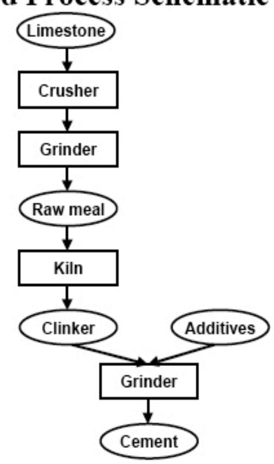
Cement Product Manufacturing

Cement is one of the most carbon-intensive industries in California. The cement and concrete sectors account for an annual 12 mmtCO_2e in California,[1] or nearly 2.5 percent of total state greenhouse gas emissions in 2004, but less than 1 percent of the state's NAICS revenue (0.4 percent) or employment (0.2 percent). However, cement and concrete are a vital input into commercial building and highway construction sectors and, as such, an important part of the California economy. Additionally, 40 percent of cement is imported into CA from around the world,[2] and the impacts of AB 32 policies are a concern both to the industry itself and for leakage considerations.

Simplified Process Schematic for Cement Making



Cement is an "inorganic, non-metallic substance with hydraulic binding properties and is used as a bonding agent in building materials."[3] The cement production process begins when limestone is harvested from a quarry near the processing plant. Shipping costs for the raw material necessitates building the refinery near the limestone source, unless the material is shipped overseas in which case the plant must be near a port. The raw material is then transported to the plant where it is processed through a crusher and grinder and blended with a mix of siliceous, aluminous, and ferrous materials into raw meal. The raw meal is heated to over 3000°F in a kiln then rapidly cooled to yield clinker, which

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[1] PIER Energy-Related Environmental Research. "Emission Reduction Opportunities for Non-CO2 Greenhouse Gases in California." California Energy Commission (2005): CEC-500-2005-121.
[2] Tom Pyle, "Overview: AB 32 Implementation Status," California Air Resources Board, 2008.
[3] PIER Public Interest Energy Research. "Optimization of Product Life Cycles to Reduce Greenhouse Gas Emissions in California." California Energy Commission (2005) CEC-500-2005-110-F.

contains the hardening agent alite (tricalcium silicate). Clinker is then ground into a fine powder and mixed with 3-5 percent gypsum, an additive that aids in cement setting.[4]

This process is energy intensive, and uses a number of different energy inputs. In California, the cement manufacturing process consumed 1,600 GWh of electricity, 22 million therms of natural gas, 2.3 million tons of coal, 0.25 tons of coke, and numerous waste materials (e.g., tires).[5] Correspondingly, there are a variety of strategies to reduce greenhouse gas emissions from cement manufacturing, and a wide range of costs for these different strategies, depending on the technologies adopted and production tax credits. The remainder of this section describes four of these options: energy efficiency improvements, fuel switching, greater use of fly ash, and burning of waste tires. Adopting these strategies could lead to reductions that total 5.4 mmtCO2e/yr by 2020, with a cost-effectiveness ranging between 0 and \$119/tCO_2e.[6]

There are a number of potential options for improving energy efficiency in cement production. The main energy efficiency opportunities in kiln operation for clinker production include pre-heating, "optimization of the clinker cooler, improved burners, and process control and management systems."[7] Other potential improvements in energy efficiency come from reductions in electricity consumption through the use of more efficient grinding and motor systems for processing limestone. Significant energy efficiency gains for cement manufacturing in CA have already been made through the use of dry processing technology that consumes less water and energy than wet processing. Sweeney et al. (2008) estimate that energy efficiency gains in the cement industry can generate a 0.8 mmtCO_2e reduction at \$33/tCO_2e. Barriers to adopting more energy efficient kilns, crushers and grinders include limited capital, concerns involving interruption of the production process, facility managers' lack of information, and the durability and reliability of the new equipment.[8]

Natural gas consumption in the cement industry is the most energy intensive in the kiln. A kiln uses about 10 percent electricity, with the remaining fuel primarily from coal, pet coke, and some natural gas. As of 2005, one California plant out of 11 utilizes 100 percent natural gas to heat the kiln as opposed to coal and pet coke.[9] Two reports show the cost of mitigation by using 100 percent natural gas to be expensive. ARB estimates the cost for replacing coal and pet coke with natural gas as \$137.76/tCO_2e, with an annual reduction of 2.2 mmtCO_2e.[10] Sweeney et al. (2008) find the same potential for emission

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[4] LBNL Environmental Energy Technologies Division. "Case Study of the California Cement Industry." U.S. Environmental Protection Agency (2005): LBNL 59938.
[5] (LBNL 2005)
[6] Sweeney et al. "A Cost-effectiveness Analysis of AB 32 Measures." Stanford University (2008).
[7] (PIER-110 2005)
[8] (LBNL-59938 2005)
[9] (LBNL-59938 2005)
[10] CARB California Air and Resources Board. "NRDC Cement GHG Reduction Calcs Final." (2008)

reductions, but at a slightly lower cost of $119/t$CO_2$e.[11] The largest barrier to fuel switching for cement manufacturers is clearly the cost, and as a policy measure would likely fail a cost-effectiveness test.

Clinker can be blended with various forms of aggregate (limestone, fly-ash, steel slag, and Cemstar®) that require less energy in the manufacturing and use processes. Of these forms of aggregate, limestone seems the most promising for adoption in California, as it is more abundant than fly-ash or blast furnace slag, which must be imported. Fly-ash can be used as pozzolan and is an abundant by-product of power plants. Adding limestone would lead to CO_2 emission reductions of 436 ktCO_2 per year, or 5 percent of the total emissions of the CA cement industry, at a cost of $0.7/t CO_2, reflecting the cost of delivery, storage, and electricity consumption.[12] Fly-ash has a net zero cost ($0/t$CO_2$e) and an estimated reduction potential of 2.4 mmtCO_2e.[13] The primary barrier to adoption is the continued difficulty in obtaining approval for use through government and industry standards for product composition.[14]

Waste tires can be used as an alternative to coal for heating the kiln. LBNL estimates that a 20 percent replacement of fossil fuels by waste fuels would result in a reduction of 616 ktCO_2 per year, even though CO_2 emissions from kilns will increase. The reduction in pollution comes from reducing the quantity of tires being incinerated without energy recovery.[15] In 2004, permits for burning tires were issued by the EPA to seven CA plants. Four of the participating plants incinerated over 71,000 tons of scrap tires.[16] Continued barriers to adoption include the need to maintain clinker and fuel composition, which physically limits the adoption threshold. Also, there is public resistance to incinerating tires and the EPA permit is not a rubber stamp.[17]

Semiconductor Manufacturing

A semiconductor is a solid piece of silicon that has electrical conductivity and is used in almost any electrical device that needs to do a calculation. The semiconductor industry is a "technology enabler" in that its level of production has direct effects on multiple industries. Innovation and R&D can constitute up to 20 percent of annual revenues, and capital production on semiconductor fabrication plants, or "fabs," can consume up to 25 percent of annual revenue. The semiconductor is a major source of revenues ($20 billion in 2002) and jobs (99,714 in 2002) for the California economy.[18]

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[11] (Sweeney 2008)
[12] (PIER-110 2005)
[13] Sweeney et al., 2008.
[14] (PIER-110 2005)
[15] (PIER-110 2005)
[16] (PIER-110 2005)
[17] (PIER-110 2005)
[18] BEA, 2002 Census

Global Warming Potentials of Gases Analyzed in this Report

Greenhouse Gas	Global Warming Potential (GWP)
Methane (CH_4)	21
Sulfur Hexafluoride (SF_6)	23,900
Tetrafluoromethane (CF_4)	6,500
Hexafluoroethane (C_2F_6)	9,200
Octafluoropropane (C_3F_8)	7,000
Octafluorocyclobutane (C_4F_8)	8,700
Trifluoromethane (HFC-23)	11,700
Nitrogen Trifluoride (NF_3)	8,000

The semiconductor industry emitted 2 mmtCO_2e in 2005, and following baseline trends emissions will increase to 7.74 mmtCO_2e annually by 2020.[19] The process-related greenhouse gas emissions in semiconductor manufacturing are collectively referred to as perfluorocompounds (PFCs). PFCs have a significantly greater impact on atmospheric warming per mass unit compared to CO_2 (Figure @@).[20] In this section, we outline six technologies to reduce PFC emissions in the semi-conductor industry: plasma etching, remote cleaning, catalytic abatement, capture/recovery, thermal destruction, and clean room efficiency. The cost-effectiveness of these technologies is variable due to different tax rates and discount rates.

Plasma etching involves using high GWP gases to create an architecture of circuitry features on a silicon wafer's surface. The new process technology would isolate the etching tool from the fab's waste stream, oxidizing the GWP gases before the exhaust reaches the stack.[21] The costs of reductions in PFCs for adopting the new process technology range from \$12.86/tCO_2e for 0.72 mmtCO_2e of mitigation by 2010, to \$22.99/tCO_2e for 1.65 mmtCO_2e by 2020.[22] Barriers to adopting this technology include the low technical applicability, which is the degree to which the adoption of the process technology reduces baseline emissions. Another adoption barrier is market penetration, the percent of emissions from a given source that are expected to be addressed by a given option. The market penetration for plasma etching is only 55 percent.[23]

The remote clean process uses fluorine gas (F_2) as a cleaning agent for removing residue from the dielectric chamber.[24] Fluorine gas is not a global warming gas, unlike the conventional compounds used

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[19] (PIER-121 2005)
[20] (PIER-121 2005)
[21] Emissions of High Global-Warming Potential Gases- Semiconductor Industry: Abatement Technologies. "Technology Options for the Near and the Long Term." U.S. Climate Change Technology Program (2005).
[22] (PIER-121 2005)
[23] (PIER-121 2005)
[24] (PIER-121 2005)

for cleaning, such as NF_3, C_2F_6, and SF_6.[25] Plasma abatement has an incremental reduction ranging between 1.64 mmtCO2e at a break-even price of \$20.39/tCO_2e in 2010 to 3.76 mmtCO_2e in 2020 with a cost effectiveness of \$38.48/tCO_2e. Adopting the technology has a one-time capital cost of \$90.76/tCO_2e, which covers the cost of purchasing and installing the equipment.[26] Besides the high capital cost, there have been no other reports on barriers to adoption.

Catalytic abatement is a four-step process that essentially breaks PFCs into CO_2 and HF through diluting and heating processes prior to feeding it though the scrubber.[27] Catalytic abatement is highly effective, with destruction removal emission of over 95 percent for different PFCs.[28] Potential reductions from catalytic abatement total 0.26 mmtCO_2e with a cost-effectiveness of \$20.45/tCO_2 in 2010, and 0.61 mmtCO_2e with a cost-effectiveness of \$33.87/tCO_2e in 2020. Catalytic abatement has a market penetration of 20 percent, likely due to the high capital cost of \$67.35/tCO_2e.[29]

Capture/recovery with a membrane is another process technology which separates unreacted and/or process-generated fluorinated compounds from other gases using a membrane as a filter. The capture/recovery process has the potential to abate 0.24 mmtCO_2e at a cost of \$22.30/tCO_2e in 2010 and 0.56 mmtCO_2e at a cost of \$30.38/tCO_2e in 2020. Capture/recovery has a market penetration of 8 percent, again likely due to high capital costs.[30]

Thermal destruction reduces emissions from the etching and CVD chamber cleaning process.[31] Thermal destruction can reduce emissions by 0.24 mmtCO_2e by 2010 and 0.56 mmtCO_2e by 2020, at average abatement costs of \$29.96/tCO_2e and \$48.57/tCO_2e for 2010 and 2020, respectively. Based on the high capital costs (\$93.39/tCO_2e) and high annual costs (\$8.98/tCO_2e), more incentives may be necessary to encourage market penetration.[32]

The clean room is a dust free area where semiconductors are processed. Increased ventilation, efficiency improvements to process controls, cooling systems, and air handling are all potential process technologies for improving clean room energy efficiency.[33] Increasing clean room energy efficiency by 30 percent could lead to annual reductions of 0.72 mmtCO_2e.[34] However, compressed production cycles

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[25] Brown, Roy S. and Joseph A. Rossin Guild Associates Inc. "Catalytic Process for Control of PFC Emissions." Semiconductor International (2001).
[26] (PIER-121 2005)
[27] (PIER-121 2005)
[28] (Semiconductor 2001)
[29] (Brown 2001)
[30] (PIER-121 2005)
[31] (PIER-121 2005)
[32] (PIER-121 2005)
[33] (PIER-121 2005)
[34] (PIER-121 2005)

leave little time for efficiency improvements, and energy costs might only represent a small percentage of total production costs, both representing barriers to adoption.[35]

HFC Manufacturing and Disposal

Hydrofluorocarbons (HFCs) are a major source of greenhouse gas emissions in California, and HFC reductions represent a significant share of planned emission reductions. ARB's strategy for HFC abatement focuses specifically on refrigerant HFC-134a, which, with an extremely high GWP of 1,300, is the most commonly used refrigerant. HFCs can be used in motor vehicle air conditioning (MVAC) and retail cans as well as commercial refrigeration. Baseline HFC emissions are expected to grow from 14.32 mmtCO_2e in 2010 to 24.38 mmtCO_2e by 2020. ARB estimates that 8.5 mmtCO_2e can be reduced from this baseline by 2020,[36] at a cost that Sweeney et al. (2008) estimate at $28/mmt$CO_2$e. More specifically, ARB estimates reductions of high-GWP refrigerants at 3.5 mmtCO2e for vehicles and cans and 5 mmtCO2e for commercial refrigeration.[37] Two major reduction areas for reductions, which we examine here, are HFC-134a reductions in MVAC servicing, and refrigerant recovery from decommissioned shipping containers.

There are a variety of ways to reduce HFC-134a in MVAC servicing, and many of these are interrelated. One strategy is to ban the retail sale of HFCs in 12-oz cans. The estimated cost of a can is approximately $10 and 2-4 million are sold in CA each year. Dividing this cost by the estimated emission reductions gives a preliminary cost effectiveness range, from $12-40/t$CO_2$e.[38] Banning cans would lead to a reduction of 0 mmt in 2010 and 2.4 mmt by 2020.[39] Banning cans would only eliminate the supply on one end while leakage would continue to occur throughout the life-cycle of the MVAC, eventually tapering off and reducing greenhouse gas emissions as the cars with the leaky MVACs are serviced and HFC-134a is properly disposed of. The costs of eliminating the cans could be offset by the jobs increased in professional installation.

Focusing more on the MVAC manufacturer, another option is to use low-GWP (under AB 1493 legislation) gases like HFC-152a. Substituting HFC-152a has a high capital cost of $192.33/t$CO_2$e with benefits of $54.15/t$CO_2$e.[40] Emissions would be reduced by 0.1 to 0.9 mmtCO_2e by 2020.[41] Barriers to adoption include the technical difficulties with enforcing this regulation.

Another option for the mechanic focuses on including a leak-tightness check on vehicular inspections that can be implemented at the same time as a smog check. Estimates are that this would reduce

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[35] (PIER-121 2005)

[36] (PIER-121 2005)

[37] California Air and Resources Board. "Work Plans for Potential GHG Reduction Measures." Air and Resources Board (2005)

[38] Potts, Winston. "Reduction of HFC-134a Emissions From Nonprofessional Servicing of Motor Vehicle Air Conditioning Systems (MVACs)." Climate Action Team 2008.

[39] (CARB 2005)

[40] (PIER-121 2005)

[41] (CARB 2005)

leakage by 50 percent.[42] Industry determined a windfall profit to the professional mechanic, who in 2006 on average charges $147 for recharge service, on the order of more than $166 million.[43] CEC estimates a $10.89/tCO_2e cost with $6.23/tCO_2e in benefits.[44] By 2010, reductions can be between 0.4 mmt and 1.4 mmtCO_2e, and by 2020, between 0.3 mmtCO_2e and 0.9 mmtCO_2e.[45] Barriers to adoption include the cooperation from the Bureau of Automotive Repair and may necessitate legislation. Professionals already have the equipment and training to service MVAC systems in a more efficient manner. However, reductions vary based on what other measures are implemented. For example, these costs would be borne by the consumer, who obtains partial savings by being legally not able to buy the can.

Refrigerant recovery entails properly disposing of HFC-134a, of which decommissioned shipping containers are a major source. ARB estimates that the reduction will be less than 0.1 mmtCO2e in 2020.[46] The equipment to cover the cost of recovering the refrigerant may cost up to $5,000. The CEC estimates a one-time capital cost of \$26.19/tCO_2e, with annual payments of \$3.40/tCO_2e, and \$1.69/tCO_2e in benefits.[47] Issues that need to be addressed for the population of commercial systems include their emission rates and the rate of turnover of these systems. Barriers include the need to identify an enforcement mechanism to regulate proper disposal.

Waste Management

There are 159 waste management sites in California with current GHG emissions of 8.4 mmtCO_2e. A large portion of these emissions comes from methane, which has a GWP 21 times higher than CO_2.[48] The California Integrated Waste Management Board (CIWMB) is the regulatory authority in charge of waste management and, recognizing the links between waste and greenhouse gas emissions, is also a member of the CAT.[49] The CIWMB breaks landfills down into categories based on the content of the landfill, ranging from concrete to e-waste, compost to hazardous medical waste.[50] Landfill size ranges from less than 100,000 tons of waste to over 1,000,000 tons. Assuming baseline growth, methane emissions will increase from 10.64 mmtCO_2e in 2010 to 11.43 mmtCO_2e by 2020.[51]

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[42] (CARB 2005)
[43] (Potts 2008)
[44] (PIER-121 2005)
[45] (CARB 2005)
[46] Potts, Winston and Leeman, Whitney. “Refrigerant Tracking, Reporting and Recovery Program.” Air and Resources Board (2007)
[47] (PIER-121 2005)
[48] (CARB 2005)
[49] CIWMB California Air and Resources Board. “Climate Action Team Proposed Early Actions to Mitigate Climate Change in California.” California EPA (2008).
[50] (CIWMB 2008)
[51] (PIER-121 2005)

Table 15: Landfill Size Category Characteristics

Landfill Category (short tons WIP)	Number of Landfills 2000[a]	Average Landfill Age (yrs)[b]	Average Landfill Acreage (acres)[b]	Total WIP Contained in All Landfills in Size Category (short tons)[a]
< 100,001	87	33	2.1	8,700,000
100,001–200,000	13	24	3.8	2,390,000
200,001–300,000	10	22	5.6	2,795,000
300,001–400,000	7	26	7.6	2,545,000
400,001–500,000	10	28	10.3	5,000,000
500,001–1,000,000	20	28	17.8	14,960,000
> 1,000,000	12	38	38.6	27,400,000

[a] BFRS (2005).

[b] Calculated using CEC (2004a).

The potential for reducing emissions of non-CO_2 gases in landfills is significant and low cost. In 2020, California could achieve 2.44 mmtCO_2e reductions at a break-even cost equal to or less than zero, depending on the discount rate, the tax rate, and the landfill's size and age.[52] Currently, all large, major landfills in California use methane capture or destruction process technology.[53] For landfills with the mitigation technology already installed, the goal is to increase the efficiency of methane capture and energy recovery above 85 percent.[54]

One innovative sub-technology within the Landfill Methane Capture Strategy scenario is a bioreactor landfill, where liquid or air is dripped through the waste in order to accelerate biostabilization.[55] Estimated total GHG emissions reductions of 1.0 mmtCO2E for 2010 and 4.0 mmtCO2E for 2020.[56] The IWMB, working with the ARB, is jointly developing regulation and a guidance document for landfill operators that will recommend technologies and best management practices for improving landfill design, construction, operation, and closure for the purpose of reducing GHG emissions. Separately, the EPA is in the process of developing the New Source Performance Standards/Emission Guidelines (NSPS/EG) for landfills.

Projected costs vary based on the scenario. Parameters include the size of the landfill, the year (2010 or 2020), discount rate, and tax rate.[57] With a 4 percent discount rate, implementing the process technology has a cost-effectiveness ranging from a high of \$4.68/tCO_2e for a landfill with a WIP (Waste in Place) greater than 1 million tons and continuously decreases to \$1.39/tCO_2e for a landfill with a WIP between than 200,000 and 300,000 tons. With a 20 percent discount rate and a 40 percent tax rate,

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[52] (PIER-121 2005)
[53] Sweeney, 2008.
[54] (PIER-121 2005)
[55] (CIWMB 2008)
[56] (PIER-121 2005)
[57] (PIER-121 2005)

break-even pricing has substantially different costs, ranging from \$1.35/tCO_2e for 1 million short tons to \$7.17/tCO_2e for 300,000 to 400,000 short tons.[58]

These ranges provide evidence for the dramatic impact that financial incentives have on greenhouse gas mitigation. With a 4 percent tax rate, the costs of abatement are positively related to the WIP; as the size of the landfill grows, break-even pricing grows. However, with a 20 percent discount rate and a 40 percent tax rate, the costs and WIP are inversely related.[59] Break-even costs can be substantially higher but are always under \$10/tCO_2e, regardless of landfill size of discount rate. Other estimates have similar greenhouse gas abatement amounts (2.3 mmtCO2e) but significantly higher costs, in this case between \$34/tCO_2e and \$42/tCO_2e.[60]

Baseline emissions from landfills are uncertain, which may be the variable that leads to confusion on the cost-effectiveness of adopting new processes.[61] There is a low technical applicability and no market penetration for the installation of direct gas use as landfills.[62] At the lowest WIP (<100,001), direct gas projects have capital costs of \$429,026 and O&M costs of \$13,942 and are correlated positively with WIP increase.[63] Such high-perceived capital costs likely affect adoption.

Materials/Waste Types

Appliances	Food Waste	Packaging
Asphalt	Glass	Paint
Batteries	Hazardous Waste	Paper
Biomass	Health Care Waste	Pesticides
Biosolids	Herbicides	Plastics
Cellular Phones	Holiday Waste	Recycled-Content Products
Christmas trees	Household Hazardous Waste	Rerefined Oil
Compost	Hypodermic Needles	Rigid Plastic Packaging Containers
Computer Monitors	Ink and Toner Cartridges	RPPC
Computers	Litter	Rubber
Construction/Demolition Debris	Lumber	Sharps
CRTs	Medical Waste	Solvents
Diapers	Metals	Trash Bags
E-Waste	Mulch	Universal Waste
Electronic Products	Newsprint	Used Oil
Electronic Waste	Oil	Waste Tires
Fluorescent Tubes	Oil Filters	White Goods
Food Scrap	Organics	Wood

Recycling is another important option for decreasing waste emissions. In 2006, California achieved a 52 percent waste reduction, equivalent to 3 mmtCO_2e, meeting the mandate for AB 939. Seventy-seven percent of all the waste generated in California was diverted from landfills. The goal is to "achieve high recycling levels and move towards zero waste."[64] The IWMB approved a Scope of Work for a Lifecycle

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58 (PIER-121 2005)
59 (PIER-121 2005)
60 (Sweeney 2008)
61 (Sweeney 2008)
62 (PIER-121 2005)
63 (PIER-121 2005)
64 (CIWMB 2008)

Assessment and Economic Analysis goal to provide an additional 3-5 mmtCO_2e by 2020. The cost of these measures is estimated at \$23/tCO_2e.[65]

[65] (Sweeney 2008)