ELECTRIC POWER RESEARCH INSTITUTE

Quantifying the Benefits of Using Coal Combustion Products in Sustainable Construction

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REPORT SUMMARY

Electric utilities produce more than 130 million tons (118 million metric tons) of coal combustion products (CCPs) annually. Approximately 50 million tons (45 million metric tons) are used in a wide variety of applications. This report examines the environmental and cost benefits associated with the most common uses of CCPs in construction activities—replacement of portland cement in concrete, replacement of gypsum in wallboard, and replacement or improvement of soil in geotechnical applications.

Background

Use of coal as an energy source has steadily increased over the last 30 years, and coal will continue to be an important fuel for the foreseeable future. As a result of increased coal use and new air emissions controls, the production of coal combustion products is also steadily increasing. In 2007, 131.1 million tons (119 million metric tons) of CCPs were produced in the United States. The fraction of CCPs used beneficially is also increasing, due to the desirable attributes of CCPs as construction materials and increased interest in sustainable construction and development. Use of CCPs in lieu of other construction materials yields savings in energy and water use and reductions in greenhouse gas emissions. These savings are accrued because CCPs are used essentially “as is:” no mining, processing, or transformation is required, thereby eliminating emissions and resource consumption associated with conventional construction materials and processes.

Objectives

To quantify the environmental benefits of using CCPs in place of other raw materials such as portland cement, gypsum, and granular fill in construction applications

Approach

The project team used life-cycle analysis programs to quantify the benefits of using CCPs from electric power production in sustainable construction. The analysis focused on the most ubiquitous CCPs (fly ash, bottom ash, and flue gas desulfurization gypsum) and their most common applications (concrete production, wallboard manufacturing, and geotechnical applications) as identified through an analysis of industry CCP use data for 2007. The team made comparisons between the energy consumption, water use, and greenhouse gas (GHG) emissions associated with conventional materials and procedures and those associated with employing CCPs. They also quantified cost savings. Life-cycle analysis results are presented on a unit basis (savings per ton of CCP used) for each material and application. Accrued annual savings from using CCPs in construction applications were determined by multiplying modeled unit savings by industry CCP consumption volumes by application for 2007.

Results

Based on 2007 data, CCP use reduces energy consumption by 63 trillion Btu, water consumption by 5.9 billion gallons (22.3 billion liters), and GHG emissions by 10 million tons (9 million metric tons) CO_2 equivalents (CO_2e). Cost savings range from $2.4 to $7.8 billion.

The greatest environmental benefits in sustainable construction are currently being realized by using CCPs (mainly fly ash) in concrete production. Use of fly ash as a cement substitute saved more than 55 trillion Btu of energy and reduced GHG emissions by 9.6 million tons (8.7 million metric tons) CO_2e in 2007. Using CCPs for geotechnical applications also resulted in significant energy savings (4.3 trillion Btu) and modest reductions in water consumption (0.17 million gallons [0.64 million liters]) and GHG emissions (0.3 million tons [0.27 metric tons] CO_2e). Smaller savings in energy consumption (0.3 trillion Btu) and GHG emissions (0.03 million tons [0.027 million metric tons] CO_2e) are achieved using FGD gypsum in wallboard manufacturing at current FGD usage rates. Avoided CCP disposal resulted in savings of 3.7 trillion Btu of energy and a reduction of CO_2e emissions by 0.3 million tons (0.27 million metric tons) in 2007.

EPRI Perspective

Use of CCPs in construction activities steadily increased from 1940 through 2007, with total use exceeding 40% of the CCPs produced in 2007. This trend yields significant environmental benefits associated with both decreased disposal requirements and decreased need for mining and processing of other raw materials. As illustrated by the environmental and cost savings quantified in this report, CCP use is an important consideration as the United States and other countries move toward more sustainable construction practices. EPRI supports a broad range of research on engineering and environmental aspects of various CCP applications.

Keywords

Coal combustion products
Beneficial use
Sustainable construction
Greenhouse gas

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

The United States Energy Information Administration (EIA) reported that coal combustion generated 33% of the total Btu energy produced in the United States in 2007. Moreover, coal combustion contributed to 50% of the electrical power generating capacity of the nation (EIA 2009a,b). Use of coal as an energy source has steadily increased over the last 30 years, and coal will continue to be an important fuel for the foreseeable future. As a result of increased coal use and new air emissions controls, the production of coal combustion products (CCPs) is also steadily increasing (Figure 1-1). In 2007, 131.1 million tons of CCPs were produced in the United States (ACAA 2008). Fly ash (71.7 million tons), bottom ash (18.1 million tons), and gypsum from flue gas desulfurization (FGD) operations (12.3 million tons) constituted the majority (78%) of the CCPs produced in 2007. Beneficial use in construction and other applications consumed 47% (48.2 million tons) of the fly ash, bottom ash, and FGD gypsum that was produced in 2007. The remaining 53% (53.9 million tons) was disposed of or stored in impoundments or landfills.

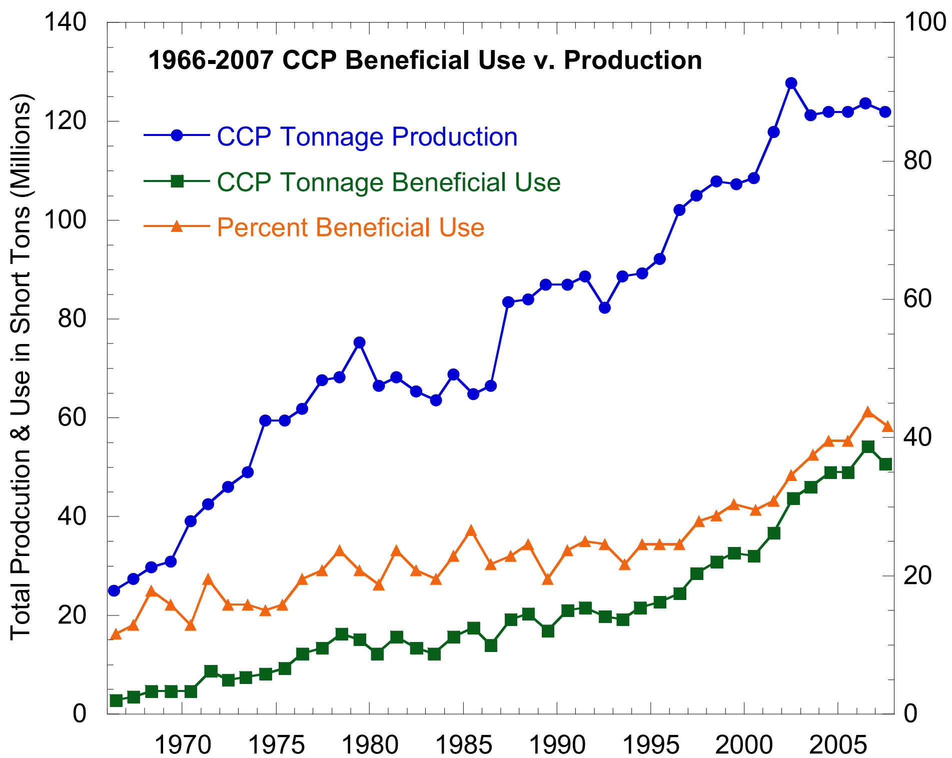

Figure 1-1
Historical production and use of CCPs (adapted from ACAA 2009).

Fly ash is a fine powdery material collected from the exhaust of a coal combustion chamber; it is pozzolanic and can be cementitious. The majority of fly ash use is associated with cement and concrete (55% of total used in 2007), with partial replacement of portland cement in concrete being the most common use (43% of total fly ash used) (ACAA 2008). Geotechnical applications, which include roadway base and subbases, subgrade stabilization, and embankments and structural fills, are also significant uses of fly ash (28% of total fly ash used in 2007) (ACAA 2008).

Bottom ash is a coarse granular residue (gravel-size and/or sand-size particles) from coal combustion; it has a chemical composition similar to that of fly ash (EPA 2008, FHWA 2008). Because the particles are larger, bottom ash is used as substitute for conventional aggregates such as sands and gravels, primarily in geotechnical applications (55% of total bottom ash used in 2007) (ACAA 2008).

FGD gypsum is a by-product of flue gas desulfurization at coal-fired power plants that use wet scrubbers and forced oxidation to reduce SO_2 emissions. The gypsum produced by the desulfurization process is mineralogically identical to natural gypsum ($CaSO_4 \bullet 2H_2O$), making FGD gypsum an ideal replacement for mined gypsum used to manufacture wallboard. In 2007, 75% of FGD gypsum produced was used beneficially, 90% of which was used to produce wallboard. Other significant uses of FGD gypsum include agriculture and cement/concrete production (ACAA 2008).

Use of CCPs in construction materials has been steadily increasing (Figure 1-1), and in some applications (such as wallboard and portland cement concrete) CCPs are now considered as standard or required materials in manufacturing and construction. The fraction of CCPs used beneficially is increasing (Figure 1-1) due to the desirable attributes of CCPs as construction materials and increased interest in sustainable construction and development. For example, production of portland cement accounts for 5 to 8% of annual CO_2 emissions worldwide (Anderson 2008, Reiner and Rens 2006). Replacing a portion of the portland cement with fly ash reduces the CO_2 emissions associated with production of portland cement proportionally. Energy and water use associated with cement production are also reduced. These savings are accrued because the fly ash is used essentially "as is"; no processing or transformation is required, thereby eliminating emissions and resource consumption associated with creating a construction material.

Although the contribution of CCPs in construction to sustainability is logical, a quantitative assessment of beneficial use of CCPs has not been conducted (past studies focused on one material, such as concrete or wallboard). The study described in this report was conducted to quantify the environmental and economic benefits of using CCPs in each of the major construction applications. The focus was on fly ash, bottom ash, and FGD gypsum because of the preponderance of these CCPs relative to other by-products of coal combustion. The primary uses of fly ash, bottom ash, and FGD gypsum (2007 data) are summarized in Table 1-1 and are shown graphically in Figure 1-2. Geotechnical applications are lumped together in Figure 1-2 and include uses of CCPs for structural fill and embankments and for road base/subbase soil modification and stabilization. Cement and concrete, geotechnical applications, and wallboard manufacturing consume 72% of the CCPs that are used beneficially. Consequently, this study focused on these three applications for each of the three CCPs considered. The analysis focused on the benefits of using CCPs in terms of reductions in greenhouse gas (GHG) emissions, reductions in consumption of energy and water, and economic savings. Avoidance of landfill disposal costs was also considered in the analysis.

Table 1-1
CCP production and use in 2007 (adapted from ACAA 2008).

Application	Fly Ash	Bottom Ash	FGD Gypsum
	(short tons)	**(short tons)**	**(short tons)**
1. Concrete, Concrete Products, Grout	13,704,744	665,756	118,406
2. Blended Cement, Raw Feed for Clinker	3,635,881	608,533	656,885
3. Flowable Fill	112,244	0	0
4. Structural Fills and Embankments	7,724,741	2,570,163	0
5. Road Base/Subbase Soil Modification and Stabilization	1,234,095	1,116,429	0
6. Mineral Filler in Asphalt	17,223	21,771	0
7. Snow and Ice Control	0	736,979	0
8. Blasting Grit and Roofing Granules	0	71,903	0
9. Mining Applications	1,306,044	165,183	0
10. Gypsum Panel Products (Wallboard)	0	0	8,254,849
11. Waste Stabilization and Solidification	2,680,348	7056	0
12. Agriculture	49,662	2546	115,304
13. Aggregate	135,331	806,645	70,947
14. Miscellaneous	1,025,724	530,574	11,880
Total CCPs Used	**31,626,037**	**7,303,538**	**9,228,271**
Total CCPs Produced	**71,700,000**	**18,100,000**	**12,300,000**

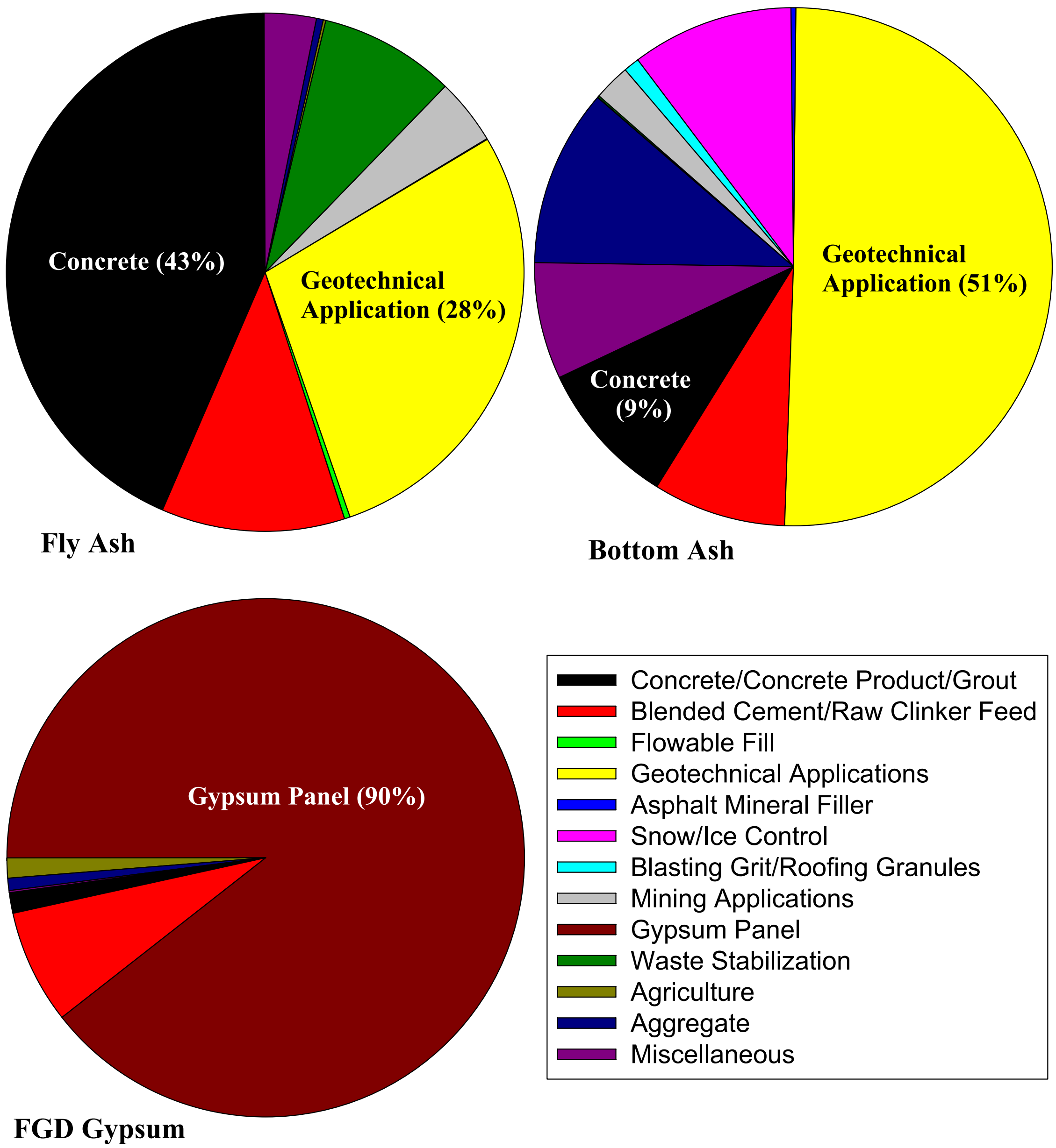

Figure 1-2
Uses of fly ash, bottom ash, and FGD gypsum by application (gypsum panel = wallboard).

2
LIFE CYCLE ANALYSIS MODELS

Environmental benefits of using CCPs in sustainable construction were estimated using life cycle analysis models. Economic benefits were calculated based on the monetary value of the environmental benefit. Unit benefits (for example, environmental benefits per ton of CCP used in the given application per year) were obtained from predictions made with BEES (NIST 2007), SimaPro (Pré Consultants 2009), and PaLATE (RMRC 2004) life cycle analysis programs. Predictions with BEES were made by EPA (2008). The BEES predictions were independently verified and updated as part of this study. Predictions using SimaPro and PaLATE were modeled as part of this study. Descriptions of each model are provided in the following sections.

BEES Model

The Building for Environmental and Economic Sustainability (BEES) model was developed by the National Institute of Standards and Technology (NIST 2007) for life cycle analysis of building construction. BEES 4.0 contains environmental data for over 230 products across a wide range of building elements including beams, columns, wall insulation, and ceiling finishes.

Environmental data for a variety of concrete products (such as concrete columns, walls, slab on grade, and beams) are included. The user can compare the environmental performance data of each of these products using different predetermined concrete mix-designs, some of which include fly ash. A summary of the databases used to compile the information used in BEES can be found in NIST (2007).

The BEES environmental performance data serve as quantitative estimation of the energy and resource flows into a product as well as releases to the environment from the product. Total output is summed across all stages of the product life cycle for a unit product (for example, one cubic yard of concrete). Manufacturer-specific unit environmental impact data for production of a product are obtained primarily using a unit process and facility-specific approach. Output from BEES includes energy use, water use, and atmospheric emissions.

SimaPro Model

SimaPro is a life cycle analysis program developed by Pré Consultants that can be used to conduct detailed analyses of complex products and processes (Pré Consultants 2009). SimaPro provides a high degree of flexibility because it contains data profiles representing production, transport, energy production, product use, and waste management processes for thousands of materials. SimaPro quantifies inflows and outflows of resources, products, emissions, and waste flows during product manufacturing. SimaPro integrates all inputs (resources) and outputs (emissions and waste) by tracing all the references established on process trees from one process stage to another. Output from SimaPro includes energy, fresh water use, and atmospheric emissions. Results are displayed as life cycle inventory flows (for example, pollutant emissions, energy use, and water use).

To use SimaPro, a process tree is constructed that describes all relevant processes in the life cycle. A network is created that identifies input and output processes and product stages are defined that describe the composition of the product, the use phase, and the disposal route. Each product stage refers to a process. Waste disposition at the end of life cycle is also defined. The computations made by SimaPro rely on information from the EcoInvent database (Pré Consultants 2009) and integrated Swiss databases (for example, ETH-ESU 96, BUWAL250).

PaLATE Model

The Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) is a life cycle assessment tool that contains environmental and engineering information and data to evaluate the use of conventional and recycled materials in construction and maintenance of pavements (Horvath 2004). The user defines the dimensions of each layer in the pavement, the distance between the project site and material sources, and the density of the construction materials. These yield types and volumes of construction materials, sources and hauling distances, a set of construction activities, and a set of prescribed maintenance activities. From this information, PaLATE calculates cumulative environmental effects such as energy and water consumption as well as atmospheric emissions.

Several different sources of information and analysis methods are used in PaLATE to characterize the environmental impact of road construction projects. For this study, the environmentally augmented economic input-output analysis (EIO-LCA), a Leontief general equilibrium model of the entire U.S. economy, was employed. The economy is divided into a square matrix of 480 commodity sectors. The economic model quantifies energy, material, and water use as well as emissions. Because EIO-LCA emission factors are available in metric tons per dollar of sector output, PaLATE uses average U.S. producer prices ($/metric ton, for example, from Means 2008) to calculate emissions per mass of material used. The databases used in PaLATE are described in Horvath (2004).

Methodology for Determining Benefits

The environmental and economic benefits of CCP use were quantified by computing differences in energy expenditure, water consumption, and GHG emissions between conventional materials and those produced with CCPs, as predicted by the life cycle analysis codes, BEES, SimaPro, and PaLATE. Three major applications were considered: concrete, wallboard, and geotechnical applications using fly ash and bottom ash. Unit impacts (environmental impacts per 1 ton of CCP used in manufacture per year) derived for concrete using BEES was developed from EPA (2008). Unit impacts resulting from wallboard production were modeled using SimaPro; unit impacts for geotechnical applications were modeled using PaLATE. Total annual benefits for all applications were obtained as the product of unit benefits for energy, water, or GHG emissions and the most recent annual beneficial use quantity (in tons) provided by ACAA (2008) (Table 1-1). Unit financial savings for energy and water were generated using financial data given by the National Propane Gas Association (NPGA 2006) and NUS Consulting (2006). The social carbon cost (SCC) was used to calculate the financial benefit of the reduction of greenhouse gases (CO_2 equivalents, CO_2e) from CCP use as a construction material. The SCC incorporates social benefits of CO_2 reduction into a cost benefit analysis of regulatory actions. The SCC was set at $5.20 or $68.00 per metric ton of carbon (2009 US dollars) to reflect low and high cost scenarios based on recommendations in US DOE (2010).

3
RESULTS

Fly Ash Use in Concrete

Unit benefits of using fly ash as a cement substitute in concrete were obtained from the life cycle analysis (LCA) modeling with BEES described in EPA (2008). The BEES functional unit was 1 cubic yard of structural concrete having a compressive strength of 4000 psi and a 75-yr lifespan. System boundaries for the analysis are shown in Figure 3-1. The BEES program incorporates round-trip transportation distances of raw materials from extraction sites (quarries, power plants, and so on) to ready-mix concrete plants using data provided by NIST (2007). The analysis assumed that 0.24 tons of cement was required to produce 1 ton of concrete (Lippiatt 2002). Conventional concrete was assumed to contain no CCPs. For concrete manufactured with CCPs, 15% of the portland cement was replaced by fly ash at a 1:1 (by weight) substitution ratio. Discussions with representatives in the ready-mix concrete industry indicated that this replacement rate is conservative (that is, higher rates are common in practice). The Federal Highway Administration (FHWA 2003) and the Portland Cement Association (PCA 2009) also suggest that 15-30% of the portland cement in concrete can be replaced by fly ash. Use of fly ash or other CCPs in production of portland cement was not incorporated into the analysis.

For concrete production, transport distances for portland cement and fly ash to the ready-mix plant were both assumed to be 60 mi. Therefore, no differential in benefits due to differences in raw material transport was considered. A sensitivity analysis was conducted to assess the significance of this assumption, as transport distances for fly ash tend to be less than those for portland cement (see Appendix A). Increasing the transport distance for portland cement to 100 mi while keeping fly ash transport distance fixed at 60 mi showed that the environmental benefits would increase by only about 4%, suggesting that differences in raw material transport distance can be considered negligible.

Unit benefits of replacing portland cement with 15% fly ash (benefit/ton of fly ash) for energy consumption, water consumption, GHG emissions, and their corresponding financial savings are shown in Table 3-1. Environmental benefits are primarily obtained by avoiding cement production.

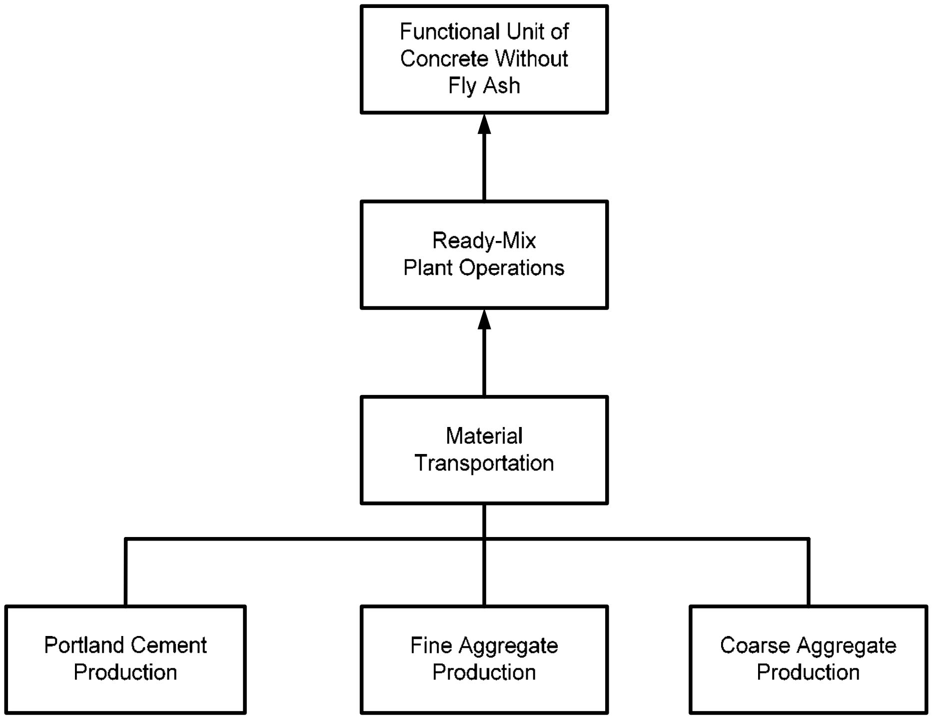

Figure 3-1
System boundary for 4000 psi concrete production without fly ash (adapted from EPA 2008). Replacement of cement by fly ash adds an additional branch in the tree parallel to the cement branch.

Table 3-1
Benefits obtained by replacing 15% of portland cement with fly ash (adapted from EPA 2008).

Benefit		Savings/ton fly ash
Energy	Savings (million Btu/ton fly ash)	4.0
	Financial Savings (US$/ton fly ash)	123.5
Water Use	Savings (gal/ton fly ash)	90.1
	Financial Savings (US$/ton fly ash)	0.23
GHG Emissions	CO_2e (ton/ton fly ash)	0.7
	Financial Savings (US$/ton fly ash)	3.29 ~ 43.00

FGD Gypsum in Wallboard Manufacturing

Unit benefits of using FGD gypsum as a substitute for conventional gypsum in wallboard manufacturing were obtained with SimaPro using the EcoInvent and US LCI (NREL 2000) databases as inputs, the cumulative energy demand (CED) (version 1.07) assessment method for energy consumption, and the BEES (version 4.02) assessment method for water consumption and GHG emissions. The analysis considered wallboard manufactured with 100% natural gypsum or 100% FGD gypsum.

The system boundary for production of stucco (moist gypsum to create wallboard sheet) is shown in Figure 3-2 for virgin and FGD gypsum. Discussions with industry representatives indicated that the resources associated with predrying FGD gypsum at the wallboard plant are comparable to or lower than those associated with milling and predrying virgin gypsum. Therefore, the resources associated with processing virgin and FGD gypsum at the wallboard plant were conservatively assumed to be equal. Consequently, gypsum mining was the only factor contributing to environmental differences between wallboard manufacturing using virgin gypsum and FGD gypsum (Figure 3-2).

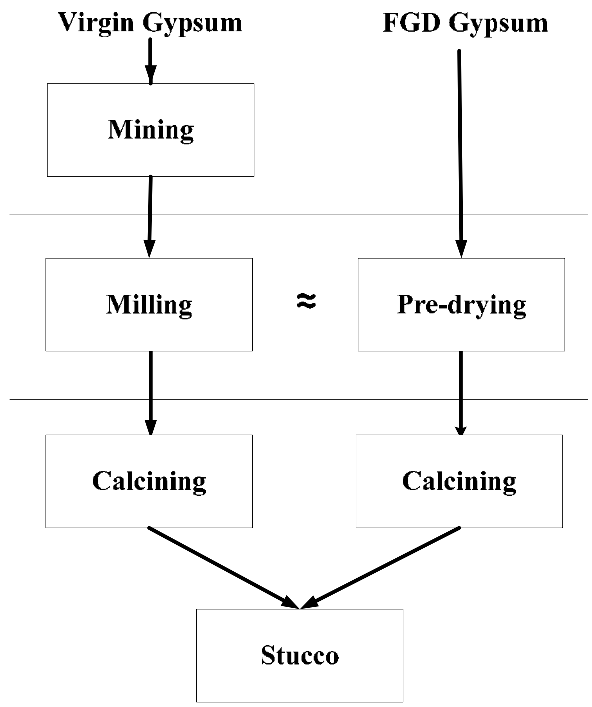

Figure 3-2
System boundary for stucco production during wallboard manufacturing using virgin gypsum or FGD gypsum.

The EcoInvent database employed by SimaPro uses a Swiss electricity mix. To make the analysis more representative of U.S. conditions, the database was modified using a U.S. electricity mix (NREL 2000). The modified network of gypsum mining can be found in Appendix B.

Transport of natural gypsum can require greater energy and result in increased greenhouse gas emissions compared to FGD gypsum, especially for wallboard manufacturing plants constructed adjacent to coal-fired power plants employing wet scrubbers for FGD. This benefit is difficult to quantify and was not included in the analysis (that is, transportation energies for virgin gypsum and FGD gypsum were assumed to be identical). This assumption resulted in additional conservatism in the analysis.

Unit benefits in terms of energy consumption, water consumption, and GHG emissions obtained by replacing natural gypsum with FGD gypsum in wallboard (benefits/ton) and the corresponding economic savings are shown in Table 3-2. These benefits are achieved by avoiding the water use, energy consumption, and emissions associated with mining virgin gypsum.

Table 3-2
Benefits for 100% FGD gypsum replacing 100% virgin gypsum.

Benefit		Savings/ton FGD gypsum
Energy	Savings (million Btu/ton FGD)	0.04
	Financial Savings (US$/ton FGD)	1.09
Water Use	Savings (gal/ton FGD)	575
	Financial Savings (US$/ton FGD)	1.44
GHG Emissions	CO_2e (ton/ton FGD)	0.003
	Financial Savings (US$/ton FGD)	0.01 ~ 0.18

Fly Ash and Bottom Ash in Geotechnical Applications

Unit benefits of using fly ash or bottom ash in geotechnical applications were evaluated using PaLATE (RMRC 2004). The analysis considered structural fills as well as roadway applications (bases, subbases, and subgrades).

For structural fills, fly ash and bottom ash were assumed to replace sand and gravel at a 1:1 (volume) replacement ratio. The same equipment and effort were assumed for placement of conventional soils and CCPs. Fly ash and bottom ash were assumed to be placed at a dry unit weight of 1.25 ton/yd^3 (RMRC 2008); conventional soils were assumed to have a dry unit weight of 1.60 ton/yd^3 (Tanyu et al. 2004).

For roadway construction, fly ash was assumed to be used as a stabilizer for subgrades at a 10% dosage in lieu of excavation of soft soil and replacement with crushed rock, as described in Edil et al. (2002). A 10% dosage is conservative because fly ash dosages used for stabilization typically range from 10 to 20%. Bottom ash was assumed to replace sand and gravel used in base and subbase courses at 1:1 replacement (by volume), as suggested by FHWA (2008).

Structural numbers and layer coefficients are used in road designs to determine the necessary layer thickness needed to sustain designed traffic loads. A structural number represents the structural requirement needed for a particular road design. A layer coefficient represents the structural characteristics of a construction material and can be used with the structural number to determine the required road thickness. The PaLATE analysis for fly ash stabilization compared roadway subbase constructed with a structural number of 2.8 and a layer coefficient of 0.18 for conventional construction with crushed rock and a layer coefficient of 0.13 for fly-ash-stabilized subgrade (Geo Engineering Consulting 2009). As a result, a 16-inch-thick layer of crushed rock and a 22-inch-thick layer of fly ash stabilized subgrade were analyzed. The difference in energy required for placement was also considered. Stabilized subgrade is constructed using a reclaimer to blend fly ash into the existing subgrade. For crushed rock, the subgrade is removed using an excavator. The dry unit weight of the fly-ash-stabilized subgrade was assumed to be 1.38 ton/yd^3, as documented by Edil et al. (2002).

Benefits of using bottom ash were computed by comparing roads constructed with a subbase consisting of 100% bottom ash or Wisconsin Grade 2 granular fill (sand or gravel). The two granular layers were designed to have the same structural number (1.6) using a layer coefficient of 0.08 for granular backfill and a layer coefficient of 0.06 for bottom ash, as suggested by Geo Engineering Consulting (2009). This resulted in a 20-inch-thick subbase layer of conventional granular fill and a 27-inch-thick layer of bottom ash. Equipment used to install the Grade 2 granular material and the bottom ash was assumed to be the same. The bottom ash was assumed to have a unit weight of 1.25 ton/yd^3, whereas the granular fill was assumed to have a unit weight of 1.60 ton/yd^3.

Unit benefits of using fly ash or bottom ash in structural fills and embankments are summarized in Tables 3-3 (fly ash) and 3-4 (bottom ash). Unit benefits of replacing crushed rock with fly-ash-stabilized subgrade are summarized in Table 3-5, and unit benefits of replacing conventional granular subbase with bottom ash are summarized in Table 3-6.

Table 3-3
Benefits from replacing sand and gravel with fly ash in structural fill.

Benefit		Savings/ton fly ash
Energy	Savings (million Btu/ton fly ash)	0.19
	Financial Savings (US$/ton fly ash)	5.79
Water Use	Savings (gal/ton fly ash)	0.008
	Financial Savings (US$/ton fly ash)	0.00002
GHG Emissions	CO_2e (ton/ton fly ash)	0.011
	Financial Savings (US$/ton fly ash)	0.05 ~ 0.68

Table 3-4
Benefits from replacing sand and gravel with bottom ash in structural fill.

Benefit		Savings/ton bottom ash
Energy	Savings (million Btu/ton bottom ash)	0.15
	Financial Savings (US$/ton bottom ash)	4.49
Water Use	Savings (gal/ton bottom ash)	0.005
	Financial Savings (US$/ton bottom ash)	0.0001
GHG Emissions	CO_2e (ton/ton bottom ash)	0.01
	Financial Savings (US$/ton bottom ash)	0.05 ~ 0.61

Table 3-5
Benefits from replacing crushed rock with fly-ash-stabilized subgrade.

Benefit		Savings/ton fly ash
Energy	Savings (million Btu/ton fly ash)	1.8
	Financial Savings (US$/ton fly ash)	56.6
Water Use	Savings (gal/ton fly ash)	0.07
	Financial Savings (US$/ton fly ash)	0.0002
GHG Emissions	CO_2e (ton/ton fly ash)	0.15
	Financial Savings (US$/ton fly ash)	0.71 ~ 9.21

Table 3-6
Benefits from replacing Wisconsin Grade 2 granular fill subbase with bottom ash.

Benefit		Savings/ton bottom ash
Energy	Savings (million Btu/ton bottom ash)	0.17
	Financial Savings (US$/ton bottom ash)	5.28
Water Use	Savings (gal/ton bottom ash)	0.007
	Financial Savings (US$/ton bottom ash)	0.00002
GHG Emissions	CO_2e (ton/ton bottom ash)	0.01
	Financial Savings (US$/ton bottom ash)	0.05 ~ 0.61

Benefits of Avoided CCP Disposal

Using CCPs in sustainable construction activities results in additional environmental and economic benefits through avoided landfill disposal. These additional savings were calculated using life cycle inventory (LCI) data for construction, operation, and maintenance costs for Subtitle D (nonhazardous municipal solid waste) landfills in EREF (1999). Environmental impacts associated with construction, operation, and maintenance of Subtitle D landfills were assumed to be similar to those of Subtitle C disposal facilities. Using Subtitle D LCI information is conservative because Subtitle C landfills employ more sophisticated containment systems and additional restrictions on operations, waste acceptance, and disposal that increase emissions as well as consumption of energy and water. The model system boundaries for a landfill life cycle defined by EREF are shown in Figure 3-3. The major components are landfill construction, landfill operation, landfill closure, landfill postclosure care, and leachate treatment (leachate treatment costs are normalized over a 100-yr period starting from initial waste placement).

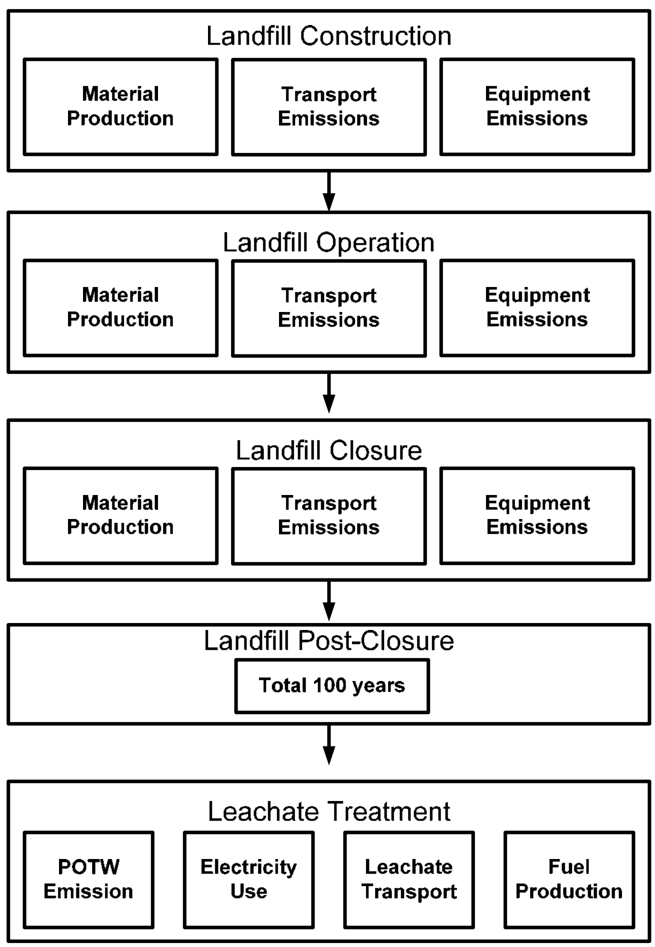

Figure 3-3
Life cycle system boundaries for landfilling (adapted from EREF 1999).

Life cycle inventory data are summarized in Tables 3-7 through 3-11 for each major component of the landfilling process shown in Figure 3-3. Any inventory information that was specific to municipal solid waste and not applicable to CCP disposal was excluded. Methane (CH_4) reported in Tables 3-7 through 3-11 is from equipment and processes associated with construction and closure of a MSW landfill and not from waste decomposition.

Table 3-7
Total LCI attributable to landfill construction (data from EREF 1999).

Parameters	Material Production	Transport Emissions	Equipment Emissions	Total
Energy (Btu/ton)	0	26,710.7	0	26,710.7
CO_2 (lb/ton)	1.47	0.26	1.09	2.82
Methane (lb/ton)	0.01	0.001	0.005	0.016

Table 3-8
Total LCI attributable to landfill operations (data from EREF 1999).

Parameters	Plastic	Soil	Steel	Fuel	Transport Emissions	Equipment	Total
Energy (Btu/ton)	43.9	1,206.3	2,671.1	44805.1	0	0	48,726.4
CO_2 (lb/ton)	0.0017	0.194	0.49	0.734	0.048	6.176	7.64
Methane (lb/ton)	1.4 E-06	0.00008	0.0004	0.0034	-	-	0.0039

Table 3-9
Total LCI attributable to landfill closure (data from EREF 1999).

Parameters	Material Production	Transport Emissions	Equipment Emissions	Total
Energy (Btu/ton)	24,987.45	0	0	24,987.45
CO_2 (lb/ton)	2.43	0.586	0.352	3.37
Methane (lb/ton)	0.0017	-	-	0.0017

Table 3-10
Total LCI attributable to landfill postclosure care (data from EREF 1999).

Parameters	Total 100 Years
Energy (Btu/ton)	2,498.75
CO_2 (lb/ton)	0.338
Methane (lb/ton)	0.00017

Table 3-11
Total LCI attributable to leachate management for 100 years (data from EREF 1999).

Parameters	POTW* Emissions	Leachate Treatment	Electricity	Fuel	Total
Energy (Btu/ton)	0	0	2671	1120	3791
CO_2 (lb/ton)	0	0.17	0.408	0.019	0.594
Methane (lb/ton)	0	-	0.0012	0.00009	0.001

*Publicly owned treatment works

A summary of the LCI information for all landfilling processes is shown in Table 3-12. The total economic benefits of avoided landfill disposal are summarized in Table 3-13. Economic benefits were derived by multiplying the unit savings by the amount of avoided landfilling (that is, total amount of fly ash, bottom ash, and FGD being beneficially used for concrete, wallboard, and geotechnical applications in 2007). A summary of the unit impacts associated with CCP disposal is shown in Table 3-14. The CO2 equivalence reported in Table 3-14 includes CO2 savings and methane savings, with the latter converted to CO2e by assuming 1 ton CH4 = 23 tons CO2e.

Table 3-12
Benefits due to avoided landfilling of recycled CCPs (fly ash, bottom ash, and FGD gypsum).

Component	Energy (Btu/ton)	CO_2 (lb/ton)	Methane (lb/ton)
Construction	26,711	2.82	0.016
Operation	48,726	7.64	0.0039
Closure	24,987	3.37	0.0017
Postclosure	2499	0.34	0.0002
Leachate	3791	0.59	0.001
Total	106,714	14.76	0.023

Table 3-13
Economic benefits due to avoided landfilling of fly ash, bottom ash, and FGD gypsum currently used in sustainable construction.

	Unit Cost	Quantity	Total
Construction	\$300,000/ac	383 cumulative acreage	\$115 million
Operation	\$6/ton	34.6 million tons	\$208 million
Closure	\$150,000/ac	383 ac	\$57 million
Postclosure	\$15,000/ac	383 ac	\$6 million
Leachate	\$0.04/gal	315 million cumulative gal	\$13 million
Total			\$0.4 billion
Commercial Landfills (Average tipping fee for Subtitle D = \$40/ton)*			\$1.4 billion
Commercial Landfills (Average tipping fee for Subtitle C = \$150/ton)			\$5.2 billion

*Wisconsin DNR (2009)

Table 3-14
Benefits profile for avoided landfilling of fly ash, bottom ash, and FGD gypsum currently used in sustainable construction.

Benefit		Savings/ton CCP
Energy	Savings (million Btu/ton CCP)	0.11
	Financial Savings (US\$/CCP)	3.37
GHG Emissions	CO_2e (ton/ton CCP)	0.008
	Financial Savings (US\$/ton CCP)	0.04 ~ 0.47

Cumulative Benefits

Total annual benefits of using CCPs in construction applications are reported in Table 3-15 in terms of reductions in energy use, water consumption, and global warming potential (in CO_2e based on BEES global warming potential characterization factors reported in NIST 2007). Total savings for each application were computed as the product of the annual use of each CCP in each use application (Table 1-1) and the derived unit benefits (Tables 3-1 through 3-6, 3-13, and 3-14).

The largest environmental benefit in sustainable construction is currently accrued by using fly ash in concrete production. Use of fly ash as a cement substitute annually saves more than 55 trillion Btu of energy and reduces GHG emissions by 9.6 million tons CO_2e (Table 3-15). Using FGD gypsum in wallboard manufacturing results in modest annual energy savings (0.3 trillion Btu), substantial annual savings in water consumption (4.7 billion gal), and a small annual reduction in GHG emissions (0.03 million tons CO_2e). Geotechnical applications of CCPs result in moderate annual savings in energy consumption and CO_2 emissions at current usage rates, and modest annual savings in water consumption. Financially, the greatest benefits are obtained using fly ash in concrete, followed by use of CCPs in geotechnical applications, and FGD gypsum in wallboard manufacturing. The financial benefits are closely aligned with benefits associated with reductions in energy consumption and GHG emissions.

Table 3-15
National annual savings obtained by using CCPs in sustainable construction.

Resource	Concrete	Wallboard	Geotechnical	Landfill Avoidance
Energy (trillion Btu)	55	0.3	4.3	3.7
Water (million gal)	1200	4700	0.17	Not Known
CO_2e (million ton)	9.6	0.03	0.3	0.3
Financial (billion $)	1.7 ~ 2.3	0.02	0.13 ~ 0.15	0.5 ~ 5.3*

*Includes landfill tipping fee ($0.4 billion ~ $5.2 billion) and environmental costs.

Reductions in energy use, water consumption, and GHG emissions are obtained by avoiding production of conventional materials. In contrast to the construction materials they replace, CCPs are by-products of energy generation and are not produced specifically for construction applications. Consequently, the resources embodied in CCP production are accounted for in electricity production and are expended regardless of whether CCPs are used beneficially.

The benefits from avoiding disposal are also shown in Table 3-15. Avoided landfilling accounts for a savings of 3.7 trillion Btu of energy and a reduction of CO_2e emissions by 0.3 million tons. The combined financial savings ranges considerably, from $0.5 billion annually for a Subtitle D-style landfill operated on site by utilities to $5.3 billion annually for off-site commercial disposal in a Subtitle C landfill. Disposal in an off-site commercial Subtitle D landfill would likely cost $1.4 billion annually. These commercial disposal costs are based on a tipping fee of $40/ton for a Subtitle D landfill and $150/ton for a Subtitle C landfill (Wisconsin DNR 2009 and telephone interviews with solid waste industry representatives).

The total annual benefits obtained from using CCPs in sustainable construction applications are summarized in Table 3-16. Using CCPs in construction applications results in a reduction in energy consumption of 63 trillion Btu, a reduction in water consumption of 5.9 billion gallons, and a reduction in CO_2e emissions of 10 million tons. The financial savings ranges from $2.4 to $7.8 billion. These benefits may increase markedly in the future given the current interest in creating "greener" concrete by increasing the fly ash content, the increased production of FGD gypsum (and corresponding impacts on wallboard manufacturing) that is anticipated as more power plants employ wet scrubbers, and the increased use of fly ash stabilization to reduce the cost and increase the service life of roadways.

Table 3-16
Summary of environmental savings achieved by using fly ash, bottom ash, and FGD gypsum in each major application.

Material	Application	Energy (trillion Btu)	Water (million gal)	CO_2e (million ton)
Fly Ash	Concrete	55	1200	9.6
	Structural Fill	1.5	0.06	0.08
	Road Base	2.2	0.09	0.19
Bottom Ash	Structural Fill	0.4	0.01	0.03
	Road Base	0.2	0.01	0.01
FGD Gypsum	Wallboard	0.3	4700	0.03
Landfilling		3.7	Not Known	0.3
Total		63	5900	10

4
SUMMARY AND CONCLUSIONS

This study has quantified the environmental and economic benefits from each major use of fly ash, bottom ash, and FGD gypsum in sustainable construction. Savings associated with reductions in energy and water consumption and lower GHG emissions are accrued by avoiding material production (mining and processing). CCPs are by-products of energy generation and are not produced specifically as construction materials. Consequently, the resources embodied in CCPs are accounted for in electricity production and are expended regardless of whether CCPs are used beneficially.

The total environmental benefits obtained by replacing conventional construction materials with CCPs are significant. Annually, approximately 63 trillion Btu of energy is saved, 10 million tons of CO_2e emissions are avoided, and 5.9 billion gallons of water are not consumed. The financial savings are large as well: $2.4-7.8 billion is made available for other uses by using CCPs in sustainable construction. These quantities indicate that CCP use in construction contributes significantly to sustainability in the United States.

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A

SENSITIVITY ANALYSIS FOR TRANSPORTING CEMENT AND FLY ASH

A sensitivity analysis was conducted to evaluate how differences in transportation distance for cement and fly ash delivery to a ready-mix concrete plant affect energy use and GHG emissions. Transportation distances for cement tend to be longer than those for fly ash due to the more uniform distribution of coal-fired power plants compared to portland cement productions facilities. The analysis assumed that fly ash was transported 60 mi to the plant and that the cement was transported 60 to 100 mi.

The analysis showed that the difference in energy consumption and GHG emissions increases as the transportation difference increases. However, the differences were only approximately 4% at the maximum practical difference in transport distance (100 mi). Thus, the effect of difference in transportation distance was considered negligible relative to other sources of energy use and GHG emissions in this study.

Table A-1
Effect of difference in transportation distance on energy consumption when transporting cement and fly ash to ready-mix concrete plants.

Distance difference = cement – fly ash (mi)	Energy Use (billion Btu)			Energy savings from transportation (%) = (c/49.4) x 100
	Cement (a)	Fly Ash (b)	Difference (c) = a-b	
0	1194.2	1345.9	-151.6	-0.3
10	1393.3	1345.9	47.4	0.1
20	1601.8	1345.9	255.9	0.5
30	1800.8	1345.9	454.9	0.9
40	1999.9	1345.9	654.0	1.3
50	2198.9	1345.9	853.0	1.7
60	2397.9	1345.9	1052.1	2.1
70	2597.0	1345.9	1251.1	2.5
80	2796.0	1345.9	1450.1	2.9
90	2995.0	1345.9	1649.2	3.3
100	3525.8	1345.9	2179.9	4.4

Table A-2
Effect of difference in transportation distance on GHG emissions when transporting cement and fly ash to ready-mix concrete plants.

Distance difference = cement – fly ash (mi)	CO_2e Emission (ton)			CO_2e savings from transportation difference (%) = (c/3,270,329 ton) x 10
	Cement (a)	Fly Ash (b)	Difference (c) = a-b	
0	30,166	29,394	772	0.0
10	40,222	29,394	10,828	0.3
20	50,277	29,394	20,883	0.6
30	60,333	29,394	30,939	0.9
40	70,388	29,394	40,994	1.3
50	80,444	29,394	51,050	1.6
60	90,499	29,394	61,105	1.9
70	100,555	29,394	100,555	3.1
80	110,610	29,394	110,610	3.4
90	120,666	29,394	120,666	3.7
100	130,721	29,394	130,721	4.0

B

SIMAPRO MODELING TREE FOR GYPSUM MINING

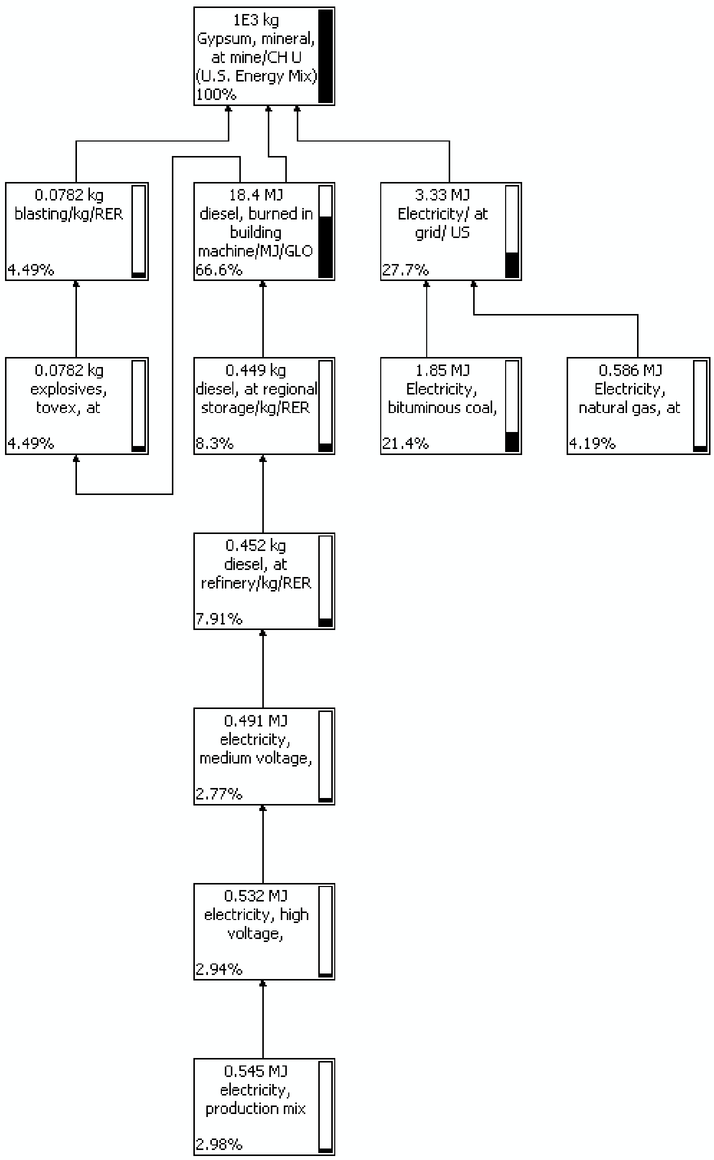

Figure B-1
SimaPro network diagram for mining 1000 kg of gypsum.

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