Max Tech Appliance Design:

Potential for Maximizing U.S. Energy Savings through Standards

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Abstract

This study surveyed the technical potential for efficiency improvements in 150 categories of appliances and equipment representing 33 quads of primary energy use across the US economy in 2010 and (1) documented efficient product designs, (2) identified the most promising cross-cutting strategies, and (3) ranked national energy savings potential by end use. Savings were estimated using a method modeled after US Department of Energy priority-setting reports—simplified versions of the full technical and economic analyses performed for rulemakings. This study demonstrates that large savings are possible by replacing products at the end-of-life with ultra-efficient models that use existing technology. Replacing the 50 top energy-saving end-uses (constituting 30 quads of primary energy consumption in 2010) with today's best-on-market equivalents would save ~200 quads of US primary energy over 30 years (25% of consumption anticipated there from). For the 29 products for maximum feasible savings potential could be estimated, the savings were twice as high. These results demonstrate that pushing ultra-efficient products to market could significantly escalate carbon emission reductions and is a viable strategy for sustaining large emissions reductions through standards. The results of this analysis were used by DOE for new coverage prioritization, to identify key opportunities for product prototyping and market development, and will leverage future standards rulemakings by identifying the full scope of maximum feasible technology options. High leverage products include advances lighting systems, HVAC, and televisions. High leverage technologies include electronic lighting, heat pumps, variable speed motors, and a host of controls-related technologies.

Introduction

It is well established that energy efficiency is typically the least cost approach to carbon emissions reductions and that major climate disruption cannot be avoided without aggressive and rapid efficiency improvements. Moreover, national investments in energy efficiency can be highly cost effective. For example, the cumulative impacts of residential energy efficiency standards from 1987 – 2050 are expected to yield a benefit/cost ratio of 2.71:1 [1].

With an eye toward identifying promising candidates and strategies for energy efficiency regulation, the Max Tech and Beyond project sought to answer the following questions: How much energy could the United States save if the most efficient (Max Tech) design options currently feasible were adopted universally? What design features could produce those savings? How would the savings from various technologies compare? To answer these questions, the Max Tech and Beyond project examined energy end-uses in the residential, commercial, and, in some cases, the industrial sectors considering the energy savings potential and design characteristics of best-on-market products, best engineered products (that is hypothetical products that could be produced using best-on-market components and technology), and emerging technologies.

This paper presents the results of three analyses based on that work:

- an analysis of the cross-cutting strategies most promising for reducing appliance and equipment energy use,
- a product-level analysis of energy savings potential, and
- a macro-analysis of the U.S. energy-saving potential inherent in promising ultra-efficient appliance technologies.

Methods

Given the many thousands of candidate products, we used an multi-faceted, iterative research approach to limit the potential of missing important end-uses, technologies, and design strategies, within time and costs constraints. Leveraging well over a century of cumulative experience in appliance energy analysis, the project began with a series of brainstorming sessions with the Energy Efficiency Standards team at Lawrence Berkeley National Laboratory (LBNL). At various times involving a dozen technical staff, the sessions were punctuated strategically by systematic data collection efforts for energy efficient technologies documented in academic, industry, and sources. We took both a top-down and bottom-up approach to identify potential both by end use by strategy:

- The top-down approach: Residential and commercial energy end-use consumption was broken down into as fine a resolution as possible and ranked to avoid missing potentially significant end-uses. Annually the US DOE presents US energy use forecasts in its Annual Energy Outlook (AEO) [2], based on results from the Energy Information Administration's (EIA) National Energy Modeling System [3], which builds its estimates based on appliance-level energy use data. To obtain energy use estimates at the appliance level we ran NEMS (the 2010 EIA release) using the AEO reference case assumption, and extracted the finest resolution data there from.

- The bottom-up approach: Products were considered as composites of a relatively small number of common functions (heating, cooling, lighting, blowing, pumping, compressing, force-applying, computing, displaying, and so on). We then considered the best-available technologies to serve those functions and how such technologies might be combined into ultra-efficient products.

Although data on the energy efficiency of various products are abundant in product catalogs—and some sources, in particular the websites of ENERGY STAR® and the California Energy Commission [CEC], even compile that information—it is more difficult to determine what technologies and components are used to achieve those high efficiencies. Indeed, such information often is regarded as proprietary. One source has that information in relative abundance, but only for certain products covered by energy efficiency standards: the engineering analysis chapters of the Technical Support Documents (TSDs) of the U.S. Department of Energy’s appliance standards rulemakings.[4] A meta-analysis of data contained in recent TSDs revealed a number of critical cross cutting design strategies.

Data collection included:

- exhaustive review of TSDs produced for DOE’s energy efficiency standards rulemakings, as discussed above;
- exhaustive review of energy efficient appliance databases on the CEC [5] and ENERGY STAR [6] websites;
- systematic examination of recent technology reports from key sources such as TIAX [7], ASHRAE [8],and *Appliance Magazine*;
- keyword searches of other industry and academic journals;
- targeted Internet searches;
- participant observations at the American Council for an Energy Efficient Economy (ACEEE) Summer Study and ACEEE Behavior, Energy, and Climate Change Conference; and
- consultation with industry and research experts on lighting, televisions, transformers, motors, pumps, compressors, and magnetic refrigeration

In addition, we contracted detailed reports on key products from industry experts for the following technologies: consumer electronics, lighting (general, fluorescent, high intensity discharge), motors, air conditioning, industrial pumps, and compressors.

Results

Cross-cutting strategies with major energy savings potential

A handful of cross-cutting technologies and strategies that are applicable to many products and sectors have the potential to yield large energy savings. Table 1 shows the estimated energy savings of Max Tech technologies relative to standard appliance design practices and technologies, ranked in approximate order of product-level energy savings potential. While electronic lighting and heat pumps stand out as technologies with very large product-level energy savings, controls-related strategies stand out in terms of both extremely large energy savings potential in many cases and the remarkably broad applicability of the concept from the micro-chip level in computers to variable-speed control of large scale industrial pumps.

Taking a closer look at two of these technologies indicates large potential energy and cost savings:

- Using variable-speed drives (VSDs) in all appropriate motor applications today would save an estimated ~9% of U.S. electricity (see Appendix A). Given that energy use can reach 90% of the life-cycle cost of a large industrial motor, the cost of a VSD motor can pay back within a year.

- In recent years, highly efficient permanent magnet (PM) motors have been cost-negative compared to comparable-capacity induction motors, because their very small size saves significant quantities of copper and steel. The potential savings are largest for small motors (< 10 horsepower), in part because relatively stringent standards are in place for larger motors. For these motors, PM rotors save 7 – 15% over current shipments and about 5% over the practical limit on induction motors. Admittedly, though, the relative prices of these motors could change rapidly, given the volatility of metals prices and the scarcity and geographic concentration of the rare earth (permanent magnet) materials. If PM materials become too constrained variable reluctance motors are an alternative with efficiency intermediate between induction and PM motors.

- Applying lighting best practices (efficient lamps, fixtures, and controls) throughout the U.S. economy today would save ~9% of U.S. electricity, cutting lighting energy consumption in half and saving almost 100 quads of primary (power plant) energy in 30 years.

Table 1. Cross-cutting energy-saving design options, ranked by approximate energy-saving potential.

Approach	Products to which strategy is applicable	Comments	Energy-saving potential (approximate)
Max Tech (market-proven technologies)			
Electronic lighting (fluorescent and LED) replace conventional incandescent lighting	Mostly residential lighting	Only the residential sector remains dominantly incandescent. Although LED and CFL efficacies currently are similar, LED efficacies are expected to increase faster and have a higher technical potential to do so.	~ 75% (commercial) ~ 60% (residential)
Heat pump technology (HP, air and ground source) replace standard electric and gas heating	Water heaters, space heaters, and clothes dryers	Uses reverse-refrigeration cycle, efficiency can be enhanced by use of CO_2 as refrigerant, absorption cycle use for gas-heat pump	~ 70% or more for CO_2-based electric HP ~40-50% for gas absorption HP ~ 25% – 50% dryers ~ 30% – 40% space heating
Controls 1: Add power management	Lighting, consumer electronics; heating, ventilation, and air conditioning (HVAC) systems; many appliances	Impact appears large, but involves large uncertainties; depends on the application and user behavior. Included are on/off controls, multi-level output, and output modulation. For electronic devices, includes more intelligent sleep modes and power scaling for chips.	~ 50% – 70% (TVs) ~ 20% – 50% (lighting) ~ 5% – 30% (other electronics)
Controls 2: variable-speed drives (VSDs) replace single speed	Compressors, pumps, blowers, dishwashers, refrigerators, and air conditioning systems	Advantageous only for applications that involve variable load conditions.	~30% – 50%
Controls 3: multiple smaller components or devices to replace one larger one	Transformers, power supplies, compressors, and pumps	Applies to power conversion technologies and related systems that, at low loads, operate at low efficiencies. Turn off unneeded systems and operate the others at conditions closer to optimal efficiency.	~ 20% – 50%
Efficient motors (many approaches: permanent magnet rotors, die-cast copper rotors, laminated amorphous metal cores, variable reluctance motors)	Any product that has a motor (from consumer electronics, to appliances, to large industrial machinery, and agricultural pumping equipment)	Different efficiency strategies may apply to different applications. In general the efficiency improvement potential is greater in smaller motors because current efficiency standards are already relatively high for large motors.	~ 10% – 40%
Improved power supplies	Consumer electronics		~ 2 – 5%
Beyond Max Tech (emerging technology)			
Organic LED	Electronic displays (portable electronics, TVs); lighting	Currently used primarily for only small displays because of cost.	~50 – 90%

Table 2 compares residential lighting, motors, and various heat pump applications for which we are able to break down and compare energy usage in detail. We could not analyze the commercial and industrial sectors in the same way. As Table 2 shows, although lighting clearly has significantly larger product-level energy-savings potential (with an even greater potential if controls are included), the combined savings from technologies that address heat pump applications is comparable to the savings for lighting and motors.

Table 2 Estimated U.S. residential energy savings if all standard technologies had been Max Tech in 2010.

Standard Technology	Replacement Technology	Energy Use[a] (TWh)	Savings Potential[b] (%)	Energy Savings (TWh/yr)
Lighting (incandescent, including reflector lamps)	Fluorescent or LED	212	60	127
Electric water heaters	Heat pump	130	50	65
Electric space heaters other than heat pumps	Heat pump	53	35	19
Electric clothes dryers[c]	Heat pump	43	38	16
Motors (all applications)[d]	VSD	527	40	158

[a] U.S. residential energy use by each standard technology in 2010. Values were estimated using the Energy Information Administration's (EIA's) National Energy Modeling System software (NEMS: http://www.eia.doe.gov/oiaf/aeo/overview/). In its *Annual Energy Outlook* (AEO) (http://www.eia.doe.gov/oiaf/aeo), EIA presents U.S. energy forecasts annually based on NEMS. Forecasts are needed to estimate current year energy use because actual data are not yet available. Although NEMS builds its estimates based on appliance-level energy use data, only broader end-uses are released. To obtain energy use estimates at the appliance level for the residential sector, we ran NEMS (the 2010 release) based on the AEO reference case.

[b] Based on the midrange of savings assumptions given in Table 1.

[c] Heat pump dryers are now on the market in Europe. In fact, Switzerland's recent energy efficiency standard for dryers effectively banned all but heat-pump dyers. See for example [11].

[d] Based on the following assumptions: motors account for 38% of residential electricity use (see Appendix A, Table 4); 75% of those are motors would benefit from VSD; and penetration of VSDs in appliances currently is negligible.

Product-level analysis of energy savings potential

Energy savings potential was estimated for over 150 products. In many cases, for example in the ENERGY STAR databases, energy use or efficiency is reported with no description of the technology responsible for the savings. Figure 1, documents the product-level energy savings potential (best-on-market with respect to shipment weighted average) for the top 20 performers. It should be noted that small differences in energy savings potential should not be considered significant because it was not possible to impose an absolutely consistent measure of comparison given the nature of the available data.

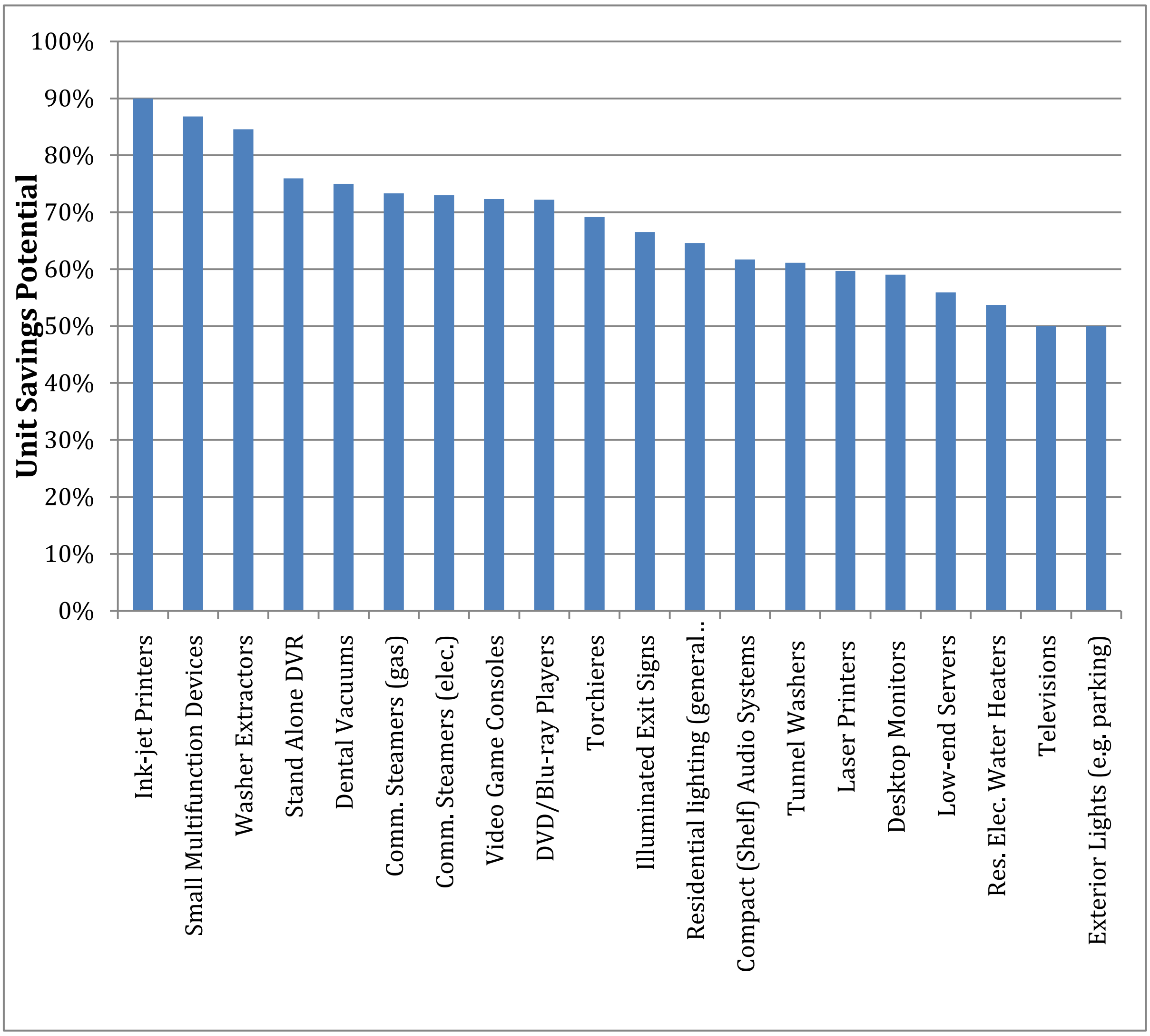

Figure 1.Top 20 end-uses ranked by per unit savings potential. Savings based on best-on-market efficiency versus average efficiency of current shipments.

Macro-analysis of the U.S. energy-saving potential of ultra efficient products

Technical Savings Potentials

We calculated the technical energy savings that would be obtained over 30 years, if the products sold today immediately started being replaced the best-on-market products or with Max Tech (maximum technically feasible products) as old products failed. The method was modeled after DOE priority-setting reports, which serve as simple versions of the full technical and economic analyses performed throughout a DOE energy conservation standards rulemaking.[11] The 30-year savings estimates incorporate all existing standards and those scheduled to come into effect (to avoid double counting). They do not account for any other mechanisms that might affect product energy use (*e.g.* building energy codes). While a standards-based model is being used here, because of the large numbers of products considered, we are making no claims as to whether or not a particular product is amenable to energy efficiency regulation. This is solely an estimate of the technical potential for energy savings.

The calculations associated with *Max Tech and Beyond*, priority-setting, and standards rulemakings all assume a 30-year analysis period and a natural replacement cycle of older units in the installed base. In this project (unlike in the standards rulemaking process), the calculation does not account for a potentially growing installed base, because complete annual shipment data were not available for all products.

The calculations distinguish between site energy use (the electricity use at the home) and source energy use (the input fuel needed to produce that electricity). Reports related to DOE priority-setting and standards rulemakings give all energy values as source (or primary) energy. In this report, site electricity, natural gas, oil/gasoline, and water consumption are all considered separately for each product and combined into total primary energy consumption per product. Site energy use was converted to source energy use using the average national *heat rate* for 2025 (the midpoint of the period considered) from the Energy Information Administration's (EIA's) forecast in its *Annual Energy Outlook* for 2009 (adjusted for the economic stimulus bill). *Heat rate* is the multiplier used to convert all site electricity consumption into primary source energy consumption, which DOE anticipates to be 10,650 British thermal units (Btu) source energy per kilowatt-hour (kWh) site energy. For natural gas, we assumed a 10% loss from source to site. We assumed that oil experienced no loss (*i.e.*, site energy equals source energy). In the case of water, energy is used to supply, transport, and for pre- and post-treatment. The embedded site energy for water was assumed to be 3.4 terawatt-hours per trillion gallons.

We considered three energy use cases: (1) the base case; (2) a most efficient (best-on-market) case; and (3) and the maximum currently feasible (Max Tech) case, where possible. These cases are described below.

Base Case

To align with DOE priority-setting studies, the total stock (number of products) is assumed to remain constant for 30 years. The stock is replaced with units typical (in terms of efficiency) of new shipments at a constant rate throughout a single lifetime representative of the product. By the end of that lifetime, all the old stock has been replaced with units typical of new shipments. No further changes in the stock occur until the end of the 30-year period. In cases where a new standard is about to come into effect, we incorporated the standard's stipulated efficiency level into the estimates of new shipment efficiencies to prevent double-counting the energy savings from new technologies that will already be achieved through Federal minimum standards.

Best-on-Market Case

In this case we again assume that the total stock remains constant for 30 years. The stock is replaced with units representing current best-on-market product, at a constant rate throughout a single lifetime representative of the product. By the end of that lifetime, all of the old stock has been replaced with today's best-on-market equivalents. No further changes in the stock occur until the end of the 30-year period.

Max Tech Case

We again assume that the total stock remains constant for 30 years. The stock is replaced with Max Tech units that could be manufactured today (or in the very near future; *i.e.*, < 5 years), at a constant rate throughout a single lifetime representative of the product. By the end of that lifetime, all of the old stock has been replaced with Max Tech units. No further changes in the stock occur until the end of the 30-year period.

Table 3 summarizes energy use and savings potentials for the best-on-market and Max Tech technologies for the top 50 products, in terms of US energy savings potential over the next 30 years. The results for the top 20 products, are also presented in graphical form in Figure 2. The table is sorted by cumulative, 30-year savings potential in the best-on-market case, since not all products have Max Tech data. In addition to the 30-year potentials, the table shows primary energy reduction potentials (in percent per device). Note that Max Tech savings potentials are often much higher than best-on-market potential. In total, among the 150 products studied, we were able to estimate Max Tech potential for 29 products. For those 29 products Max Tech savings exceeded best-on-market savings by a factor of 2 on average (weighted by current end-use energy consumption).

Table 3. Top 50 end-uses sorted by potential cumulative 30-year energy savings.

Product	Annual Primary Energy Use 2010 (quads)	Annual Reduction in Primary Energy Use for Best-on-market Product (%)	Annual Reduction in Primary Energy Use for Max Tech Product (%)	Cumulative 30-year Baseline Primary Energy Use (quads)	Cumulative 30-year Best-on-market Primary Energy Savings Potential (quads)	Cumulative 30-year Max Tech Primary Energy Savings Potential (quads)
Residential lighting (general)	2.26	65%	79%	52.3	26.5	32.5
Commercial lighting (general)	3.50	31%	57%	103.6	23.7	43.9
Res. Elec. Water Heaters	1.33	54%	62%	38.3	15.9	18.3
Central AC	1.92	39%		51.7	13.4	
General Pumps	1.53	25%	50%	46.0	10.2	20.3
Gas Furnaces	3.22	14%		94.9	8.5	
Televisions	0.87	50%	85%	18.8	7.2	12.3
Industrial lighting	0.67	35%		20.1	6.1	
Central HP	1.16	25%		31.2	5.7	
Washer Extractors	0.28	85%		8.3	5.2	
Exterior Lights (*e.g.*, parking)	0.39	50%	60%	11.6	5.1	6.1
Air Compressors	0.96	20%		28.8	5.1	
Comm. Storage Water Heaters (gas)	0.42	50%		12.7	5.1	
Street Lights	0.35	49%		10.5	4.6	
Low-end Servers	0.29	56%	95%	8.7	4.6	7.8
Res. Gas Water Heaters	1.42	13%	51%	38.1	3.7	14.6
Comm. Storage Water Heaters (elec.)	0.27	50%		8.2	3.2	
Torchieres	0.22	69%	77%	5.0	3.1	3.5
Fume Hoods	0.28	50%		8.4	2.8	
Metal Halide Fixtures	0.75	21%		20.2	2.7	
Desktop Computers	0.54	24%	69%	12.5	2.7	7.9
Ceiling Fans	0.47	47%	78%	8.5	2.6	4.3
Desktop Monitors	0.15	59%		4.0	2.2	
Dishwashers	0.24	37%	46%	6.7	2.0	2.4
Clothes Washers	0.48	21%	83%	12.7	1.9	7.7
Clothes Dryers (elec.)	0.46	16%	44%	13.8	1.6	4.4
Non-general-purpose Motors	0.19	30%		5.8	1.5	
Chillers - Centrifugal	0.21	26%		6.3	1.1	
Chillers - Air-Cooled Recip. & Screw	0.19	29%		5.6	1.1	
Compact (Shelf) Audio Systems	0.07	62%		2.0	1.1	
Liquid-immersed Transformers	0.42	21%	61%	11.6	1.0	3.1
Comm. Steamers (elec.)	0.05	73%		1.6	1.0	
Small CUAC	0.39	12%		10.8	1.0	
Refrigerators	0.87	7%	20%	21.3	0.9	2.8
Comm. Ranges (gas)	0.09	41%		2.7	0.9	
Dry-type Transformers	0.47	26%	48%	10.9	0.9	1.6
DVD/Blu-ray Players	0.05	72%		1.4	0.9	
Comm. Ovens (gas)	0.10	35%		2.9	0.9	
Large CUAC	0.35	12%		9.4	0.8	
Video Game Consoles	0.04	72%		1.1	0.7	
Boilers (gas)	0.43	10%		12.4	0.7	
Digital Satellite STB	0.07	38%		2.2	0.7	

Product	Annual Primary Energy Use 2010 (quads)	Annual Reduction in Primary Energy Use for Best-on-market Product (%)	Annual Reduction in Primary Energy Use for Max Tech Product (%)	Cumulative 30-year Baseline Primary Energy Use (quads)	Cumulative 30-year Best-on-market Primary Energy Savings Potential (quads)	Cumulative 30-year Max Tech Primary Energy Savings Potential (quads)
Very Small CUAC	0.22	15%		6.3	0.7	
Large Multifunction Devices	0.08	30%		2.4	0.7	
UPS (double conversion)	0.05	50%		1.4	0.6	
Medium Electric Motors	0.54	6%	25%	13.9	0.6	2.3
Cordless Telephones	0.10	22%		2.9	0.6	
Laser Printers	0.03	60%		1.0	0.6	
Air Cleaners/Humidifiers	0.06	33%		1.9	0.6	
Very Large CUAC	0.20	13%	79%	5.7	0.6	
TOTALS(*)	**30**			**820**	**200**	**200**

- Values rounded to two significant digits.

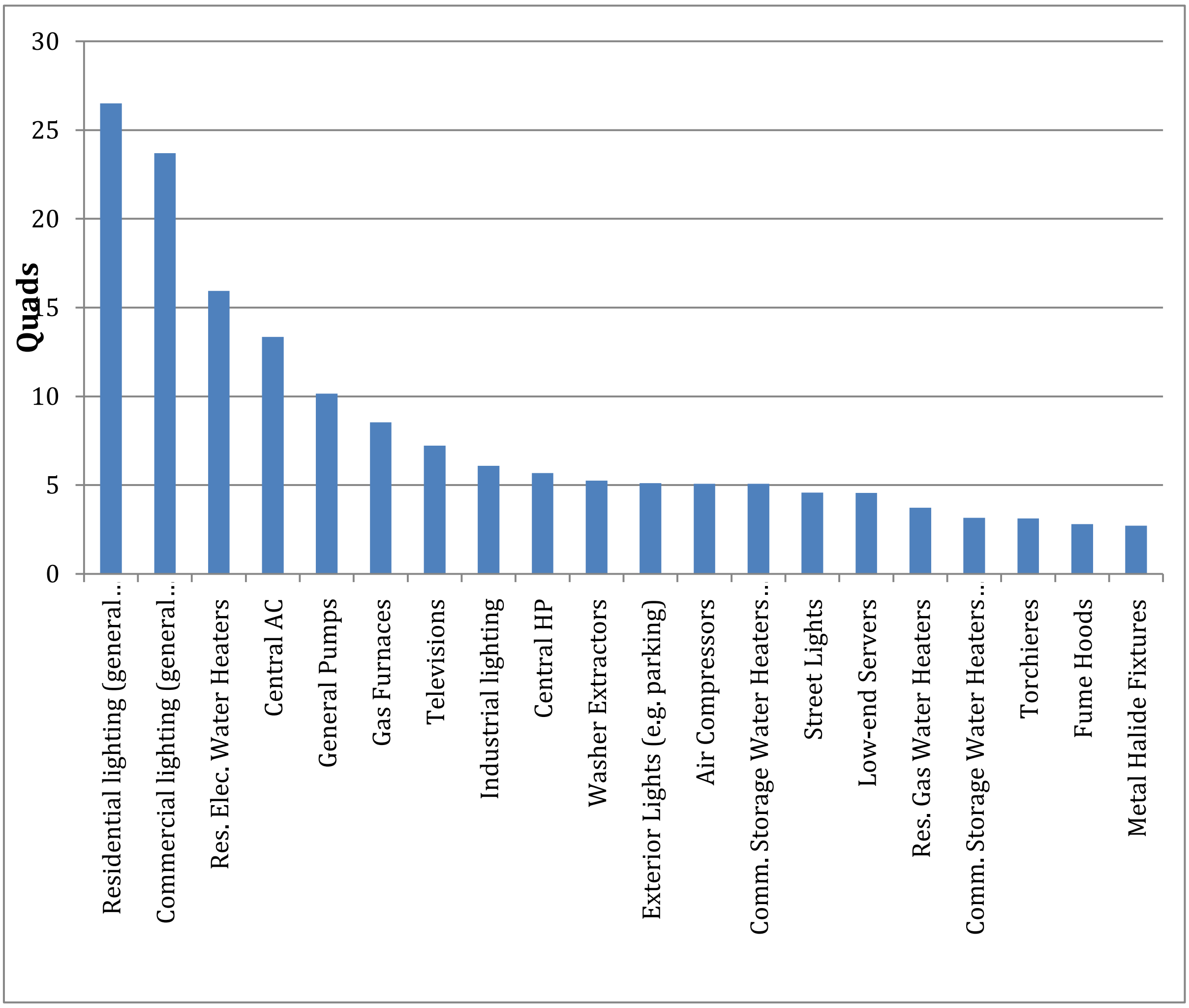

Figure 2. Cummulative 30-year energy savings potential of the top 20 products ranked by technical potential for energy savings in the US economy. Assumes that existing stock is replaced with current best-on-market product at the end of its lifetime.

Conclusions

This study demonstrates that large energy savings are possible by replacing the stock of US appliances and equipment at the end of product lifetime with high efficiency products using existing technology. Replacing the 50 top energy-saving end uses (which currently constitute 30 quads of annual primary energy consumption) with products having energy efficiencies equivalent to today's best on market products, would save the US an estimated 200 quads of primary energy over the next 30 years (25% of their anticipated baseline consumption). For the 29 end-uses for which we were able to obtain credible data to estimate maximum feasible savings potential, the savings were twice as high (50%). Those products alone have a potential to save 200 quads over 30 years, suggesting a strategic advantage, from a policy standpoint, of pushing those technology advances to market. Combining the potential of the 29 max tech products and the 21 remaining best-on-market products yields a total documented savings potential of 300 quads, which ignores additional potential of max tech advances in the latter.

This study also demonstrates that there are clear winners in terms energy-saving end uses and cross-cutting technologies and strategies. In terms of end-uses, lighting emerged as the clear winner in terms of Max Tech end-use savings potential, estimated at 76 quads over 30 year in the residential and commercial sectors alone, resulting from a combination of improved light sources, luminaires, and controls. Televisions (and other consumer electronics) also have large and growing potential, with controls dominating savings potential. Cross-cutting technologies of particular importance include heat pumps, variable speed motors, permanent magnet motors, and, as is already evident, controls strategies in general. The savings from energy management and controls can be very large and applies to products as diverse as computer micro-chips, lighting, consumer electronics, and large industrial motors.

These results demonstrate that pushing ultra-low-energy-use products to market could significantly escalate carbon emission reductions and is a viable strategy for sustaining major progress toward emissions reductions through standards. That is, continuing to drive up efficiencies at the high end of the market, using voluntary standards, information programs, and other mechanisms, enables the removal of low-performing products at the bottom of the market. That progress will not continue without appropriate incentives in place, one of which is the continued promise of increasingly stringent standards. These kinds of studies are essential, to prioritize standards efforts and thereby maximize emissions reductions and economic benefits, and to sustain progress over the long term. Accordingly results of this study were and continue to be used for prioritization of US voluntary and mandatory standards and R&D investments. Indirectly, these results also highlight the need for new appliance and equipment test procedures that can capture the energy and carbon benefits of well-established technologies, like controls, and of emerging technologies, like solar-assisted appliances, DC-based power systems, hybrid-designs, and system-based approaches. Because of constraints, this study only begins to quantify the potential savings from systems level approaches (e.g. in lighting systems) and hybrid design, which could greatly leverage the large savings demonstrated here in.

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