other groups are issued emission permits (allowances) which represent the right to emit a specific amount of the pollutant. Allowances may be banked for use in the future. The total amount of allowances available in the current period and those banked in previous periods cannot exceed the cap in the current period. Sources or companies that need to increase their emissions must buy allowances from those who pollute less. The transfer of allowances is referred to as a trade. In effect, the buyer is paying a charge for polluting, while the seller is being rewarded for having reduced emissions by more than was needed. Thus, in theory, those that can easily reduce emissions most cheaply will do so, achieving the pollution reduction at the lowest possible cost to society.

Generally, annual caps have been utilized in ongoing programs (e.g., Title IV SO_2 reduction program). However, U-ISIS does permit evaluation of potential programs with caps over user-selected time periods (e.g., 5-yearly caps). This evaluation is accomplished using,

$$totalemissions(t,j) \quad \leq \quad \mathbf{ecap(t,j)} + bnk(t,j) - bnk(t+period,j) \tag{B.8.1}$$

where

ecap(t,j) is the emission cap for pollutant *j* in year *t*, and
bnk(t+period, j) are the allowances of the pollutant **j** banked in year **t** for the year **t + period**.

Cap-and-Trade with a Minimum Reduction Requirement

While designing a cap-and-trade program, there may be an interest in requiring a minimum level of emission reduction from each affected entity. Such a requirement may be able to help address any local emissions-related concerns. In U-ISIS, this requirement can be imposed using:

$$\mathbf{emissions(t,i,j)} \quad \leq \quad \mathbf{ecpminer(t,i,j)} \tag{B.8.2}$$

where

ecpminer(t,i,j) is the unit-specific minimum emission reduction requirement for pollutant **j** in year **t**.

Emissions Limits

U-ISIS permits evaluation of the costs and emissions reductions associated with more traditional emission reduction programs utilizing unit-specific rate-based emission limits. Such requirements are imposed using

$$emissions(t,i,j) \quad \leq \quad \mathbf{el(t,i,j)} \cdot prodn(t,i) \tag{B.8.3}$$

where

el(t,i,j) is the rate-based emission limit for pollutant **j** in year **t** and every affected unit **i** complies with this limit.

Allowance Price Inputs

In some cases, there may be an interest in endogenously determining the level of emission reduction corresponding to a certain allowance price. This information may be useful, for example, in a situation where an allowance price is set for reducing emissions from many industrial sectors. In such a case the levels of emission reductions corresponding to the same allowance price may be different for the sectors under consideration. The emissions response to a given allowance price is driven by the following term in the objective function (see section B.1),

$$\sum_{t,j} \mathbf{dis(t)} \cdot \mathbf{alprice(t,j)} \cdot totalemissions(t,j) \tag{B.8.4}$$

where

alprice(t,j) is the exogenous allowance price of pollutant **j** in year **t**.

Note that the allowance price inputs scheme above is equivalent to emission-tax-based programs in which affected units or companies pay a tax for every unit of pollution they produce. Thus this scheme can also be used to evaluate such programs.

B.9 Optimization and Post-Processing

In U-ISIS, the input data are pre-processed to arrive at suitable input parameters for use in the model equations explained in this chapter. Once the data have been pre-processed, U-ISIS solves for the appropriate levels of production, imports and controls required to meet the constraints associated with commodity demand and emissions, while maximizing total surplus. Once the surplus maximization problem has been solved, the results are post-processed to obtain parameters and level values of the variables of interest. The key variables of interest are: production level of each production unit to meet regional demand, level of imports in each region, installation of various controls, emissions, and various costs. Output data are written in appropriate worksheets in an Excel workbook and further linked to various plots to enable visual presentation and analyses of the results.

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