Title

An Analysis of Measures to Reduce the Life-Cycle Energy Consumption and Greenhouse Gas Emissions of California's Personal Computers

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FINAL PROJECT REPORT

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Project title: **An Analysis of Measures to Reduce the Life-Cycle Energy Consumption and Greenhouse Gas Emissions of California's Personal Computers**

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1 INTRODUCTION

Personal computers (PCs) are one of the most ubiquitous and indispensable electronic devices in use within California's homes and businesses. More PCs are estimated to be in use in California than in any other U.S. state. According to the latest published estimates from U.S. Department of Energy (DOE), 11.5 million PCs were installed in California's homes (as of 2001) and 6.5 million PCs were installed in California's commercial buildings (as of 2003) (U.S. DOE 2003, 2006a).[1] Based on these DOE data and recent PC sales data, it was estimated in this research project that as of 2005 nearly 19 million PCs were installed in California homes and businesses and that this number is expected to grow significantly through 2012.

This research project focused on evaluating a set of realistic measures aimed at reducing the life-cycle energy use and GHG emissions associated with operating and maintaining California's residential and commercial PC stock (hereafter referred to simply as "California's PC stock"). The term "maintain" is used here to describe the ongoing process of replacing, upgrading, and discarding obsolete PCs within California's PC stock as necessary. The project employed a life-cycle assessment (LCA) approach to characterize both direct and indirect energy use and GHG emissions. Direct energy use and GHG emissions were defined as the energy use and GHG emissions attributable to the operational electricity consumption of California's PC stock. Indirect energy use and GHG emissions were defined as the energy use and GHG emissions attributable to activities that support ongoing PC stock maintenance, namely, the manufacture of new PCs and PC components as needed and the end-of-life treatment (i.e., waste disposal and recycling) of obsolete PCs and PC components.

In this research project, the potential reductions in life-cycle energy use and GHG emissions associated with the measures considered were projected through the year 2012. The purpose of this work was to characterize the effectiveness of these measures to inform PC-related policies for near-term energy efficiency improvements and GHG emission reductions in the State of California. Baseline projections were first established for the life-cycle energy use and GHG emissions associated with operating and maintaining California's PC stock from 2005 to 2012. These baseline projections were made using best-available data from public sources for all key modeling parameters. Whenever possible, ranges for key modeling parameters were established to account for published data variations. Two future scenarios were considered: a low energy use and GHG emissions scenario ("low scenario") and a high energy use and GHG emissions scenario ("high scenario"). The purpose of the two-scenario approach was to establish preliminary upper and lower bounds on the results based on the feasible data ranges identified from the literature for key modeling parameters. The potential reductions in life-cycle energy use and GHG emissions associated with the measures considered were then projected for each scenario over the same time period.

[1] Commercial PC estimate was derived by: (1) assuming that 8.6 million PCs were installed in commercial buildings in the Pacific Census Region in 2003, based on the U.S. DOE 2003 Commercial Building Energy Use Survey (CBECS) (U.S. DOE 2006), and (2) assuming that 75% of Pacific Census Region commercial sector employment (as defined by the 2003 CBECS) and hence PC usage occurs in California based on employment data from the U.S. Census Bureau (U.S. Census Bureau 2006).

2 RESULTS

2.1 California PC Stock Growth

Table 1 summarizes the projected growth in California's residential PC stock from 2005 to 2012. Projections were made for the total number of PCs installed in California homes as well at the number of notebook PCs, desktop PCs with cathode ray tube (CRT) monitors, and desktop PCs with flat panel displays (FPDs) that comprise California's residential PC stock.

The data on total PCs in Table 1 were derived based on California's projected population growth from the California Department of Finance (California DOF 2004, 2006) and estimated PC penetrations in California homes from the U.S. DOE Residential Energy Consumption Survey (RECS) (U.S. DOE 2003) and the California Residential Appliance Saturation Survey (RASS) (Kema-Xenergy et al. 2004). Furthermore, an average of 2.85 persons per California household was assumed (California DOF 2005; U.S. Census Bureau 2006). For the low scenario, it was assumed that the average 2003 California residential PC penetration of 0.94 PCs per household (RECS and RASS average) would remain constant through 2012. For the high scenario, it was assumed that the average 2003 California residential PC penetration would rise linearly to 1 PC per household by 2012.

Table 1. California Residential PC Stock Projections, 2005-2012

Year	California Population	Low Scenario				High Scenario			
		Total PCs	Notebook PCs	Desktop PCs		Total PCs	Notebook PCs	Desktop PCs	
				w/ CRT	w/ FPD			w/ CRT	w/ FPD
2005	37,005,000	12,102,422	2,987,441	5,651,521	3,463,460	12,398,645	3,060,563	5,789,849	3,548,233
2006	37,461,449	12,251,703	3,263,952	4,521,725	4,466,026	12,626,549	3,363,814	4,660,069	4,602,666
2007	37,917,899	12,400,984	3,585,559	3,563,154	5,252,271	12,856,280	3,717,201	3,693,973	5,445,106
2008	38,374,348	12,550,265	3,948,239	2,790,313	5,811,714	13,087,838	4,117,356	2,909,832	6,060,650
2009	38,830,798	12,699,546	4,348,121	2,166,738	6,184,688	13,321,222	4,560,973	2,272,805	6,487,444
2010	39,246,767	12,835,588	4,776,365	1,648,788	6,410,436	13,542,466	5,039,408	1,739,589	6,763,469
2011	39,703,216	12,984,869	5,238,323	1,227,347	6,519,199	13,779,424	5,558,860	1,302,449	6,918,114
2012	40,159,666	13,134,150	5,725,155	880,400	6,528,596	14,018,208	6,110,514	939,659	6,968,035

The data on notebook PCs in Table 1 were derived by first assuming a residential notebook PC penetration of 21% in 2001 based on national-level RECS data (U.S. DOE 2003). Next, the 2005 residential notebook PC penetration was estimated at 25% based on 2001-2005 notebook and desktop PC sales data (InfoTech Trends 2006) and an assumed average residential PC replacement life of 4.2 years.[2] Lastly, the notebook PC penetration was projected from 2005 to 2012 based on a projected compound annual growth rate in notebook PC sales of 18% (InfoTech Trends 2006), a projected compound annual growth rate in desktop PC sales of 2% (InfoTech Trends 2006), and the assumed average residential PC replacement life.

[2] Based on an average residential PC life of 4 years (Kawamoto et al. 2001), an assumed PC upgrade life extension of 2 years (Masanet and Horvath 2006), and the assumption that 10% of residential PCs are currently upgraded on an ongoing basis.

The data on desktop PCs with CRT monitors versus FPDs were derived in a similar fashion by first assuming a 2005 residential FPD penetration of 38% based on historical PC monitor sales data. Then, the residential FPD penetration was projected through 2012 using published FPD worldwide sales projection data (DisplaySearch 2005) and an assumed replacement life of 4 years for residential displays (Kawamoto et al. 2001). The well-documented rise in popularity and affordability of FPDs is projected to lead to a California residential FPD penetration of nearly 90% by 2012.

Table 2 summarizes the projected growth in California's commercial PC stock from 2005 to 2012. Because no published estimates on the total number of PCs installed in California commercial buildings were available, a 2005 estimate of 6,490,000 California commercial PCs was derived based on CBECS and U.S. Census Bureau data (see footnote 1). A 90% confidence interval of +/- 840,000 PCs was derived for this estimate using the relative standard error values reported for the CBECS data (U.S. DOE 2006a). For the low scenario, the lower 90% confidence limit was used for the 2005 total installed PC estimate in Table 2. For the high scenario, the upper 90% confidence limit was used for the 2005 total installed PC estimate in Table 2.

The projected growth in total commercial PCs from 2005 to 2012 was estimated for the low scenario assuming a projected annual growth rate of 1.6%. For the high scenario, a projected annual growth rate of 1.9% was assumed. These high and low growth rate estimates were based on a feasible range established from published projected annual growth rates for California's commercial space and commercial sector employment (U.S. DOE 2006b, California EDD 2006).

Table 2. California Commercial PC Stock Projections, 2005-2012

Year	Low Scenario				High Scenario			
	Total PCs	Notebook PCs	Desktop PCs		Total PCs	Notebook PCs	Desktop PCs	
			w/ CRT	w/ FPD			w/ CRT	w/ FPD
2005	5,831,306	1,447,286	2,767,834	1,616,186	7,605,738	1,887,686	3,610,070	2,107,982
2006	5,922,338	1,552,481	2,235,571	2,134,286	7,749,857	2,031,547	2,925,425	2,792,885
2007	6,014,791	1,689,710	1,775,719	2,549,361	7,896,707	2,218,389	2,331,308	3,347,009
2008	6,108,687	1,854,099	1,400,416	2,854,171	8,046,339	2,442,212	1,844,623	3,759,504
2009	6,204,048	2,041,977	1,094,738	3,067,333	8,198,806	2,698,525	1,446,724	4,053,558
2010	6,300,899	2,250,417	839,545	3,210,937	8,354,163	2,983,757	1,113,126	4,257,280
2011	6,399,261	2,476,911	629,352	3,292,998	8,512,463	3,294,852	837,180	4,380,431
2012	6,499,159	2,719,175	454,882	3,325,102	8,673,763	3,629,005	607,084	4,437,674

The Table 2 projections for notebook PCs, desktop PCs with CRT monitors, and desktop PCs with FPDs were derived using similar approaches as those used for the residential PC projections in Table 1. For commercial notebook PCs, an initial 2004 penetration of 25% was assumed (Mitchell 2005). The commercial notebook PC penetration was then projected to 2012 based on an assumed commercial notebook PC replacement life of 3.1 years, an assumed commercial desktop PC replacement life of 4.2 years, and the projected compound annual growth rates for

notebook and desktop PC sales described for residential PCs above.[3] For commercial desktop PCs with FPDs, an initial 2003 penetration of 17% was assumed (Roberson et al. 2004). The commercial PC FPD penetration was then projected through 2012 using the FPD sales projection data described for residential PCs above and an assumed replacement life of 4 years for commercial displays (Kawamoto et al. 2001). As for residential desktop PCs, the penetration of commercial desktop PCs with FPDs is also expected to rise to nearly 90% by the year 2012.

2.2 Direct Energy Use and GHG Emissions

Table 3 summarizes the assumed average 2005 unit energy consumption (UEC) values for California's residential PC stock based on the UEC approach documented by Kawamoto et al. (2001). Data are provided per device for PC control units, CRT monitors, FPDs, stand-alone notebook PCs, and notebook PCs that regularly use an external FPD in lieu of the internal screen. The data for the low scenario assume the highest estimates for power management enabling rates and the least power-intensive estimates for daily usage patterns compiled from recent publicly-available data sources (Kawamoto et al. 2001; EPIC-ICT 2006; U.S. EPA 2005; Foster and Calwell 2003; Nordman et al. 2000; Socolof et al. 2001). The data for the high scenario assume the lowest estimates for power management enabling rates and the most power-intensive daily usage patterns compiled from the above data sources. All UEC values were converted to primary energy use and GHG emissions in Table 3 using average conversion factors for California of 9.2 megajoules per kilowatt-hour (MJ/kWh) and 0.4 kilograms of carbon dioxide equivalents per kilowatt-hour (kg CO_2e/kWh) (Masanet et al. 2005; Marnay et al. 2002).

Table 3. 2005 Direct Energy Use and GHG Emissions (Per Device), Residential PCs

Device	Low Scenario			High Scenario		
	UEC (kWh/yr)	Primary Energy Use (MJ/yr)	GHG Emissions (kg CO2e/yr)	UEC (kWh/yr)	Primary Energy Use (MJ/yr)	GHG Emissions (kg CO2e/yr)
PC control unit	67	612	26	208	1916	82
CRT monitor	61	561	24	162	1490	64
FPD	32	298	13	84	776	33
Notebook PC	28	262	11	75	690	30
Notebook PC w/ external FPD	63	581	25	167	1533	66

Table 4 summarizes the assumed average 2005 UEC values for California's commercial PC stock. The low scenario assumes the highest estimates for power management enabling rates compiled from the data sources listed in the previous paragraph. The high scenario assumes the lowest estimates for power management enabling rates compiled from these data sources. An average commercial usage scenario from Kawamoto et al. (2001) was used. All UEC values were converted to primary energy use and GHG emissions in Table 4 using the above conversion

[3] Based on an average commercial notebook PC life of 3 years (Dunn 2005), an average commercial desktop PC life of 4 years (Kawamoto et al. 2001), an assumed notebook PC upgrade life extension of 1 year, and assumed desktop PC upgrade life extension of 2 years, and the assumption that 10% of commercial PCs are currently upgraded on an ongoing basis.

factors. The UEC estimates in Table 4 do not include potential reductions in PC usage within California associated with business travel due to lack of data.

Table 4. 2005 Direct Energy Use and GHG Emissions (Per Device), Commercial PCs

Device	Low Scenario			High Scenario		
	UEC (kWh/yr)	Primary Energy Use (MJ/yr)	GHG Emissions (kg CO2e/yr)	UEC (kWh/yr)	Primary Energy Use (MJ/yr)	GHG Emissions (kg CO2e/yr)
PC control unit	240	2206	95	272	2502	108
CRT monitor	167	1535	66	201	1846	79
FPD	88	809	35	105	963	41
Notebook PC	88	813	35	101	930	40
Notebook PC w/ external FPD	202	1855	80	230	2116	91

Table 5 summarizes the projected annual direct primary energy use and GHG emissions of California's PC stock (residential plus commercial) from 2005 to 2012 using the data in Tables 1-4. No published estimates could be found on the percentage of notebook PCs that are used with an external FPD (as opposed to stand-alone use) in residential and commercial scenarios. It was therefore assumed that 50% of commercial notebooks and 25% of residential notebooks would be used with an external FPD based on observation and expert judgment.

It was further estimated in Table 5 that the 2005 UEC values in Tables 3 and 4 would remain constant through 2012. For PC control units and notebook PCs, this estimate was based on the simplifying assumption that increases in PC operating power requirements (through increased PC usage and increasing energy consumption by power hungry components such as graphics cards) would be offset on an aggregate level by the adoption of more energy efficient processors (see for example Gomes (2006)) and more energy efficient power supplies (see for example Ashley (2004)) over the same time period. For displays, it was assumed that the energy efficiency of current CRT monitor and FPD technologies would remain stable through 2012.

It can be seen in Table 5 that although the total number of PCs in California is expected to rise significantly between 2005 and 2012 (see Tables 1 and 2), the annual primary energy use and GHG emissions of California's PC stock are expected to decline over the same period due to increasing penetrations of energy efficient notebook PCs and FPDs. Based on the projections in Table 5, it is estimated that cumulatively over the period 2005-2012 California's PC stock will consume directly 208-435 PJ of primary energy and will emit directly 9-19 million Mg of CO_2e.

Table 5. Direct Energy Use and GHG Emissions Projections, California PC Stock (Residential + Commercial) 2005-2012

Year	Low Scenario		High Scenario	
	Primary Energy Use (PJ/yr)	GHG Emissions (10^6 Mg CO_2e/yr)	Primary Energy Use (MJ/yr)	GHG Emissions (10^6 Mg CO_2e/yr)
2005	28.0	1.20	57.9	2.49
2006	27.4	1.18	56.8	2.44
2007	26.8	1.15	55.7	2.40
2008	26.2	1.13	54.7	2.35
2009	25.7	1.11	53.8	2.31
2010	25.2	1.09	52.8	2.27
2011	24.8	1.07	51.9	2.23
2012	24.3	1.05	51.0	2.20
Total	**208.3**	**8.97**	**434.6**	**18.71**

2.3 Indirect Energy Use and GHG Emissions

Tables 6 and 7 summarize the projected numbers of new notebook PCs, PC control units, CRT monitors, FPDs, and upgrade kits that must be manufactured each year to replenish California's PC stock from 2005-2012 for the low scenario and high scenario, respectively. The data in Tables 6 and 7 were estimated based on the stock projections in Tables 1 and 2, the assumed replacement lives and upgrade life extensions of each device discussed in Section 2.1, and the assumption that 10% of California's PC control units and notebook PCs (both residential and commercial) are currently upgraded on an ongoing basis.[4]

Table 6. Projected New PC Devices Manufactured (Low Scenario) for California's PC Stock (Residential + Commercial), 2005-2012

Year	Low Scenario					
	Notebook PCs	PC Control Units	CRT Monitors	FPDs	Notebook Upgrade Kits	Control Unit Upgrade Kits
2005	1,370,427	3,150,355	1,345,380	2,312,763	107,386	319,409
2006	1,455,566	3,052,699	1,184,929	2,788,616	107,386	319,409
2007	1,503,473	2,976,990	990,566	2,878,637	104,139	319,409
2008	1,803,180	3,024,996	669,855	2,599,979	130,219	332,164
2009	1,970,086	2,811,611	416,126	3,092,808	140,922	315,036
2010	2,083,321	2,675,803	411,786	3,369,248	145,838	305,270
2011	2,284,388	2,553,517	358,933	3,298,198	161,637	297,699
2012	2,570,548	2,547,850	148,437	2,884,319	187,147	302,500

[4] No reliable published data could be found on the extent to which upgrading is currently practiced in the United States for residential and commercial PCs. Recent data from Europe suggest that as few as 2% of residential and commercial users will upgrade a PC at the end of its useful life (Jönbrink and Amen 2006). In this study, a rate of 10% is conservatively assumed for California based on observation and expert judgment.

Table 7. Projected New PC Devices Manufactured (High Scenario) for California's PC Stock (Residential + Commercial), 2005-2012

Year	High Scenario					
	Notebook PCs	PC Control Units	CRT Monitors	FPDs	Notebook Upgrade Kits	Control Unit Upgrade Kits
2005	1,561,444	3,580,409	1,525,725	2,615,910	121,627	353,148
2006	1,663,378	3,456,388	1,326,832	3,168,750	121,627	353,148
2007	1,723,923	3,367,827	1,097,773	3,287,226	118,007	353,148
2008	2,082,588	3,446,190	804,125	2,998,712	148,956	370,648
2009	2,282,326	3,261,438	490,798	3,575,819	161,280	358,041
2010	2,424,166	3,094,330	460,018	3,910,722	167,379	345,639
2011	2,678,670	2,953,795	384,688	3,850,433	187,311	336,783
2012	3,024,854	2,961,488	211,239	3,410,866	217,417	344,619

Table 8 summarizes the projected numbers of each PC device that will be discarded each year from California's PC stock between 2005 and 2012 for the low and high scenarios. The data in Table 8 were derived by performing a device input-output balance each year using the data in Tables 1, 2, 6 and 7.

Table 8. Projections for PC Devices Discarded from California's PC Stock (Residential + Commercial), 2005-2012

Year	Low Scenario				High Scenario			
	Notebook PCs	PC Control Units	CRT Monitors	FPDs	Notebook PCs	PC Control Units	CRT Monitors	FPDs
2005	1,073,860	3,194,093	2,846,988	764,150	1,216,267	3,519,412	3,141,257	854,447
2006	1,073,860	3,194,093	2,846,988	1,146,225	1,216,267	3,531,476	3,141,257	1,281,671
2007	1,044,637	3,194,093	2,408,990	1,528,300	1,183,693	3,531,476	2,657,986	1,708,895
2008	1,276,113	3,308,887	1,817,998	1,562,863	1,458,610	3,688,977	2,074,951	1,758,724
2009	1,382,325	3,154,729	1,345,380	2,312,763	1,582,396	3,575,515	1,525,725	2,615,910
2010	1,446,638	3,079,594	1,184,929	2,788,616	1,660,500	3,481,397	1,326,832	3,168,750
2011	1,595,935	2,994,326	990,566	2,878,637	1,848,122	3,389,085	1,097,773	3,287,226
2012	1,841,453	3,027,767	669,855	2,599,979	2,139,047	3,447,210	804,125	2,998,712

Table 9 summarizes the projected annual indirect primary energy use and GHG emissions associated with the maintenance of California's PC stock (residential plus commercial) from 2005 to 2012. The projections in Table 9 were derived using the data in Tables 6-8 and data on the indirect primary energy use and GHG emissions requirements associated with the manufacture of new PC devices and the end-of-life treatment of discarded PC devices tabulated

in Masanet and Horvath (2006).[5] A recycling rate of 100% was assumed for notebook PCs, CRT monitors, and FPDs in California and a recycling rate of 15% was assumed for PC control units in California based on national-level estimates (Masanet and Horvath 2006).

Based on the projections in Table 9, it is estimated that cumulatively over the period 2005-2012 California's PC stock will consume indirectly 298-343 PJ of primary energy and will emit indirectly 26-31 million Mg of CO_2e.

Table 9. Indirect Energy Use and GHG Emissions Projections, California PC Stock (Residential + Commercial) 2005-2012

Year	Low Scenario		High Scenario	
	Primary Energy Use (PJ/yr)	GHG Emissions (10^6 Mg CO_2e/yr)	Primary Energy Use (MJ/yr)	GHG Emissions (10^6 Mg CO_2e/yr)
2005	39.2	3.03	44.6	3.45
2006	38.9	3.20	44.1	3.64
2007	37.7	3.21	42.7	3.66
2008	37.1	3.23	42.9	3.71
2009	36.1	3.39	42.0	3.92
2010	36.5	3.49	42.3	4.05
2011	36.5	3.49	42.4	4.07
2012	36.0	3.43	42.5	4.03
Total	**298.1**	**26.47**	**343.3**	**30.52**

[5] To generate the projections in Table 9, data on the primary energy use and GHG emissions associated with the manufacture and end-of-life treatment of notebook PCs were derived from data for PC control units from Masanet and Horvath (2006) due to a current lack of publicly-available LCA data for notebook PCs. It was also assumed that an "upgrade kit" would consist of a new hard disk drive and the addition of 256MB to 512MB of memory for both residential and commercial PC control units and notebook PCs. It was assumed that 790 MJ of primary energy would be used and 72 $kgCO2_e$ would be emitted during the manufacture of each upgrade kit based on estimates obtained from Carnegie Mellon's Economic Input-Output Life-Cycle Assessment database (Carnegie Mellon University 2006).

2.4 Baseline Projections

Table 10 presents the baseline projections of primary energy use and GHG emissions associated with operating and maintaining California's PC stock (residential plus commercial) from 2005 to 2012, based on the data summarized in Tables 5 and 9.

Table 10. Direct and Indirect Energy Use and GHG Emissions Projections, California PC Stock (Residential + Commercial) 2005-2012

Year	Low Scenario						High Scenario					
	Primary Energy Use (PJ/yr)			GHG Emissions (10^6 Mg CO_2e/yr)			Primary Energy Use (PJ/yr)			GHG Emissions (10^6 Mg CO_2e/yr)		
	Indirect	Direct	Total	Indirect	Direct	Total	Indirect	Direct	Total	Indirect	Direct	Total
2005	39.2	28.0	67.2	3.03	1.20	4.24	44.6	57.9	102.5	3.45	2.49	5.94
2006	38.9	27.4	66.2	3.20	1.18	4.38	44.1	56.8	100.9	3.64	2.44	6.08
2007	37.7	26.8	64.4	3.21	1.15	4.37	42.7	55.7	98.4	3.66	2.40	6.05
2008	37.1	26.2	63.4	3.23	1.13	4.36	42.9	54.7	97.6	3.71	2.35	6.06
2009	36.1	25.7	61.9	3.39	1.11	4.49	42.0	53.8	95.7	3.92	2.31	6.24
2010	36.5	25.2	61.8	3.49	1.09	4.57	42.3	52.8	95.1	4.05	2.27	6.32
2011	36.5	24.8	61.3	3.49	1.07	4.56	42.4	51.9	94.3	4.07	2.23	6.30
2012	36.0	24.3	60.3	3.43	1.05	4.47	42.5	51.0	93.5	4.03	2.20	6.22
Total	**298.1**	**208.3**	**506.5**	**26.47**	**8.97**	**35.43**	**343.3**	**434.6**	**777.9**	**30.52**	**18.71**	**49.22**
% Total	**59%**	**41%**	**100%**	**75%**	**25%**	**100%**	**44%**	**56%**	**100%**	**62%**	**38%**	**100%**

2.5 Primary Energy Use and GHG Emissions Reduction Potential

Table 11 summarizes the specific measures that were considered in this project, which are aimed at reducing the life-cycle energy use and GHG emissions associated with operating and maintaining California's PC stock. The general modeling framework for evaluating the effectiveness of the measures listed in Table 11 (with respect to the baseline projections presented in Table 10) as well as the data assumptions related to the evaluation are discussed in detail in Masanet and Horvath (2006). The evaluation of measures performed in this project was focused solely on quantifying the technical potential of the measures in Table 11 (i.e., economic, social, and institutional barriers were not considered). Furthermore, it was assumed that all measures could be implemented in 2005 to quantify the maximum theoretically achievable (i.e., upper bound) reductions in primary energy use and GHG emissions associated with the measures through the year 2012.[6]

[6] However, the baseline projections presented in this report and the modeling framework developed in this research project (described in Masanet and Horvath (2006)) can easily be used to evaluate alternate assumption scenarios, such as when measures are rolled out over several years or are implemented at less than technically-achievable implementation levels.

Table 11. Summary of Measures Considered

Measure	Description
A	Replace all CRT monitors with FPDs
B	Enable power management on 100% of PC control units, notebook PCs, and displays
C	Utilize only ENERGY STAR certified PC control units, notebook PCs, and displays[7]
D	Turn off all PC control units, notebook PCs, and displays during non-use hours
E	Upgrade 100% of PC control units and notebook PCs to extend life by 2 years
F	100% recycling of PC control units

Tables 12 and 13 summarize the estimated technical potential for reductions in cumulative primary energy use and GHG emissions (2005-2012) associated with the measures considered in this research project for the low and high scenarios. The data in Tables 12 and 13 are presented in a cumulative fashion to demonstrate the potential of combined measures (as opposed to the application of individual measures in isolation).

The cumulative, technically-achievable reduction in primary energy use over the period 2005-2012 given the combined application of measures in Table 11 to California's PC stock is estimated at 35% to 45%, or 178-349 PJ. The cumulative, technically-achievable reduction in GHG emissions over the period 2005-2012 given the combined application of these measures to California's PC stock is estimated at 16% to 26%, or 6-13 million Mg of CO2e.

Table 12. Cumulative Direct and Indirect Primary Energy Use and GHG Emissions Associated with Measure Application (Low Scenario), 2005-2012

Scenario	Low Scenario							
	Primary Energy Use (PJ/yr)				GHG Emissions (10^6 Mg CO_2e/yr)			
	Indirect	Direct	Total	% of Baseline	Indirect	Direct	Total	% of Baseline
Baseline	298.1	208.3	506.5	100%	26.47	8.97	35.43	100%
A	271.4	194.3	465.7	92%	28.17	8.36	36.53	103%
A+B	271.4	125.9	397.2	78%	28.17	5.42	33.58	95%
A+B+C	271.4	116.5	387.9	77%	28.17	5.01	33.18	94%
A+B+C+D	271.4	106.3	377.7	75%	28.17	4.58	32.74	92%
A+B+C+D+E	228.1	108.3	336.4	66%	25.43	4.66	30.09	85%
A+B+C+D+E+F	220.2	108.3	328.5	65%	24.99	4.66	29.65	84%

[7] This research project did not consider the new ENERGY STAR 4.0 specification for PC devices, which will take effect on July 20, 2007 (U.S. EPA 2006), because the new specification was issued subsequent to the completion of this project.

Table 13. Cumulative Direct and Indirect Primary Energy Use and GHG Emissions Associated with Measure Application (High Scenario), 2005-2012

Scenario	High Scenario							
	Primary Energy Use (PJ/yr)				GHG Emissions (10^6 Mg CO_2e/yr)			
	Indirect	Direct	Total	% of Baseline	Indirect	Direct	Total	% of Baseline
Baseline	343.3	434.6	777.9	100%	30.52	18.71	49.22	100%
A	312.8	404.9	717.7	92%	32.45	17.43	49.88	101%
A+B	312.8	209.5	522.3	67%	32.45	9.02	41.47	84%
A+B+C	312.8	196.2	509.0	65%	32.45	8.44	40.90	83%
A+B+C+D	312.8	170.5	483.3	62%	32.45	7.34	39.79	81%
A+B+C+D+E	263.9	174.0	437.8	56%	29.35	7.49	36.84	75%
A+B+C+D+E+F	255.0	174.0	429.0	55%	28.86	7.49	36.35	74%

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