California's Energy Future - Buildings & Industrial Efficiency

California Council on Science and Technology
November 2012

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ACKNOWLEDGEMENTS

We would like to thank the Stephen Bechtel Fund and the California Energy Commision for their contributions to the underwriting of this project. We would also like to thank the California Air Resources Board for their continued support and Lawrence Livermore National Laboratory for underwriting the leadership of this effort. In addition, we thank all of the California's Energy Future (CEF) committee members who provided input in the course of developing the set of portraits and technology evaluations presented here. We are indebted to the many people who reviewed this report at various stages, including: M. Daniel DeCillis (CCST staff), David Goldstein (Natural Resources Defense Council), Dan Kammen (CEF committee member), Nate Lewis (CEF committee member), Jane Long (CEF committee co-chair), Maxine Savitz (CEF committee member), and Gernot Wagner (Environmental Defense Fund). If we forgot to acknowledge anyone else who contributed, we apologize for the omission and are grateful for the suggestions.

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Library of Congress
Cataloging Number in Publications Data Main Entry Under Title:
California's Energy Future:
Buildings and Industrial Efficiency
November 2012
ISBN-13: 978-1-930117-73-0

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Message From CCST

The California Council on Science and Technology (CCST) has produced a series of reports documenting the technology required to meet radical greenhouse gas (GHG) emission cuts by 2050 (80% below 1990 levels). As part of this study, CCST is pleased to present the results of an analysis of buildings and industrial energy efficiency potentials in California, including replacement of natural gas combustion with electricity. This study is part of the California's Energy Future (CEF) project, which was undertaken to help inform California state and local governments of the scale and timing of decisions that must be made in order to achieve the state's goals of significantly reducing total GHG emissions over the next four decades.

California's Global Warming Solutions Act of 2006 (AB32) and Executive Order S-3-05 set strict standards for the state to meet. In order to comply, California needs to reduce its greenhouse gas emissions to 80% below 1990 levels by 2050 while accommodating projected growth in its economy and population. This will likely require maximizing efficiency in all economic sectors, electrification of much of the transportation sector and many stationary uses of heat, a doubling of electricity production with nearly zero emissions, and development of low-carbon fuels. Achieving these efficiency and electrification goals will require concerted State effort to overcome economic, institutional and other barriers to implementation. This report is a summary of both maximum "stress test" and realistic potentials of these technologies for California, for the residential and commercial buildings sector, and the industrial sector. A separate report on the transportation sector which includes information on vehicle efficiency, was published in December 2011, and is available on the CCST website.

We believe that the CEF buildings and industrial efficiency report presents valuable insights into the possibilities and realities of meeting California's future energy needs and GHG emissions targets by 2050, and hope that you will find it useful.

Jane C.S. Long
California's Energy Future Committee
Co-chair

Miriam John
California's Energy Future Committee
Co-chair

I. Introduction

This report summarizes some of the work of the California's Energy Future (CEF) committee to quantify the potential for reductions in energy demand through increased energy efficiency throughout the California economy between the present day and 2050. This work took place between April 2009 and January 2011, while improvements to the efficiency analysis itself continued through April 2012. The report developed and explored California's possible efficiency and electrification pathways through 2050 in California in the buildings and industrial sectors (the transportation sector is dealt with in a separate report; see Yang et al., 2011, though demand projections for all sectors, including transportation, are summarized in the current report). It does not consider specific policy requirements to achieve these goals; that is the focus of a new effort called the *California's Energy Future Policy* project, for which work is still ongoing. Where possible, we have identified barriers to implementation, opportunities and synergies with other activities, and highlighted research needs, but the focus of the report is on the technical requirements of achieving high efficiency gains in the State.

Analysis consisted both of a set of "stress test" (maximum technical potential) and a set of "realistic" cases (assuming aggressive but achievable policy mechanisms, and tolerance of modest cost increases). The stress test analyses, the details of which can be found in the appendices, tested whether a single strategy (e.g., efficiency) could alone solve the energy and emission problem. Because population and economic growth are projected in the business-as-usual (BAU) case to roughly double the total demand for energy services by 2050, achieving 80% GHG reduction from 1990 levels actually requires a 90% reduction from 2050 BAU emissions. It was concluded that efficiency alone was not able to achieve this formidable target, but the analyses did provide insights about the upper limits of each technical solution.

Three realistic cases were examined in the main CEF study:

- **Case C (Conventional):** BAU growth in demand in all sectors, based on extrapolation of state projections (see the section, *Growth Scenario Description*)
- **Case E (Efficiency and Electrification):** Starting from Case C, aggressive efficiency and electrification in the Buildings, Industry and Transportation sectors
- **Case H (Hydrogen)**: As for Case E above, but with maximum feasible penetration of hydrogen as well

In both the E and H cases, fuel switching and load shifting were included in the analysis. We discuss Case E in detail below, but only summarize Case H briefly, as it is treated in detail in a separate report on energy system portraits (Greenblatt and Long, 2012).

In addition, two behavior change cases, based on Cases E and H, respectively, were developed assuming additional economy-wide demand reductions from behavior. These are also discussed in Greenblatt and Long (2012).

Approach and Assumptions

Residential and Commercial Buildings Efficiency

For both the stress test and realistic cases, there was limited quantitative data upon which to base our estimates, so the approaches described here relied heavily on expert opinion.

We began with a stress test analysis, detailed in the section, *Residential and Commercial Buildings*, and in *Appendix B*. For this analysis, we obtained data and projections for electricity and gas usage in the California residential and commercial sectors (McCarthy et al., 2006, 2008). We analyzed the fraction of total energy consumed by end use (space cooling, lighting, etc.), and systematically estimated potential efficiency savings by end use, broken down into four categories of savings: reduced capacity (down-sizing, such as smaller refrigerators, or space conditioning one room rather than the whole building), increased efficiency (often through new technology), reduced usage (a combination of technology-facilitated control and behavior change[1]), and system integration (combining elements of several service categories). We estimated the potential savings from each category and end use, drawing on published studies (e.g., Desroches and Garbesi, 2011), anecdotal evidence (e.g., Golden, 2010) and expert judgment (e.g., Lutz, 2009). Electrification of natural-gas-based end uses was also included.[2] Many potential savings were judged to be the same for the residential and commercial sectors. These efficiency savings estimates were then multiplied to obtain total potential savings by end use, and weighted by projected business-as-usual (BAU) 2050 end use energy demand to produce a total savings estimate for the residential and commercial buildings sectors. Technical potential savings in both sectors were approximately 90% relative to BAU. For details, see *Appendix B*.

The stress test demonstrated that one could *technically* reduce energy use sufficiently to meet California's 80% GHG reduction goal in the residential and commercial buildings sector. However, these savings were not deemed economically feasible, especially in retrofitted buildings. Also, similar levels of savings were not found in other sectors, e.g., industry (see the section, *Industrial Efficiency*) or transportation (Yang et al., 2011), so the overall conclusion of the efficiency stress test was that a 90% reduction in energy use was not technically achievable.

To develop realistic efficiency potentials, we began by talking with Dr. Iain Walker, a whole-building efficiency expert at Lawrence Berkeley National Laboratory (Walker, 2009, 2010). From his experience studying both building retrofits and new construction, we developed target efficiency levels in the near-term (2015-2025) and long-term (2040-2050) time horizons. However, Dr. Walker was not able to provide definitive estimates of savings potentials, due to the scarcity of real-world data, so these estimates were fairly crude. Nonetheless, from these estimates, we constructed efficiency adoption curves between 2010 and 2050, which allowed most of the technical efficiency potential (up to 80% savings relative to today) to be realized for new construction by 2040, but only 60% by 2050 for retrofits, due to the assumed higher cost and challenge of capturing all the potential savings.

Finally, we developed simple building stock turnover models for the residential and commercial sectors, using estimates of new construction, demolition and retrofits. National estimates of total housing stock and annual new residential construction were extrapolated from *Annual Energy Outlook* (EIA 2006, 2010) projections through 2035, and scaled to 2050 projections for California (McCarthy

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[1] Behavior change was recognized as a key factor in reducing usage. However, because this effect was treated as a separate case in the realistic analysis that followed, behavior change was broken out separately from technology-based reduced usage in the stress test so that the total savings due to behavior change could be quantified in our estimates. We assumed that behavior change in the residential sector contributed to about a 20% overall reduction; without it, total energy savings in the residential sector decreased from 91% to 89% relative to BAU. We did not make estimates of behavior change in the commercial sector.

[2] Note that electrification was considered solely for its GHG reduction benefit, not necessarily its cost-effectiveness in light of currently low natural gas prices.

et al., 2006, 2008). Demolition rates in the residential sector were calculated from differences between projected annual changes in building stock and new construction, averaging 0.3%/yr over 2005-2050. Commercial sector total floorspace was estimated from California projections for 2050 (McCarthy et al., 2006, 2008), scaled annually by projected California population (DOF, 2004). While estimates of both commercial building stock and new construction were also available nationally (EIA 2006, 2010), the derived demolition rates (0.8 to 1.1%/yr) were much higher than assumed in previous California studies (0.5%/yr; CEC, 2005b), so the latter estimate was used in our modeling.

To estimate retrofit rates, we calculated what sustained annual rate would be required for all buildings to be retrofit by 2050 that were built prior to 2010 and were not demolished. This scenario was chosen to ensure that all (or very nearly all) buildings contributed to statewide efficiency savings. The required retrofit rate was about 1.8%/yr for residential buildings and 1.7%/yr for commercial buildings. These rates are much lower than recent observed residential retrofit rates for all purposes (approximately 10%; Walker, 2010), so as a fraction of total retrofit activity, represents an achievable goal. However, until recently most retrofits have not emphasized efficiency but tend to focus on increasing space, convenience or luxury (e.g., kitchen makeovers), so there is a significant challenge to making efficiency retrofits a priority.

The results of the stock turnover-constrained efficiency models were about a 40% efficiency savings in the 2050 building stock relative to 2010 for both the residential and commercial sectors. We then compared our results to other studies, and found that our estimates lay in the middle of the range: some studies estimated smaller or similar efficiency potentials (Interagency Working Group, 2000; Wei et al., 2011; Williams et al., 2011a, 2011b), while others, including the state of California itself in setting its building efficiency targets, assumed much larger potentials (CPUC, 2011; Meyers et al., 2009; NAS, 2010).

Industrial Efficiency

Our estimate of the decrease in 2050 energy consumption from BAU in the industrial sector was derived from two complementary approaches. First, a top-down technical potential energy efficiency assumption was made, based on projections from the California Energy Commission (CEC) and U.S. Department of Energy (DOE) that explored the thermodynamic limits of manufacturing processes. This approach was used to estimate "stress test" levels of efficiency improvement, obtaining about 60% savings potential in the manufacturing sector relative to a "frozen" efficiency case (see Appendix C).

To obtain estimates for our realistic case, a bottom-up approach was used. Because this sector is comprised of many disparate industries, not all of which had extensive efficiency data available, we focused our attention on two major sectors: oil and gas refining (60% of industrial energy use) and the food industry (17% of energy use). For remaining sectors, similar processes (e.g., boiler systems, process heating, motor systems) were examined for savings potential based on commercially-available technologies, and then the fraction of total industrial activity involving that process was estimated by industry sector. The realistic estimate assumed a gradual electrification of natural-gas-based heating (primarily process heating) as equipment was replaced beginning in 2020 consistent with typical rollover rates, and reaching 50% penetration in 2050.

For the oil extraction and refining industry, the assumption was made that oil (and to a lesser extent, natural gas) demand is greatly reduced by 2050, due to large-scale vehicle and building electrification and the increased use of biofuels. We did not calculate the energy requirements of replacement industries in this case, which may have led to an overestimation of the potential savings, but we assumed that any biofuel production that emerges in-state would have very different energy use requirements than crude oil refineries, and in many cases would likely be provided entirely by biomass feedstocks (and thus require no additional energy inputs).

The stress tests and realistic cases looked only at efficiency gains relative to today's levels, but because BAU has historically included a sizable amount of efficiency improvement in the industrial sector without explicit policy (termed "autonomous" efficiency gains), we have assumed a similar amount of such gains in the BAU scenario—about 40% in 2050 relative to 2010.[3] Therefore, much of the efficiency improvement identified for the industrial sector is subsumed in the BAU, allowing less room for improvement on top of these gains. Still, our assessment indicated that the potential for a 48% overall reduction in energy use relative to BAU was possible in the realistic case, primarily from large scale replacement of the oil and gas extraction and refining industries.

Growth Scenario Description and Sources

The CEF project used estimates of population and economic growth to project future demand. The growth scenarios are based on the Advanced Energy Pathways (AEP) study (McCarthy et al., 2006, 2008) produced by researchers in the Institute of Transportation Studies at UC Davis, which are based on extensions of projections from California's Integrated Energy Planning (IEPR) reports from 2003 and 2005 (CEC 2003a, 2005f), along with a number of supporting sources (see below). Appendix A of the AEP study (McCarthy et al., 2008), along with its accompanying Excel spreadsheets, contains virtually all the information needed for a detailed set of scenarios of California's energy demand through 2050.

We assumed California's population would grow to 54.8 million, approximately 50% larger than in 2005 (36.6 million), based on California Department of Finance projections (DOF, 2004). The scenario was silent on details of how that population would be distributed within the state, but analysts generally assume that growth in the Central Valley will be more rapid than growth in dense urban coastal areas without strong policy to favor urban over suburban development. Recent projections from the California Department of Finance (DOF, 2006a) indicate that Central Valley regions will grow 114-153% between 2006 and 2050, as opposed to 31-56% in coastal regions. (See Figure 1.)

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[3] Note that the industrial sector is unlike the residential and commercial buildings sectors, where autonomous efficiency gains have historically been very low, and were assumed to be virtually zero in the BAU scenario (see Appendix B for more details).

	Population Year				
Climate Zone	2006	2025	2050	Average Gain	Population Gain
Zone 1	846,344	1,039,430	1,292,114	53%	445,770
Zone 2	1,211,250	1,772,387	2,931,650	142%	1,720,400
Zone 3	3,183,561	4,574,292	7,536,625	137%	4,353,065
Zone 4	5,159,160	6,204,363	8,064,664	56%	2,905,504
Zone 5	3,193,991	3,638,839	4,008,835	26%	814,844
Zone 6	1,385,607	1,705,152	2,176,508	57%	790,901
Zone 7	641,352	950,821	1,621,847	153%	980,494
Zone 8	7,063,285	8,355,344	9,261,886	31%	2,198,601
Zone 9	3,121,611	3,594,827	3,999,907	28%	878,296
Zone 10	4,111,744	6,017,745	8,780,878	114%	4,669,134
Zone 11	2,320,476	2,669,568	2,958,309	27%	637,833
Zone 12	1,406,382	1,617,957	1,792,956	27%	386,574
Zone 13	3,066,820	3,732,038	4,508,728	47%	1,441,908
Zone 16	449,433	517,045	572,969	27%	123,536
Total	37,161,015	46,389,809	59,507,876	60%	22,346,861

Table 1. Projected population growth in California through 2050 by climate zone[4]. The four highest-growth regions are highlighted, and are all in the Central Valley
Source: California Department of Finance (DOF, 2006a)

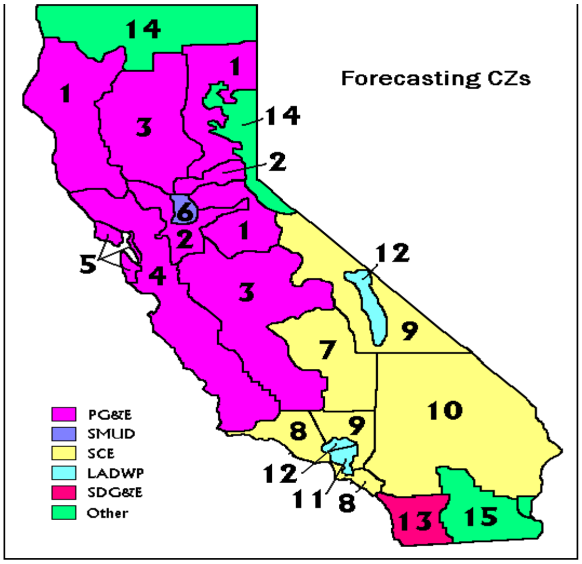

Figure 1. California climate zones

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[4] No population projections were available for Climate Zones 14 and 15. Both of these climate zones are sparsely populated, have relatively low energy consumption levels, and are generally considered to be similar to Climate Zones 1 and 10, respectively (CEC, 2007, p. 13).

Following AEP's baseline growth scenario, wealth measured by the Gross State Product (GSP) is projected to grow from approximately \$40,000 per year per person to \$91,000 per year per person (in constant 2000 dollars). This represents an annual per person growth rate of 1.8%, in line with historical U.S. averages since 1970 (US Census, 2010). In absolute terms, annual GSP increases from roughly \$1.5 trillion to \$5.0 trillion, an annual growth rate of 2.75%. This growth rate is based on (and is set to be the same as) that experienced in California between 1990 and 2003 (CEC, 2005b).

It should be emphasized that our study is predicated on economic growth. The AEP baseline scenario on which it is based was considered "moderate" before the 2009 economic downturn, but might be now regarded as a robust growth scenario. While representing a highly desirable future, economic growth comes with higher energy utilization, and therefore represents a greater carbon challenge than if the California economy does not grow as projected. On the other hand, if economic growth proves more robust than projected under the baseline scenario, the carbon challenge would be even more difficult to meet, that is, there would be more carbon emissions to eliminate. However, there would also be more money with which to drive the changes required.

We assume that the rest of the U.S. develops along similar lines as California. Therefore in terms of shared energy resources, California cannot take more than its "fair share" (expressed as a fraction of U.S. population—about 12.5% in 2050) in meeting its energy needs (US Census, 2008).[5]

Our scenario does not account for the impacts of climate change in 2050 that might affect both demand (hotter summers requiring more air conditioning; insufficient fresh water requiring more pumping energy and/or desalination, etc.) and renewable resources (wind, solar, hydro). These effects were not included explicitly due to the lack of high-resolution models that could confidently project these potential changes. The assessment of these effects was beyond the scope of our study, but remains a valid concern.

Data sources used to construct the AEP scenarios are summarized in Table 2. The recent economic downturn has caused more recent versions of these sources to revise downward their demand projections. As discussed above, our study takes a very long-term view, and consequently expects the economy to eventually recover; we thus use the baseline AEP scenario in our modeling, but have not modified it based on recent projections. These references are provided in the table for interested readers, however.

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[5] The reference projection for the U.S. is 439 million people in 2050.

Parameter(s)	Sector(s)	Scenario(s)	Reference(s)	Years	Available updated reference(s)
Population	All	Baseline, baseline low efficiency, baseline high efficiency	DOF (2004)	2000-2050	DOF (2007)
		Maximum	Landis and Reilly (2003)	2003-2100	
Gross State Product (GSP)	All	Baseline	CEC (2005b)	1990-2003	
		Maximum	CEC (2005d)	2003-2016	
		Minimum	Modified from CEC (2005b)	1990-2003	
Persons per household	Residential	All	DOF (2006b)	2000-2006	DOF (2010)
Single-family households	Residential	Baseline, baseline low efficiency, baseline high efficiency	DOF (2006b)	2000-2006	DOF (2010)
		Minimum, maximum	Quantum/Itron (2006)	2005-2050	
Electrical energy use intensity	Residential	All	Quantum/Itron (2006)	2005-2050	CEC (2009), Page A-1, PDF page 279
		Baseline	CEC (2005a)	2006-2016	CEC (2009), EIA (2010)
	Commercial, industrial, agricultural, other	Baseline	CEC (2003b)	2003-2013	CEC (2009), EIA (2010)
	Commercial	Baseline high efficiency, minimum	CEC (2005c)	2005-2016	
			USGBC (2005)	N/A	
	Industrial	All	KEMA (2006)	2005-2016	
			EIA (2006)	2006-2030	EIA (2010)

Natural gas energy use intensity	Residential commercial, industrial, agricultural, other	Baseline	CEC (2003b)	2003-2013	CEC (2009), EIA (2010)
	Residential, commercial	Baseline high efficiency, minimum	CEC (2005c)	2005-2016	
	Commercial	Baseline high efficiency, minimum	USGBC (2005)	N/A	
	Industrial	All	EIA (2006)	2006-2030	Baseline: CEC (2009), EIA (2010)
			Itron et al. (2006)	2005-2015	
Floorspace	Commercial	Baseline	CEC (2003b)	2003-2013	CEC (2009)
Shipments	Industrial	Baseline	CEC (2003b)	2003-2013	
			CEC (2005a)	2006-2016	
Vehicle miles travelled, vehicle stock, fuel economy, fuel demand	Transportation	Baseline	CEC (2005e)	2005-2025	EIA (2010) has some information
Heavy duty fuel economy, airplane fuel economy	Transportation	All	EIA (2006)	2005-2030	

Table 2. Data sources for AEP demand scenario projections.
Source for all columns except rightmost: McCarthy et al. (2008), Tables A-2 and A-4.

Table 3 indicates additional sources consulted in constructing the CEF scenarios.

Parameter(s)	Sector(s)	Scenario(s)	Reference(s)	Years
Electric vehicle fuel economy	Transportation	Baseline	Yang et al. (2009)	N/A
Airplane vehicle miles travelled	Transportation	Baseline	Yang (2010)	2005-2050

Table 3. Additional sources used for CEF demand scenarios.

The AEP scenarios include uncertainty about the future of California's population, economic growth, and policies regarding energy efficiency and vehicle usage (annual miles traveled), and developed a set of bounding cases that spanned ranges in each variable. From these cases, CEF selected a single combination that was judged to be representative of a moderate growth energy demand future for California. CEF chose the moderate population growth (to ~55 million in 2050, 150% of the 2005 value. Likewise, CEF chose the combination of AEP's "baseline drivers" scenario, which simulated fairly aggressive economic growth (2.75% annual growth through 2050, to $91,000 annual average per person income), and the "moderate efficiency" scenario, which indicated a modest future commitment to energy efficiency. The one exception was a revision to airplane vehicle-miles traveled, based on recent communication with one of the AEP authors, indicating that efficiency would likely be higher than previously projected (Yang, 2010). See Table 4 for explicit enumeration of parameter values assumed.

Parameter	Units	2005	2050	AEP Scenario
General				
Population	Millions of people	36.6	54.8	Baseline drivers
Gross State Product (GSP)	$1000 GSP/yr/person	40.2	91.0	Baseline drivers
Sector-specific				
Residential	People per household	3.00	3.01	Baseline drivers
Commercial	Sq. ft. of floorspace/person	166	185	Baseline drivers
Industrial	$1000 industrial shipments/yr/person	16.1	34.9	Baseline drivers
Agricultural	$1000 GSP/yr/person	40.2	91.0	Baseline drivers
Other (non-transport)	N/A	1	1	N/A
Light duty vehicles	Vehicles/person	0.71	0.94	Baseline drivers
	Miles/vehicle/yr	11,500	11,500	Moderate efficiency
Heavy-duty vehicles	Miles/$1000 GSP	16.3	9.5	Moderate efficiency
Airplanes	Miles/$1000 GSP	137.5	70.8	Custom (Yang, 2010)
Bus	Miles/person/yr	530	530	Moderate efficiency
Rail-passenger	Miles/person/yr	98	98	Moderate efficiency
Rail-freight	Ton-miles/$1000 GSP	6.2	4.87	Moderate efficiency
Marine	Miles/$1000 GSP	1.09	0.48	Moderate efficiency

Table 4. Parameter assumptions for CEF baseline cases

Summary of Stress Tests

Questions

The following questions were addressed for each of the stress tests:

1. Could a given single technology approach solve the emission problem in 2050?
2. If no, why? How far could you get?
3. If yes, what is required to do it? What obstacles would have to be overcome? What would have to happen?
    a. What build rate or turn over rate would be required?
    b. What policy would be required?
    c. Would cost be an issue?
    d. What are the resource limitations and what do they mean for California (e.g., using 25% of water supply, or 15% of the land is a non-starter for California)
    e. What technology limitations would have to be overcome?
    f. Etc.
4. Conclusions:
    a. Salient points – where does scaling up become really hard? Is there a break point?
    b. What difference would behavior change make?

The following base cases were used as starting points in the stress tests:

- **BAU Case E (Electricity-Dominant):** Very aggressive electrification in all sectors where such a switch is possible, e.g., all buildings and industry, and much of transportation.
- **BAU Case H (Hydrogen-Dominant):** Very aggressive electrification AND hydrogen substitution where possible (industry and much of transportation).
- **BAU Case C (Conventional Fuels):** Same fuel supply mix as 2005, e.g., no electrification or hydrogen.

Case E, not surprisingly, has the highest demand for electricity, while Case C has the highest demand for hydrocarbon fuels. Only Case H has any demand for hydrogen, and it is built upon Case E, such that aggressive electrification is pursued in tandem with fuel switching to hydrogen, resulting in an intermediate demand for electricity.

Results

Table 5 shows overall demand results for the three BAU scenarios without any efficiency gains. For BAU Case E (and H), it is assumed that half of electrified heat is installed via heat pumps, and half via electric resistance heating,[6] and for transportation, it is assumed that today's efficiency levels are

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[6] This BAU scenario assumed electrification without regard for efficiency. However, a wholesale switch to the lowest capital cost (but least efficient) electric technology, resistance heating, is not always the rational economic choice even for consumers with very short payback period expectations. Rather than perform a detailed cost-benefit analysis for each end-use, an arbitrary designation of 50% electric resistance and 50% heat pump technology was chosen, allowing plenty of room for efficiency improvement.

obtained for electric vehicles—levels which are actually assumed to be sustained through 2050 in the efficiency stress test case as well (E). For BAU Case H, it is assumed that hydrogen combustion is used in buildings and industrial applications, and hydrogen fuel cells are used in vehicles. BAU Case C assumes the same mix of fuel types as in 2005.

		2005	2050		
			BAU Case E	BAU Case H	BAU Case C
Energy Carrier	**Units**		**Maximum Electrification**	**Maximum Electrification and Hydrogen**	**Conventional (Carbon) Fuels**
Electricity	TWh/yr	271	1,161	804*	467
Gaseous fuel	Ggge/yr	12.3	0	0	23.9
Liquid fuels	Ggge/yr	27.0	14.5	14.5	48.0
Hydrogen	TgH_2/yr, about same as Ggge/yr	0	0	23.1	0

Table 5. BAU Demand Summary
* For the supply case where hydrogen is made from electricity, electricity demand more than doubles from this value.

Stress Case E: Efficiency and Electrification

This case focuses on simply reducing end-use energy by an amount sufficient to meet the standard for 2050. While we assume a significant shift in the type of end-use energy (away from fuels and toward electricity), the GHG intensity profiles of the energy system remain as they are today.[7] So we attempt to reduce energy intensity—that is, reduce the amount of energy required to do the same amount of work—by 90%, so that we can continue to provide energy using the same mix of (mostly fossil) fuels as we do today. We have to reduce demand by 90%, not 80%, because economic and population growth roughly double the demand for energy relative to the 1990 level, which is most evident for the BAU Case C that assumed no change in the fuel mix (see Table 5).

The conclusion of this exercise (details of which are found in *Appendices 1* and *2*, and in Yang et al., 2011) is that a 90% reduction in energy use is technically possible, but unrealistically demanding, for the residential and commercial buildings sector. A 90% reduction is not technically feasible for the industry or transportation sectors. Consequently, it is not possible to meet the 2050 emission goals solely through efficiency and electrification gains.

Each of these sectors is discussed in the following pages. For each sector, the potential for additional savings through behavior change is also estimated.

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[7] The combination of efficiency and electrification is important, as many electric-based technologies are much more efficient than their combustion-based equivalents (e.g., electric-drive vehicles, heat pump water heaters). Extensive fuel switching makes calculating net emissions complex, because the emissions profile of the electricity system will affect the result. We ignore this for now, and instead focus on absolute reductions in end-use energy demand.

Residential and Commercial Buildings

The technical potential of a residential or commercial building today is approximately 90% more efficient than the existing stock. (See Appendix B for detailed information on how this result was obtained). In order to achieve this potential in all buildings by 2050, the following technical targets must be achieved:

1. All new buildings and the devices within them are built to be as highly efficient as possible starting in 2015, at a rate of approximately 200,000 residential homes and 135 million square feet (Msf) of commercial space per year.
2. All existing buildings are either demolished or retrofitted to minimum energy use:
    a. Demolition rate is roughly 0.3%/yr for residential and 0.5%/yr for commercial. By 2050, 12% of the existing 2015 residential building stock (1.6 million homes), and 22% of existing 2015 commercial building stock (1,550 Msf), would be demolished.
    b. The required retrofit rate to reach all remaining buildings by 2050 is 2.1%/yr for residential (280,000 homes per year in 2015) and 2.0%/yr for commercial (140 Msf per year in 2015).

Costs would be as follows:

1. With today's technology, the long-term cost premium for new buildings may be near zero, based on expert opinion; however, detailed information is lacking.
2. Deep efficiency retrofits are very expensive now ($100,000 per residential building, or roughly $40 per square foot, essentially an infinite payback period), but are expected to decline in the future as technology and training improves. With mortgage-linked financing, payback periods of 15-30 years could be acceptable, but this requires roughly a factor-of-four drop in cost.

Policies required by 2015 include:

- Aggressive, best-in-class standards for buildings and appliances
- Financing mechanisms in place
- Subsidies to allow cost-effective retrofitting today
- Workforce training to enable the above numbers of homes and businesses to be built or retrofitted to new codes. Lack of a trained workforce is a major constraint that must be overcome.

Behavior change: By estimating the reduction potential from behavior change in each end use category, we estimate that full implementation of behavior change may reduce unit energy use by an additional 10-30%; for the sector overall, about a 20% reduction in energy use is possible. See the section, *Role of behavior change*, and *Appendix B*, Table B.2 and Table B.3, for more information.

In conclusion, building efficiency measures cannot physically be scaled up to reduce energy use by 90% relative to BAU, or roughly 80% below the 1990 level, without very aggressive policy, ample financing, and dramatic reductions in retrofit costs, which when taken together present an extremely formidable challenge.

Industry

We estimate, through a variety of methods (described below), that industry could deploy sufficient efficiency measures by 2050 to lower energy consumption by 55% relative to BAU projections. Note that unlike residential and commercial buildings, the BAU case assumes a 40% efficiency savings (or "autonomous" savings[8]) in 2050 as compared to 2005 levels, due to cost-effective efficiency improvements that would be adopted without additional policy incentives.

The 55% decrease in 2050 energy consumption from BAU is derived from two components. First, top-down technical potential energy efficiency assumptions are made for manufacturing sectors that utilize projections from CEC (2009) and DOE "bandwidth" studies (see DOE references in Appendix C) that explore the thermodynamic limits of manufacturing processes. Secondly, the assumption is made that oil (and to a lesser extend, natural gas) demand is greatly reduced, by large-scale vehicle and building electrification, and the increased use of biofuels. Manufacturing efficiency savings are estimated to be about 33% relative to BAU efficiency levels while 90% of the oil refining industry is assumed to be replaced. We do not calculate the energy requirements of replacement industries in this case, which may lead to an overestimation of the potential savings, but assumed that any biofuel production that emerges in-state would have very different energy use requirements than crude oil refineries.

Costs of improved efficiency vary with industrial sector. The industries that require "low-quality" heat (temperatures at or below 100°C), such as food processing, plastics and some chemical industries, can potentially switch very cost-effectively to electric-based heating. Those industries that require temperatures of several hundred degrees Celsius or greater, such as iron, cement and glass manufacturing, however, must make greater changes to their process flow designs; while unit level electric heating technologies do exist (electric arc, microwave, electric boilers), they are often much more expensive to operate than conventional combustion-based alternatives. Additionally, electrified heating production systems at high temperature do not now exist in most industry sectors and thus require development.

The manufacturing sector historically spends ~$200 billion/year on energy and capital expenditures, or 6-7% of revenues. The manufacturing sector overall has relatively low spending on R&D (~4% of revenues for R&D) and energy-intensive industries spend less than 2% of revenue on R&D.

In the medium term, McKinsey (2009) estimates that $113 billion investment is needed for 18% savings in 2020 while Elliott (2010) estimates that $200-300 billion is needed by 2025 for a 25-30% energy intensity reduction in the U.S., or about $20 billion per year. This translates to a ~10% increment above what industry historically spends on energy and capital expenditures.

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[8] "Autonomous" refers to the energy savings that are projected to occur without additional energy policies, incentives, programs or activities that would occur beyond what currently exists as status quo today (e.g., normal end-of-life equipment replacement). Industry autonomous savings are typically a higher number than residential or commercial efficiency, since industry is highly motivated to reduce costs and improve overall production efficiency to increase profitability and market share. The autonomous efficiency rate is based on historical trends. Energy-intensive industries such as steel and petroleum typically take direct steps that reduce energy consumption and energy costs while non-energy-intensive industries can indirectly reduce energy consumption through enhanced production processes and improved product designs.

We estimate that an additional 30% savings are possible with a combination of behavior changes, stemming from both consumer preferences and industrial practices, which would bring total savings relative to BAU to 69%. Including industrial behavior change practices only, savings would be reduced to 62%. These estimates are, however, based on qualitative arguments and therefore have large uncertainty. See Appendix C for a fuller discussion of these assumptions.

Transportation

The CEF committee found that it is not possible to achieve the necessary 80% reductions in the transportation sector emissions through efficiency improvements alone, or through a combination of factors including the estimated vehicle efficiency improvement potential, limited opportunities for electrification, and the slow pace of fleet turnover. The CEF transportation report (Yang et al., 2011) detailed the following main conclusions, based on aggressive policies to approach the technical efficiency potentials in the next few decades, while assuming historically-supportable, but aggressive, turnover rates:

- As discussed in the section, *Growth Scenario Description*, based on projections from numerous sources, demand for transportation is expected to continue to expand, both in terms of miles per person and vehicle ownership (for light-duty vehicles). By 2050, total vehicle mile demands for light- and heavy-duty vehicles are projected to double, demand for air travel is projected to increase 75%, and demands for bus, rail and marine transport are expected to scale with population, a 50% increase from today.
- The maximum realistically achievable average fuel efficiency improvement to conventional (non-electric) light-duty vehicles in 2050 is 42 miles per gallon gasoline equivalent (mpgge), roughly a doubling of today's fuel efficiency. With hybrid (non-plug-in) electric technology, this efficiency could be increased to 64 mpgge, approximately triple today's level. With plug-in capability and an assumed mix of hybrid and pure-electric vehicles, the average efficiency using liquid fuels is projected to double again to 126 mpgge. However, even this level of efficiency is insufficient to reduce fuel consumption 80% below the 1990 level.
- In order to reach 80% fleet penetration of light-duty electric vehicles by 2050, the annual average growth rate of sales would have to be 37% per year, assuming sales began in 2015, and exceed 90% market share after 2035. Even this target is not sufficient, given projected increases in population growth and vehicle ownership, to reach the GHG reduction goal for this subsector. But a less aggressive estimate was used in the realistic scenario, that assumed 58% fleet penetration in 2050, with new vehicle sales reaching 69% in 2050.
- Heavy-duty transport (freight trucks) have a maximum potential efficiency improvement around 50%, through engine hybridization, adding a bottoming cycle, improved aerodynamics, decreased rolling resistance, longer/multiple trailers, and improved logistics. A realistic improvement estimate is 30%.
- For air travel, a 70-80% efficiency improvement is technically feasible, through a combination of more efficient jet engines, advanced lightweight materials, improved aerodynamics, more substantial design changes (such as blended wing aircraft), and improved flight planning and air traffic management. Feasible improvements, however, are estimated to be in the 50-55% range.
- For bus and rail transport, electrification was deemed feasible for nearly 100% of the fleet by 2050, both in the stress and realistic cases.
- Improvements in marine transport were estimated to be 40% in the realistic case. No stress test estimate was provided.

Stress Case H: Efficiency with Electrification and Hydrogen

While there are some advantages to using hydrogen in combination with electrification in some sectors (detailed below), overall stress test objectives cannot be met by adding hydrogen.

Hydrogen offers some advantages over electricity for industrial processes and vehicles. For industry, combustion of hydrogen allows higher temperatures to be reached than is possible with natural gas, so it may offer a lower-cost route to decarbonization than electrification. For vehicles, highly-efficient fuel cells allow similar electric-drive technology to be utilized as in an electric vehicle, but the greater energy density of hydrogen allows for longer range, expanding the utility of light-duty vehicles with hydrogen. Still, these gains are not as important for longer-distance vehicles such as heavy-duty trucks, airplanes, trains or ships. For more discussion, see Greenblatt and Long (2012).

The challenge to using hydrogen in vehicles is that fuel cell vehicle (FCV) technology is in early stages of commercialization, though there is the expectation of significant cost reductions over the next decade. Still, a number of significant challenges exist for this technology. See discussions in Greenblatt and Long (2012) and Yang et al. (2011) for more details.

Stress Case C: Efficiency with Conventional Fuels

Efficiency using only a conventional energy system configuration (i.e., without electrification), cannot reduce 2050 energy demand 80% below 1990 levels in any sector. For industry and transportation, this was not possible with electrification included, so it was not possible without it. For residential and commercial buildings, about 80% of savings are achieved without electrification. The addition of heat pump technology for space and water heating, which affords a roughly twofold increase in efficiency of these systems, brings the total savings to approximately 90%.

Role of Behavior Change

Buildings

The role of behavior change was explicitly ignored in the above discussion, to separate its effect from those due purely to technology, policy and cost. There could be much potential in voluntary reduction in energy consumption, with acceptable or even beneficial lifestyle impacts for many people (e.g., substituting a bicycle for vehicle transportation, which boosts exercise).

Among behaviors affecting building energy consumption are the following general categories. For each end-use category, we estimated the reduction potential due to decreased use stemming from behavior change; in some cases, part of the usage reduction was non-behavior based (e.g., decreased on-mode time for electronics using occupancy sensors). Overall for the sector, we estimate about a 20% reduction in energy use is possible. Note that estimates are based on expert judgment, and are not considered definitive by any stretch; however, other studies suggest that household behavior changes can cut energy demand by up to 22% (Dietz et al., 2009; AAA&S, 2011; see discussion in Greenblatt and Long, 2012), consistent with our estimates.

Behavior change actions identified (see Table B.2 and Table B.3 in Appendix B for details):

- Greater extremes in building temperatures, lower hot water temperatures, lower light levels and higher moisture content of clothing and dishes
- Greater time to provide desired outcomes, e.g., air-drying of clothing
- "Right-sized" (i.e., smaller) appliances, such as refrigerators and clothes washers
- Less habitable space (the "small home" movement being a primary example)
- Less reliance on electrical work in favor of manual effort, e.g., manual egg beaters
- Less reliance on electronic entertainment, e.g., playing the guitar instead of watching TV
- Sacrificing quality, e.g., air-dried clothing is often stiffer than when heat-dried
- Lifestyle decisions, e.g., choosing a single family/less urban versus multi-family/more urban environment
- Interactions with other behaviors, such as telecommuting
- Technologies which can amplify/reinforce behavior changes, such as room-dependent space conditioning, and occupancy sensors to power down devices when not in use

Industry

A combination of behavioral changes both in industry and consumers may conspire to lower the overall industrial energy demand significantly.

Industry changes that might lower energy use include:

- Designs that use less raw materials to produce the same products (dematerialization)
- Designing more integrated products that reduces the total number of products produced (e.g., combination of internet modem, wireless router, set-top box and digital video recorder in a single device)
- Designing longer-lasting products that need replacement less frequently
- Extending the length of product design cycles, reducing waste in production lines, etc.
- Inclusion of life-cycle analysis and impacts in business practices, such as supply chain management and product design
- Designing for ease of recycling or re-use
- Material changes for the same functionality but with less energy-intensive materials, e.g., composite replacements for steel
- Business model changes from consumer ownership to rental/service, which could result in more repair and re-use, better recycling and disposal of products, and better-maintained, and thus more efficient, end-use products

Consumer changes include:

- Increasing re-use and repair of old products, extending product use lifetime, especially for consumer electronics and computers
- Preference for (probably simpler) products that require less energy to produce, which could be enabled by the widespread availability of life-cycle energy assessment data that is starting to enter the marketplace
- Less desire for products overall ("simple living" movement)
- Recycling paper, plastic, metals, etc. as much as possible
- Diet change: less calories, less energy-intensive red meat and dairy
- Wasting less food

- Minimizing use of packaging and disposable products, e.g., no plastic water bottles, purchasing bulk foods with re-useable bags or containers
- Use of rechargeable batteries

The above-listed industrial changes would be driven at least partially by customer preference and/or regulation, in addition to industry culture change. Policies as well as cultural changes will need to be developed to encourage adoption.

While difficult to quantify, we crudely estimate that up to an additional 30% of savings may be possible with behavior changes. These changes are envisioned to consist of roughly equal contributions from both industrial practices and consumer behavior.

Transportation

Behavior changes for transportation that could make a difference include the following:

- Consumer preferences in lower vehicle performance and smaller size, which might be enabled by pricing strategies (e.g., feebates), could dramatically improve efficiency. For instance, a shift towards a greater percentage of cars than light trucks (currently a roughly 50:50 split).
- Reductions in vehicle miles travelled (VMT) per person would help lower vehicle energy use, through less use of vehicles, shortening trips, combining trips, and shifting to more efficient modes of transportation, such as self-powered or public transit.
- Eco-driving (also known as "hypermiling" or the "Prius effect"), a growing practice by which drivers attempt to maximize their fuel efficiency through modified driving habits (slower acceleration and braking, coasting, keeping tires properly inflated, etc.), usually with direct feedback through an instantaneous mpg indicator that is increasingly found in newer vehicles, including the Toyota Prius.

Realistic Demand Cases

Unlike the stress test cases, the realistic demand cases assumed achievable levels of efficiency and electrification, based on modeled stock turnover rates of buildings, industrial equipment and vehicles, and 2050 penetration levels consistent with anticipated competition with alternative technologies (e.g., the limited range of electric vehicles implies some liquid fuel consumption would remain, either by hybrid gasoline/plug-in electric vehicles or gasoline-only vehicles). Details are explained in each case below.

Case E: Demand Reduction Through Efficiency and Electrification

Summary

The results of our efficiency and electrification analysis are shown in Table 6, which is a top-level comparison among 2005, 2050 BAU Case C, and 2050 Realistic Case E energy demands by sector and fuel type, including differences between BAU and realistic, broken down between efficiency and electrification. Demand for all fuels nearly doubles in the BAU case relative to 2005. In the realistic case, while demand for gaseous and liquid fuels is generally somewhat lower than in BAU (in most sectors, even lower than in 2005), electricity demand *increases* relative to BAU. This is because the realistic case accounts for increased electrification, which creates new demand at the same time that the energy intensity drops dramatically due to efficiency measures (see efficiency column, which compares energy intensity between BAU and realistic cases). We can view this phenomenon as a challenge to eliminate emissions from the electricity portfolio at the same time as generation capacity more than doubles.

			Demand Case and Year			Change in Demand (BAU to Realistic)		
Sector	Energy Carrier	Units	Historical 2005	BAU Case C 2050	Realistic Case E 2050	Due to Efficiency	Due to Electrification	Net
Residential	Electricity	GWh/yr	84,781	136,513	145,176	-40%	77%	6%
	Gaseous fuel	TBtu/yr	525	801	144	-40%	-70%	-82%
Commercial	Electricity	GWh/yr	96,381	162,163	123,104	-40%	27%	-24%
	Gaseous fuel	TBtu/yr	184	327	59	-40%	-70%	-82%
Industrial*	Electricity	GWh/yr	53,866	111,319	108,707	-24%	28%	-2%
	Gaseous fuel	TBtu/yr	679	1,591	592	-58%	-12%	-63%
	Liquid fuel	Mgge/yr	2,340	4,679	2,487	-39%	-13%	-47%
Agriculture and Other	Electricity	GWh/yr	36,236	56,961	37,327	-40%	9%	-34%
	Gaseous fuel	TBtu/yr	36	40	7	-40%	-70%	-82%
Transport (see below)	Electricity	GWh/yr	0	0	88,936	N/A	N/A	N/A
	Liquid fuel	Mgge/yr	20,155	35,698	10,811	-51%	-38%	-70%
GRAND TOTAL	**Electricity**	**GWh/yr**	**271,264**	**466,956**	**503,249**	**-36%**	**69%**	**8%**
	Gaseous fuel	**TBtu/yr**	**1,423**	**2,758**	**802**	**-50%**	**-42%**	**-71%**
	Liquid fuel	**Mgge/yr**	**22,495**	**40,378**	**13,298**	**-50%**	**-34%**	**-67%**
Transport breakdown:								
Light-Duty Vehicles	Electricity	GWh/yr	0	0	73,105	0%	N/A	N/A
	Liquid fuel	Mgge/yr	14,655	25,469	5,705	-60%	-44%	-78%
Heavy-Duty Vehicles	Electricity	GWh/yr	0	0	8,717	0%	N/A	N/A
	Liquid fuel	Mgge/yr	4,000	7,875	4,456	-31%	-18%	-43%
Airplanes**	Liquid fuel	Mgge/yr	304	522	245	-53%	0%	-53%
	(Full demand)		(3,800)	(6,527)	(3,068)			
Buses	Electricity	GWh/yr	0	0	4,645	0%	N/A	N/A
	Liquid fuel	Mgge/yr	625	937	0	0%	-100%	-100%
Passenger Rail	Electricity	GWh/yr	0	0	1,449	0%	N/A	N/A
	Liquid fuel	Mgge/yr	88	132	0	0%	-100%	-100%
Freight Rail	Electricity	GWh/yr	0	0	1,019	0%	N/A	N/A
	Liquid fuel	Mgge/yr	33	88	0	0%	-100%	-100%
Marine**	Liquid fuel	Mgge/yr	450	675	405	-40%	0%	-40%
	(Full demand)		(1,801)	(2,700)	(1,620)			

Table 6. Demand comparisons by sector and fuel type

*Efficiency changes include effects of oil industry downsize on industrial energy demand.

**For airplanes and marine transport, the fraction of total demand that is assumed to be purchased inside California is shown, with total estimated demand in parentheses. Only the in-state quantities are included in the Grand Total, consistent with the approach used by the California Air Resources Board for estimating the statewide GHG inventory.

The details of this analysis are presented below in three segments: residential and commercial buildings, industry and transportation.

Residential and Commercial Buildings

Summary

The stress test for buildings indicated that approximately 90% energy savings from BAU is technically possible, when combined with 100% electrification. The main challenge to implementing such monumental efficiency gains is building turnover. With projected average annual rates of new construction of approximately 1.2% in the residential sector and 1.6% in the commercial sector, and assuming annual rates of retrofits of 1.81%/yr (residential) and 1.65%/yr (commercial), even with the most aggressive efficiency measures, it will take roughly until 2050 to affect the entire building stock of California, assuming every building is eventually retrofitted or demolished.

In addition, the level of efficiency improvement chosen when a building is newly constructed or retrofitted is currently highly variable, and critically affects the average building stock efficiency that is achieved. Best practices in new designs are able to achieve close to the stress test savings today, but these will only be realized under ideal circumstances, and at significantly higher cost than current practice. In our model, we assumed a schedule of gradually increasing levels of efficiency improvement compared to today, reaching 80% by 2040 for new buildings and 60% by 2050 for existing buildings. These estimates were based on scant empirical evidence, however, and could be substantially improved.

The energy efficiency of California's building stock therefore depends on four critical factors: building stock turnover, standards for buildings and devices, electrification, and cost differentials. When taken together, California residential and commercial buildings will thus probably achieve significantly less than the ideal stress test efficiency gains. A realistic estimate is constructed below.

Technical Assumptions

Projections of housing stock and commercial floorspace for 2005 and 2050 were taken from the AEP study (McCarthy et al., 2006, 2008). New construction in the residential sector was obtained from national averages provided by Annual Energy Outlook projections (EIA, 2006, 2010) extrapolated from 2035 to 2050, while demolition rates were derived from differences between projected annual changes in stock and new construction. For the commercial sector, total stock was scaled to projected California population (DOF, 2004), and the commercial demolition rate was taken from a California Energy Commission estimate (CEC, 2005b); therefore new construction was estimated from the annual increase in commercial building stock and demolition.[9] These results were expressed as rates and are shown in Table 7 and Table 8.

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[9] EIA (2006, 2010) also provided national estimates of stock and new construction in the commercial sector, allowing a derivation of demolition rates similar to the residential sector. However, the rates obtained (0.8 to 1.1%/yr) were much higher than assumed in previous California studies (0.5%/yr; CEC, 2005b), so the latter estimate was used in our modeling.

We assumed that an increasing fraction of the stress test potential would be achievable in both new and retrofit residential and commercial buildings, but that the full potential would not be realized on average, even in 2050, due to the wide range of building types and the many competing building design needs other than efficiency. The average efficiency improvement of retrofit buildings was also assumed to remain lower than for new construction, due to higher costs of working within an existing structure.

In our model, we assumed that all new buildings beyond 2015 are built to be 20% more efficient than today, increasing to 40% by 2020, based loosely on the California Public Utilities Commission goals (CPUC, 2011). For retrofits, a 30% average efficiency improvement by 2020 was assumed, based on anecdotal evidence of achievable retrofit improvements in actual homes (Walker, 2009). Both of these goals are achievable now with current technology, and we estimate that it is feasible, though challenging, to continue making efficiency improvements up to 80% based on two studies (Fraunhofer Institute, 2009; ZECBC, 2010), which we assume occurs by 2040 for new buildings and then remains at that level. For retrofits, a maximum efficiency improvement of 60% was assumed by 2050. This schedule of efficiency improvement was based on very limited empirical evidence, however, and could be substantially improved. See Table 7 and Table 8.

	2010	2015	2020	2030	2040	2050
Annual fraction of homes that are:						
New construction	1.55%	1.55%	1.58%	1.26%	1.01%	0.75%
Retrofits	1.81%	1.81%	1.81%	1.81%	1.81%	1.81%
Demolished	0%	0.17%	0.16%	0.27%	0.28%	0.09%
Total homes (millions)	12.4	13.3	14.2	15.8	17.0	18.2
Annual efficiency improvement schedule*						
New construction	0%	20%	40%	60%	80%	80%
Retrofits	0%	15%	30%	40%	50%	60%
Average efficiency of building stock*						
New construction	0.0%	0.9%	3.1%	8.7%	14.3%	18.7%
Retrofits	0.0%	0.8%	2.7%	7.9%	14.2%	21.7%
Total	0.0%	1.6%	5.8%	16.6%	28.4%	40.4%

Table 7. Schedule of efficiency improvements to residential buildings
*Relative to BAU, which assumes essentially no per building improvement between 2005 and 2050.

	2010	2015	2020	2030	2040	2050
Annual fraction of floorspace that is:						
New construction	1.78%	1.96%	1.84%	1.62%	1.46%	1.33%
Retrofits	1.65%	1.65%	1.65%	1.65%	1.65%	1.65%
Demolished	0.50%	0.50%	0.50%	0.50%	0.50%	0.50%
Total floorspace (billion sq. ft.)	6.5	6.9	7.4	8.4	9.3	10.1
Annual efficiency improvement schedule*						
New construction	0%	20%	40%	60%	80%	80%
Retrofits	0%	15%	30%	40%	50%	60%
Average efficiency of building stock*						
New construction	0.0%	1.1%	3.6%	10.2%	17.1%	23.3%
Retrofits	0.0%	0.7%	2.4%	6.9%	12.0%	17.7%
Total	0.0%	1.8%	6.0%	17.1%	29.1%	41.0%

Table 8. Schedule of efficiency improvements to commercial buildings
*Relative to BAU, which assumes essentially no per building improvement between 2005 and 2050.

For residential buildings, the retrofit rate (1.81% per year) was chosen to allow every building in California to be retrofit by 2050—assuming only buildings built before 2010 would be retrofit, minus the fraction that is demolished each year (about 0.3% on average). For commercial buildings, a lower retrofit rate was chosen (1.65% per year), due to the higher annual rate of both new construction (~1.6%) and demolition (0.5%), so that all pre-2010 buildings would be retrofit by 2050. The schedule of retrofit efficiencies was identical to that of residential buildings. In both cases, the rates were much lower than recent observed retrofit rates for all purposes (approximately 10%; Walker, 2010), but the emphasis until recently has seldom been on efficiency improvements, especially in retrofits.

These assumptions, plus the assumed rates of new construction, retrofit construction, and demolition, were used in simple stock turnover models for the residential and commercial buildings sectors, in order to calculate net efficiency improvements for the building stock overall. An extremely fast ramp-up in the first ten years (2010-2020) reflected the increasing number of new and retrofit buildings that are built to higher efficiency standards, up from essentially zero today.

Such a pathway will require aggressive new building standards, the first of which will need to be put in place immediately. This approach will ensure that every building in 2050 is significantly more efficient than today's building stock, resulting in an average efficiency improvement of about 40% for both residential and commercial buildings in 2050.

Figure 2 illustrates the average efficiency improvement of new and retrofit buildings each year for residential and commercial sectors. Figure 3 and Figure 4 illustrate the fraction of building stock affected in the residential and commercial sectors, respectively (where demolished buildings are assumed to be rebuilt to new building standards). Note that because of the different assumed rates of demolition, about 14% of residential buildings are demolished and rebuilt between 2010 and 2050, while 26% of commercial buildings are rebuilt. Figure 5 and Figure 6 show the resulting increases in efficiency from new and retrofit buildings, showing that in the residential sector, 46% of the savings come from new construction, while in the commercial sector, 57% of savings come from new construction.

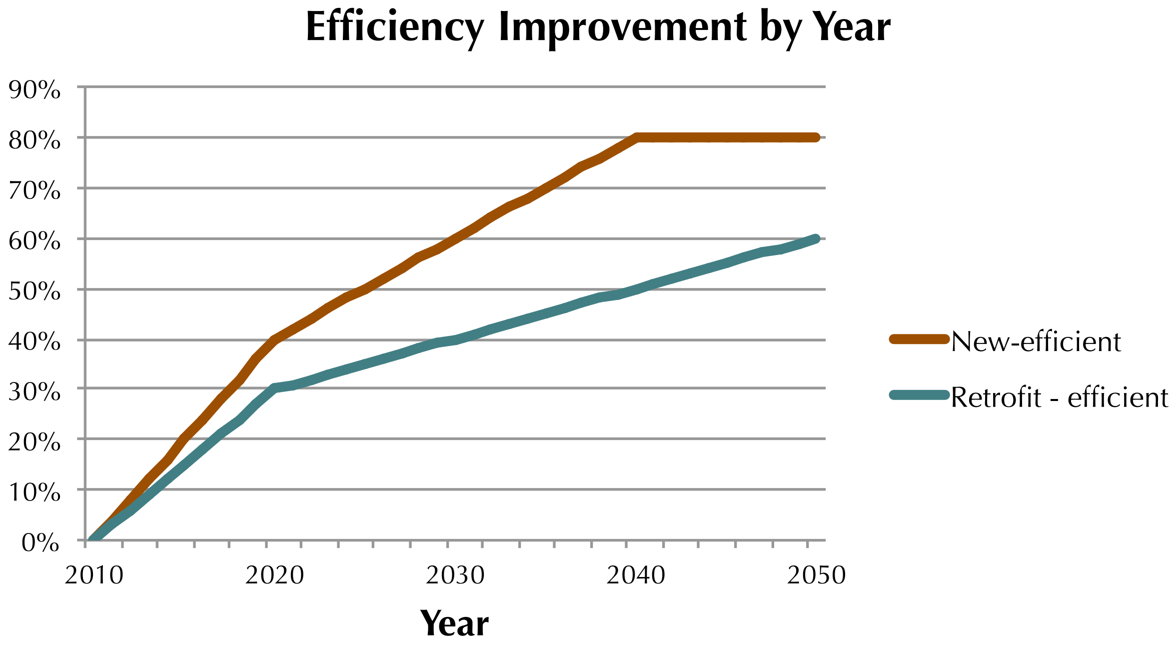

Figure 2. Average efficiency improvement of residential and commercial buildings by year

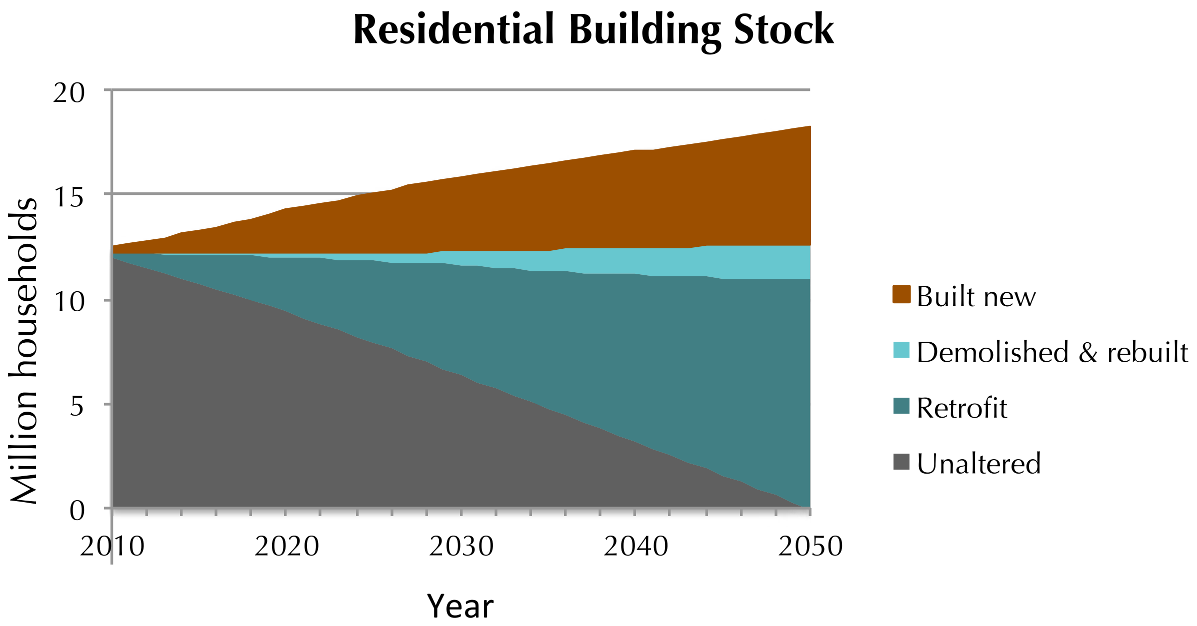

Figure 3. Residential building stock turnover

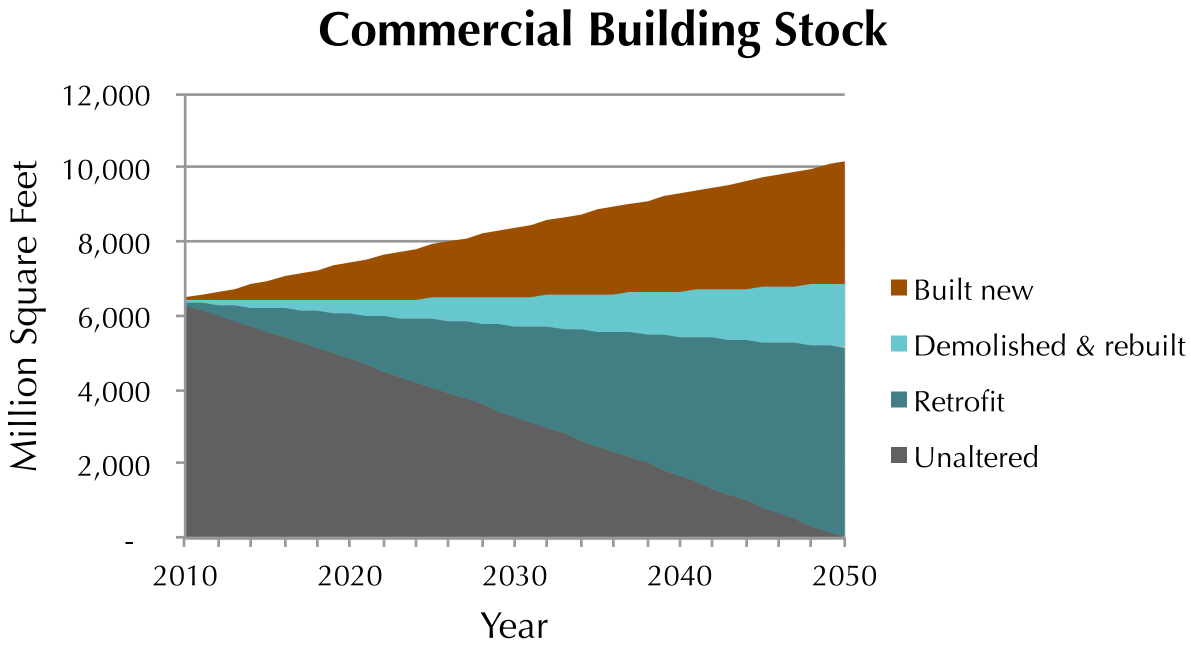

Figure 4. Commercial building stock turnover

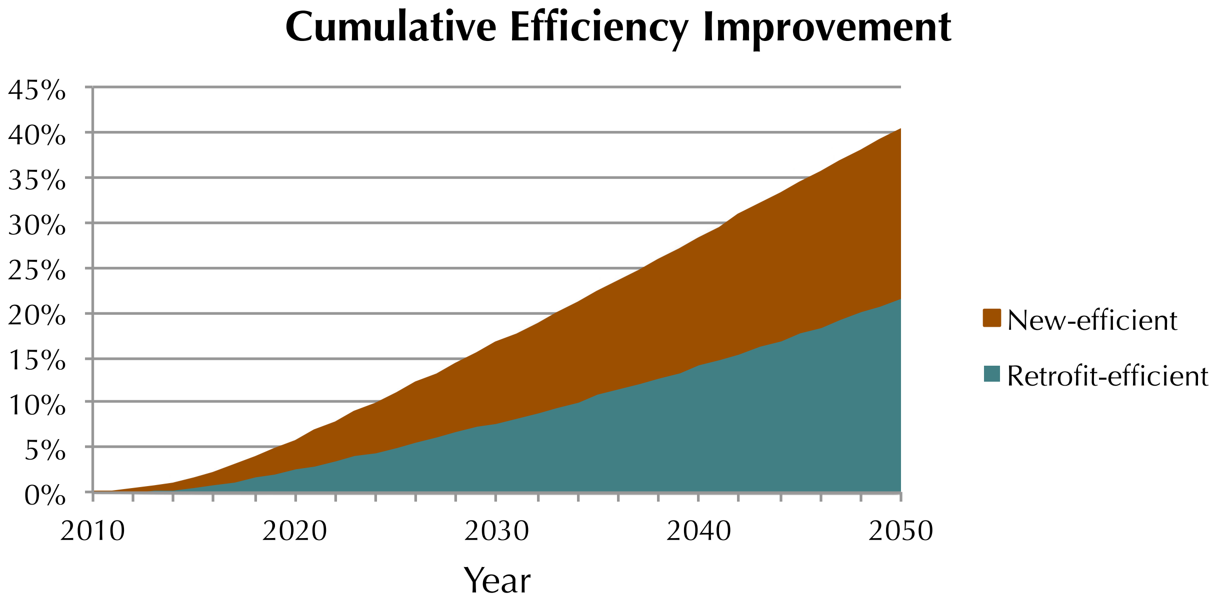

Figure 5. Cumulative efficiency improvement in residential buildings (relative to baseline)

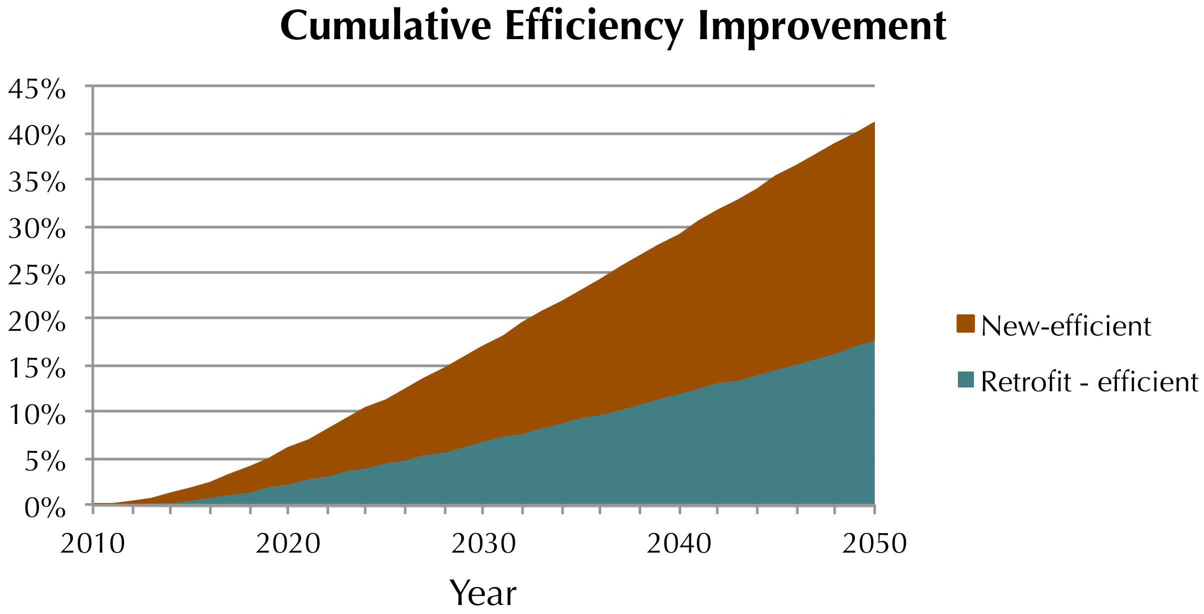

Figure 6. Cumulative efficiency improvement in commercial buildings (relative to baseline)

Our overall efficiency estimates are bracketed by results from other studies. A widely-cited 2000 study, *Scenarios for a Clean Energy Future*, published by five of the U.S. national laboratories (Interagency Working Group, 2000), found that reductions in U.S. residential and commercial building energy use of between 4% and 10% (depending on the scenario) were possible in 10 years, and between 10% and 20% in 20 years, relative to a BAU scenario. The CEF sector-wide average efficiencies for 2020 and 2030 (about 6% and 17%, respectively) fall between these sets of results.

Williams et al. (2011a, 2011b) assumed annual rates of efficiency improvement in residential and commercial buildings were an average of 1.4%/yr for electricity, 1.7%/yr for natural gas, and 1.6%/yr overall, resulting in reductions of about 40-50% in energy consumption in 2050, consistent with the CEF estimates. According to the study, these rates were "high but…not unprecedented, either by historical standards or by values reported in long-term energy efficiency technical potential studies. Currently, California's utility-based energy efficiency programs result in electricity reductions that are generally less than 1% [per year]." Similarly, in the study by Wei et al. (2011), 38% building electricity savings were assumed in their maximum efficiency case in 2050 relative to a frozen efficiency case.

Other recent studies suggest more aggressive efficiency savings are possible. A recent paper by Meyers et al. (2009) suggests that the average existing U.S. home could save 39% (range of 33% to 62% per home) of primary energy exclusively through the use of automated control systems for heating, ventilation and air conditioning (HVAC) and plug loads, and upgrading to high-efficiency ENERGY STAR appliances. The *America's Energy Future* study (NAS, 2010) indicated potential savings in 2030 in the residential and commercial buildings sector of 17.4 quads out of a projected 46.5 quads in the base case (EIA, 2010), or 37% savings, with most of the savings attributed to electricity (14.4 quads). However, it also stated, "the barriers to improving energy efficiency are formidable."

The California Public Utilities Commission *Strategic Plan* (CPUC, 2011) contains even more optimistic targets than these studies. It aims to make all new California homes consume net zero energy by 2020, with efficiency providing at least 35% savings over the 2005 Title 24 standard, and 90% of new homes providing at least 55% savings. For existing homes, the Plan calls for an average efficiency improvement of 40% by 2020. These goals, if realized, would more than achieve the CEF 2050 target for the residential sector by 2020.[10] However, progress toward these goals has been slow; a recent study by CalCEF, the BlueGreen Alliance, and UC Berkeley Labor Center estimates that "at the current rate, it will take 290 years to reach the targets set out in the plan to be achieved within the next eight years." (Bamberger et al., 2012).

In terms of electrification, the CEF model assumed 70% of building heat would be electrified by 2050. This was a technical estimate, not an economic one; to our knowledge, no detailed cost-benefit calculation for building electrification has been performed, and we have not considered how the recent drop in natural gas prices would make electricity less cost-competitive. By contrast, Williams et al. (2011a, 2011b), assumed 30% electrification of non-transport fuel use, and 65% of non-heating/cooling fuel use, while Wei et al. (2011) assumed progressive penetration of electric space and water heating technology, reaching 100% saturation of water heating and residential space heating by 2040, and ~90% saturation of commercial space heating by 2050.

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[10] For the commercial sector, the CPUC plan proposes that 100% of new buildings, and 50% of existing buildings, be net zero energy by 2030, but is silent on efficiency targets.

Technological Maturity

The level of maturity of efficient building technologies is shown in Table 9. We used the same 4-bin notation as employed in previous CEF reports, where bin 1 was commercially available, bin 2 was in demonstration, bin 3 was in development, and bin 4 was at the research stage. See Table 3 in Greenblatt and Long (2012) for more information.

Bin	Space Conditioning and Building Envelope	Water Heating	Appliances	Electronics	Other
1	High-efficiency furnaces (including heat pumps), high-efficiency air conditioning equipment, occupancy sensors, fiberglass super-insulation, cool roofs	High-efficiency water heaters, on-demand water heaters	ENERGY STAR appliances (~20%), soil sensing clothes- and dishwashers, horizontal- axis clothes washers, high-spin clothes dryers	Automatic sleep mode, more efficient transformers	More efficient motors and fans, LED lighting, magnetic induction cooktops
2	Vacuum panel insulation, whole-building optimal energy management	Heat pump water heaters, solar hot water, waste heat recovery, whole-system integration	Higher efficiency appliances (~40-50%)	Network proxying	Organic LED lighting
3	Non-invasive insulation retrofits				
4			Magnetic refrigeration		

Table 9. Technology bin assignments (see text for bin definitions)

Costs

The cost of higher efficiency buildings differs dramatically between new and existing buildings. Today, some researchers claim that a new building can be constructed to be 40-50% more efficient with no difference in up-front cost (Walker, 2009), though the literature is virtually silent on this matter. Current zero-energy commercial buildings specify demand reductions of 70-80% (with the reduction to zero net energy coming from renewable generation) (ZECBC, 2010). Other studies, including a pan-E.U. study, also claim demand reductions from baseline at the 80% level for new buildings (Fraunhofer Institute, 2009). We assumed that as efficient building practices expand, one will be able to achieve highly efficient new buildings at the same cost as standard buildings today.

By contrast, the costs of efficiency retrofits to existing buildings are significantly higher than standard building practice. For an average-sized home (approximately 2,500 square feet), retrofit costs range from $10,000 for a 25% efficiency improvement, to $25,000 for a 40% improvement to more than $40,000 for a 70% improvement (Golden, 2010). Going for the highest possible "deep" efficiency retrofit (~80%) can push the cost to as much as $100,000 (Walker, 2009). However, Keesee (2012) recently proposed the "Pretty Good Home" retrofit concept that achieves up to 60% improvement for pre-1978 homes in Sacramento for less cost than conventional retrofits.[11] It achieves this by avoiding expensive quantitative measurements such as blower door tests and building simulation, opting instead for a prescriptive list of improvements that generally result in large energy savings in a majority of homes. Once the building envelope has been improved, a critical step is to measure heating and air conditioning loads of existing equipment, providing a direct measure of the required (usually much smaller) capacities of new, more efficient units which are then installed as a final step.

Costs climb dramatically as efficiency improvement increases, mainly due to the need to remove much of the existing inefficient building systems—essentially the home must be rebuilt from the framing (or even the foundation). Technology to allow less destructive retrofits would also dramatically lower costs, enabling higher efficiency gains to be achieved. However, building standards can require much more efficient construction than is currently practiced, and help lower the cost differential of higher efficiency by driving demand for these technologies.

The U.S. home renovation market is a $150-250 billion/yr industry (Walker, 2010; Remodeling, 2010), with approximately 10% of homes being renovated in some fashion annually. Work tends to focus on form and aesthetics, not efficiency, so energy savings are typically much less than in new construction. With an average renovation cost per home on the order of $20,000, the increased cost for a deep energy retrofit is very prohibitive. Therefore, a third challenge is achieving maximum efficiency gains, which is closely coupled to cost, particularly for retrofits.

Some studies cite more optimistic figures, however. The NAS study (2009) which indicated a 37% savings potential in residential and commercial buildings in 2030, cites an average U.S. "cost of conserved energy" of 2.7 ¢/kWh for electricity as compared to a roughly 10 ¢/kWh average retail cost, and for natural gas, $6.9 per million Btu (residential) and $2.5 per million Btu (commercial) as compared to retail costs of roughly $12 per million Btu. This suggests considerably lower investment cost to achieve a high level of savings.

One opportunity is that for major renovation, it may in some cases be less costly to simply demolish the existing building and create a new, more efficient structure from the ground up. Policy could be geared to encourage demolition over preservation, which would accelerate this trend. This was not assumed in the cases explored here, however.

The energy consumed by building equipment—HVAC, hot water heaters, major appliances (refrigerator, stove, dishwasher, etc.), and miscellaneous (primarily electronic) devices—can in many cases be radically improved using currently available technology. While first costs are often

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[11] Specifically, the efficiency upgrade cost was between $17,000 and $42,000 across six homes ranging from approximately 1,000 to 1,500 square feet, representing 13-35% of total project cost that also included non-efficiency upgrades and, in one case, rooftop solar PV. Note that projects received incentives and tax credits of between $3,500 and $16,400 (the highest value representing the home with PV). The first-year utility bill savings were between $737 and $2,444, representing a net return on investment of 6-32% per year (Keesee, 2012).

significantly higher than equipment with typical efficiencies, the total lifecycle cost is in many cases comparable or even superior. Moreover, the costs of more efficient equipment have been falling dramatically over the past several decades, and further cost reductions are likely to be possible in the future (Desroches et al., 2012). Policies to encourage such efficiency improvements have mostly been generated at the federal level (e.g., DOE, 2011; ENERGY STAR, 2011), but state efforts, particularly in California, are sometimes able to move more quickly than federal actions (e.g., CEC, 2010).

Reliability

Greatly increased efficiency will lower the peak energy demand significantly, improving grid reliability. However, the greater reliance on electricity will mean that demand growth will continue at a pace comparable with historical rates, despite efficiency gains. Long-term resource planning will be required to ensure that adequate generation, and especially transmission, capacity are added well in advance of demand constraints. Demand response technology, while strictly speaking not an efficiency improvement, will become part of the overall "intelligence" of appliances and buildings. This will allow consumers to lower costs somewhat by optimizing their time of use, and also will allow for less reliance on fossil (mostly natural gas) generation for load balancing.

Resource Constraints

While a well-trained, competent workforce in efficient building technology is currently in short supply (Golden, 2010), no material or other resource constraints could be identified that might limit implementation of more efficient technologies.

Policy Assumptions

The main challenge to implementation of energy efficiency is shifting consumer focus away from first cost and toward lifecycle cost. A number of strategies, some more successful than others, have been attempted in the U.S. and elsewhere, including standards, efficiency labeling, rebates, tax incentives, voluntary targets, bulk government purchases, and consumer education. A combination of minimum efficiency standards along with efficiency labeling, when updated frequently, has proven very effective for residential and commercial appliances, and would be the recommended path to maximize efficiency gains rapidly, along with research and development funding for less proven but promising technology.

A recent assessment (Fuller et al., 2010) of past residential retrofit programs in the U.S. indicates a very wide range in participation, from less than 1% to almost 90%. While financial incentives play an important role, the study concluded that they are not the main driver of participation. Marketing strategy is key, as it determines participation levels, and past programs have been largely unsuccessful in convincing large numbers of people to make efficiency improvements. The study concluded that focusing on a small target audience initially is a more cost-effective strategy than a blanket campaign, and programs should aim for simplicity and speed, and plan to be in business for many years. Innovation and measuring success are also vital design elements, and a prepared, professional workforce for doing the retrofit work is key. Table 10 summarizes these strategies.

Area	Strategy	Comment
Marketing	Sell something people want	High home energy use is not currently a pressing issue for many people; find a more appealing draw such as health, comfort, energy security, competition, or community engagement to attract interest
	Study the target population	A blanket marketing campaign to reach everyone will likely be ineffective and expensive, especially at the start of a program. Find and target early adopters. Tailor messages to this audience. Demographics can help segment the market and select optimal strategies, but you can also segment the market by personal values, interest in hot issues such as health concerns, or likelihood of getting savings.
	Partner with trusted messengers	Larger subsidies and more voluminous mailings don't necessarily win over more customers. Programs can and should have a local face, with buy-in from community leaders. Tapping trusted parties, such as local leaders and local organizations, builds upon existing relationships and networks.
	Choose language carefully	Avoid meaningless or negatively-associated words like "retrofit" and "audit". Use words and ways of communicating that tap into customers' existing mental frames. Encourage program staff and contractors to use specific vivid examples, personalize the material wherever possible, frame statements in terms of loss rather than gain, and induce a public commitment from the homeowners.
	Contractors are program ambassadors	Contractors, more than any other party, are the people sitting across the kitchen counter making the final sales pitch to a homeowner—contractors are often the public face and primary sales force for the program. Most programs that succeed in performing a significant number of energy upgrades have worked closely with contractors. Conversely, poor first impressions or shoddy work by contractors can reflect poorly on the program.

	Touch the client more than once	The advertising industry's "three-times convincer" concept means that the majority of people need to be exposed to a product message at least three times before they buy into it. Energy efficiency is an especially tough product—it can be expensive and can't be readily touched, tasted, or seen—and that calls for a layered marketing and outreach approach that achieves multiple touches on potential participants
Program Design and Implementation	Make it easy, make it fast	Offer seamless, streamlined services—package incentives, minimize paperwork, and pre-approve contractors—give people fewer reasons to decide against home improvements by making it simple.
	Contractors should be full partners	Contractors are the key point of sale for home energy improvements. They already understand the traditional renovation and home improvement market, and have access to customers who may initially want to replace a furnace but may be open to other improvements. It's imperative to design a program that contractors want to sell—and convince them that the opportunity is worth the time and money to get the appropriate training and equipment.
	Financial incentives do matter	Program experience shows that incentives do motivate the choice to do home upgrades, and can be extremely important to get a program off the ground.
	A well-qualified workforce and trustworthy work are vital	Promoting a program aggressively before contractors can handle the workload can lead to disgruntled customers. Solid performance builds trust with customers by reliably producing energy savings, as well as the health, safety, and comfort benefits of home energy improvements.
	Persistence and consistency	It takes time for partnerships to take root, for word to reach consumers, and for contractors to respond to the opportunity. Consistent programs that last for more than a year or two can create a more robust market for home energy improvements; ephemeral programs can undermine trust.
	Know success and failure by measuring it, and experiment to figure out what works	Designing for data collection and evaluation at the start allows for mid-stream adjustments, better selection among strategies, and knowing success when it arrives. It is important to pilot strategies before launching full-scale programs and to test a variety of strategies to learn what works.

Table 10. Strategies for increasing participation in energy efficiency improvement programs
Source: Fuller et al. (2010)

In California, currently only about 5% of residential space and water heating uses electricity, when measured on a thermal equivalent basis. While some improvements can be made to existing natural gas combustion technology, a much more efficient option is to convert to electric heat pump technology, which uses one-third (or less) of the energy[12]. Doing so would reduce by 87% natural gas consumption in homes. The remaining 13% of natural gas (primarily clothes drying and cooking) use could also be replaced with much more efficient, electricity-based alternatives, though for cooking, there may be an owner preference for gas (about 70% of residential cooking in California uses natural gas). The challenges of making such a wholesale conversion to electricity are first cost, appliance/building standards, and construction industry practice. The CEF realistic case assumes 70% average building stock conversion to electricity-based heating by 2050.

For commercial buildings, natural gas consumption data by end use was not available, so we have simply assumed that the same overall potential was achievable in this sector as for the residential sector.

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[12] To be fair, such a comparison must take into account the thermal conversion efficiency of electricity generation. If one assumes electricity is produced by natural gas with ~35% efficiency, the two approaches (natural gas combustion, or a high-efficiency electric heat pump) consume essentially the same amount of fuel. However, if one produces the electricity with little or no fossil fuel, the electric option is far preferable. In any case, using electric heat pump technology is far more efficient than electric resistive heating, regardless of the method of electricity production.

Barriers

The main barriers to improving energy efficiency are summarized below in Table 11.

Barrier	Examples	Possible Mitigation Strategies	Level of Difficulty
Cost	Retrofit cost prohibitive	Increased adoption will lower costs	Medium
Labor	Trained workforce in short supply	Increased vocational and architectural school training, on-the-job training, increased public awareness and support	Medium
Lack of confidence, belief in efficiency benefits	Few examples of success, and high variability among existing programs	Adoption of best practices; improved data collection; new financing mechanisms to shift risk from consumer to builder (possibly with public subsidy)	Easy-Medium
Financing	Limited financing for efficiency improvements	Greatly expanded, long-term financing options; long-term (permanent?) public commitment to subsidize efficiency	Medium
Public policy – new construction	Current new building codes weak	Aggressive new construction building codes	Medium
Public policy - retrofits	Current existing building codes weak; retrofit programs overwhelmingly voluntary	Aggressive existing building codes coupled with strong requirements for compliance at time of sale and/or permit	Medium-Hard

Table 11. Barriers to building efficiency improvement

Potential Synergies

By lowering the overall demand for electricity, efficient buildings can play an important role in lowering peak demand, which makes the electricity delivery system less expensive to operate, more reliable, and, in principle, less carbon-intensive since there is less reliance on natural gas for meeting peak demand. A more complete discussion of this complex topic can be found in the load balancing section of a separate CEF report on fossil and renewable electricity (Greenblatt et al., 2012).

Discussion

There are several strategies for increasing efficiency gains over what was assumed in Case E. The first is simply that retrofit improvement potentials may have been underestimated; as the recent study by Meyers et al. (2009) suggests, savings of 40% may be achievable without touching the building envelope, which is where most of the expense lies. The second option is that older, less efficient buildings could be removed and replaced with much more efficient buildings, which might be possible at lower cost than attempting to preserve the original building. Policies to encourage increased demolition, while preserving buildings of historical value, should be explored. The third option relates to behavior change, something that is explored separately in the behavior change case discussed in Greenblatt and Long (2012).

Industry

Summary

Industrial efficiency can be improved by an estimated 48% relative to BAU through a combination of aggressive improvement in process efficiency, waste heat recapture, better product and production facility design, supply chain optimization, and electrification of thermal processes which currently utilize fossil fuels. Because this sector is comprised of many disparate industries, not all of which had extensive efficiency data available, we focused our attention on two major sectors: oil and gas refining (60% of industrial energy use) and the food industry (17% of energy use). Critically, because of anticipated reduced demand for fossil fuels elsewhere in the economy, it is assumed that the refining industry will largely vanish (up to 90% reduction, depending on final scenario; see discussion in next section) by 2050. For remaining sectors, a process approach was used, where similar processes (e.g. boiler systems, process heating, motor systems) were examined for savings potential and then the fraction of total industrial activity involving that process estimated by industry sector, based on Masanet et al. (2011). This essentially assumes a frozen process demand breakdown for boiler systems, process heating, combined heat and power (CHP), and other end use processes by industrial sector. For example, glass manufacturing and cement production are dominated by process heating currently, and this is expected to be true in the future. Thus this assumption is probably reasonable for most industry sectors. One exception is that the fraction of CHP could increase above current levels, for example in the food and beverage industry and in the chemical industry. Large-scale biofuel production is not modeled in this context (but GHG emissions due to biofuel production are estimated using a lifecycle emissions factor), and potential interactions of the biofuel industry with other industry sectors are beyond the scope of this study.

Technical Assumptions

Unlike the buildings sector, the UC Davis scenario on which the CEF cases are based (McCarthy et al., 2006, 2008) assumed about a 40% autonomous efficiency improvement within industry in the BAU case, acknowledging a continuation of historical progress and of the profit incentive. Therefore, much of the efficiency improvement identified for the industrial sector is subsumed in the BAU, allowing less room for improvement on top of these gains. Still, our assessment indicates the potential for about a 48% overall reduction in energy use in the realistic case, relative even to BAU.

As large changes have occurred in the industrial sector in recent years, both in California and in the rest of the U.S., with much manufacturing shifting to other countries, it was very difficult to project future changes, beyond some key assumptions:

- Because of the massive reductions in CO_2 emissions from liquid fuels that will be required as part of the overall GHG reduction target, we assumed a significant reduction (up to 90%) in petroleum refining in California,[13] which currently accounts for 60% of California's industrial energy consumption. For the biofuel industry, we did not make any explicit assumptions regarding energy use, but rather relied on overall efficiency and lifecycle GHG estimates (from Youngs et al., in prep.) to calculate that industry's impact on statewide biofuel supply and emissions.
- We assumed that the food industry, which is currently the largest non-petroleum energy user in the industrial sector (it accounts for 17% of non-petroleum energy use), would remain a California-based industry, due to the local nature of the product.
- We assumed that new industries will emerge to replace what may disappear, with similar energy use requirements (a vast oversimplification, but without detailed knowledge of what future industries might be, the approximation makes the fewest assumptions).

Unit technology energy efficiency improvements in process heating and steam systems rely on better operational and maintenance practices, process optimization, and improved insulation. Variable speed motor systems offer significant savings opportunities in motor systems. Automated sensors and control systems and IT-interfaced "smart manufacturing" have a large role across end uses. A detailed description of California industrial end use energy efficiency savings for 2020 and 2050 can be found in Masanet (2011). A recent National Academy study (2009) on energy efficiency projects 14-22% industrial energy savings by 2020.

Beyond this, RD&D in design and system integration can be as important as unit technologies, as focusing on unit level "deemed savings" does not always translate to actual savings. Important elements in system design and system integration include:

- Process intensification, e.g., integrating chemical separation and synthesis, distillation processing, etc.
- Waste heat recapture
- Product design for reuse and recycling
- Production and factory design
- Supply chain management/optimization

Moreover, there is a high degree of customization and specialization across industry sectors that makes a single set of industry-wide solutions inappropriate.

A key requirement for the reduction in industrial energy use would be the widespread electrification of process heating using advanced technology. The case assumes 50% market share, starting in 2020. With annual stock turnover rates of 2.5% (e.g., assumed 40-year lifetime), there would be only one chance to intercept equipment replacement, with a resulting stock penetration of process heating electric equipment of only 35-40% by 2050.

See Table 12 for a detailed breakdown of reductions by fuel type and category.

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[13] The assumption of 90% reduction was made in the context of sufficient biofuel availability. However, in developing our Median supply case and its many sensitivities (described in Greenblatt and Long, 2012), it was found that in most cases, biofuels were not sufficient to displace 90% of fossil fuels. In these cases, the needed fraction of the refining industry was retained, increasing energy demand.

	Electricity	Natural Gas	Petroleum
Efficiency relative to BAU*	1%	0%	-16%
Oil industry downsize†	-23%	-58%	-47%
Electrification	+28%	-12%	-13%
Net change	-2%	-63%	-47%

Table 12. Industrial demand reduction assumptions

* BAU assumes efficiency changes of 28% to 38% (depending on the fuel), close to the improvements estimated here. Therefore, net efficiency change from BAU is almost zero.

† Because refining only constitutes ~60% of the industrial sector, the effects on energy reductions of a 90% reduction in the oil industry are not as pronounced across the entire sector.

Technological maturity

Table 13 summarizes key advanced technologies by bin number and by their expected year of maturity. Table 14 estimates the technologies by bin number that will be available in 2050 to contribute toward a solution.

Bin	Category	2010	2020	2030
1	Reactions and Separations	- Hybrid distillation systems	- Advanced water removal technologies - New manufacturing processes for olefin, chlor-alkali, ammonia, and chemical pulp production	- New membrane materials - Process intensification
	Waste energy recovery	- 2nd gen Super boilers - Ultra-high-efficiency furnace	- 2nd generation Super boilers - Ultra-high-efficiency furnace	- High-temperature (>700ºC) heat-to-electricity unit
	Sustainable Manufacturing	- Aggressive adoption of best operating practices, controls, monitoring	- Integration, Predictive operations, sensors - Advanced forming, joining, assembly	- Advanced functional materials and coatings
	High Temperature Processing	- New materials for large-scale production and deployment.	- Lower energy, high-temperature materials processing	- Material processing for emerging industries
2-3	Reactions and Separations	- Advanced water removal technologies - New manufacturing processes for olefin, chlor-alkali, ammonia, and chemical pulp production	- New membrane materials - Process intensification	
	Waste energy recovery		- High-temperature (>700ºC) heat-to-electricity unit	

	Sustainable Manufacturing	- Integration, predictive operations, sensors - Advanced forming, joining, assembly	- Advanced functional materials and coatings	
	High Temperature Processing	- Lower energy, high-temperature materials processing	- Material processing for emerging industries	
4	Reactions and Separations	- New membrane materials - Process intensification	- New membrane materials - Process intensification	
	Waste energy recovery	- High-temperature (>700ºC) heat-to-electricity unit	- High-temperature (>700ºC) heat-to-electricity unit	
	Sustainable Manufacturing	- Advanced functional materials and coatings	- Advanced functional materials and coatings	
	High Temperature Processing	- Material processing for emerging industries	- Material processing for emerging industries	

Table 13. Industrial implementation roadmap
Adopted from DOE (2007).

Bin Number	Technologies
1	Ultra high-efficiency furnaces, controls and monitoring systems, waste heat recovery systems
2	Membrane technology for separations, super boilers, advanced/hybrid distillation, solar boiler systems
3	Integrated & predictive operations/sensors, advanced materials and processing, electrified process heating (e.g., microwave), process intensification
4	New membrane materials, advanced materials/ coatings

Table 14. Efficient industrial technologies by technology bin

Costs

The current costs of implementation are difficult to estimate. McKinsey (2009) estimates $113 billion nationally for 18% savings in 2020, whereas ACEEE (Elliott, 2009) estimates a cost of $200-300 billion through 2025 for the U.S. for a 25-30% reduction in energy intensity.[14] These figures are roughly ~10% above what industry historically spends on energy and capital expenditures.

Extrapolating this to the future is difficult. Much of industrial energy savings beyond BAU efficiency gain is from oil and gas industry replacement, and the costs for building up in-state biorefinery capacity are significant (see details in Youngs et al., in prep.). Costs for electrified process heating are not well-characterized, and raw cost numbers for electrification could present a misleading picture because electrified heating offers potential productivity and process control benefits that can offset conversion costs. However, if we extrapolate the above linear trend, to achieve in 2050 a 70% savings relative to today (equal to ~50% savings in 2050 on top of a ~40% BAU efficiency gain[15]), it would require sustaining a similar level of effort over the next 40 years—that is, approximately $500 billion in total. Of course, this estimate assumes that the cost of achieving higher efficiency is no more expensive than for lower efficiency improvements, which is not necessarily true in general. However, unit costs are expected to decline with innovation, processing learning, and production scale.

For some applications, the cost of improvement is modest and can be accomplished during one equipment turnover cycle (typically 10-20 years). For other applications, particularly electrified process heating, the cost may be more prohibitive, so that dedicated policy must be put in place to support this transition.

Reliability

It is expected that there would be a significant positive impact on California energy reliability and security, because of reduced energy demand, particularly from a much-reduced dependence on imported oil.

Resource Constraints

There are no foreseeable shortages of commodities such as water or steel. The potential phaseout of the petroleum industry will have large repercussions in the electricity supply and/or biofuel supply industries, but these are covered in their respective sections.

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[14] There is a distinction between energy intensity and energy savings, but they are equivalent if we consider a "frozen intensity" (energy/GDP) case, and take savings relative to that due to efficiency changes, and ignore structural changes. This is a bit artificial, but simplifies the discussion here.

[15] The effects of combined efficiency savings are calculated by multiplying the remaining energy use, that is, 1 – efficiency savings. So in this calculation, $0.7 = 1 - (1 - 0.5)(1 - 0.4)$.

Policy and Barriers

Barriers to implementation are summarized in Table 15 and Table 16 below.

In general, the highest barriers to efficiency improvements include: the risk-averse nature of the industry, which limits investment in more efficient technology; steep learning curves and high costs for implementation of unfamiliar technologies; a lack of organizational structure to manage energy use; competition for capital for new processes and products, particularly for larger companies; and tax policies (such as depreciation schedules) that tend to discourage industry from implementing energy efficiency measures.

General policies that support increased energy efficiency in industry include R&D support, investment tax credits and efficiency incentives, and mandatory retirement of less efficient equipment. Voluntary industry sector targets for energy intensity coupled with penalties after several years have been shown to work in some European countries, but have not been pursued in the U.S. due to industry opposition.

Widespread dissemination of best efficiency practices and systems through educational institutions and workplace trainings, aggressive standards, and rigorous standards enforcement will be needed. Long-term consistent government support is crucial to overcome barriers (McKane, 2007). More federal and state financial incentive programs are needed, for example, to adopt best-in-class energy efficient or emissions reduction equipment. Standards and protocols for energy management practices should be prioritized. Since this may not be part of current practice, preparing workforce training programs to support such practices are needed as well.

Two existing federal programs address some of the barriers in Table 15: "Save Energy Now" and "Superior Energy Performance." Save Energy Now is a national program at the company or plant level with the goal of 25% reduction in energy intensity over the next 10 years. This assumes a -1% annual rate of autonomous change and 1.8% annual energy efficiency gain above that. The program provides a wide variety of resources to participants including coaching, energy management best practices, and in some cases outsourced implementation. Save Energy Now is a voluntary program without incentives or penalties. Still, several industry energy efficiency experts that were consulted for this report expressed high confidence in the U.S. achieving a 25% energy intensity reduction by 2020. Much of this savings is projected to be "low-hanging fruit" so to go beyond this level, more R&D is required to further reduce energy intensities. The impact of such a program could be greater with the threat of penalties or with the incentives of tax credits but these do not exist today. The benefit of this program is that a structure of targets and timeframes and government resources has been set up which will be very useful if carbon price policies are implemented.

A second related national program is the "Superior Energy Performance" (SEP) program. This is a plant-level certification program that is coupled with government education and support programs. To receive certification, a 5% minimum energy intensity reduction needs to be demonstrated over three years and energy management practices must be in conformance to specified standards. Currently the program is in a national demonstration phase with 1-2 sites per state, and the program is expected to accelerate in 2011, when ISO 50001 energy management standards are released. Key issues in this program are developing messages for why companies and plants should join the program and quantifying the value of establishing energy management systems (McKane, 2007).

Both Save Energy Now and SEP could be expanded to become wider scale national programs that are consistent with meeting long-term emissions reductions. A first step would be to establish target levels of energy intensity in 2020 and providing incentives for meeting targets early, as well as penalties for not meeting targets. This could be coupled with tax incentives and loan guarantees for efficiency upgrades. Mandatory energy intensity levels would likely meet with industry opposition, and such a program would be difficult to achieve politically. At the least, increased funding should be provided for industry specific guidebooks and training.

Save Energy Now and SEP address many of the general barriers in Table 15. Not explicitly addressed, however, are regulatory barriers or coordination among industry/utilities and government. Industry electrification barriers are also not addressed by the two programs, and lack R&D funding, technology piloting/demonstration centers, and incentive programs.

For electrification, the highest barriers are the highly integrated nature of existing systems, and the perceived high costs of electric equipment. Many electro-technologies and their capabilities are viewed as unknowns. This is especially a problem in industries with low margins that employ older baseline technologies and that have a shortage of engineering expertise.

Significantly increased and sustained funding in electro-technology R&D as well as demonstration centers and pilot sites would be enormously helpful to address industry education and risk aversion barriers and would be critical to meet the industry electrification targets delineated in this report. Increases in discretionary spending would be contentious in the current political environment, and sustained funding is hampered by the absence of a long-term national energy plan.

To avoid special land, water or materials needs, well-funded RD&D programs would be required to address resource depletion, along with the rapid training of a skilled inspection and certification workforce to ensure best practices are being implemented.

Barrier	**Example**	**Mitigation**	**Difficulty to Overcome**
Risk Aversion	General organizational inertia to change standard operation practices due to risk aversion, perceived uncertainty and/or interruption of normal business processes	Establishment of more advanced technology and electro-technology application centers for demos and pilots Increased funding for industry specific guidebooks and training Establish target levels of energy intensity with threat of penalties/tariffs or voluntary agreements	High
Elevated hurdle rate and high transaction costs	Many examples of decision not to change process despite significant projected savings (glass, food)	Energy management practices/training Emerging energy management standards ISO 50001 Energy assessment/training Incentives and grants Voluntary agreements	High
Competition for Capital	Limited capital among marketing, sales, manufacturing, R&D, and other functions.	Safety and compliance are number one priorities for capital within each industry business, so tighter climate policies required	High
No organizational structure to manage energy use	Operations budget separate from capital allocation budget; Competition for capital	Energy management best practices, systems Monitoring/Verification/Records of energy savings EMS/Energy Manager system integration	High
Lack of understanding or capability on how to implement energy efficiency	Facilities which lack engineering support for monitoring/redesign	Protocols for System Assessment Protocols for Monitoring & Verification CEC/SEP Certification programs Training for Implementation and Inspection	High

Lack of government, utility, industry coordination	Industry capital equipment cycles 10-20 years non-overlapping with 1-2 year utility programs; Distorted price signals	Government/ utility/ industry partnerships for long-term planning and program structures and targets Time of use pricing programs	Medium
Low awareness of energy efficiency	Lack of data on specific end use energy consumption, Energy auditing weak	Ratings and Designations for Facilities ISO 50001 Operation Standards (expected 2011) EPA End Use Guidebooks & Focus Groups Online Databases for Combined Heat and Power and End-use installations Training programs for energy assessment, auditing	Medium
Distorted Price Signals	Lack real time price pricing signals to industrial customers; tax depreciation schedules that discourage investment in efficient equipment	Time of Use pricing programs, modifications to tax policy	Medium
Regulatory issues	Disincentive to change emissions due to lengthy regulatory review requirement	Streamline regulatory review	Medium

Table 15. General barriers for industrial efficiency improvements

Barrier	Example	Mitigation	Difficulty to Overcome
Highly integrated existing systems	Petroleum refining/ petro-chemicals	Incentives for new plant design with lower energy intensity	High
Economic: energy cost	Cost of electric heating higher than gas heating	Minimum carbon price for greater certainty Establishment of more advanced electrotechnology application centers for demos and pilots	High
Economic: capital cost	Microwave heating systems more expensive than fuel systems	Incentive programs, government/ industry partnership for higher end use efficiency Rebates to mitigate higher capital costs	High
Procurement and Distribution availability	Lack of off-the-shelf electric equipment but availability of fossil fuel dryer (food sector)	R&D targeting advanced electric heating technologies	High

Table 16. Electrification barriers.

Potential Synergies

As mentioned for buildings above, by lowering the overall demand for electricity, efficient industry can play an important role in lowering peak demand, which makes the electricity delivery system less expensive to operate, more reliable, and, in principle, less carbon-intensive. See the CEF fossil and renewable electricity report (Greenblatt et al., 2012) for a more in-depth discussion.

Discussion

Items that would lead to more energy savings, and hence less emissions, include:

- Industry manufacturing energy savings derived from efficiency measures may be an underestimation of the overall potential, since non-energy driven process/product improvements may also result in energy savings. However, many of these savings were captured in the autonomous BAU baseline.
- The CEF economic growth assumptions appear to be more aggressive than those of some other studies. Different assumptions about changes in sector makeup and growth could possibly give lower emissions results.

Items that would lead to less energy savings, and hence more emissions, include:

- Electrification adoption rates are more aggressive than other studies, and some might argue they are unrealistic, given the lack of existing funding and programs for development and deployment.
- Increases in CHP are not included, following the logic that the energy system needs to move sharply away from combustion processes altogether. Increasing CHP might be useful in meeting medium term goals, but it is not consistent with 80-90% reductions.
- In the medium term, while the electricity supply mix still has significant carbon emissions per unit energy, electrification could increase emissions.

Transportation

The transportation sector was analyzed in detail in a separate CEF report on transportation (Yang et al., 2011). The analysis found that the demand for liquid fuels could be reduced through a combination of improvements in conventional efficiency, and electrification in most transportation subsectors. While light-duty vehicles could achieve significant reductions in fuel demand (almost 80%) relative to BAU, and 100% of buses and rail transport, only about 18% of heavy-duty vehicle transportation, representing half of short-distance delivery truck energy use, could likely be electrified, and aviation and marine transport would continue to require liquid hydrocarbon fuels, because of energy density considerations. Overall demand would be about 70% lower than BAU, but liquid fuel demand would still be strong, about 11 billion gallons gasoline equivalent (bgge) per year, roughly half of today's total liquid fuel demand across all sectors.

Hydrogen fuel cells could further reduce liquid fuel demand; see discussion of Case H (hydrogen) below. All solutions would use bin 1 and bin 2 technologies, though key component costs (batteries, fuel cells and H_2 storage) are currently high and need to be reduced by a factor of 2 or more for widespread adoption.

For light-duty vehicles, a category which represents by far the largest portion of transportation fuel demand, achieving high fleet penetration of efficient and alternatively fueled light-duty vehicles by 2050 will require rapid market adoption in the next decades. However, universal plug-in vehicle adoption appears unlikely, for two reasons. First, dedicated, off-street parking is available to less than 50% of car owners at home, and to an even smaller fraction of urban-parked vehicles that would benefit the most in short-range substitution of electricity for fuels. Second, for larger vehicle sizes, battery costs will be high.

Table 17 summarizes the feasible reductions by transportation sector in the Realistic Case E. Discussions of technological maturity, costs, reliability, barriers, policy requirements and potential synergies can be found in Yang et al. (2011).

Subsector	Fuel Demand (Bgge/yr) 2005	BAU Case C 2050	Realistic Case E 2050	Difference from BAU to Realistic 2050	Demand change from BAU to Realistic 2050: Due to Efficiency	Due to Electrification	Realistic 2050 Electricity Demand (TWh/yr)
Light-duty Vehicles	14.7	25.5	5.7	-78%	-60%	-44%	73.1
Heavy-duty Vehicles	4.0	7.9	4.5	-43%	-31%	-18%	8.7
Aviation	0.3	0.5	0.2	-53%	-53%	0%	0
Buses	0.6	0.9	0	-100%	0%	-100%	4.6
Passenger Rail	0.1	0.1	0	-100%	0%	-100%	1.4
Freight Rail	0.03	0.1	0	-100%	0%	-100%	1.0
Marine Transport	0.5	0.7	0.4	-40%	-40%	0%	0
Total	20.2	35.7	10.8	-70%	-51%	-38%	88.9
Fraction of Total Energy System	90%	88%	81%	-7%			18%

Table 17. Transportation sector assumptions for Business-As-Usual (BAU) and Realistic Cases.

Case H: Demand with Hydrogen

The hydrogen case is treated in detail in a separate CEF report on energy system portraits (Greenblatt and Long, 2012) and in the CEF transportation report (Yang et al., 2011). In summary, starting from Case E, all energy sectors were examined to determine the realistic level of hydrogen adoption, if any, in conjunction with the efficiency and electrification already assumed in the base case. It was determined that a demand of 7,980 GgH_2/yr (about 8 bgge/yr) would be feasible by 2050. This would displace about 7 bgge/yr of liquid and gaseous hydrocarbon fuels and 50 TWh/yr of electricity, saving about 40 $MtCO_2e$/yr in GHG emissions. The fraction of hydrogen assumed for each sector, the assumed efficiency, and the resulting demand, are summarized in Table 18. About 20% of industrial energy use, 56% of light-duty vehicles, 9% of heavy-duty vehicles (equal to half of the portion that was electrified in the Realistic Case E), and 100% of buses, were assumed to be converted to hydrogen. The largest demands for hydrogen came from the industrial and light-duty vehicle sectors.

Sector*	Fraction of 2050 Demand			Hydrogen Efficiency	Hydrogen Demand (GgH_2/yr)
	Carbon Fuels	Electricity	Hydrogen		
Industry	51%	27%	21%	20% better than HC fuels	3,160
Transportation					
Light-duty Vehicles	22%	22%	56%	79 mpgge	4,230
Heavy-duty Vehicles	82%	9%	9%	25 mpgge	170
Buses	0%	0%	100%	70 seat-mpgge	420
TOTAL					**7,980**

Table 18. Technical assumptions for hydrogen (Case H)
*Omitted sectors were assumed to have no or very little hydrogen demand potential.

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Appendix B: Building & Industry Energy Efficiency Stress Test

Overview

The stress test explored the aggressive deployment of best available energy efficiency technologies into all buildings and industrial sectors by 2050. Overall demand reduction target is 90% relative to conventional fuel-based baseline end-use (Case C, see Table B.1), assuming no conversion among energy carriers (e.g., electricity substitution for hydrocarbon fuels).

Sector	Electricity Demand, TWh*/yr	Natural Gas Demand, billion therms/yr	Liquid Fuel Demand, bgge**/yr
Residential	136.5	8.0	0
Commercial	162.2	3.3	0
Industrial	111.3	15.9	4.7
Agriculture & Other	57.0	0.4	0
Transportation	0.0	0.0	43.7†
Total	467.0	27.6	48.4

Table B.1. 2050 energy demand for Case C (conventional fuels)

* TWh = terawatt-hours (equivalent to billion kilowatt-hours)

** bgge = billion gallons gasoline equivalent

† Gross demand that includes out-of-state consumption in the aviation and marine transportation sectors. In subsequent realistic case analysis, these contributions were reduced by 92% and 75% respectively to account for significant out-of-state usage, following the conventions of CARB (2009).

Thus, a 90% reduction across all sectors would result in a 2050 target demand of 46.7 TWh/yr electricity, 2.8 billion therms/yr of natural gas, and 4.8 bgge/yr of liquid fuels (note that massive fuel switching, primarily to electricity, is permissible and expected). In addition our projections already assume some autonomous energy efficiency savings (see discussion below).

These goals are considered extremely aggressive compared to other studies, e.g., the 2007 PIER study of the residential sector (CEC, 2007) assumes in their most aggressive case a decline to 68 TWh/yr in 2050 (using same population projection as we have, 54.8 million), about five times the 2050 target demand for this sector (13.7 TWh/yr). Even the less aggressive "Green Dream" case (84 TWh/yr in 2050, about the same as today) assumes "smaller home sizes, construction methods that employ greater insulation and infiltrations standards, enforced passive cooling and shading in hot regions, the elimination of oversized air conditioners, required periodic heating, ventilation and air conditioning (HVAC) maintenance, improved ducting design and installation, refrigerator size constraints, the elimination of second refrigerators, more daylighting in home design, the elimination of standard efficiency light bulbs and effective light controlling sensors for all indoor and outdoor light fixtures" (p. 28).

2050 CO_2 Emissions

We assume no changes in the energy supply mix relative to today, so with 90% reduction in energy demand, CO_2 emissions are approximately 90% lower as well, consistent with achieving a target of 80% below the 1990 level, approximately 81 million metric tons of CO_2 ($MtCO_2$) per year.

Summary of the Narrative

This scenario is considerably more complex than the supply-based cases, because there are many end-use technologies involved for each of three main sectors:

1. Residential buildings
2. Commercial buildings
3. Industrial facilities (see Appendix C)

Agricultural and "Other" sectors were not explicitly examined, as there is less information about them. Since their combined demand is only 5% of the total, we considered them inconsequential, provided these sectors can make similarly deep cuts as the other sectors.

To achieve the deep cuts in energy use, advanced technology combined with some behavior changes will be required, along with aggressive deployment to fully penetrate the building and industrial stock by 2050. We have developed a simple model to infer what retrofit rate is needed to ensure full penetration.

For industry, while energy efficiency or energy intensity (energy required per unit of output) can improve significantly, energy use in 2050 will be highly dependent on the actual mix of sectors (e.g., size of petroleum industry vs. chemicals vs. electronics). We follow industry sector projections from the CEC (2009) report, but this is a key uncertainty in projecting long-term industry energy reduction potentials. A larger shift toward the services sector and a smaller manufacturing sector would result in lower overall energy usage.

Technology Overview

In the residential and commercial building sectors, the following main service categories were considered (in rough order of declining baseline energy use):

- HVAC (space heating, ventilation and both central and room air conditioning)
- Water heating (including heating for dishwashers and clothes washers, and solar water heating)
- Miscellaneous devices (electronics, office equipment and other appliances)
- Refrigeration (refrigerators and freezers)
- Lighting (both interior and exterior)
- Clothes washing and drying
- Cooking
- Dishwashing
- Swimming pool and hot tub equipment (swimming pool pumps, hot tub pumps, solar pool pumps, swimming pool heating and hot tub heating)

For each service area, we have divided the reduction challenge into four components, improvements of which can have a multiplicative effect on energy savings (see following section):

- Reduce capacity (down-size, as in smaller refrigerators; or heating and cooling by room rather than a central air system)
- Increase efficiency (often through new technology)
- Reduce usage (combination of technology-facilitated control and behavior change)
- System integration (combining elements of several service categories)

Behavior change was recognized as a key factor in reducing usage. However, because this effect was treated as a separate case in the realistic analysis that followed, we separately estimated the contribution toward reduced usage from behavior change in the residential sector so that the total savings due to behavior change could be quantified in our estimates. We assumed that behavior change contributed to between a 10% and 30% reduction in energy use depending on the end-use sector. Weighting each of these contributions by the overall baseline energy use of the end-use, we estimated an overall reduction due to behavior change of 20%. See Table B.2 below and the following section for details. While a large contributor on its own, behavior change had a rather modest impact on total energy savings in the residential sector, because overall savings were already very large: without behavior change, total savings decreased from 91% to 89% relative to BAU. We did not make estimates of behavior change in the commercial sector.

Technologies Commercially Available Now

Some researchers claim that advanced efficiency techniques are already able to routinely achieve whole-building energy savings of 40% for new construction (Walker, 2010), with no difference in up-front cost, through techniques such as:

- Sealing of building envelope
- Insulation of building shell (wall cavities and exterior), attic, ducts and pipes
- Low-emissivity windows
- High-efficiency heating, ventilation and cooling system
- Instant (or solar) hot water instead of hot water tank
- Good framing design: saves money on installation & materials, provides a better thermal envelope, and to some extent reduces external surface area
- Placement of heating and cooling systems inside conditioned space
- Highest efficiency available lighting and appliances

Achieving higher levels of efficiency is certainly feasible, as this report will demonstrate. A recent real-world example is a new LEED Platinum home in New Jersey which achieves 59% energy savings over conventional homes (Goodman, 2009; Martin, 2009). Such efficiency achievements currently require additional techniques that are more expensive, but much of these costs can be recouped through lifetime energy savings.

There are ample opportunities to save even more, by capturing the lifetime energy savings through policy mechanisms (described below).

Table B.2 and Table B.3 below list each end-use category along with estimated savings potential, if fully implemented, which were based on available estimates (e.g., Desroches and Garbesi, 2011) and expert judgment to estimate the potential savings from each category and end use, drawing on our experience with estimating the technical efficiency potentials of buildings and appliances.

Note the combined savings is obtained from individual savings via the following formula:

Total unit reduction (%) = 1 - (1 - Capacity) x (1 - Efficiency) x (1 - Usage) x (1 - Integration)

Category	Unit Reduction in					Percentage of 2050 Baseline Energy Use	Total % Reduction in 2050
	Capacity	Efficiency	Usage*	Integration	Total		
Water heating	75%	60%	30% (20%)	30%	95%	14.8%	14.0%
Dishwasher	30%	50%	10% (10%)	0%	69%	1.0%	0.7%
Water Heating for Dishwasher	N/A	N/A	N/A	N/A	100%	6.6%	6.6%
Clothes Washer	30%	45%	20% (20%)	0%	69%	0.3%	0.2%
Water Heating for Clothes Washer	N/A	N/A	N/A	N/A	100%	7.7%	7.7%
Clothes Dryer	30%	75%	30% (30%)	20%	90%	5.3%	4.7%
Miscellaneous (electronics)	30%	75%	30% (10%)	10%	89%	12.1%	10.8%
Cooking	0%	70%	30% (10%)	0%	79%	5.1%	4.0%
Refrigerator	20%	60%	20% (20%)	10%	77%	3.8%	2.9%
Freezer	20%	60%	20% (20%)	10%	77%	0.9%	0.7%
Swimming Pool Pump	0%	30%	30% (10%)	0%	51%	1.4%	0.7%
Hot Tub Pump	0%	30%	30% (10%)	0%	51%	0.6%	0.3%
Hot Tub Heating	60%	76%	30% (10%)	20%	95%	2.2%	2.1%
Lighting	30%	70%	30% (10%)	0%	85%	5.7%	4.9%
Space Heating	50%	70%	75% (30%)	25%	97%	27.4%	26.6%
Furnace Fan (ventilation)	30%	50%	50% (30%)	0%	83%	0.6%	0.5%

Central AC	60%	56%	75% (30%)	30%	97%	2.5%	2.5%
Room AC	60%	60%	75% (30%)	30%	97%	0.2%	0.2%
Solar Water Heat	N/A	N/A	N/A	50%	50%	0.1%	0.0%
Pool Water Heater	N/A	N/A	N/A	50%	50%	1.1%	0.5%
Pool Pump (Solar)	N/A	N/A	N/A	50%	50%	0.8%	0.4%
WEIGHTED TOTAL	**36.1%**	**56.1%**	**38.1% (20.4%)**	**30.5%**	**91.0%**		**91.0%**

Table B.2. Residential Sector
* Estimate of the contribution of behavior change to savings in usage is shown in parentheses.

Category	**Unit Reduction in**					**Percentage of 2050 Baseline Energy Use**	**Total % reduction in 2050**
	Capacity	**Efficiency**	**Usage**	**Integration**	**Total**		
Cooling	60%	50%	75%	30%	97%	15.8%	15.2%
Heating	50%	70%	75%	25%	97%	1.6%	1.6%
Ventilation	30%	50%	50%	0%	83%	13.0%	10.7%
Water heating	75%	60%	30%	30%	95%	0.8%	0.8%
Cooking	0%	70%	30%	0%	79%	4.8%	3.8%
Refrigeration	20%	60%	20%	10%	77%	14.9%	11.4%
Exterior Lighting	40%	50%	20%	0%	76%	4.7%	3.6%
Interior Lighting	30%	70%	30%	0%	85%	25.9%	22.1%
Office Equipment	30%	75%	30%	10%	89%	8.1%	7.2%
Miscellaneous	30%	75%	30%	10%	89%	10.5%	9.3%
WEIGHTED TOTAL	**33.0%**	**63.6%**	**38.5%**	**8.7%**	**85.7%**		**85.7%**

Table B.3. Commercial Sector. Note baseline energy use calculated only for electricity (gas data was not available)

What follows is a detailed list of technologies and strategies that form the basis of our estimates within each end-use category and savings component.

Heating, Ventilation and Air Conditioning (HVAC)

Space heating:

- Reduce capacity: Increasing insulation, including eliminating gaps and installing low-emissivity windows, is the single largest step one can take toward reducing the capacity of the HVAC system. Passive solar heating can significantly lower the heating load. Reducing building volume is another step, though this falls into the category of behavior change.
- Increase efficiency: The conversion from a furnace or resistive heating to a central heat pump can vastly improve the efficiency of the heating system. For coastal California, heat pumps are better than condensing gas boilers, but the best solutions are regionally designed.
- Reduce usage: Part-time, part-space control, the use of CO_2 occupancy sensors, and utilizing a dynamic comfort range can together afford dramatic reductions in usage.
- System integration: Adding a heat exchanger to the ventilation system, capturing heat from wastewater will reduce the need for heating even more, though some gain is offset by need for more power by heat exchange fans. A new innovation in solar PV combines the electricity generation with air heating, boosting the efficiency (and benefit/cost ratio) of a solar PV system for room conditioning.

Ventilation (furnace fan):

- Reduce capacity: Air-tight shell; well-designed, small-diameter ducts or hydronic heat with condensing boiler
- Increase efficiency: Efficient fan/pump.
- Reduce usage: CO_2 sensor control, dynamic comfort range.
- System integration: No identified opportunities.

Central Air conditioning:

- Reduce capacity: In addition to savings for heating (insulation, etc.), cool roofs have been shown to reduce AC loads by 20% (Chen, 2004).
- Increase efficiency: High-efficiency, variable-speed fans and compressors can achieve double the current average efficiency. For California, evaporative coolers work well in most regions, and are more efficient than conventional AC. The Coolerado boasts an impressive 80% savings, but is not yet widespread (see advanced technology discussion).
- Reduce usage: Part-time, part-space, CO_2-sensor control, dynamic comfort range, ambient/night cool.
- System integration: Solar absorption cooling, intelligent pre-cool. Improved lighting (incandescent high infrared lighting is 20% HVAC adder in California) via LED or day lighting + coatings; EMS install and optimization.

Room air conditioning:

- Reduce capacity: See central air conditioning above.
- Increase efficiency: Baseline efficiency is lower than for central AC, hence higher savings possible in moving to central AC. however, switch to central AC would mean larger capacity and higher energy consumption, partly offset by higher efficiency.
- Reduce usage: See central air conditioning above.
- System integration: See central air conditioning above.

Water Heating

General hot water:

- Reduce capacity: Solar hot water (50% savings) x elimination of heat loss through a combination of insulated pipes, closer placement of tank to use, and use of on-demand recirculation loop (40% savings; a pilot study by LBNL indicates wasted hot water in a home varies from 10% to more than 80%; Lutz et al., 2009) x reduced hot water temperature since less losses through pipes (20% savings) = 75% savings overall. Tankless systems are probably not the best option in general, but could use instant heat in some spigots, depending on usage. Disadvantage of electric instantaneous is high power demand, which contributes to peak electricity.
- Increase efficiency: Best-in-class gas-fired heat pump replacing inefficient gas heater.
- Reduce usage: Better controls to reduce unnecessary use of hot water, e.g., separate hot-only knob on faucets, low-flow shower head with flow interrupter (Lutz, 2009).
- System integration: Recover waste heat (discharge from shower drain, dishwasher, clothes washer, faucets). Combine heating (radiant) and water heating (Lutz, 2009).

For dishwasher and clothes washer hot water use, savings is 100% as we assume no hot water from water heater will be used (modern detergents greatly reduce need for hot water).

Commercial hot water may have widely varying opportunities for savings as compared to residential, but it was not possible for us to evaluate each of these diverse uses separately, so we assume the overall savings potential was the same as for residential.

Miscellaneous Devices and Office Equipment

Electronics and other devices are rapidly changing areas, so it is impossible to predict technologies and use patterns in 2050, but based on what we know, some trends are indicated:

- Reduce capacity: Integrate (fewer devices with more functions), e.g., computers and entertainment centers (TV, music, etc.)
- Increase efficiency: Increase use of sleep mode (50% savings alone). Programmable circuit breakers. Lower-power technology such as more efficient motors, lower-power electronics. Reduce sleep mode power consumption to <0.1 W (essentially zero), perhaps through ambient energy (kinetic, thermal, PV; see advanced technology discussion below). DC circuit estimated power savings 10% or less, but possible.

- For TVs: Light-emitting diode (LED) lighting technology for display screens is available now, and organic LED (OLED) displays with no backlighting and no liquid-crystal display (LCD) layer are available for small screens now.
- Reduce usage: Auto-off detection technology, including use of "microsleep" states (rapidly switching device between sleep and on state, without noticeable impact on user, so computers can effectively sleep between keystrokes). Proxying to network allows devices to power down when only maintaining a network connection is required.
- System integration: Waste heat to Water Heating (though as energy use is reduced, the gain is comparatively smaller).

Refrigeration

- Reduce capacity: Smaller refrigerators, freezers (as is widespread in Europe); Re-design and commissioning of refrigeration systems to avoid part-load operation (25% demand reduction food industry).
- Increase efficiency: Vacuum insulated panels (commercial but not yet widespread; new 2014 federal efficiency standards could increase use of this technology in some product classes), variable compressor (near-term technology); switch to non-ozone depleting refrigerant (ammonia or CO_2). Refrigeration optimization (reducing losses in coolant distribution, improved insulation, variable-speed drives on cooling system); Cooling circulation pumps (e.g., variable-speed drives); Maintenance and diagnostics (cleaning coils, purging ref. loops of entrained air); Absorption chillers (waste heat vs. power re-vaporizes refrigerant); Gas engines to drive compressor instead of electric motor. Advanced refrigeration (food/beverage industry): 50% energy reduction roadmap by 2020 (adsorption heat pumps, tri-generation, magnetic refrigeration—see advanced technology discussion below).
- Reduce usage: More use of fresh food (behavior change), longer-shelf life prepared foods. Efficient operations, e.g., optimal defrosting, optimal use of refrigerated space, opening refrigerated space as short as possible. Thermal storage in food industry (e.g., off-peak ice "pond" for cooling); caves for barrel storage in wine industry.
- System integration: Integrate with HVAC, waste heat from refrigerator to water heating or phase change. Improved building insulation. Gas engine with variable engine speed to drive compressor with waste heat utilized to pre-heat water or for space heating at plant.

Lighting

Interior lighting:

- Reduce capacity: The use of daylighting, combined with blinds to reduce unwanted illumination, and task lighting can reduce the overall level of electric illumination required.
- Increase efficiency: The installed base of lighting in 2008 was still about 80% incandescent (Canseco, 2009). Efficiency gain of switching entirely to fluorescent lighting (with electronic ballasts) is 3-4x more efficient per bulb. Light-emitting diode (LED) "bulbs" for

general purpose use are still a few years away, but are expected to provide another factor of ~2x improvement (See below section for discussion of LED bulbs). Assuming baseline of 25% incandescent/75% CFL in 2050, efficiency gain is 40% in switching entirely to CFLs, times another 50% going to LEDs.
- Reduce usage: Occupancy and ambient light sensors can significantly reduce the need for illumination. Improved and integrated lighting controls (auto dimmers, timers, sensors), modular area controls, training personnel to switch off lights. Poor system design is a limitation today.
- System integration: None identified.

Exterior lighting (commercial only):

- Reduce capacity: While widely used for nighttime safety illumination, we believe that thoughtful reductions and better color rendering can result in a reduced psychological need for illumination (see PEC, 2009).
- Increase efficiency: High-intensity discharge (HID) lamps are already efficient, but a new microwave generator technology just announced (Ceravision) to replace the arc discharge mechanism is 2x as efficient. Another nearly as efficient option is LED lamps, but there can be heat dissipation issues at high intensity.
- Reduce usage: Occupancy and ambient light sensors can reduce the need for illumination, but opportunities are more limited than in indoor settings.
- System integration: None identified.

Clothes Washing and Drying

Clothes washers:

- Reduce capacity: Auto-size and soiling detection can reduce capacity needed.
- Increase efficiency: Energy and water factor improvements for clothes washers by switching to horizontal axis (see DOE, 2009).
- Reduce usage: Washing less often (as a behavior change) can significantly reduce usage. (Washing at lower temperature reduces hot water need, but this is dealt with separately under water heating.)
- System integration: None identified. Ability to recover waste heat, either for use elsewhere in building, or for dryer (but not available if eliminate hot water). Combining functions of washer and dryer. Reuse water.

Clothes dryers:

- Reduce capacity: Auto-size and dampness detection can reduce capacity needed.
- Increase efficiency: Heat pump technology.
- Reduce usage: The use of a clothesline can be greatly expanded.
- System integration: High-spin dryer cycle. Drier clothes from washer reduces drying load. Combining functions of washer and dryer.

Cooking

- Reduce capacity: None identified.
- Increase efficiency: Magnetic induction (already widespread in high-end stoves). Increased use of microwave technology.
- Reduce usage: Auto-detect; integrated timers; temperature sensor to auto-regulate stove power.
- System integration: None identified.

Dishwashing

- Reduce capacity: Modular (per serving) design, automatic dirt detection could reduce the amount of energy and water.
- Increase efficiency: Energy and water factor improvements.
- Reduce usage: (Switching to hand washing is less efficient, so not a good behavior substitution.) Stop rinsing before putting dishes in dishwasher.
- System integration: None identified (heat recovery from wastewater and reuse of water, while useful, do not save any energy if hot water use is eliminated as we assume.)

Swimming Pool and Hot Tub Equipment

Pool pumps:

- Reduce capacity: None identified.
- Increase efficiency: Higher efficiency motors
- Reduce usage: Auto-detect; integrated timers
- System integration: None identified

Pool heating equipment:

- Reduce capacity: Smaller pool or tub (20%), solar hot water (50%).
- Increase efficiency: Increased insulation; heat pump technology.
- Reduce usage: Auto-detect; integrated timers
- System integration: Integrate with HVAC, water heating

Correction from Frozen Efficiency

Combined with the fraction of total building energy consumed by that end-use category, the estimates in Table B.2 and Table B.3 result in an **overall savings potential for the residential and commercial sectors of 91% and 86%, respectively.** Note we have assumed these improvements against a *frozen efficiency assumption,* which is not true for the 2050 projected baseline Case C in all sectors (though the effect was weak for the residential and commercial sectors). Therefore, in Table B.4 below we correct our projections to account for the efficiency gain assumed already in the baseline to arrive at projected final efficiency savings.

	Units	Electricity	Natural Gas	Petroleum	Rounded Correction	Corrected Unit Reduction*
Residential	per household	+8%	+2%	n/a	**+5%**	**91%**
Commercial	per square foot	+0.7%	+6%	n/a	**+5%**	**85%**
Industrial	per industrial $ Gross State Product	-36%	-37%	-38%	**-40%**	(see Industrial Stress Test in Appendix C)
Agriculture	per $ Gross State Product	-58%	-69%	n/a	**-60%**	n/a
Other	per person	+18%	-23%	n/a	**0%**	n/a

Table B.4. Percent change between 2005 and 2050 Case C
*Corrected unit reduction = 1 - (1 - unit reduction)/(1 - rounded correction)

Note there is a possibility of significant rebound effect (increase use of some services such heating/cooling, hot water, lighting, etc. due to the much lower energy cost) which have not been factored into the above estimates.

Our conclusion, therefore, was that while a ~90% energy reduction was technically possible in the residential and commercial buildings sectors, such a reduction was not possible across all sectors (including transportation; see Yang et al., 2011), and, therefore, efficiency as a single intervention strategy could not pass the stress test.

Advanced Technologies

There were not many identified technologies, save for the following:

- Clothes washing: Xeros has invented a very low water and energy-based cleaning technology based on nylon beads which absorb dirt from slightly humid clothing. Use of this technology could dramatically reduce energy demand, as well as hot water demand (though other reductions already reduce this demand considerably). Moreover, nearly dry clothing would require very little drying (Xeros, 2011).
- Miscellaneous devices:
  - Large organic LED (OLED) displays have been demonstrated, but have far too short an operating life.
  - Transition metal switchable mirrors for efficient dimming of daylight windows.
  - Quantum dot color displays. This technology is not yet commercial, but allows further energy savings in display devices because quantum dots allow emission at specific wavelengths, so color filters, which absorb a considerable amount of light, are not needed. This is more speculative technology, and might take 20 years to mature.
  - Networking: an IEEE standard called "Energy Efficient Ethernet" was finalized in 2010. Enables ports to "sleep" when no network traffic is present, with huge

    energy savings potential.
  - Ambient/kinetic energy for standby devices: Thermoelectric effect (Majumdar, 2010).
- Refrigeration:
  - Magnetic refrigeration is a proven technique for scientific applications, but has yet to be proven commercially viable. Estimate of savings over state-of-art conventional technology unknown.
- Lighting:
  - The typical luminous efficiency (lumens/Watt) of LEDs is still a little lower than regular fluorescent bulbs, but they are directional and more useful for low power applications. However, high-efficiency LEDs are being developed with 160+ lumens/W, compared to CFLs at 100 lm/W. There are still heat sensitivity issues, however.
- HVAC:
  - The Coolerado AC boasts up to 80% energy savings over traditional ACs. Uses evaporative cooling technology but doesn't increase humidity in the output air stream. Has only just become commercial - very little market penetration, yet perfect for California's hot/dry weather (Coolerado, 2011).

Schedule of Construction and Operation

With nearly every technology already commercially available, building and appliance standards, along with an aggressive and thorough retrofit program, will be the dominant mechanisms required to deeply penetrate these technologies into the building stock. Simply requiring new buildings and appliances to use state-of-the-art efficient technology will be inadequate, as only about 1.2% of residential and 1.6% of commercial building stock is built new each year. With attrition (about 0.3% of residential and 0.5% of commercial buildings are demolished each year),[16] about 50% of current buildings in California will have survived in 2050. Recognizing that even the most aggressive timetable will still take few years to ramp up adoption of technology and building design techniques, only 35% (residential) to 45% (commercial) of 2050 building stock will be built with state-of-the-art technology. Therefore, 55-65% will need to be retrofitted over this same period. With growth in building stock, this translates to a yearly retrofit rate of about 2% for both residential and commercial buildings, if fully operational by 2015.

Figures B.1 and B.2 illustrate the level of effort required (where "new" and "retrofit" indicate those buildings using maximum efficiency measures, assumed available starting in 2015):

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[16] Residential demolition rates obtained from annual differences between new construction and net additions to housing stock (EIA 2006, 2010). The commercial demolition rate was taken from estimates from the California Energy Commission (CEC, 2005b).

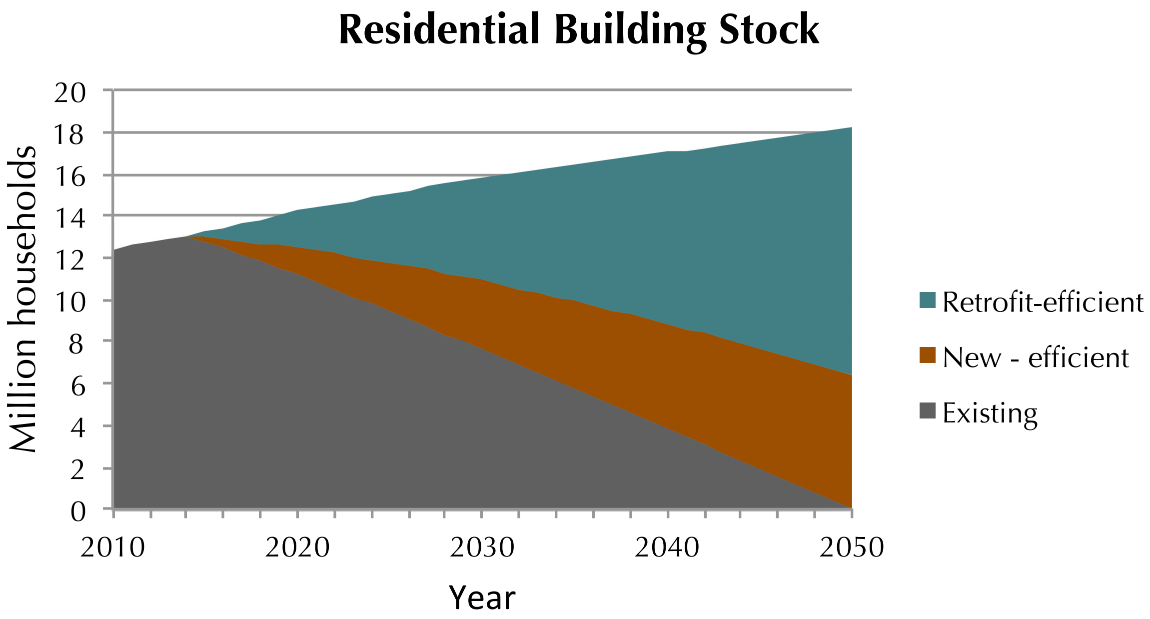

Figure B.1. Stock turnover simulation results from efficiency improvements in residential buildings.

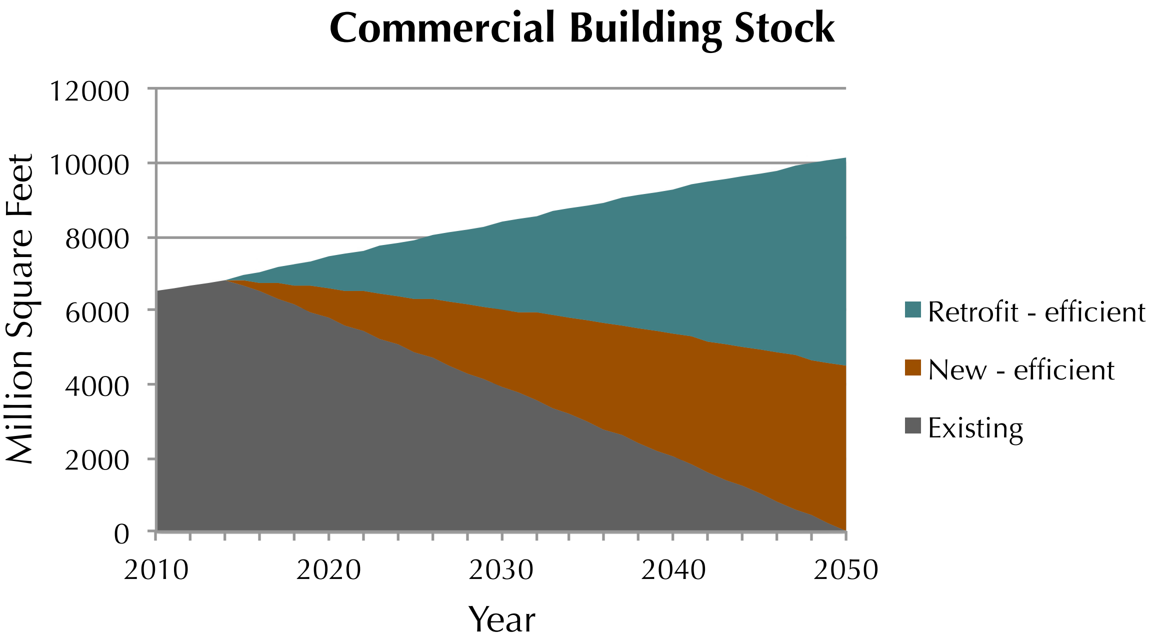

Figure B.2. Stock turnover simulation results from efficiency improvements in commercial buildings.

A proposed schedule might consist of the following:

- Beginning in 2012, building and appliance codes begin to be aggressively improved, along with statewide enforcement through an incentive program whereby cities compete for the highest rates of compliance, with financial rewards.
- At the same time, the CEC funds a new R&D program to identify promising areas for further efficiency improvement.
- In order to allow the highest rates of efficiency improvements to be realized, builders must have a way to capture lifetime energy savings and justify spending more up front. Several statewide mechanisms will therefore be established to allow for ample financing so that deep efficiency becomes an integral and cost-effective component of every building project, both new and retrofit (see below for a discussion of financial mechanisms).
- By 2015, there is a codified set of standards which capture a sizable fraction (say, 50%) of the efficiency improvements described above. By 2020, the remaining 50% of improvements have been incorporated into standard practice.
- Over this same period, an aggressive government-backed retrofit program is established for all residential and commercial buildings, with a goal of retrofitting 2% of residential building stock, or 300,000 units per year in 2020, expanding to 400,000 units per year in 2050.
    - By comparison, the recently-approved CalSPREE program (CPUC, 2010), the largest-ever of its kind, aims to retrofit 130,000 homes over 2010-2012 with 20% savings, at a cost of $750 per home.
- For commercial buildings, the required rate is 140 million square feet per year in 2020, expanding to 190 million square feet per year in 2050.
- If it is determined that newer standards, techniques or technologies might become available later than 2020, the retrofit rate will need to be increased further, in order to revisit those buildings which were retrofit too early to benefit from the full set of energy-saving innovations.

The challenge is significantly greater for retrofits, which require working with existing structures for which most of the investment has already been made. To achieve these very deep energy savings, buildings must be stripped down essentially to their frames, in order to provide access to duct work, and allow installation of both interior and exterior insulation. A combination of technological advances to make retrofits cheaper and/or less invasive (see below), and policy advances to make efficiency improvements mandatory at the time other major renovations are undertaken, can largely address this issue, but challenges will remain.

Some analysts believe that action can take place much more quickly. According to McKinsey & Co.'s recently released report on U.S. energy efficiency potential (McKinsey and Co., 2009), the U.S. economy has the potential to reduce annual non-transportation energy consumption by roughly 23 percent by 2020. Although not explored in the report, if the same annual rate of improvement were maintained through 2050, the total reduction below baseline would be 65%. The cost of such an effort is discussed below. It is our belief, however, that with California buildings already far more efficient than the rest of the country, the state's share of these savings would be smaller. Also, such early efficiency investment would have to extend much more significantly in subsequent decades to reach our ambitious target levels.

An E.U. report (Fraunhofer Institute, 2009) projects potential savings in E.U. countries through 2030, and concludes a technical potential relative to baseline by sector:

- Residential buildings: >80%
- Commercial buildings: >50%
- Industry: 20%

It also observes that costs of efficient technologies have decreased by 2-3 times over short periods (2-7 years), presumably indicating a transition from small-production-volume premium products to large-production-volume.

Construction and Annual Operating Costs

The current cost of a whole home, deep efficiency (>75% savings) retrofit is estimated to average around $100,000 for a 2,500 square foot home (Walker, 2010). Given an average yearly California energy bill of $1,500-1,800 (Walker, 2010), it would require too long of a payback period to be cost-effective. Therefore, the cost of efficiency improvements must come down by a factor of approximately three, together with innovative financing mechanisms to allow very long (e.g., 30-year) payback periods (see section below), in order to make such improvements break-even, and society may have to indefinitely bear some of the cost, through subsidy, loan underwriting, etc.

On other hand, the annual home retrofit budget in the U.S. is $225 billion, at an average cost of $15,000 per home, assuming 15% of U.S. building stock, or approximately 15 million homes per year, are retrofit (this includes kitchen and bathroom remodels, window replacement, extensions to existing homes, etc.). Piggybacking on 10-15% of these retrofit homes for deep efficiency retrofits could satisfy the 2%/yr requirement to retrofit all building stock by 2050 (discussed above).

According to McKinsey & Co.'s recently released report on U.S. energy efficiency potential (McKinsey, 2009), the U.S. economy has the potential to reduce annual non-transportation energy consumption by roughly 23 percent by 2020. The up-front cost of such an effort ($520 billion) would be more than paid back double from energy savings through 2020: $1.2 trillion in all.

Resource Requirements

Unless our evaluation missed key material requirements, no rare materials are needed to greatly increase efficiency. Annual water requirements would be no greater than today, and would likely result in a significant reduction in municipal water construction in tandem with energy savings.

The largest asset requiring attention is the skilled workforce, which on the whole has not been trained to design, construct or inspect buildings with efficiency in mind, let alone radical efficiency improvements. Rapid training is critically needed in all areas, including:

- Architectural firms
- Building code standards
- Appliance standards (this effort takes place at the national level in the U.S., but has recently started to move in the right direction, though more aggressive measures are needed)

- Construction companies, particularly general contractors who are on the whole small businesses (build 4-5 homes per year), and therefore difficult to reach all players in the industry
- Inspection: Enforcement of building codes in California tends to be lax, due to decentralization (administered at city or county level, not state-wide)
- Educational institutions
- Public service/awareness campaigns in the non-profit sector

Financing

Successfully implementing radical efficiency will require a profound shift from a focus on up-front cost to lifetime cost, and to enable this shift, new, creative sources of financing are necessary. Major categories of instruments include those listed below in Table B.5:

Type	Administration	Type of retrofit	Payback period	Primary sector(s)	Notes
Energy savings performance contract	State or local governments	Moderate level (what can be guaranteed)	10-15 years	State government; MUSH (municipalities, universities, schools, hospitals)	Use of energy service company (ESCO) with savings guarantee
Property-assessed clean energy (PACE)	Local governments	Comprehensive	15-20 years	Residential and commercial	Stalled in 2010 after Fannie Mae/Freddie Mac withdrew support for mortgages with PACE liens
On-bill repayment	Utilities	Comprehensive	5-7 years (loan) 10-15 years (tariff; could be longer)	Small commercial; MUSH (municipality, university, school, hospital); residential experience limited	Can address renters; much more effective when done as tariff attached to property
Energy efficient mortgage	Private lenders	Comprehensive	15-30 years	Residential	Much more popular for retrofits than home purchases

Revolving loan funds	State or local governments, private lenders	Tend to be small ($2,000 to $10,000)	Under 10 years	Commercial	Less effective without leverage of private capital
Property transfer tax	State or local governments	Comprehensive	N/A	Any	
Rebates/tax credits	Federal, state & local governments, utilities (when mandated by state PUC)	Small (few thousand $)	N/A	All	Target specific products or actions rather than sector
Consumer education	Federal, state & local governments, non-profit organizations	N/A	N/A	Residential	Focus on life cycle cost rather than sticker price

Table B.5. Financing mechanisms required to advance energy efficiency.

Administering entities are different for each strategy, with differences in reach and challenge (smaller institutions like municipal governments are often overwhelmed by setting up complex new programs, whereas state-level entities or private companies have more personnel).

Most strategies listed as capable of financing comprehensive retrofits require long payback times, from 10 to 30 years.

All strategies above have been proven somewhere in the market, with the exception of a property transfer tax, which is untested, though based on a seismic transfer tax currently implemented in some parts of California. The concept is that at the time of building sale, if certain efficiency measures have not been implemented, a fixed percentage of the building's value (e.g., 0.5%) is excised and placed into a fund, which the new owner can reclaim at a future date for the purpose of paying for efficiency improvements.

There is less experience with residential markets, because transaction costs are higher as a fraction of the total cost. This is particularly true for ESCOs, which have no presence in residential markets. However, progress is being made elsewhere, particularly with on-bill programs (7 programs in 5 states + Manitoba, Canada) and PACE (programs in 17 states, including 3 in California, 14 new laws passed in 2008, though withdrawal of support by Fannie Mae and Freddie Mac in 2010 has placed program in jeopardy). On-bill programs are especially attractive when they take the form of a tariff, allowing the repayment obligation to be attached to the property, not the borrower. It is also one of the few mechanisms which can benefit renters as well as homeowners. However, both are relatively complex to set up, so require dedicated utilities for on-bill programs, or dedicated/visionary local government staffs for PACE programs. "Outsourcing" of program administration to a statewide entity may be an attractive solution.

Also note that much of the financing is going to install solar PV currently, even though it is one of the least cost-effective options for reducing energy cost.

Energy efficient mortgages have not received much attention, particularly for home sales, though the federal government is pushing this.

This points up a general challenge, which is that much more needs to be done to educate consumers of the value of efficiency improvements. A consumer-education focused campaign, led by opinion leaders in government (from the President to the local mayor) as well as civil society (celebrities, etc.) could do much to raise awareness.

Related Technologies

The following related technologies were identified:

- Smart grid infrastructure will not play a major role, but can help: Whole house energy monitoring, device-level control, and time of day price signals
- Infrared scanning technology to provide rapid identification of building envelope leaks during retrofit or new-building inspection
- Standardization/automation of components designed with efficiency in mind (pre-insulated ducting, wall sections, etc.)

Total Costs by 2050

Cost estimates for new construction are from Walker et al. (2009):

- Costs assume current construction costs for a 2,000 square-foot detached residential home
- Cost differentials by technology:
    - Insulation costs
        - Ceiling ranges from $300-$1100 depending on R-value
        - Wall: $200-$3000 (much higher at 2x higher R values, but "in cold climates...may still be a wise option")
        - Floor: $300-$1400 depending on R-value
        - Overall (Ceiling + wall + floor) cost ranges from $800-$5500
    - Window costs
        - Range from $1200-$3200 depending on technology type
        - Noted that in real projects only some windows may need upgrading
    - HVAC costs
        - Water heater: Range from $200 (electric water heater) to $2700 (solar water heater)
        - Space heating: $200 (high eff (90%) gas furnace) to $9200 (radiant floor heating); $3500 option (geothermal heat pump) is one of 2 called out as being cost-effective over 30 yrs.
        - AC: $2300-$4500
        - Overall costs: $2700-$16,400
    - Duct & pipe sealing
        - Kitchen hot water $180
        - Water heater wrap $110

        - Duct sealing $320
        - Air sealing to 0.5 changes per hr $680
        - All 4: $1290
- Overall: (sum of above): $5,990-$26,190 (average around $13,500), resulting in total savings of 60% (baseline = 41,000 kWh/yr or 220 kWh/m^2/yr)
- If implement all savings, payback is about 50% in 30 years, so cost is approximately 2x as large as required to be cost-effective.
- Comparison to existing home projects:
    - Energy use varies from 13-107 kWh/m^2/yr = 6-49% of baseline, most in the ~20% range.
    - Use of solar thermal heating is extensive

We estimate that the long-term cost premium for highly efficient new buildings is close to zero.

By comparison, current costs of efficiency retrofits are much more expensive, on order of $100,000 for a 2,500 square foot (sf) home ($40/sf). This is due to the high cost of invasive treatments, particularly wall and window retrofits. However, the long-term cost premium for retrofit buildings may approach $10 per square foot ($25,000 per home) if advances in technology can be realized and/or creative policy to allow efficiency retrofits to be required when other retrofits are performed. The U.S. home renovation market is a $250 billion/yr industry; presumably, huge leverage can be applied to piggyback on this cash flow.

We assume the per sq. ft. retrofit cost drops linearly from $40 in 2010 to $10 in 2050. Without better cost information, we assume the same costs apply to the commercial sector.

Stress Test

Technology Constraints

As mentioned above, the main constraints appear to be:

- Speed of building and appliance standards implementation
- Mechanisms for financing
- Training of workforce
- Speed/comprehensiveness of retrofit implementation
- Technological barriers are modest, e.g., we have pushed beyond what is currently in the market, but in most cases only by a few years. In a few cases, new technology may be required to get us all the way to the final efficiency targets indicated

What are the technology gaps for future technologies? That is, what are the gaps between what is needed to make these future technologies commercially available and what technology is actually available today? Beneficial technological advances include:

- Better ways to insulate walls – injection/expansion systems that fill the cavity through a small hole, create an air seal and do not blow walls apart with expansion. Perhaps with sophisticated through-wall monitoring, a relatively small number of holes can be drilled,

keeping costs low.
- Develop methods of retrofitting windows, rather than complete replacement, which is costly and labor-intensive
- Reliable, robust easy to install solar hot water with storage
- Better diagnostics for auditing heating cooling insulation, etc. Most tools designed for modern offices, not old homes
- Better dehumidification devices (approaches other than vapour compression technology or dessicants)
- Better ventilation systems that are optimized for energy use and indoor air quality, by changing time of operation (an active area of research)
- Thermal energy storage
- Simple to use automatic controls that people will like, and won't override
- Scalability of new industry applications and processes, e.g., membrane separation (see Industry Efficiency in Appendix C).
- Significant innovation in new industrial processes, materials and feedstocks, process intensification, highly integrated and optimized factories.

Would policy changes or additional R&D allow greater or faster scale up of the technologies cited in this narrative? More aggressive efficiency standards for both appliances (already proven very effective in the U.S., but has operated too slowly; there has been a strong desire in the Obama administration to accelerate this process) and buildings could stimulate innovation and bring down costs more quickly. But standards must be coupled to:

- Folding efficiency into other building improvements or remediation, where wall interiors are exposed, occupants displaced, etc.
- Standardization of deep energy retrofits. While medium-level efficiency improvements (~25% savings) will be unique to each building, depending on the efficiency of various components already installed, deep efficiency retrofits will almost always have the same "to do" list, regardless of building history or climatic zone, so the approach can be standardized, and thus less costly.
- Performance standards, and the will to enforce them
- Certification mechanisms to ensure good quality among many small contractors (such as Building Performance Institute)

Physical Constraints

No land, building materials, water, fuel, or other physical constraint was identified.

Economic Constraints

The main economic constraint is financing (see discussion above). However, possible lower costs of materials, labor, fuel, etc., for construction may emerge, especially as both California and elsewhere scale up.

Fuller (2011) makes the important point that deep residential retrofits may not be cost-effective for a very long time. As a result, social (e.g., government) institutions may need to commit to long-term financial assistance in order to reap the societal benefit of higher building efficiency.

Social Infrastructure Constraints

These constraints consist mainly of a shortage of skilled workers (see discussion above), in particular a lack of sufficient numbers of engineers and regulators.

Policy Constraints

The current pace of building and appliance efficiency standards are inadequate to meeting the ambitous targets of the stress test. A dramatic speedup (and possibly redesign) is needed this decade in order to reach the target levels.

Conclusions

There are major hindrances to scale up, though mainly institutional and financial, not technical (except in a few instances). The maximum practical scale up under current conditions might attain a modest (25%) reduction in energy use relative to the baseline, which would be insufficient to even keep energy use at current levels.

Acknowledgements

The authors would like to thank the following Lawrence Berkeley National Laboratory staff for contributing to this study: Louis Desroches, Merrian Fuller, Asa Hopkins, Jim Lutz, Eric Masanet, Michael McNeil, Bruce Nordman, Mary Ann Piette, Iain Walker, and Tim Xu.

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Appendix C: Details of Industrial Efficiency Stress Test

Case Summary

The industrial energy efficiency stress test considers the industrial manufacturing sector, in particular those sectors listed in Table C.2 (representing North American Industry Classification System (NAICS) codes 311-339), since the manufacturing sector is the most studied in existing reports. In particular, it does not include the oil and gas extraction industry. The energy savings of the oil and gas extraction industry was not studied in great detail, and the overall savings and electrification potential for fossil fuel extraction was taken to be the average of the manufacturing sector overall.

The industry energy efficiency stress test takes two approaches for energy savings potential: a "top-down" and a "bottom-up" approach. The top-down method utilizes existing studies from the California Energy Commission (CEC, 2009) and the U.S. Department of Energy ("energy bandwidth" studies: DOE, 2004-2007a) and a simple penetration model to estimate technical efficiency potential by industry sector. Conversely, the bottom-up approach assumes varying degrees of electrification and a penetration model of increasing electrification primarily in process heating. Two cases for the petroleum industry are considered: a petroleum fuel replacement case where 90% of petroleum refining is assumed to vanish by 2050, and one with business as usual (BAU) growth. Both the top-down and bottom-up approaches give a similar range of results: bounding cases give 69-73% energy savings versus a frozen efficiency baseline or 38-47% energy savings versus an autonomous baseline (where the autonomous baseline assumes 50% energy intensity savings versus the frozen baseline from 2010 to 2050); and realistic "aggressive" cases give 57-66% energy savings from the frozen baseline or 13-33% savings from the autonomous baseline (see Table C.1). Both approaches assume a 30% energy savings from behavior changes (see section, *Output Reduction* for details).

Comparing the energy saving potentials of top-down versus bottom-up approaches, aggressive electrification of steam systems and process heating can be viewed as one pathway to meet the top-down derived energy savings bounding case technical potential. Similarly, the case of aggressive electrification of process heating can be viewed as one pathway to achieve the realistic top-down derived energy savings technical potential.

Key barriers to increasing energy savings in industry are risk aversion in industry management to depart from accepted production methods, as well as the lack of management structures or organizational structures to implement new, more efficient processes. For large-scale electrification scenarios, the key barrier is cost, with the cost of electrically-produced heat currently several times the cost of direct fuel-fired heat. Thus in the absence of low-priced electricity and/or much higher fuel costs, increased productivity or enhanced product quality is required to justify the conversion to electro-technology.

						Autonomous 50% savings 2050		Autonomous 35% savings 2050	
Type	**Case**	**Energy Intensity Savings**	**Energy Intensity Savings vs Frozen BL**	**Behavior Savings (Demand Reduction)**	**Energy Savings w/ Behavior vs Frozen Baseling**	**Energy Intensity Savings vs Autonomous Baseline**	**Energy Savings w/ Behavior vs Autonomous Baseline**	**Energy Intensity Savings vs Autonomous Baseline**	**Energy Savings w/ Behavior vs Autonomous Baseline**
TD	PIER + Behavior	35%	35%	30%	55%	-30%	9%	0%	30%
TD	**Aggressive**	**51%**	**51%**	**30%**	**66%**	**2%**	**31%**	**25%**	**47%**
TD	Aggressive w/o petrol replacements	42%	42%	30%	59%	-16%	19%	11%	38%
TD	Bounding	60%	60%	30%	72%	20%	44%	38%	57%
TD	Bounding w/o petrol replacement	56%	56%	30%	69%	12%	38%	32%	53%
BU	**Aggressive**	**48%**	**48%**	**30%**	**64%**	**-4%**	**27%**	**28%**	**49%**
BU	Aggressive w/o petrol replacements	38%	38%	30%	57%	-24%	13%	6%	34%
BU	Aggressive 2	52%	52%	30%	66%	4%	33%	38%	57%
BU	Aggressive 2 w/o petrol replacements	43%	43%	30%	60%	-14%	20%	22%	45%
BU	Bounding	62%	62%	30%	73%	24%	47%	48%	63%
BU	Bounding w/o petrol replacement	57%	57%	30%	70%	14%	40%	34%	54%

Table C.1. Summary of Industry energy savings.

Demand Scenario in 2050

In the industrial sector, the following technology areas were considered, in rough order of declining baseline energy use:

- Process heating
- Motors systems
- Boiler/steam systems

For the 2050 demand scenario, a synthesis is taken of the CEC (2009) report and the CEF Industry growth assumptions. CEC data is taken for electricity and natural gas demand and Gross State Product (GSP) by industry sector in the base year 2006. CEC annual growth rates by sector are then adjusted to meet the CEF assumption of a cumulative annual industry GSP growth rate of 2.65%. Table C.2 shows industry sectors by NAICS code and 2050 projected gas demand. The largest demand sectors in 2050 are projected to be petroleum and coal products manufacturing, chemical manufacturing, plastics and rubber products manufacturing, food and beverage, and sugar products & fruit and vegetables. Table C.2 data for 2050 energy use reflects a frozen energy intensity assumption at 2006 energy intensities. As in the CEC report, a simplifying assumption is made that GSP is a proxy for industrial output, since actual industry output by sector is not readily available. This neglects "sector change" that may occur as some industry sectors shift from manufacturing/goods based output to service based output.

NAICS	Description	2006 GSP $M	2006 MTh	CEF Annual Growth	2050 GSP $M	2050 Mth
311x, 312	Food and Beverage	15812	359	1.2%	26522	603
3113, 3114	Sugar and Confectionary Products; Fruit and Vegetable Process	3201	265	0.4%	3768	311
313	Textile Mills	562	55	0.3%	646	64
314	Textile Product Mills	659	13	0.5%	829	16
315, 316	Apparel and Leather Product Manufacturing	4712	5	-0.5%	3822	4
1133, 321	Logging and Wood Product Manufacturing	2254	12	0.5%	2752	15
322x	Paper Manufacturing (excluding Mills)	2504	42	1.7%	5346	90
3221	Pulp, Paper, and Paperboard Mills	366	52	0.9%	535	76
323	Printing and Related Support Activities	4378	14	1.6%	8760	29
324	Petroleum and Coal Products Manufacturing	3110	571	1.6%	6344	1164
325	Chemical Manufacturing	21097	100	4.2%	127345	603
326	Plastics and Rubber Products Manufacturing	4826	35	5.0%	40500	293
327x	Nonmetallic Mineral Product Manufacturing (ex. Glass)	5055	114	2.1%	12412	279
3272	Glass Manufacturing	984	115	-0.4%	819	96
3273	Cement	2462	45	3.1%	9239	170
331	Primary Metal Manufacturing	2561	79	0.7%	3482	107
332	Fabricated Metal Product Manufacturing	10158	89	1.9%	22887	201
333	Machinery Manufacturing	8723	26	2.9%	30165	91
334x	Computer and Electronic Product Manufacturing (ex. Semiconductor)	69249	38	2.7%	224595	124
3344	Semiconductor and Other Electronic Component Manufacturing	21935	27	2.7%	71329	87
335	Electrical Equipment, Appliance , and Component Manufacturing	3216	5	3.8%	16343	26
336	Transportation Equipment Manufacturing	12208	48	2.4%	35140	137
337	Furniture and Related Product Manufacturing	3121	8	-0.5%	2554	6
339	Miscellaneous Manufacturing	11061	21	1.4%	20170	39
	Totals	**214212**	**2139**		**676304**	**4633**

Table C.2. Industry sectors by NAICS code with projected GSP and gas demand by sector in 2050. Note: MTh = million therms.

Final energy demand in 2050 will be dependent on the assumptions of industry sector growth and evolution. For industry, while energy efficiency or energy intensity (energy required per unit of output) can improve significantly, energy use in 2050 will be highly dependent on the actual mix of sectors (e.g., the size of the petroleum industry versus chemicals versus electronics). We follow industry sector projections from the CEC (2009) report, but this is a key uncertainty in projecting long-term industry energy reduction potentials. A larger shift toward the services sector and a smaller manufacturing sector would result in lower overall energy usage.

We note that some sectors may shrink faster than projected in Table C.2, while other sectors may grow more rapidly and other new sectors or new technologies may emerge with the net effect being extremely difficult to predict. For this study, we consider two demand cases: the baseline scenario shown in Table C.2 and a second scenario of petroleum fuel replacement. In the latter case, we assume that the 90% of the petroleum refining sector that currently produces liquid fuels is replaced by other non-fossil fuels, but that 10% of the sector remains to produce petro-chemicals. We assume that this replacement will not add energy use to the state – e.g., petroleum fuel replacement will be either net zero energy biofuels, or importation of fuels from out of state. Reducing petroleum fuel consumption by a specified percentage will not necessarily reduce industry activity by that percentage, and a large-scale shift in a major industry like petroleum will shift jobs to other industries and energy demand can thereby be shifted. For this study however, we do not consider these effects but assume the full credit of reducing the petroleum refining sector by 90% in 2050.

Output Reduction

The total energy savings in industry can be written:

Total Saving (Industry) **= 1 -** **Lower Energy Intensity** **X** **Output Reduction**

The energy savings equation here will refer to end-use energy, not primary energy savings, per the CEF methodology of disaggregating energy demand from energy supply. For the bounding case, we will try to achieve maximal end-use efficiency savings irrespective of cost and primary energy supply. Most existing studies focus on the energy intensity term in the expression above because the output reduction term is difficult to quantify and is often associated with "behavior changes" among consumers. For this study, we assume 30% demand reduction from two sources: redesign within industry ("light weighting," service life extension, material substitution, designs to facilitate recycling, etc.) and "behavior change" from consumers. This is an aggressive assumption and is motivated by the following factors: 5-15% end use electricity savings from existing behavioral studies and projections, 10-20% electricity savings demonstrated in emergency situations (IEA, 2005), and 10-15% from redesign within industry. For example, the non-destructive reuse of steel from old buildings, with a fabrication step, but without melting and recasting can result in significant greenhouse gas (GHG) emissions reduction. Similarly, recycling rates can improve over current rates: plastics from current 5% to estimated 30% maximum rate, paper from 43% current to 81% maximum, and aluminum from current 39% to 90% (Allwood, 2010). Some manufacturers might also pursue a business model of longer life materials and increased revenues from services, or more centralized delivery of products and services. Although consumer electricity savings from in-home displays and emergency reductions in peak power use do not translate directly to industry demand reduction, these examples illustrate how increased consumer awareness and education can lead to behavior modifications. Building energy efficiency and building appliance trend toward smaller systems, less usage, and greater system integration are expected translate to lower materials usage.

Trends toward networked communication and greater product transparency (social networking, life cycle analysis, increased product information, online product rating services, etc.) are also expected to contribute to greater consumer awareness and potentially lead to lower overall product demand and correspondingly lower industry demand.

Short-Term Energy Savings

Short-term energy savings are projected to be 25-30% over the next 10 years mainly from operational practices and improved maintenance without high capital expense or a significant amount of equipment replacement. An example is provided for the process heating segment in Table C.3 (DOE, 2007b). "Low-hanging fruit" includes air/fuel optimization, wall heat insulation and advanced controls as well as incorporating other best operations and best maintenance practices. Further retrofitting work can be done such as the installation of advanced burners, and preheating of combustion air or incoming load to bring cumulative savings above 30%. For the industry sector in the short term, McKinsey estimates 18% energy savings in 2020 with a $113 billion investment (McKinsey, 2009) and a benefit to cost ratio of 4:1, indicating the sub-optimality of current industry operations from an energy standpoint.

Similar short-term energy savings can be realized in steam and motor systems from maintenance, operational measures, and control measures without major capital investment. For boiler use and steam systems there are opportunities on the distribution side such as thermal recapture at the back end of steam systems, while maintenance items such as faulty valves and system-related problems can also give large savings. For motor systems, an estimated 20% savings can come from routine maintenance, while for applications with variable loads, larger savings (up to 50%) can be realized with the adoption of variable-speed motor systems.

Measure	Individual Savings	Cumulative Savings
Air/fuel Ratio Optimization	5%	5%
Wall Heat Losses	2%	7%
Furnace Heat Transfer	5%	12%
Advanced Burners/controls	5%	16%
Preheat Combustion Air	15%	29%
Fluid or Load Preheating	5%	32%

Table C.3. Process heating savings measures that can be implemented in the short term.

CEC and DOE Bandwidth Studies

For industry, there are four key focus areas for energy efficiency and energy usage reduction:

- Industrial reactions and separations
- High-temperature processing
- Waste heat minimization and recovery
- Sustainable manufacturing

The transformational themes for industry energy efficiency are moving processes to lower, but still elevated temperatures, capturing waste heat, reducing process steps, and improving yields (DOE, 2007c). However, in contrast to existing advanced efficiency techniques in buildings, a significant amount of research and development (R&D) is required to achieve maximum energy savings beyond today's state-of-the-art technology.

Two primary studies are used for the top-down estimates: the CEC (2009) report and U.S. Department of Energy Bandwidth studies. The CEC report includes technical potential energy savings estimates for the industry sector in the state of California versus a frozen baseline at 2006 energy efficiency levels. The study considers process savings in the major industrial end uses [process heating, steam systems, motor systems, lighting and heating, ventilation and air conditioning (HVAC)] by industry sector. Most of the savings are from measures that can be applied broadly to a given end use: e.g., improved process control and improved insulation for steam systems, or heat recovery and efficient scheduling for process heating. Sector-specific measures include solar boilers in food and beverages, membrane separation for food, petroleum, and chemicals, and process intensification for petroleum and chemicals. The latter can refer to the tighter integration of reaction and separation steps and/or redesign of process and factory flows to reduce overall space and energy requirements. Aggregated technical potential savings are estimated to be a 28% decrease in electricity consumption in 2050 and a 45% drop in natural gas consumption.

The DOE Bandwidth studies are a series of reports describing the theoretical minimum process energies in several energy-intensive industries as determined by thermodynamic limits. Three levels of process energy are described:

1. State-of-the-art process energy – the energy required using existing best-in-class equipment and technologies
2. "Practical minimum process energy" – the energy projected using emerging technology currently in development.
3. Theoretical minimum energy - the minimum process energy required by thermodynamics to convert raw materials into products under ideal conditions

For example, for the chemical industry, 28% savings is projected from current state-of-the-art technologies, 71% savings at today's practical minimum process energy, and 88% minimum energy. Table C.4 shows a summary of state-of-the-art savings and maximum energy savings for six energy-intensive industry sectors. Note that the practical minimum process energy is a moving target and its value will decrease over time as more advances are made in R&D; the DOE studies consider the limits of existing process technologies. Often perceived technological barriers are surmounted with clever engineering or alternative approaches. An example from the microelectronics industry is that in the 1970's the industry spoke of the "1µm barrier" or half-pitch barrier to optical lithography for printing circuit patterns, and these limitations of classical optics have been surmounted by technical advances such as phase shifting masks, spatial frequency multiplication and other advanced pattern-transfer techniques to pattern deep submicron features.

Manufacturing Sector	State of Art Savings	Max Energy Savings
Paper Manufacturing	32%	59%
Pulp, Paper, and Paperboard Mills	28%	42%
Petroleum and Coal Products	18%	71%
Chemical Manufacturing	18%	88%
Glass Manufacturing	32%	61%
Primary Metal Manufacturing		50%

Table C.4. DOE bandwidth savings estimates for six industry sectors.

Top-Down Technical Potential

We take the DOE bandwidth minimum energy as the natural gas technical potential for the six industry sectors in Table C.3 and for the remaining sectors, the CEC (2009) technical potentials are assumed (Table C.5).

NAICS	Description	Technical Potential Max (PIER, BW)	Ref
311x, 312	Food and Beverage	58%	PIER09
3113, 3114	Sugar and Confectionary Products; Fruit and Vegetable Process	57%	PIER09
313	Textile Mills	28%	PIER09
314	Textile Product Mills	29%	PIER09
315, 316	Apparel and Leather Product Manufacturing	16%	PIER09
1133, 321	Logging and Wood Product Manufacturing	30%	PIER09
322x	Paper Manufacturing (excluding Mills)	59%	DOE BW
3221	Pulp, Paper, and Paperboard Mills	42%	DOE BW
323	Printing and Related Support Activities	27%	PIER09
324	Petroleum and Coal Products Manufacturing	71%	DOE BW
325	Chemical Manufacturing	88%	DOE BW
326	Plastics and Rubber Products Manufacturing	27%	PIER09
327x	Nonmetallic Mineral Product Manufacturing (ex. Glass)	48%	PIER09
3272	Glass Manufacturing	57%	DOE BW
3273	Cement	43%	PIER09
331	Primary Metal Manufacturing	48%	DOE BW
332	Fabricated Metal Product Manufacturing	29%	PIER09

333	Machinery Manufacturing	30%	PIER09
334x	Computer and Electronic Product Manufacturing (ex. Semiconductor)	30%	PIER09
3344	Semiconductor and Other Electronic Component Manufacturing	28%	PIER09
335	Electrical Equipment, Appliance, and Component Manufacturing	30%	PIER09
336	Transportation Equipment Manufacturing	28%	PIER09
337	Furniture and Related Product Manufacturing	32%	PIER09
339	Miscellaneous Manufacturing	29%	PIER09

Table C.5. Technical energy savings potential estimates for natural gas by industry sector.

For the electricity sector, we take the technical potential in the CEC/DOE bandwidth studies for process heating and motor systems, while for facilities HVAC, lighting, and other facilities electrical demand, we adopt the aggressive savings potential from the commercial buildings sector energy efficiency projections from Appendix B.

For the gas sector, we adopt a simple penetration model as follows. We assume that there is a one-time opportunity to intercept new equipment over the next 40 years or equivalently, a 2.5% annual turnover rate (see Chapter 5 in Interlaboratory Working Group, 2000). A 25% improvement in energy intensity is achieved in the first ten years mainly from operational tightening and improved maintenance and controls. There is high confidence for this initial improvement based on existing programs such as "Save Energy Now" described below and discussion with industry energy efficiency experts. Starting in 2021 there is constantly improving energy intensity to the technical potential limit in 2050. We assume that the energy intensity performance of replacement equipment tracks this energy intensity performance curve for the period under study, 2010-2050. For the chemicals example, this gives a lower intensity savings in 2050 vs. the technical potential (60% vs. 88%).

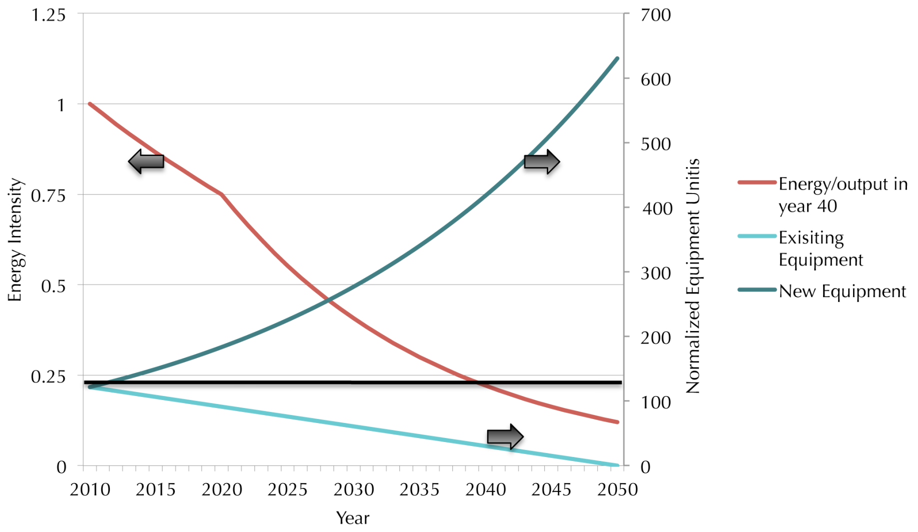

Figure C.1. Penetration model for chemicals. All equipment is replaced by 2050 with equipment energy intensity improving every year.

Results of the top-down modeling are shown in Table C.6 below. All cases assume a 30% energy savings from demand reduction stemming from behavior changes as described above. We also assume that all petroleum fuel is replaced within the California economy and that the industrial energy demand associated with its production is also removed, either by net zero energy biofuel production or out-of-state biofuel production. We assume that 10% of the petroleum sector related to non-fuel products remains and that the chemical sector is still intact which does not account for interactions or production shifting resulting from curtailed petroleum refining.

Bounding cases assume full technical potentials are achieved by 2050 in every sector and give 44% and 38% energy savings versus the autonomous baseline for the cases of petroleum fuel replacement and no petroleum fuel replacement respectively. Incorporating the penetration model described above gives 31% and 19% savings versus the autonomous baseline, for the cases of petroleum fuel replacement and no petroleum fuel replacement respectively.

It is critical to note that in industry, "technical" potential (end use energy efficiency or primary energy) is often insufficient when deciding the desirability of a proposed change and that one must adopt a systems perspective that can include product quality issues, throughput, process interactions, and other factors. Metal slab heating for forging provides an illustrative example. Electrical induction heating has lower overall cost despite three times the capital cost and 30% higher energy cost due to material savings with high-quality output (less wasted output) and lower operational and maintenance costs than typical fuel-fired slab furnaces (Schmidt, 1984).

						Autonomous 50% savings 2050		Autonomous 35% savings 2050	
Type	**Case**	**Energy Intensity Savings**	**Energy Intensity Savings vs Frozen BL**	**Behavior Savings (Demand Reduction)**	**Energy Savings w/ Behavior vs Frozen Baseling**	**Energy Intensity Savings vs Autonomous Baseline**	**Energy Savings w/ Behavior vs Autonomous Baseline**	**Energy Intensity Savings vs Autonomous Baseline**	**Energy Savings w/ Behavior vs Autonomous Baseline**
TD	PIER + Behavior	35%	35%	30%	55%	-30%	9%	0%	30%
TD	Aggressive	42%	42%	30%	59%	-16%	19%	11%	38%
TD	Aggressive w/o petrol replacements	51%	51%	30%	66%	2%	31%	25%	47%
TD	Bounding	56%	56%	30%	69%	12%	38%	32%	53%
TD	Bounding w/o petrol replacement	60%	60%	30%	72%	20%	44%	38%	57%

Table C.6. Top down estimates of industry energy savings in 2050.

Description of Technologies

The following briefly describes considered technologies, all of which are commercially available now unless noted.

Motor Systems

- Reduce capacity: Correct motor sizing for optimal performance to avoid lower efficiency with partial loading. This can cut losses in half. The ideal approach is to develop novel processes with much lower mechanical power requirement.
    - Grinding (in non-metal minerals, 90% energy input lost as waste heat), so move toward non-mechanical milling technology (not commercialized yet).
- Increase efficiency: NEMA high-efficiency motors; premium lubricants (3% system efficiency savings); copper rotor motors reducing resistive heating in stator windings, changing rotor to die-cast copper for lower rotor, core, stray load losses; High temperature superconductor motors; adjustable speed drives (up to 60% energy savings in non-fully loaded systems); improved pump systems; improved fan systems (cog belts, smaller fans for systems with fan oversizing); improved compressed air systems. 15-25% total energy savings with emerging technology (IEA, 2008).
- Reduce usage: Improved motor practice (preventive/predictive maintenance): 2-30% energy savings.
- System integration: process intensification designs for integration of processes and flows

Process Heating

- Reduce capacity: heat recovery, process controls, process intensification to integrate process steps into installations with smaller footprints and reduced operating costs. E.g., advanced distillation columns with improved heat integration; compact conversion/separation reactors in chemical industry.
- Increase efficiency: Measures dependent on industry and application. For example, advanced separation technology (process intensification and membrane separation in petroleum refining/chemical industry); efficient new furnace designs; semi-continuous steel making process; fully electric molders in plastics (up to 50% savings), improved oven management in food. Cross cutting items include heat recovery, improved insulation, improved equipment maintenance, process controls, efficient scheduling, improved combustion control, combustion system maintenance.
- Reduce usage: efficient scheduling
- System integration: integration of processes and flows for smaller footprint and increased efficiency

Steam Systems

- Reduce capacity: Process integration through systematic thermal energy demand analysis for minimum thermodynamic heating and cooling requirements. Re-use of waste heat in paper drying (pulp and paper).
- Increase efficiency: Combined Heat and Power (CHP) or heat pump replacing steam boiler. Efficiency measures include: improved insulation, improved heater circuit controls, steam system generating pressure reduction, vapor recompression (0-20% savings), flash condensate (0-10%), return condensate (10%), steam traps (5%), insulation pipeline (5%). Super boiler (transport membrane condenser, compact convective zones, compact humidifying air heater) for stock replacement. Petro-chemicals steam cracking measures

include higher temperature furnaces, gas turbine integration CHP, advanced distillation columns and combined refrigeration plants (up to 10% savings total). Water treatment to reduce scale and corrosion.

- Reduce usage: Chemical industry: new catalysts and process routes to reduce usage; Routine maintenance (steam traps, valves, heat-transfer surfaces). New cleaning technologies and better choice of materials for water cleaning (food and beverages). Solar thermal concentration (food and beverages) and solar water heating (wineries).
- System integration: Flue gas heat recovery/ economizer, blowdown steam heat recovery, hot condensate return piping systems

Additional HVAC Measures in Industry

- Variable air volume systems; heat recovery systems (wheels, heat pipes, run-around loops); improved ceiling insulation; direct fired natural gas space heaters; high-efficiency condensing furnace/boiler (from 80% to >90% efficiency, e.g., pulse combustion, condensing boilers); Stack heat exchanger; Duct insulation. Cooling system improvements (lower temperature of condenser water, separate high-temperature chillers for process cooling). Cooling system maintenance: correct head pressure, correct refrigerant levels, appropriate condensers for part load, cleaning.

How Much Industry Electrification is Possible?

Based on the results from Table C.6, one can ask how much electrification is included in the top-down savings estimates? This is not directly answered in the DOE Bandwidth studies since these studies represent technical potential limits and not a set of pathways. To achieve DOE bandwidth minimum process energies, however, novel processes or new materials are likely required, probably accompanied by large-scale process intensification and membrane separation across industry sectors in addition to other breakthrough technology developments.

For the most part, existing or emerging technologies are considered and no information is provided on the relative energies of fuel switching. The CEC (2009) study likewise does not focus on fuel switching or electrification. In this study, the bulk of the energy savings derive from common improvements or upgrades to end use application families (steam systems, process heating, motor systems). Exceptions are steam systems with mechanical vapor recompression and membrane separation for food/petroleum/chemicals, and these measures contribute less than 1% additional electricity demand. The question "how much industry electrification is possible?" can be broken into two questions: for a given industry sector, which end uses can be electrified, and second, which electro-technology can be utilized?

In the bounding case, we assume that everything is electrified. A wide variety of existing electro technologies can be utilized for process heating [Microwave, Radio Frequency (RF), Induction, Plasma, Ohmic, Ultraviolet, etc.] and electric boilers can be deployed for steam systems. Of course, this ignores the higher cost of electrical heating, electricity supply-dependent GHG emissions, and the fact that although all of these technologies exist and are deployed in some form today, off-the-shelf end use equipment for most industry applications does not exist. In a more realistic case, one should consider when GHG emissions are favorable as a function of the electricity supply and/or when operational costs become competitive as a function of electricity price, gas prices and the future price of carbon. Based on GHG crossover analysis and operation cost analysis (described below) we build realistic scenarios as follows: assume heat pumps achieve full market penetration by 2050, process heating starts to electrify in 2020, and electric boiler begins market penetration at the earliest in 2045. We assume that this is coupled with aggressive energy efficiency measures and that there is an aggressive shift to cleaner electricity supply.

The main barrier for electrification is cost and the fact that on a per Btu basis, electrically produced heat is 2-4 times more expensive than direct fuel based heating systems. However, energy considerations such as fuel/electricity cost are usually not sufficient to assess electrification potential. Despite the cost barrier, electrified process can offer other benefits (sometimes called "form values") depending on the application: improved product quality, higher throughput, space savings, better process control, or superior directionality (see Table C.7). At the same time, design and integration issues must be addressed. Electric systems often require custom design and engineering and low margin or non-advanced technology industry sectors (e.g., glass, food) are not budgeted or staffed for this.

In U.S. industry as a whole, electricity makes up a small fraction of process heating and steam systems. About 5.8% of fired heaters are electric and 0.67% of steam systems are electric.

Electrification Potential Matrix	**Electo-boiler Example**
Technical Requirements	
Process temp, pressure	Meets required process ranges
Process volume, capacity	Meets required process ranges
End use efficiency	Superior at rated capacity and across ranges of lower capacity
Design and Integration Issues	
Unit Re-design/ Re-engineering Requirements	Generally manageable since replacing similar form factor
Process & System Integration/ de-Integration Requirements	Probably ok for food; Challenging for petro-chemicals
"Form Values"	
Throughput/ Space/ Volume	Equivalent to better
Product quality/ product yield	Generally higher quality steam
Process control/ window/ directionality	Similar performance
Cycling	Faster ramping
Other	Very quiet
Economic and Environmental Considerations	
Capital costs - retrofit vs. replacement	Generally equivalent to lower; however, new electrical subsystem would raise costs
Operating costs	Depends on electricity, gas prices. Plentiful nuclear can make off-peak use economical
Maintenance costs	Generally lower; but new water conditioning operational issues
GhG savings	Depends on electricity supply
Environmental missions cost savings	Can help meet attainment goals

Table C.7. Industry electrification potential matrix of considerations.

Electrification Potential

We studied two large sectors in some detail (food and beverages, plastics and rubber) to try to validate the assumption of large-scale electrification technical potential (Brown, 1996). For example, food and beverages utilize fairly low process temperatures (230°C bread oven, 175°C boiler system) and food processing fuel-fired heating should be electrifiable (drying in dairy industry, ovens in baking, snack food, and meat industries, frying in the poultry and snack food industries). Currently electric process heating is just 3.3% of food and beverage heating and electric steam systems and less than 1% of the market. In the plastic and rubber sector, process heating electrification potential is similarly large. Fuel based thermal drying at 80°C is an opportunity for many products (butyl, polybutadiene, polyisoprene, synthetic EP rubber, dipped latex fabricated rubber, molded latex fabricated rubber). High fuel consumption for curing (150°C) is another opportunity for electric replacement.

Also in this section we consider one end use replacement item: electric boilers. These offer superior end-use efficiency over fossil fuel fired boilers over a large range of operational loading (Figure C.2) and industrial electrode boilers have lower capital and operations and maintenance (O&M) costs. This assumes that new electrical systems or distribution upgrades are not required by the facility. Operationally, electric boilers are simple to operate but maintenance requires attention to water conditioning to avoid scale buildup and arcing. The ability to maintain efficiency over load changes is advantageous for many applications (e.g., pulp and paper). In the U.S. southeast, where off-peak electricity is provided by inexpensive nuclear power, electric boilers are deployed in a diverse range of applications (hospitals, universities, pulp, electronics, textiles) in a dual boiler mode where gas-fired boilers operate at times of peak electric rates and electric boilers operate during off-peak times. Electric boilers also offer the advantage of low environmental emissions (criteria pollutants) in urban areas. Electric boilers have large technical potential to replace conventional boilers, but may not make sense for GHG emissions or cost reasons, to be explored in the next section.

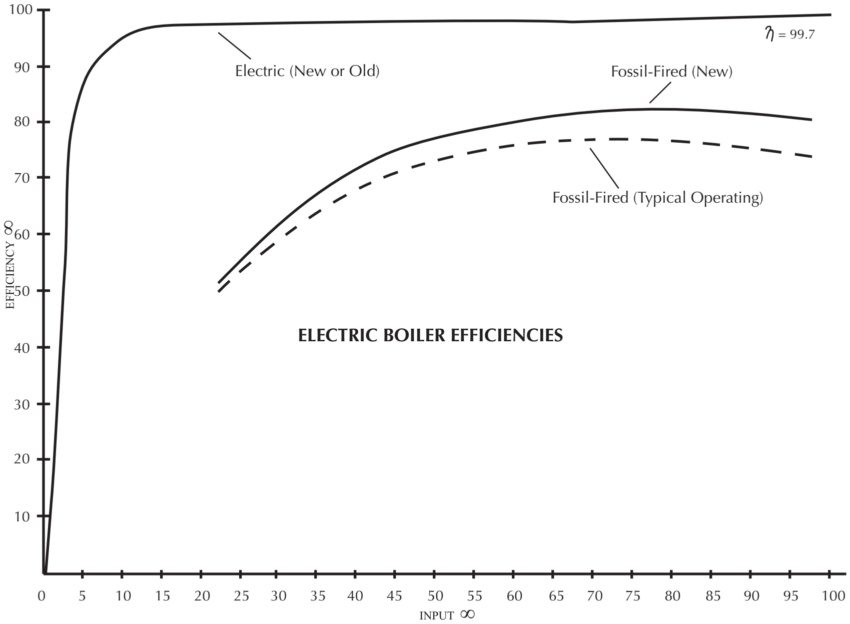

Figure C.2. Electric boiler efficiencies vs. fossil fired boilers.

Electro Technology GHG Crossover and Fuel Cost

A cleaner electricity supply favors electrification if goal is to reduce GHG. For illustration, we model this with an electricity supply in the state of California that steadily increases its percentage of non-fossil supply to 90% of electricity in 2050 from approximately 36% in 2010 (non-fossil supply includes nuclear, geothermal, hydropower, and other renewable sources such as wind and solar). Figure C.3 shows the example of an electric boiler with 99.7% end use efficiency vs. a gas boiler with 80% efficiency. Under this scenario, electric boilers become favorable from a GHG emissions standpoint in about 2034, or when the non-fossil electricity supply percentage is about 68%. We note that Duke Energy employs electric boilers in South Carolina with nuclear power, constituting 60% of electricity supply for economic reasons as noted above.

Similar crossover points can be obtained for other electro-technologies using the efficiency ratios of fossil fuel based systems vs. electricity alternatives (Table C.8). For example, an open cycle mechanical vapor recompression heat pump for chemical separation can have a coefficient of performance (COP) of 5-8 compared to a natural gas boiler at 75% efficiency (EPRI, 2009). We see that five technologies (heat pumps, arc furnace, melting technologies, electrolytic reduction) are favorable today; five heating technologies become favorable in 5 years; and electric boilers and electric drives do not become favorable until 2035. Note that these results are geographic specific and different electricity supply mixes and evolution would give different results. For GHG reduction, process heating seems a promising sector for electrification in the near term and boilers in the longer term.

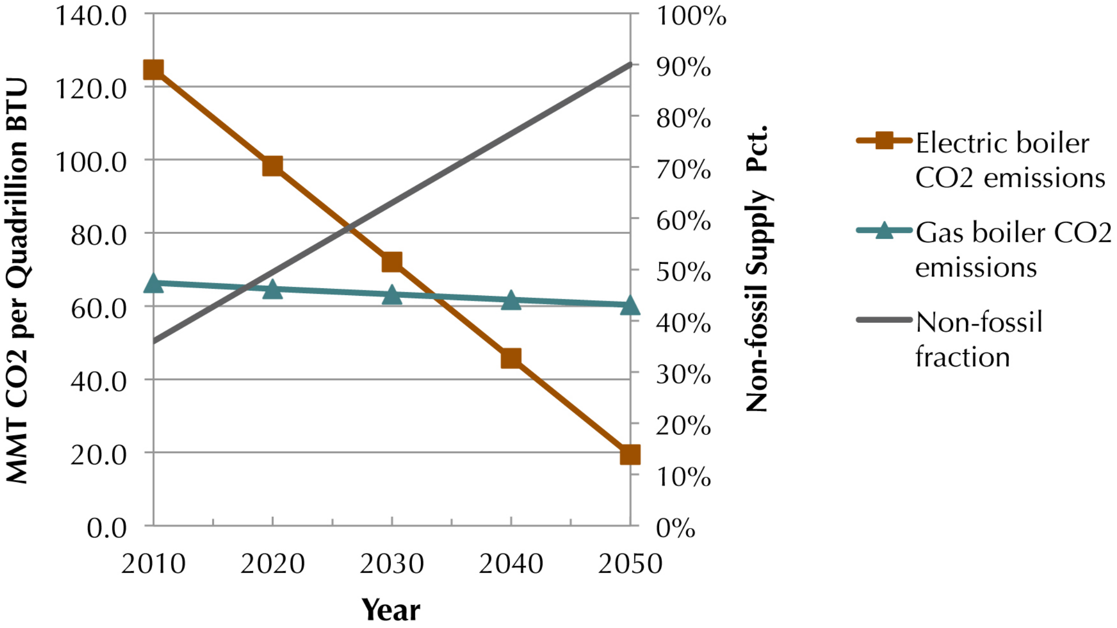

Figure C.3. Electric boiler and gas boiler GHG emissions vs. non-fossil electricity supply

Replacement Electric Technology	Displaced Fossil-Fueled Technology	Efficiency Ratio: Fossil Fuel to Electricity	Date GhG Favorable
Heat Pumps	Natural Gas Furnace	0.14	Today
Electric Arc Furnace	Coke Blast Furnace	0.11	Today
Electric Induction Melting	Natural Gas Furnace	0.29	Today
Plasma Melting	Natural Gas Furnace	0.29	Today
Electrolytic Reduction	Natural Gas Furnace	0.25	Today
Induction Heating	Direct-Fired Natural Gas	0.47	2014
Radio Frequency Heating	Direct-Fired Natural Gas	0.47	2014
Microwave Heating	Direct-Fired Natural Gas	0.47	2014
Electric Infrared Heating	Direct-Fired Natural Gas	0.47	2014
UV Heating	Direct-Fired Natural Gas	0.47	2014
Electric Boilers	Fossil-Fueled Boiler	0.8	2034
Electric Drives	Steam Drives	0.86	2037

Table C.8. Replacement electric technology efficiency ratios and GHG favorable dates. (Efficiency ratios from EPRI, 2009).

A second comparison can be made on the basis of energy costs. Again we assume a steady increase of non-fossil electricity supply to 90% in 2050, and aggressive carbon price increases rising to \$200-300/tCO_2 by 2050.[17] Fossil heating is assumed to be 47% of electric heating efficiency (Table C.8). At current approximate energy prices, electrical process heat is about three times more expensive than gas-fired heating. Electric heating is not competitive with fossil based heating until the price of carbon is in the \$150/tCO_2 range (Figure C.4). Thus other product and/or process benefits are required to drive early adoption. In general electrical heating offers better control, more directionality, and a smaller equipment footprint. Microwave or RF heating systems for example can save space, improve product quality, and increase throughput. These benefits can outweigh the higher capital costs and/or energy costs for microwave systems. For example, in the food sector, the drying of many products (e.g., premium dog food, macaroni) can have tight process windows between over drying / product cracking and under drying / excess moisture leading to compromised product quality. In these cases, RF heating can offer superior product control and product quality vs. fossil fired ovens. However, product benefits from electrical heating are difficult to generalize and must be considered on a case-by-case basis.

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[17] Note this is higher than many studies estimate is required for significant emissions reductions. However, the aggressive California GHG target may necessitate such high carbon prices, so we have assumed it for the purpose of the crossover calculation.

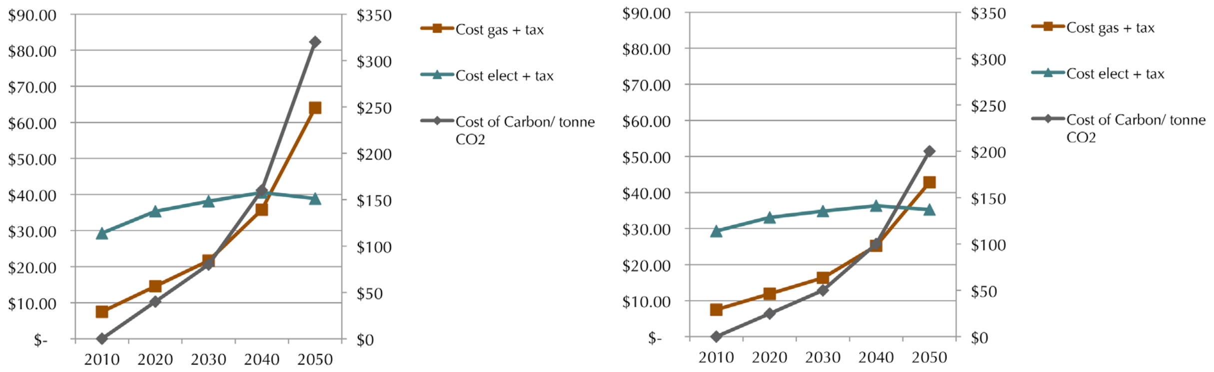

Figure C.4. Energy costs for electric process heating vs. fossil fuel based heating as a function of carbon price for two carbon price pathway cases.

Similarly, for the same steady increase in non-fossil electricity supply, for a baseline cost of \$.10/kWh for electricity and \$0.75 per therm of natural gas, electric boilers are not competitive in energy cost even at \$250/tCO_2. Countering this, electric boilers can add value from superior performance: in the case of a paper recycling plant in the south, electric boilers delivered higher yield and fewer paper breakages due to better response to changes in operational loading.

Electrification Scenarios

For the electrification scenarios, we keep the electricity sector's savings potential as in the top-down estimates, but assume that the gas sector has varying degrees of electrification. For the latter, we also assume 25% further savings from operational, control, and maintenance tightening, and 30% savings from behavior driven demand reduction.

We do not combine the top-down technical potentials with the electrification efficiency gain to avoid double counting. The technical potential may include electrification as a possible pathway (for example, novel separation technologies such as membrane/pump systems) and secondly, some measures contributing to the technical potential are based on existing fossil-fuel based industrial processes such as combustion optimization and control, or waste heat recapture which may not be applicable in the electrification scenario.

Here, the bounding case is to assume all end uses that are currently fossil fuel fired are electrified. Gas-fired process heating is fully replaced by a variety of electro technologies (microwave/RF, induction, plasma, ohmic, ultraviolet, infrared) and gas-fired steam systems are replaced by electric boilers. We also assume that CHP and co-generation are replaced by on-site renewable generation and electric boilers. Solar boilers (low process steam pressure) are assumed to capture 15% of the overall market primarily in the food/beverage and fruits and vegetables sector (CEC, 2009), and heat pump market share of 15% (EPRI, 2009) is fully realized. Heat pump market share is determined by several factors including to what degree heat pumps exist already in various industry sectors and to what degree opportunities exist with favorable design/layout considerations and manageable temperature lift differentials. We also assume gas to electric efficiencies as in Table C.8, "frozen" from 2010-2050. There is minimal R&D in electro-technologies today so capital, O&M costs, and energy costs are not necessarily trending downward. With increased R&D investment these metrics could improve, but fossil fuel efficiencies may also improve over time.

We also assume that all petroleum fuel is replaced within the California economy and that the industrial energy demand associated with its production is also removed, either by net zero energy account for interactions/production shifting resulting from curtailed petroleum refining.

The full electrification bounding case is found to save 76% energy from the frozen efficiency gas demand and require additional electricity in the amount of 24% frozen efficiency electricity demand. Overall, a 73% energy savings is realized versus the frozen efficiency demand. It is interesting to note that the full electrification scenario offers a savings rate very similar to the top-down bounding case savings potential of 72%. Electrification can thus be viewed as one pathway that can achieve technical potential savings. Note that some industries will be difficult to electrify without extensive process system redesign due to intensive process integration and "non-linear" processing that exists today (petroleum and chemicals). Other industries with more decoupled, "linear" process flows (e.g., food/beverages) may be less difficult to electrify. Including the petroleum fuel industry results in 70% overall energy savings with 32% additional electricity required relative to frozen efficiency demand.

Two realistic cases are considered. The first case assumes electric process heating captures 50% of the market share for new and replacement equipment continuously starting in 2020, with no penetration of electric boilers. This results in an overall energy savings of 64% with 26% of the frozen efficiency gas demand and additional electricity demand that is 7% of the frozen demand. Including petroleum fuel yields 57% overall energy savings, 34% remaining gas demand, and additional electricity 9% of frozen demand (Table C.9).

The second, more aggressive electrification realistic case assumes electric heaters capture 100% of the market share for new and replacement equipment continuously starting in 2020 and electric boilers similar market penetration starting in 2045. This case gives 66% overall energy savings with 16% remaining fuel compared to the frozen baseline and additional electricity demand that is 13% of frozen demand. The case including petroleum fuel yields 60% overall energy savings, 21% remaining fuel demand, and additional electricity that is 16% of frozen baseline.

						Autonomous 50% savings 2050		Autonomous 35% savings 2050	
Type	**Case**	**Energy Intensity Savings**	**Energy Intensity Savings vs Frozen BL**	**Behavior Savings (Demand Reduction)**	**Energy Savings w/ Behavior vs Frozen Baseling**	**Energy Intensity Savings vs Autonomous Baseline**	**Energy Savings w/ Behavior vs Autonomous Baseline**	**Energy Intensity Savings vs Autonomous Baseline**	**Energy Savings w/ Behavior vs Autonomous Baseline**
BU	Aggressive	48%	48%	30%	64%	-4%	27%	28%	49%
BU	Aggressive w/o petrol replacements	38%	38%	30%	57%	-24%	13%	6%	34%
BU	Aggressive 2	52%	52%	30%	66%	4%	33%	38%	57%
BU	Aggressive 2 w/o petrol replacements	43%	43%	30%	60%	-14%	20%	22%	45%
BU	Bounding	62%	62%	30%	73%	24%	47%	48%	63%
BU	Bounding w/o petrol replacement	57%	57%	30%	70%	14%	40%	34%	54%

Table C.10. Bottom up estimates of industry energy savings in 2050 based on wider scale industry electrification
Table C.10. Key barriers to achieving higher energy efficiency in industry.
Table C.11. Key barriers to achieving higher degree of electrification in industry.

Barrier	Example	Mitigation	Difficulty to Overcome
Risk Aversion	Many examples of decision not to change process despite significant projected savings (glass, food)	Establishment of more advanced technology and electrotechnology application centers for demos and pilots Increased funding for industry specific guidebooks and training Establish target levels of energy intensity with threat of penalties/tariffs or voluntary agreements	High
Elevated hurdle rate and high transaction costs	Many examples of decision not to change process despite significant projected savings (glass, food)	Energy management practices/ training Emerging energy management standards ISO 50001 Energy assessment/ training Incentives and grants Voluntary agreements	High
No organizational structure to manage energy use	Operation budget separate from capital allocation budget	Energy management best practices, systems Monitoring/ Verification/ Records of energy savings EMS/ Energy Manager system integration	High
Lack of understanding or capability on how to implement energy efficiency	Facilities which lack engineering support for monitoring/ redesign	Protocols for System Assessment Protocol for Monitoring & Verification CEC/SEP Certification programs Training for Implementation and Inspection	High
Lack of government utility, industry coordination	Industry capital equipment cycles 10-20 years non-overlapping with 1-2 year utility programs	Government/ utility/ industry partnerships for long term planning and program structures and targets	Medium
Low awareness of energy efficiency	Lack of data on specific end use energy consumption, Energy auditing weak	Ratings and Designations for Facilities ISO 50001 Operation Standards (expected 2011) EPA End Use Guidebooks & Focus Groups Online Databases for CHP and End-use installations Training programs for energy assessment, auditing	Medium
Regulatory issues	Disincentive to change emissions due to lengthy regulatory review requirement	Streamline regulatory review	Medium

biofuel production or out-of-state biofuel production. We assume that 10% of the petroleum sector

Barrier	Example	Mitigation	Difficulty to Overcome
Highly integrated existing systems	Petroleum refining. Petro-chemicals	Incentives for new plant design with lower energy intensity	High
Econimic: energy cost	Cost of electric heating higher than gas heating	Minimum carbon price for greater certainty Establishment of more advanced electrotechnology application centers for demos and pilots	High
Economic capital cost	Microwave heating system more expensive than fuel systems	Incentive programs, government/ industry partnership for higher end use efficiency Rebates to mitigate higher capital costs	Medium
Procurement and Distribution availability	Lack of off-the-shelf electric equipment but available of fossil fuel dryer (food sector)	R&D targeting advanced electric heating technologies	Medium

related to non-fuel products remains and that the chemical sector is still intact, which does not

Key Industry Barriers

Key industry energy efficiency barriers include risk aversion, lack of consistent organization structure to manage energy use, no budget/staffing for custom design/engineering that may be needed, low awareness of energy efficiency, and lack of understanding on how to implement energy efficiency. For most of industry, keeping the production line up and running is job #1. Many electro-technologies and their capabilities are viewed as unknowns. This is especially a problem in industries with low profit margins and/or a low technology base. A list of general industry barriers and mitigation steps is given in Table C.10 and a list of industry electrification barriers in Table C.11.

Long-term consistent government support is crucial to overcome barriers (McKane, 2007). More federal/state financial incentive programs are needed, for example, to adopt best-in-class efficiency or emissions. Electro-technology demo centers/pilot sites can be enormously helpful to address the education/awareness barrier.

General policies that will support increased energy efficiency in industry include R&D support, life cycle costing methodologies, subsidies (e.g., investment tax credits, efficiency incentives), innovative financing for energy efficiency investment, and mandatory retirement of less efficient equipment. Standards for industry equipment can be challenging due to heterogeneity. Voluntary industry sector targets for energy intensity coupled with penalties after several years have been shown to work in some European countries, but have not been pursued here due to industry opposition.

Two existing federal programs address some of the barriers in Table C.10: “Save Energy Now” and “Superior Energy Performance.” Save Energy Now is a national program at the company or plant level with the goal of 25% reduction in energy intensity over the next 10 years. This assumes a 1% rate of autonomous change and 1.5% energy efficiency gain above that. The program provides a wide variety of resources to participants including coaching, energy management best practices, and in some cases outsourced implementation. Save Energy Now is a voluntary program without incentives or penalties. Still, several industry energy efficiency experts consulted for this report expressed high confidence in the U.S. achieving 25% energy intensity reduction by 2020. Much of this savings is projected to be “low-hanging fruit,” so to go beyond this, more R&D is required to further reduce energy intensities. The impact of such a program could be greater with the threat of penalties or the incentives of tax credits but these do not exist today. The benefit of this program is that a structure of targets and timeframes and government resources has been set up which will be very useful when carbon cap and trade is implemented.

A second related national program is the “Superior Energy Performance” (SEP) program. This is a plant-level certification program coupled with government education and support programs. To receive certification, 5% minimum energy intensity reduction needs to be demonstrated over three years and energy management practices must be in conformance to specified standards. Currently the program is in a national demonstration phase with 1-2 sites per state, and the program is expected to accelerate in 2011 when ISO 50001 energy management standards are released. Key issues in this program are developing messages for why companies and plants should join the program and quantifying the value of establishing energy management systems (McKane, 2007).

Save Energy Now and SEP address many of the general barriers in Table C.10. Not explicitly addressed however are regulatory barriers or coordination among industry/utilities and government. Industry electrification barriers, as well as R&D funding, technology piloting/demonstration centers, and incentive programs, are also not addressed by the two programs.

Implementation Plan

The following policy actions are recommended:

- Pursue Save Energy Now program to increase participation rate with the goal of 25% energy intensity savings by 2020. Similarly, initiate a campaign to increase awareness in SEP energy management benefits targeting aggressive implementation of ISO 50001 standards and protocols in 2011-2013.
- Increase CEC/federal research, development, and demonstration (RD&D) funding for basic industrial end uses and electro-technology process heating.
- Provide incentives for adoption of best-in-class energy efficient equipment. Incentives together with increased RD&D funding are required in order to achieve the best-in-class penetration model described above.
- Pursue aggressive streamlining and consolidation of regulatory review process.
- Initiate CEC/ industry group/ utility discussions for long-term planning and program structures and targets. For example, stakeholders can identify key gaps in training and personnel requirements, develop incentives for new plant design with lower energy intensity, and discuss key implementation barriers to greater electrification of industrial processes.
- Within the next two years, the CEC should formally adopt energy intensity reduction targets for industry sectors. A rough guideline is 2.8% annual energy intensity savings (25% reduction by 2020) coupled with incentives for compliance or early compliance and to be most effective, penalties if targets are not met.
- Establishment of advanced industrial technology and electro-technology application centers for education, demonstrations, and pilots.

Several measures require support or coordination with the federal government to be successful, and ideally all of these measures should be supported by the federal government.

Cost Estimates

McKinsey estimates a $113 billion cost for 18% savings in 2020. ACEEE estimates $200-300 billion for 25-30% savings from now to 2020-2025 in the U.S. To put this into context, an additional $20 billion per year is a 10% adder above baseline industry energy expenditures and capital expenditures. A long-term energy report for California by Energy and Environmental Economics (E3, 2009; Williams et al., 2011) included some cost estimates by sector, but costs were not a focus of their modeling effort, and were highly uncertain due to large uncertainties in fuel costs and costs of emission reduction measures. E3 projected net costs in the industrial sector to be $50 billion a year in 2050 in the state for electricity consumption, fuel consumption, and emission reduction measures with an energy reduction of 62% from the baseline case.

In industry there is consistent underinvestment for R&D in energy-intensive industries with R&D less than 2% of overall revenues from 1988 to 2003 for energy-intensive industries (wood products, paper, petroleum, chemical, non-metallic minerals, primary metals) compared to 4% for the overall manufacturing sector.

More R&D investment specifically aimed at basic industrial end uses and electro-technology process heating is imperative in order to meet the realistic scenarios as well as the expansion of existing programs to increase awareness and education and the establishment of more demonstration and piloting programs on electro technologies.

Acknowledgements

We would like to thank the following individuals for helpful discussions: Neal Elliott, Eric Masanet, Aimee McKane, Steve Pietsch, and Heather Youngs. Clark Gellings, Phillip Schmidt, Preston L. "Pete" Roberts, and Roger Paules were particularly helpful regarding industry electrification.

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Appendix D: California's Energy Future Full Committee

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Appendix E: California Council on Science and Technology

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