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**Reducing California's Greenhouse
Gas Emissions through Product
Life-Cycle Optimization**

*Eric Masanet, Lynn Price, Stephane de la Rue du Can,
Lawrence Berkeley National Laboratory*

Ernst Worrell, Ecofys

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ABSTRACT

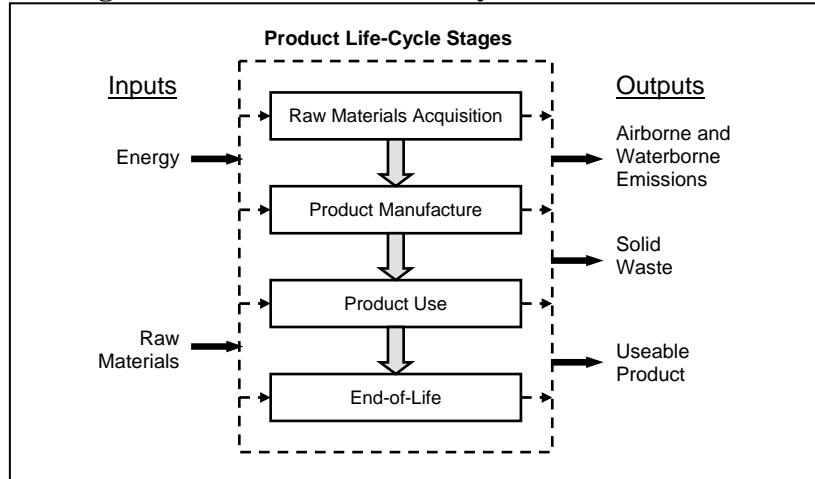
Product life-cycle optimization addresses the reduction of environmental burdens associated with the production, use, and end-of-life stages of a product's life cycle. In this paper, we offer an evaluation of the opportunities related to product life-cycle optimization in California for two key products: personal computers (PCs) and concrete. For each product, we present the results of an explorative case study to identify specific opportunities for greenhouse gas (GHG) emissions reductions at each stage of the product life cycle. We then offer a discussion of the practical policy options that may exist for realizing the identified GHG reduction opportunities. The case studies demonstrate that there may be significant GHG mitigation options as well as a number of policy options that could lead to life-cycle GHG emissions reductions for PCs and concrete in California.

Introduction

Life-cycle optimization involves evaluating the environmental burdens associated with all stages of a product's life in an effort to identify approaches for minimizing those burdens. Life-cycle optimization is based on the methodology of life-cycle assessment (LCA), a systematic approach in which the necessary inputs of energy and materials and subsequent outputs of emissions and wastes are quantified at each stage of a product's life cycle (i.e., raw materials acquisition, product manufacturing, product use, and product end-of-life/disposal). The inputs and outputs at each life-cycle stage are then aggregated to provide a full "cradle to grave" estimate of a product's environmental burdens. The LCA framework is depicted schematically in Figure 1. Life-cycle optimization extends traditional LCA analysis by identifying specific opportunities that may exist for reducing environmental burdens at each stage of a product's life cycle; it can therefore provide a holistic "cradle to grave" approach for identifying policies that promote energy efficiency improvements and greenhouse gas (GHG) emissions reductions for a given product or class of products.

In this paper, we present the results of life-cycle optimization case studies for two products that are manufactured and consumed on a large scale in California: personal computers (PCs) and concrete. Both products are extremely important in California from an economic and environmental perspective. In each case study, we identify measures for GHG emissions reductions across the product life cycle and present preliminary estimates of the technical potential for GHG emissions reduction associated with each measure. To conclude the paper, we offer an initial exploration of the practical opportunities and policy options in California for promoting life-cycle optimization for the two products evaluated.

Figure 1. The Product Life-Cycle Assessment Framework



Case Studies

The results presented in this section are based on product life-cycle optimization case studies that were conducted for PCs and concrete produced, consumed, and discarded in California on an annual basis. Specifically, the goals of these case studies were: (a) to estimate the total life-cycle GHG emissions arising from the manufacture, use, and end-of-life disposition of these products in California on an annual basis, (b) to identify specific GHG mitigation measures across the life cycle of each product that could be implemented to reduce California's annual GHG emissions, and (c) to estimate the technical potential for annual GHG emissions reductions in California that could be realized with each identified measure.

Personal Computers

California is the nation's largest manufacturer of computer equipment and is home to several major U.S. PC companies, including Hewlett-Packard, Apple, and Sun Microsystems. California's importance to the \$47 billion per year U.S. computer industry is undeniable: 33% of the nation's value added computer manufacturing operations occur within the state (U.S. Census 2005). California's "hi-tech" sector, which manufactures the semiconductors, printed circuit boards, and myriad other electronic components that support the global PC industry, employs over 700,000 people and is the second-largest source of employment in the state (CEC 2004).

Fittingly, Californians also consume more PCs than any other state. In 2001, an estimated 7.9 million PCs were in use in California households, nearly twice as many as in Texas, the nation's next largest consumer of PCs (U.S. DOE 2001). A similar number of PCs is expected to be in use in California's commercial and industrial buildings (Kawamoto et al. 2001). California's enormous appetite for PCs inevitably leads to high PC obsolescence rates: an estimated 10,000 PCs reach the end of their useful life in California every day (CAW 2004).

Table 1 summarizes our estimates for the GHG emissions arising from the manufacture, use, and end-of-life disposition of PCs in California each year. We estimate that over 4 million metric tons of CO₂ equivalents (Mt CO₂e) are emitted each year by California's PC manufacturing operations; an additional 1.7 Mt CO₂e are estimated to be emitted from the use-stage electricity consumption of PCs in California each year. Our combined estimates for the GHG emissions occurring during PC manufacture and PC use in California each year total nearly 6 Mt CO₂e—an amount equivalent to roughly 1.5% of California's 1999 statewide net GHG emissions (CEC 2002). We further estimate that an additional 3.9 kilotons of CO₂ equivalents (kt CO₂e) will be emitted each year from the disposal and demanufacturing processes that are necessary to handle California's continuous stream of discarded obsolete PCs.

Table 1. Annual GHG Emissions of PC Manufacture, Use, and End-of-Life Disposition in California

Life-cycle Stage	Mt CO ₂ e/yr
Manufacturing	4.2
Use	1.7
End-of-Life	3.9e-3
Total	5.9

The estimates in Table 1 are derived from a variety of published data sources.¹ To estimate the annual GHG emissions associated with PC manufacturing operations in California, we focused our analysis on the manufacture of PC control units. It was assumed that PC displays—cathode ray tube (CRT) monitors and liquid crystal displays (LCDs)—are manufactured entirely outside of California based on recent market data (Williams 2003) and therefore that the manufacturing-stage GHG emissions associated with displays are not attributable to California.

We arrived at our estimate of the annual GHG emissions attributable to PC control unit manufacturing in California by utilizing life-cycle inventory (LCI) data for the manufacturing of a generic PC control unit published by Williams (2003, 2004) as our primary data source. We employed a three-step approach. First, we assumed that 169 million PC control units are produced globally each year, based on 2003 market data (Gartner Dataquest 2004). Second, we multiplied the LCI data for manufacturing a single generic PC control unit by our assumed annual production volume of 169 million units to estimate the total global GHG emissions arising from PC control unit manufacture each year. Third, we estimated California's annual share of global GHG emissions arising from PC control unit manufacturing based on international and domestic market share data for the PC control unit manufacturing operations occurring in California (such as semiconductor manufacture, printed circuit board manufacture, final PC control unit assembly, etc.).²

¹ The full methodology and assumptions for the estimates in Table 1 are provided in Masanet et al. (2005).

² The full details and assumptions for this three-step approach are provided in Masanet et al. (2005).

To estimate the annual GHG emissions associated with PC use in California, we assumed that 16 million commercial, industrial, and residential PCs are in use in California, 80% of which were assumed to use CRT monitors and 20% of which were assumed to use LCDs (Roberson et al. 2001). We estimated the annual electricity consumption of California's PCs using power consumption and usage pattern data for PC control units, CRT monitors, and LCDs from Kawamoto et al. (2001), Roberson et al. (2004), and Socolof et al. (2001). We converted use-stage electricity consumption to GHG emissions using a 1999 average emission factor of 0.396 kg CO₂/kWh for the state of California (Marnay et al. 2002).

To estimate the GHG emissions associated with the end-of-life processing of PCs in California each year, we assumed a discard rate of 10,000 PCs per day (CAW 2004), or 3.6 million PCs per year. It was assumed that 100% of discarded CRT monitors and LCDs would be recycled due to the passage of California's landmark Electronic Waste Recycling Act of 2003, which mandates the recycling of waste PC displays in California. It was assumed that only 8% of PC control units would be recycled—PC control unit recycling is currently not covered by the Electronics Waste Recycling Act—based on recent estimates of PC recycling rates in the United States (Matthews & Matthews 2003). The remaining 92% of PC control units were assumed to be disposed of via landfill. We estimated the GHG emissions associated with landfilling PC control units using LCI data from Franklin Associates (1994) and McDougall et al. (2001); the GHG emissions of demanufacturing and recycling PC control units, CRT monitors, and LCDs were estimated using electronics recycling facilities data (Masanet et al. 2005).

For each stage of the PC life cycle, we then identified potential measures for reducing California's annual GHG emissions. For each measure, we estimated the maximum technical potential for GHG emissions reduction in California based on the baseline assumptions we used to derive the estimates in Table 1. In practice, a measure's technical potential is nearly impossible to realize due to a wide variety of factors, including economic constraints, institutional and organizational barriers, and behavioral inertia. However, the technical potential is still a useful metric in illustrating the order of magnitude of potential GHG reduction associated with each measure. The measures and technical GHG reduction potentials identified for PCs are as follows:

- *Reducing PFC emissions in the semiconductor manufacturing process.* Under the U.S. EPA's PFC Reduction and Climate Partnership for the Semiconductor Industry (U.S. EPA 2004), participating semiconductor manufacturers commit to reducing PFC emissions to 10% below their 1995 baseline level by 2010. If this initiative had 100% participation from California-based semiconductor manufacturers, PFC emissions from California's semiconductor industry could be reduced by 30% from 2000 levels, leading to GHG emissions reductions of 0.26 Mt CO₂e/yr.
- *Improving manufacturing energy efficiency.* The benefits of clean room energy-efficiency measures have been well documented: efficiency improvements to process controls and air handling, ventilation, and cooling systems can reduce energy consumption by 30-60% (Naughton 2000). Assuming a conservative 30% improvement in clean room energy efficiency for California-based clean rooms over the current baseline, we estimate that annual GHG emission reductions in California would be 0.72 Mt CO₂e.

- *Maximizing the energy efficiency of California’s PC stock.* If all of California’s residential, industrial, and commercial PCs employed the most energy-efficient control units and displays as certified by the U.S. ENERGY STAR[®] program (U.S. EPA 2005), we estimate that California’s PC stock would consume 6% less electricity per year, leading to annual GHG reductions of 0.10 Mt CO₂.
- *Maximizing the utilization of PC power management features.* We estimated that only 25% of California’s PC control units and 75% of California’s PC displays utilize power management features (Nordman et al. 2000; Roberson et al. 2004). If 100% of California’s PC stock employed power management for both control units and displays, however, the annual savings in electricity consumption would be substantial. We estimate that for the case of 100% power management utilization, the electricity consumption of California’s PC stock would be reduced by 28%, leading to annual savings of 0.50 Mt CO₂.
- *Switching from CRT monitors to LCDs.* LCDs consume significantly less energy during operation than CRT monitors (Socolof et al. 2001). If all of California’s CRT monitors were replaced by LCDs, we estimate that California’s PC stock would consume 28% less electricity per year, leading to annual savings of 0.50 Mt CO₂.
- *Upgrading PCs to extend their useful life.* PC upgrading has been suggested as an effective strategy for reducing the environmental impacts associated with a PC’s life cycle—by reducing the demand for newly-manufactured PCs, the environmental burdens arising from PC manufacturing are reduced. We estimate that upgrading 100% of California’s 16 million PCs to extend their life by 50% would lead to GHG emissions reductions of nearly 19 kt CO₂ per year.

Table 2 summarizes the identified measures for PCs and the estimated technical potential GHG reductions associated with each measure. The percent savings in Table 2 are in relation to the estimated total annual life-cycle GHG emissions from PCs in California in Table 1 (i.e., 5.90 Mt CO₂e/yr).

Table 2. Summary of Potential Measures for Reducing GHG Emissions Across the PC Life Cycle in California

Life-Cycle Stage	Measure Description	Technical Potential for GHG Reduction	
		Mt CO ₂ e/yr	%
Manufacturing	Reduce PFC emissions from semiconductor manufacturing	0.26	4%
	Improve clean room energy efficiency	0.72	12%
Use	Maximize PC energy efficiency	0.10	2%
	Maximize PC power management utilization	0.47	8%
	Switch from CRT monitors to LCDs	0.48	8%
End-of-Life	Upgrade PCs to extend useful life	0.02	0.3%

It must be noted that the estimates in Table 2 are inherently rough as the baselines from which they are derived are based on secondary data from a wide range of sources—including many LCI data for which the uncertainty is unknown—as well as many simplifying assumptions

(Masanet et al. 2005). Additionally, the use-stage estimates in Table 2 do not address the increasing penetration of energy-efficient PCs and LCDs that is likely to occur naturally due to regular PC stock turnover. Thus the estimates in Table 2 should be interpreted as illustrative of the potential GHG reductions for PCs in California rather than as definitive. Nonetheless, the estimates in Table 2 are useful in illuminating the potential order of magnitude of GHG reduction associated with each measure and can be a valuable first step toward launching more detailed analyses of GHG reduction potential.

Concrete

Concrete is manufactured using a mixture of 10-15% cement, 60-70% aggregates (gravel or crushed stone and sand), and 10-15% water. In 2002, California produced over 11 million tonnes of cement in eight plants, making California the largest cement-producing state in the United States (USGS 2003). In California, the cement industry employs approximately 2,000 workers and has an annual value of shipments of about \$850 million (Coito 2004). Concrete is used for many different applications, including the construction of commercial buildings and road construction. The concrete and ready-mix industries in California together employ over 16,000 employees and have an annual value of shipments of around \$2.8 billion.

Table 3 summarizes our estimates of the life-cycle GHG emissions associated with the manufacture, use, and end-of-life disposition of concrete in California each year.³ The total life-cycle GHG emissions of concrete amount to 11.4 Mt CO₂e per year, or nearly 3% of California's 1999 statewide net GHG emissions (CEC 2002).

Table 3. Annual GHG Emissions of Concrete Manufacture, Use, and End-of-Life Disposition in California

Life-Cycle Stage	Product	Mt CO₂e/yr
Manufacturing	Cement	10.4
	Concrete	1.0
	Total	11.4
Use	Concrete	--
End-of-Life	Concrete	0.02
Total		11.4

The estimates in Table 3 are derived from a variety of published data sources. For cement manufacture, we employ a GHG emissions intensity estimate of 1,047 kg CO₂e/t cement for the U.S. cement sector; this estimate was provided by Carnegie Mellon University's Economic Input-Output Life Cycle Assessment (EIO-LCA) database (CMU 2004). The EIO-LCA GHG emissions intensity estimate was adjusted to reflect the fact that California's cement

³ The full methodology and assumptions for the estimates in Table 3 are provided in Masanet et al. (2005).

manufacturing industry is 11% more energy efficient than the U.S. average (Masanet et al. 2005). Next, we multiplied the adjusted energy intensity for California cement manufacture (932 kg CO₂e/t) by the estimated 2001 production volume of cement for concrete in California (11.2 million tonnes) (USGS 2003) to arrive at our Table 3 estimate of 10.4 Mt CO₂e/yr for cement manufacture.

We estimated that the energy consumed in aggregate mining, mixing, shaping, and transport for final concrete manufacture produces an additional 1.0 Mt CO₂/yr (Heijningen et al. 1992) at the manufacturing stage. Energy consumption during the use stage of concrete was assumed to be negligible.

At the end-of-life stage, concrete can be recycled as roadfill and aggregate. The California Integrated Waste Management Board (CIWMB) estimates the total amount of concrete waste in California at only 400,000 tonnes annually (CIWMB 1999), suggesting that large amounts of concrete are recycled. Assuming a GHG emissions intensity for concrete waste collection and disposal of 46.6 kg CO₂e/t (Franklin Associates 1994; McDougall et al. 2001), we estimate GHG emissions of 0.02 Mt CO₂e/yr for concrete end-of-life disposition in California. This estimate addresses only disposal GHG emissions and does not include the GHG emissions arising from concrete recycling operations in California each year (e.g., the GHGs arising from crushing, screening, etc.) due to lack of published data.

For each stage of the concrete life cycle, we then identified potential measures for reducing California's annual GHG emissions. For each measure, we estimated the maximum technical potential for GHG emissions reduction in California based on the baseline assumptions we used to derive the estimates in Table 3. As in the PC case study, our estimates for the technical potential associated with each identified measure are of a preliminary nature and should therefore be interpreted as illustrative rather than definitive. The measures and technical GHG reduction potentials identified for concrete in California are as follows:

- *Improving energy efficiency in cement manufacture.* The greatest gain in reducing energy input and related GHG emissions in cement manufacture may come from improved fuel efficiency. Fuel efficiency measures include optimization of cement clinker coolers, improvement of preheating efficiency, improved burners, and process control and management systems (Worrell and Galitsky 2004). Assuming a technical potential for energy efficiency improvement in California of 22% (Coito 2004), we estimate that total GHG emissions of cement manufacture could be reduced by 0.19 Mt CO₂/yr.
- *Using waste-derived fuels in cement manufacture.* Following the lead taken by the cement industry in Europe, the use of waste fuels has steadily increased in the U.S. cement industry (Worrell and Galitsky 2004). We assume that on average a 20% replacement of fossil fuels by waste fuels is possible in cement kilns in California, which would result in a GHG reduction of 0.62 Mt CO₂/yr.
- *Using blended cement.* Blended cements, in which cementitious alternatives (such as fly-ash from coal fired power stations) are inter-ground with cement clinker, can significantly reduce CO₂ emissions from cement manufacturing. The inter-grinding of clinker with other

additives can reduce the energy used (and CO₂ emitted) in cement clinker production and can also lead to a reduction in CO₂ emissions during cement calcination (Masanet et al. 2005). Based on average savings for the U.S., we estimated that the total reduction in GHG emissions would be 0.55 Mt CO₂/yr assuming a replacement of 20% of Portland cement production by blended cement in California, although we note that this may be difficult due to lack of availability of blending materials.

- *Adding limestone to Portland cement.* When ground limestone is inter-ground with cement clinker to produce cement, the needs for clinker-making and its associated calcinations are reduced. This reduces energy use in the cement kiln and in clinker grinding and also reduces CO₂ emissions from calcination and energy use. Adding 5% limestone would reduce fuel consumption by 5%, power consumption for grinding by 3.3 kWh/t cement, and CO₂ emissions by almost 5% leading to total CO₂ emission reductions of 0.44 Mt CO₂/yr (Masanet et al. 2005).
- *Increasing concrete recycling.* A study by the U.S. Environmental Protection Agency (2003) estimated the net benefit of recycling concrete as aggregate at 2.1 kg of carbon per tonne of recycled concrete. Assuming that all 400,000 tonnes of waste concrete in California can be recycled each year, the total GHG emissions reduction from recycling California's waste concrete would be roughly 4 kt CO₂/yr.

Table 4 summarizes the identified measures for concrete and the estimated technical potential GHG reductions associated with each measure. The percent savings in Table 4 are in relation to the estimated total annual life-cycle GHG emissions from concrete in California in Table 3 (i.e., 11.4 Mt CO₂e/yr).

Table 4. Summary of Potential Measures for Reducing GHG Emissions Across the Concrete Life Cycle in California

Life-Cycle Stage	Measure Description	Technical Potential for GHG Reduction	
		Mt CO ₂ e/yr	%
Manufacturing	Improve energy efficiency	0.68	6.0%
	Use waste-derived fuels	0.62	5.4%
	Use blended cement	0.55	4.8%
	Add limestone to Portland cement	0.44	3.8%
End-of-Life	Increase concrete recycling	0.004	0.03%

Discussion of Policy Opportunities

Personal Computers

In the manufacturing stage, we estimate that the greatest technical potential for GHG emissions reduction in California is associated with clean room energy efficiency improvements. However, it has been estimated that many clean room energy efficiency opportunities in the U.S. are currently unrealized due to wide range of factors. For example, extremely compressed production cycles may leave little time for efficiency improvement, companies may worry that

the introduction of new technologies will affect production reliability, or there may be a general lack of awareness of the financial benefits of energy efficiency improvements (Robertson 1996). Policy efforts to publicize success stories that quantify the financial benefits of clean room energy efficiency improvements and to promote the adoption of facility environmental management standards focused on continuous improvement (such as ISO 14000) might help to overcome this inertia.

There are also appreciable GHG reductions that might be realized in California through the continued reduction of PFC emissions in semiconductor manufacturing. Much work is occurring on this front through the U.S. EPA's PFC Reduction/Climate Partnership for the Semiconductor Industry. Nevertheless, for such voluntary initiatives to be successful, a high rate of industry participation should be encouraged in California.

Increasing the utilization of power management features during the use phase of the PC life cycle might also lead to significant reductions in California's GHG emissions. However, power management technology cannot reach its full potential if PC users do not fully utilize this feature. Its potential will also be reduced if PC users leave their PCs on overnight or during extended periods of nonuse. These barriers might be overcome through the deployment of facility "switch-off" policies and campaigns to encourage PC users to enable power management features in PCs that do not do so automatically. We estimate that roughly 75% of the electricity consumed by PCs in California is due to industrial and commercial PCs (Masanet et al. 2005). Thus, power management campaigns for California businesses could be particularly effective.

Two additional strategies for reducing the use stage GHG emissions of California's PCs are the promotion of energy-efficient PC control units and displays (e.g., those that are ENERGY STAR certified) and the encouragement of the use of LCDs due to their superiority in energy efficiency compared to CRT monitors. Given that PCs in California businesses are estimated to consume the majority of PC use-stage energy in California, energy efficiency campaigns aimed at California businesses could be very effective. Both strategies could be integrated with the promotion of PC power management in commercial and industrial facilities to comprise a comprehensive, multi-pronged energy efficiency campaign aimed at California businesses.

Significant GHG emission reductions might also be realized by delaying PC disposal/recycling for as long as possible by extending the life of PCs through upgrading. PC upgrading could be promoted through educational campaigns to highlight its environmental benefits, through institutionalized PC upgrade policies in large office environments, and by promoting the purchase of PCs that are designed for ease of upgrading via institutional green procurement policies (discussed in the next paragraph).

The encouragement of institutional "green procurement" policies might also have a significant impact. Green procurement initiatives reward PC manufacturers that produce energy-efficient, easily-upgradeable, and easily-recyclable PCs by giving those manufacturers preferential purchasing status. For example, institutional buyers could require all purchased PCs to be certified to the most stringent ENERGY STAR standards (among other eco-labels). Another strategy would be for institutional buyers to purchase only IEEE 1621 compliant PCs, a standard

which ensures that PC power management features are consistent, intuitive, and easily enabled by the user. The adoption of green procurement policies by California businesses and government agencies (an enormous market for PCs) could help promote PCs that are upgradeable, energy efficient, and recyclable, leading to significant California GHG reductions.

Concrete

Energy efficiency in cement manufacture represents the most important source of potential emission reductions in the life cycle of concrete. Energy efficiency improvement in the cement industry has been supported by several federal agencies (e.g., U.S. DOE, U.S. EPA), state agencies (e.g., California Energy Commission), and utilities (for a recent overview of industrial energy policies in various countries, see Galitsky et al. 2004).

Our estimates suggest that the use of waste-derived fuels might have a large impact on GHG emissions from cement manufacturing. The use of waste fuels is primarily covered by the environmental permitting process, although permitting (especially for hazardous wastes) is often hampered by local objections to this option. Even so, a cement kiln is a very efficient way to destroy hazardous wastes, destroying 99.9999% of the toxic compounds, and emitting virtually no toxic pollutants. Including the effects on GHG emissions in the evaluation of the permits, as well as within waste management policy in the state, may accelerate the adoption of permits for cement kilns to burn waste fuels in an environmentally sound and safe manner.

We also estimate that changes in the composition of cement (e.g., blended cement and limestone addition) might also offer a substantial potential to reduce GHG emissions from the concrete life cycle. The main policies in supporting the production of alternative compositions of cement are standards, specifications, and purchasing requirements or preferences. There are now new ASTM standards that allow for cement with up to 5% ground limestone still to be classified as Portland cement. However, this innovation has not yet been approved by important users, such as the California Department of Transportation (CalTrans). On the basis of the potential reduction in GHG emissions due to the use of alternative cements, we recommend that state agencies and cities prefer the use of blended cements in appropriate projects.

Our analysis also showed appreciable GHG reductions can be realized in California through increased recycling of concrete. In California, the CIWMB already supports the recycling of concrete as aggregate (through the California Senate Bill SB1374). CalTrans and other agencies also support further studies on the use of recycled concrete aggregate in road construction. Policies for promoting further study and adoption of recycled concrete as aggregate—in roadfill, for example—would help California maximize its concrete recycling rates.

Conclusion

GHG emissions, with respect to climate change, represent one of the most significant societal costs associated with energy consumption. In this paper, we presented a preliminary roadmap for reducing these high GHG “costs”—both energy-related and process-related—across

the life cycle of PCs and concrete in California each year. While our analysis is of a preliminary nature, our estimates are useful in illuminating the order of magnitude of potential GHG reductions associated with each identified measure. This information, coupled with our suggested policy opportunities, should prove useful in launching more detailed policy analyses (which would include detailed studies of measure penetration, cost benefit analyses, assessments of technological feasibility, etc.) to support GHG reduction policy initiatives in California.

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