Title

Max Tech and Beyond: Maximizing Appliance and Equipment Efficiency by Design

Author

Desroches, Louis-Benoit

Publication Date

2011-07-20

Max Tech and Beyond

Maximizing Appliance and Equipment Efficiency by Design

Principal Authors
Louis-Benoit Desroches and Karina Garbesi
(Environmental Energy Technologies Division)

Contributing Consultants
James Beck, Independent Consultant (Electronics)
Nicole Graeber, California Lighting Technologies Center (Lighting)
Gunnar Hovstadius, Gunnar Hovstadius Consulting LLC (Pumps)
Michael Scholand, Navigant Consulting Inc. (Fluorescent and HID Lighting)
Charlie Sellers, Independent Consultant (Motors)
Tom Taranto, Data Power Services, LLC (Air Compressors)
Paul Waide, Navigant Consulting Inc. (Air Conditioners)

Project Contributors
Chris Bolduc
Gabriel Burch
Griffin Hosseinzadeh
Seth Saltiel

Lawrence Berkeley National Laboratory
One Cyclotron Road
Berkeley, CA 94720

July 20, 2011

The work described in this report was funded by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, Building Technologies Program under Contract No. DE-AC02-05CH11231.

Disclaimer

Acknowledgements

The work described in this report was funded by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, Building Technologies Program under Contract No. DE-AC02-05CH11231.

The authors thank the following individuals for their significant contributions to this work.

- Antonio Bouza and Robert Van Buskirk at DOE for initiating the project and providing advice and input while it was being carried out.
- The following members of Lawrence Berkeley National Laboratory's appliance standards team for their gracious input on potential max tech products: Barbara Atkinson, Mia Forbes Pirie, Jeffery Greenblatt, Asa Hopkins, Sanaee Iyama, Alex Lekov, Michael McNeil, Steven Myers, Chun Chun Ni, Greg Rosenquist, Hongxia Shen, Andy Sturges, and Camilla Dunham Whitehead. We also wish to thank Steven Lanzisera (LBNL), Alan Meier (LBNL), Bruce Nordman (LBNL), Chris Calwell (Ecos Consulting), Moonis Ally (Oak Ridge National Laboratory), Van Baxter (ORNL), Patti Garland (ORNL), Bo Shen (ORNL), Ed Vineyard (ORNL), and anonymous reviewers from Argonne National Laboratory for insightful discussions and comments.

Table of Contents

List of Tables

List of Figures

The accompanying spreadsheet is available at:

http://efficiency.lbl.gov/bibliography/max_tech_and_beyond

Acronyms and Abbreviations

AC	air conditioning or alternating current
ACEEE	American Council for an Energy Efficient Economy
AFUE	annual fuel utilization efficiency
Btu	British thermal unit
CEC	California Energy Commission
CFL	compact fluorescent light bulb
cfm	cubic feet per minute
CHP	combined heat and power
CLTC	California Lighting Technology Center
COP	Coefficient of performance (for heat pumps: heat output divided by work input)
CUAC	Commercial unitary air conditioning
DC	direct current
DOE	Department of Energy
DVR	digital video recorder
EEE	energy efficient Ethernet
EER	energy efficiency ratio (instantaneous cooling efficiency, Btu/W-hr)
EF	energy factor
EIA	Energy Information Administration
EISA	Energy Independence and Security Act
EPA	Environmental Protection Agency
EPAct	Energy Policy Act
FEMP	Federal Energy Management Program
HID	high-intensity discharge
HP	heat pump or horsepower
HPS	high-pressure sodium
HSPF	heating season performance factor
HVAC	heating, ventilation, and air conditioning
kWh	kilowatt-hour
LDAC	liquid-desiccant air conditioner
LED	light-emitting diode
LPS	low-pressure sodium
lm	lumens
MH	metal halide
NEMA	National Electrical Manufacturers Association
NREL	National Renewable Energy Laboratory
PD	positive displacement (pump)
SEER	seasonal energy efficiency ratio (seasonally averaged energy efficiency; Btu/W-hr)
STB	set-top box
TWh	terawatt-hour (*i.e.*, 10^{12} watt-hours)
Tgal	trillion gallons (*i.e.*, 10^{12} gallons)
VSD	variable-speed drive (a.k.a. variable-speed motor used to drive other variable-speed applications, such as an air compressor or a pump)
W	watt

Executive Summary

In support of prioritization for new national energy efficiency standards, the goal of this project was to identify and rank by national energy-savings potential the best practices in appliance and equipment design across the residential, commercial, and (in some cases) the industrial sectors. The project sought to define “max tech” designs, which combine all existing best practices into single appliances or pieces of equipment (few existing products actually do so). The broad scope of the project necessitated the use of a fairly coarse net, often requiring a focus on generalized design principles and approximate energy savings that can be obtained in different applications.

Advanced components and operational strategies used in best-on-market products and emerging technologies were studied to determine their savings potential and applicability to other types of appliances and equipment. In total, over 150 types of product categories were studied, regardless of power source. This report documents the findings on the top 50, in terms of their estimated national energy savings potential (the full sample is documented in the accompanying spreadsheet). While energy use information is generally readily available for most best-on-market products, design information is typically very limited. This is especially true for max tech designs. Nevertheless, this report has estimated the energy use of such max tech designs for approximately 20% of the products considered.

Figure E1 ranks the top 20 energy end-uses in terms of percentage energy-saving potential. Figure E2 ranks the top 20 end-uses based on their potential 30-year energy savings nationally. Note that the two figures do not highlight the same set of end-uses, reflecting different priorities for energy efficiency standards. Many applications offer large per-unit energy savings for all sectors of the economy. When ranked by national energy-saving potential, however, a few clear leaders emerge: lighting (all sectors), electric water heaters, central air conditioners (AC), general pumps, gas furnaces, and televisions.

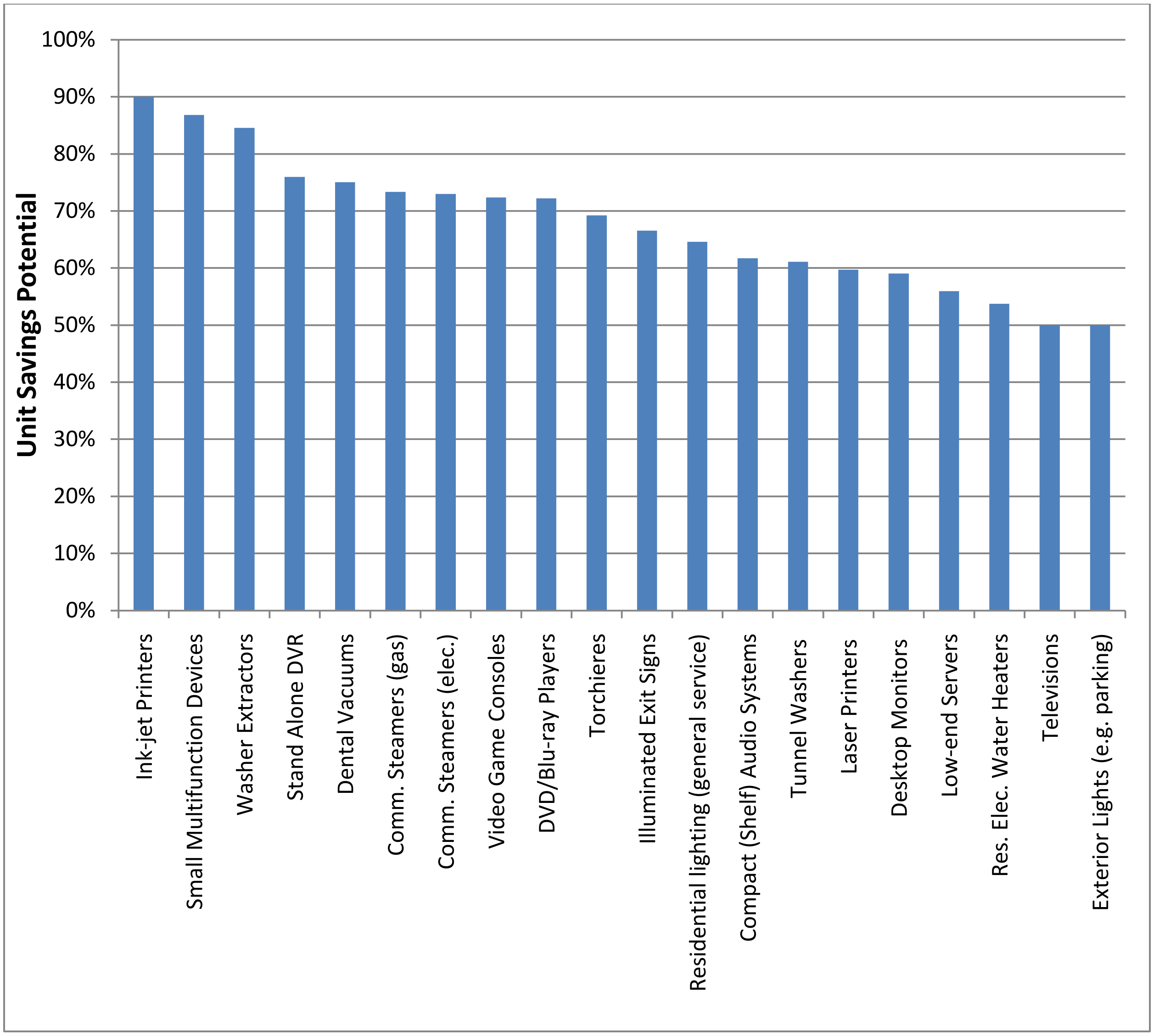

Figure E1. Top 20 end-uses ranked by per-unit energy-saving potential.

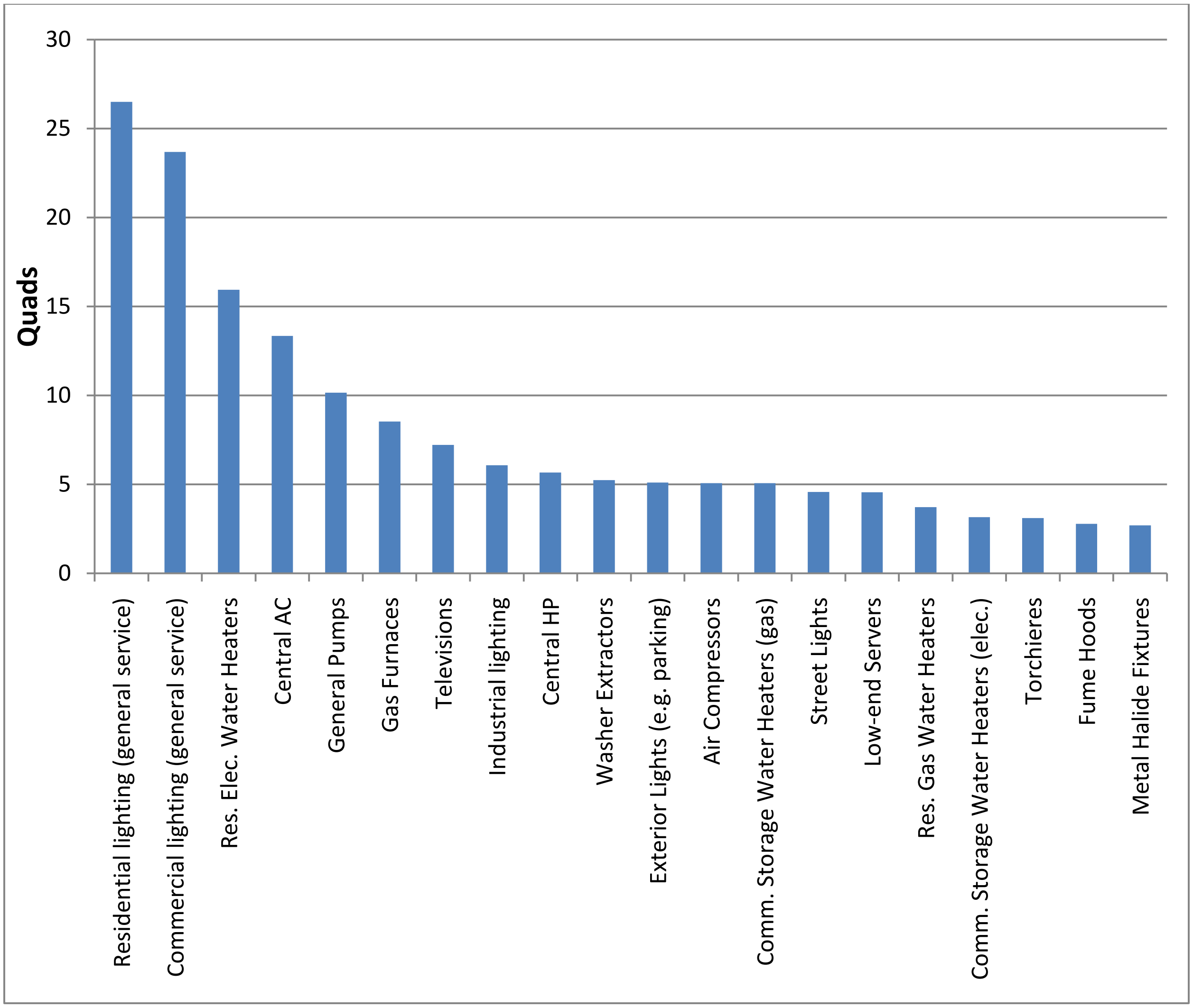

Figure E2. Top 20 end-uses ranked by 30-year energy-saving potential nationwide.

A few extremely potent cross-cutting technologies are applicable to a range of appliances and equipment and/or useful across sectors. Some examples include advanced lighting technologies (including sensors and controls in many applications), power management strategies of various kinds (especially in electronics, heat pumps, variable-speed drives to operate variable-speed compressors, pumps, and fans), and brushless direct current (DC) permanent magnet rotors (or variable-reluctance motors, to obviate the need for scarce rare earth materials). Organic light-emitting diodes (OLEDs) appear to be the most important emerging technology in terms of the magnitude of associated potential energy savings.

This study illustrates both the large savings that can be obtained by aggressive adoption of high efficiency products and the importance of getting max tech products to market. For the products for which max tech energy usage could be estimated, max tech energy savings exceeded best-on-market energy savings on average by a factor of 2.5. If all of the technical potential (from moving to best-on-market designs) is realized for the top 50 appliance and equipment types detailed in this report, the nation would save an estimated 200 quads in the next 30 years. Adopting max tech designs increases the savings even further. Clearly max tech products are worth immediate investment, and lessons from these products can be extrapolated to other products. Studies such as this help to further product development and advancement in terms of efficiency, to help stimulate technologies that can go well beyond current best-on-market.

Introduction

It is well established that energy efficiency is most often the lowest cost approach to reducing national energy use and minimizing carbon emissions. National investments in energy efficiency to date have been highly cost-effective. The cumulative impacts (out to 2050) of residential energy efficiency standards are expected to have a benefit-to-cost ratio of 2.71:1.[1] How much energy could the United States save if the most efficient design options currently feasible were adopted universally? What design features could produce those savings? How would the savings from various technologies compare? With an eye toward identifying promising candidates and strategies for potential energy efficiency standards, the *Max Tech and Beyond* project aims to answer these questions.

This project examined energy end-uses in the residential, commercial, and in some cases the industrial sectors. The scope is limited to appliances and equipment, and does not include building materials, building envelopes, and system designs. This scope is consistent with the scope of DOE's appliance standards program, although many products considered here are not currently subject to energy efficiency standards.

The analysis attempts to consolidate, in one document, the energy savings potential and design characteristics of best-on-market products, best-engineered products (*i.e.*, hypothetical products produced using best-on-market components and technologies), and emerging technologies in research & development. As defined here, emerging technologies are fundamentally new and are as yet unproven in the market, although laboratory studies and/or emerging niche applications offer persuasive evidence of major energy-savings potential. The term "max tech" is used to describe both best-engineered and emerging technologies (whichever appears to offer larger savings). Few best-on-market products currently qualify as max tech, since few apply all available best practices and components.[2] Nevertheless, it is important to analyze best-on-market products, since data on truly max tech technologies are limited.

The three primary analyses presented in this report are:

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

---

[1] Meyers S., McMahon J.E., McNeil M. and Liu X. *Impacts of US federal energy efficiency standards for residential appliances.* Energy 28: 2003, pp. 755–767.

[2] The Technical Support Documents published by DOE in support of the appliance standards program sometimes use the term "max tech" to refer to best-on-market products, if no higher efficiency levels are considered as part of the analysis. That is not the case in this report.

Methods

Leveraging decades of cumulative experience in appliance energy analysis, the project began with the iterative development of a list of prime candidates for energy savings, including products both covered and not covered by federal efficiency standards. This list served as a starting point for more systematic data gathering. Given the many thousands of potential candidate products, a strategic approach was used to identify and focus on those having the greatest potential to reduce national energy use. Systematic searches for energy efficient technologies from government, industry, and academic sources were coupled with both top-down and bottom-up approaches to limit the possibility of missing important end-uses, technologies, and design strategies.

- The top-down approach: Residential and commercial energy-end use consumption were broken down into as fine a resolution as possible and ranked to avoid missing any potentially significant end-use products. The Energy Information Administration (EIA) publishes annual U.S. energy-use forecasts in its Annual Energy Outlook[3], based on results from the National Energy Modeling System[4]. The model builds its estimates based on appliance-level energy use data, though only the broader aggregations of end-uses are reported in publications. To obtain energy use estimates at the appliance level, this report uses NEMS (the 2010 EIA release) using the AEO reference case assumption.

- 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). The project sought to identify the most efficient technologies available to serve those functions. This facilitated the identification of important cross-cutting technologies.

Data Sources

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, 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 this information in relative abundance for products covered by energy efficiency standards: the engineering analysis chapters of the Technical Support Documents (TSDs) published by DOE in support of appliance standards rulemakings.[5] A meta-analysis of data contained in recent TSDs, examining and comparing energy efficiency design options across product types, provided an excellent foundation for the project.

Data collection included:

- exhaustive review of TSDs produced for DOE's energy efficiency standards rulemakings, as discussed above;

---

[3] U.S. Energy Information Administration, *Annual Energy Outlook*. http://www.eia.doe.gov/oiaf/aeo.

[4] U.S. Energy Information Administration, *National Energy Modeling System*: An Overview. http://www.eia.doe.gov/oiaf/aeo/overview/.

[5] U.S. Department of Energy, *Appliances and Commercial Equipment Standards*. http://www1.eere.energy.gov/buildings/appliance_standards/

- exhaustive review of energy efficient appliance databases on the CEC[6] and ENERGY STAR[7] websites;
- systematic examination of recent technology reports from key sources such as TIAX,[8] ASHRAE,[9] and *Appliance Magazine*[10];
- keyword searches of other industry and academic journals;
- targeted Internet searches;
- participant observations at the American Council for an Energy Efficient Economy (ACEEE)[11] Summer Study and ACEEE Behavior, Energy, and Climate Change Conference (November 2010); and
- consultation with industry and research experts on lighting, televisions, transformers, motors, pumps, compressors, and magnetic refrigeration.
- contracts with industry experts to provide detailed reports on the following key technologies: consumer electronics, lighting (general, fluorescent, high intensity discharge), motors, air conditioners, industrial pumps, and compressors.

Quantifying Energy Savings

As indicated above, a primary task of the *Max Tech and Beyond* project was to quantify the energy-saving potential of candidate technologies. Most product categories utilize specific metrics to rate the efficiency of a given product (*e.g.*, energy factor, energy efficiency ratio, lumens per Watt, etc.). The definition of such energy efficiency metrics differs among technologies, however, and the usual metrics do not encompass all possible energy-saving measures. Specifically, typical efficiency metrics do not capture the savings from control technologies that turn devices off or down depending on demand. In addition, many products are currently growing in capacity or service, while maintaining a constant level of efficiency (*e.g.,* television screen sizes are increasing, refrigerator capacity is increasing). Despite the gains in efficiency, these products continue to consume more energy. Therefore relying on an efficiency metric alone can be misleading.

For this project, the metric used is the total anticipated energy savings (*e.g.*, quads/yr saved). This incorporates the potential benefits of control strategies. Admittedly, given that there are no agreed-upon test procedures for many products that can consistently quantify the energy use of products under field-representative conditions, this metric creates only approximate comparisons.

---

[6] http://www.appliances.energy.ca.gov/QuickSearch.aspx
[7] http://www.energystar.gov/index.cfm?c=products.pr_find_es_products
[8] http://www.tiaxllc.com/a/tech_rpts.php
[9] http://www.ashrae.org/publications/page/540
[10] http://www.appliancemagazine.com/contents/index.php
[11] http://www.aceee.org/

Cross-cutting Energy Saving Technologies

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 energy savings of advanced technologies relative to standard appliance design practices and technologies, ranked in approximate order of product-level energy savings potential. The estimates are based on the information on individual appliances and equipment presented in the *Ultra Efficient Design Options* section of this report. While electronic lighting and heat pumps stand out as technologies with very large product-level energy savings potential, controls-related strategies stand out in terms of both extremely large potentials in many cases and the remarkably broad applicability of the concept. Controls can be utilized from the microchip level in computers to variable-speed control of large-scale industrial pumps.

Table 1. Cross-cutting energy-saving design options, ranked by approximate energy-saving potential. (Orange shading indicates controls; green indicates an emerging technology.)

Approach	Products to Which Strategy is Applicable	Comments	Energy-Saving Potential (approximate)
Market-proven Technologies			
Electronic lighting (fluorescent and LED) replace conventional incandescent lighting	Many; replacing incandescent bulbs, primarily in the residential and commercial sectors	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 (air and ground source) replace standard electric and gas heating	Water heaters, space heating, and clothes dryers	Uses reverse-refrigeration cycle, efficiency can be enhanced by use of CO2 as refrigerant, absorption cycle use for gas-heat pump	~ 50% - 70+% water heaters ~ 25% – 50% dryers ~ 30% – 40% space heating
Controls 1: 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)	Compressors, pumps, blowers, dishwashers, refrigerators, and air conditioning systems	Advantageous only for applications that involve variable load conditions.	~30% – 50%
Controls 3:	Transformers,	Applies to power conversion	~ 20% – 50%

Approach	Products to Which Strategy is Applicable	Comments	Energy-Saving Potential (approximate)
using multiple smaller components or devices to replace one larger one	power supplies, compressors, and pumps	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.	
Efficient motors (many approaches)	Any product that has a motor (from major consumer appliances to industrial machinery)	Different efficiency strategies may apply to different applications; in general will have greater impacts on smaller motors.	~ 10% – 40%
Improved power supplies	Consumer electronics		~ 2 – 5%
Emerging Technology			
Organic LED	Electronic displays (portable electronics, TVs); lighting	Currently used primarily for only small displays because of cost.	~50 – 90%

Taking a closer look at two of these technologies reveals their large energy and cost savings potentials:

- Using variable-speed drives (VSDs) in all appropriate motor applications today would save an estimated 9% of U.S. electricity. 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. Interestingly, in recent years highly efficient permanent magnet motors have been cheaper to manufacture compared to induction motors of the same capacity, because their compact size saves significant quantities of copper and steel.[12]
- Applying lighting best practices (efficient lamps, fixtures, and controls) throughout the U.S. economy today would save an estimated 9% of U.S. electricity, cutting lighting energy consumption in half and saving almost 100 quads of primary (power plant) energy over 30 years.

Table 2 compares residential lighting, motors, and various heat pump applications for which energy usage data are available in detail. Commercial and industrial sectors could not be analyzed in the same way. As Table 2 shows, although lighting clearly has significantly larger product-level energy-saving 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 or motors.

---

[12] The relative price of high-efficiency permanent magnet motors and induction motors could change rapidly, given the volatility of metals prices and the scarcity and geographic specificity of the rare earth materials used in permanent magnet motors.

Table 2. Estimated U.S. residential energy savings if all standard technologies had been replaced with advanced, efficient technologiesin 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] With the exception of motors and electric space heaters, the energy use numbers are taken from the analysis presented in the *Energy-Saving Potential of Ultra-Efficient Appliances and Equipment* section of this report (and detailed in the accompanying spreadsheet). The energy use of electric space heaters was estimated from the National Energy Modeling System developed by the EIA.

[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.[13]

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

---

[13] See for example, P. Rogemma, "Sustainability in Europe." *Appliance Magazine*. June 2007: http://www.appliancemagazine.com/editorial.php?article=1769&zone=1&first=1

Energy-Saving Potential of Ultra-Efficient Appliances and Equipment

The energy-savings potential of over 150 products was estimated from a wide variety of sources (see the *Ultra-Efficient Design Options* section of this report for more information on individual products). As indicated above, the term "best-on-market" is used to describe best-in-class products that are available on the market. For many product categories, "best-on-market" corresponds to the best ENERGY STAR-qualified product. The term "max tech" is used to describe products that either (a) could be assembled using commercialized component technologies although no such products exist (*i.e.*, best engineered); or (b) incorporate emerging technologies that likely will be commercialized soon (*i.e.*, emerging technologies in research & development). The *Max Tech and Beyond* project also investigated highly speculative technologies in the early stages of research, where found. Such promising "beyond" max tech technologies were placed on a watch list, but were not considered when calculating energy-savings potentials. All of these designs are generically referred to as "ultra-efficient" designs.

This report presents the technical energy savings that could be obtained over 30 years, if products sold today were replaced at the end of their lifetimes with best-on-market or max tech versions. How fast these products penetrate the installed base depends on how quickly such products are naturally replaced. Technical savings potentials represent savings achievable as specific technologies gradually replace older stock—they may not reflect the actual savings potential achievable through minimum energy conservation standards. The calculation is 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.[14] Based on the simpler model, relative energy use and savings potentials identified through the *Max Tech and Beyond* project can be compared with results from other DOE analyses. Given that a primary driver for this research is to inform DOE's energy conservation standards program, such comparisons are important.

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. This project is also limited in scope to appliances, equipment, and lighting, and does not include building envelopes or energy generation. The calculations do not account for any other mechanisms that might affect product energy use (*e.g.*, building energy codes).

The calculations reported here reflect the potential for savings if standards were set immediately at a level achieved by either current best-on-market or max tech technologies. The 30-year savings estimates incorporate all existing standards and those scheduled to come into effect (to avoid double counting). While a standards-based model is being used here, because of the large numbers of products considered, no claims are being made 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.

---

[14] DOE. (2005). *Appendix A: FY2005 Technical Support Document*. Prepared in support of DOE's 2005 Priority Setting, updating the FY2003 priority setting. http://www1.eere.energy.gov/buildings/appliance_standards/pdfs/fy05_priority_setting_app_a.pdf

The calculations distinguish between site energy use and primary source energy use (*i.e.*, the input fuel needed to produce that energy). Converting site energy values into primary source energy values incorporates transmission line losses, distribution losses, and/or generation losses. 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 electricity was converted to primary source energy using the average national site-to-source factor in 2025 (the midpoint of the period considered) from the EIA's forecast in its *Annual Energy Outlook* for 2009 (adjusted for the economic stimulus bill). This factor equals 10,650 British thermal units (Btu) source energy per kilowatt-hour (kWh) site electricity. For natural gas, a 10% loss was assumed from source to site. Oil was assumed to experience 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 electricity for water was assumed to be 3.4 TWh/Tgal, consistent with DOE's appliance standards analysis for water-using appliances.

Three energy-use scenarios were considered: (1) the base case; (2) a best-on-market case; and (3) a max tech case (where available). These cases are described below.

Base Case

To align with previous DOE priority-setting studies, the total stock (number of products) is assumed to remain constant for 30 years. The stock is replaced with typical units (in terms of efficiency) found in current 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, that standard's stipulated efficiency level is incorporated into the estimates of new shipment efficiencies to prevent double-counting the energy savings from new technologies that are already achieved through Federal minimum standards.

Best-on-Market Case

The total stock is assumed to remain constant for 30 years. The stock is replaced with units representing the best-on-market units available today, 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 units that are currently best-on-market. No further changes in the stock occur until the end of the 30-year period.

Max Tech Case

The total stock is assumed to remain 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.

Technical Savings Potentials

Table 3 summarizes energy use and savings potentials for best-on-market and max tech technologies for the top 50 products, in terms of U.S. primary energy savings potential over 30 years. All 150+ products are included in the accompanying spreadsheet. The table is sorted by the best-on-market case, since not all products have max tech data. Note that the potential savings from max tech products typically greatly exceeds those of best-on-market products (on average by a factor or 2.5), underscoring the great potential for additional savings from technology diffusion. In addition to the 30-year potentials, the table shows annual primary energy reduction potentials (in percent per device). For details regarding the assumptions and calculations incorporated here, please refer to the accompanying *Max Tech and Beyond* spreadsheet document.

Table 3. Top 50 products 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 service)	2.26	65%	79%	52.3	26.5	32.5
Commercial lighting (general service)	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	

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)
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	
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	

Ultra-Efficient Design Options

This section catalogs ultra-efficient design options found to have significant energy-saving potential for appliances and equipment. The section describes both best-on-market and max tech designs (*e.g.*, best engineered and emerging technologies in R&D). Entries appear in alphabetical order.

Ceiling Fans and Ceiling Fan Light Kits

A residential ceiling fan is a non-portable device suspended from the ceiling to circulate air via the rotation of fan blades. Most ceiling fans have an integral or attachable light kit. Light kits are a complete lighting unit consisting of lamp(s) and ballasts (when applicable) or LEDs, together with the parts designed to distribute the light, position and protect the lamp, and connect the lamp to the mains.

Older ceiling fans are made with a standard shaded pole motor and incandescent lights. The motor typically consumes 35 watts (W), and the lighting 120 W. The fan itself provides roughly 100 cubic feet per minute per watt (cfm/W) of air circulation.

Newer ceiling fans use a split-capacitor motor and fluorescent lighting. Current ENERGY STAR-compliant models gain roughly 15% efficiency for the motor (30 W). Fluorescent bulbs gain 75% efficiency for the light (30 W). The best-on-market units on the market use a DC motor and fluorescent lighting, improved fan blade design with proper balance, and sealed bearings. The best-on-market motor consumes 10 W, and the lights 30 W. The best-on-market fan on the market achieves 680 cfm/W on low setting (motor uses 2 W) [1]. The max tech ceiling fan uses a direct-current (DC) motor with airfoil-shaped fan blades and LED lighting. The motor consumes 5W to achieve 1360 cfm/W (fan energy only), and the lights consume 10W [2].

A design option for ceiling fans in large, open commercial spaces is to replace many small units with a single large fan (see [3]). A large fan can displace the same volume of air using a lower speed, and because air resistive losses are non-linear with speed, efficiency is gained in operating at lower speeds. Lower speeds also provide a gentler breeze and reduced motor noise.

References

[1] U.S. Environmental Protection Agency (EPA). *ENERGY STAR program for residential ceiling fans*. http://www.energystar.gov/index.cfm?fuseaction=find_a_product.showProductGroup&pgw_code=CF

[2] Pacific Gas and Electric Company (PG&E). (2004). *Codes and Standards Enhancement Initiative: Analysis of Standards Options for Ceiling Fans*. Prepared for PG&E by Davis Energy Group Energy Solutions. May 9. http://www.energy.ca.gov/appliances/2003rulemaking/documents/case_studies/CASE_Ceiling_Fan.pdf

[3] Big Ass Fans. http://www.bigassfans.com/

Central Air Conditioners and Heat Pumps

DOE has established minimum performance standards for central air conditioners (ACs) and heat pumps (HPs). Effective January 23, 2006, ACs and HPs must have a minimum of 13 for seasonal energy efficiency ratio (SEER), and HPs must have a minimum of 7.7 for heating seasonal performance factor

(HSPF). Older AC units in the stock have an average efficiency of 11.8 SEER, and older HPs have an average efficiency of 11.8 SEER and 7.5 HSPF.

DOE is updating its standards for ACs and HPs. DOE estimates that current ACs and HPs achieve a current-sales shipment-weighted average 13.8 SEER and 13.9 SEER/8.0 HSPF, respectively [1]. The best-on-market units, according to ENERGY STAR, achieve 23 SEER for ACs and 22 SEER/10.5 HSPF for HPs [2], [3], and 24+ SEER units have become available. The primary challenge to achieving these potential efficiencies is to ensure that the entire system, including the air handler/blower normally associated with the furnace, is replaced when the efficient AC/HP is installed. Otherwise the achieved efficiency will be much less than the rated efficiency. The large efficiency gains come primarily from a variable-speed/modulating compressor and air handler. The highest gain achievable comes from a VSD with a brushless DC permanent magnet motor. The VSD allows for continuous lower-level cooling, eliminating the need for full-on/full-off cycling. Continuous lower-level cooling eliminates compressor cycling; improves evaporator coil performance (easier to maintain operating temperature); and eliminates cold, clammy conditions.

Additional savings are associated with providing regionally appropriate ACs and HPs. Because the Southwest has low ambient humidity, for example, ACs in that region do not need the operating temperature of the refrigerant in the evaporator coil to be low. Because they do not need to dehumidify the air, ACs designed for the Southwest can operate at a higher evaporator coil temperature, thereby saving energy. Similarly, a HP designed for northern climates can utilize a multi-stage compressor, large heat exchangers, and optimized controls. Such regionally appropriate designs could save 20% to 25% [4].

A different design option for high-humidity regions is a desiccant wheel used for dehumidification. Desiccants (such as silica gel) adsorb water vapor and release heat, which efficiently dehumidifies air. Then ACs can operate at higher refrigerant temperatures (air reheating lessen the need for a very cold evaporator coil) using smaller compressors. Even though the desiccant slightly warms the air, energy savings on building cooling systems are estimated to be approximately 25% [5]. The desiccant wheel is regenerated to the outside air (*i.e.*, the water content is removed) using waste heat, sunlight, or a heating element. Typical desiccants include silica gel, lithium chloride, and synthetic polymers. Water may be used as a refrigerant.

Evaporative coolers are well known for saving energy. Southern California Edison, for example, offers rebates on hundreds of models of residential evaporative coolers produced by six companies [6]—but conventional models are effective only in dry climates that require moderate cooling. DOE’s National Renewable Energy Laboratory (NREL) has developed an enhanced evaporative cooling system that uses a combination of membranes, evaporative cooling, and liquid desiccants. Unlike standard evaporative coolers, the system can operate in hot-humid climates, matching the performance of a traditional vapor-compression air conditioner (*i.e.*, one that does not add moisture to the supply air). The device, called a desiccant-enhanced evaporative air conditioner (DEVap), has the potential to reduce energy consumption for cooling by 50% to 90%, though some technical issues remain [7].

Another efficient dehumidification option is the multiple small-plate dehumidifier. In a conventional AC system operating in a humid environment, the evaporator coil is at a very low temperature to condense as much water as possible out of the air. This process leaves the conditioned air uncomfortably cold, so it must be reheated slightly before being distributed throughout a building, a process that wastes energy. Multiple small-plate dehumidifiers work essentially like heat-recovery units. There is a heat exchanger between the incoming and outgoing air (from the evaporator coil). Air is pre-cooled slightly before reaching the evaporator, and outgoing air is reheated from the incoming air stream. This design option removes the reheating unit from the AC, saving energy (claims of up to 50%). Nautica Dehumidifiers offers such units [8].

Another option for improving the efficiency of ACs/HPs is to couple them with small solar panels. This option is especially effective for ACs having a usage pattern that correlates well with periods of strong sunshine. The manufacturer Lennox briefly offered such a model (XPG20).

Energy recovery wheels/ventilators allow a transfer of heat (sensible and latent) and moisture between incoming and exhausting air. This enables incoming ventilation air to be pre-treated for temperature and humidity depending on the season. Energy recovery wheels not only reduce heating and cooling loads, but allow for smaller capacity equipment to be installed. Humidity levels are also relatively stable throughout the year in all conditions. Such systems may lead to 30% savings in some climate zones [9]. Note that recovery systems that transfer only sensible heat are known as heat recovery systems.

See Commercial Air-Conditioning for a discussion of evaporative pre-cooling.

See Water Heaters (Electric) for a discussion of integrated HVAC and water heating heat pumps.

See Commercial Air Condition and Heating Equipment for a discussion on variable refrigerant flow systems. Such systems are potentially viable for larger homes to enable multi-zone controls.

References

[1] U.S. Department of Energy (DOE). *Technical Support Document for Central Air-Conditioners and Heat Pumps*. Under Development.

[2] U.S. Environmental Protection Agency (EPA). *ENERGY STAR program for central air conditioners*.
http://www.energystar.gov/index.cfm?fuseaction=find_a_product.showProductGroup&pgw_code=CA

[3] EPA. *ENERGY STAR program for air-source heat pumps*.
http://www.energystar.gov/index.cfm?fuseaction=find_a_product.showProductGroup&pgw_code=EP

[4] American Council for an Energy-Efficient Economy. Information regarding regionally appropriate ACs and HPs.
http://old.aceee.org/emertech/2009_HotDryAC.pdf
http://old.aceee.org/emertech/2009_NorthernHP.pdf

[5] Slayzak, S.J., and Ryan, J.P. (2000). *Desiccant Dehumidification Wheel Test Guide*. Prepared for DOE by the National Renewable Energy Laboratory.

[6] Southern California Edison. *Energy Efficient Evaporative Cooling Rebate*. Funded by the California Public Utilities Commission. http://www.sce.com/residential/rebates-savings/heating-cooling/evaporative-cooling.htm

[7] National Renewable Energy Laboratory (NREL). DEVap. http://www.nrel.gov/features/20100611_ac.html

[8] Nautica Dehumidifiers. http://www.nauticadehumid.com

[9] Shen, B. (2011). Private communication.

Clothes Dryers (Residential)

A promising technology for clothes drying (other than simple line drying) is the heat pump clothes dryer, which operates much like a small air conditioner. It extracts heat at one temperature and releases that heat at a higher temperature. Heat pumps work well when the temperature difference is small, becoming less efficient as the difference increases. A typical heat pump uses 1 kWh of electricity to move 2 kWh of heat.

In a heat pump dryer, the air typically moves in a closed loop, although open-loop models exist. The heat-dissipating (condenser) side of the heat pump heats the air. The hot air is blown through the drum, where it evaporates water from the clothes. The air cools somewhat and its humidity increases. Then the air passes the heat-extracting (evaporator) side of the heat pump, where the air is cooled further so the moisture condenses out. The air can then be recycled and heated again. Either the condensed moisture is collected in a separate container, or the dryer is connected to a drain pipe.

Because heat pump dryers generally operate in a closed loop, the dryer produces almost no indirect load on a building’s heating, ventilation, and air conditioning (HVAC) system. For baseline technologies, ambient air is often pulled constantly into the dryer, requiring that new outside enter the home and be conditioned. This extra load on the HVAC system can be a substantial effect on the dryer’s overall energy use [1].

Heat pump dryers generally have longer drying cycles than baseline technologies (approximately 80 minutes). Because this feature may lessen consumer utility, efforts are being made to shorten drying times. On the other hand, heat pump dryers do not require venting or ductwork, and thus can be located anywhere in the home, making retrofits especially easy. Additionally, heat pump clothes dryers do not heat the air to as high a temperature as conventional dryers do, which is gentler on clothes [1]. Lower temperatures also mean less heat added to the HVAC load.

Heat pump dryers have the potential to save between 25% and 50% in electricity use compared to a conventional electric clothes dryer. These products are commercialized and widely available in Europe and Japan. They have a 25% market share in Switzerland, where, starting in 2012, only heat pump dryers will pass that country’s efficiency requirements.

Gas dryers often run at a single maximum heat output and simply turn on and off as needed to maintain a particular air temperature. If the gas burner in those dryers could respond more subtly to changes in interior dryer temperature and humidity, energy use and drying times could be reduced without subjecting clothing to overly high temperatures.

A prototype gas dryer (developed by TIAX LLC) that incorporates temperature modulation achieved 13% to 23% energy savings and 20% to 40% time savings compared to a conventional natural gas dryer. These results could benefit consumers, who prefer that their dryers keep pace with the cycle time of their washer so they can complete multiple loads of laundry as rapidly as possible [1].

The best available electric dryers incorporate intelligent moisture sensing to determinate when to terminate drying. Such sensors do not measure temperature as a proxy, but measure humidity levels in the drum throughout the drying cycle. When the humidity level drops and then stabilizes at a low level, the dryer automatically enters a stage in which the heating element cycles on and off. This capability prevents over-drying and heat damage to the clothes. After several iterations, if the humidity remains low, the dryer terminates the cycle.

In baseline units having less reliable humidity sensors (*i.e.,* those using temperature change as an indirect measurement of humidity), the on/off heating cycle can consume a significant amount of energy (perhaps 33% of the cycle total [1]), much of it unnecessary because the clothes are sufficiently dry. By refining the moisture-sensing capability, total energy can be reduced by 15% over baseline units. This reduction, which provides an energy factor of 3.4 pounds of clothing per kilowatt-hour, matches the maximum efficiency level identified in DOE's preliminary analysis of residential clothes dryers and has been confirmed to be commercially available [1], [2].

Microwave dryers work like a microwave oven. A magnetron tube converts electricity to microwave energy, which is directed at the wet clothes. The microwaves heat the water in the clothes, evaporating the water, which then is vented. The Electric Power Research Institute and American MicroTech have developed some test models. Problems have been encountered when the clothes contain metal, such as zippers, buttons, or coins, which can cause arcing and potentially a fire. Further development has led to a hybrid design that uses microwave heating while the clothes are wet (and won't burn) and uses hot air to finish the drying [1].

Microwave dryers are faster than conventional hot-air dryers, but are unlikely to be much more efficient. It takes as much microwave energy to heat the clothes and evaporate the water as it takes to dry the clothes using another energy source. The potential savings relates to not having to heat a large volume of air. The energy consumed by the magnetron roughly balances the energy saved by heating less air, however. Some savings in energy has been reported if the drying is done slowly, but conventional dryers also save energy if they dry more slowly. Microwave dryers may enter the marketplace for rapid drying of very small loads, but they will not become an energy efficient technology for mainstream clothes drying [1].

References

[1] Bendt, P., Calwell, C., and Moorefield, L. (2009). *Residential Clothes Dryers: An Investigation of Energy Efficiency Test Procedures and Savings Opportunities*. Prepared for the Natural Resources Defense Council by Ecos Consulting.

[2] DOE. (2010). *Preliminary Analysis Technical Support Document for Residential Clothes Dryers and Room Air Conditioners.* http://www1.eere.energy.gov/buildings/appliance_standards/residential/preliminary_analysis_tsd.html

Clothes Dryers (Large Commercial)

Large commercial clothes dryers, which have capacities in the range of 120 to 700 pounds per load, typically are found in large (or off-site) facilities. Such dryers may be designed as stand-alone units or pass-through units used in conjunction with tunnel washers. Large-capacity dryers use natural gas [1]. Specifically excluded from this category are the smaller, single-load, coin-operated, residential-style clothes dryers (sometimes referred to as soft-mount units).

Large commercial dryers are already relatively efficient because they tend to be used by laundry businesses, for which large gas usage is an incentive to conservation. Modest further improvements are possible, for instance through pre-heating the inlet air and providing better modulation controls. Based on our research, a 15% improvement seems possible.

References

[1] Zogg, R., *et al.* (2009). *Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances*. Final report prepared for DOE's Building Technologies Program by Navigant Consulting, Inc. December. 446 p. http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf

Clothes Washers (Residential)

A potential technology for washing clothes utilizes nylon beads. Clothes are washed using only a minor amount of (cold) water and a handful of nylon beads. The clothes become only slightly damp. The nylon polymer has an inherent polarity that attracts stains. Under humid conditions, the nylon polymer becomes highly absorbent. Dirt is not just attracted to the surface; it is absorbed into the center of the bead. Clothes are cleaned as the nylon beads are tumbled gently with the dampened garments. Nylon also is highly resilient, and can be re-used multiple times without losing its strength. The beads are collected at the end of the wash cycle and reused in subsequent cycles.

This technology option is still in a prototype stage. Savings are estimated to be approximately 15%, associated with machine energy (shorter cycle times). The small amount of cold water used per cycle results in 100% savings in water heating energy, and 100% savings in clothes dryer energy (clothes emerge only damp and will line dry quickly). Water savings of 90% are estimated. One remaining issue is how to mass produce and recycle the nylon beads efficiently [1].

The best-on-market residential clothes washers currently available are front-loading (corresponding to EL7 in DOE's analysis [2]). Design options that achieve this efficiency level include high capacity; high spin speed; water recirculation; internal water heating; improved sensors (temperature, flow level, *etc.*); and improved automatic controls. Front-loading washers are mechanically simple and do not require a gearbox (unlike top-loaders). Because the drum lies sideway, however, front-loaders require a tight seal around the door. The door must be locked shut throughout the wash cycle. The bellows assembly attached to the gasket around the door can collect dirt and moisture, which can encourage mildew growth. As a result, front-loaders require a regular freshening cycle.

Machine energy is a generally small compared to the water-heating energy, but addressing both can result in large savings. Given the different requirements of the wash and spin cycles, speed control is particularly important in washing machines. Variable-speed drives equipped with brushless DC permanent magnet motors could achieve savings greater than 30%, even in traditional machines [3], [4]. Coupling such savings with the water-related energy savings (low volume or low temperature) could result in highly efficient machines.

Our calculated energy-use values for residential clothes washers assume 295 operating cycles per year, 37% of households having electric water heating, and 59% of households having gas water heating [2].

References

[1] Xeros Ltd. http://www.xerosltd.com/index.htm

[2] DOE. (2010). Materials provided in support of stakeholder negotiations—residential clothes washers. http://www1.eere.energy.gov/buildings/appliance_standards/residential/clothes_washers.html

[3] Murray, A. (2006). "Appliance motors turn green." *Machine Design*. Dec. 14, p. 106–113. http://machinedesign.com/article/appliance-motors-turn-green-1214

[4] Biesen, E. (2006). "Motors and air-moving devices, continuously variable." *Appliance Magazine*. Oct. http://www.appliancemagazine.com/zones/supplier/18_motor_mfg/editorial.php?article=1561&zone=18&first=1

Clothes Washers (Large Commercial)

This product category includes the largest-capacity multi-load washers/washer extractors and tunnel washers. Specifically excluded from this category are single-load, coin-operated, residential-style clothes washers. Multi-load clothes washers have a capacity in the range of 35 to 900 pounds per load. After the wash cycle, water is extracted via a high-speed spin cycle that can produce hundred of gravitation forces (g's). This high-speed spin reduces the energy required for drying clothes. Multi-load washers and washer extractors are durable, high-volume, high-utilization equipment designed for large commercial environments [1].

Tunnel washers typically are found in large, usually off-premise laundry facilities that serve large commercial and industrial clients. Tunnel washers continuously move clothing through a series of compartments (usually via a screw-type mechanism), while water generally moves in a counter-flow. There is usually a press at the end to extract water from the clothing. Typical capacities range from 350 to 6,600 pounds per hour [1]. Tunnel washers are efficient for their capacity: water is used for more than one batch of clothing, reducing the energy used to heat the water. Thus one efficient design option is to switch, where possible, from many individual multi-load washers to a single tunnel washer.

The greatest potential energy savings for washers of all types comes from switching to a cold-water wash cycle, using either a specially designed detergent or an advanced ozone cleaning system. Utilizing a low-temperature wash can cut energy use dramatically (nearly 90% for commercial multi-load washers).

As for residential washers, another emerging technology involves nylon beads. Very little water is required to facilitate soil being transferred from the clothes to the beads. After a wash cycle completes, the beads are collected and reused, and clothes emerge virtually dry. The total potential energy savings, including the resultant dryer savings, are high [2]. There are concerns regarding the embedded energy of the nylon beads, as well as the fraction of used beads that will be recycled (after multiple washings). This technology is currently being tested by commercial facilities in Europe.

References

[1] Zogg, R., *et al.* (2009). *Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances*. Final report prepared for DOE's Building Technologies Program by Navigant Consulting, Inc. December. 446 p. http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf

[2] Xeros Ltd., developers of "virtually waterless" laundry cleaning. http://www.xerosltd.com/

Commercial Air-Cooled Unitary Air Conditioning and Heating Equipment

Commercial packaged air conditioning and heating equipment includes air-cooled, electrically operated, unitary central air conditioners and heat pumps for commercial applications. The equipment is classified as follows, based on cooling capacity in Btu/hour.

- *Very Small* (also known as commercial 3-phase central AC/HP): less than 65,000 Btu/hour
- *Small*: 65,000 to 135,000 Btu/hour
- *Large*: 135,000 to 240,000 Btu/hour
- *Very Large*: 240,000 to 760,000 Btu/hour

For very small equipment, this report assumes 1,000 hours per year of cooling at full capacity (or equivalent) and 2,000 hours per year of heating at full capacity (or equivalent). These values are consistent with the test procedure for residential heat pumps.

For the other sizes, this report assumes 2,000 hours per year of cooling at full capacity (or equivalent) and 1,000 hours per year of heating at full capacity (or equivalent). These values are consistent with average national cooling and heating hours in commercial spaces [1]. These estimated hours take into account the higher cooling loads in larger commercial settings.

For the very small units energy efficiency ratios (EERs) were converted to SEER and HSPF by extrapolating the relationship established for residential heat pumps [2]. Summarized below are the best-on-market air-cooled AC and HP units on the market in early 2010, according to the Air-Conditioning, Heating, and Refrigeration Institute [3]. The technologies utilized usually include (but are not limited to) some combination of: variable-speed compressors or optimized compressors for a given capacity, efficient variable-speed blowers and fans, improved heat exchangers (*e.g.*, brazed plate and micro-channel), and optimized refrigerants. Variable-speed compressors and fans allow for smoother, quieter operation and improved lifetime thanks to reduced on-off cycling and softer starts. The max tech in VSD technology uses brushless DC permanent magnet motors. Very small air conditioning and heating equipment

Air Conditioners

SEER	Capacity (Btu/hr)	Manufacturer
17.25	35,600 – 37,000	Lennox
17.00	35,000 – 60,000	Lennox

This report assumes that a SEER of 17.0 is a reasonable estimate of the best-on-market products in this category. The current minimum standard is 13 SEER.

Heat Pumps

SEER/HSPF	Capacity (Btu/hr)	Manufacturer
16.4 / 9.0	36,000 / 34,000	Trane, American Standard
16.0 / 9.0	47,500 / 44,500	Trane, American Standard
15.2 / 8.6	57,000 / 55,000	Trane, American Standard

This report assumes that a SEER of 16.0 and HSPF of 9.0 are reasonable estimates of the best-on-market products in this category. The current minimum standards are 13 SEER and 7.7 HSPF.

Small air conditioning and heating equipment

Air Conditioners

EER (no heating/with heating)	Capacity (Btu/hr)	Manufacturer
13.9/13.8	106,000	AAON
13.3/13.2	105,000	AAON
13.0/13.0	89,000	Trane, American Standard
12.8/12.7	128,000	AAON

This report assumes that an EER of 13.0 is a reasonable estimate of the best-on-market products in the category. The current minimum standard is 11.2 EER (with no integrated heating).

Heat Pumps

EER/COP*	Capacity (Btu/hr)	Manufacturer
11.5 / 3.4	90,000 and 120,000	Lennox, Goodman
11.4 / 3.5	75,000 / 71,000	Trane, American Standard
11.2 / 3.3	87,000 / 86,000 and 98,000 / 94,000	various

* COP = coefficient of performance, used for heat pumps, is the ratio of heat output to the high temperature reservoir divided by work input

This report assumes that an EER of 11.4 and a COP of 3.4 are reasonable estimates of the best-on-market products in this category. The current minimum standards are 11.0 EER (with no integrated heating) and 3.3 COP.

Large air conditioning and heating equipment

Air Conditioners

EER (no heating/with heating)	Capacity (Btu/hr)	Manufacturer
12.8/12.6	236,000	Lennox
12.7	194,000	Aaon
12.5	212,000	Aaon
12.4	178,000	various

This report assumes that an EER of 12.7 is a reasonable estimate of the best-on-market products in this category. The current minimum standard is 11.0 EER (with no integrated heating).

Heat Pumps

EER/COP	Capacity (Btu/hr)	Manufacturer
11.0 / 3.3	182,000 / 192,000	various
11.0 / 3.2	146,000 – 176,000	various

This report assumes that an EER of 11.0 and COP of 3.3 are reasonable estimates of the best-on-market products in this category. The current minimum standards are 10.6 EER (with no integrated heating) and 3.2 COP.

Very large air conditioning and heating equipment

Air Conditioners

EER (no heating/with heating)	Capacity (Btu/hr)	Manufacturer
12.0	248,000	Lennox
11.7	248,000	Lennox
11.5	240,000	various

This report assumes that an EER of 11.7 is a reasonable estimate of the best-on-market products in this category. The current minimum standard is 10.0 EER (with no integrated heating).

Other Advanced Technologies

Evaporative coolers are extremely efficient cooling technology. While early models were restricted to moderate, dry climates, advanced evaporative-cooler technologies (indirect, and indirect-direct) facilitate better performance over more of the country. Utilizing the Maisotsenko cycle, indirect evaporative coolers can provide approximately 80% energy savings compared to standard vapor-compression air conditioners. Indirect evaporative coolers add no moisture to the air (unlike direct evaporative coolers), because the cooled moist-air never comes in direct contact with the indoor environment. Rather, the ‘coolth’ is transferred to an indoor air stream through a heat exchanger. An example of this technology is the Coolerado air conditioner [4]. Indirect-direct (aka two-stage evaporative coolers) has similar advantages, but still optimally operates in hot dry climates like Phoenix and Las Vegas.

To operate in more humid environments advanced evaporative coolers can be desiccant enhanced or combined with a vapor compression cycle. For example, the liquid desiccant air conditioner (LDAC) can achieve large savings in commercial applications. As in the residential application, liquid desiccants are used to dehumidify air in preparation for latent cooling via evaporation (perhaps with a standard vapor-compression boost). Heat needed to regenerate the desiccant can be obtained from any sources: waste heat, combined heat and power systems, solar energy, or conventional fossil sources. This technology has the potential to save 60% to 70% of the energy used by traditional vapor-compression systems, though some technical issues remain [5].

Active chilled-beam systems are commercial AC systems that run chilled water, instead of chilled air, throughout a commercial building. The chilled water can provide radiant cooling, or can be used with a forced-air heat exchanger at the point of end-use. Because water has a much higher heat capacity, by both mass and volume, than does air, distributing chilled water instead of air saves energy. Additionally, the floor-to-floor heights required to contain a chilled water system are shorter than for an air system. Fan energy is replaced with pump energy, which is approximately a factor of seven lower (for an equivalent distribution of cooling capacity). Overall system energy is reduced by 15% to 20% [6].

Commercial ground-source heat pumps are an established technology that offers high savings potential (approximately 60%), but requires high initial costs that may scare away building owners. The cost-effectiveness of ground-source heat pumps is generally better than solar PV systems, however, and PV systems have an appreciable penetration in commercial buildings. Modern one-pipe loop designs for ground-source HPs are simpler to install and maintain than older ones [7]. Many commercial and high-rise buildings in the developing world (in particular China and India) have ground-source heat pumps.

Multi-split variable refrigerant flow (VRF) systems are technically not unitary systems, but they provide an important alternative to unitary systems and thus the discussion is included here.

Multi-split systems include a centralized outdoor unit, refrigerant piping throughout the building, and indoor units in multiple rooms or zones (systems can also be designed to provide heating). The main advantages of such a system include no ductwork throughout the building, individualized control for optimum user comfort, and the ability to address buildings with mixed loads or thermal zones. Such systems are especially useful in multi-storey buildings and in retrofits, avoiding long duct runs. Multi-split systems have been used in Asia for some time now, and are only recently gaining favor in the U.S. The savings potential of such systems over comparable constant-volume ducted systems is 30-40%, although a direct comparison of efficiency metrics isn’t yet possible due to the VRF capability to simultaneously heat and cool [8], [9].

Most of the equipment described above can benefit from a simple measure known as evaporative pre-cooling. Prior to contact with the evaporator of a traditional vapor-compression cycle, outside air can go through a brief evaporative cooling section to pre-cool the air. Excess humidity introduced by evaporative pre-cooling is condensed out during contact with the evaporator coil. This improves the system efficiency of the vapor-compression system (by reducing the thermal gradient) without adding excess moisture. Savings are significant, deployable at large scale, and achievable at very low cost [10].

References

[1] Somasundaram, S., *et al.* (2000). *Screening Analysis for EPACT-Covered Commercial HVAC and Water-Heating Equipment*. Prepared by Pacific Northwest National Laboratory for DOE. Report PNNL-13232. April. http://www.pnl.gov/main/publications/external/technical_reports/PNNL-13232.pdf

[2] DOE. Commercial Unitary Air Conditioners and Heat Pumps. Ongoing rulemaking. http://www1.eere.energy.gov/buildings/appliance_standards/commercial/cuac_draft_analysis.html

[3] Air-Conditioning, Heating, and Refrigeration Institute. http://www.ahrinet.org/

[4] Website for Coolerado Corporation: http://www.coolerado.com/

[5] American Council for an Energy-Efficient Economy (ACEEE). (2009). *Emerging Technologies Report: Liquid Desiccant Air Conditioner.* June. 4 p. http://old.aceee.org/emertech/2009_LiqDesiccant.pdf

[6] ACEEE. (2009). *Emerging Technologies Report: Active Chilled Beam with DOAS.* August. 7 p. http://old.aceee.org/emertech/2009_ChillBeam.pdf

[7] ACEEE. (2009). *Emerging Technologies Report: Commercial Ground-Source Heat Pumps—One-Pipe Loops.* August. 5 p. http://old.aceee.org/emertech/2009_CommGSHP.pdf

[8] Heschong Mahone Group, Inc. (2011). Private communication.

[9] Shen, B., and Vineyard, E. (2011). Private communication.

[10] Shen, B. et al. (2010). *Direct Evaporative Precooling Model and Analysis*. In preparation.

Commercial Food Equipment

Commercial food equipment typically is found in restaurants, institutions, and similar venues. Equipment includes ovens, ranges, griddles, broilers, fryers, steamers, and soft drink dispensers. Except for soft drink dispensers, all equipment can use either electricity or natural gas, with natural-gas units being more common.

The energy use and savings potential of all commercial food equipment except soft drink dispensers is well characterized by several studies (*e.g.*, [1], [2]). The savings potential stems largely from: infrared burners, power burners, pulse combustion, increased insulation, electric ignition, heat pipe or induction griddles, reduced idle energy consumption, and connectionless steamers [1], technologies that already are used in some models. Connectionless steamers also achieve 90% water savings, since water is reused in the system.

Energy use for soft drink dispensers was estimated based on manufacturer specifications. Savings potential is assumed to be 30%, largely from improvements to the compressor and refrigeration components. A thorough technical study on soft drink dispensers is needed.

References

[1] Zogg, R., *et al.* (2009). *Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances*. Final report prepared for DOE's Building Technologies Program by Navigant Consulting, Inc. December. 446 p. http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf

[2] Fisher, D., *et al.* (2002). *Commercial Cooking Appliance Technology Assessment*. Prepared for Enbridge Gas Distribution and Pacific Gas and Electric Company by Fisher-Nickel, Inc. FSTC Report No. 5011.02.26. http://www.fishnick.com/equipment/techassessment/Appliance_Tech_Assessment.pdf

Computing & Office Equipment

This product category includes personal computers, servers, printers, multifunction devices, FAX machines, scanners, and uninterruptable power supplies, the energy use and savings potential of which has been characterized or summarized in several reports (*e.g.*, [1], [2], [3]).

Ignoring the potential energy savings from computer displays, which are addressed in the section on televisions, most of the energy-saving potential for this category lies in proper power management, both of operating modes (*e.g.*, automatically enabled sleep settings, network proxying protocols) and of the computer microchips (consolidating activity in high-use circuits and isolating and shutting down blocks of circuits that are not needed).. A recent example of a system on a chip (SoC) targeted for handheld devices such as smartphones uses 19 different controlled power domains to optimize power consumption. Adding the isolation and control circuits reduced the chip standby power by 50x compared to the previous generation SoC. Active power was reduced as well, by a factor of 2.4x for web browsing and 3.0x for displaying video [4]. Strategies to manage power states are described below, but can also include simple measures such as using master/slave connections (*e.g.*, plugging a monitor's power cord directly into a desktop computer, which can turn off the monitor as the computer goes to sleep/off). Other general strategies applicable to multiple devices include occupancy sensors that can control the power state of the device.

Advanced disk drives and power supplies can further increase savings. Solid state drives, which are beginning to be incorporated in some laptop computers, can cut disk energy use significantly compared to standard mechanical drives, because they have no moving parts. OCZ Enterprise claims overall disk energy savings of 99% [5]. Samsung claims power savings of 70% in active mode and 83% in idle mode for data center applications. Solid state drives also increase disk speed and reduce weight. Thanks to modern switching technology in switch-mode models, power supplies already have high efficiencies (approaching 90%). Additional advances might increase that efficiency by another 5%.

There is a high per-unit energy-saving potential for low-utilization equipment such as personal computers and smaller-volume printers. In addition to power management, desktop computers could incorporate the ultra-efficient components typically found in laptop computers. The best-on-market laptops achieve ENERGY STAR 5.0 rating and consume 52 kWh/year (residential use) and 22 kWh/year (commercial use) [1], [2]. Because of the built-in incentive to maximize battery life, laptop computers already are so efficient component-wise they offer little in potential savings beyond power management.

For networked servers, virtualization allows more efficient utilization, reducing the number of units needed. Virtualization can reduce electricity consumption of servers in one location by 70%. There are challenges in virtualizing data centers, such as inadequate bandwidth in the legacy power circuit and reduced redundancy in computing capability. Server virtualization is an acceptable strategy for approximately 80% of the market [2].

For large, multifunction devices and other high-volume office equipment that utilizes laser printing technology, the primary savings potential comes from managing the fuser roller temperature of the laser imaging device (using both lower temperatures and allowing fast warm-up from sleep). Using an advanced toner that works at lower temperatures can reduce energy consumption by 30%. This report assumes a 30% potential for most office equipment, unless power management provides a greater potential [2].

Uninterruptable power supplies (UPSs) can be improved be eliminating the double-conversion design of individual UPSs, which involves higher losses due to multiple conversions, and by moving toward a decentralized UPS system design [2]. Decentralized systems operate at a more optimum load factor, in that some UPSs can be turned off when not needed, and reduce losses attributable to over-sizing.

References

[1] Roth, K., *et al.* (2007). *Residential Miscellaneous Electric Loads: Energy Consumption Characterization and Energy Savings Potential*. Prepared for DOE's Building Technologies Program by TIAX LLC. TIAX reference no. D0370. July. 197 p. http://www.iepec.org/TIAX_MiscElecLoadsReportToDOE.pdf

[2] Zogg, R., *et al.* (2009). *Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances*. Prepared for DOE's Building Technologies Program by Navigant Consulting, Inc. December. 446 p. http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf

[3] Peters, J., *et al.* (2010). *Electronics and Energy Efficiency: A Plug Load Characterization Study*. Final report prepared for Southern California Edison by Research Into Action, Inc. SCE0284. January. 254 p. http://www.calmac.org/publications/BCE_FINAL.pdf

[4] Islam, R., *et al.* (2010). *Power Reduction Schemes in Next Generation Intel® ATOM™ Processor Based SoC for Handheld Applications.* Proceedings of the 2010 IEEE Symposium on VLSI Circuits, June.

[5] OCZ Enterprise. (no date). *OCZ SSDs and Energy Efficiency*. White paper on green computing. 2 p. http://www.oczenterprise.com/whitepapers/ssds-and-energy-efficiency.pdf

Consumer Electronic Products

Consumer electronic products encompass an array of items, including compact (shelf) audio systems, component audio systems, clock radios, home theater systems, DVD/Blu-ray players, and video game consoles. Televisions, set-top boxes, computers, and network equipment, frequently considered consumer electronics, are addressed here separately because of their complexity. The energy use and saving potential of consumer electronic products have been characterized (or summarized) in several important reports (*e.g.*, [1], [2], [3], [4]). The annual energy use of the above product classes is reasonably well determined, with the exception of video game consoles.

Although estimates of the energy-saving potential of video game consoles differ significantly because of large uncertainties in gamer behavior, the potential energy savings may rival that of TVs and computers. Specifically, data are lacking on the amount of time that consoles are left on when not in use. Video game consoles generally do not include power management features, resulting in significant energy consumption. There is an incentive to leave game consoles on, because the status of the game cannot be saved easily if the device is turned off. The results in Table 3 of this report assume that 20% of video game users (heavy users) leave their consoles on for an additional 2,000 hrs/yr beyond active playing time (a far more conservative estimate than some others provide [2]). For video game consoles, this report assumes a 3-hour power-down feature (present on best-on-market consoles) significantly reduces non-playing idle time [2]. Assuming that 10% of gamers leave their consoles on 24 hours a day and the rest shut them off immediately after use, a 1-hour shutoff after inactivity would provide an estimated energy savings of 27% averaged over all game consoles. It is important to stress that the amount of energy saved with a power-down feature depends highly on the average gamer's behavior, about which there are little definitive data. Further study is necessary to properly characterize the energy use of video games.

In addition, there is a wide range of power consumption among consoles, depending on the level of graphics processing. For example, the Wii typically consumes less than 20 W, whereas the PlayStation 3 can average 150 W. The two consoles provide different game play emphasis, however, so their energy use cannot be compared simply [2].

For all product classes of consumer electronics except video game consoles, the savings potential was determined by comparing the best-in-class devices to the average energy use [1]. Compared to video game consoles and the televisions, set-top boxes, computers, and network equipment that are discussed separately, savings potentials for consumer electronic are small. Product lifetime is assumed to be 7 years for audio/video products, and 5 years for video game consoles [2].

References

[1] Roth, K., *et al.* (2007). *Residential Miscellaneous Electric Loads: Energy Consumption Characterization and Energy Savings Potential*. Prepared for DOE's Building Technologies Program by TIAX LLC. TIAX reference no. D0370. July. 197 p. http://www.iepec.org/TIAX_MiscElecLoadsReportToDOE.pdf

[2] Horowitz, N., *et al.* (2008). *Lowering the Cost of Play: Improving the Energy Efficiency of Video Game Consoles*. Natural Resources Defense Council (NRDC) and Ecos Consulting. NRDC issue paper. November. 29 p. http://www.nrdc.org/energy/consoles/files/consoles.pdf

[3] Peters, J., *et al.* (2010). *Electronics and Energy Efficiency: A Plug Load Characterization Study*. Final report prepared for Southern California Edison by Research Into Action, Inc. SCE0284. January. 254 p. http://www.calmac.org/publications/BCE_FINAL.pdf

[4] The Nielsen Company (2007). *The State of the Console: Video Game Console Usage, Fourth Quarter 2006*. Nielsen Wireless and Interactive Services. http://dataforbreakfast.com/wp-content/uploads/2007/08/nielsen_report_state_console_03507.pdf

Cooktops/Ranges (Residential Electric)

Typical residential electric cooktops are about 70% to 75% efficient in terms of converting electricity into useful heat for cooking. The rest is lost mostly to heating the kitchen air. Advances in the design of electric cooktops maximize the contact between the cooktop and a pot or pan and minimize losses to the air. Nevertheless, substantial losses remain.

The more efficient induction cooking technology, although not a new concept, has seen little market penetration. Induction cooktops utilize rapidly oscillating magnetic fields that induce miniature electric currents in a pot (with corresponding electric resistance heating). Other magnetic losses in the pot generate additional heat. In its 1993 TSD [1] DOE estimated that induction cooktops can achieve an 85% efficiency (a 10% to 15% improvement). However, in the 2009 Final Rule for Residential Dishwashers, Dehumidifiers, and Cooking Products, and Commercial Clothes Washers [2] inductions cookers were screened out from further consideration because there was no verified test procedure available. Although the market share is small, there are many models on the market, both commercial and residential, including models produced by Whirlpool, Frigidaire, and Electrolux [2].

Advantages of induction cooktops include instantaneous adjustment of the cooking heat (comparable to cooking with natural gas), rapid boiling of water, safety (no open flame and no hot element), and increased flexibility in terms of pot/pan shape. Current disadvantages include the inability to use non-ferrous cookware (such as copper or aluminum) or curved cookware, although effort is being made to address those limitations. Currently, a special induction disk may be used as a heating element for non-ferrous cookware [2].

References

[1] DOE. (1993). Technical Support Document Energy Conservation Standards for Consumer Products Cooking Products

[2] DOE. (2009) Technical Support Document for the Final Rule for Residential Dishwashers, Dehumidifiers, and Cooking Products, and Commercial Clothes Washers, Chapter 5, Engineering Analysis. http://www1.eere.energy.gov/buildings/appliance_standards/residential/cooking_products.html

[3] theinductionsite.com. *Induction Cooking Pros and Cons*. http://theinductionsite.com/proandcon.shtml.

Dishwashers (Residential)

Recent, advanced dishwashers from Bosch and Siemens use zeolithic drying to improve efficiency [1]. During the dish-drying stage, air is circulated through a chamber containing zeolithic particles. Zeoliths are compounds that release heat as they absorb moisture, and require heat to release the moisture. Dishwashers that incorporate a compartment containing aluminum silicate zeolithic compounds (approximately 1 kilogram) can reduce energy and drying times. After the wash/rinse cycles, the humid air is dried rapidly and heated without electricity. The trapped moisture is released when the zeolite is heated at the beginning of the next wash cycle. Because the released moisture contributes to the water needed for washing, and part of the energy used for this purpose is recaptured during the drying cycle, there is a net energy (and water) savings. Siemens claims that the zeolithic drying system reduces electricity consumption by 20% compared to "conventional models from [Europe's] highest energy efficiency category".

As with many other appliances, dishwashers are starting to incorporate variable-speed drives and brushless DC permanent magnet motors to improve energy efficiency [2]. The Turkish manufacture Arçelik and the Swedish manufacture Electrolux began incorporating this technology around 2004 [3].

References

[1] Siemens.
http://www.siemens.com/innovation/en/publications/publications_pof/pof_spring_2010/zeolith.htm

[2] Murray, A. (2006). "Appliance motors turn green." *Machine Design*. Dec 14, p. 106 – 113.
http://machinedesign.com/article/appliance-motors-turn-green-1214

[3] Russell, J. (2004). "Pumping technology into new products." *Appliance Magazine*. Oct.
http://www.appliancemagazine.com/editorial.php?article=607&zone=1&first=1

Distribution Transformers

Distribution transformers include dry-type and liquid-immersed units. In 2007 DOE adopted Federal standards for most transformers through its usual rulemaking process. But for low-voltage, dry-type transformers, the most current standard comes from EPACT 2005. This report uses the values for high-efficiency units contained in the engineering analysis for the 2007 transformer rulemaking.

Based on a 2007 DOE Technical Support Document , the following energy-loss levels are achieved by the liquid-immersed and dry-type transformers (of average capacity with a standard load) [1]:

	Liquid-immersed	**Dry-type**
In stock	1,700 kWh/yr	6,300 kWh/yr
New shipments	1,450 kWh/yr	3,250 kWh/yr
Best on market	1,150 kWh/yr	2,400 kWh/yr
Max Tech	560 kWh/yr	1,700 kWh/yr

Potential future technologies include an amorphous metal core, hexaformer geometry, and intelligent control systems. Amorphous core materials have the potential to pass the efficiency of the max-tech level for liquid-immersed transformers to stacked-core dry-type transformers. This design option was screened out of DOE's 2007 standards analysis. The extent to which the option would improve efficiency (rather than simply changing the economics of efficiency) is unknown.

Hexaformer distribution transformers utilize an atypical geometry that can reduce losses by 30% (consistent with the annual energy consumption values for the above "best-on-market" case) [2]. Coupling hexaformer transformers with an intelligent control system, and replacing a single large transformer with several smaller ones, can reduce losses by approximately 50%. Most single transformers operate at low average loads (about 20% of capacity), even though transformers are tested at 35% load and perform more efficiently at high loads. Utilizing smaller transformers and a control system, an individual transformer can be operated at a higher percentage of rated capacity for the same load, and if the load spikes, the control system can engage additional transformers. Warner Power recently developed such a product, consisting of three small transformers coupled with a control system, called SmarTran [3]. SmarTran, which can be used on existing substations, has less noise, lower weight, lower in-rush energy, and smaller volume than traditional transformers.

References

[1] DOE. (2007). *Technical Support Document: Energy Efficiency Program for Commercial and Industrial Equipment: Electrical Distribution Transformers*. Prepared for DOE's Building Technologies Program by LBNL and Navigant Consulting, Inc. September. http://www1.eere.energy.gov/buildings/appliance_standards/commercial/distribution_transformers_fr_tsd.html

[2] Hexaformer. http://www.hexaformer.com/Home.htm

[3] SmarTran. http://www.warnerpower.com/pdf/SmarTran%20Sept%202010.pdf

Furnaces (Residential)

Residential furnaces typically provide space heating through the combustion of natural gas, which heats air passing through the furnace. Airflow is produced via a furnace fan. Combustion gases are vented out of the house. For this report, only non-weatherized residential furnaces (excluding mobile home furnaces) are considered. The current minimum annual fuel-utilization efficiency (AFUE) for gas furnaces is 78%, which in 2015 will increase to 80%. ENERGY STAR-qualified residential gas furnaces currently must have an AFUE of 90% or greater. Given that current shipments are roughly 60% at 80 AFUE and 40% at 92 AFUE, this report assumes that on average new shipments have 84 AFUE. In the best-on-market units, called condensing furnaces, heat from the combustion waste gases is recovered and the water vapor condenses. The best condensing furnaces provide 98% AFUE and incorporate fully modulating furnace fans [1].

References

[1] DOE. (2007). *Residential Furnaces and Boilers Final Rule Technical Support Document.* Prepared for DOE's Building Technologies Program by LBNL and Navigant Consulting, Inc. September. http://www1.eere.energy.gov/buildings/appliance_standards/residential/fb_tsd_0907.html

Illuminated Exit Signs

An illuminated exit sign, which is mounted permanently, is an internally lit sign designed to identify the exit of a building. EPAct 2005 adopted ENERGY STAR version 2.0 standards as minimum standards for illuminated exit signs, effective for all signs manufactured on or after January 1, 2006 [1]. The definition adopted includes only signs bearing the legend "EXIT," plus any directional indicators. The standard requires an input power of 5 W or less per illuminated face, which effectively phased out incandescent bulbs in favor of light-emitting diodes (LEDs). Once EPAct mandated the ENERGY STAR 2.0 standards, there was no reason for ENERGY STAR to recommend the same minimum, so the ENERGY STAR specification for illuminated exit signs was suspended effective May 1, 2008.

In 2002, LED exit signs comprised 80% of the market, those using compact fluorescent lightbulbs (CFLs) 15%, and those using incandescent bulbs 5% [2]. Because the conversion to LED exit signs progressed rapidly, it is reasonable to assume that virtually all exit signs today are LED. Average units consume 6 W, for a total consumption of 52.6 kWh/yr [2]. Some newer best-on-market units consume 2 to 4 W (depending on LED color), for a total consumption of 17.5 to 35 kWh/yr. This report assumes 26.3 kWh/yr. Premium, highly efficient designs (including edge-lit LED exit signs) consume only 1 W, equivalent to 8.8 kWh/yr.

Max tech technologies include electroluminescent exit signs, sometimes referred to as light-emitting capacitor (LEC) exit signs, that consume less than 0.2 W, equivalent to 1.8 kWh/yr. Both photoluminescent and tritium-based exit signs consume no power and require no electrical supply. Both types of signs meet or exceed National Fire Protection Association and Underwriters Laboratories 924 standards for luminance. Tritium-base exit signs pose no health risk, because the small radiation level cannot escape the glass and metal housing. If the exit sign were to break, the tritium would disperse quickly to levels equal to naturally occurring tritium. This report assumes a max tech level that is an average between non-electrical and LEC exit signs, equivalent to 0.9 kWh/yr.

References

[1] EPA. (no date). ENERGY STAR program requirements for exit signs: eligibility criteria. Version 3.0. http://www.energystar.gov/ia/partners/product_specs/eligibility/exit_signs_elig.pdf

[2] DOE. (2008). *Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications*. Prepared for DOE's Building Technologies Program by Navigant Consulting, Inc. September. 116 p. http://management.energy.gov/documents/Energy_Savings_Light_Emitting_Diodes_Niche_Lighting_Apps.pdf

Lighting

Lighting offers enormous energy-savings potential. While lighting standards have tended to focus on the efficiency of lighting components (lamps and ballasts), this report considers savings that can be obtained from all components that are together included in lighting systems. Some improvements represent extensions of technologies that have been on the market for decades, such as improvements in fluorescent and high-intensity discharge (HID) technologies. Others represent radical departures, such as integrated lamp/light-pipe systems and photovoltaic (PV)-assisted lighting systems that use the DC output of the PV system directly. All lighting applications are discussed here, including residential, commercial, industrial, and street lighting.

The commercial sector offers large savings potentials from replacing old inefficient T12 fluorescent tubes with highly efficient T5 or T8 tubes; high-efficiency fixtures (*e.g.*, reflective coatings, low obscuration); and sensors/controls that provide dimming, multi-level lighting, and/or on-off capabilities. Similar technologies can be used in the residential sector, where incandescent bulbs also can be replaced with compact fluorescent bulbs, with LEDs being a likely future replacement. The California Lighting Technology Center estimates that sensors and controls have the potential to save, on their own without changing the bulb technology, approximately 20% (residential), 50% (commercial), and 20% (industrial—parking lot/garage lamps only). In the commercial and industrial sectors, most of the savings would derive from dimming lights to 50% or lower when no one is present (a large part of the operating day).

High-intensity discharge (HID) and low-pressure sodium (LPS) lamps are used in large-scale commercial, industrial, and street-lighting applications. LPS lamps have much higher efficacies (approximately 200 lumens per watt [lm/W]) and better lumen maintenance than current HID lamps. Unfortunately, their poor light quality (essentially monochromatic yellow) compared to HID lamps limits their market share to applications where light quality is not an issue. Therefore, although LPS should be considered the max tech in lighting, it has little potential to displace HID lamps, which are used specifically because they render better quality light that allows color differentiation.

There are three primary categories of HID lamps. From highest to lowest efficacy they are: high-pressure sodium (HPS, 120 to 130 lm/W); metal halide (MH, 75 to 125 lm/W); and mercury vapor (MV, 25 to 60 lm/W). Whereas the efficacies of MV and HPS lamps have been relatively static for the past several decades, the efficacies of MH technologies have been improving consistently. MH efficiencies now approach those of HPS lamps, and continue to increase, while providing vastly superior light quality. Given the broad applicability of HID technology (with wattages ranging from 20 to 1,000), MH lamps are widely anticipated to take over the HID market. Among MH lamps, probe-start lamps are common in the installed base, but they are 15% less efficient than pulse-start lamps (commonly used in new shipments), which in turn are 21% less efficient than the highest-efficiency units available.

Ceramic MH lamps are considered the next-generation white-light HID lamp, anticipated to provide efficacies of 150 lm/W within 5 years. Philips introduced the unsaturated ceramic MH lamp, which offers improved efficiency, dimmability without color shift, faster run-up to full brightness, mercury free design, and longer lifetime. The lamps achieve 120 lm/W (initial), and manufacturers estimate that their performance can be improved to 150 lm/W within 5 years. Improvements in MH lamp technology are likely to be well received and mass produced.

High-efficiency plasma lamps can replace the HID lamps typically used for indoor high-bay lighting. High-efficiency plasma lamps use microwave frequency generators to ignite plasma in a compact, transparent bulb. The design incorporates a small, highly efficient 90 lm/W bulb, lumen maintenance of 90%, real-time dimming to 20%, hot re-strike capability, and flexible dose chemistry (*i.e.*, flexible output spectrum) [1]. Other similar electrodeless lamps, such as induction lamps, are being developed. Once designs are optimized, electrodeless lamps have the potential to achieve staggering efficiencies of 200 lm/W.

Although LEDs are just emerging on the market for ambient lighting, they are improving rapidly, and many prototypes achieve high efficiencies. Cree, Inc., has developed technology to achieve 160+ lm/W with a blue LED, and 100+ lm/W with a warm white (3000 Kelvin) LED [2]. Unfortunately, to date these achievements are typically for ideal conditions—field performance is usually lower. Nevertheless, the efficiencies and colors of LEDs are rapidly surpassing those of fluorescent lamps, and soon will surpass other lighting technologies as well. Philips recently unveiled their EnduraLED bulb, a replacement for standard 60-W incandescent bulbs. The EnduraLED bulb achieves 67 lm/W (equal to or surpassing the best CFLs), provides excellent color rendering, and is fully dimmable (unlike CFLs). Philips has extended their EnduraLED line to include various lamp types for a range of applications.

The light output from LEDs can be made more attractive with the aid of quantum dots. Quantum dots are nearly perfect absorbers and emitters of light that provide a highly tunable output spectrum. This feature enables the creation of a color filter involving almost no losses that can turn harsh blue-white light from a typical LED into a warm light that closely resembles an incandescent source. Because blue-white LEDs are more efficient, this setup yields the highest efficiency and maintains the warm light important to consumers. QD Vision company produces such quantum dot filters [3].

Several municipalities have pilot programs to evaluate the effectiveness of LED street lights. LED street lights offer increased bulb lifetime (and thus reduced maintenance costs), precise directionality, and improved color rendering over the ubiquitous high-pressure sodium lamp. In terms of lumens per watt, current LEDs are inferior to HPS. Because of the LEDs' improved color rendering, however, lower absolute light levels may achieve satisfactory illumination (based on anecdotal evidence). Thus, even though LEDs are less efficient, lower absolute wattage lamps can be installed to provide the perceived service [4]. The savings potential of street lights requires further study.

Finally, improvements in traditional fluorescent technology are still possible, although research incentives are minimal. Manufacturers estimate that a further 15% reduction in energy use in standard fluorescent lamps is possible because of advanced phosphors, fill gas, cathode coatings, and UV-reflective glass coatings. Given the enormous installed base of fluorescent fixtures, the importance of increased efficiency in those lamps cannot be overstated.

Two technologies bear mention in terms of radical low-carbon departures from conventional lighting. First, EPA is supporting development of a lighting system that integrates daylighting, electric lighting, and lighting controls into a light-pipe system (under development at Texas A&M) [5]. Additionally, photovoltaic (PV) integrated direct-DC lighting technologies are entering the commercial market, including Nextek Power Systems' 24-volt (V) DC lighting system [6]. The product integrates with the

Armstrong's 24-V ceiling system [7], which was designed to meet the EMerge Alliance 24-V standard [8]. DC electricity from the PV system is fed into the bus that integrates into the framework of suspended commercial ceilings, avoiding the losses inherent in converting power from DC to AC (for distribution within the building) and back to DC for use with fluorescent or LED lighting. This system fits well in commercial applications, where loads are closer to the solar peak than are residential loads; rectified AC power is used when needed.

References

[1] Ceravision. http://www.ceravision.com/Page/Home

[2] Cree, Inc. http://www.cree.com/

[3] QD Vision. http://www.qdvision.com/

[4] City of Raleigh, North Carolina. (2009). LED Street Lighting Test Project Report. April. 3 p. http://progress-energy.com/custservice/shared/LEDStreetLightTestProjectReport.pdf

[5] National Center for Environmental Research. http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/8994/report/0

[6] Nextek Power Systems. http://www.nextekpower.com/applications/high-efficiency-dc-lighting

[7] Armstrong Commercial Ceilings and Walls. DC Frexzone Grid. http://www.armstrong.com/commceilingsna/article55189.html

[8] EMerge Alliance Standard Overview. http://www.emergealliance.org/en/standard/index.asp

Motors

Almost one motor lifetime has passed since the EPAct 1992 standards for electric motors first went into effect, with considerable focus by DOE since [1], [2], [3]. EISA 2007 prescribed new standards for medium sized electric motors (1 – 200 HP)[4]. As of January 1, 2010, standards mandate NEMA Premium efficiency single-speed, polyphase, continuous-duty, induction motors of squirrel-cage design that are 600 volts or less [4]. The standards specify required minimum full-load efficiencies (efficiencies at partial load, which can be much lower than at full load are not addressed). The standard levels increase with motor size, as shown in the figures below, and are set separately for open and enclosed motors, and 2-, 4-, and 6-pole motors. Although the market still advertises NEMA Premium as the superior product, there are rebate programs for motors that exceed NEMA Premium efficiency by 1 percentage point. This report assumes an efficiency of 90% for new shipments for the average medium-sized motor, corresponding. For larger motors, efficiencies can be pushed well beyond 90%.

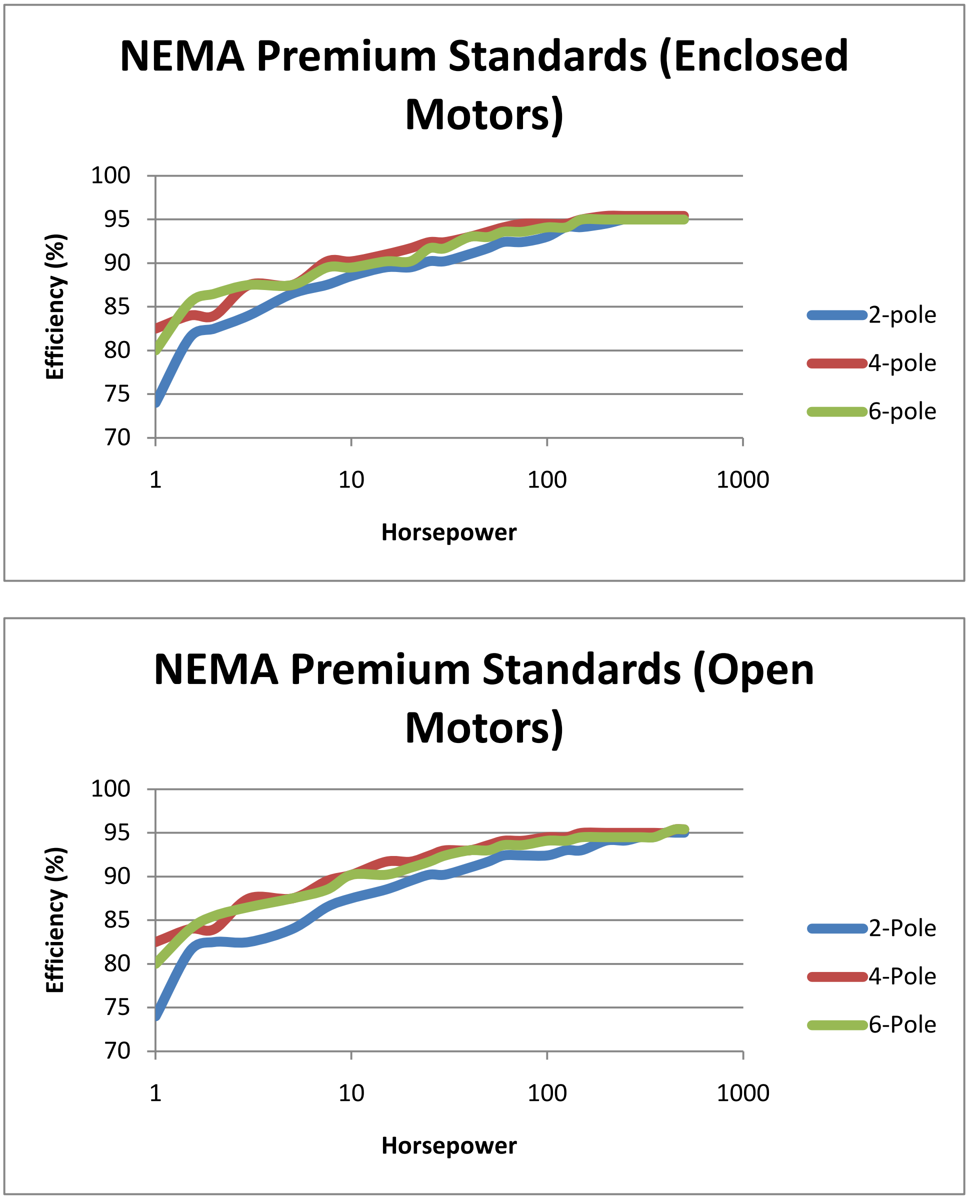

Figure 1. Efficiencies for NEMA Premium motors, both enclosed and open.

Similarly, energy efficiency standards were released for small electric motors (0.25 – 3 HP) in March 2010 [5]. As with medium size motors, the minimum required efficiency levels vary by motor size, design, and number of poles, with values ranging from 62.2% for a 0.25HP capacitor-start, induction run and capacitor-start capacitor-run motor to 86.9% for a four-pole polyphase motor.

Although single-speed induction motors dominate the market, brushless DC permanent magnet (BDCPM) motors are the best-on-market motors. The permanent magnet rotor in these motors avoids the rotor magnetization losses inherent in standard induction motors and to a lesser extent in variable reluctance motors. Low heat losses also can lower cooling energy needs, producing secondary energy savings. In addition, BDCPM motors are more compact. For example, a recent study found that the materials needed to build an efficient axial permanent magnet motor were 45% less than those needed to build the same-capacity standard induction motor. The savings in copper and steel more than offset the higher cost of the permanent magnet material [6] (although rare earth metals are potentially supply constrained and therefore vulnerable to large price fluctuations). As shown in Figure 2, the savings from BDCPM motors compared to average new (induction) motors depends on motor size, being particularly large in small motors. In addition, brushless DC permanent magnet motors do not have as sharp a drop-off in efficiency at low loads as do standard motors.

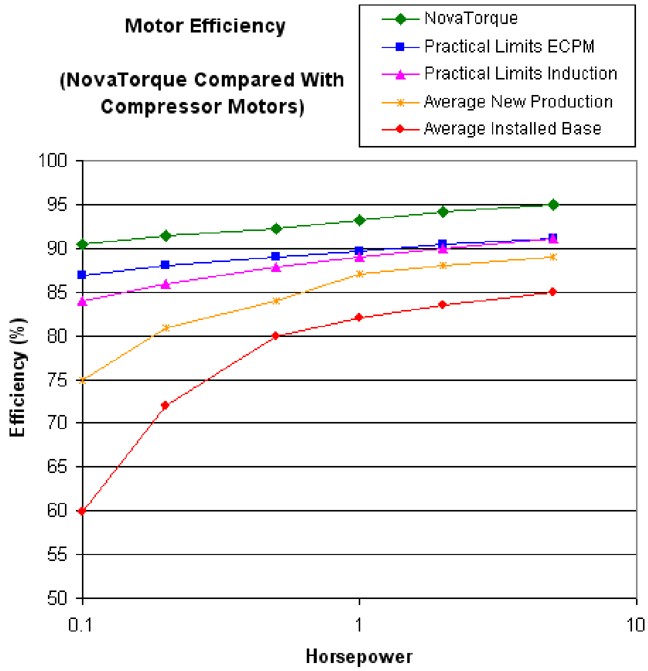

Figure 2. Sample data for brushless DC permanent magnet motors (ECPM), reproduced with permission from NovaTorque [7].

The max tech brushless DC permanent magnet motor would have interior magnets in the rotor, along with other efficiency improvements such as advanced core design (the max tech is laminated amorphous metal), low-resistance conductors, and low-friction bearings. It is not clear that any brushless DC permanent magnet motor on the market combines all these technology options.

Variable-speed motors can achieve even larger savings, not only because they often use efficient brushless DC permanent magnet motors, but also because they respond to load conditions so as to reduce energy demand in the system being driven by the motors. For example, if fluids are pumped at lower speeds through tubes, pipes, and valves, lower fluid resistance results. In HVAC applications, driving the system at just the level needed avoids the need to over-compensate, thereby avoiding inefficiencies and the wear-and-tear associated with frequent start up and shut down. Thirty to forty percent savings are typical for such applications. For air compressors, this report assumes a 20% energy reduction for best-on-market units.

References

[1] DOE Office of Industrial Technologies. (2002). *United States Industrial Electric Motor Systems Market Opportunities Assessment*. December. 386 p. http://www1.eere.energy.gov/industry/bestpractices/pdfs/mtrmkt.pdf

[2] DOE. (1999). *Opportunities for Energy Savings in the Residential and Commercial Sectors with High Efficiency Motors*. Final report prepared for DOE by Arthur D. Little, Inc. Reference 35495-14. December. 131 p. http://www.totalenergycompany.com/pdf/Motor_Efficiency_DOE1999.pdf

[3] DOE. (2005). *Appendix A: FY2005 Technical Support Document*. Prepared in support of DOE's 2005 Priority Setting, updating the FY2003 priority setting. http://www1.eere.energy.gov/buildings/appliance_standards/pdfs/fy05_priority_setting_app_a.pdf

[4] DOE (2010). Appliance and Commercial Equipment Standards, *Electric Motors*, http://www1.eere.energy.gov/buildings/appliance_standards/commercial/electric_motors.html

[5] DOE. (2010). *Small Electric Motors Final Rule Technical Support Document*. http://www1.eere.energy.gov/buildings/appliance_standards/commercial/sem_finalrule_tsd.html

[6] Petro, J. (2009). *Cost efficient construction of high efficiency motors.* Presented at Energy Efficiency in Motor Driven Systems (EEMODS) 2009. http://www1.cetim.fr/eemods09/pages/programme/044-Petro-final.pdf

[7] NovaTorque, Inc.
http://www.novatorque.com/

Network Equipment

Network equipment includes commercial network switches, commercial routers and wireless access points, security equipment, equipment from Internet service providers, residential modems, and residential routers. This equipment is used to connect endpoint devices (such as computers, servers, printers, etc.) to internet service providers and manage the IP traffic over the network. Networks are often structured as redundant trees, where leaves are the endpoint devices. In 2008, network equipment was estimated to consume 18 TWh, or about 1% of building electricity [1].

In commercial environments network switches are an integral part of local networks. Network switches are defined as "devices that choose a path for Ethernet frames based on layer 2 or layer 3 (Internet protocol [IP]) information" [1]. (The 3 layers are link, network, and application.) The type of commercial switch used depends on (1) whether it is managed or unmanaged (depending on network layers); (2) the speed (10/100 megabits/second, 1 gigabit/second, or 10 gigabits/second); and (3) whether they are modular (*i.e.*, reconfigurable). For this report, all these products are grouped into a single product class.

Routers are defined as "devices that route (layer-3 switch) IP traffic with high throughput but not generally categorized as switches." Commercial wireless local area network devices are defined as “access points intended for enterprise networks” [1]. In general these products can be subdivided into low-end, mid-range, and high-end classes depending on speed. For this report, all these products are grouped into a single product class.

Security equipment is defined as “devices that provide firewall, packet content filtering, and other security services” [1]. Devices may be integrated (low-end, mid-range, or high-end) to provide multiple security services, network-based in-line devices, or network access-control devices. For this report, all these products are grouped into a single product class. There were an estimated 2.5 million commercial security devices in use in 2008 [1].

Internet service provider equipment (alternatively customer access equipment) is defined as “equipment in service provider branch offices that terminate broadband links” [1]. Equipment includes multiplexers that provide digital subscriber line access, cable modem termination systems, optical line terminals, and other customer access equipment. For this report, all these products are grouped into a single product class.

Residential cable modems provide “a cable broadband link with minimal connections for the user.” A modem for a residential digital subscriber line (DSL) provides “a DSL broadband link with minimal connections for the user” [1]. Cable and DSL modems may include integrated WiFi access devices. Residential WiFi routers are “a device with Ethernet connectivity and 802.11x connectivity” [1].

The energy use and saving potential of network equipment recently was characterized [1]. The savings originate from (1) more efficient integrated power supplies, (2) managing individual port power, and (3) better use of capacity. Large network devices often include multiple integrated power supplies for redundancy, typically with substantial additional power losses. Individual network ports are powered continuously, even when no cable is plugged in or when there is no active data traffic through the port. The recent development of energy efficient Ethernet (EEE) will help address this issue, although both ends of a network link must be EEE-enabled to achieve energy savings. This technology allows Ethernet ports to shut down when no network traffic is present, waking up periodically to check for signals. Enabling network ports to “sleep” in this fashion could save roughly 50% of the energy consumed per port (ports consume much of network equipment energy), or 12% of total national network energy. Finally, network equipment typically consumes the same power regardless of utilization. Network devices usually are oversized, often resulting in <1% utilization. Designing network devices that scale in power in response to utilization would provide large savings [1].

This report assumes (conservatively) that the best-on-market network equipment (*e.g.*, efficient power supplies providing higher utilization) incorporates an average 15% efficiency improvement compared to conventional equipment. Individual products may differ substantially from this value. Adopting every efficient strategy could result in energy savings of 50%. Additional study is warranted on the possibility of utilizing network proxying protocols for some product classes, although this strategy is generally more appropriate for end-use devices (*e.g.*, computers).

References

[1] Lanzisera, S., Nordman, B. and Brown, R. (2010). *Data Network Equipment Energy Use and Savings Potential in Buildings*. Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings, August.

Packaged Water Chillers

Packaged water chillers (also referred to simply as chillers) serve to cool large commercial buildings. Their cooling capacity can range from approximately 10 tons to more than 2,000 tons. Smaller units are factory-designed and prefabricated, whereas some larger units may be custom-built. Chillers typically use a vapor-compression cycle, but can also use an absorption cycle. If waste heat is available from a commercial or industrial process, absorption chillers have the potential to offer significant savings over vapor-compression chillers. Absorption chillers currently represent only about 1% of the market [1].

Vapor-compression chillers may be configured as centrifugal, large rotary screw, reciprocating, scroll, or small screw. Chillers may use an air-cooled or a water-cooled condenser. For this report, chillers are placed into one of three product classes (although further subdivisions exist based on capacity): (1) air-cooled reciprocating, scroll, and small screw; (2) water-cooled reciprocating, scroll, and small screw; and (3) water-cooled centrifugal and rotary screw.

The average installed unit efficiency and energy use for chillers is well characterized by a Canadian study, which concluded that typical chillers operate for 1,000 full-load-equivalent hours per year [1]. This report assumes, however, that this cooling capacity is spread out across 2,000 part-load hours per year. This assumption better represents field usage.

The energy-saving potential for chillers was determined by comparing best-in-class chiller specifications from the Federal Energy Management Program (FEMP)[1], although FEMP is revising its chiller specifications in collaboration with LBNL [2]. On average, current FEMP levels represent approximately a 25% reduction in energy use, which is consistent with industry journal articles that suggest energy use can be improved 25% by adopting variable-speed compressors and other part-load control strategies [3]. Max tech variable-speed drive technology is discussed in the motors section.

An emerging technology for chillers uses an adsorption cycle, as opposed to either a vapor-compression or an absorption cycle. Traditional absorption chillers use water as a refrigerant and lithium bromide as an absorbent. Water/ammonia is also common in industrial settings. Adsorption chillers, on the other hand, adsorb water vapor onto a silica gel desiccant to drive a refrigeration cycle. Adsorption chillers consume almost no electricity (nearly 100% savings over vapor compression) and avoid the chemical issues surrounding absorption chillers (toxicity, corrosiveness, solidification, hazardous disposal). Like absorption chillers, adsorption chillers require a thermal source to drive the refrigeration cycle (hot water in the case of adsorption chillers), and thus are most ideal for industrial applications involving production of significant waste heat, combined heat and power (CHP), or solar energy [4].

Another promising technology for chillers is the oil-free, magnetic-bearing, variable-speed centrifugal compressor. According to a U.S. Navy Technology Validation study, such compressors can reduce energy consumption by 40% to 60%, more than the 25% achievable with standard variable-speed compressors.

In addition to being integrated with new packaged units, centrifugal compressors can be retrofit into existing installations. This option has the potential for a lower initial cost and quick payback [5].

See Commercial Air-Conditioning for a discussion of evaporative pre-cooling.

References

[1] Caneta Research Inc. (2003). *Market and Benchmark Analysis for Packaged Water Chillers*. Prepared for Natural Resources Canada by Caneta Research, Inc.

[2] Lekov, A., Fujita, S., and Greenberg, S. (2008). *FEMP Chiller Efficiency Requirements Update*. Prepared for DOE by LBNL.

[3] Dieckmann, J., *et al.* (2010). "Variable frequency drives, Part 3: VFDs for large chillers: large energy savings per installation (emerging technologies)." ASHRAE *Journal*. June. p. 58.

[4] Eco-Max Chillers. http://www.eco-maxchillers.com/

[5] Pacific Northwest National Laboratory (PNNL). (2010). *Evaluation of a Variable-Speed Centrifugal Compressor with Magnetic Bearings*. Prepared for DOE's Federal Energy Management Program by PNNL. June. 4 p. http://www1.eere.energy.gov/femp/pdfs/etcs_vscompressor.pdf

Pumps (Residential, Commercial, and Industrial)

Pump applications range from tiny (*e.g.*, medical applications) to among the largest of human endeavors (*e.g.*, regional water pumping). Thus only the broadest of prescriptions regarding efficient pumping technologies can be made. Certain strategies and technologies are, however, relevant to almost any scale, application permitting. There are two primary types of pump, centrifugal (or rotodynamic), and positive displacement (PD). PD pumps use pistons, screws, sliding vanes, and rotary lobes to capture and push discrete volumes of liquids in enclosed chambers. Centrifugal pumps use various wheel-like impellers to accelerate fluid in open channels, then convert kinetic energy to pressure in a diffuser. Although PD pumps generally are more efficient, they are less amenable to pumping highly heterogeneous fluids (*e.g.*, sewage). In many applications the two types of pumps are not interchangeable.

The total US energy use used for pumps, is most easily accounted for in the industrial sector, because large pumps are typically purchased individually for custom-designed applications. In contrast, in the residential and commercial sectors, pumps are more often sold packaged into other appliances and equipment (*e.g.*, in HVAC systems, refrigeration systems, clothes washers and dishwashers, or hydronic heating systems) rather than sold alone (*e.g.*, sump pumps or water-well pumps). Pumps account for an estimated 27% of industrial energy use [1]. According to industry experts, rotodynamic pumps constitute about three-fourths of the industrial market and positive displacement pumps about one-fourth. Electricity consumption accounts for more than 85% of the life-cycle cost of a typical industrial pump. Improving pumping efficiency makes economic sense.

Centrifugal and PD pumps have different performance characteristics, as shown in Figure 3. The flow rate of PD pumps is constant, independent of the fluid pressure (head) (graph on right). Although flow rates of PD pump are relatively independent of the fluid viscosity, they may increase with viscosity because of the reduction in leakage at the chamber boundaries. The opposite is true of centrifugal pumps, the flow rate of which drops significantly with increased head or fluid viscosity (graph on left).

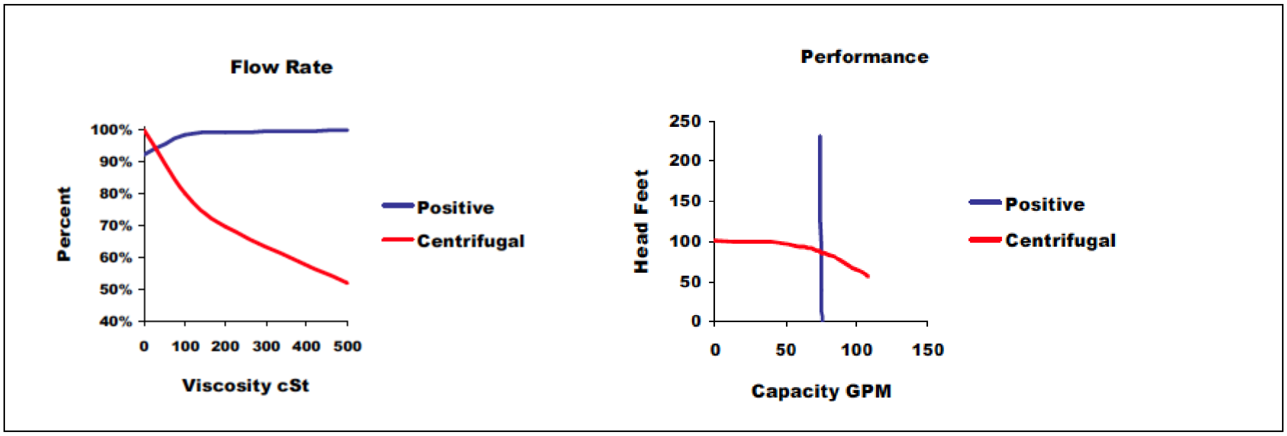

Figure 3. Effects of fluid viscosity (left graph) and head (right graph) on flow rate of typical centrifugal and positive displacement pumps. Figure reproduced with permission from Viking Pump, Inc., A Unit of IDEX Corporation. Source: [2].

Pumping efficiency depends on many factors: the technology of the pump, the design of the pumping system (*e.g.*, the length and diameter of pipes through which the fluid is pumped), and potentially variable environmental conditions (head) and operating conditions (torque demand, speed settings, fluid viscosity, *etc.*). This section focuses only on how pump technologies can affect efficiency. DOE provides extensive guidance on pumping system design on its Industrial Technologies website (http://www1.eere.energy.gov/industry/bestpractices/motors.html).

Large pumps (>30 kW) typically are sold separately from the motors that drive them, so motor efficiency is not accounted for in the rated efficiency. Instead, pump efficiency is defined as the hydraulic fluid power output divided by the mechanical power delivered to the shaft by the motor. Some pumps are packaged with associated motors (typically small systems, but also submersible pumping systems of all sizes, because of the need to protect the motor). Packaged systems include most wastewater applications; well pumps; pumps for hydronic heating systems, swimming pools, and gardens; and small pumps included in appliances. For packaged (pump and motor) systems, the “wire to water” efficiency, which includes the motor efficiency, typically is specified.

Figure 4 compares typical efficiency characteristics of centrifugal and positive displacement pumps. The efficiencies of PD pumps (blue) generally are greater than those of centrifugal pumps (red) and are relatively independent of fluid pressure (head) and viscosity. In contrast, centrifugal pumps have a sharply peaked efficiency curved, with greatly reduced efficiencies above and below the maximum efficiency point. If centrifugal pumps are not operated at their maximum efficiency points, their efficiencies decline greatly, as happens in many, if not most, of their applications. Therefore, efforts to improve pumping efficiency focus primarily on centrifugal pumping applications.

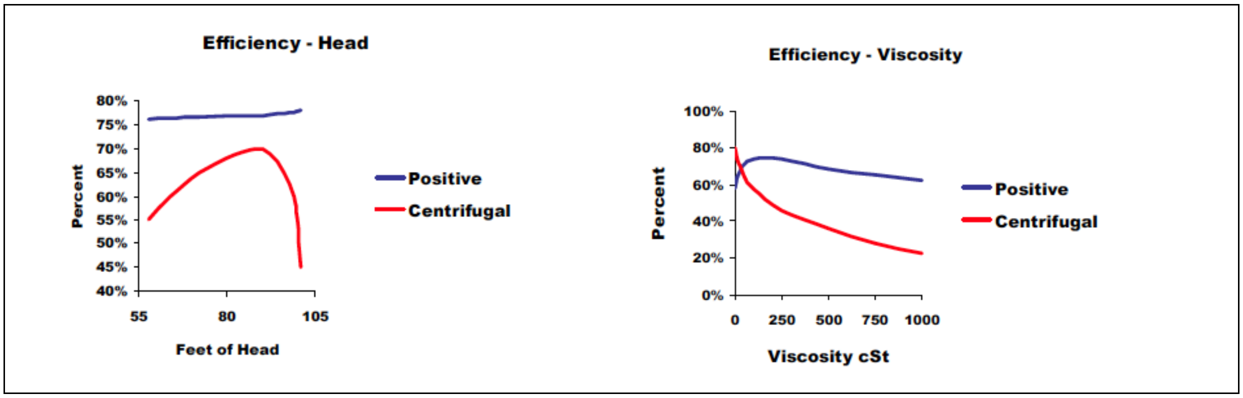

Figure 4. Effects of head (left graph) and viscosity and on the efficiency of typical centrifugal pumps and positive displacement pumps. Figure reproduced with permission from Viking Pump, Inc., A Unit of IDEX Corporation. Source: [2].

There are two major reasons centrifugal pumps generally are not operated at their maximum efficiency point. First, in variable-load applications, the pump is sized for the maximum load, but may rarely operate at that load. (Loads vary both because of variable environmental conditions and variable operating demands.) Second, there is a general tendency to oversize pumps to account for potential engineering errors, future load expansion, and other uncertainties. Additionally, complex fluid pathways can result in oversized pumping systems. If connecting piping remains fairly straight, this reduces pump power requirements. Indeed, DOE estimates that “75% of pump systems are oversized, many by more than 20%” [3].

In 1999 a new-style centrifugal pump was introduced called the N-pump, which has significantly better efficiency and clog resistance than standard centrifugal pumps and has peak efficiencies that vie with PD pumps. Figure 5 and Figure 6 show the performance characteristics (head versus flow) of the Flygt N-pump. Note that although the peak efficiency of the N-pump is high, no centrifugal pump can operate at its maximum efficiency throughout the entire range of operating conditions. On the other hand, the N-pump is capable of pumping sewage and sludge having high solids contents, which would be impossible with a PD pump. According to industry experts, N-pumps can reduce pump energy use by as much as 40%.

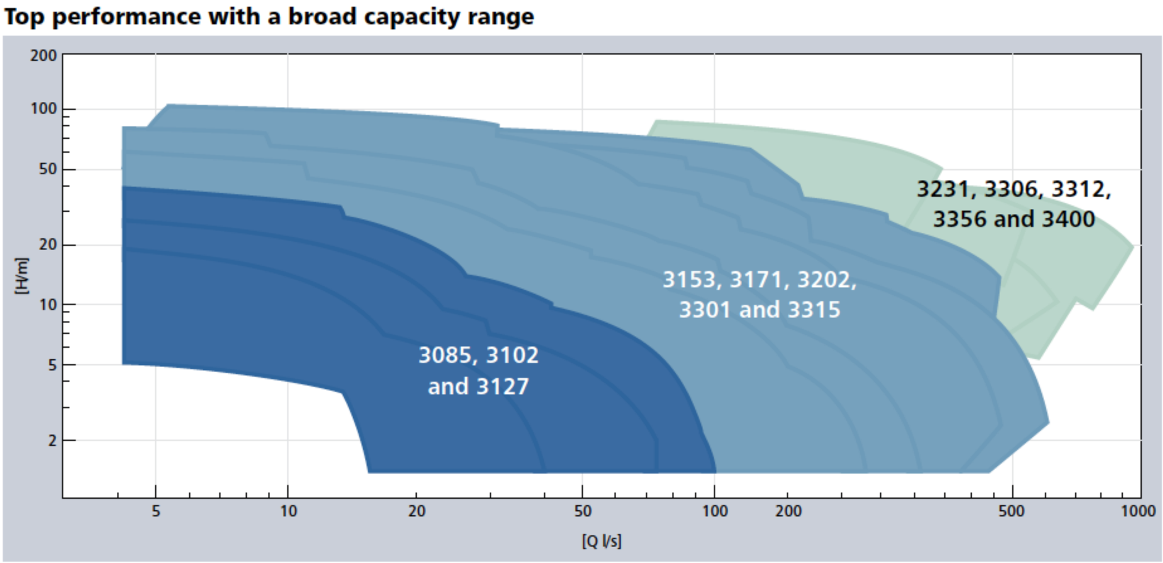

Figure 5. Performance curves for Flygt N-pumps ranging from 1.3 to 310 kW. (far-left curve to far-right curve; model numbers indicted on plot). The figure shows head (H in meters) verus flow (Q in liters per second). Reproduced with permission from ITT Waste and Wastewater. Source: [4].

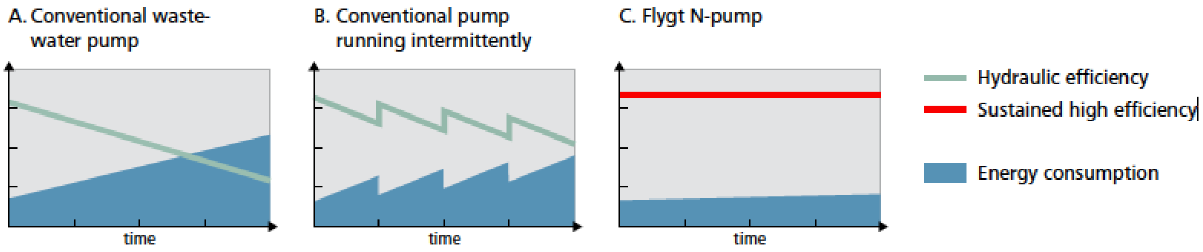

Figure 6. The efficiency of Flygt N-pumps (red line) do not decline over time from clogging, as with conventional pumps (green line). Reproduced with permission from ITT Waste and Wastewater. Source: [4].

For many applications, using variable-speed drives (VSDs) to operate pumps offers large energy savings and improved performance and reliability, along with reduced life-cycle costs and short payback times (< a few years). According to DOE's *Variable Speed Pumping Guide*, "With rotodynamic pump installations, [energy] savings of between 30% and 50% have been achieved in many installations by installing VSDs. Where PD pumps are used, energy consumption tends to be directly proportional to the volume pumped and savings are readily quantified" [3].

Grundfos, a Danish company, and Wilo, a German company, use permanent magnet motors in their small variable-speed pumps, potentially reducing pumping energy use by 70% to 90%, according to BuildingGreen.com [5], [6]. Available in the United States since 2007, these small submersible pumps are used for hydronic heating systems that have integrated sealed motors. In the past, VSDs were add-ons to large pumping systems. This may be the earliest application in which VSDs are integrated into a small pumping system. According to [5], the pumps cost about 50% more than standard pumps, but payback in 1.5 to 3 years. Such systems are being incorporated in ultra-efficient refrigeration and air conditioning equipment (*e.g.*, [7], [8], [9]).

This report assumes that the best-on-market pumps available achieve 25% savings (assuming proper sizing). This report assumes max tech pumps achieve 50% efficiency for all categories of pumps. These estimates attempt to account for the fraction of pumps that can benefit from variable-speed designs (as opposed to constant head, constant flow applications).

References

[1] Lawrence Berkeley National Laboratory, Resource Dynamics Corporation, and Alliance to Save Energy. (2006). *Improving Pumping System Performance: A Sourcebook for Industry*. U.S. Department of Energy, Energy Efficiency and Renewable Energy, Industrial Technologies Program. May. http://www1.eere.energy.gov/industry/bestpractices/motors.html

[2] PumpSchool.com. *When to use a positive displacement pump*. http://www.pumpschool.com/intro/pd%20vs%20centrif.pdf

[3] Europump and the Hydraulic Institute. (2004). *Variable Speed Pumping: A Guide to Successful Applications: Executive Summary*. U.S. Department of Energy, Energy Efficiency and Renewable Energy, Industrial Technologies Program. May. http://www1.eere.energy.gov/industry/bestpractices/motors.html

[4] ITT Water and Wastewater. *Flygt N-pump series: self-cleaning pumps with sustained high efficiency*. Product specifications sheet #896876. Flygt N-pump series 1. Master 1. 20100701. Reproduced with permission from ITT.

[5] BuildingGreen.com. (2010). “High-efficiency, variable-speed pumps from Wilo and Grundfos: product review.” *Environmental Building News*. Vol. 19, No. 9. September. http://www.buildinggreen.com/auth/article.cfm/2010/8/30/High-Efficiency-Variable-Speed-Pumps-from-Wilo-and-Grundfos/

[6] Grundfos. *Permanent magnet*. http://www.grundfos.com/web/homecbs_asia.nsf/Webopslag/BAFA8025CDFA823AC1256C4C0074F6FF

[7] Hoshizaki America, Inc. *Reach in refrigerators and freezers.* http://www.hoshizakiamerica.com/reachins.asp

[8] SunWise Technologies, Inc. *SunDanzer^{TM} battery free solar refrigerators*. http://www.sundanzer.com/images/pdf_BattFreeSpecs.pdf

[9] Biesen, E. (2006). “Motors and air-moving devices, continuously variable.” *Appliance Magazine*. Oct. http://www.appliancemagazine.com/zones/supplier/18_motor_mfg/editorial.php?article=1561&zone=18&first=1

Refrigerators (Residential and Commercial)

There are many options for reducing the energy use of refrigerators, which, combined, could achieve large energy savings. Options include separate variable-speed compressors for cold food storage and freezer (providing for less frequent freezer defrost); optimized refrigerant (and air) temperatures; top-mounted condensing coils with no fan; vacuum-insulated panels; improved gasket seals; adaptive defrost and anti-sweat heaters; improved heat exchangers; and the use of DC fan motors. New Federal energy efficiency standards will require refrigerators to become on average 25% more efficient in the near future, a change that was incorporated into the base-case calculation [1]. The best-on-market refrigerators use approximately 30% less energy than the current minimum standard (*e.g.*, Sun Frost [2]). By combining every option, a max tech “engineered” refrigerator would use 40+% less energy [1]. Because the separate cold storage/freezer option was not explored in the latest DOE energy conservation standard, the true potential savings from max tech are unknown.

Instead of a vapor-compression cycle, refrigerators potentially could use a magnetic refrigeration cycle. This technology remains largely in the research stage, but is used in some specialized ultra-low-temperature laboratory environments. At least one company claims to have developed a residential version [3]. The potential savings are unclear, but the design would eliminate the need for refrigerants (with their associated environmental concerns) and compressors. Thermoacoustic refrigeration is also being researched.

Many of the above strategies are also applicable to commercial refrigeration systems. In addition, each of the following advanced technologies offers potential energy use reductions of 10% to 30% for commercial systems: a ground-coupled refrigerant loop for supermarkets (*i.e.,* one that operates similarly to a ground-source heat pump); advanced air curtains; solid state or fiber optic lighting; and monitoring controls [4].

References

[1] DOE. (2005, 2010). *Technical Support Document, Notice of Proposed Rulemaking, Refrigerators, Refrigerator-Freezers, and Freezers.* http://www1.eere.energy.gov/buildings/appliance_standards/residential/refrigerators_freezers.html

[2] Sun Frost. http://www.sunfrost.com/

[3] Camfridge. http://www.camfridge.com/

[4] Goetzler, W., *et al.* (2009). *Energy Savings Potential and R&D Opportunities for Commercial Refrigeration*. Final report prepared for DOE’s Building Technologies Program by Navigant Consulting, Inc. September. 211 p. http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_refrig_report_10-09.pdf

Set-Top Boxes

Set-top boxes are devices that connect a television and an external source of signal, turning the signal into content that is displayed on the television screen or other display device. Set-top boxes can be subdivided according to the type of signal used to deliver content (none, analog, digital, high-definition [HD] digital); the technology used to communicate with the content provider (cable, satellite); and whether it has a built-in digital video recorder (DVR). This report does not examine analog-to-digital converter boxes, which were produced to facilitate the switch to digital over-the-air broadcasts. Although digital tuners are set-top boxes, all TVs sold today incorporate them, so most converter boxes will disappear from the market in the near future. In addition, analog-to-digital set-top boxes have a voluntary labeling program through ENERGY STAR.

The types of set-top boxes (STBs) considered in this report include: (1) stand-alone DVR, (2) analog STB, (3) digital cable STB, (4) digital cable STB with DVR, (5) digital satellite STB, (6) digital satellite STB with DVR, (7) HD digital cable STB, (8) HD digital cable STB with DVR, (9) HD digital satellite STB, and (10) HD digital satellite STB with DVR.

The savings potential for STBs was determined by studying best-in-class devices and comparing them to those that use an average amount of energy [1]. The energy-saving potential is high because some STBs continuously spin the hard disk (if present) and continuously communicate with the service provider. Managing those two functions and making them more intermittent would provide significant savings, but requires an intelligent power management strategy that can put the STB in deep sleep when not in use. Other efficient design options include power supplies that involve fewer energy losses and more efficient integrated chips.

References

[1] Roth, K., *et al.* (2007). *Residential Miscellaneous Electric Loads: Energy Consumption Characterization and Energy Savings Potential*. Prepared for DOE's Building Technologies Program by TIAX LLC. TIAX reference no. D0370. July. 197 p. http://www.iepec.org/TIAX_MiscElecLoadsReportToDOE.pdf

Televisions (also Monitors and Displays)

This report assumes 5 hours per day active use for TVs, or 1,825 hours per year, the usage ENERGY STAR and the California Energy Commission (CEC) assume in their calculations. The technologies below are summarized largely from the CEC analysis of TV standards [1].

New phosphors, improved cell design, improved gas mixtures, and optimized electronic circuits present the primary technological improvements currently available to reduce energy consumption in plasma TVs. Some new plasma models consume 50% less power than comparable older models. The Advance Plasma Display Development Center Corporation is developing a plasma display that can achieve 10 lumens/watt, which corresponds to a power draw of 70 W for a 42" TV.

The standard fluorescent backlight typically used in a LCD display is a cold cathode fluorescent light (CCFL). Significant energy savings can be achieved by switching to a flat fluorescent light, which is thinner, lighter, more uniform in brightness, and brighter overall. Another option is to use a hot cathode fluorescent light, which uses 40% less energy than a CCFL. Light-emitting diodes (LEDs) also can serve as a backlight technology, offering improved dynamic contrast, longer lifespan, deep (*i.e.*, true) blacks, and dramatic reductions in energy consumption.

Significant improvements also are possible by limiting the light lost from the backlight to the viewer via color filters, the light-dispersive film behind the LCD layer, and the LCD/glass layer itself. Improving the dispersing film, or including a polarization recycler, can reduce power consumption by 30% to 40%.This technology is commercialized, for example by 3M and Agoura).

Liquid crystals require polarized light in order to function, and so a LCD optical stack contains at least two polarizers (sandwiching the liquid crystal layer). Polarizing filters eliminate roughly 50% of the incident light, which typically is lost as waste heat. The first polarizer in the optical stack, however, can be modified to include a polarization recycler. In essence, the light filtered out by the first polarizer can reflect internally and attempt to pass through the filter multiple times. This technology allows far more of the initial light to eventually pass through the first polarizer. Polymer-stabilized, vertical alignment liquid crystals improve transmissivity by 30% over current liquid crystals. Examples in development include the AMVA5 liquid crystal from AU Optronics Corporation [2].

Sharp has developed a LCD TV with 4 subpixels (red/green/blue/yellow) instead of the traditional 3 (red/green/blue [RGB]) [3]. Sharp claims that, in addition to more faithfully representing yellow colors, the technology improves efficiency because yellow is a common color, and less light is lost when filtered by a yellow filter (instead of the equivalent RGB). These claims require testing, but are plausible. Other manufacturers are experimenting with different combinations of multi-pixel designs, such as including a white or light-blue subpixel. Energy savings remain unknown, especially considering the reduced coverage by going from 3 to 4 subpixels.

An emerging technology that may be commercialized soon is color-sequential LCD. Color-sequential imaging operates by sequentially and rapidly showing RGB images, instead of using RGB subpixels. The frame rate must be high enough so that the human eye perceives sequential RGB images as a single image (without blur). The backlight can consist of optimized individual red, green, and blue LEDs. The advantage of this design is that it eliminates color filters (and their associated optical losses) and improves the aperture ratio (the ratio of display that transmits light, as opposed to the pixel circuitry) by going from 3 subpixels to a single pixel. Unfortunately, liquid crystal technology does not yet respond fast enough to enable color-sequential LCD, although improvements are being made [2].

Both LCD and plasma TVs can benefit from active power management features, such as automatic brightness control based on ambient lighting; brightness control synchronized with picture content (*i.e.*, deeper blacks); and presence sensors to turn the display off when no viewers are present. Such features can reduce overall power consumption by approximately 50% to 70%. The current implementation of automatic brightness control in the ENERGY STAR test procedure can lead to gaming the test, however, which does not reduce electricity consumption under field conditions.

The best-on-market flat-panel TVs are assumed to be superior to older generation flat-panel TVs because they contain currently available energy efficient technologies. Today's LCDs are 60% more energy efficient than previous LCDs (*e.g.*, LED backlights, power management), and today's plasma TVs are 50% more energy efficient than just a few years ago (new phosphors and gases, power management). This report assumes max tech TVs contain a suite of technological improvements, including aggressive power management. Such TVs have a unit energy consumption that is probably similar to a TV that incorporates organic light-emitting diodes (OLEDs) (see below). Max tech TVs are assumed to consume 90% less energy than an average low-end LCD TV currently available.

Organic light-emitting diodes (OLEDs), which are used in some products (*e.g.*, mobile phones), have the potential to revolutionize the display and lighting sectors. An OLED is similar to a standard LED, but uses a plastic polymer instead of semi-conductors as the substrate. The plastics can be deposited in very thin, flexible films. OLEDs are small enough to eliminate backlighting entirely—the OLEDs themselves serve as light-producing pixels. The end result is a display panel that is remarkably thin compared to current models, is flexible, and has the potential to consume far less power than any current technology (in a few years for larger displays). Current applications must be small (*i.e.*, cell phone and PDA screens), although there are commercialized panels at roughly 12 to 15 inches. Quality and lifetime issues remain. White-light OLEDs remain largely in the development stage, but they could become more widely available by 2015. Prototype panels at 50"+ have been demonstrated. OLED TVs at 50" and beyond likely will be commercially achievable in a few years.

Laser phosphor displays, another new technology, provide a display that is emissive in nature, with individual phosphors excited by low-energy blue-violet lasers. The lasers are directed onto the precise phosphor lines via a series of mirrors. Prysm has used this technology to develop large-format displays having low power consumption [4]. Currently, it seems impractical to adopt this technology in smaller formats (such as televisions).

Another emerging technology is quantum dots. Quantum dots are nearly perfect absorbers and emitters of light, providing a highly tunable output spectrum. This quality enables them to be used in various optical applications that require precise color control and improved gamut, including displays and lighting (in order to generate white light). Quantum dots currently are commercialized in niche markets, but have the potential to become more widespread by 2015 [5].

References

[1] California Energy Commission. (2009). *2009 Appliance Efficiency Rulemaking, Phase I, Part C. Docket #09-AAER-1C*: *Staff Report.* CEC-400-2009-024. September. http://www.energy.ca.gov/2009publications/CEC-400-2009-024/CEC-400-2009-024.PDF

[2] AU Optronics Corporation. http://www.auo.com/

[3] Sharp Quattron. http://www.sharpusa.com/ForHome/HomeEntertainment/LCDTVs/WhatIsQuattron.aspx

[4] Prysm. http://www.prysm.com/

[5] QD Vision. http://www.qdvision.com/

Water Heaters (Electric)

(The following discussion also applies to electric water heating in commercial buildings.)

Current electric heat-pump water heaters achieve an energy factor (EF) of 2.2 or greater, compared to electric resistance water heaters, which have an EF of 0.90 [1]. (The energy factor for water heaters is defined as thermal energy added to the water divided by the electric energy input to the heater.) Current technology does not include recovery of waste heat (*i.e.*, a coupled air conditioner-heat pump water heater) that could increase efficiency further. The best-on-market unit, according to ENERGY STAR, achieves an EF of 2.5 (and includes an electric booster element as backup). The calculation in this report assumes the resistance backup heater is not used.

Products are available for converting a storage water heater (electric or gas) to an electric heat pump water heater. This retrofit product easily attaches to the top of the existing storage water heater (requiring the existing top to be removed). This product is significantly cheaper than a purpose-built heat pump water heater, and achieves nearly as high an efficiency rating (2.1 EF) [2]. One limitation to retrofit heat pump water heaters is that the refrigerant coil must be immersed in the water (as opposed to coiling around the outer wall of the unit). Safety regulations require that when refrigerant coils are immersed in water, the tube must be double-walled, limiting the heat-transfer efficiency.

Drain-water systems are another option. They recover the heat from hot water in drain-water pipes and use it to pre-heat the incoming water supply. One way to achieve this effect is to use a highly conductive pipe material such as copper to wrap the incoming cold water pipe around the outgoing drain pipe. A drain-water system works best when long-duration flows of hot water down the drain occur at the same time as flows of cold water into the storage tank, such as during a shower. The system does not work well during a bath, for example, because there may not be a simultaneous flow of cold water into the water heater while the bathtub is draining. Alternatively, drain-water heat recovery can be implemented locally at each faucet or showerhead, where the heat exchanger transfers heat from the drain pipe to the incoming cold water pipe. This implementation raises the temperature of the incoming cold water, enabling the user to use less water in achieving the desired water temperature. This set-up would enable the system to work for almost any application [3]. The thermodynamic availability is potentially low in most applications, however, especially if the drain water contains significant contaminants that could reduce the effectiveness of a heat exchanger. Energy use reductions from the baseline are uncertain and dependent on usage patterns. In addition, the installation and maintenance costs are likely to be very high in space-constrained homes.

Integrated HVAC and water heating units can potentially produce large energy savings. Heat-pump-based integrated systems utilize the waste heat from the space cooling system for the water heating system. Testing and modeling of air-source systems in five major U.S. cities suggests possible combined savings of 46-67%. Ground-source systems can achieve savings greater than 50% [4], [5], [6]. The prototype model tested included variable speed compressors, and thus separately, the water heating and HVAC units were efficient designs. Electric heat-pump water heaters can be designed to use CO_2 as a refrigerant. The use of CO_2 requires very high pressurization, but offers improved efficiency over other refrigerants. Under typical operating conditions, CO_2 heat-pump water heaters have an EF of 3.0 or greater (SANYO claims an EF of 3.75 on some models with outside air temperatures of 20 degrees Celsius). In addition, CO_2 is non-toxic with an ozone depletion potential of 0 and a global warming potential of 1 (compared to other refrigerants with GWP > 1500). CO_2 heat-pump water heaters are becoming common in Japan due to a strong subsidy program [7].

References

[1] DOE. (2010). *Residential Heating Products Final Rule*. http://www1.eere.energy.gov/buildings/appliance_standards/residential/heating_products_fr.html

[2] AirGenerate. http://www.airgenerate.com/

[3] Zogg, R., *et al.* (2009). *Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances*. Prepared for DOE's Building Technologies Program by Navigant Consulting, Inc. December. 446 p. http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf

[4] Muphy, R.W. *et al*. (2007). *Air-Source Integrated Heat Pump for Net-Zero-Energy Houses: Technology Status Report.* Prepared for DOE by Oak Ridge National Laboratory, ORNL/TM-2007-112. July. 93 p.

[5] Muphy, R.W. *et al*. (2007). *Ground-Source Integrated Heat Pump for Net-Zero-Energy Houses: Technology Status Report.* Prepared for DOE by Oak Ridge National Laboratory, ORNL/TM-2007-177. December. 78 p.

[6] Baxter, V. *et al*. (2008). *Development of a Small Integrated Heat Pump (IHP) for Net Zero Energy Homes*. 9th International IEA Heat Pump Conference. May.

[7] Shibata, Y., Murakoshi, C., and Nakagami, H. (2006). The CO_2 Heat Pump Water Heater as a New Countermeasure Against Global Warming: Drastic Improvement in Energy Efficiency in Three Years Since Its Debut. Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings, August.

Water Heaters (Gas)

(The following discussion also applies to gas water heating in commercial buildings.) About 60% of residential water heaters use natural gas as fuel. Typical gas storage water heaters have an energy factor of approximately 0.6, although upcoming standards will raise that to approximately 0.67 EF. Condensing gas storage water heaters can reduce energy consumption by about 20%, for an EF as high as 0.85. Such technology is not new, but has been slow to penetrate the market because of higher initial costs.

Absorption heat pump water heaters (which use heat as their energy source) could reduce water heater energy consumption by 40% to 50% [1]. Again, the absorption cycle is not new technology (for example, mobile home refrigerators use it), but only recently have manufacturers developed reliable absorption heat pump water heaters.

Solar thermal water heaters are gaining popularity with rising energy prices and government rebates. Once again, the technology is not new, but reliability and cost have improved. Most solar water systems include a backup heat source (gas or electric). A solar water heating system can reduce energy consumption by 50% or more [2].

Like electric water heaters, a gas water heating systems can possibly benefit from drain-pipe heat recovery (see above).There is some initial development by some manufacturers of gas-fired absorption heat pumps with EFs up 1.4 [3], but these units have yet to be commercialized in the U.S. The absorption cycle is well-known (and has been used in refrigerators for many years), but its application to water heaters is relatively new.

Gas-fired instantaneous (demand) water heaters are becoming popular in the U.S. Instead of storing hot water in a tank, hot water is generated on demand with a very strong burner element. This eliminates all standby losses associated with tank water heaters. The burner, however, is less efficient than in a storage system. As such, instantaneous water heaters potentially perform less efficiently in certain applications, such as in homes with high water demand (multiple inhabitants), homes with multiple simultaneous uses for hot water (shower, clothes washer, dishwasher), and homes with widely spaced end uses. In such cases, water heating is less efficient with an instantaneous water heater [2]. Utilizing multiple demand water heaters located at the source (*e.g.*, shower) improves the efficiency of the system (at much higher installed cost), but it does not use less energy than a heat pump water heater.

References

[1] Oak Ridge National Laboratory. (no date). *New gas-fired heat pump technologies help chill greenhouse effect*. http://www.ornl.gov/info/ornlreview/rev28_2/text/gas.htm

[2] American Council for an Energy-Efficient Economy. *Water heating*. http://www.aceee.org/consumer/water-heating

[3] Vineyard, E. (2011). Private communication.