A Tool to Prioritize Energy Efficiency Investments

Philip Farese, Rachel Gelman, and Robert Hendron
National Renewable Energy Laboratory (NREL)

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-6A20-54799
August 2012

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Executive Summary

To provide analytic support of the U.S. Department of Energy's (DOE) Office of the Building Technology Program (BTP) we developed a comprehensive, straightforward Microsoft Excel-based tool to provide an open and objective comparison of the hundreds of investment opportunities available to BTP. This tool uses established methodologies to evaluate the energy savings and cost of those savings of these investment opportunities. Specifically the methodologies include:

- Calculating the levelized cost of conserved energy (CCE) using net present value calculations of the costs and benefits of each opportunity
- Tracking energy use through stock-and-flow calculations to determine the "economic potential": that energy savings where the benefits of investments made exceed the cost of those investments
- Evaluating the savings the market can adopt using Bass-model technology diffusion calculations.

We identified over 770 energy efficiency measures through literature review and expert interviews each of which was supported by peer-reviewed publication, laboratory testing, in-situ (i.e., "pilot") testing, engineering-macroeconomic analysis (e.g., through the technical support documents of BTP's Equipment and Appliance Standards Program), building-energy use modeling, or verified savings through mass adoption (e.g., utility or other energy efficiency programs).

Finally, each of these measures was analyzed with the tool both individually and in the context of the full portfolio of possible measures. This work demonstrates multiple pathways to achieve approximately 50% savings from the baseline projected building energy use in 2030. It further demonstrates that the average cost of these savings is less than half the production cost of energy (as compared to currently available or near-term resources). We also reproduce findings of recent reports showing that approximately 30% energy savings remains possible with currently available and cost effective efficiency measures. Finally, we identify that emerging technologies (i.e., with expected market availability in 5-10 years) can increase this to approximately 65% savings while including technologies in earlier stages of development increase savings to approximately 80%.

We anticipate that this analysis, made possible through the objective comparison provided by the evaluation tool, will provide perspectives on energy savings possible with R&D and identify promising technologies to research. This tool, developed to support BTP in portfolio design, will be made available for continued public use in the future.

1 Introduction

Attempts to understand, analyze, and seize the opportunity energy efficiency presents date back nearly four decades to the oil crises the U.S. faced in 1973 and 1979. Early researchers (Meier 1982; Meier Wright Rosenfeld 1983) developed a methodology for characterizing energy saving opportunities, which we term herein "measures" according to their potential "economical savings" and the "levelized cost of conserved energy". These quantities represent, respectively:

- The reduction in U.S. annual energy use that could be captured if 100% of the market adopts the energy-using technology that provides services at the lowest lifecycle cost rather than a standard unit as forecast in an accepted baseline
- The present value of the incremental investment in this technology divided by the present value of energy saved over the baseline energy use. Discount rates used to calculate present values vary from approximately 3% (i.e., inflation) to 6-10% (i.e., historic rates of returns on bonds or securities) to even 20-40% (i.e., rates observed to govern some decisions).

These works also developed the concept of an "accounting framework" to insure that an organization pursuing multiple measures accounts for the energy captured by each measure pursued without "double counting" any energy savings.

Other works (SERI 1982; Interlaboratory Working Group on Energy-Efficient and Clean-Energy Technologies 2000; National Academy of Sciences 2009; Choi-Granade 2009) have used these techniques to understand the possibility to meet future demand for energy services with advanced technologies that use less energy to provide those services. These works have had several design principles in common, notably considering economic potential, focusing on a 10-20 year time horizon, and limiting measures considered to those available at the time of their writing. They consistently identified the opportunity to reduce energy use over a 10 year horizon by 16-28% (Choi-Granade 2009) and over a 20-year horizon by 23-32% (National Academy of Sciences 2009) through commercially available energy efficiency measures. The most aggressive of these (SERI 1982) also identified a 57% technical potential reduction in the residential sector and a technical savings of 50% in commercial retrofit measures and 75% commercial new building measures.

Building on this legacy, we developed a prioritization tool to aggregate and analyze (with a consistent methodology) the many building efficiency measures available for investment by the U.S. Department of Energy's (DOE) Energy Efficiency and Renewable Energy (EERE) Office of the Building Technologies Program (BTP). BTP can consider a very large number of investment opportunities that cover technologies in all major end-use areas. Projected energy consumption by end use in 2030, expressed in primary[1] energy use in quadrillion British thermal units (Btu) annually (quads) in 2030 in both residential and commercial buildings (respectively) include (Energy Information Agency 2011):

[1] Primary or "source" energy represents energy in the form it is first accounted (e.g., Btu of coal, oil, or natural gas) before transformation to secondary or tertiary forms (e.g., electricity). End-use, or "site" energy refers to energy used in buildings settings (e.g., to light, heat, or cool buildings).

- Heating (Residential: 5.2 Quads, Commercial: 2.2 Quads)
- Cooling (Residential: 3.1 Quads, Commercial: 2.0 Quads)
- Ventilation (Residential: 0.6 Quads, Commercial: 2.0 Quads)
- Lighting (Residential: 1.4 Quads, Commercial: 3.9 Quads)
- Water heating (Residential: 3.1 Quads, Commercial: 0.9 Quads)
- Refrigeration (Residential: 1.5 Quads, Commercial: 1.6 Quads)
- Washing and drying (Residential: 1.5 Quads, Commercial: 0.4 Quads)
- Cooking (Residential: 0.8 Quads, Commercial: 0.3 Quads)
- Miscellaneous loads, mostly electrical (Residential: 6.2 Quads, Commercial: 6.1 Quads).

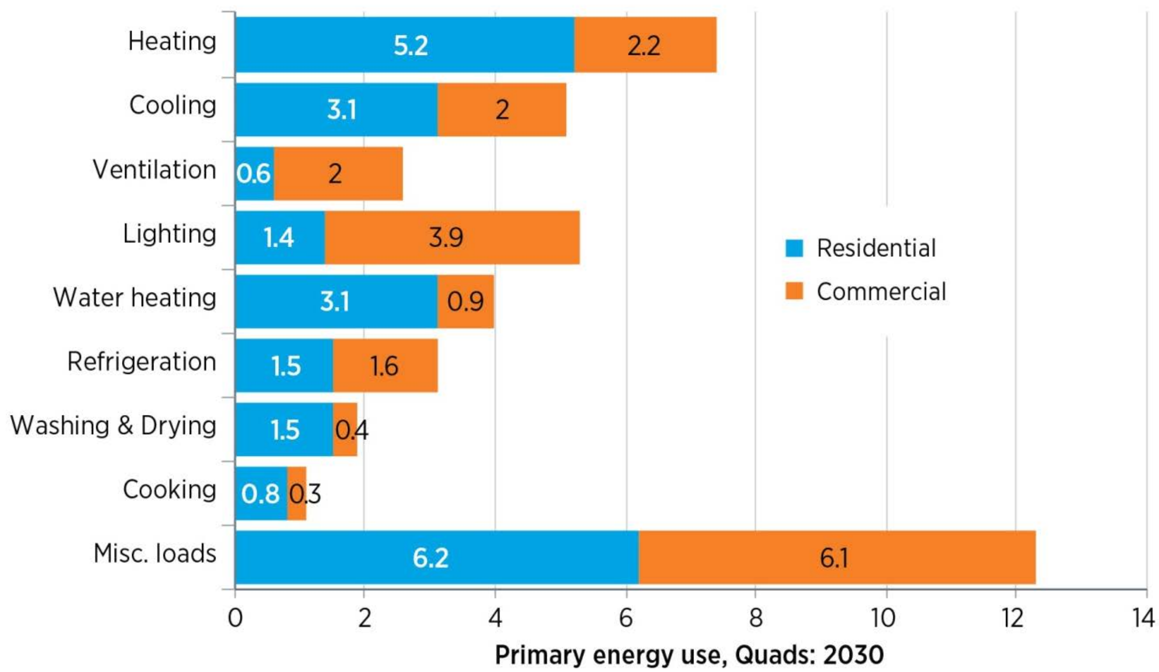

Figure 1. Baseline energy use adapted from Annual Energy Outlook, 2010

The aggregate of these technologies represents a total of 42.6 quads expected annual primary energy use by building-related activities in 2030 under the scope[2] addressable by BTP. The inclusion into our scope of two major technology element, data centers (forecast to represent 2.2 quads in 2030) and community infrastructure (including distribution transformers, waste water treatment, irrigation that are forecast to represent cumulatively 2.2 quads in 2030), remains unclear; excluding these reduces the scope of our analysis to 38.2 quads expected energy use in 2030 absent BTP involvement.

[2] Primary energy use estimated from the Energy Information Agency's *Annual Energy Outlook*, 2010. Miscellaneous loads exclude commercial unspecified loads which lack sufficient data for analysis. Washing and drying include only machine energy (i.e., not hot water) with commercial washing and drying energy use estimated from other sources. Residential ventilation represents furnace fans and boiler circulation pumps.

BTP has multiple strategies at their disposal to capture the available energy savings in these areas including researching and developing emerging technologies (i.e., those that can be commercialized within five years), deploying those technologies using multiple approaches (e.g., labeling efficient homes and products, developing specification and voluntary agreements through stakeholder alliances, advancing building science to demonstrate savings and performance in situ), and developing building codes and appliance standards to lock in savings as required by statute. The prioritization tool provides an objective comparison of new and existing measures and is being used to inform decision-making with respect to BTP's portfolio of projects. Four criteria drove the tool's design at the outset of its development, namely that the tool would be:

- **Comprehensive**. Include most (i.e., ideally all, but realistically 90% or more) known energy efficiency measures that have been proven to save energy in residential and/or commercial buildings.
- **Open**. Though "proving" savings is a challenge (and a research area in its own right) we include in the analysis any measure that has laboratory demonstrated, field tested, or analytically derived (if peer reviewed) savings.
- **Straightforward**. We limit input, output, and applied analytical techniques to firmly established methods that can be empirically explained and avoided "machine logic" elements. As a result, the calculations were limited to stock-and-flow and technology-diffusion-based logic rather than simulation such as probabilistic, agent-based, or discrete choice modeling.
- **Objective**. Integrating inputs from hundreds of sources and dozens of expert interviews placed significant requirements on applying "judgment" regarding what inputs to admit. As expected for such work we hold all experts and sources to the same objective bar regardless of their reputation or our opinions regarding the efficacy or cost effectiveness of the measures they submitted.

This report and a forthcoming journal publication describe the results of the following process:

- **Build the "engine".** Devise a stock-and-flow technology-diffusion model to apply consistent baseline assumptions and analysis techniques to estimate energy savings and cost of conserved energy as described in sections 2-6.
- **Populate the "database"**. Use journal publications, reports, technical support documents (from the BTP Appliance and Equipment Efficiency Standards Program), and tools supporting the Energy Information Administration's (EIA's) Annual Energy Outlook to create an initial measure list. To evaluate the potential we aggregated ~400 measures as an initial set.
- **Conduct a review with lab experts**. Engage in a first review where National Laboratory program managers reviewed the preliminary findings and database to determine any data gaps or inaccuracies.
- **Share findings with BTP staff**. Engage in multiple rounds of review and application of the tool to provide analysis in support of strategic planning demonstrated the

usefulness of the tool while refining its outputs. The goal is as an open source, evergreen tool that can inform program planning and benefit analysis.

- **Review inputs and expand the measure list**. Conducted a more comprehensive and detailed review including 65 experts involved in buildings research and deployment who further challenged, refined, and improved the dataset and other inputs to the tool.
- **Publicize the tool and findings**. This report represents the first step in a multi-step publication process. We will detail the methodology (this report), share the most significant findings (journal publications in preparation), and plan to make the fully operational spreadsheet and supporting spreadsheet tool available for public use and refinement.

Given the limited funding, aggressive timescale, and simplifying assumptions required, we provide the following caveats about this analysis:

- **An 80/20 solution**. This work was originally designed to provide 80% of "the answer" using 20% of the time required to arrive at the full answer. The results likely represent more of a 55/5 solution: 55% of "the answer" using 5% of the time required for the full answer. Given the vast challenge of optimizing the built environment we anticipate this work has invested no more than 5% of the total resources needed to achieve "the full answer" to this problem.
- **Limited precision**. Though many of the resources cited have used detailed energy modeling to estimate the cost and impact of the measures, we performed no supplemental energy modeling to determine input values. As such we estimate national, or at best climate-regional, impacts without exploring the potential impacts for more granular geographic regions.
- **Sufficient accuracy**. Estimating the accuracy of each measure is beyond the scope of work. Few of the resources used provide an uncertainty estimate on their benefits. However, by performing sensitivity analysis as discussed in Section 7.3, we believe our ultimate estimate of total cost-effective energy savings is accurate to +/-10% as detailed in section 7.
- **Ultimate responsibility**. Despite having used the data and perspectives of many excellent researchers the ultimate responsibility for these findings rests with the authors of this report.

This report contains the following sections:

- **Introduction**. Provides the objectives, design philosophy, process, and caveats of the work
- **Measure design philosophy**. Outlines the approach to data collection, measure refinement, and baseline development
- **Baseline energy use and technical potential calculation**. Details the mathematical underpinnings for the calculations of energy efficiency benefits

- **Stock-and-flow model and economic potential calculation**. Further details our stock-and-flow methodology and the resulting definition of "economic energy efficiency potential"
- **Adoption logic**. Discusses the application of technology-diffusion (i.e., Bass-model), presents some alternatives, develops multiple means for parameter estimation, and discusses limitations of this approach
- **Staging logic**. Details how our model moved from single-measure evaluation to a portfolio of multiple measures by attributing savings to the least costly measures while aggregating benefits and evaluation costs
- **Outputs and their uses**. Provides an overview of the main outputs of this work, including evaluation of the potential of individual measures, de-selection of measures to include in a program portfolio, identification of long-term vision targets, and evaluation of technical limits to individual end uses
- **Conclusion**. Shares information about the concurrent publications that are underway as well as planned and potential future work
- **Appendices**. Provide additional detail regarding the researchers' baseline assumptions, inputs for each measure, and a full bibliography of all sources consulted.

2 Measure Design Philosophy

This section focuses on three topics related to data gathering and characterization in the prioritization tool: selection criteria for measures to admit to the database, characterization of the data elements required, and a brief discussion of the baseline used to characterize current and future energy use.

2.1 Approach to Data Collection

As discussed in the introduction we sought to gather credible data on any building-related energy efficiency solution including technologies, system solutions, business models, and enabling elements (e.g., behavioral "nudges" and building energy modeling).[3] We remained open-minded to the measures that were considered but also thoughtful regarding what data were sufficiently credible for inclusion.

As a result, to date, we have identified 770 energy efficiency measures to consider. The measures were drawn from literature review and expert interviews; each supported by peer-reviewed publication, laboratory testing, in-situ (i.e., "pilot") testing, engineering-macroeconomic analysis (e.g., through the technical support documents of BTP's Appliance and Equipment Efficiency Standards Program), building-energy use modeling, or verified savings through mass adoption (e.g., utility or other energy efficiency programs). These 770 measures include multiple views on a single measure (e.g., different Energy Factors of tankless water heaters, different costs for dynamic windows as either new or replacement windows, "max-tech" appliances vs. individual component upgrades). Eliminating all such overlapping measures reduces our dataset to 497 possible measures. Of these 411 presented sufficiently credible data for inclusion in the analysis. Appendix 2 characterizes these 411 measures by providing their most significant inputs and primary sources for those inputs. As mentioned in the introduction, the tool and measures therein went through two rounds of multiple laboratory and stakeholder review,[4] including:

1. Building energy experts at Pacific Northwest National Laboratory, Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, and NREL reviewed the initial selection set, methodology, and preliminary findings. The experts provided extremely helpful direction on ways to refine and expand the work.
2. BTP "performers" (i.e., researchers funded by BTP) provided feedback on the inputs used. We presented them the opportunity to share their perspective on the sources consulted and inputs used and to provide additional or alternate inputs supported by credible sources as outlined above.

We envision continuing this process of expanding the measures considered, refining the inputs, and updating inputs as technologies and markets develop. This approach provides a comprehensive and internally consistent dataset of energy efficiency measures which, in itself, is of value.

[3] The tool is also capable of representing policy actions or other programs through the adoption coefficient approach (see Section 5); however, policy analysis was outside the scope of our work.
[4] Despite having used the data and perspectives of many excellent researchers, the ultimate responsibility for these findings rests with the authors of this report.

2.2 Data Required of a Measure for Its Inclusion in the Selection Set

Three pieces of data characterize any measure to be included in the dataset: energy efficiency, cost, and market. This section details these data requirements and concludes with a list of other meta-data used to characterize each measure.

2.2.1 Energy Efficiency Data

Energy efficiency data represents the change in energy use the measure causes. Typically this results in a percentage decrease in site (end use) and source (primary) energy use over the existing baseline technology mix. Savings are expressed in a variety of units such as the equipment efficiency level (e.g., Seasonal Energy Efficiency Rating (SEER) or Energy Efficiency Rating (EER) for air conditioning, Annual Fuel Utilization Efficiency (AFUE) for furnaces, Energy Factor (EF) for water heating, and R-value for windows or insulation) or as the aggregate energy savings for the end-uses impacted. However, this can include fuel switch measures (e.g., moving from an electric resistance water heater to a tankless gas water heater or from an oil boiler/furnace to an electric heat pump) which may increase or decrease site or source energy. We include fuel switching measures that decrease source energy (even if they increase site energy) but exclude those measures that increase source energy (even if they decrease site energy). Section 3 details how the model applies this efficiency data to determine the total energy savings and cost of that energy savings.

2.2.2 Cost Data

Cost data represents the difference in capital, operations, and maintenance costs between the measure being analyzed and the typical unit in the baseline. This represents the most challenging piece of data to acquire given complicating factors such as regional variations in labor and equipment prices, volatility in raw material prices, uncertainty in costs of products not yet brought to market, profit margins and other business expenses, and compression of manufacturing costs and other costs as production increases. Our goal is to present the retail price of installed measures at the time of significant market adoption. We define this as when sales volume is sufficient to support full production of a manufacturing facility; we approximate this as 5% of the total market size. Undoubtedly, the cost estimation represents the value with the greatest uncertainty in the analysis; as such we are careful to test the sensitivity of our conclusions to larger (+/-50%) variations in the cost estimates. Note that we reduce the marginal cost over time as described in section 4.3.

2.2.3 Market Data

Market data represents the total equipment stock and energy use that the measure strives to address. This will typically be characterized by what end-uses (e.g., cooling, heating, lighting), building types (e.g., new, existing, single family homes, supermarkets, etc.), and other measure-specific characteristics (e.g., cooking devices, climate zones) the measure can impact. It requires identifying three elements for each year of the analysis 2010-2035:

- End-use (also known as site) energy indicates how much energy, characterized as described above, each measure can impact

- Fuel type specifies what fuel or fuel mix is used to supply that end-use energy demand; this is required to convert from end-use to primary energy impacts

- Equipment stock represents the total number of appliances, pieces of equipment, number of buildings, or total square footage of building space each measure must impact to capture its full market potential.

We use two methods to estimate the market size; these are detailed in Section 6.2. The first draws directly from the data source's own description of the market and such resources as the *Building Energy Data Book*.

2.3 Overview of Data Used to Create Baseline Energy Use

The prioritization tool uses EIA's *Annual Energy Outlook 2010* (AEO 2010) as the basis for its baseline energy use. The AEO has been providing projections of energy supply and demand since the 1980s. It typically forecasts 20 years or more, is currently updated annually, and represents the most commonly used resource for energy use projections. It is straightforward, but somewhat time consuming, to update this baseline to future AEO editions.

We base much of the market information on the detailed output tables available from the EIA by request. These files provide more detailed data than the AEO publications; specifically we use the pivot tables indicating the energy use and stock for each enduse, fuel type, equipment class, building type, and census region. We develop our baseline by identifying the energy uses that BTP can impact and supplement this EIA data with other research as necessary. In total the baseline used for most of the analysis conducted represents annual primary energy use of 40.5 quads in 2030 which, as explained below, is 5.9 quads less than the full AEO 2010 forecast. The tool can vary this baseline if needed to analyze other opportunities such as lighting energy use in industrial establishments or outdoor spaces. In particular, our 40.5 Quads of energy use include the following details, here aggregated into commonly used end-use groups:

- **Heating** (Residential: 5.2 Quads, Commercial: 2.2 Quads): contains all primary and secondary heating for commercial and residential applications including all technologies (e.g., furnaces, boilers, heat pumps, roof top units) and all fuels (e.g., natural gas, electricity, heating oil/distillate fuel, wood).
- **Cooling** (Residential: 2.9 Quads, Commercial: 2.0 Quads): represents all energy used to cool and air condition buildings; though more than 9% electricity natural gas and other fuel fired cooling equipment is allowed.
- **Ventilation** (Residential: 0.6 Quads, Commercial: 2.0 Quads): includes both heating/cooling distribution energy (i.e, furnace fans and circulation pumps) and air-quality requirements; this is entirely fueled by electricity.
- **Lighting** (Residential: 1.4 Quads, Commercial: 3.9 Quads): includes all lighting technologies and applications in homes and commercial buildings. The tool can also optionally analyze 0.6 Quads of commercial lighting and 0.8 Quads of outdoor lighting as appropriate to the baseline for a given scenario.
- **Water heating** (Residential: 2.9 Quads, Commercial: 0.7 Quads): represents consumption of all fuels (primarily natural gas and electricity) for all uses of hot water including clothes washing, dish washing, hygiene, and others.

- **Refrigeration** (Residential: 1.5 Quads, Commercial: 1.6 Quads): contains all residential and commercial refrigeration applications (other than space cooling) including home refrigerators and freezers, supermarkets, and other commercial refrigeration applications such as food service, food sales and laboratories. It is important to note this does not include "industrial" applications such as food processing or transportation; also it exceeds the AEO as more detailed resources were available (Goetzler, et al., 2009).
- **Washing and drying** (Residential: 1.5 Quads, Commercial: 0.3 Quads): includes dishwashing machine energy (0.4 Quads), clothes washing machine energy (0.1 Quads), and clothes drying machine energy (1.2[5] Quads) but excludes hot water; machine hot water use, representing 0.4 Quads for dishwashing and 0.6 Quads for clothes washing, is captured and categorized under water heating. Note that that energy use here also departs from the AEO estimate as a similarly more detailed resource is available (Goetzler 2009) and will likely be incorporated into future AEo estimates.
- **Cooking** (Residential: 0.8 Quads, Commercial: 0.3 Quads): represents conventional (i.e., range and oven) and microwave cooking in residential homes and all food preparation in commercial buildings.
- **Miscellaneous loads** (Residential: 6.2 Quads, Commercial: 4.6 Quads): includes only energy use we were able to characterize in detail. Enduses in the detailed output tables include ceiling fans, coffee makers, DVD players, home audio, PCs, "rechargeable" devices, Spas, security systems, TVs, and "electric other". We also identified and include in our baseline energy use for dehumidifiers, pool pumps, video game consoles, vacuum cleaners, elevators (i.e., in multi-family homes) and "vampire loads" representing standby energy use from not-otherwise-identified devices. Commercial AEO enduses include PCs and non-PC office equipment (2.1 Quads combined) and 2.5 Quads of commercial energy classified by the AEO as "Other uses".[6] Measures we were able to characterize include pumps, transformers, elevators and escalators, water treatment and irrigation, and fume hoods.
- **Typically excluded** (Residential 0.4 Quads, Commercial: 5.5 Quads): excludes from our baseline (in most analysis) energy uses that lack sufficiently detail to analyze and those outside the scope of BTPs influence. The detailed AEO tables for residential categorize 3.0 Quads as "Electric Other"; we were only able to detail 2.6 Quads as described in "Miscellaneous loads" above. The detailed AEO tables for commercial include two categories difficult to analyze, namely "Other" (4.1 Quads electricity, 0.5 Quads of other fuels) and "Unspecified" (3.1 Quads of electricity, 1.2 Quads of other fuels). All 1.7 Quads of other fuels lie outside BTP's scope (and most lack sufficient detail for analysis); the remaining 7.1 Quads of electricity break down as follows. One major technology element, data centers (forecast to represent 2.0 Quads in 2030),

[5] Numbers do not total due to rounding.

[6] The AEO indicates this includes miscellaneous uses, such as service station equipment, automated teller machines, telecommunications equipment, medical equipment, pumps, emergency generators, combined heat and power in commercial buildings, manufacturing performed in commercial buildings, and cooking (distillate), plus residual fuel oil, liquefied petroleum gases, coal, motor gasoline, and kerosene.

are typically excluded from the baseline because they are outside BTP's current scope, though they are included in the baseline for technical analysis and other applications of the tool. The 1.8 Quads of the electricity lacks sufficient detail to analyze, 2.5 is classified in miscellaneous loads above, and 0.9 has been identified using detailed resources as described in the "refrigeration" and "washing and drying" uses described above.

These data are summarized in Table 1.

In conclusion, it is worth noting that there is significant flexibility in defining the baseline for the tool to allow additional analysis. For example, identifying a citable data source that specifies only federal building energy use would allow us to tailor the analysis to solely that segment. Similarly, the tool could perform analysis for specific states or localities, other nations, or even the entire world if sufficiently reliable and detailed energy use information becomes available.

Table 1. Baseline Energy Use in the Prioritization Tool to Analyze the BTP Portfolio

2030 Primary energy use in baseline (Quads)			
Enduse	**Residential**	**Commercial**	**Total**
Heating	5.2	2.2	7.4
Cooling	2.9	2.0	4.9
Ventilation	0.6	2.0	2.6
Lighting	1.4	3.9	5.3
Water heating	2.9	0.7	3.6
Refrigeration	1.5	1.6	3.1
Washing & Drying	1.5	0.3	1.8
Cooking	0.8	0.3	1.1
Misc. loads	6.2	4.6	10.8
Typical baseline	23.0	17.6	40.6
Data centers	N/A	2.0	2
Electric, insufficient data	0.4	1.8	2.2
Other insufficient data	0.0	1.7	1.7
Total excluded	0.4	5.5	5.9
AEO 2010 forecast	23.4	23.1	46.5

In Table 1, data are detailed by standard end-use categories with exclusions identified and compared to the *Annual Energy Outlook 2010* forecast for 2030.

3 Baseline Energy Use and Technical Potential Calculation

This section provides information about our treatment of the tools methodology and describes the mathematical formulation of energy use, efficiency, and service demand. This section also shows the formulas used in the engine that performs the energy use and cost calculations and introduces the technical potential of an energy efficiency measure, including its calculation.

3.1 Mathematical Formulation and Baseline Definition

No commonly accepted definition for energy efficiency exists. For the purposes of identifying opportunities to improve the annual energy use associated with buildings on a macroeconomic scale we define for each "service" delivered (e.g., maintain an occupied space at a comfortable temperature, providing sufficient light):

$$U = S \times E^{-1} \times D$$

[BTU/year] = [Units] x [BTU/service demand] x [Service demand/unit/year]

Where:

- *U* is the total energy use associated with the service (e.g., trillion Btu primary energy per year)
- *S* is the equipment stock associated with the service (e.g., number of furnaces in use in homes in 2010, square feet of floor space)
- *E* is the efficiency (or more formally intensity) indicating the energy required to meet the service demand (e.g., Btu of heat output per Btu of fuel input or lumens per watt per square foot of floor space); note that this quantity divides the other quantities on the right-hand side of the equation (i.e., the superscript denotes inverse)
- *D* is the annual service demand per unit stock (e.g., Btu of heating required to maintain occupant comfort per home, lumens per year per square foot of building space).

The tool analyzes the opportunity for an energy savings measure to reduce energy use (*U* in the formula above) in a specific market. We define:

- **Measure**: a change in the technology, system, behavior, or other aspects of energy used to provide a given service. Examples applicable to the BTP include researching and developing light emitting diodes to replace existing, less efficient light sources; developing technical specifications for rooftop units; and developing and enforcing minimum efficiency standards for home refrigerators.
- **Market**: the specific (macroeconomic) subset of building energy use applicable to a given measure. Examples include all high-quality lighting applications in homes and commercial buildings; commercial cooling in all buildings (or specific climate zones or building types); and all home refrigerators to be purchased after a certain year.

The technical potential represents the first analytic quantity of interest. It corresponds to the change in energy use in a market realized by implementing a given measure in that market. It also represents the theoretical maximum change in energy available as it is free of practical constraints such as financing and deployment considerations. The model defines the technical potential as measured from a baseline specific to the measure and the market. Given the intimacy between the baseline and technical potential, we define them both here simultaneously.

The following equation expresses the total baseline energy use, U^b, in a given year, (y), of a given market comprising the sum of annual baseline energy use of *i* technologies relevant to that market, or:

$$U^b(y) = \sum_i U_i^b(y) = \sum_i S_i^b(y) \times (E^{-1})_i^b(y) \times D_i^b(y) = \sum_i S_i^b(y) \times C_i(y)$$

Where, given data available for most of the measures in the tool:

- $U_i^b\ (y)$ represents the annual energy use in the baseline of technology i
- $S_i^b(y)$ represents the baseline stock of technology *i* in the market analyzed in year y
- $C_i(y)$ is the energy use (or "consumption") per unit stock of the technology in year y.

Additionally we can define the following two quantities that relate energy use to service demand:

- $E_i^b\ (y)$ represents the efficiency expressed in energy use per unit of service demand for technology *i* in year y
- $D_i^b(y)$ is the service demand in the market (e.g., lumen-hours of lighting) met by technology i in year y.

3.2 Baseline Energy Use and Technical Potential in the Engine

As described in more detail below, we use a simplified stock-and-flow model composed of two alternatives to represent a measure's impact. In reality an energy user will not just have two options but will employ a technology or procedure drawn from hundreds of alternatives. For example a commercial building operator replacing lighting has dozens of lamp, ballast, luminaire, and control choices to make a fully functioning system. Similarly a home owner purchasing a new refrigerator will select from dozens of models with different sizes, annual energy use specifications, designs (e.g., freezer on top vs. side-by-side), and features (e.g., icemaker, through-the-door water dispenser). The prioritization tool analyzes the potential impact of a single measure by representing these hundreds of choices with two alternatives:

1. The "measure" to be evaluated: specifies the technology or procedure being analyzed that is providing energy savings (e.g., condensing furnaces for homes, retro-commissioning a building). We use the subscript "m" to denote this alternative in equations.
2. The "existing" mix of choices: represents the average of all choices currently in use other than the measure to be evaluated. Typically this will represent the population-weighted average of all available technologies (e.g., the average home furnace

efficiency of 0.82 Average Fuel Utilization Efficiency (AFUE), deciding not to retro-commission a building). The subscript "e" denotes this alternative in equations.

Alternatives can most easily be considered technologies but can include energy services, policies, or any measure that intervenes in the economy to change energy use patterns. For example to evaluate the energy savings of the measure, "increase purchases of condensing furnaces for homes" then alternative 1, or "m", represents a state-of-the-art condensing furnace with an AFUE of 98%; alternative 2, or "e", represents the average of the currently installed base with an AFUE of 84%. Similarly the measure "Retro-commission commercial buildings, would take "m" as the decision to retro-commission the buildings and the corresponding "e" alternative would be the decision not to do so. More detail on these alternatives follows.

3.2.1 "Existing" Mix of Alternatives

In all cases we will evaluate placing a measure (e.g., a highly efficient 23 cubic foot home refrigerator) into a market (e.g., primary refrigerators in all single-family, multi-family, and mobile homes). Ideally we would characterize the existing mix technologies by specifying the efficiency of every unit in use, or (more realistically) by specifying a number (e.g., 5-20) of efficiency classes and the stock of each class. For example, in analyzing home furnaces we would need to know the current stock and purchases for all available models. With seven manufacturers capturing almost all of U.S. sales, each offering similar products there are hundreds of available models, all with slightly different real-world efficiency characteristics. In this case it would be possible to simplify this categorization to typical efficiencies (i.e., AFUE) sold in the past two decades; for example one manufacturer offers models with AFUE ratings including 98.5%, 96.6%, 96.5%, 95.0%, 93.0%, 92.0%, 81.0%, 80.0%, and 78.0%. For this example, the appliance standard program does provide a technical support document including this information for historical purchase and forward-looking projections. However, because these data are not available for most measures, we represent the existing mix of "inefficient" technologies by the average efficiency of the currently deployed stock. This characterizes the baseline in year y_0, by its energy use per unit stock, $C_e^b(y_0)$, and the total stock, $S_i(y_0)$. In our gas furnace example this corresponds to y_0 = 2011, $C_e^b(y_0)$ = 83.8% AFUE, and 45 million units. The derivation of these parameters from available data is discussed below.

3.2.2 "Measure" To Be Evaluated

Measure savings are defined as "equipment upgrade" or "demand reducing" which refers to the principle means by which a measure saves energy. Naturally a given measure may both reduce (or increase) demand and upgrade (or worsen) the efficiency of the equipment. We require this simplifying assumption because typically data are only available for the energy use, not both the energy use and service demand; as such we categorize each measure as either:

1. **"Equipment upgrade."** The measure deployed does not impact service demand but does improve equipment efficiency. Replacing a home furnace with a more efficient model (e.g., upgrading from AFUE 0.82 to AFUE 0.92) represents such a savings. In the simplifying case where the baseline is either all the existing alternatives or the measure we are evaluating, we note that the measure does not impact demand, i.e., $D_m^b(y) = D_e^b(y)$, but improves efficiency: $E_e^b(y) \neq E_m^b(y)$. We reference the percentage reduction in energy use of measures of this type to the average efficiency in the starting year of the analysis. Because the average stock after the starting year of the analysis

changes—ideally improves in terms of efficiency over time—the percentage of energy savings changes (likely decreasing over time). The spreadsheet therefore calculates the energy use per unit in a future year *y>0* as:

$$C_m^b(y) = min\Big(\, C_m(y_0), C_e^b(y)\Big)$$

We use the minimum function to be sure that energy use of the measure remains less than or equal to the "existing" mix.

2. **"Demand reducing."** The measure does not change the equipment efficiency but does impact service demand once deployed (e.g., improved controls, improved operation through maintenance, and reduced waste) in which case the converse holds: $D_m^b(y) \neq\ D_e^b(y)$, but $E_e^b(y) = E_m^b(y)$. The spreadsheet therefore calculates the energy use per unit in all years as:

$$C_m^b(y) = \frac{C_m^b(0)}{C_e^b(0)} \times C_e^b(y)$$

We label the latter as "demand reducing" because the opportunity to reduce service demand persists as the market improves the efficiency of its energy-using stock. We label the former as "equipment upgrade" because improvements in stock efficiency are gradually adopted into the baseline and thus the opportunity to improve to the specified technology level is not persistent over time. Relaxing the simplifying assumption that a measure either reduces demand or upgrades equipment would require a full stock-and-flow treatment of hundreds of technology options. Initial comparisons of the tool's output to the full stock-and-flow model used for developing the recent refrigerator standard (Building Technology Program, 2012) indicated this would provide only a slight improvement in the accuracy of the calculations so is deemed beyond the tool's scope.

3.3 Calculating the Baseline Energy Use

Given the above definitions, it is now straightforward to see that the baseline energy use in a particular year for a particular market is:

$$U^b(y) = S_m^b(y) \times C_m(y) +\ S_e^b(y) \times C_e(y)$$

Typically the tool is striving to specify these four parameters for each of 25 years, y=2011-2035, as such we have 100 values to determine. Given the measure's efficiency improvement we have $C_m(y)$ as described in section 2.2 above. To calculate the baseline values $S_e^b(y)$ and $C_e^b(y)$, the calculation requires two data elements and an equation defined by three parameters that are derived by minimizing an objective function (describe below). These five elements are:

- **Data element #1**. Total energy used in the market by year, $U^b(y)$; this is typically provided as site energy and then converted to source energy given data availability and to allow calculation of fuel switching options. Most measures use data from the National Energy Modeling System (NEMS) output tables available from EIA for the years 2010-2035 as discussed in section 2.3.

- **Data element #2**. Total stock in the market, $S^b(y) = S_e^b(y) + S_m^b(y)$. These data are also typically gathered from the detailed NEMS output tables.

- **Fit parameter #1**. Annualized change in the per-unit energy consumption, C_e, of the "existing" mix of alternatives: *f*. This represents the average efficiency improvements of the enduse expressed as percent per year. In the limiting case where $S_m^b(y) = 0$ for all years then *f* takes the value $f = 1 - \left(\frac{C_e(2035)}{C_e(2011)}\right)^{\left(\frac{1}{(2035-2011)}\right)}$
- **Fit parameters #2 and #3**. Bass adoption coefficients "*p*" and "*q*" (see description in Section 5.5 and (Bass 1969)) used to compute the share of annual sales of the measure being analyzed.

With these data and variables the engine calculates:

$$U^b(y) = S_m^b(y) \times C_m^b(y) + \ (S^b(y) - S_m^b(y)) \times (C_e^b(y_0) \times (1-f)^{(y-y_0)})$$

where:

- $U^b(y)$ is the market specific energy use in the year *y* provided as a tool input as described above.
- $S_m^b(y)$ derives from the Bass adoption coefficients fit; as described in section 5.1, $S_m^b(y_0)$ is taken as 0 in the first year of the analysis, y_0, (i.e., before product introduction there are none in the stock) and all subsequent years $S_m^b(y) = (p + q \times F(y)) \times (1 - F(y))$, where $F(y) = \frac{S_m^b(y-1)}{S^b(y)}$. $S^b(y)$ is the total stock in the market (typically taken from the detailed tables as described above), and *p* and *q* are the adoption coefficients described in section 5.5.
- $S^b(y)$ is the total stock in year *y* provided as a tool input as described above.
- $C_m^b(y)$ is the energy use per unit stock of the measure being analyzed. It represents a user input for each measure and must be specified as "equipment upgrade" or "demand reducing" as described above. These are taken from the data sources as described above and detailed in Appendix 2.
- $C_e^b(y_0)$ is the average efficiency in the first year of analysis, y_0. It is directly calculated from the data: $C_e^b(y_0) = \frac{U^b(y_0)}{S^b(y_0)}$.
- *f* is fit parameter #1: the annual improvement in the "existing" mix of alternatives. It represents the gradual change in the equipment stock exclusive of the measure being analyzed. For example, currently window stock is improving from an R-value of around 1 in the 1990's to over 1.5 today; this improvement will likely continue as R-3 windows represent a significant share of the purchases even if R-5 never reach meaningful scale in the marketplace. The fit parameter *f* captures this trend of improving window performance excluding the measure we could analyze (i.e., increasing R-5 adoption through volume purchase programs or ENERGY STAR most efficient labeling).

This presents us with the challenge of fitting 25 data points (i.e., the energy use in each year $U^b(y)$ for all y 2011-2035) using three variables: *f*, *p*, and *q*. The tool uses Excel Solver to fit these parameters under reasonable constraints: $0 < p < 0.1$, $0 < q < 0.25$, $-5\% < f < 5\%$. We deem these ranges reasonable because:

- A negative "p" or "q" coefficient in the Bass model is not well defined unless we allow these coefficients to vary with time. Allowing time varying coefficients was explored and deemed beyond the scope of this tool given the data requirements and limited data availability.
- Literature review (Elliott 2004) of modeling using the Bass coefficient across many types of technologies suggests p and q rarely exceed these maximum.
- The average and standard deviation of *f*, *p,* and *q* were 0.16%, 0.11%; 0.5%, 1.2%; and 0.5%, 3.7% respectively.

We include a fourth parameter, the range of years over which to fit, to the fitting procedure when total energy use data is particularly complicated. This allows the fit to ignore years with well forecast data that falls outside the functional form (e.g., a transition in appliance standards such as caused by the Energy Independence and Security Act of 2007).

We use an objective function, *Z*, which represents the weighted sum of four terms with weights chosen to give similar importance to the known and forecast years. Specifically we construct:

$$Z = \mathrm{w}_0 \times \sqrt{\chi^2} + \mathrm{w}_1 \times \Delta\mathrm{U}_{2035} + \mathrm{w}_2 \times \Delta\mathrm{U'}_{2035} + \mathrm{w}_3 \times \Delta\mathrm{U''}_{2035}$$

- $\sqrt{\chi^2}$: The square root of the sum of the squared difference between the data provided for $U^b(y)$ and the fit values for all years *y* in the fit range. We multiply this by $w_0 = 1$.
- Final year (U): We add the difference between the fit and data values for the final year, i.e., $\frac{w_1}{U^b(2035)} \times \left|U^b(2035) - \widetilde{U}^b(2035)\right|$, where $\widetilde{U}^b$ indicates our baseline fit. We take $w_1 = \frac{65}{3}$ as this final year represents one of the three most influential quantities with "forecasting power" on the 65-extrapolated data points.
- Slope (U′): We add to this sum year the difference in first derivative between the data and the fit of the final five years of the fit period, i.e., $\frac{w_2}{U^b(2035)} \times \left|\left(U^b(2035) - U^b(2030)\right) - \left((\widetilde{U}^b(2035) - \widetilde{U}^b(2030)\right)\right|$. We also take $w_2 = \frac{65}{3}$ as the slope holds also represents one of the three most influential quantities with "forecasting power" on the 65-extrapolated data points.
- Curvature (U″): We add to this sum of χ^2 and the final year the difference in derivative between the data and the fit of the final five years of the fit period, i.e., $\frac{w_3}{U^b(2035)} \times \left|\left(U^b(2035) + 2 \times U^b(2033) - U^b(2029)\right) - (\widetilde{U}^b(2035) + 2 \times \widetilde{U}^b(2033) - \widetilde{U}^b(2029))\right|$. We also take $w_3 = \frac{65}{3}$ as to give this second derivative also one-third the "forecasting power" on the 65-extrapolated data points.

Using a total of four three parameters introduces a high probability that the optimized value returned by the solver represents a best-fit solution that is local to the initial starting conditions rather than a global best-fit solution. We use initial conditions representing absence of the advanced measure from the market place, i.e., $p = q = 0$ with *f* set as the average annual efficient improvement of the stock. To reduce the probability of finding a local best-fit that does not represents the global best fit we randomize the starting positions over the allowed range and perform six random fit operations per measure. We determined that six randomized staring points was likely sufficient for finding a global minimum by performing ten random fit operations on 100 measures and noting that no reduction in the optimization occurred for these measures in random fits 7-10. We can loosely interpret the optimization function as the average annual uncertainty in the fit; the average and median of our optimization function are 1.4% and 0.7% respectively. Any measure that exceeded 5% was refit with additional random iterations until the optimization function returned was less than this 5% threshold; this was required for 39 measures.

3.4 Calculating the Technical-Minimum Energy Use and Technical Potential

In order to calculate the potential for energy efficiency we needed to move beyond the baseline and create alternate scenarios of energy use for the "markets" in to which we are evaluating the measures. The market for a measure consists of selected existing energy using technologies that could be displaced by the measure. The baseline energy use associated with these units is the existing energy use of the market. The difference between the market's baseline use and energy use in some scenario *X* is wholly expressed by changing the stock for the existing mix of "inefficient" technologies and measure being evaluated, i.e., $S_e^X(y) \neq S_e^b(y)$ and $S_m^X(y) \neq S_m^b(y)$. Thus, we can use the formulation given in sections 3.1 and 3.3. to define the energy efficiency potential of scenario *X*, $EE^X(y)$, as the difference in the energy consumption between these two scenarios, *P*, in the market where we are deploying our energy efficiency measure:

$$P^X(y) = U^b(y) - U^X(y) \text{ , where:}$$
$$U^b(y) \text{ is defined above and}$$
$$U^X(y) = S_m^X(y) \times C_m(y) + S_e^X(y) \times C_e(y)$$

The simplest quantity to calculate is the technical-minimum energy use and the corresponding technical potential energy efficiency savings. If we imagine replacing all the existing stock with the measure which impact that is being evaluated we can take for all years *y*: $S_e^X\ (y) = 0$ (i.e., none of the existing stock remains) and $S_m^X\ (y) = S\ (y)$ (i.e., the measure represents the entire stock in each year). This represents the absolute most energy savings a measure offers in year *y*; it does not take into account any real world considerations such as equipment lifetime and turn over or market share/technology adoption considerations. These considerations will be addressed with their own energy use scenarios ("economic-minimum" and "adoption-based" respectively) in later sections.

To denote the technical potential we can use the superscript *A* to identify the technical-minimum (i.e., all the potential) and $S(y)$ to represent the total equipment stock in year *y*. The equations simplify to:

$$U^A(y) = S(y) \times C_m(y) \text{, and}$$
$$P^A(y) = U^B(y) - U^A(y) = S_e^B(y) \times C_e(y) + S_m^B(y) \times C_m(y) - S(y) \times C_m(y),$$
$$\text{upon simplifying:}$$
$$P^A(y) = S_e^b(y) \times C_e(y) - [S(y) - S_m^b(y)] \times C_m(y).$$

Put simply, the energy use in the technical-minimum scenario represents replacing all stock with the efficient stock. The potential for energy efficiency is the difference between the energy used in the baseline and this technical-minimum energy use. It represents the absolute most energy savings offered by the efficiency-measure being analyzed as measured from the baseline scenario. For example, R-10 windows represent a significant improvement over the currently installed base of windows which, across commercial and residential buildings, average an R-value of R-1.8 (D&R International Ltd. 2010). As such, R-10 windows offer an ~82% reduction in energy lost by conduction through windows. Currently 2,460 Trillion Btu of primary energy is lost by conduction through windows, thus the technical potential is about 2,020 Trillion Btu (i.e., 82% of 2,460). It is important to note that capturing this potential requires replacing every window in the U.S. with an R-10 window; this would be neither a feasible nor cost-effective way to save energy.

4 Stock-and-Flow Model and Full-Adoption-Based Potential Calculation

The economic-minimum energy use, and corresponding full-adoption-based efficiency potential, represents a second valuable scenario to consider. It represents the least expensive means to deploy a given efficiency measure into the marketplace. Measures therefore fall into one of two categories defined as follows:

- **End-of-life replacement.** The total installed cost of efficient equipment and appliances is typically much larger than the value of the energy savings they provide (i.e., the present value of the energy savings) over currently installed stock. As such, the only time it may be economically rational to adopt the efficiency measure is when the currently deployed appliance or equipment is retired at the end of its life. This is typically the case for equipment and appliances such as refrigerators, furnaces, boilers, etc.
- **Accelerated replacement.** The present value of the energy savings of other efficiency measures, such as home retrofits and many lighting technologies, exceed the full, installed cost of the efficiency measure. It is economically rational to replace all of the currently deployed stock immediately with the efficiency measure.

We must identify each measure as either an end-of-life or accelerated replacement. Further, we must track over time the stock deployed to determine when units are replaced, eliminated, or added; this is often called a stock-and-flow model. If a measure is cost-effective, defined in section 6 as having a cost of conserved energy lower than the cost of energy for the fuel purchases the measure reduces, this potential corresponds to the economic potential or NPV-positive potential. It corresponds to the scenario where the measure being analyzed represents all purchase; therefore after one full equipment lifetime, 100% of the stock efficiency measure and the technical potential is attained.

4.1 The Stock-and-Flow Model

Ideally one would know the date of purchase and retirement of each and every appliance or piece of equipment in the market and over the time period analyzed. Clearly this level of data is not generally available and would be very costly and logistically difficult to develop. Failing that one could use the recent (e.g., the last 10-20 year) history of purchases and existing stock of classes of efficiency; this approach is taken by both NEMS and the Building Technologies Program's Appliance and Equipment Standards Program. Future purchases are then based on an expected lifetime that determines retirement and replacement of existing stock, growth (potentially) that determines introduction of new stock, and elimination (potentially) that represents retirement without replacement.

4.1.1 Design

The team developed a simple stock-and-flow model in Microsoft Excel that operates on nine families of stock categorized according to their state in the previous year as follows. Each family can be either new additions, up for replacement, or existing (i.e., not up for replacement but possibly eligible for early retirement). New additions require no further characterization while the other two categories are each divided into four families by splitting on two additional variables:

- **Potential action**. These variables can be either eliminated from the stock or replaced (i.e., at end-of-life) or considered for early replacement.
- **Efficiency.** These variables are either the existing mix of "inefficient" technologies or the measure being analyzed (i.e., efficient).

Year Y – 1 stock		
Year Y status	**Year Y action**	**Family (Year Y)**
New	Year Y new additions	9. New
End-of-life (i.e., up for replacement)	Eliminated	1. Eliminated, end-of-life, efficient
		2. Eliminated, end-of-life, inefficient
	Replaced	3. Replaced, end-of-life, efficient
		4. Replaced, end-of-life, inefficient
Existing (may be eligible for early retirement)	Eliminated	5. Eliminated, existing, efficient
		6. Eliminated, existing, inefficient
	Considered for early retirement	7. Early-retired, existing, efficient
		8. Early-retired, existing, inefficient

Figure 2. Categorization of equipment into nine classifications according to efficiency and potential action they undergo when flowing stock from year y-1 to year y.

This presents us with the nine families each having its own treatment in the stock-and-flow calculation. If we assume an existing share of stock in year y=0 (typically this will be all, or nearly all, the existing mix of "inefficient" technologies) we can see that for a given year y>0 the change in stock by type for the full-adoption-based potential is as follows:

1. **Eliminated, end of life, efficient**: are removed from the stock in year y
2. **Eliminated, end of life, inefficient**: are also removed from the stock in year y
3. **Replaced, end of life, efficient**: remain efficient in year y
4. **Replaced, end of life, inefficient**: are replaced with efficient stock in year y
5. **Eliminated, existing, efficient**: are removed from the stock in year y
6. **Eliminated, existing, inefficient**: are also removed from the stock in year y

7. **Replaced, existing, efficient**: remain efficient in year y
8. **Replaced, existing, inefficient**: are replaced with efficient stock in year y only if the measure is of the accelerated replacement type and is available in year y but not in year y-1
9. **"New"**: enter the economic scenario stock as efficient stock; did not exist in year y-1.

4.1.2 Limitations of Our Data and Methodology

Because the information used is the total stock and total energy beginning in 2009, it is worth noting the following assumptions and limitations. If we use the subscript on the stock to denote the family (using *T* to denote the total), then the stock-and-flow model is defined by the following rules:

- "New" and "eliminated" are net additions and eliminations. If the total stock in some year *y* is greater than in year the previous year, *y*-1, we assume that the difference $\Delta S = S_T - S_{N-1} \geq 0$ are all new (i.e., family 9) and there is no stock eliminated (i.e., families 1, 2, 5, and 6 are all unpopulated): $S_9 = \Delta S$; $S_1 = S_2 = S_5 = S_6 = 0$. This assumption introduces no inaccuracy, uncertainty, or information loss into the tool as typically, such as with "pre-70's wall retrofits" and other measures targeting existing buildings only, it is clear that there is no "new" stock entering.
- Similarly, when stock are eliminated (i.e., $\Delta S < 0$), we assume that $S_9 = 0$; $S_1 + S_2 + S_5 + S_6 = -\Delta S$.
- Finally, our limited history and detail require two approaches to determine the number of efficient and existing stock eligible for end-of-life replacement (i.e., $S_{eol,m}(N) = S_1(N) + S_3(N)$; $S_{eol,e}(N) = S_2(N) + S_4(N)$ as determined by the lifetime of the measure being analyzed, *L*, and the year, *y*:
  - If $y - L < 2009$ then the total stock eligible for end-of-life replacement is calculated by dividing the stock in 2009 (assumed to be all the existing mix of "inefficient" technologies) by the lifetime L; i.e., $S_1(N) + S_3(N) = \frac{S_m(2009)}{L_m} = 0; S_2(N) + S_4(N) = \frac{S_e(2009)}{L_e}$. This represents the assumption that the total stock was constant in all previous years and equal to the stock in 2009. This does introduce uncertainty and a potential inaccuracy as stock likely grew or shrank by some amount in the previous years.
  - If $y - L \geq 2009$ then the total stock eligible for end-of-life replacement equals the purchases of stock in year y-*L*; calculation of this quantity is defined below.

4.1.3 Stock Flow Calculations

In the general case each of these nine families has one of four calculations performed on it in transferring its stock from one year to the next (i.e., "flowing" the stock over time). With the initial conditions established this rule-set completely defines the flow calculations needed to determine the share of each stock, thus fully defining any scenario energy use and savings potential. The four calculations and where they apply are described below and shown in Figure 3.

Year Y Calculations by Family	
Calculation performed	**Family**
A. Competed	9. Year Y new additions
	4. Replaced, end-of-life, inefficient
B. Flow in (i.e., not competed)	3. Replaced, end-of-life, efficient
	7. Early-retired, existing, efficient
C. Eliminated	1. Eliminated, end-of-life, efficient
	2. Eliminated, end-of-life, inefficient
	5. Eliminated, existing, efficient
	6. Eliminated, existing, inefficient
D. Possibly switched	8. Early-retired, existing, inefficient

Figure 3. Identification of how stock-and-flow calculation treats each equipment classification.

A. **"Competed"**: families 9 (New) and 4 (Replaced, end of life, inefficient) in year *y*-1 are divided according to the scenario-specific rules (as described for the maximum-adoption potential in section 4.2 or the bass-adoption potential in 5.5) to determine the fraction that are the existing mix of "inefficient" technologies versus the measure. In the case of the full-adoption-based scenario, the efficient measure captures 100% of this stock as explained above.

B. **"Flow-in"**: families 3 (Replaced, end of life, efficient) and 7 (Replaced, existing, efficient) remain 100% the efficient measure from year *y*-1 to year *y*. Typically, family 7 will be unused, as early retirement of efficient stock is an unnecessary (and undefined) operation (i.e., the original stock was already retired and replaced with efficient stock). Assuming family 3 remains efficient implies that once a customer has adopted an efficient measure that consumer will always repurchase that measure (or potentially purchase an even more advanced measure).

C. **"Eliminated"**: families 1, 2, 5, and 6 are removed from the stock in year *y*. The number of stock in other families requires first calculating the stock in these four as follows. If $\Delta S < 0$:

a. Family 2 (Eliminated, end of life, inefficient) are eliminated first, up to the total number of the existing mix of "inefficient" technologies that are eligible for end-of-life replacement; i.e., $S_2(N-1) = \min\left(-\Delta S(N), S_{eol,e}(N-1)\right)$.

b. Family 1 (Eliminated, end of life, efficient) are eliminated next, up to the total number of the measure being analyzed that are eligible for end-of-life replacement, i.e., $S_1(N-1) = \min\big(-\Delta S(N) - S_2(N-1), S_{eol,m}(N-1)\big)$.

c. Family 6 (Eliminated, existing, inefficient) are eliminated third. Note that stock in this family represent the existing mix of "inefficient" technologies of stock removed from service before the end of their useful life and is required to be less than the total number of existing mix of "inefficient" technologies of stock in service in the previous year: $S_6(N-1) = \min(-\Delta S\ (N) - S_2(N-1) - S_1(N-1), S_e(N-2))$.

d. Finally, family 5 (eliminated, existing, efficient) are eliminated last. Similar to family 6, stock in this family represent previously purchased stock of the measure being analyzed that are retired before the end of their useful life. Also similar to family 6, they are calculated by taking: $S_5(N-1) = \min(-\Delta S\ (N) - S_2(N-1) - S_1(N-1) - S_6(N-1), S_m(N-2))$

D. **"Possibly switched":** Family 8 (replaced, existing, inefficient) represents stock from the existing mix of "inefficient" technologies eligible to be retired early and simultaneously replaced with the measure being analyzed. Typically this represents some type of retrofit activity such as retro-commissioning an existing commercial building or blowing insulation into un-insulated wall cavities in existing buildings. It includes all stock from the existing mix of "inefficient" technologies that are not eliminated or eligible for end-of-life replacement; i.e., $S_8(N-1) = S_e(N-1) - S_2(N-1) - S_4(N-1) - S_6(N-1)$. This calculation is only performed if the measure is suitable for accelerated replacement; otherwise, $S_8(N-1) = 0$.

Individual scenarios are defined by changing the operations performed on each of these four sets of families. For most measures in our current database, only the performance calculation for "competed" and "possibly switched" families changes. Specifically, for the full-adoption-based scenario, all stock in these families (i.e., 4, 8, and 9) are replaced with the measure being analyzed (i.e., efficient) at the end of their lifetime (or as soon as the technology is available if eligible for "early retirement"). A second scenario, the bass-adoption-based energy use scenario (discussed in section 5), applies a Bass adoption model to the "competed" and "possibly switched" families to determine the share of purchases that are efficient.

This procedure fully defines the stock-and-flow calculation for a two-family model with known total stock: we classify the stock in year *y*-1 into these nine families which then determines the mix of stock in year *y*. We repeat this classification in year *y* to determine the mix of stock in year *y*+1, and so on. The tool implements this procedure in Excel as described above and as documented in Figure 4.

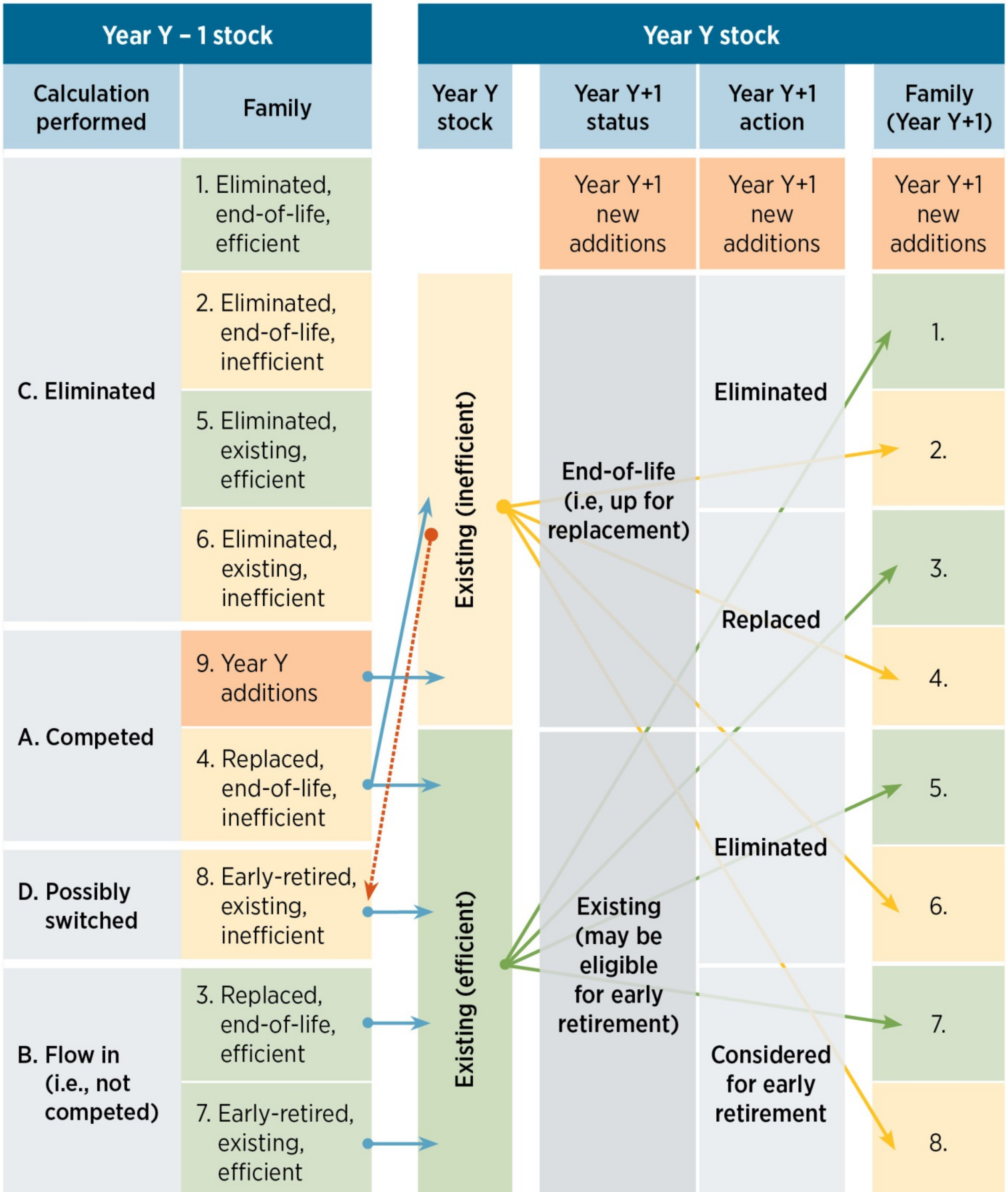

Figure 4. Graphical depiction of our stock-and-flow calculation.

Blue lines indicate flow of stock before it is identified as efficient or inefficient; red, dashed show a "negative" flow to stock (i.e., elimination); yellow and green show inefficient and efficient stock flows (respectively).

4.2 Calculating the Full-Adoption-Based Energy Use and Economic Potential

The process of calculating the economic-minimum energy use and economic potential follows the same procedure used above to calculate the technical-minimum energy use and technical potential. Using the superscript *G* to represent the full-adoption-based scenario we express the energy use, *U*, in this scenario as:

$$U^G(y) = S_m^G(y) \times C_m(y) + S_e^G(y) \times C_e(y),$$

Where we recall that for each year, *y*:

- *S* indicates the equipment stock
- C indicates the energy use per unit stock, and
- The subscripts, *m* and *e* represent the measure being analyzed and the existing mix of "inefficient" technologies of alternatives, respectively.

We can now calculate the energy savings potential, *P*, as:

$$P^G(y) = [S_e^G(y) \times C_e(y) + S_m^G(y) \times C_m(y)] - [S_e^b(y) \times C_e(y) + S_m^b(y) \times C_m(y)],$$

Or equivalently:

$$P^G(y) = [S_e^b(y) - S_e^G(y)] \times C_e(y) + [S_m^b(y) - S_m^G(y)] \times C_m(y)$$

The quantities $S_e^G(y)$ and $S_m^G(y)$ are determined using the stock-and-flow calculation described above.

4.3 Treatment of Cost Compression

The stock-and-flow model also approximates the "learning curve" effect: the empirical fact that technology costs decrease over time in proportion to the cumulative volume of sales. Specifically we characterize each measure by its incremental price at the time of commercialization. "Time of commercialization" roughly corresponds to production volumes from one full factory (or one at-scale workforce) where economies of scale are captured. We apply a learning curve that reduces cost by 30% (F. Ferioli, 2009); (Weiss, Patel, & Junginger, 2010) per doubling of cumulative purchases of the efficiency measure.

4.4 Example Full-Adoption-Based Potential Calculation

Continuing on the example that concluded our treatment of the technical potential in section 3, we can calculate the full-adoption-based potential for R-10 windows. The lifetime for windows currently installed is approximately 30 years. Because the tremendous cost of replacement windows in a home (typically \$10,000-\$20,000) does not justify their lifetime energy savings our measure, "upgrading windows to R-10" is an "end-of-life" stock-and-flow calculation (i.e., family 8, "early-retired existing inefficient", representing calculation "D" from Figure 3, is not upgraded).

Our analysis neatly breaks into two time periods; the first is the "transition" period: the first 30 years after R-10 windows enter the market during which 2.5% (i.e., 1/40th) of previously-installed windows are replaced with R-10 windows and all new purchases are R-10 windows. During this period purchases in each family for each calculation performed as described above are as follows:

A. Competed: Families 4 and 9 become R-10 windows

B. Flow: Family 3 is unoccupied (i.e., no R-10 windows have reached the end of their life) and family 7 unused (i.e., there is no reason to early-replace R-10 windows)

C. Eliminated: Families 1, 2, 5, and 6 are vacant because our data source indicates the stock (i.e., number of windows or number of homes) is increasing

D. Possibly switched: Family 8 is unoccupied because this is not an early-retirement measure.

Once the transition period has passed we are in a steady state where all windows, existing, end-of-life, and new, are R-10 windows. Only new purchases (family 9) and replaced, end-of-life efficient (family 3) are non-zero and all purchases are of R-10 windows.

Figure 5 shows the energy use scenarios for the baseline case (blue), technical (red), and full-adoption-based (green) scenarios. The difference between the red and blue lines presents the technical potential in a given year while the difference between the green and blue lines provides the economic potential in a given year. Note the transition phase (2011-2041) for the full-adoption-based scenario that shows the stock turn-over as the efficiency is captured and the steady state phase where the technical and full-adoption-based scenarios are identical (i.e., all stock is R-10 windows). While this analysis provides a more realistic calculation of the potential

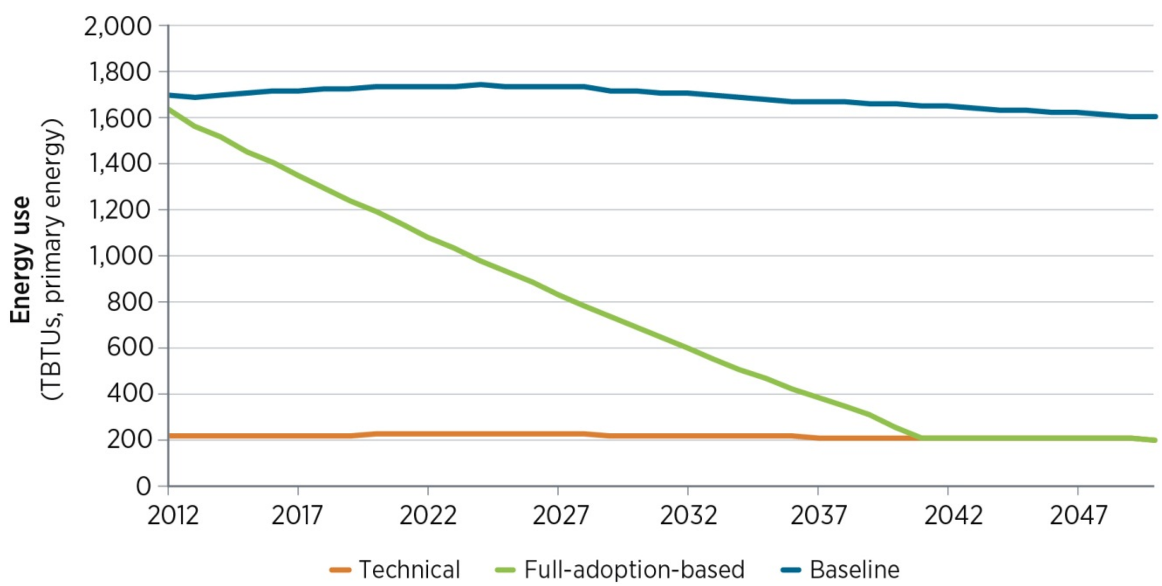

Figure 5. Primary energy use

R: R-10 windows

Technical, Full-adoption-based, and Baseline energy scenarios for R-10 windows.

energy benefits of R-10 windows, it still does not provide information on the cost effectiveness (i.e., at current and future prices does the cost of R-10 windows justify their investment by homeowners) nor the likely uptake (i.e., what fraction of the 100% of purchases assumes are likely to be R-10 windows). Cost effectiveness in particular should be analyzed in concert with this analysis.

5 Adoption Logic and Adoption-Based Potential

This section describes the standard approach to technology diffusion as introduced by Frank Bass (Bass 1969) and our implementation of the Bass model described. We proceed to support our choice of this model by discussing alternatives, reviewing procedures to determine model parameters, and discussing model limitations. We conclude by describing how we construct an energy use scenario and its energy efficiency potential; we also describe how to apply the Bass model to these equations to define the adoption-based potential.

5.1 Description of the Bass Adoption Curve

The Bass adoption model (Bass 1969) describes the diffusion of a new technology introduced into an existing market using the fraction of sales in a given year *y:* F*(y)*. It models technology adoption in a manner similar to disease infection. It is defined by two parameters, p, and q, using the differential equation:

$$\frac{dF(y)}{dt} = (p + q \times F(y)) \times (1 - F(y))$$

The coefficients "p" and "q" represent the effectiveness of communication on the adoption of the technology. They typically take values between 0 and 1 and can be interpreted as:

- "p": The influence of mass-media, sales and marketing, and other "external" factors. In management and marketing communities it is often called the external parameter because it is used to represent the positive effect that marketing has on driving "innovators" to adopt a new technology. It is helpful to think of this as the first year sales ($F(y_0)=p$) which shows that, at low adoption ($F(y) << 1$) p represents the annual growth in market share.
- "q": Word-of-mouth communication in the (social) marketplace. This is often termed the "word-of-mouth" effect on the "imitators" and represents the empirically observed increase in sales as "innovators" interact with non-innovators to increase awareness and drive product adoption. It is helpful to think of "q" as the annual growth rate of F. This can be seen by noting that with $p<<q$ and with ($F(y) << 1$) we can approximate $1-F(y) = 1$to note that $\Delta F(y) \sim (q \times F(y))$, or $\frac{\Delta F(y)}{F(y)} \sim q$.

Note that we take the initial condition that for all years prior to market introduction, y_0, $F(y) = 0$. Our tool implements this (computationally) by taking $\Delta F(y)$ as the change in sales fraction from year y-1 to year y as:

$$\Delta F(y) = (p + q \times F(y-1)) \times \left(1 - F(y-1)\right)$$

5.2 Estimation of "*p*" and "*q*" Parameters

As mentioned in the baseline discussion above, our procedure of fitting to the NEMS forecast provides the baseline "p" and "q" coefficients. Defining alternate cases (other than the technical-minimum and adoption-based scenarios that do not use the adoption logic) requires modifying these "p" and "q" coefficients. We use an existing set of ten pairs of "p" and "q" coefficients showing the adoption of energy efficient technologies after intervention in the marketplace by DOE (Anderson 2004). These coefficients are binned into five ranges of "p" and "q" to derive a bin spacing of 0.0139 and 0.117 for "*p*" and "*q*" respectively. The scenario then defines the impact depending on the type of intervention as follows:

- Research and development (R&D) efforts increase the "*q*" coefficient by the greater of one bin-spacing and 50% of the baseline value. This represents improvement in product quality, cost reduction, and other factors that will accelerate the network effect. R&D can also accelerate the year of market introduction. Per the National Research Council (National Research Council 2004) we default to a value of five years and introduce variations when the advanced technologies seem more or less likely to succeed.
- Deployment efforts increase the "*p*" coefficient by the greater of one bin-spacing and 50% of the baseline value. This represents the market transformation effort induced by programs such as ENERGY STAR.
- Standards and codes efforts set adoption to 100% in the year they take effect.

A second approach would determine the coefficients in light of the market environment (e.g., complexity of supply chain, means of product distribution) and technology attributes (e.g., auxiliary benefits, payback times, capital requirements) the measure strives to change. A third approach could focus on the historic impact of different program types (e.g., ENERGY STAR impacts) rather than the markets the measures seek to impact. We pursued neither approach to completion given data and time requirements.

5.3 Extensions and Alternatives to the Bass Adoption Model

Extension and alternatives to the Bass adoption approach exist (Mahajan Muller and Bass 1990); we review them briefly to demonstrate that the Bass model is a sufficiently accurate representation of consumer behavior for the data we have gathered. Many researchers have contributed to the field begun by Bass in 1969. Recent reviews by Peres et al. (2010) and Mahajan, Muller, and Bass (1990) have highlighted the pros, cons, and challenges of the various extensions (e.g., multiple levels of "early adopter," and addition of price) and alternatives [e.g., affordability and marketing impacts (Golder and Tellis 1998)]. The majority of this work has focused on private-sector marketing analysis, including sales forecasting to accelerate adoption and maximize sales of a given product. Estimating potential future benefits of actions (Anderson 2004) (e.g., advertising, price reductions) represent the other typical application of this work. One essential difference between these two approaches is our simplifying assumption that market adoption approaches 100% over time. Often marketers are trying to determine the total market future sales and market penetration whereas we have a-priori defined the total market.

With that difference in mind we explored three variations to a 100% ultimate penetration Bass model in light of the uncertainty of estimating our Bass coefficients. Figure 6 shows the maximum excursion from our modeled adoption as follows. The top panel displays the adoption assumed correct using a Bass with "*p*" value of 0.234 and "*q*" of 0.075 (values approximately equal to the average of our database). It presents two realizations of each of the following four alternate models:

- Bass model where the "*p*" values were changed to 0.035 and 0.018 and *q* is held constant. This variation in "*p*" represents +50%/-30% uncertainty in the coefficient;

an uncertainty roughly equal to the standard deviation of "p" in our data set. This uncertainty drives a +/-4-year uncertainty in date of 50% market adoption and a +/-4%-uncertainty in adoption level after 40 years.

- A first extension to the Bass model that allows for a group of early innovators that only receive influence from external factors. We vary the size of this population from 10% to 20% of the population. The "p" parameter is taken as the same for all of the population and chosen so the model gives the same 40-year adoption as the correct Bass model.
- A second extension of the Bass model that smoothly varies either the "q" parameter ($q_t = q_0 \times F_t^a$) or the "p" parameter ($p_t = p_0 \times (1 + F_t)^{-b}$). The coefficients a and b are chosen so this model gives the same 40 year adoption as the correct Bass model.
- An alternative to the Bass model that determines adoption based on affordability (Golder and Tellis 1998), consumer sentiment, and market push. We use an annual price-reduction (10%), inflate personal income at 3.3% annually, and fix "consumer sentiment" constant. The two realizations apply Gaussian distributions of market presence, each with a width of 10 years; one is peaked at 2012 and the other at 2020, as indicated.

In Figure 6, the bottom panel shows the difference of each of the models from the correct Bass model, where:

- The red line represents the standard deviation of both realizations of the three models that were examined beyond the Bass model (i.e., red, green, and purple in the top panel)
- The green line provides the maximum positive deviation of these six models from the correct Bass model
- The blue line is the maximum negative deviation of these six models from the correct Bass model
- The black dotted lines show the deviation of each of the Bass models (p=0.03) arising from uncertainty in the Bass parameters.

Note that the deviation from the central model arising from the uncertainty in Bass parameters brackets deviations from the other models in most years. This suggests to us using an extension of, or alternative to, the Bass model provides limited benefits (i.e., second order corrections). To test the sensitivity of our conclusions to the adoption parameters we vary these coefficients (both systematically and randomly) and note the impact (see section 7).

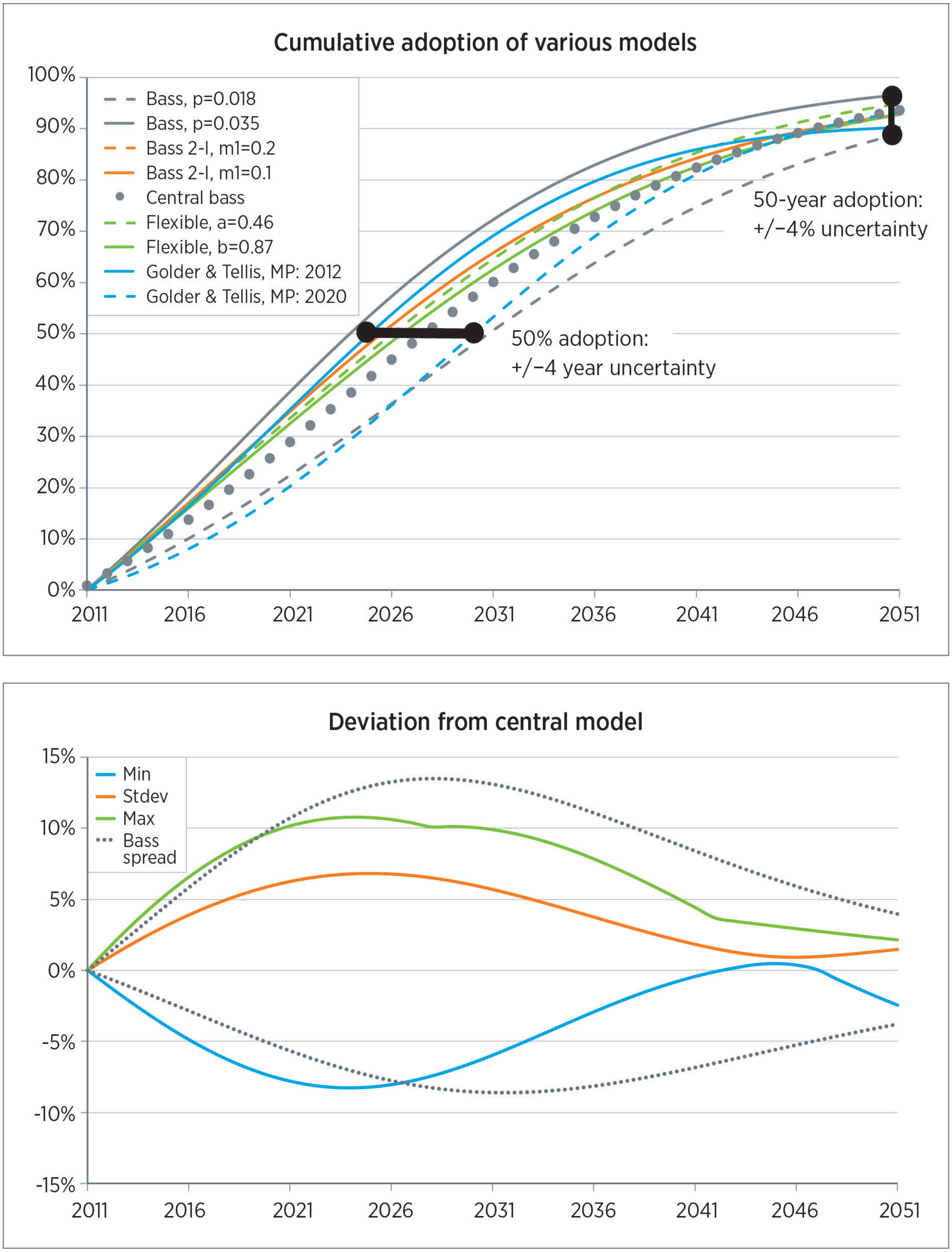

Figure 6. Adoption rate uncertainty arising from variations in adoption model selected.

5.4 Limitations

Despite limitations, the Bass model remains highly relevant because of its ability to fit empirical data well and its simplicity of interpretation. A select set of limitations addressed by the model include:

- **Market size.** The Bass model poorly predicts ultimate market penetration. We have defined 100% penetration for each measure's market, thus eliminating the need to determine the ultimate market size and eliminating it from our implementation of the Bass model. This addresses the concerns of its changing over time and eliminates the error introduced by fitting for this parameter. However, this does represent a simplifying assumption; if the source material(s) used provide an inaccurate characterization of the ultimate market size then that error will be systematically introduced to the estimate.
- **Competition and interaction with other measures.** The Bass model omits the impact of future generations of the technology. We first estimate the impact of each technology independently and then calculate the impact of future generations by including the entire "portfolio" of measures. This provides a first order estimation of interactions and competitions but does not include non-linear effects. The procedure for this "staging" calculation is described in section 6.
- **Market and product attributes.** The Bass model does not connect adoption coefficients to "common sense" attributes such as cost and auxiliary benefits. We attempted to address this limitation with our second alternative of defining "*p*" and "*q*" coefficients; we anticipate this will be a fruitful area of future work.

Given the limitations of the Bass model and the scope of work, there are several factors that we remain unable to address:

- **Stationary assumption.** We assumed "*p*" and "*q*" do not change over time (other than when estimating the impacts of an intervention in a given scenario). As this is the simplification of a complicated market into two parameters we would expect these two parameters to change over time; data and approaches to do so remain outside the project scope.
- **Repurchase dynamics.** We also make the simplifying assumption that once a consumer has adopted the advanced technology they necessarily adopt it at the (future) time of replacement.
- **Other factor.** One can levy other limitations with this approach, including the desire to include factors such as multiple-stage adoption, detailed sub-population analysis, impact of multiple actors with divergent goals, and inclusion of supply chain or other manufacturing and distribution concerns.

We feel that the above approaches sufficiently analyze the size of the uncertainty and limit potential errors within the context of data publically available as of the writing of this report (Golder & Tellis 1998). Future work may include improving the quality and volume of data available to improve on the parameter estimation and addressing the three limitations that were not addressed (as outlined above).

5.5 Defining the "Bass-Adoption-Based" Potential

Following the convention described above and using the superscript "*H*" to represent the Bass-adoption-based scenario we express the energy use, U, in this scenario as:

$$U^H(y) = S_m^H(y) \times C_m(y) + S_e^H(y) \times C_e(y),$$

Where we recall that for each year, *y*:

- S indicates the equipment stock
- C indicates the energy use per unit stock, and
- The subscripts, m and e represent the measure being analyzed and the existing mix of "inefficient" technologies of alternatives, respectively.

We can now calculate the Bass-adoption-based energy savings potential, *P*, as:

$$P^H(y) = [S_e^H(y) \times C_e(y) + S_m^H(y) \times C_m(y)] - [S_e^b(y) \times C_e(y) + S_m^b(y) \times C_m(y)],$$

Or equivalently:

$$P^H(y) = [S_e^b(y) - S_e^H(y)] \times C_e(y) + [S_m^b(y) - S_m^H(y)] \times C_m(y)$$

The quantities $S_e^H(y)$ and $S_m^H(y)$ are determined using the stock-and-flow calculation described in section 4, but now the calculations labeled "A. Competed" and "D. Possibly switched" outlined in Figure 3 are treated differently. In the case of the full-adoption-based potential calculation (i.e., scenario *F* described in Section 4.2), the efficient technology represents 100% of purchases of families in these categories. In the "Bass-adoption-based" potential the families in these categories represent the full market size that can be addressed in each year. The measure being analyzed captures the share of this full market in a given year, *y*, as given by the Bass equation (Section 5.1) where the first year of technology availability, y_0, is the year following completion of R&D efforts (or 2010 if the measure does not require R&D). The Bass coefficients specific to this measure and the treatment of both R&D and standards are detailed in Section 5.2. In summary, selection of the parameters "*p*" and "*q*" vary with time as the nature of the implementation of the energy efficiency measure changes such that:

R&D efforts[7]: increase the "*q*" coefficient as discussed above. Also, they accelerate the year of market introduction by 0-7 years (National Research Council, 2004).

Deployment efforts[8]: increase the "*p*" as discussed above.

Standards and codes efforts[9]: set adoption to 100% in the year they take effect.

Statistics on the baseline, R&D-aided "*q*", deployment-aided "*p*" and years in which appliance standards are applied for the measures in the tool are shown in Table 2.

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[7] If a measure is already on the market this lever is not applied.
[8] If a measure is widely adopted this lever is not applied.
[9] Standards and codes levers are only applied to applicable technologies (e.g., it is unlikely one could develop a standard requiring switching from desktop to laptop computers).

Table 2. Bass Adoption Coefficients from Fit to the Baseline Energy Use for Measures in Full Data Set

	p	q
Min:	0.00%	0.00%
Max:	10.0%	25.0%
Median	0.5%	0.5%
Average	1.2%	3.7%
Standard deviation	2.0%	6.6%

This energy use scenario provides potential savings that are necessarily less than the full-adoption-based potential calculated above. Also, it is both a more realistic (i.e., accurate) characterization of what is most likely to happen after technology introduction but considerably more uncertain given the complexity of market dynamics and the limitations in estimating the "p" and "q" coefficients.

To continue the example developed above using R-10 windows Figure 7 adds to Figure 5 the light-blue line indicating the energy use for the Bass-adoption-based scenario. In this scenario R&D investments accelerate the time of significant market entry by 5 years and increase the "q" coefficient from 0.1% in the baseline to 6.0%. Additionally deployment efforts (e.g., ENERGY STAR labeling) increase the "*p*" coefficient from 0.1% in the baseline to 1.5%. Finally buildings codes that take effect in 2030 insure that all windows installed in homes meet or exceed R-10.

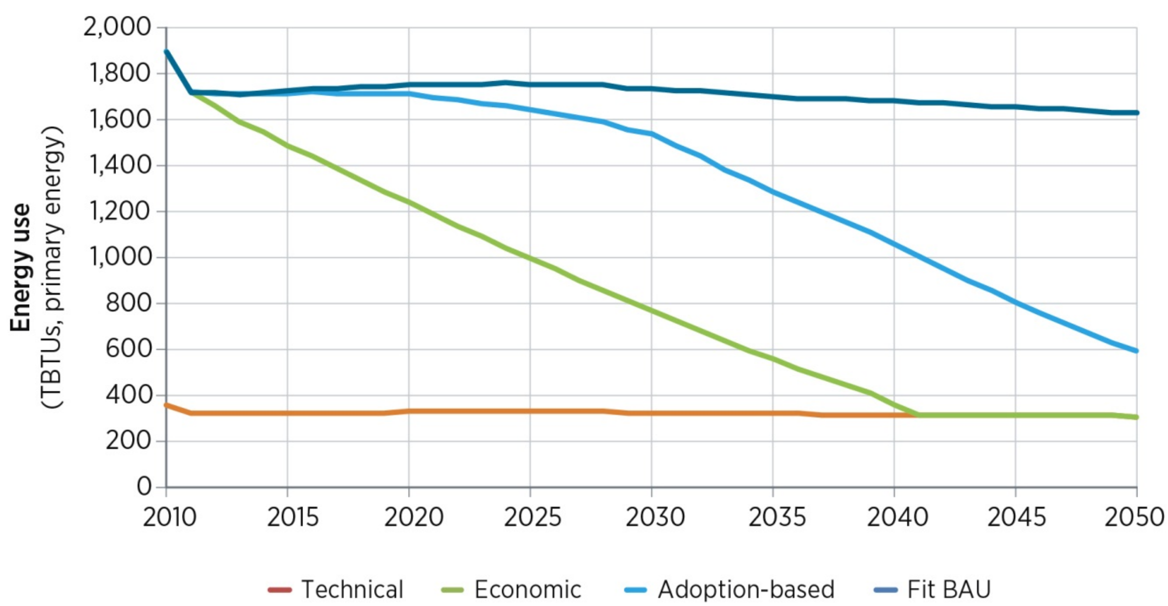

Figure 7. Primary energy use

R: R-10 windows

Bass-adoption-based energy use scenarios for R-10 windows.

This third potential calculation, in addition to the technical and full-adoption potential calculations described above, completes the suite of efficiency potentials we have used to analyze measures. In aggregate they offer the ability to provide a series of satisfying vantage points that can surface technical, economic, or market concerns associated with a particular measure.

6 Developing a Portfolio: Staging Logic

This section describes the method used for aggregating the many measures analyzed into a portfolio of measures to deploy. It motivates the need for an accounting framework (Meier 1982) to "stage" the measures to avoid counting savings that could be captured by multiple measures more than once. It then details the four-step iterative approach to aggregating these savings. Finally it provides an interpretation of these portfolios for the three efficiency potential scenario calculations discussed previously.

Having now calculated the energy use and savings of each measure, we can now build a full scenario by aggregating the impacts of all measures in a given portfolio. However, this requires introducing an accounting framework to avoid "double-counting" savings and attributing any savings that would be double-counted in proportion to the measures pursuing that savings. By first treating each measure against the "flat landscape" where no other measures are introduced (i.e. the "un-staged" technical, full-adoption, and bass-adoption energy potentials defined in sections 3, 4, and 5) and then considering their benefits in the context of other efforts we provided an additional "lens" through which to view the relative benefits of each measure.

We refer to this procedure as "staging" the benefits; it requires a four-step iterative process. First we stage[10] the benefits from lowest to highest based on cost of conserved energy (CCE) [11]. Second we evaluate the overlap of each measure's market to those with a lower CCE as detailed in section 6.2. Third we determine the nature of the interaction between the measures as detailed in section 6.3. Fourth we calculate the "staged savings" by subtracting the savings of all lower-cost measures from each measure in light of steps two and three as detailed in section 6.4. Finally we iterate this process by re-sorting the list by cost of conserved energy and repeating the process until obtaining a stable solution. Each step of this process is detailed below.

It is important to note that staging by CCE is analogous to the procedure used by utilities and regulators to minimize the present value of investments needed to provide energy to consumers. As such, the staging by CCE minimized investments. It does not maximize the energy savings at a given investment level nor minimize the investment needed to reach a desired savings. These later two operations are significantly more complicated. Neither of these alternate optimizations admits an algorithmic approach, both require Monte-Carlo simulations such as used for building energy modeling (e.g., OptiPlus, BeOpt).

6.1 Staging by Cost of Conserved Energy

We begin this process by calculating one of the most critical quantities in the entire analysis—the cost of conserved energy. The CCE is analogous to the often used levelized cost of energy or levelized cost of electricity (LCOE), which is commonly used in analysis by electric utilities:

$$LCOE = \frac{\sum_{y=0}^{N} \frac{F(y)}{(1+d)^y}}{\sum_{y=0}^{N} \frac{E(y)}{(1+d)^y}}$$

[10] "Stage" refers to our process of ordering measures from lowest to highest cost of conserved energy.

[11] This quantity has also been abbreviated as COCE, LCOCE, or LCCE where the later two abbreviate levelized cost of conserved energy.

Where:

d is the discount rate or cost of capital used to value future expenses in current year dollars

$F(y)$ is the total financial expenditures (i.e., capital and maintenance, but not energy costs) in year y; technically these expenditures include capital, financing costs, operations, maintenance, fuel, and all costs used to generate the electricity

$E(y)$ is the energy generated in year y.

Since energy efficiency represents a counterfactual saved energy measured from a baseline rather than energy produced, the cost of **conserved** energy requires reference to a baseline as described in the discussion of scenario calculation above. Specifically for a scenario, X, compared to a baseline B we can define:

$$CCE = \frac{\sum_{y=0}^{N} \frac{\left(F^X(y) - F^B(y)\right)}{(1+d)^y}}{\sum_{y=0}^{N} \frac{\left(E^B(y) - E^X(y)\right)}{(1+d)^y}}$$

Where the superscripts refer to the baseline or scenario being analyzed as described above. We calculate this quantity for each measure m as the tool provides all these quantities for each measure in both the baseline B and scenario X to be analyzed.

The CCE represents the lifetime cost of providing a service that otherwise would be provided by less efficient equipment in energy units [e.g., \$/million BTU (10^6MMBTU, cents/kilowatt-hour (kWh)]. We find this metric to be superior to payback time, net present value of benefits, benefit-to-cost ratio, internal rate of return, and other cost metrics because it avoids explicitly assuming future energy prices. By instead expressing the cost as an equivalent energy price, it facilitates comparison of measures to volatile energy prices, other measures, and local or time-dependent effects that can significantly affect the assumed energy prices. It is worth noting that this metric can include un-priced externalities such as carbon price[12], opportunity value of time, and so on if they are used in the payment stream in the above equation. Finally note that it is straightforward to approximate the payback time from CCE; if we take the measure lifetime as L and the energy price as P the payback time is:

$$T \sim \frac{CCE}{P} \times L$$

The tool creates a staged potential estimate by ranks from lowest to highest CCE all measures the scenario includes. "Ties" in cost are broken by re-ranking all ties from greatest to least potential energy savings in that scenario [i.e., $\sum_{y=0}^{N}\left(E^B(y) - E^X(y)\right)$]. Thus, we build our portfolio by progressively comparing each measure with all lower CCE measures and reducing the savings to

[12] Although beyond the scope of this work, it is worth noting that carbon benefits could be expressed in the CCE as a non-zero financial savings, $F^B(y)$, in each year they are captured or added to the energy price to which a measure's CCE is compared (but not both counted as a savings and included in the energy price).

avoid “double counting” any savings that are already attributed to lower CCE measures. This requires detailed accounting as described below.

6.1.1 Identifying the Discount Factor to Value Future Costs and Benefits

Discount factors express how future costs and energy savings are valued in today’s terms as used in the equations for LCOE and CCE discussed above. There is no generally accepted answer for what the “right” discount rate is, though several concepts and ranges are commonly discussed. These include:

Real and nominal rates: differ on the treatment of inflation. Multiple agencies, such as the Bureau of Economic Analysis and the Federal Reserve Board, monitor the price of goods over time. The various forms of the Consumer Price Index (CPI) represent one commonly used estimate of inflation. A full treatment of inflation is well beyond the scope of this work; it suffices to observe the long-run inflation rate in the US is approximately 3.0-3.5%. Thus “real” discount rates which are net of inflation will typically be 3-3.5% below nominal rates. Specifically to convert from nominal to real discount rates one should divide the nominal rate by $(1+i)$, where i is the inflation rate.

Social costs: typically range from 0-3% real (3%-6% nominal) as estimated by the Congressional Budget Office and the Office of Management and Budget. This represents the rate of return on a “risk free” investment.

Investment costs: include greater risk and so, as suggested by the Capital Asset Pricing Model (CAPM), are typically higher, in the range of 6-10% real (9%-13% nominal).

Financing costs: vary greatly given the type of financing. Financing types can include secured loans like a home mortgage (historically ranging from a nominal cost of 3% (today’s record low) to almost 20% (in the mid-80’s)) or commercial property or small business loan (in a similar range, though typically 3 or more percentage points higher). Unsecured loans, such as revolving credit lines including credit cards, are typically higher: in the range of 6% to 20% or higher depending on credit worthiness

Behavioral rates: can represent how a consumer makes decisions trading off current and future cash rewards and costs. Significant research exists exploring these topics; it suffices for our purposes to observe that behavioral discount rates can be 40% or higher.

For our analysis we chose a social discount rate where we apply the nominal value of 6%. This views our efficiency opportunities as a society wide investment, an appropriate lens for public sector organizations to use. Sensitivity of our results to this assumption are treated in section 7.1.2.

6.2 Evaluating Market Overlap

We next evaluate the potential market overlap between measures by characterizing the market addressed by each measure using a “micro-segment” matrix. This matrix effectively divides all building-related energy use into 2,510 segments of energy use (plus 38 markets that are uncategorized by the matrix such as ATM machines and data centers), thus averaging ~16 trillion Btu per “micro-segment” as they divide the ~40,600 trillion Btu of our baseline energy use identified in section 2.1 and Table 1. We determine the energy use of each use of each micro-segment by characterizing seven enduse groups with relevant variables as described in detail in section 6.3 below. This characterization (i.e., defining segments and calculating their size) was driven by the ~300 hundred sources used to generate the measure database though the total energy use is taken from NEMS/AEO.

Each measure is characterized by a "micro-segment" vector, μ_m, of 2,510 elements each taking the value 0-100% to indicate what portion of that micro-segment the measure can address. We can perform two important calculations with this construct. First, if we build a vector, U_{micro}, of length 2,510 elements where each element represents the energy use of a micro-segment we obtain the total energy use, U_m, of the measure's market by taking the dot product: $U_m = U_{micro} \cdot \mu_m$. Alternatively if we construct the matrix, K, by placing the energy use of each micro-segment along the diagonal elements then we can determine the overlap between two measures (i.e., the size of the market energy use and stock common to both) by calculating the dot product $\chi_{1,2} = \mu_1 \cdot \mathrm{K} \cdot \mu_2$, or equivalently $\langle \mu_1 | K | \mu_2 \rangle$. Examples of both these operations are provided at the conclusion of section 6.2.1

6.2.1 Defining the "Micro-segments"

Creating our micro-segment vector, μ_m, or matrix, K, is easily done by considering each of seven enduse groups in turn. We can easily list the first six enduse groups by the enduse and the principle variables used to characterize them. By specifying the portion of each variable to which the measure applies and performing the necessary multiplication we quickly identify the value of each element of μ_m and K.

Lighting: encompasses each of four sectors categorized by four technologies {incandescent, fluorescent, high intensity discharge, other}, given in TBTUs:

Residential {798; 324; 0; 249}

Commercial: {124; 3,694; 67; 0}

Industrial: { 0; 238; 361; 1}

Outdoor: {34, 75, 668, 20}

Cooking: requires specification for each of the two major fuels and each of two sectors the energy use of the relevant eight most significant devices {microwave, stove, range, boiler, fryer, griddle, steamer, food prep}, given in TBTUs:

Residential electric: {169; 426; 0; 0; 0; 0; 0; 100}

Residential gas: {0; 237; 0; 0; 0; 0; 0; 0}

Commercial electric: {N/A; 28; 3; 2; 12; 8; 16; 22}

Commercial gas: {0; 71; 6; 25; 34; 13; 16; 0}

Hot water, washing, and drying: combines both the machine energy and energy used to heat water for washing and other uses as follows {dishwasher- machine, clothes washer- machine, clothes dryer, dishwasher- hot water, clothes washer- hot water, non-machine hot water}, given in TBTUs:

Residential electric: {340; 86; 942; 46; 253; 0; 1;265}

Residential gas: {0; 0; 83; 44; 217; 0; 1;213}

Residential distillate: {0; 0; 0; 3; 14; 0; 83}

Commercial electric: {45; 17; 40; 102; 95; 0; 88}

Commercial gas: {0; 0; 171; 58; 205; 0; 326}

Commercial distillate: {0; 0; 0; 0; 6; 0; 11}

Refrigeration: (requires separate treatment for each of three principle sectors: residential, supermarkets, and non-supermarket commercial. Specifying each major device in pairs of {existing buildings, new buildings} we have, given in TBTUs:

Residential:
Primary, full size, with ice maker: {725, 265};

Primary, full size, no ice maker: { 181, 66};

Primary, compact: {4.1, 1.5};

Secondary: {13, 5}

Top loading freezer {123, 45};

Front loading freezer {79, 29}

Supermarket:
Compressors {241, 231}

Display cases {138, 133}

Condensers {138, 133}

Beverage merchandisers {30, 29}

Walk-in refrigerators {26, 25}

Walk-in freezers {8, 8}

Ice machine {9, 9}

Reach-in freezer {6, 6}

Reach-in refrigerators {26, 25}

Non-supermarket commercial:
Beverage merchandisers {725, 265}

Ice machine {181, 66}

Vending machine {123, 45}

Walk-in freezers {79, 29}

Reach-in freezer {13, 5}

Reach-in refrigerators {4, 1}

Television and personal computers: Each sector's new and existing building use of four technologies Desk-, Lap-, Displays, and TVs is detailed, given in TBTUs:

Residential {Desk- {146, 53}, Lap- {103, 38}, Displays {41, 15}, TVs {1053, 385}}

Commercial {Desk- {181, 174}, Lap- {8, 8}, Displays {28, 27}, TVs {0, 0}}

Ventilation: For each sector we identify the energy use in {existing, new} building pairs for each of three technologies {circulating pumps, constant air ventilation (CAV), and variable-air ventilation (VAV)}, given in TBTUs; additionally we note that 70% of commercial ventilation energy is used for heating/cooling distribution and 30% for outdoor air delivery while 100% of residential energy is used for heating/cooling distribution:

Residential: {circulating pumps: {110,40}, CAV: {305, 112}, VAV: {0,0}}

Commercial: {circulating pumps: {68,65}, CAV: {299, 287}, VAV: {655,630}}

Space conditioning (heating and cooling): Shown below are the far more complicated space conditioning vectors prior to their full cross multiplication but after combining sector and end-use elements. The first line provides the sector and end-use energy use given in TBTUs; the following lines present the portion of each of these four quantities in the indicated class of variable:

Sector and end-use: {residential heating, residential cooling, commercial heating, commercial cooling} = {5161, 2925, 2215, 1977}

Vintage: {pre-2010, "new"}:

Residential heating: {73%, 27%}

Residential cooling: {73%, 27%}

Commercial heating: {51%; 49%}

Commercial cooling: {51%, 49%}

Building load: {attic, walls, basement, infiltration, doors, window-conduction, window-radiation, internal}:

Residential heating: {16%, 25%, 19%, 37%, 5%, 34%, -1%, -35%}

Residential cooling: {15%, 10%, -6%, 18%, 0%, 1%, 34%, 29%}

Commercial heating: {23%, 39%, 21%, 34%, 0%, 43%, -3%, -58%}

Commercial cooling: {1%, 1%, -6%, -4%, 0%, -9%, 40%, 77%}

Climate zone: using the five provided through RECS/CBECS surveys:

Residential heating: {18%, 33%, 29%, 13%, 7%}

Residential cooling: {4%, 14%, 21%, 22%, 40%}

Commercial heating: {18%, 33%, 29%, 13%, 7%}

Commercial cooling: {4%, 14%, 21%, 22%, 40%}

Equipment type: {air-source heat pump, ground-source heat pump, furnace/roof-top unit, boiler/ centrifugal chiller, sectional heating/residential-style central air conditioning, electric radiator/wall/window air conditioner, other}

Residential heating: {5.6%, 1.0%, 59.6%, 20.8%, 0.0%, 10.2%, 2.9%}

Residential cooling: {23%, 2%, 0%, 0%, 65%, 9%, 1%}

Commercial heating: {6%, 1%, 60%, 21%, 0%, 10%, 3%}

Commercial cooling: {2%, 0%, 29%, 25%, 8%, 16%, 21%}

6.2.2 Example Micro-segment Calculations

Out first example will create the energy use, $U_m = U_{micro} \cdot \mu_m$, of a contrived market using the micro-segment vector, μ_m. For example, consider a measure that addressed only residential air conditioning in new homes servicing heat loads through attics in climate zone 5 employing central air conditioning. First note that, for this example, all non-space-conditioning micro-segments take the value "0". Next we create each of the micro-segment elements for space conditioning by cross-multiplying the various matrices detailed in section 6.2.1. For our example we have:

Total residential air conditioning: 2925, times

Portion of cooling in new homes (27%), times

Portion of cooling attributable to attic loads (15%), times

Portion of cooling in climate zone 5 (40%), times

Portion met through central air conditioning (AC) (65%), = 30.8 TBTUs

This approach has significant limitations if we were to use the micro-segment data directly. In this example it is likely that in climate zone 5 (i.e., the hottest and sunniest climate zone) both the attic portion (15%) and the portion met through central AC (65%) will likely be more than the U.S. average assumed here. However, as we typically use hundreds or thousands of these micro-segments when defining a market, there is less of a chance to encounter these errors. With sufficient time and data availability (the latter representing the greater constraint), it becomes easier to more accurately represent the micro-segment energy use numbers.

Given this complexity a second example is warranted, in this case we will compute the market overlap between two measures: $\langle \mu_1 | \mathrm{X} | \mu_2 \rangle$. Consider a measure that addressed commercial gas stove, gas ranges, and gas broilers. For this example we would compute the micro-segment contributions as follows:

Note that the space cooling, lighting, hot water, washing, and drying variables are all 0; thus, there is no energy use for this measure in any of the corresponding micro-segments used to represent those end uses.

Cooking presents three attributes each with their own variables: Sector {residential, commercial}, Fuel {electric, gas, distillate}, and Device {microwave, stove, range, boiler, fryer, griddle, steamer, food prep},[13] or using initials: {r, c}, {e, g}, {m, s, r, b, f, r, s, p}. We therefore represent our measure of commercial gas ranges as: Sector {0,1}, Fuel {0,1}, and Device {0,1,1,1,0,0,0,0}.

We then generate the vector characterizing the market by taking the outer product of these values. Using initials this results in 32 non-zero elements of the vector μ_1: {rem, res, rer, reb, ref, reg, res, ref, rgm, rgs, rgr, rgb, rgf, rgg, rgs, rgf, cem, ces, cer, ceb, cef, ceg, ces, cef, cgm, cgs, cgr, cgb, cgf, cgg, cgs, cgf}.The example measure is then: $\mu_1 = \{0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 0, 0, 0, 0\}$.

[13] Residential food preparation includes toasters, toaster ovens, and coffee makers.

Next we instead consider a (fictitious) measure that only applied to some portion, v, of gas and electric ranges built by some manufacturer or before some year, we would have replaced the Device vector with {0,0,v,0,0,0,0,0} and obtained: $\mu_2 = \{0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, v, 0, 0, 0, 0, 0, 0, v, 0, 0, 0, 0, 0\}$.

Finally, through the various sources discussed previously, we have estimated the primary energy use for each of these micro-segments and can create the on-diagonal elements of the 32x32 sub-matrix X, or equivalently the elements of U_{micro}, namely, in TBTUs: {169, 426, 0, 0, 0, 0, 0, 100, 0, 237, 0, 0, 0, 0, 0, 0, 0, 28, 3, 2, 12, 8, 16, 22, 0, 71, 67, 25, 34, 13, 16, 0}.

As such, the resultant estimate for the market size is

$U_1 = U_{micro} \cdot \mu_1$ = 71+67+25=163 TBTUs

Taking f=25% for the other market (i.e., gas and electric ranges) would yield a market of:
$U_2 = U_{micro} \cdot \mu_2 = 25\% \times (3 + 67) = 17.5$ TBTUs.

Finally, the overlap between these two markets is given by only the last six elements of the above, namely:
$\chi_{1,2} = \langle \mu_1 | \mathrm{X} | \mu_2 \rangle = \{25\%, 0, 0, 0, 0, 0\} \times \{67, 25, 34, 13, 16, 0\} \times \{1,1,0,0,0,0\} =$ 16.75 TBTUs.

6.2.3 Evaluating Market Overlap

Recall that in our data gathering we used individual research reports and the National Energy Modeling System (NEMS) detailed tables to develop a market size estimate for each measure. Now with the micro-segment approach we have a second method to estimate the market size: U_m. This provides both a check to the first estimate of market size as well as the above described method to determine market overlap.

While some measures draw on the same citations for both methods, others represent fully independent characterizations and all result from independent excel calculations. We compared the estimated market size from each method for each measure to identify errors and estimate uncertainty. A statistical analysis on the difference in total energy consumption in 2030 between the two methods for all 400 markets reveals:

Sufficiently accurate: The average and median of the absolute value of the difference between the two market analyses are 33 and 10 TBTUs respectively. This is considerably smaller than the average and median market sizes of 1,215 and 497 TBTUs respectively. Even more compellingly, the average and median of the absolute value of the percent difference are 5.8% and 1.7%.

Few large deviations: Most (86%) of the markets match to within 10%; only 3 of 295 markets used in the primary analysis exceed 25% uncertainty (16 of the 400).

Unbiased results: The average and median deviations of -0.1 and 0.0 TBTUs are well within the standard deviation of the deviation (60) and much less than the average and median market sizes (1,215 and 497 respectively) indicating that neither method is biased large or small compared to the other.

6.3 Determining the Nature of Interaction Between Measures

Once we have identified the market overlap for two measures we must determine how the earlier-staged measure has impacted the market size and savings opportunity of the later staged measure. Interactions between measures take one of three forms as labeled in table 3:

Independent: the measures do not interact. A full treatment of all measures in a building-by-building analysis would likely have interaction between all measures. However, for most cases, these interactions are much smaller than magnitude of the enduse savings. One simulation study (Ugursal & Fung, 1994) suggests that in Canadian homes every MMBTU of site-energy savings increases heating load by 0.57 MMBTUs. In U.S. homes we would expect some heating load increase less than or equal to this load and a corresponding decrease in air-conditioning. Thus the relative impact on primary energy use will be the sum of two offsetting effects that vary by climate zone. We neglect all such induced loads categorizing their interactions as independent.

Market reducing. Some savings measures decrease the energy use a second measure can address without impacting the percent savings that second measure provides. The interaction between improving a building's air conditioning efficiency and its envelope (e.g., installing highly-insulating windows) demonstrate this. Taking this as the total market overlap between measures 1 and 2 (e.g., cooling energy lost by conduction through windows) in energy units as $M_{1,2}$ and the savings as a percent of the market addressed for each as p_1 and p_2, the energy savings in the overlap market for each independently would be: $P_1 = M_{1,2} \times p_1$, and $P_2 = M_{1,2} \times p_2$. However, if we stage measure 1 first, the savings from measure 2 are reduced to:

$$P_{2,1} = \left(M_{1,2} - P_1\right) \times p_2 = M_{1,2} \times (1 - p_1) \times p_2 = P_2 - p_2 \times P_1.$$

Savings reducing. The final form addresses measures where one measure directly reduced the savings of a second typically because the two measures improve the same system component (e.g., advancing from a typical R-2 window to R-5 will reduce the benefit calculated by the measure advancing from a typical R-2 to R-10). In the latter case, and using the same notation, the savings from the second measure is:

$$P_{2,1} = M_{1,2} \times p_2 - P_1 = M_{1,2} \times (p_2 - p_1) = P_2 - P_1.$$

We take this quantity to be positive definite; a negative value indicates that measure 1 saves more energy than measure 2, therefore, measure 2 should not be deployed.

The form an interaction between two measures takes is characterized by the "component" the measure addresses. The component characterization and comparison matrix is provided in Table 3. It follows that the energy savings of the measure 1 (i.e., staged first) on the savings of measure 2 (i.e., staged second) is reduced by the quantity: $P_2 - P_{2,1} = \pi_{1,2} \times P_1$, where: $\pi_{1,2}$=0, p, or 1 for forms 0, 1, and 2, respectively. Table 3 categorizes the interaction between the 28 different components used to describe measures in the tool, where:

NA: indicates a comparison that never should occur (i.e., the markets are assumed or approximated not to overlap)

0: specifies components that do not interact: the higher CCE savings remain unaffected by lower CCE measures in their market

1: indicates interactions where the lower CCE measure reduces the market size but not the percent savings of the higher CCE measure

2: indicates interactions where the lower CCE measure reduces the market size and savings of the higher CCE measure.

Table 3. Interaction Between Components Describing Measures in Tool

Current component	System	Use intensity	Maintenance	Standby	Parasitic	Whole building	Controls	Windows	Walls	Roof	Basement	Doors	Infiltration	Distribution	Lamp	Ballasts	Luminaire	Compressor	Condenser	Evaporator	Heat exchanger	Thermal transfer	Heat loss (non-envelope)	Power supply	Sprayer	Motor	Spin cycle	Other
System	2	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	0
Use intensity	1	2	1	0	0	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
Maintenance	1	1	2	NA	NA	2	1	1	1	1	1	1	1	1	NA	NA	NA	1	1	1	1	1	1	NA	NA	1	NA	0
Standby	2	0	NA	2	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Parasitic	2	0	NA	1	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Whole building	2	1	1	0	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	0
Controls	2	1	1	0	0	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
Windows	2	1	1	0	0	2	1	2	0	0	0	0	0	1	NA	NA	NA	1	1	1	1	NA	NA	NA	NA	NA	NA	0
Walls	2	1	1	0	0	2	1	0	2	0	0	0	0	1	NA	NA	NA	1	1	1	1	NA	NA	NA	NA	NA	NA	0
Roof	2	1	1	0	0	2	1	0	0	2	0	0	0	1	NA	NA	NA	1	1	1	1	NA	NA	NA	NA	NA	NA	0
Basement	2	1	1	0	0	2	1	0	0	0	2	0	0	1	NA	NA	NA	1	1	1	1	NA	NA	NA	NA	NA	NA	0
Doors	2	1	1	0	0	2	1	0	0	0	0	2	0	1	NA	NA	NA	1	1	1	1	NA	NA	NA	NA	NA	NA	0
Infiltration	2	1	1	0	0	2	1	0	0	0	0	0	2	1	NA	NA	NA	1	1	1	1	NA	NA	NA	NA	NA	NA	0
Distribution	2	1	1	0	0	2	1	1	1	1	1	1	1	2	NA	NA	NA	1	1	1	1	NA	NA	NA	NA	NA	NA	0
Lamp	2	1	NA	0	0	2	1	NA	NA	NA	NA	NA	NA	NA	2	1	1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0
Ballasts	2	1	NA	0	0	2	1	NA	NA	NA	NA	NA	NA	NA	1	2	1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0
Luminaire	2	1	NA	0	0	2	1	NA	NA	NA	NA	NA	NA	NA	1	1	2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0
Compressor	2	1	1	0	0	2	1	1	1	1	1	1	1	1	NA	NA	NA	2	1	1	1	NA	NA	NA	NA	NA	NA	0
Condenser	2	1	1	0	0	2	1	1	1	1	1	1	1	1	NA	NA	NA	1	2	1	1	NA	NA	NA	NA	NA	NA	0
Evaporator	2	1	1	0	0	2	1	1	1	1	1	1	1	1	NA	NA	NA	1	1	2	1	NA	NA	NA	NA	NA	NA	0
Heat exchanger	2	1	1	0	0	2	1	1	1	1	1	1	1	1	NA	NA	NA	1	2	2	2	NA	NA	NA	NA	NA	NA	0
Thermal transfer	2	1	1	0	0	2	1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	2	NA	NA	NA	NA	NA	0
Heat loss (non-envelope)	2	1	1	0	0	2	1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	2	NA	NA	NA	NA	0
Power supply	2	1	NA	0	0	2	1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	2	NA	NA	NA	0
Sprayer	2	1	NA	0	0	2	1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	2	0	0	0
Motor	2	1	1	0	0	2	1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	2	0	0
Spin cycle	2	1	NA	0	0	2	1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	0	2	0
Other	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Key

0 - do not apply previous savings

1 - Reduce current use by previous use

2 - Subtract previous savings from current savings

6.4 Calculating the "Staged" Savings

Finally, given a set of N measures sorted by increasing CCE, we can calculate the "staged" savings π_N, of measure N given the saving previously accounted for as:

$$\pi_N = P_N - \sum_{i=2}^{N-1} \left(f_{i,N} \times \pi_i \right) - f_{1,N} \times P_1$$

Note that we use the un-staged savings of the first measure (P_1) and the staged savings (π_i) of all subsequent measures as it holds for the first measure that $P_1 = \pi_1$. This quantity is again taken as positive definite indicating that a measure where all possible savings were captured by previous measures will offer no additional savings. For example, if a SEER 24 central A/C stages before SEER 21 then the staged savings of the SEER 21 unit is 0 since the SEER 24 unit already captured all savings available to the SEER 21 unit. Additionally, as we are using a national average we take the conservative assumption that the "staged" cost of conserved energy increases to:

$$CCE_{staged,N} = CCE \times \frac{P_N}{\pi_N}$$

This equation is accurate once all previous measures have gained 100% market adoption; prior to that the actual cost of conserved energy for a measure, m, in an average building will range from CCE_N *to* $CCE_{staged,N}$ depending on which of the less costly measures have been deployed into that building. Table 4 shows that for our example including five technologies $CCE_{unstaged} =$ \$13.61 while $CCE_{staged} =$ \$16.73.

6.5 Iteration

Finally we iteratively sort the measures by increasing "staged" cost of conserved energy. We continue this resorting process until the order has converged to a stable solution for the scenario being analyzed. Note that any scenario's potential savings can be staged; as discussed in section 7, staging the maximum-adoption potential is akin to performing a traditional "economic potential" analysis whereas staging the bass-adoption potential is useful for representing prospective benefits from program activities.

To conclude the example developed above using R-10 windows, we consider a highly simplified staging calculation for home energy use that includes five measures: condensing furnace standard, SEER 24 central air-conditioner (a research & development measure), and SEER 21 central air conditioner (a deployment measure), R-5 window (deployment), and R-10 window (R&D). Table 4 shows the staged and un-staged savings and CCE for each measure; it also indicates, for each measure, the energy savings captured by all previously staged measures. It is instructive to note:

For each measure, the sum of the staged savings and all previously captured savings is equal to the un-staged savings.

Staging reorders the measures: SEER 21 CAC drops from the 3rd to 5th most cost effective because (after R&D efforts) SEER 24 units will be lower cost and capture all their savings.

If we were to set our cost-effectiveness criteria at an LCOE of \$15/MMBTU (typical of today's residential energy prices) four of our measures (i.e., all except R-10 windows) would be cost effective; after staging, however, only two of our measures (SEER 24 CAC and R-5 windows) remain cost effective.

Without staging we would significantly overestimate the total energy savings of these measures as 3,410 TBTUs/year in 2030 rather than 1,860 TBTUs/year; this results from eliminating double counting in the two CAC and two window measures.

Table 4. Staged and "Un-staged" Energy Savings

		Unstaged			Staged		
Measure	**N**	**Initial staging**	**Energy savings**	**CCE ($/MMBTU)**	**Final staging**	**Energy savings**	**CCE ($/MMBTU)**
SEER 24 (R&D)	97	1	816	$3.50	1	816	$3.56
R-5 windows (Deploy.)	642	2	661	$6.36	2	627	$6.71
Condensing furnace (Std.)	112	4	303	$13.61	3	246	$16.73
R-10 windows (R&D)	421	5	817	$29.27	4	171	$144.00
SEER 21 (Deploy.)	98	3	813	$10.19	5	0	N/A
Total:			3,410			1,860	

	Energy savings captured by prev. measures			
Measure	**SEER 24**	**R-5 windows**	**Cond. furnace**	**R-10 windows**
SEER 24 (R&D)	N/A	N/A	N/A	N/A
R-5 windows (Deploy.)	34	N/A	N/A	N/A
Condensing furnace (Std.)	0	57	N/A	N/A
R-10 windows (R&D)	3	627	16	N/A
SEER 21 (Deploy.)	813	0	0	0

Table 4 shows energy savings (a trillion Btu of maximum-adoption energy savings in 2030) and cost ($/MMBTU, primary) for five related home heating- and cooling-related efficiency measures.

7 Outputs and Their Uses

The prioritization tool enables multiple calculations and many analyses of interest for stakeholders interested in exploring energy efficiency measures in any context. We can create portfolios of energy savings for each of the efficiency potential scenarios described above: technical, full-adoption-based, and bass-adoption-based. Each of these portfolios then has a unique interpretation and implication, and, in turn, reveals:

Technology limits. Using the technical potential only and considering the contributions of all technologies identified will reveal the technical lower-limit for energy use (i.e., maximum energy efficiency savings) from known technologies with sufficiently well characterized cost, performance, and market-size information.

Efficiency "potential" studies: We use supply curves that include all measures of interest, calculate the staged maximum-adoption potential, sort them by ascending CCE, and chart their cost versus their accumulated energy savings.

Benefits estimation. Selecting specific measures and staging the adoption-based potential shows the aggregate programmatic benefits of a potential portfolio.

Each of these approaches provides a unique and valuable "lens" from which to view the potential for energy efficiency. This section provides insight into these outputs by examining the technology limits and efficiency potential following an analysis of approximately 450 building efficiency measures as detailed in Appendix B.

7.1 Technology Limits

The technological minimum energy use indicates the total possible energy savings available to U.S. energy users regardless of cost for currently available technologies. We include all technologies identified in our database of 450 measures including those on the market today, at late stages of development, and at early stages of applied research as detailed in Appendix B. Building this unconstrained portfolio (i.e., considering all possible energy saving measures) and evaluating the potential in aggregate and for each end use reveals a cumulative 80% energy savings detailed in Table 5**.** Some of the most promising technologies contributing to these savings in each enduse include:

Heating: Heat pump technology is poised to transform the way we heat our homes with extensions to cold climates (offering COPs of 2 or higher even at 0 degrees Fahrenheit), integration of heating, cooling, and air conditioning, and ground source heat pumps (GSHP) which have a current "max-tech" COP of 8 (Hughes 2008). Even accounting for the average conversion from end-use to primary energy of 3.1 these offer over 60% reduction in energy use compared to 100% efficient fuel combustion.

Cooling: Liquid desiccant presents near term savings of 40-60% (Eric Kozubal 2011) while other technologies including thermo-acoustic and thermo-tunneling offer similar or larger savings in the long term (Brown Dirks Fernandez & Stout 2010).

Lighting: CFLs and lighting controls offer savings of about 35% (Navigant Consulting 2012)in the near term with LEDs offering considerably higher cost-effective savings of 85% (i.e., increasing Lumens per watt to ~259 (Bardsley Consulting et.al. 2012))

Water heating: Solar water heaters offer demand reduction of about 50% (70%-90% in hot climates) while electric heat pumps offer 50% (Baxter et.al. 2005) improvement in efficiency over today's electric resistance heaters with advanced electric and gas absorption heaters pushing that limit to about 80% in the years to come (Hepbasli & Kalinci 2009).

Envelop improvements: As detailed in Appendix B multiple roofing, window, wall, and basement technologies are available today to reduce unwanted thermal losses and gains of each element by 50% or more.

Cross-cutting: Design, control, operational, and maintenance improvements detailed in Appendix B also offer 10-20% savings that cut across multiple enduses.

Also, for each end use, use our staging procedure to consider the cumulative impact of all technologies. If we accumulate all savings regardless of CCE we produce the technical energy efficiency savings possible after deploying all measures. It is important to note that this "technology limits" analysis provides only a perspective on what energy savings are possible with fully unconstrained thinking (i.e., no treatment of cost, markets, or government role in driving energy efficiency). It does, however, highlight how far the United States is from engineering and thermodynamic limits to its energy use, which suggests that continued innovation, research, and development is warranted (American Energy Innovation Council 2011). It should be further noted that this is likely an underestimate as more energy saving technologies will likely emerge over time. An in-depth treatment of technologies by end use is the subject of a paper in preparation.

Table 5. Technical Energy Savings Possible in 2030 with R&D and Full Deployment

End use	2030 Baseline energy use (Trillion BTUs primary energy)	2030 Technical minimum energy use (Trillion BTUs primary energy)	2030 Technical potential savings (primary energy)
Residential sector	23,350	4,720	80%
Heating	5,160	550	89%
Cooling	3,100	160	95%
Ventilation	570	220	61%
Lighting	1,370	170	88%
Water heating	2,890	400	86%
Refrigeration	1,540	470	69%
Cooking	830	480	42%
Washing-drying	1,700	510	70%
MELs	6,190	1,760	72%
Commercial sector	19,270	4,380	77%
Heating	2,220	100	95%
Cooling	1,980	160	92%
Ventilation	2,010	620	69%
Lighting	3,890	320	92%
Water heating	730	60	92%
Refrigeration	1,590	530	67%
Cooking	320	180	44%
Washing-drying	430	130	70%
MELs	6,100	2,280	63%
Total:	42,620	9,100	79%

Efficiency "Potential" Studies

By using the full-adoption-based and bass-adoption-based scenario outlined above we can generate efficiency supply curves showing available energy savings and the cost of those savings in a fashion similar to seminal reports of the past three decades (SERI 1982; Meier Wright Rosenfeld & H. 1983; Interlaboratory Working Group on Energy-Efficient and Clean-Energy Technologies 2000; Siddiqui 2009; National Academy of Sciences 2009; Choi-Granade 2009).

By specifying which measures to include we can develop appropriate goals and a corresponding long-term vision for a portfolio of investments. In particular we interpret:

Ultimate savings: the full-adoption potential represents the ultimate (albeit unrealistic) energy savings from the studied measures. Actually capturing this economically attractive potential would require a society-wide push (Choi-Granade 2009).
Captured savings: the Bass-adoption-based potential represents the savings that may be captured with existing policy, statutory authority, and investment. Other stakeholders (e.g., manufacturers, utilities, state and local governments, and end users) must remain active partners to realize these savings (Siddiqui 2009).

Figure 8 shows one realization of the "ultimate savings" supply curve as determined by analyzing the measures accordingly and taking a snapshot of the data in 2030. The blue dotted line indicates a CCE of $0.00/MMBTU (i.e., measures below this line justify their investment by savings capital and maintenance costs alone), and the green dotted lines indicate the typical range of energy costs today. By comparing each measure's CCE to the cost of energy it is saving (i.e., fuel and time-of-day specific pricing) and selecting those with a lower CCE than energy price we derive the conventional "economic (energy) potential" which shows a possible annual primary energy savings of 55% (23.7 quads) in 2030. Also, by integrating the total present value investments of all cost effective measures in this curve and dividing by the total present value energy savings of all cost effective investments we obtain an average CCE of $1.30 suggesting an average payback time of 2 years. Naturally there are significant uncertainties and variables that impact this ultimate savings. We briefly explore below:

- The impact of technology selection set
- Variations in discount factor
- The impact of the cost of energy
- Uncertainty in measure savings
- Uncertainty in measure price
- Impact of "rebound" effects.

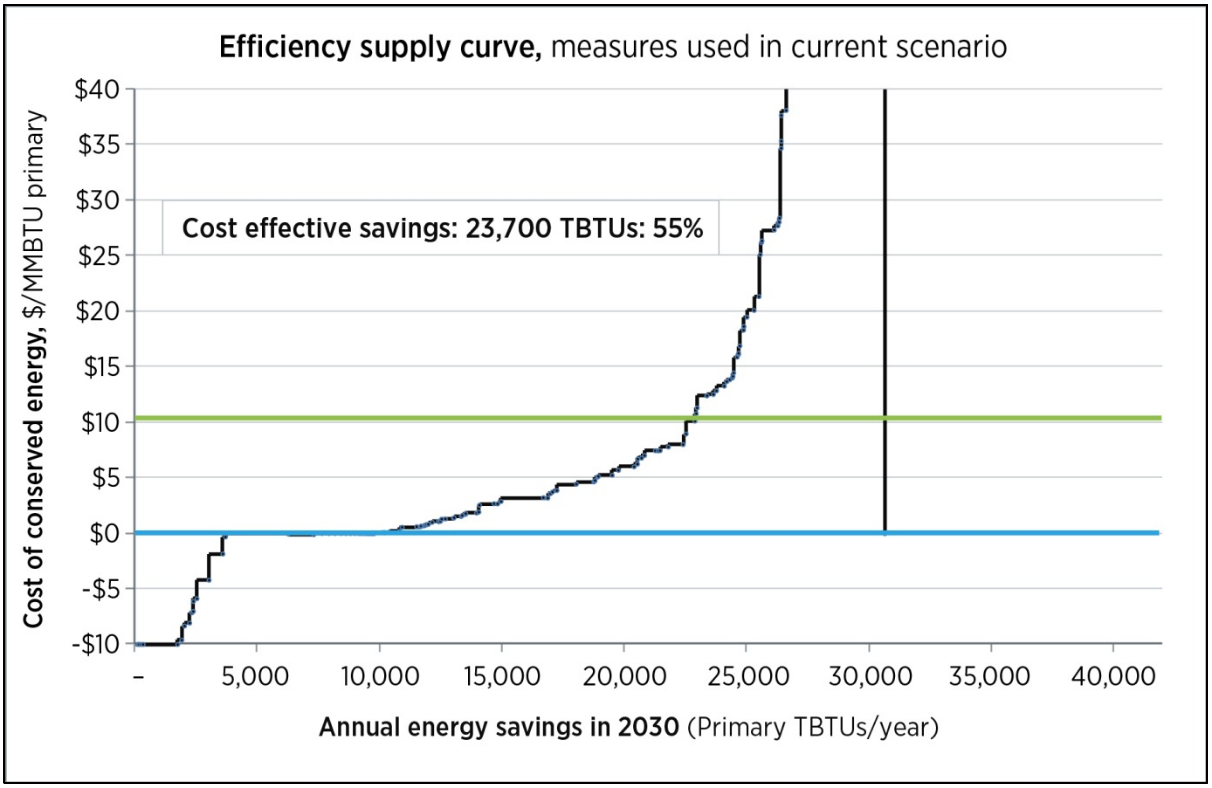

Figure 8. Energy efficiency supply curve showing annual economic savings in 2030.

7.1.1 Technology Selection Set- reproducing Related Work

It is important to note that the ultimate savings potential identified in figure 8, unlike others published to date, includes significant expected technology development in addition to measure deployment and codes and standards activity. In fact, if we include all emerging technologies expected to reach the market within five years and include cost-effective and not-cost effective measures the energy savings grows to 72% (30.6 Quads).

The inclusion of emerging technologies departs from the methodology of many of the historic analyses of energy efficiency potential. When we limit the measures the tool analyzes to only currently-available, cost-effective measures, as was done most recently in two influential reports (Choi-Granade. 2009) (National Academy of Sciences 2009), and use the same discount rate (10%) and energy price for cost effectiveness[14] as used in those reports we reproduces the ~30% energy savings potential identified in those reports. Table 6 summarizes the efficiency potential of the five efficiency potential analyses mentioned in this section, namely the technical; economic; emerging technology, full-adoption; National Academies approach; and McKinsey approach.

14 National Academies indicates in Table 1.2: “Levelized cost of energy savings is less than the national average electricity and natural gas prices" while McKinsey states: "Levelized cost of energy savings is less than the national average electricity and natural gas prices."

Table 6 shows the considerable energy savings available through five analyses. National Academies (National Academy of the Sciences; National Academy of Engineering; National Research Council 2009) and McKinsey (Choi-Granade 2009) approaches attempt to repeat the analysis presented in their respective reports; they reproduce the ~30% cost effective savings found therein. Economic extends this analysis to include technologies expected to enter the market and be cost effective within five years. "Emerging technologies, full adoption" and "Full technical" represents the potentials of emerging technologies and all analyzed technologies regardless of cost-effectiveness.

Table 6. Energy Savings Identified in Five Analyses

Efficiency potential scenario	Potential Primary TBTU/ year, 2030	Percent of baseline	CCE ($/MMBTU, primary)
Full technical	33,520	78%	N/A
Emerging technology, full-adoption	30,600	71%	N/A
Economic	23,671	55%	$1.21
National Academies approach	14,100	32%	$1.91
McKinsey approach	14,600	33%	$0.82

7.1.2 Variations in Discount Factor Significantly Change the Potential

Discount factors express how future costs and energy savings are valued in today's terms as used in the equations for LCOE and CCE discussed in section 6.1. A brief discussion of the various choices for discount rates is presented there. The following figure shows the impact on the average cost of conserved energy, economic potential, and full-adoption-based potential as we vary the discount factor. One can observe that the difference between the social (3%) and behavioral (40%) discount-rate-based potentials of 7,300 TBTUs/year in 2030 goes a long way (i.e., accounting for 31% of the potential) to explaining why an efficiency gap exists. Similarly the difference between the financing and social discount-rate-based potentials of 5,200 TBTUs suggests the portion of this gap (i.e., 22%) that financing mechanisms could address.

Table 7. Variation of Economic-potential Scenario with Changes in Discount Factor

Discount factor	Potential Primary TBTU/ year, 2030	Percent of baseline	CCE ($/MMBTU, primary)
0%	25,500	59%	N/A
3%	23,700	55%	N/A
6%	23,700	55%	$1.91
10%	22,600	53%	$1.90
20%	18,500	43%	$1.55
40%	16,400	38%	$1.20

In Table 7, economic potential represents energy savings from all currently available and emerging technologies that are cost-effective; it uses the full-adoption-based potential.

7.1.3 Increasing Energy Prices Drive a Corresponding Increase in Potential

Using our economic potential scenario which gave 53% as the efficiency potential of cost-effective technologies including emerging technologies we can vary energy prices of fuels independently to understand the sensitivity our findings to energy prices. Table 8 presents our findings for ten scenarios that vary energy prices from the AEO 2010 business-as-usual as follows:

-50%: decreases all fuel prices by 50% from the AOE 2010 baseline
Low gas: drops the forecast natural gas by 50% to $6.70 $/MMBTU in 2030
High gas: doubles the forecast natural gas price to $26.90 $/MMBTU in 2030
+50%: increase all fuel prices by 50% from the AEO 2010 baseline

The resulting efficiency potentials are shown in Table 8 below.

Table 8. Variation of Economic-potential Scenario with Changes in Energy Price

Energy price scenario	Potential Primary TBTU/ year, 2030	Percent of baseline	CCE ($/MMBTU, primary)
Low prices (-50%)	20,800	48.5%	$1.23
Low gas	22,000	51.5%	$1.63
High gas	25,000	58.5%	$2.61
High prices (+50%)	25,400	59.3%	$3.09

7.1.4 Uncertainty in Savings Can Impact Measure Selection

Most references consulted are unable to provide robust uncertainty estimates for their technology- or national-impact- analysis. Provided these uncertainties are not correlated we would anticipate that our conclusion of economic-potential and technical potential are robust to errors in savings estimates of individual measures. To test this theory we introduced 20% uncorrelated errors to each measures savings estimate by multiplying the percent savings of each by a Gaussian-distributed factor with mean 1.0 and standard deviation 0.2, recalculating their measure energy savings, and restaging the analysis. Eight such Monte-Carlo realizations revealed a 2.4 percentage point standard deviation in the economic potential; that is to say our 1-sigma confidence interval accounting for savings uncertainty is 52.9%-57.7%.

7.1.5 Uncertainty in Measure Cost can Also Impact Measure Selection and Total Savings Potential

We repeated this procedure varying only the measure cost with the same Gaussian-distributed factor to reveal a 1-sigma variance of only 0.8 percentage points. Thus we expect a 1-sigma confidence interval accounting for cost of 54.5%-56.1%. Assuming these two uncertainties are uncorrelated suggests a total uncertainty of our economic potential of 2.5%; using the expected value of 55.3% suggests a 98% chance the economic potential exceeds 50%.

7.1.6 Rebound Effects Convert Savings to Value

The engineering efficiency analysis presented herein was primarily developed to provide analytic insights in support of strategic planning and budget impact analysis. It is not meant to forecast expected future energy use but calculate possible future scenarios to enable decision-making. However it is worth noting that in this "market-engineering analysis," any macro-economic effects such as price elasticities, direct rebound, indirect rebound, or other macro-economic effects were not included. The potential impacts of these effects include:

Direct rebound includes increases in service demand "directly" because of improved efficiencies. Studies have shown that it varies from 0-40% by end use (Sorrell Dimitropoulos & Sommerville 2009). Weighting the enduse specific estimates by their share of energy savings provides a range of 2%-23% with a central value of 13%. Incorporating these impacts reduces the adoption-based potential energy savings from 30% to 23%-28% and increase CCE by 4%-32%. However, note that in many of these cases, the services delivered (e.g., Lumen-hours per square foot of illuminated space or hours of comfortable in-building environment provided) have increased. This represents capture of a net benefit: service demand and therefore quality of life or utility have increased.

Indirect rebound represents increased energy use in the economy as the expenditures saved through efficiency measures are spent on other goods and services. Energy is used to create these goods and deliver these services; this is often referred to as "imbedded" energy. We estimate this as the ratio of total U.S. energy expenditures to total U.S. gross-domestic product; this is approximately 8% (Energy Information Agency 2011). One would thus expect indirect rebound of 8% (i.e., expenditures formerly 100% energy are now 8% energy). This effect alone would reduce the energy savings to 18,490 TBTUs/year and increase CCE to $2.98 however, this also represents capture of a net benefit.

Price elasticities and macro-economic effects are outside the scope of this analysis; there is no rigorous empirical observation (i.e., other than computer simulation) demonstrating the scale of these effects.

It is worth noting that 2010 total energy expenditures of $1,205 Billion included $250 Billion in residential and $178 in commercial expenditures (Energy Information Agency 2012). It is apparent that significant financial savings can result by capturing these energy savings. Lacking a robust estimate of GDP and energy expenditures that account for the savings possible in 2030 we apply the percentage savings identified in table 2 to 2010 expenditures and provide the resultant savings in table 5. Note that this does not account for market dynamics that could significantly change the U.S. energy system and expenditures if such massive efficiency potential were captured.

Table 9 shows the direct and indirect rebound effects that are likely to reduce the energy savings identified in our analysis. Applying end-use specific direct-rebound effects (Sorrell Dimitropoulos & Sommerville 2009) reveals the impact of the 13% average reduction. Similarly, assuming financial savings are reinvested in line with current spending patterns and attributing the resultant 8% indirect rebound effect further reduces savings. Ultimately, we apply the savings net of these rebound effects to 2010 expenditures to reveal the possible annual reduction in expenditures assuming no major macro-economic changes.

Table 9. Direct and Indirect Rebound Effects Likely to Reduce Energy Savings

Scenario	Engineering estimate of savings	Savings net of direct rebound	Savings net of direct and indirect rebound	Reduction in expenditures net of rebound ($, Billion)
Full technical	78.3%	68.1%	62.7%	$268,200
Emerging technology, full-adoption	71.5%	62.2%	57.2%	$244,800
Emerging technology, economic	55.3%	48.1%	44.3%	$189,400
National Academies approach	31.7%	27.6%	25.4%	$108,600
McKinsey approach	32.7%	28.4%	26.2%	$112,000

8 Conclusions

This toolset provides a comprehensive set of calculations needed to determine the prospective benefits from energy efficiency measures under the simplifying assumptions detailed above. It provides an objective analytic framework, a landscape of measures, and a level playing field upon which these measures can compete. The tool enables one to vary input parameters of unknown certainty and examine the results through sensitivity analyses. The outputs from the analysis can be viewed from various perspectives such as technical limits or efficiency potential. Thus a portfolio analysis might use various "lenses" beyond this to examine the potential effect of staging or the influence of adoption on market penetration and therefore impact. What results is a prioritized list of opportunities worthy of further investigation, a catalog of opportunities that are likely of low priority and an extensive dataset with which to compare a broad range of opportunities. For DOE, developing a programmatic strategy may require additional investigation, such as in-depth market/supply chain analysis and an assessment of the appropriateness of DOE's role in intervening with the development and deployment of a particular measure. A future publication will provide a more in-depth presentation of results and discussion, highlighting those sectors and technologies that are likely to have the greatest influence on U.S. energy efficiency. Essentially, we aspire to keep this tool "evergreen" to easily aggregate available opportunities, compare those opportunities on a level playing field, and track progress toward a more energy efficient future.

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Appendix A: Baseline Assumptions

The Energy Information Agency (EIA) produces the *Annual Energy Outlook* to provide multiple perspectives on the future of energy supply and demand in the United States. It uses the National Energy Modeling System (NEMS) to project the production, imports, conversion, consumption, and prices of energy through 2030. Extensive documentation is available at http://205.254.135.24/oiaf/aeo/overview/ where the following is summarized:

"The National Energy Modeling System (NEMS) is a computer-based, energy-economy modeling system of U.S. through 2030. NEMS projects the production, imports, conversion, consumption, and prices of energy, subject to assumptions on macroeconomic and financial factors, world energy markets, resource availability and costs, behavioral and technological choice criteria, cost and performance characteristics of energy technologies, and demographics. NEMS was designed and implemented by the Energy Information Administration (EIA) of the U.S. Department of Energy (DOE)."

We use the detailed output spreadsheets that provide detailed stock and end-use energy information disaggregated by end use, fuel type, equipment class (i.e., technology), building type, and census division. These spreadsheets provide a consistent and comprehensive basis from which to compute the energy use each measure can address (i.e., its "market"). Additional resources, both general and specific to each measure, allow us to aggregate or further divide this dataset to best represent the market each measure can impact. The general resources used for multiple measures include the Commercial Building Energy Consumption Survey (CBECS), 2003; the Residential Energy Consumption Surveys (RECS) of 2005 and 2009; and the Building Energy Data Book (BEDB) of 2009.

The measure entitled "R: Poor attics to R-40" provides a useful example demonstrating how we create a complicated market. This measure applies to energy lost through roofs in all homes built prior to the period of analysis (taken as 2010) that have insufficient attic insulation in their attics. We compute the stock and energy use in this market as follows:

We begin with the total stock of homes in the NEMS output files.

Using the average home lifetime of 80 years provided by RECS, we can determine the number of homes each year remaining in the stock (i.e., we reduce the stock in year y by $1/80^{th}$ of the stock in year y-1).

We also use RECS, 1987 (updated to the current day) to estimate that 64% of these existing homes have not had their insulation improved; this provides the total stock and a scaling factor, *f*.

Finally, we use the BEDB (2009) to note that 16% of heating and 15% of cooling energy is attributed to losses through the roof. As a result, the "market" of energy use for this measure is $f \times (15\% \times C + 16\% \times H)$, where C and H are the total cooling and heating building energy use, respectively.

NEMS provides projected consumption estimates through 2035. We would like to remove "edge effects" in calculating the savings and economic benefits and estimate the expected deployment of the advanced measure in the baseline. To do this, we use a three-parameter fit as described in

Section 3.3, which extends the data to 2100 and estimates the diffusion of the advanced measure in the base case.

Finally, as noted in section 6.2.3, we do estimate markets twice: once using this method without reference to or constraints by any other measures, and a second time using the micro-segment approach (as detailed in section 2). In this example our two methods estimate energy lost through poorly insulated attics as 595 and 597 TBTUs, respectively; a difference of only two TBTUs and agreement of approximately 0.3%.

Appendix B: Input Table

Table 2 provides the essential elements of the "input" table as gathered from the hundreds of sources outlined in the bibliography. The fields in this table include:

Description of the measure: provides the sector ("R:" for residential; "C:" for commercial; "O:" for industrial, outdoor, or other; and "A:" for all) and a brief measure description (limited to 32 characters total). Note that "no FS" indicates fuel switching (e.g., from gas in the base case to electricity after deploying the measure) that is not included while "FS only" includes only fuel switching.

Energy savings: expresses the percentage savings over the baseline. The column labeled "SD?" indicates if this measure is represented as service "demand reducing" or as an "equipment upgrade" (see discussion in Section 3.2.2). The column labeled "Fuel switch?" indicates if the measure changes the service from using one fuel to another (e.g., replacing a gas furnace with a ground-source heat pump).

Price: represents the present value of the price difference per unit between the existing mix of "inefficient" technologies and measure being analyzed; the units are provided in the adjacent column.

Units & capacity: indicates the assumed typical equipment size or quantity needed per unit stock; also provides the units (e.g., per house, per square foot of building space, or per lamp) used in columns "3. Price" and "6. Market size, 2030".

Market description: provides a brief description of the market.

Market size, 2030: indicates the stock in the market in 2030 expressed in units as provided in "4. Capacity" above.

Site use: indicates the site, also known as end use, energy in trillion Btu (TBTUs) per year in 2030.

Source use: indicates the source, also known as primary or total, energy in TBTUs per year in 2030.

Max adopt: indicates the maximum-adoption potential in source energy in TBTUs/year in 2030.

CCE: indicates the cost of conserved energy in $/MMBTU, source. This does include cost compression as calculated in the economic potential scenario.

Life: provides the average lifetime, in years, of the existing mix of alternatives in the market the measure addresses.

Also, "Primary sources uses" provide the source or sources from which numbers used to calculate savings were directly drawn. "Data used and/or methodology" briefly explains how those data were used to represent the measure in our tool. "Other supporting sources" provides a list of other sources that informed our treatment of each measure.

1. Description of the measure	2. Energy savings			3. Price	4. Units & capacity	5. Market description	6. Market size, 2030	7. Site use	8. Source use	9. Max adopt	10. CCE	11. Life	12. Used in scenario?			
	Percent	SD?	Fuel switch?										McK	NAS	Emerg	Tech
C: Develop automated whole building diagnostics	13%	Yes		$2.04	per square foot	C: HVAC, lighting, and half of refrigeration	103,945	4,728	10,509	266	$15.60	10	No	No	No	No
C: Optimize whole-building controls	28%	Yes		$2.36	per square foot	C: All energy use in commercial buildings >100,000 ft^2	35,538	3,247	7,854	2,197	$2.53	10	No	No	Yes	Yes
R: Develop effective full-home automation systems	6%	Yes		$600	per home	R: All consumption	141	11,750	23,242	1,041	$3.39	20	No	No	Yes	Yes
R: Improve billing information to reduce energy waste and accelerate efficient equipment deployment	3%	Yes		$9	per unit	R: All consumption	141	11,750	23,242	686	$0.46	1	No	No	No	Yes
C: Develop R-10 windows	84%	Yes		$10.66	per square foot; wall: floor space of .9, window fill ratio of 0.4	C: Window conductive loss	103,945	732	736	304	$104.88	40	No	No	Yes	Yes
C: Add aerogel insulaton (i.e., R-21 assembly) to walls	47%	Yes		$2.37	per square foot; wall: floor space of .9, window fill ratio of 0.4	C: Heating and cooling from walls	93,550	739	857	255	$29.65	40	No	No	Yes	Yes
C: Add vacuum insulated panels (VIP) to walls	75%	Yes		$4.16	per square foot; wall: floor space of .9, window fill ratio of 0.4	C: Heating and cooling from walls	93,550	739	857	402	$32.99	40	No	No	Yes	Yes
C: Develop cool roofs with surface reflectance of 0.75 for use in hot climates	15%	Yes		$0.16	per square foot; 3.7 floors/building average	C: Commercial cooling in hottest 2 climates	49,772	423	1,292	170	$2.30	20	No	No	Yes	Yes
C: Develop dynamic windows for use in existing buildings (excludes equipment downsizing benefit)	44%	Yes	FS	$4.32	per square foot; wall: floor space of .9, window fill ratio of 0.4	C: Commercial solar heat gain cooling load	103,945	270	823	182	$62.87	40	No	No	Yes	Yes
C: Develop dynamic windows for use in new buildings (includes equipment downsizing benefit)	44%	Yes		$2.52	per square foot; wall: floor space of .9, window fill ratio of 0.4	C: Solar heat gain cooling in new	50,966	132	404	144	$41.02	40	No	No	Yes	Yes
C: Develop insulating paints (i.e., add R-0.75 per surface painted)	3%	Yes		$0.01	per square foot; wall: floor space of .9, window fill ratio of 0.4	C: Heating and cooling from walls	93,550	739	857	18.9	$4.38	10	No	No	Yes	No
C: Further increase use and performance of dedicated outdoor air systems (with Energy recovery)	11%	Yes		$0.08	per square foot	C: All office HVAC	17,749	284	866	99.6	$0.76	20	No	No	No	No
C: Implement predictive heating/cooling algorithms	10%	Yes		$0.25	per square foot; 1 zone per 1,500 sq. ft.	C: Commercial HVAC	103,945	3,192	3,601	340	$3.88	20	No	No	No	No
C: Improve duct routing practices in new buildings	16%			$0	per square foot	C: All furnaces and A/C heating & cooling (i.e., ducts) in new buildings	50,966	875	1,278	142	$0	60	No	No	No	No
C: Incorporate vestibules for building entrances	54%	Yes		$0.78	per square foot; two vestibules per 15,000 sq. ft.	C: No vestibule infiltration	51,972	306	447	260	$6.49	40	No	No	No	Yes
C: Increase duct insulation from R-4 to R-8 in new buildings	9%	Yes		$0.32	per square foot	C: New buildings, heating & cooling uninsulated ducts	5,097	137	248	18.6	$6.49	40	No	No	No	Yes
C: Increase rate of retro-commissioning commercial buildings	16%	Yes		$0.30	per square foot	C: Commercial HVAC	103,945	3,192	6,017	904	$3.08	5	Yes	Yes	No	Yes
C: Increase roof insulation (i.e., R-30) in existing buildings	42%	Yes		$0.28	per square foot; 210,800 ft^2 school	C: Heating and cooling loads through attics, existing commercial	52,979	226	269	108	$7.90	20	Yes	Yes	Yes	Yes

Primary sources used	Data used and/or methodology	Other supporting sources
TIAX. Energy Impact of Commercial Building Controls and Performance Diagnostics?: Market Characterization, Energy Impact of Building Faults and Energy Savings Potential. Construction 413 (2005).	"it could reduce building energy consumption by 5-20%" The average of 5% and 20% was used. Cost estimated to be the same as 1.5 EMS (1.5*$1.36/ft²) (see Measure 719). The baseline is assumed to have no EMS.	
TIAX. Energy Impact of Commercial Building Controls and Performance Diagnostics?: Market Characterization, Energy Impact of Building Faults and Energy Savings Potential. Construction 413 (2005).	TIAX: "Heating: 10%, Cooling 20%, Ventilation 0%". "Overall it would appear the first cost of an OWBCS associated with an EMCS would be similar to the cost of a higher-end Whole Building Diagnostics implementation less the cost of additional sensors, i.e., on the order of $100000". Installed cost of an EIS for a 100,000 ft² office building was $136,000. Assumes an EMS is required ($136,000) plus an additional $100,000 for the OWBCS controls/ sensors/software. Assumes 20% savings for EMS alone followed by 10% for OWBCS.	
Cost: Williams, Matthews, Breton, and Brady; "Use of a Computer-Based System to Measure and Manage Energy Consumption in the Home" IEEE 2006	Use average of $1000 today and cost compressed $200 to get $600	Wireless home automation networks: A survey of architectures and technologies
Cripps, A., Raw, G. & Ross, D. Energy Demand Research Project: Final Analysis Approved by. 179 (2011).	The particular combination of advice and historic feedback on consumption that EDF deployed (along with smart meters) reduced electricity consumption by 2.3% overall3 in the first in-trial year.4 The effect was persistent into the second in-trial year (4.0% saving). Used: Average of two years at 2.3% and 4%	Darby, S. The Effectiveness of Feedback on Energy Consumption: A Review For Defra of The Literature On Metering, Billing and Direct Displays. Change 24 (2006).
6. Apte, J. & Arasteh, D. Window-Related Energy Consumption in the US Residential and Commercial Building Stock. Buildings 1-38 (Berkeley, CA, 2006). Personal communication: various window experts	See tables 4 and 7 for use and savings. Calculated from first principles; costs from NREL bottom-up VIG build	Arasteh, Dariush; Selkowitz, Steve; Apte, Josh; LaFrance, Marc. Energy Impacts of Today' s Window Stock
Savings: first principles increasing R-value by 10 per inch to R-21 assembly Cost: Personal communication Symposium participants: $4.39/sq. ft. floor space of retrofit. Aspen Aerogel Spaceloft™: A Revolution in Building and Construction Insulation. Aspen Aerogels (2001)	47% savings (increase assembly from R-11 to R-21) at $2.37/sq. ft.	
S.J. Rusek et al, CSI Elevated Temperature Conductivity and Rapid Conductivity Test Method, Quietflex Goodman Global, USA; 10th International Vacuum Insulation Symposium (9/2011). A. Parekh et al., Incorporation of Vacuum Insulation Panels in a Wood Frame Net Zero Energy Home, National Resources Canada, Canada; 10th International Vacuum Insulation Symposium (9/2011)	Savings: first principles. Costs: personal communication from symposium participants	
Konopacki, S., Akbari, H., Pomerantz, M., Gabersek, S. & Gartland, L. Cooling Energy Savings of Light-Colored Roofs for Residential and Commercial Buildings in 11 U.S. Metropolitan Areas. 117 (1997).	Supporting calculations in tool	
Lee, E.S., Yazdanian, M. & Selkowitz, S.E. The Energy-Savings Potential of Electrochromic Windows in the US Commercial Buildings Sector. Building 1-42 (2004). Cost: Personal communication - manufacturers and experts	~95 TBTUs savings at 40% market penetration	Arasteh, D.; Selkowitz, S.; Apte, J.; "Zero Energy Windows"; 2006 ACEEE Summer Study on Energy Efficiency in Buildings
Lee, E.S., Yazdanian, M. & Selkowitz, S.E. The Energy-Savings Potential of Electrochromic Windows in the US Commercial Buildings Sector. Building 1-42 (2004). Cost: Personal communication - manufacturers and experts	~95 TBTUs savings at 40% market penetration	Arasteh, D.; Selkowitz, S.; Apte, J.; "Zero Energy Windows"; 2006 ACEEE Summer Study on Energy Efficiency in Buildings
First principles; K value of 0.1 W/m/K, 50 mils paint thickness on 2 surfaces	Increase R-value of standard walls by 0.4 at a cost of current paint additives	Nansulate claims K=0.017, likely arising from spurious testing as this rivals vacuum
BA Thornton; W Wang; Y Huang; MD Lane; B Liu; "Technical Support Document: 50% Energy Savings for Small Office Buildings"	Calculated from data in chapter 5	
Savings: Cho, Energy Conservation and Management 44 (2003); Cost: Nest (http://www.nest.com/inside-and-out/)	The results show that use of the predictive control strategy could save between 10% and 12% energy during the cold winter months. The energy savings are somewhat higher during mild weather conditions.	
Southface Energy Institute, *FEMP Technology Alert: Air Distribution System Design*, 2003	Southface: "The efficiency of air distribution systems has been found to be 60-75% or less; Properly designed and installed duct systems can have efficiencies of 80% or more for little or no additional cost." Savings estimate is 16%=1-0.675/0.8	
Elaine Hale, Matthew Leach, Adam Hirsch, and Paul Torcellini, "General Merchandise 50% Energy Savings Technical Support Document"; NREL/ TP-550-46100 September 2009	Reduce the front door infiltration from 0.253 to 0.158 ACH. The cost… replacing two, 8-ft tall sliding doors with a total surface area of 120 ft² with four, 7-ft tall sliding doors and adding 30 linear feet of interior walls: $5,853	http://www.hortondoors.com/content.aspx?cid=1232
Cost: NREL retrofit measure database. Savings: First principles of moving ducts from R-4 to R-8 as per recent code changes		LBNL. 2011. Thermal Energy Distribution Website. ducts.lbl.gov.
"Building Commissioning: A Golden Opportunity for Reducing Energy Costs and Greenhouse Gas Emissions", Mills, E.; Energy Efficiency (2011) 4:145–173	Table 3 indicates total primary energy savings in existing buildings of 16%	Mills, E., Friedman, H., Powell, T., Bourassa, N., Claridge, D., Haasl, T., & Piette, M. A. (2004). "The cost-effectiveness of commercial-buildings commissioning: A meta-analysis of energy and non-energy impacts in existing buildings and new construction in the United States." Lawrence Berkeley National Laboratory Report No.56637 http://cx.lbl.gov/2004-assessment.html.
NREL. 2011. Advanced Energy Retrofit Guide for K-12 Schools (Draft). EERE Report DOE/GO-102011-3467. Project Lead: Robert Hendron	$108,2915 total cost, $59,858 incremental cost for replacing insulating sheathing with R-24 for 210,800 ft² school in Chicago, assumes roof is being replaced anyway. Energy savings based on increasing R-14 to R-24 EPS.	

1. Description of the measure	2. Energy savings			3. Price	4. Units & capacity	5. Market description	6. Market size, 2030	7. Site use	8. Source use	9. Max adopt	10. CCE	11. Life	12. Used in scenario?			
	Percent	SD?	Fuel switch?										McK	NAS	Emerg	Tech
C: Increase roof insulation (i.e., to R-30) in new buildings	50%	Yes		$0.88	per square foot; 45,000 ft^2 grocery store, 460,000 ft^2 office, 50,000 ft^2 retail	C: Heating and cooling loads through attics, new commercial	50,966	218	258	129	$25.16	20	No	No	Yes	Yes
C: Increase use of current-generation cool roofs in hot climates	5%	Yes		$0.03	per square foot; 3.7 floors/building average	C: Commercial cooling in hottest 2 climates	49,772	423	1,292	68.6	$1.07	20	No	No	No	No
C: Increase use of efficient window attachments	54%	Yes		$0.51	per square foot; 14 windows / 3000 sq. ft.	C: Windows that can benefit from attachments	51,972	501	767	251	$3.45	40	Yes	Yes	Yes	Yes
C: Install energy recovery ventilators (ERV) in new buildings	26%	Yes	FS	$0.92	per square foot	C: All HVAC in new buildings	50,966	1,565	2,950	867	$3.78	20	Yes	Yes	Yes	Yes
C: Install low-e storm windows	58%	Yes		$0.36	per square foot; wall: floor space of .9, window fill ratio of 0.4	C: Radiative and conductive window load - single pane, primary energy	55,091	694	1,029	658	$1.24	40	No	No	Yes	Yes
C: Install low-e window films (in all climates)	59%	Yes		$0.81	per square foot; wall: floor space of .9, window fill ratio of 0.4	C: Non low-e glass in pre-2010 buildings	19,519	43	133	104.8	$8.71	40	No	No	No	No
C: Paint exterior walls with a "cool" paint color	6%	Yes		$0	per square foot	C: Commercial cooling in hottest 2 climates	49,772	423	1,292	41.5	$0	10	No	No	No	Yes
C: Reduce window area by 20% in new buildings	9%	Yes		-$0.19	per square foot; 50,000 ft^2 retail store	C: All energy use in new commercial buildings	50,966	999	2,415	108	-$9.60	20	No	No	Yes	Yes
C: Require building commissioning in new buildings	13%	Yes		$0.30	per square foot	C: All HVAC in new buildings	50,966	1,565	2,950	313	$4.77	10	Yes	Yes	Yes	Yes
C: Seal ducts in existing buildings	20%	Yes		$0.41	per square foot	C: heating & cooling in existing buildings w/unsealed	47,681	835	1,514	184	$4.15	40	No	No	Yes	Yes
C: Use "standard" duct sealing in new buildings	10%	Yes		$0.33	per square foot	C: All furnaces and A/C heating & cooling (i.e., ducts) in new buildings	50,966	875	1,650	149	$8.41	40	No	No	Yes	Yes
C: Use best available duct sealing (i.e., beyond codes) in existing, large buildings	16%	Yes		$0.33	per square foot	C: Commercial heating and cooling in large existing buildings (>10,000 ft^2)	42,648	1,045	1,678	230	$3.66	10	Yes	Yes	Yes	Yes
C: Use best available duct sealing (i.e., beyond codes) in existing, small buildings	5%	Yes		$0.33	per square foot	C: Commercial heating and cooling in small existing buildings (<10,000 ft^2)	10,331	247	396	14.8	$12.57	10	No	No	Yes	Yes
C: Use best available duct sealing (i.e., beyond codes) in new, small buildings	5%	Yes		$0.33	per square foot	C: Commercial heating and cooling in small new buildings (<10,000 ft^2)	9,938	237	381	14.1	$26.70	10	No	No	Yes	Yes

Primary sources used	Data used and/or methodology	Other supporting sources
Leech, M. et. al.; "Grocery Store 50% Energy Savings Technical Support Document", National Renewable Energy Laboratory (2009). Leech, M. et. al.; "Technical Support Document: Strategies for 50% Energy Savings in Large Office Buildings", National Renewable Energy Laboratory (2010). Hale E. et. al.; "Technical Support Document: Development of the Advanced Energy Design Guide for Medium Box Retail—50% Energy Savings", National Renewable Energy Laboratory (2008)	Costs and performance drawn from upgrading ASHRAE code roof insulation to most cost effective point from indicated source. R-15 to R-30 upgrade, $0.88/sq. ft. average cost	
Konopacki, S., Akbari, H., Pomerantz, M., Gabersek, S. & Gartland, L. Cooling Energy Savings of Light-Colored Roofs for Residential and Commercial Buildings in 11 U.S. Metropolitan Areas. 117 (1997).	Supporting calculations in tool	
Savings: first principles calculation from R- and SHGC- impacts of product. Price: Comfortex. Manufacturer & expert interviews	Savings: adding R_value of 1.75 and reducing SHGC to 0.35. Price: Comfortex current prices compressed 1/3rd to represent learning curve. Market: assumes 50% of windows benefit from attachments	Kotey, N.A., Wright, J.L., Barnaby, C.S., Collins, M.R., "Solar Gain Through Windows with Shading Devices: Simulation versus Measurement," ASHRAE Transactions, Vol. 115, Pt. 2, (2009)
Chiras, D. 2009. Energy-recovery Ventilators: Ventilate Your Home with Minimal Energy Loss. Mother Earth News. http://www.motherearthnews.com/Green-Homes/Energy-Recovery-Ventilator.aspx?page=4#ixzz1yRuXsH6b U.S. Department of Energy. 2005. Residential Energy Consumption Survey. http://205.254.135.7/consumption/residential/data/2005/hc/hcfloorspace_char/pdf/tablehc1.1.2.pdf	Chiras: "Energy-recovery ventilators are a well-developed technology. Their prices range from about $500 to $1,700, not including installation.". "Most energy-recovery ventilation systems on the market today recover about 70 to 80 percent of the energy in the outgoing air, transferring it to the incoming air." DOE RECS: Average ft^2 = 2170. Cost estimates for residential ERVs are close to $2000 installed based on Chiara article, assuming a high-end multi-point system. Average house is 2170 ft^2. Assumes 70% reduction of infiltration load, which is 37% of the heating load.	NREL. 2011. Advanced Energy Retrofit Guide for K-12 Schools (Draft). EERE Report DOE/GO-102011-3467. Project Lead: Robert Hendron
Kohler, C. *Letter report for low-e storm window retrofits*, 2006	"A simulation study in 2004 has shown that by using pyrolitic "hard" low-e coatings will increase from approximately 15% of the home's heating energy to 18%. The additional cost is...on the order of $100." Note: 18% of home heating/cooling is 58% of window load heating/cooling	
Huang, J. Computer Simulation Analysis of the Energy Impact of Window Films In Existing Houses. Selkowitx, S. Personal communication	Tables 12-16 used to generate estimate of population average. Simplified to SHGF and used vs. existing baseline. Improving SHGF from 0.74 to 0.30 on windows incurring the greatest load	
Tom Petrie, Jerry Atchley, Phil Childs, and André Desjarlais; "Energy Savings for Stucco Walls Coated with Cool Colors" ORNL (12/2007)	"Savings are 4-9% compared to non-IR reflecting walls"	Additional support by running HES Pro in multiple climate zones to verify savings
220. Hale, E., Leach, M., Hirsch, A. & Torcellini, P. General Merchandise 50% Energy Savings Technical Support Document General Merchandise 50% Energy Savings Technical Support Document. 188 (2009). http://www.nrel.gov/docs/fy08osti/42828.pdf.	Hale: 1000 ft^2 window area in baseline, $47.23/$ft^2$. Assumes 20% reduced window area contributes 50% of total energy savings associated with glazing area, which averages about 8% of whole-building energy use.	
"Building Commissioning: A Golden Opportunity for Reducing Energy Costs and Greenhouse Gas Emissions", Mills, E.; Energy Efficiency (2011) 4:145–173	Table 3 indicates total primary energy savings in new buildings of 13%	Mills, E., Friedman, H., Powell, T., Bourassa, N., Claridge, D., Haasl, T., & Piette, M. A. (2004). "The cost-effectiveness of commercial-buildings commissioning: A meta-analysis of energy and non-energy impacts in existing buildings and new construction in the United States." Lawrence Berkeley National Laboratory Report No.56637 http://cx.lbl.gov/2004-assessment.html.
Modera, M. *Fixing Duct Leaks in Commercial Buildings* ASHRAE Journal June 2005. TIAX. Energy Impact of Commercial Building Controls and Performance Diagnostics?: Market Characterization, Energy Impact of Building Faults and Energy Savings Potential. Construction 413 (2005).	Modera: 80% heating season duct efficiency (See Figure 2 and measured duct efficiency data cited throughout the article. 7.5 cents/ft^2 added for diagnostic testing (TIAX 2005). Nominal sealing cost is 33 cents/ft^2 for consistency with Measure 92. Energy savings assumed to be double the savings in new homes from Measure 92.	
Modera, M. *Fixing Duct Leaks in Commercial Buildings* ASHRAE Journal June 2005. Aeroseal website. http://www.aeroseal.com/problem-we-solve/FAQ-commercial.html	Modera: 80% heating season duct efficiency (See Figure 2 and measured duct efficiency data cited throughout the article. 50% improvement is assumed over the 80% duct efficiency baseline. Price based on average of three Aeroseal case studies and estimated payback of 2.5 years ($0.33/$ft^2$=$247*2.5 years/1879 ft^2)	13. Goetzler, W., Zogg, R., Burgos, J., Hiraiwa, H. & Young, J. Energy Savings Potential and RD & D Opportunities for Commercial Building HVAC Systems. 289 (2011).
Modera, M. *Fixing Duct Leaks in Commercial Buildings* ASHRAE Journal June 2005.	Modera: "Using the power 2.4 from Franconi et al.,5 a 15% leak translates to a 40% increase in fan power." "Researchers at Lawrence Berkeley Laboratory measured duct leakage in six large commercial buildings, three of which showed 5% leakage, while the other three showed 15%, 17% and 25% supply duct leakage." Assumes 16% savings based on reduction in leakage from 15% to 7.5% and exponent of 2.4. Assumes 50% reduction in leakage rate due to aerosol sealing. Assumes same cost as Measure 92.	Goetzler, W., Zogg, R., Burgos, J., Hiraiwa, H. & Young, J. Energy Savings Potential and RD & D Opportunities for Commercial Building HVAC Systems. 289 (2011).
Modera, M. *Fixing Duct Leaks in Commercial Buildings* ASHRAE Journal June 2005.	Modera: 80% heating season duct efficiency (See Figure 2 and measured duct efficiency data cited throughout the article. For light commercial, the duct efficiency is about 80% in half the buildings (where the ducts are in a ceiling plenum outside the thermal boundary). Calculated 5% heating and cooling savings (50% reduction in 20% duct losses in 50% of small buildings). Price same as Measure 92.	
Modera, M. *Fixing Duct Leaks in Commercial Buildings* ASHRAE Journal June 2005. ASHRAE. 2010. Energy Standard for Buildings Except Low-Rise Residential Buildings. ASHRAE 90.1 2010.	Modera: 80% heating season duct efficiency (See Figure 2 and measured duct efficiency data cited throughout the article. For light commercial, the duct efficiency is about 80% in half the buildings (where the ducts are in a ceiling plenum outside the thermal boundary). ASHRAE: "Ductwork and all plenums with pressure class ratings shall be constructed to seal class A, as required to meet the requirements of Section 6.4.4.2.2..." Price same as Measure 92. Aeroseal isn't necessary to meet code, but is assumed for 5% improvement beyond code. Given that the code already addresses the most serious leakage (high pressure supply leakage in unconditioned space), savings in the range of 5% is assumed (50% reduction in 10% of leakage outside conditioned space in code compliant new buildings).	

1. Description of the measure	2. Energy savings			3. Price	4. Units & capacity	5. Market description	6. Market size, 2030	7. Site use	8. Source use	9. Max adopt	10. CCE	11. Life	12. Used in scenario?			
	Percent	SD?	Fuel switch?										McK	NAS	Emerg	Tech
C: Use building wrap to reduce air infiltration in new buildings	61%	Yes		$1.26	per square foot; wall: floor space of .9, window fill ratio of 0.4	C: New Heating and cooling trough infiltration	50,966	300	482	294	$14.05	80	No	No	No	No
C: Use low pressure drop air filters in ducted systems	25%			$0.04	per square foot; represents 6 filter changes over lifetime; 1 per 1,500 sq. ft. of service	C: Commercial variable volume ventilation and air handlers	23,180	451	1,377	347	$0.24	6	No	No	Yes	Yes
C: Use R-5 windows	68%	Yes		$1.83	per square foot	C: Window conductive loss	103,945	732	765	249	$20.42	60	No	No	Yes	Yes
R: Develop R-10 windows	81%	Yes		$5,687.04	per home; 192 sq. ft. glazing	R: All homes heating and Cooling lost through windows (cond)	141	1,553	1,721	817	$30.17	30	No	No	Yes	Yes
R: "Drill & Fill" walls in pre-1970 homes	60%	Yes		$6,500	per home; 30x40 home, 2 stories, 10' per story	R: Pre-1970 single family homes heating and Cooling lost through walls	38.6	199	255	179	$46.66	80	No	No	Yes	Yes
R: Add aerogel insulation (i.e., R-21 assembly) to walls	47%	Yes		$11,414	per home; 2,600 sq. ft. insulation	R: All homes heating and Cooling lost through walls	141	1,251	386	113	$440.92	40	No	No	Yes	Yes
R: Add duct insulation to existing buildings currently lacking it	40%	Yes		$0.88	per square foot	R: heating & cooling in existing buildings w/o insulated ducts	51,972	569	1,030	429	$4.04	40	No	No	No	No
R: Add duct insulation to existing homes currently lacking it	40%	Yes		$518	per home; 195 ft^2 of supply duct and 240 ft^2 return duct for 1500 ft^2 home	R: Existing homes lacking duct insulation	60.7	1,661	2,426	941	$1.21	40	Yes	Yes	No	Yes
R: Add Exterior Insulating Finishing Systems (EIFS) to walls of existing buildings (included infiltration reduction)	68%	Yes		$13,780	per home; 2,600 sq. ft. insulation	R: Pre-2010 homes heating and Cooling lost through walls	74.2	905	1,157	761	$54.39	40	No	No	Yes	No
R: Add vacuum insulated panels (VIP) to walls	75%	Yes		$20,046	per home; 2,600 sq. ft. insulation	R: All homes heating and Cooling lost through walls	141	1,251	1,600	740	$118	40	No	No	Yes	Yes
R: Added R-6 sheathing to walls of existing buildings with siding (included infiltration reduction)	51%	Yes		$2,548	per home; 2,600 sq. ft. insulation	R: Existing walls and infiltration; siding based	54.2	1,195	1,528	768	$6.61	40	No	No	No	No
R: Attic radiant barrier (existing homes)	4%			$152.71	per home	R: Pre-2010 homes heating and Cooling lost through attic	102.3	648	930	28	$19	20	No	No	No	No
R: Build new homes using 2x6, 24" on-center construction	43%	Yes		$0	per home; 30x40 home, 2 stories, 10' per story	R: New homes heating and Cooling lost through walls	39.1	346	443	183	$0	80	Yes	Yes	Yes	No
R: Build new homes using advanced framing techniques	24%	Yes		-$750	per home	R: New homes heating and Cooling lost through walls	39.1	346	443	91.3	-$19.67	80	Yes	Yes	Yes	Yes
R: Develop advanced integrated (i.e., R-75 equivalent) roof systems for existing homes	69%	Yes		$3,186.97	per home; 30x40 home, 2 stories, 10' per story	R: Existing homes heating and Cooling lost through attic (non-hot climates)	42.9	367	527	68.1	$20.75	30	No	No	Yes	Yes
R: Develop advanced integrated (i.e., R-75 equivalent) roof systems for existing homes in hot climates	55%	Yes		$3,186.97	per home; 30x40 home, 2 stories, 10' per story	R: Central cooling in existing single-family homes in hottest two climates	101	330	1,006	73.6	$28.38	40	No	No	Yes	Yes
R: Develop advanced integrated (i.e., R-75 equivalent) roof systems for new homes in hot climates	55%	Yes		$1,801.33	per home; 30x40 home, 2 stories, 10' per story	R: Central cooling in new single-family homes in hottest two climates	12.7	121	368	152	$6.82	20	No	No	Yes	Yes
R: Develop dynamic windows for use in existing homes (excludes equipment downsizing benefit)	42%	Yes		$2,304	per square foot; wall: floor space of .9, window fill ratio of 0.4	R: Pre-2010 homes heating and Cooling lost through windows (rad)	102	213	716	152	$34.25	30	No	No	Yes	Yes

Primary sources used	Data used and/or methodology	Other supporting sources
Elaine Hale, Matthew Leach, Adam Hirsch, and Paul Torcellini, "General Merchandise 50% Energy Savings Technical Support Document"; NREL/TP-550-46100 September 2009	The air barrier is assumed to reduce the envelope infiltration from 0.038 to 0.015 ACH… The cost of the air barrier is estimated at $1.40/ft^2 of exterior wall area	
"Air-Filter Life-Cycle Cost", Seyffer, C.; HPAC Engineering 9/2010	"As much as 40 percent of HVAC-system electricity demand could be reduced by applying air-filter life-cycle-cost analysis." Cost taken from manufacturer website	"Proper Air Filter Selection Goes a Long Way", Matela, D.AFE Journal 10/2010. Expert interviews suggest 25% is more typical savings
6. Apte, J. & Arasteh, D. Window-Related Energy Consumption in the US Residential and Commercial Building Stock. Buildings 1-38 (Berkeley, CA, 2006).	See tables 4 and 7 for use and savings	
6. Apte, J. & Arasteh, D. Window-Related Energy Consumption in the US Residential and Commercial Building Stock. Buildings 1-38 (Berkeley, CA, 2006).	See tables 4 and 7 for use and savings. Calculated from first principles; costs from NREL bottom-up VIG build	Arasteh, Dariush; Selkowitz, Steve; Apte, Josh; LaFrance, Marc. Energy Impacts of Today's Window Stock
Savings: first principles. Cost: NREL retrofit measure database		
Savings: first principles increasing R-value by 10 per inch to R-21 assembly. Cost: Personal communication Symposium participants: $4.39/sq. ft. floor space of retrofit. Aspen Aerogel Spaceloft™: A Revolution in Building and Construction Insulation. Aspen Aerogels (2001)	47% savings (increase assembly from R-11 to R-21) at $2.37/sq. ft.	
Same as above	Savings assumed same as residential. Cost assumptions: 2000' of duct, 12"d/3 sq. ft./ft. $2.2/ft^2 of supply duct area. 15000 ft^2 typical commercial building.	
Hendron, R., and Engebrecht, C. 2010. Building America House Simulation Protocols. DOE/GO-102010-3141. http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/house_simulation_revised.pdf. NREL Residential Efficiency Measures Database. http://www.nrel.gov/ap/retrofits/measures.cfm?gId=2&ctId=16. Mills, E.. et al. 2007. "Home Energy Saver: Documentation of Calculation Methodology, Input Data, and Infrastructure." Lawrence Berkeley National Laboratory Report No. 51938. http://evanmills.lbl.gov/pubs/pdf/home-energy-saver.pdf	Hendron: Supply duct surface area (ft^2)= 0.27 × FFA, Return duct surface area (ft^2)= 0.05 × Nreturns × FFA. NREL: $1.3/ft^2 and $1.1/ft^2 for supply (R-8) and return (R-6) ducts respectively. Mills: efficiency ducts = DF * HSE + (1− DF) *CSE. Estimated cost based on insulating 195 ft^2 of supply ducts in unconditioned space and (Hendron value for 1500 ft^2 house) and $1.3/ft^2 (NREL Retrofit Measure Database) is $254. Insulating 240 ft^2 of return ducts in unconditioned space using $1.1/ft^2 is another $264, for a total of $518. Energy savings is derived from HES Pro assumptions for duct distribution efficiency using LBNL's ASHRAE 152 model.	
Straube, J. and Smegal, J.; Building America Special Research Project: High-R Walls Case Study Analysis; Building Science Corporation 2009 (updated 2011)	Costs calculated from manufacturer quotes; savings calculated from first principles	
S.J. Rusek et al, CSI Elevated Temperature Conductivity and Rapid Conductivity Test Method, Quietflex Goodman Global, USA; 10th International Vacuum Insulation Symposium (9/2011). A. Parekh et al., Incorporation of Vacuum Insulation Panels in a Wood Frame Net Zero Energy Home, National Resources Canada, Canada; 10th International Vacuum Insulation Symposium (9/2011)	Savings: first principles. Costs: personal communication from symposium participants	
Straube, J. and Smegal, J.; Building America Special Research Project: High-R Walls Case Study Analysis; Building Science Corporation 2009 (updated 2011)	Costs calculated from manufacturer quotes; savings calculated from first principles	
Miller, W. & Kosny, J. Next-Generation Roofs and Attics for Homes. ACEEE Summer Study on Energy Efficiency in Buildings 180-195 (2008)	Analyzed savings for ducts and attic loads scaled to national average using existing stock as base	
NAHB Research Center; Southface Energy Institute; Oak Ridge National Laboratory; National Renewable Energy Laboratory; "Technology Fact Sheet: Advanced Framing" (2000)	"Fully implementing advanced framing techniques can result in materials cost savings of about $500-$1000 (for a 1,200-2,400-square-foot house, respectively), labor cost savings of between 3 and 5 percent, and annual heating and cooling cost savings of up to 5 percent." Scaled up 5% whole-building savings to share of wall load	
National Association of Home Builders, Southface Energy Institute & Oak Ridge National Laboratory, Advanced Wall Framing. U.S. Department of Energy (2000).	"Advanced framing techniques can result in materials cost savings of [$500-$1000], labor cost savings of [3-5%], and annual heating and cooling cost savings of up to 5 percent." Savings includes material cost only; average (4%) heating and cooling scaled up from full building to walls portion	Straube, J. & Smegal, J. Building America Special Research Project: High-R Walls Case Study Analysis. Building Science 68 (Somerville, MA, 2009).
Miller, W. & Kosny, J. Next-Generation Roofs and Attics for Homes. ACEEE Summer Study on Energy Efficiency in Buildings 180-195 (2008)	Analyzed savings for ducts and attic loads scaled to national average using existing stock as base	
Miller, W. & Kosny, J. Next-Generation Roofs and Attics for Homes. ACEEE Summer Study on Energy Efficiency in Buildings 180-195 (2008)	Analyzed savings for ducts and attic loads scaled to national average using new codes as base	
Miller, W. & Kosny, J. Next-Generation Roofs and Attics for Homes. ACEEE Summer Study on Energy Efficiency in Buildings 180-195 (2008)	Analyzed savings for ducts and attic loads scaled to national average using new codes as base	
Arasteh, D.; Selkowitz, S.; Apte, J.; "Zero Energy Windows"; 2006 ACEEE Summer Study on Energy Efficiency in Buildings	Table 4; baseline updated to 2010 stock	Lee, E.S., Yazdanian, M. & Selkowitz, S.E. The Energy-Savings Potential of Electrochromic Windows in the US Commercial Buildings Sector. Building 1-42 (2004). Cost: Personal communication - manufacturers and experts

1. Description of the measure	2. Energy savings			3. Price	4. Units & capacity	5. Market description	6. Market size, 2030	7. Site use	8. Source use	9. Max adopt	10. CCE	11. Life	12. Used in scenario?			
	Percent	SD?	Fuel switch?										McK	NAS	Emerg	Tech
R: Develop dynamic windows for use in new homes (includes equipment downsizing benefit)	42%	Yes		$1,344	per square foot; wall: floor space of .9, window fill ratio of 0.4	R: New. homes heating and Cooling lost through windows (rad)	4.1	69.4	233	85.0	$3.63	30	No	No	Yes	Yes
R: Develop insulating paints (i.e., add R-0.75 per surface painted)	3%	Yes		$70	per home; 2,600 sq. ft. insulation	R: All homes heating and Cooling lost through walls	141	1,251	1,558	32.9	$17.42	10	No	No	Yes	No
R: Develop lower-cost cool roofs in colors that appeal to consumers	12%	Yes		$490.75	per home; 1,150 sq. ft. roofing	R: All cooling in homes in hot climates	9.1	403	1,230	124	$1.79	20	No	No	Yes	Yes
R: Improve duct routing practices in new homes	16%			$0	per home	R: Forced hot air systems in new homes	35.0	753	1,100	85.5	$0	80	No	No	No	No
R: Increase duct insulation from R-4 to R-8 in new homes	9%	Yes		$518	per home; 195 ft^2 of supply duct and 240 ft^2 return duct for 1500 ft^2 home	R: New homes lacking duct insulation	39.1	1,094	1,981	140	$10.12	40	No	No	Yes	Yes
R: Increase use of efficient window attachments	48%	Yes		$800.80	per home; 14 windows/home	R: Windows that can benefit from attachments	70.7	918	1,361	645	$5.69	10	No	No	Yes	Yes
R: Install low-e storm windows	58%	Yes		$1,500	per home; 10 storms/home	R: Pre-2010 homes with single pane glass, conduction and radiation	47.5	563	835	548	$4.80	30	No	No	Yes	Yes
R: Install low-e window films in all climates	47%	Yes		$432	per home; 192 sq. ft. of windows	R: Pre-2010 homes with non-low-e glass	40.2	84	256	123	$5.05	30	No	No	No	No
R: Install low-e window films in hot climates	47%	Yes		$432	per home; 192 sq. ft. of windows	R: All cooling in homes in hot climates	17.0	51	157	76	$3.48	30	No	No	No	No
R: install PCM in attics in existing homes	32%	Yes		$1,000	per home; 1,000 sq. ft. insulation	R: Pre-2010 homes heating and Cooling lost through attic	102	648	930	278	$14.79	40	No	No	No	No
R: install PCM in attics in new homes	24%	Yes		$700	per home; 1,000 sq. ft. insulation	R: New homes heating and Cooling lost through attic	27.1	191	275	50.3	$16.97	40	No	No	No	No
R: install PCM in walls in new homes	32%	Yes		$1,300	per home; 2,600 sq. ft. insulation	R: New homes heating and Cooling lost through walls	39.1	346	443	111	$21.39	40	No	No	No	No
R: Install predictive thermostats (e.g., Nest)	10%	Yes		$300	per home	R: Heating and cooling	160	5,568	8,132	851	$3.89	10	No	No	Yes	Yes
R: Install programmable thermostats	4%	Yes		$90	per home	R: All heating and cooling in existing homes	102	4,028	5,884	143	$3.46	20	Yes	Yes	No	No
R: Install radiative barriers in attics	12%	Yes		$263.27	per home; 30x40 home, 2 stories, 10' per story	R: All homes heating and Cooling lost through attic	141	893	1,304	111	$12.68	20	No	No	No	No
R: Insulate crawl spaces to R-17	76%	Yes		$228	per home; 30x40 home, 2 stories, 10' per story	R: All homes heating and Cooling lost through crawl space foundation	35.2	163	238	192	$1.98	20	Yes	Yes	Yes	Yes
R: Insulate poorly-insulated attics to R-40	90%	Yes		$3,640	per home; 30x40 home, 2 stories, 10' per story	R: All homes heating and Cooling lost through poorly insulated attic	33.7	415	595	614	$7.91	40	No	No	Yes	No
R: Insulate slab foundation edges to R-10 in existing homes	85%	Yes		$1,437.22	per home; 30x40 home, 2 stories, 10' per story	R: Existing homes heating and Cooling lost through slab foundation	29.6	189	276	109	$8.21	40	No	No	Yes	Yes
R: Insulate slab foundation edges to R-5 in new homes	70%	Yes		$715	per home; 30x40 home, 2 stories, 10' per story	R: New homes heating and Cooling lost through slab foundation	10.8	71.2	104	76.5	$5.51	40	No	No	Yes	Yes
R: Insulate well-insulated attics to R-40	45%	Yes		$1,768	per home; 30x40 home, 2 stories, 10' per story	R: All homes heating and Cooling lost through moderately insulated attics	49.1	136	195	89.2	$36.12	30	No	No	No	No

Primary sources used	Data used and/or methodology	Other supporting sources
Arasteh, D.; Selkowitz, S.; Apte, J.; "Zero Energy Windows"; 2006 ACEEE Summer Study on Energy Efficiency in Buildings	Table 4; adjusted for new building codes	Lee, E.S., Yazdanian, M. & Selkowitz, S.E. The Energy-Savings Potential of Electrochromic Windows in the US Commercial Buildings Sector. Building 1-42 (2004). Cost: Personal communication - manufacturers and experts
First principles; K value of 0.1 W/m/K, 50 mils paint thickness on 2 surfaces	Increase R-value of standard walls by 0.4 at a cost of current paint additives	Nansulate claims K=0.017, likely arising from spurious testing as this rivals vacuum
Konopacki, S., Akbari, H., Pomerantz, M., Gabersek, S. & Gartland, L. Cooling Energy Savings of Light-Colored Roofs for Residential and Commercial Buildings in 11 U.S. Metropolitan Areas. 117 (1997).	Supporting calculations in tool	
Southface Energy Institute, FEMP Technology Alert: Air Distribution System Design, 2003	Southface: "The efficiency of air distribution systems has been found to be 60-75% or less; Properly designed and installed duct systems can have efficiencies of 80% or more for little or no additional cost." Savings estimate is 16%=1-0.675/0.8	
Cost: NREL retrofit measure database. Savings: First principles of moving ducts from R-4 to R-8 as per recent code changes		LBNL. 2011. Thermal Energy Distribution Website. ducts.lbl.gov.
Savings: first principles calculation from R- and SHGC- impacts of product. Price: Comfortex. Manufacturer & expert interviews	Savings: adding R-value of 1.75 and reducing SHGC to 0.35. Price: Comfortex current prices compressed 1/3rd to represent learning curve	Kotey, N.A., Wright, J.L., Barnaby, C.S., Collins, M.R., "Solar Gain Through Windows with Shading Devices: Simulation versus Measurement," ASHRAE Transactions, Vol. 115, Pt. 2, (2009)
Kohler, *C Letter report for low-e storm window retrofits*, 2006	"A simulation study in 2004 has shown that by using pyrolitic "hard" low-e coatings will increase from approximately 15% of the home's heating energy to 18%. The additional cost is…on the order of $100." Note: 18% of home heating/ cooling is 58% of window load heating/cooling	
Huang, J. Computer Simulation Analysis of the Energy Impact of Window Films In Existing Houses. Selkowitx, S. Personal communication	Tables 12-16 used to generate estimate of population average. Simplified to SHGF and used vs. existing baseline. Improving SHGF from 0.74 to 0.30 on windows incurring the greatest load	
Huang, J. Computer Simulation Analysis of the Energy Impact of Window Films In Existing Houses. Selkowitx, S. Personal communication	Tables 12-16 used to generate estimate of population average. Simplified to SHGF and used vs. existing baseline. Improving SHGF from 0.74 to 0.30 on windows incurring the greatest load	
Analysis of the Dynamic Thermal Performance of Fiberous Insulations Containing Phase Change Materials, Jan Kośny, et. al.	fitted with PCMs dropped the annual load due to ceiling and duct heat gains/losses by 23% of that computed for the SR25E75 code compliant roof and attic assembly.	Miller, W.; Kośny, J.; "Next-Generation Roofs and Attics for Homes"; 2008 ACEEE Summer Study on Energy Efficiency in Buildings
Analysis of the Dynamic Thermal Performance of Fiberous Insulations Containing Phase Change Materials, Jan Kośny, et. al.	Same as previous adjusted for cost and impacts vs. 2010 building code baseline	
Miller, W.; Kośny, J.; "Next-Generation Roofs and Attics for Homes"; 2008 ACEEE Summer Study on Energy Efficiency in Buildings	Increasing the air space from 2 to 4 in. (0.051 to 0.102 m) and adding PCM caused an additional 10% drop compared with the assembly with a 2-in. air space	Analysis of the Dynamic Thermal Performance of Fiberous Insulations Containing Phase Change Materials Jan Kośny, et. al.
Savings: Cho, Energy Conservation and Management 44 (2003); Cost: Nest (http://www.nest.com/inside-and-out/)	The results show that use of the predictive control strategy could save between 10% and 12% energy during the cold winter months. The energy savings are somewhat higher during mild weather conditions.	
Energy Information Agency. "Residential Energy Consumption Survey, 2009". Department of Energy (2012)	RECS 2009 analysis of set back behavior and penetration of programmable thermostats included in spreadsheet	
Medina, M; "On the performance of radiant barriers in combination with different attic insulation levels"; Energy and Buildings 33 (2000) 31-40	"produced yearly heat-load reductions of approximately 44, 28, and 23%." Adjusted for heating penalty and average national load as per cool roof calculations. Costs taken from manufacturer's website (6/11)"	Levins, W. P.; Karnitz, M. A.; Knight, D. K.; "Cooling Energy Measurements of Houses with Attics Containing Radiant Barriers." Medina, M; O'Neil, D; Turner, W.; Effect of Attic Ventilation on Performance of Radiant Barriers"; Transactions of the ASME Vol. 114 pf 234 11/1992. http://www.reflectixinc.com/basepage.asp?PageIndex=390;
Savings: First principles (market and baseline drawn from RECs analysis). Cost: NREL measure database		
Savings: First principles (market and baseline drawn from RECs analysis). Cost: NREL measure database		
"A Builder's Guide to Residential Foundation Insulation" King, J.; Meyer, G.	Supporting calculations in tool take savings calculated from Kansas climate zones then scaled nationally	FEMP Technology Fact Sheet: Slab Insulation", Southface Energy Institute, Oak Ridge National Laboratory
"A Builder's Guide to Residential Foundation Insulation" King, J.; Meyer, G.	Supporting calculations in tool take savings calculated from Kansas climate zones then scaled nationally	FEMP Technology Fact Sheet: Slab Insulation", Southface Energy Institute, Oak Ridge National Laboratory
Savings: First principles (market and baseline drawn from RECs analysis). Cost: NREL measure database		

1. Description of the measure	2. Energy savings			3. Price	4. Units & capacity	5. Market description	6. Market size, 2030	7. Site use	8. Source use	9. Max adopt	10. CCE	11. Life	12. Used in scenario?			
	Percent	SD?	Fuel switch?										McK	NAS	Emerg	Tech
R: Insulate basements to R-11	73%	Yes		$1,196	per home; 30x40 home, 2 stories, 10' per story	R: All homes heating and Cooling lost through basement	49.8	230	226	174	$14.48	30	No	No	Yes	No
R: Paint exterior walls with a "cool" paint color	6%	Yes		$0	per home	R: Central Cooling in hot climates	66.6	577	1,761	105	$0	10	No	No	No	No
R: poorly ins. attics to R-60	94%			$5,460	per home; 30x40 home, 2 stories, 10' per story	R: All homes heating and Cooling lost through poorly insulated attic	33.7	415	595	643	$11.85	30	No	No	Yes	Yes
R: R-19 basement	83%			$1,768	per home; 30x40 home, 2 stories, 10' per story	R: All homes heating and Cooling lost through basement	49.8	230	226	200	$18.73	30	No	No	No	Yes
R: Retrofit existing homes to highly efficient (i.e., R-30) wall construction (e.g., EIFS)	83%	Yes		$20,800	per home; 2600 square feet wall space	R: Pre-2010 homes heating and Cooling lost through walls	74.2	731	935	817	$70.74	40	No	No	No	Yes
R: Seal air-leaks existing homes (50% improvement)	50%	Yes		$900	per home; 30x40 home, 2 stories, 10' per story	R: Pre-2010 homes heating and Cooling lost through infiltration	102	1,350	1,758	943	$5.11	10	Yes	Yes	Yes	Yes
R: Seal ducts in existing homes	10%	Yes		$495	per home	R: Existing homes with unsealed ducts	88.8	2,484	4,500	355	$4.11	40	Yes	Yes	Yes	Yes
R: Use "enhanced" duct sealing in new homes	5%	Yes		$756.50	per unit	R: New homes with code-compliant duct sealing	7.9	215	314	12.4	$33.10	40	Yes	Yes	Yes	Yes
R: Use building wrap to reduce air infiltration in new homes	13%	Yes		$1,040.56	per home	R: New homes heating and Cooling lost through infiltration	39.1	515	752	75.7	$33.73	60	No	No	No	No
R: Use highly insulating (R-7) doors	75%			$90	per unit	R: All homes heating and Cooling lost through doors	141	233	265	187	$3.69	20	Yes	Yes	Yes	Yes
R: Use highly efficient (i.e., R-30) wall construction in new homes	70%	Yes		$13,000	per home; 2600 square feet wall space	R: New homes heating and Cooling lost through walls	39.1	346	443	279	$114.55	40	No	No	Yes	Yes
R: Use insulating shutters on windows	67%	Yes		$1,480	per home; 15 windows: $72/ window plus one day to install	R: All homes heating and Cooling lost through windows (cond)	141	1,553	2,269	1,579	$6.33	20	No	No	No	No
R: Use low pressure drop air filters in ducted systems	25%			$60	per home; represents 6 filter changes over lifetime	R: All furnace fan energy	88.1	186	567	198	$2.07	6	No	No	Yes	Yes
R: Use phase-change materials (PCM) in walls in new homes	32%	Yes		$4,752	per home; 1,000 sq. ft. insulation	R: New homes heating and Cooling lost through walls	39.1	346	443	111	$78.18	40	No	No	No	No
R: Use R-5 windows	63%	Yes		$973.44	per home	R: All homes heating and Cooling lost through windows (cond)	141	1,553	1,799	662	$6.36	40	No	No	Yes	Yes
R: Use radiative barriers in existing homes (includes duct-cooling benefits)	12%	Yes		$263.27	per home; 30x40 home, 2 stories, 10' per story	R: All cooling in homes in hot climates	9.1	403	1,230	137	$1.38	20	No	No	No	No
R: Use radiative barriers in new homes (includes duct-cooling benefits)	12%	Yes		$263.27	per home; 30x40 home, 2 stories, 10' per story	R: All cooling in homes in hot climates	14.6	224	683	53.2	$4.03	20	No	No	No	No
R: well ins. attics to R-60	64%			$3,900	per home; 30x40 home, 2 stories, 10' per story	R: All homes heating and Cooling lost through moderately insulated attics	49.1	136	195	126	$59.24	30	No	No	Yes	Yes
C: Add stack economizer to boilers	5%	Yes		$0.76	per square foot; 5000 kW boiler, 241,000 ft² ave. hospital	C: Space heating using boiler, existing commercial	22,335	214	215	8.43	$90.71	20	No	No	No	No
C: Increase use of most efficient (i.e., max-tech) furnaces & radiators	13%	Yes		$0.57	per square foot	C: Furnaces and boilers	92,302	1,269	1,269	100	$24.62	30	Yes	Yes	Yes	Yes
C: Reduce heater oversizing	5%	Yes		-$0.08	per square foot	C: All heating	103,945	1,862	2,183	54.9	-$7.02	30	Yes	Yes	Yes	Yes
C: Replace large-capacity boilers with cascaded-multiple boilers	20%	Yes		$0.17	per square foot	C: All boiler heating	23,487	421	481	58.7	$2.13	30	Yes	Yes	No	Yes

Primary sources used	Data used and/or methodology	Other supporting sources
Savings: First principles (market and baseline drawn from RECs analysis). Cost: NREL measure database	R-15 is effective total assembly thermal resistance after adding R-11 insulation	
Tom Petrie, Jerry Atchley, Phil Childs, and André Desjarlais; "Energy Savings for Stucco Walls Coated with Cool Colors" ORNL (12/2007)	"Savings are 4-9% compared to non-IR reflecting walls"	Additional support by running HES Pro in multiple climate zones to verify savings
Savings: first principles increasing R-value. Cost: NREL measure database	Increase from R-4 assembly to R-60	
Savings: first principles increasing R-value. Cost: NREL measure database	Increase from R-4 assembly to R-23	
Straube, J. and Smegal, J.; Building America Special Research Project: High-R Walls Case Study Analysis; Building Science Corporation 2009 (updated 2011)	Costs calculated from manufacturer quotes; savings calculated from first principles	
Savings: first principles (i.e. ,50% target). Cost: NREL retrofit measure database for this performance level		
Aeroseal website. http://www.aeroseal.com/problem-we-solve/FAQ-commercial.html	Aeroseal: $.33/ft^2 based on measure 92. Average house assumption is 1500 ft^2. Assumes twice the energy savings as new homes (Measure 91).	
Hendron, R., and Engebrecht, C. 2010. Building America House Simulation Protocols. DOE/GO-102010-3141. http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/house_simulation_revised.pdf. Modera, M. Fixing Duct Leaks in Commercial Buildings; ASHRAE Journal June 2005	Hendron: 10% supply air leakage, ~6.5% to the outside. Modera: Figure 6 ~80% reduction in leakage for Aeroseal in sections of a large office. Implication: reduce leakage (80%) from 6.5% to 1.3%. Price is a 15% discount over measure 127 because of efficiencies related to new homes vs. retrofits	
Architectural Energy Company, "Impact of Title 24 Residential Air Leakage Reduction Credit on Water-Resistive Barriers in California Homes", 2006	Blower door testing indicated that the replacement of two layers of Grade D building paper with a spun-bonded polyolefin housewrap reduced the SLA by an average of 13% (Wilcox, 2001).	
Savings: First principles (market and baseline drawn from RECs analysis). Cost: NREL measure database		
Straube, J. and Smegal, J.; Building America Special Research Project: High-R Walls Case Study Analysis; Building Science Corporation 2009 (updated 2011)	Costs calculated from manufacturer quotes; savings calculated from first principles	
Synertech Systems Corporation, "Windows and Insulating Shutters" (2007). Wenz, "Baby, it's warm inside, thanks to insulated shutters", San Francisco Chronicle, 1/19/2008	Increases R-value for window assembly to R-13 when closed; assume only closed at night for 60% heating loss reduction	
"Air-Filter Life-Cycle Cost", Seyffer, C.; HPAC Engineering 9/2010	"As much as 40 percent of HVAC-system electricity demand could be reduced by applying air-filter life-cycle-cost analysis." Cost taken from manufacturer website	Proper Air Filter Selection Goes a Long Way", Matela, D.AFE Journal 10/2010. Expert interviews suggest 25% is more typical savings
Miller, W.; Kośny, J.; "Next-Generation Roofs and Attics for Homes"; 2008 ACEEE Summer Study on Energy Efficiency in Buildings	Increasing the air space from 2 to 4 in. (0.051 to 0.102 m) and adding PCM caused an additional 10% drop compared with the assembly with a 2-in. air space	Analysis of the Dynamic Thermal Performance of Fiberous Insulations Containing Phase Change Materials Jan Kośny, et. al.
6. Apte, J. & Arasteh, D. Window-Related Energy Consumption in the US Residential and Commercial Building Stock. Buildings 1-38 (Berkeley, CA, 2006).	See tables 4 and 7 for use and savings	
Medina, M; "On the performance of radiant barriers in combination with different attic insulation levels"; Energy and Buildings 33 (2000) 31-40	produced yearly heat load reductions of approximately 44, 28, and 23%	http://www.reflectixinc.com/basepage.asp?PageIndex=390; Adjusted for heating penalty and average national load as power cool roof calculations
Medina, M; "On the performance of radiant barriers in combination with different attic insulation levels"; Energy and Buildings 33 (2000) 31-40	produced yearly heat load reductions of approximately 44, 28, and 23%	http://www.reflectixinc.com/basepage.asp?PageIndex=390; Adjusted for heating penalty and average national load as power cool roof calculations
Savings: first principles increasing R-value Cost: NREL measure database	Increase from R-23 assembly to R-60	
NREL. 2011. Advanced Energy Retrofit Guide for Healthcare Facilities (Draft). Project Lead: Robert Hendron. Kemco case study. Boiler Stack Economizer - Provides A 3 ½ Month ROI. (http://www.kemcosystems.com/Case-Studies/Food-Stack.html)	Energy savings from NREL 2011, which estimates a few percent improvement in boiler efficiency. Cost estimated from Kemco: "...annual savings was estimated at $32,880 with a 10 month payback." $27,400 for two boilers (5000 kW total), $36.73/kW, 241,000 ft^2 ave. hospital.	
Max tech: Desroches, L.-B. et al. Max Tech and Beyond. 60 (2011) Cost: Manufacturer websites	0.86 AFUE baseline, 0.98 tech limit: 11% savings from AFUE improvement directly	Choi-Granade et. Al.; "Unlocking Energy Efficiency in the U.S. Economy"; McKinsey & Company (2009)
Djunaedy, E., Van Den Wymelenberg, K., Acker, B., Thimmana, H. (n.d.). "Oversizing of HVAC System: Signatures and Penalties. Energy and Buildings." Energy and Buildings, In Press. Florida Solar Energy Center, "Right-Size Heating and Cooling Equipment", Department of Energy (2002) NREL Measure Database (for cost per unit capacity)	Pg. 6: "estimated an energy savings of 0.2% for every 1% reduction in oversizing." Pg 1: "One Florida study showed a typical 9 percent increase in annual space cooling electricity usage for units that were oversized by 50 percent or more;nearly 40 percent of contractors indicated that they purposefully over-sized equipment",assume 50% oversizing on average for cooling, 25% for heating	Choi-Granade et. Al.; "Unlocking Energy Efficiency in the U.S. Economy"; McKinsey & Company (2009)
Manufacturer (Buderus) case studies (http://www.buderus.co.uk/all-about-buderus/case-studies)	$7,227 per installation vs. $4,669; typical claims of ~20% savings in British climates	Choi-Granade et. Al.; "Unlocking Energy Efficiency in the U.S. Economy"; McKinsey & Company (2009)

1. Description of the measure	2. Energy savings			3. Price	4. Units & capacity	5. Market description	6. Market size, 2030	7. Site use	8. Source use	9. Max adopt	10. CCE	11. Life	12. Used in scenario?			
	Percent	SD?	Fuel switch?										McK	NAS	Emerg	Tech
R: Develop cold climate heat pump (no FS)	69%	Yes		$3,000	per home; 3 tons	R: Electric heating, proportion of cooling in coldest 2 climates	7.8	120	367	214	$5.12	20	No	No	Yes	Yes
R: Increase use of most efficient (i.e., max-tech) furnaces & radiators	11%	Yes		$2,160	per unit	R: All homes gas heating	76.4	3,176	3,176	293	$37.95	20	Yes	Yes	Yes	Yes
R: Install energy & enthalpy recovery ventilation (i.e., air-to-air heat exchangers)	7%	Yes		$912	per home; 100 cfm air exchange	R: Heating Total	141	4,077	4,599	224	$33.45	10	No	No	Yes	Yes
R: Install radiant heated floors in new homes	10%	Yes		$7,000	per home; 1,000 square feet	R: Forced hot air systems in new homes	35.0	753	1,100	92.4	$143.72	80	No	No	No	No
R: Install radiator reflectors	10%	Yes		$250	per home; 8 reflectors per home	R: Coils (A/C and HP) - heating and cooling	103	977	2,982	235	$6.09	10	No	No	No	Yes
R: Perform regular maintenance on heating equipment	5%	Yes		$300	per home	R: All homes heating (including sectional/secondary)	141	4,598	5,187	261	$39.84	1	Yes	Yes	Yes	Yes
R: Reduce heater oversizing	5%	Yes		-$100	per home	R: Heating Total	141	4,077	4,599	149	-$5.87	20	Yes	Yes	Yes	Yes
C: Develop and deploy dual (i.e., air and ground) source heat pumps (FS only)	69%	Yes	FS	$1.75	per square foot; 40 ton total, 10 ton ground 11,200 sq. ft.	C: Non-electric space heating, proportion of cooling, excluding coldest climate	88,598	2,006	2,810	593	$9.44	30	No	No	No	No
C: Develop and deploy dual (i.e., air and ground) source heat pumps (no FS)	34%	Yes		$2.50	per square foot; 40 ton total, 10 ton ground assumed for 15,000 sq. ft. buildings	C: Electric space heating, proportion of cooling, excluding coldest climate	5,149	265	795	198	$2.92	30	No	No	No	No
C: Develop and deploy gas-engine driven heat pumps (FS only)	-25%	Yes	FS	$9.40	per square foot; 1 ton per 280 sq. ft.	C: Cooling plus ASHP heating	103,945	721	2,200	931	$52.72	20	No	No	No	No
C: Improve auto-fault deduction in outside-air dampers	7%	Yes		$0.01	per unit; 7.5 tons/RTU, 280 ft^2/ton	C: All Commercial Heating and Cooling, RTU	29,668	192	323	6.3	$1.55	10	No	No	Yes	Yes
C: Improve auto-fault deduction in roof top units (RTUs)	9%	Yes		$0.04	per unit; 7.5 tons/RTU, 280 ft^2/ton	C: All Commercial Heating and Cooling, RTU	29,668	192	285	1.8	$3.72	10	No	No	Yes	Yes
C: Research and develop gas-powered (e.g., GAX, gas-engine) heat pumps	39%	Yes	FS	$10.02	per square foot; 40 tons for 15,000 sq. ft.	C: Electric space heating, proportion of cooling, excluding coldest climate	5,149	265	807	509	$5.43	20	No	No	No	Yes
C: Retrofit improved controls into packaged HVAC units	30%	Yes		$1.32	per square foot	C: Commercial Heating/Cooling/Ventilation (HP and RTU), existing buildings	37,975	506	971	93.0	$10.09	10	No	No	Yes	Yes
C: Use displacement ventilation in new buildings	10%	Yes		-$5	per square foot	C: All HVAC in new buildings	50,966	1,565	2,950	96.9	-$154.75	60	No	No	Yes	Yes
R: Air-source heat pump efficiency improvements through R&D	41%	Yes	Yes	$2,470	per unit	R: All non-electric heating, proportion of cooling	94.3	4,088	5,194	1,714	$5.95	20	No	No	No	No
R: Deploy minisplits heatpumps in new and appropriate existing homes	44%	Yes		$1,404	per home; 3 tons capacity (3 indoor units for mini-split)	R: Minisplit: Electric heating & cooling in all new homes + 40% of existing homes	14.1	312	951	418	$2.71	20	Yes	Yes	No	Yes
R: Develop and deploy dual (i.e., air and ground) source heat pumps (FS only)	69%	Yes	FS	$2,880	per home; 3 ton	R: Non-electric heating, proportion of cooling not in coldest 2 climates	53.8	2,424	2,790	311	$16.89	30	No	No	No	No
R: Develop and deploy dual (i.e., air and ground) source heat pumps (no FS)	34%	Yes		$2,880	per home; 3 ton total, 2 ton ground	R: Electric heating, proportion of cooling not in coldest 2 climates	35.5	460	1,405	322	$11.02	30	No	No	No	No

Primary sources used	Data used and/or methodology	Other supporting sources
Sachs et al, 2009, “Emerging Energy-Saving HVAC Technologies and Practices for the Buildings Sector.” Hallowell International; Personal communication: Bouza, DOE	Sachs represents current units offering 26% savings; Initial tests of DOE funded technology show 69% savings. Cost estimated from FOA funding target	
Max tech: Desroches, L.-B. et al. Max Tech and Beyond. 60 (2011) Cost: Manufacturer websites	0.86 AFUE baseline, 0.98 tech limit: 11% savings from AFUE improvement directly	Choi-Granade et. Al.; "Unlocking Energy Efficiency in the U.S. Economy"; McKinsey & Company (2009)
Hellevang, K. & Pedersen, C. Air-to-Air Heat Exchangers. North Dakota State University (2009)	Estimated from first principles using 3,000 HDD as U.S. average, 45 CFM as air handling treated to calculate maximum heating savings	
Watson, Richard D. Advantages of radiant heat. Fine Homebuilding June-July 1992. http://www.radiantec.com/why/technical-explanation.php. Robert Hendron, Ed Hancock; Greg Barker; Paul Reeves. 2006. An Evaluation of Affordable Prototype Houses at Two Levels of Energy Efficiency. NREL/CP-550-38774. Joseph D’agnese. 2009. Radiant Floor Heating. This Old House magazine. http://www.thisoldhouse.com/toh/article/0,,1548320,00.html	Watson: Assumed 1000 sq. ft. heated at $10/ft^2$ vs. $3000 installed for ducts, “The average 65°F radiant comfort temperature with 59°F day/night setback should reduce building heat load by 25% to 35% over convective systems.” Hendron: Radiant vs forced air in two similar houses indicated about 3% heating energy savings, to achieve equivalent mean radiant temperature, plus additional savings for water pump vs air handler fan, and for reduced infiltration. 9.5% is the geometric mean of the two studies. D’agnese: “Hot-water radiant costs more to install than other types of heating systems—from $6 to $15 per square foot depending on the method, whether you’re starting from scratch or retrofitting, and where you live.” Assumed 1000 sq. ft. heated at $10/ft^2$ vs. $3000 installed for ducts	
Novitherm website, calculation, and cost estimation tools	Assumes 8 radiators to treat per home, 10% savings in heating	
Choi-Granade et. al. (2009). “Unlocking Energy Efficiency in the U.S. Economy”. McKinsey and Company	Assumes regular maintenance underway; expert interviews provided cost and savings for incremental effort to maximize efficiency. $300 represents present value of $25 annual cost over equipment lifetime	
Djunaedy, E., Van Den Wymelenberg, K., Acker, B., Thimmana, H. (n.d.). “Oversizing of HVAC System: Signatures and Penalties. Energy and Buildings.” Energy and Buildings, In Press. Florida Solar Energy Center, “Right-Size Heating and Cooling Equipment”, Department of Energy (2002). NREL Measure Database (for cost per unit capacity)	Pg. 6: “estimated an energy savings of 0.2% for every 1% reduction in oversizing.” Pg 1: “One Florida study showed a typical 9 percent increase in annual space cooling electricity usage for units that were oversized by 50 percent or more;nearly 40 percent of contractors indicated that they purposefully over-sized equipment”, assume 50% oversizing on average for cooling, 25% for heating	Choi-Granade et. Al.; “Unlocking Energy Efficiency in the U.S. Economy”; McKinsey & Company (2009)
Hadley, D., Collins, T., Parkerk, S., Cornett, G. & Cavedo, F. Energy Savings from Dual-Source Heat Pump Technology Federal Energy Management Program E-0220 (2000)	“At the main U.S. Post Office facility in Valrico, three air- source heat pumps were retrofitted with the dual-source technology, reducing daily energy use by nearly 38%.” Multiple case studies used for average of 34% savings from ASHP	
Hadley, D., Collins, T., Parkerk, S., Cornett, G. & Cavedo, F. Energy Savings from Dual-Source Heat Pump Technology Federal Energy Management Program E-0220 (2000)	“At the main U.S. Post Office facility in Valrico, three air- source heat pumps were retrofitted with the dual-source technology, reducing daily energy use by nearly 38%.” Multiple case studies used for average of 34% savings from ASHP	
Omar Abdelaziz. Oak Ridge National Laboratory. 2011. Personal communication. RS Means. 2012. Assemblies Cost Data, 33rd Edition	Abdelaziz: Savings estimate of 30% source energy savings compared to standard electric heat pump, an increase in site energy use of 25%. Cost estimated at twice the cost of an RTU. Baseline cost from RS Means ($9.4/ft^2$ for twenty single-zone RTUs, 2 tons each, including ductwork and controls)	
TIAX. Energy Impact of Commercial Building Controls and Performance Diagnostics?: Market Characterization, Energy Impact of Building Faults and Energy Savings Potential. Construction 413 (2005).	~$30 per RTU or AHU, 7.5 tons/RTU, 280 ft^2/ton, new equipment only. 20% savings if there’s a damper failure, 35% of dampers are malfunctioning.	
TIAX. Energy Impact of Commercial Building Controls and Performance Diagnostics: Market Characterization, Energy Impact of Building Faults and Energy Savings Potential. Construction 413 (2005).	Energy savings from TIAX (9% = 0.075 Quads/0.8 Quads). $80 per RTU, 7.5 tons/RTU, 280 ft^2/ton. Assumes an EMS is present. Maintenance savings and necessary repairs are neglected.	
Jawahar, C.P. & Saravanan, R. Generator absorber heat exchange based absorption cycle—A review. Renewable and Sustainable Energy Reviews 14, 2372-2382 (2010)	Review indicates COP of 2.0/1.0 demonstrated; commercialization more likely at 1.5/0.7. The initial cost is comparable with geothermal COP of 1.5 heating, 0.7 cooling	Goffman, E. The Other Heat Pump. The Environmental Magazine 11-12 (2010)
W Wang, Y Huang, S Katipamula, MR Brambley. 2011. Advanced Controls for Existing Packaged A/C with gas heating. PNNL 20995. http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-20955.pdf	Wang: “The results from detailed simulation analysis show significant energy (24% to 35%) and cost savings (38%) from fan, cooling and heating energy consumption when packaged units are retrofitted with advanced control packages.” The average energy savings (30%) was used. Cost of $1.32/ft^2 based on sum of component measures (129, 141, 101, 104, 722). Only half the cost of an EMS was included because of synergies.	
Goetzler, W., Zogg, R., Burgos, J., Hiraiwa, H. & Young, J. Energy Savings Potential and RD & D Opportunities for Commercial Building HVAC Systems. (2011). Awbi, Energy Efficient Room Air Distribution ; Renewable Energy (15)	Technical Energy-Savings Potential: 0.17 Quads ~10% system energy savings. Costs from Argon Air estimate to install in new building	
Hewitt, N.J., Huang, M.J., Anderson, M. & Quinn, M. Advanced air source heat pumps for UK and European domestic buildings. Applied Thermal Engineering 31, 3713-3719 (2011)	Savings and cost targets reflect Building Technology Program funded targets; Hewitt et.al. demonstrate technical feasibility	
Geraghty, K., Baylon, D. & Davis, B. Residential Ductless Mini-Split Heat Pump Retrofit Monitoring. Bonneville Power Administration (2009). Desroches, L.-B. et al. Max Tech and Beyond, Appendix F. Lawrence Berkeley National Laboratory (2011).	Geraghty: Table 4 suggests 44% savings for heating; Table 6- total savings of 28%. Price from google search suggests ~30% price premium	
Hadley, D., Collins, T., Parkerk, S., Cornett, G. & Cavedo, F. Energy Savings from Dual-Source Heat Pump Technology Federal Energy Management Program E-0220 (2000)	“At the main U.S. Post Office facility in Valrico, three air- source heat pumps were retrofitted with the dual-source technology, reducing daily energy use by nearly 38%.” Multiple case studies used for average of 34% savings from ASHP	
Hadley, D., Collins, T., Parkerk, S., Cornett, G. & Cavedo, F. Energy Savings from Dual-Source Heat Pump Technology Federal Energy Management Program E-0220 (2000)	“At the main U.S. Post Office facility in Valrico, three air- source heat pumps were retrofitted with the dual-source technology, reducing daily energy use by nearly 38%.” Multiple case studies used for average of 34% savings from ASHP	

1. Description of the measure	2. Energy savings			3. Price	4. Units & capacity	5. Market description	6. Market size, 2030	7. Site use	8. Source use	9. Max adopt	10. CCE	11. Life	12. Used in scenario?			
	Percent	SD?	Fuel switch?										McK	NAS	Emerg	Tech
R: Develop most efficient (i.e., DOE road map) air-source heat pumps (no FS)	41%	Yes		$1,120	per unit	R: All electric heating, proportion of cooling	47.0	577	1,761	310	$3.90	40	No	No	No	Yes
R: Research and develop gas-powered (e.g., GAX, gas-engine) heat pumps	34%	Yes		$14,400	per home; 3 tons	R: All non-electric heating, proportion of cooling	94.3	4,088	5,194	2,010	$29.58	20	No	No	No	Yes
C: Develop air-conditioning systems customized for hot-dry climates	20%	Yes		$0.09	per square foot; 1 ton per 280 sq. ft.	C: Cooling in hot, dry climates	19,867	145	441	79.7	$1.11	20	No	No	No	Yes
C: Develop low-lift cooling	40%			$0.70	per square foot	C: Cooling and ventilation in new office buildings	8,890	123	376	163	$2.76	10	No	No	No	Yes
C: Develop magnetic bearings for chillers and RTUs	17%	Yes		$0	per square foot; 100 ton for chillers/ 7.5 ton for RTUs	C: Commercial Cooling (RTU and chiller) 100% new and 50% old	41,175	267	813	114	$0	20	No	No	No	No
C: Develop more efficient centrifugal chillers	30%	Yes		$1.24	per square foot; 1 ton per 280 sq. ft.	C: Centrifugal chillers	25,196	163	498	130	$12.70	20	No	No	Yes	Yes
C: Develop most efficient (i.e., IEER 20) roof top unit (RTU)	44%	Yes		$0.75	per square foot; 10 tons per 6,000 sq. ft.	C: Commercial cooling: Rooftop AC	29,668	192	586	252	$4.60	20	No	No	Yes	Yes
C: Develop thermoelectric subcooling for commercial RTUs	9%	Yes		$0	per square foot	C: All Commercial Cooling, RTU	29,668	192	586	43.0	$0	20	No	No	No	No
C: Develop thermotunneling cooling systems	10%	Yes		$1.07	per square foot (1 ton per 280 square feet); 5 ton model	C: Commercial Cooling (HP and RTU), 100% new and 50% old	24,074	156	476	38.1	$29.37	20	No	No	Yes	No
C: Improve evaporator fan efficiency in all A/C units	74%	Yes		$0	per square foot; 1 ton per 280 sq. ft.	C: Commercial evaporator fans	103,945	38.7	118	88.1	$0	20	No	No	No	No
C: Improve scroll compressor efficiency	28%	Yes		$0.76	per square foot; 150k sq. ft. building	C: Commercial cooling: Scroll	3,873	25.1	76.5	16.1	$7.49	20	No	No	Yes	Yes
C: Increase efficient of roof-top units (i.e., current DOE RTU-challenge specification)	38%	Yes		$0.43	per square foot; 10 RTU's per 100k sq. ft.	C: Commercial cooling: Rooftop AC	29,668	192	586	212	$3.22	20	Yes	Yes	Yes	Yes
C: Increase use of ice-storage systems to shift A/C operation to periods with lower ambient temperature	5%	Yes		$1.07	per unit; 20 tons, 8 hours per 15,000 sq. ft.	C: All cooling	103,945	673	2,053	93.0	$59.63	20	No	No	Yes	No
C: Install chilled beams in temperate climates	20%	Yes		-$1	per square foot 150 BTU/h/sq. ft.	C: New buildings H & C, except coldest two climates	33,993	715	1,348	255	-$8.07	60	No	No	Yes	Yes
C: R&D to reduce cost of adsorption chiller A/C	40%	Yes		$0.64	per square foot assuming @20-100 ton	C: Education, health care, lodging, and office	42,405	298	910	240	$3.73	30	No	No	No	Yes
C: Research magnetic cooling for air-conditioning	17%	Yes	FS	$0	per square foot	C: Cooling in humid climates	50,105	378	1,154	194	$0	20	No	No	No	No
C: Right-size A/C in new buildings	13%	Yes		-$0.43	per square foot; 1 ton per 280 sq. ft.	C: All cooling	103,945	673	2,053	202	-$15.05	20	Yes	Yes	No	Yes
C: Steam-clean A/C cools regularly for improved performance	10%	Yes		$0.20	per square foot	C: Cooling plus ASHP heating	103,945	721	2,200	192	$9.89	5	No	No	No	Yes
C: Upgrade to most efficient centrifugal chiller available	48%	Yes		$0.36	per square foot; 1 ton per 280 sq. ft.	C: Centrifugal chillers	25,196	163	498	239	$2.32	20	No	No	No	Yes
C: Use "smart" refrigerator distribution for commercial cooling	9%	Yes		$0	per square foot	C: New Commercial Cooling, RTU and Central Chiller	27,093	175	535	40.7	$0	20	No	No	No	No
C: Use desiccant wheels in hot-humid climates	13%	Yes		$0.33	per square foot	C: Cooling in hot, humid climates	30,772	286	873	83.6	$8.96	20	No	No	No	Yes
C: Use desiccant-enhanced evaporative cooling (e.g., DeVAP) in dry climates	82%	Yes	FS	$1.08	per square foot; 10 tons per 6,000 sq. ft.	C: Cooling in dry climates	53,839	295	899	699	$3.94	20	No	No	No	Yes

Primary sources used	Data used and/or methodology	Other supporting sources
Personal communication: Bouza, DOE. Hewitt, N.J., Huang, M.J., Anderson, M. & Quinn, M. Advanced air source heat pumps for UK and European domestic buildings. Applied Thermal Engineering 31, 3713-3719 (2011)	Savings and cost targets reflect Building Technology Program funded targets; Hewitt et.al. demonstrate technical feasibility	
Jawahar, C.P. & Saravanan, R. Generator absorber heat exchange based absorption cycle—A review. Renewable and Sustainable Energy Reviews 14, 2372-2382 (2010)	Review indicates COP of 2.0/1.0 demonstrated; commercialization more likely at 1.5/0.7. "The initial cost is comparable with geothermal" COP of 1.5 heating, 0.7 cooling	Goffman, E. The Other Heat Pump. The Environmental Magazine 11-12 (2010)
Desroches, L.-B. et al. Max Tech and Beyond (2011)	Pg 22: Such regionally appropriate designs could save 20% to 25% (Used lower end of range provided)	
Katipamula, S. Pacific Northwest National Laboratory. "Cost-Effective Integration of Efficient Low-Lift Baseload Cooling Equipment: FY08 Final Report", PNNL-19114 (http://www.pnl.gov/main/publications/external/technical_reports/PNNL-19114.pdf)	Large office incremental costs. Energy savings for cooling and ventilation/fans based on Case 1 to Case 8, national average, large office buildings.	
Goetzler, W., Zogg, R., Burgos, J., Hiraiwa, H. & Young, J. Energy Savings Potential and RD & D Opportunities for Commercial Building HVAC Systems. 289 (2011).	Technology is in the research stage. No reliable cost data is available. Energy savings estimate is 17% of whole building energy use.	
U.S. Navy; "Evaluation of a Variable-speed Centrifugal Compressor with Magnetic Bearings." Desroches, L.-B. et al. Max Tech and Beyond (2011)	Average of high capacity Navy (41-67%) and Desroches (26%) numbers	
Personal communication: Bouza	Cost and performance represents funded and supported DOE research product	
Goetzler, W., Zogg, R., Burgos, J., Hiraiwa, H. & Young, J. Energy Savings Potential and RD & D Opportunities for Commercial Building HVAC Systems. 289 (2011).	Technology is in the research stage. No reliable cost data is available. Energy savings potential estimated as 0.2 Quads/year out of 2.25 Quads/year (9%).	
Goetzler, W., Zogg, R., Burgos, J., Hiraiwa, H. & Young, J. Energy Savings Potential and RD & D Opportunities for Commercial Building HVAC Systems. 289 (2011).	"Applied to relevant annual energy consumption by increasing system efficiency by 10%." Premium of 20% ($1.07/ft^2) based on $9000, 5-ton system, 280 ft^2/ton.	
Acul, H. Air Cooled Condensers And Their Effect On Energy. 1-13 (2008)	Impacts estimated from table on page 11: Decrease fan use from 4.68 to 1.12 kW/h	Choi-Granade et. Al.; "Unlocking Energy Efficiency in the U.S. Economy"; McKinsey & Company (2009)
Personal communication: Bouza, DOE	28% savings from DOE Funded research target. Baseline efficiency estimated from multiple references	Manufacturer presentation (http://www.emersoncanada.ca/pages/energy/presentations/Scroll_Compressor_Technology_Optimizing_Efficiency_Feb08.pdf) and specifications: Hitachi EU Series DC Inverter controlled series, Mitsubishi R407C & 410A.
DOE; "DOE and Private Sector Partners Introduce a New Money-Saving Specification for Commercial Air Conditioners", 2011. Daikon McQuay Rebel RTU Specifications	IEER of 18, Cost and performance estimated from Challenge specifications	
Pacific Gas & Electric. "Thermal Energy Storage Strategies for Commercial HVAC Systems". PG&E, 1997. Calmac (Manufacturer) website	Citation 1, Table page 12 provides cost and efficiency data. Calmac indicates "Operation at night with 20 degree lower condensing temperatures can improve energy efficiency typically by 2 to 8%." Assume 5% (average of 208%) savings, cost from 20 tons cooling, 8 hours of capacity/ building at $100/ton-hr	
Roth, K., John, D., Zogg, R. & Brodrick, J. Chilled Beam Cooling. ASHRAE Journal 84-86 (2007). Sachs, H..; Lin, W.; Lowenberger, A.; "Emerging Energy Savings HVAC Technologies and Practices for the Buildings Sector"; ACEEE (2009)	"a chiller dedicated for chilled beam cooling has a lower temperature lift and operates at a 15% to 20% higher efficiency than for an conventional system." Multiple sources provide 20% savings estimate; currently available technology provides price estimate at -$1/sq. ft. +/- $3/sq. ft.	
Eco-max technical documentation. Desroches, L.-B. et al. Max Tech and Beyond (2011)	Used low end of manufacturer estimate	Choi-Granade et. Al.; "Unlocking Energy Efficiency in the U.S. Economy"; McKinsey & Company (2009)
Navigant. Energy Savings Potential and RD&D Opportunities for Commercial Building HVAC Systems, Navigant, September 30, 2011. http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/savings_potential_comm_hvac.pdf	"Assume 17% savings". No meaningful cost data is available because the technology is in the research stage.	
Djunaedy, E., Van Den Wymelenberg, K., Acker, B., Thimmana, H. (n.d.). "Oversizing of HVAC System: Signatures and Penalties. Energy and Buildings." Energy and Buildings, In Press. Florida Solar Energy Center, "Right-Size Heating and Cooling Equipment", Department of Energy (2002). NREL Measure Database (for cost per unit capacity)	Pg. 6: "estimated an energy savings of 0.2% for every 1% reduction in oversizing." Pg 1: "One Florida study showed a typical 9 percent increase in annual space cooling electricity usage for units that were oversized by 50 percent or more;nearly 40 percent of contractors indicated that they purposefully over-sized equipment", assume 50% oversizing on average for cooling, 25% for heating	Florida Solar Energy Center, "Right-Size Heating and Cooling Equipment", Department of Energy (2002)
Checket-Hanks, B. "Contractor Offers Hope For PTAC IAQ". The Air Conditioning, Heating and Refrigeration NEWS, March 10, 2004. Rejuvinair website	Savings (10%) and cost estimates based on Manufacturer's website	
Kistler, P. & Lintner, W. Evaluation of a Variable-speed Centrifugal Compressor with Magnetic Bearings. U.S. Navy (2010). Desroches, L.-B. et al. Max Tech and Beyond. Lawrence Berkeley National Laboratory (2011).	Descroches indicated 26% savings available today and references Kistler showing the 40-60% is possible with R&D. Cost and performance from Table 1 and Figure 6	
Goetzler, W., Zogg, R., Burgos, J., Hiraiwa, H. & Young, J. Energy Savings Potential and RD & D Opportunities for Commercial Building HVAC Systems. 289 (2011).	Technology is in the research stage. No reliable cost data is available. Energy savings potential estimated as 0.09 Quads/year out of 0.98 Quads/year (9%).	
S.J. Slayzak and J.P. Ryan; Desiccant Dehumidification Wheel Test Guide (2000). Desroches, L.-B. et al. Max Tech and Beyond (2011)	"energy savings on building cooling systems are estimated to be approximately 25%." Adjusted 25% to 12.5% to incorporate baseline improvement in A/C since publication of original source	
Eric Kozubal, Jason Woods, Jay Burch, Aaron Boranian, and Tim Merrigan. Desiccant Enhanced Evaporative Air-Conditioning (DEVap): Evaluation of a New Concept in Ultra Efficient Air Conditioning. http://www.nrel.gov/docs/fy11osti/49722.pdf	Kozubal: $15,200 for standard DX, $20,461 for DeVap (10-ton system). Assumes 10 tons per 6,000 sq. ft. for dry climates ($0.88/ft^2). ($0.20/ft^2 added for plumbing to unit) Total source energy 106,268 kWh for baseline and 10,506 for DeVAP. Source energy converted to site energy to estimate energy savings.	

1. Description of the measure	2. Energy savings			3. Price	4. Units & capacity	5. Market description	6. Market size, 2030	7. Site use	8. Source use	9. Max adopt	10. CCE	11. Life	12. Used in scenario?			
	Percent	SD?	Fuel switch?										McK	NAS	Emerg	Tech
C: Use desiccant-enhanced evaporative cooling (e.g., DeVAP) in humid climates	2%	Yes	FS	$1.17	per square foot; 1 ton per 280 sq. ft.	C: Cooling in humid climates	50,105	378	1,154	628	$4.41	20	No	No	No	Yes
C: Use liquid desiccant air conditioning in humid climates	40%	Yes		$0.50	per square foot	C: Cooling in humid climates	50,105	378	1,154	462	$2.94	20	No	No	No	Yes
C: Use Maisotsenko cycle cooling (e.g., Coolerado) in cold- and mixed-dry climates	30%	Yes		$1.79	per square foot; 1 ton per 280 sq. ft.	C: Cooling in cold and mixed dry climates	33,972	113	345	104	$31.39	20	No	No	No	No
C: Use Maisotsenko cycle cooling (e.g., Coolerado) in hot-dry climates	88%	Yes		$1.79	per square foot (-24,000 sq. ft.)	C: Cooling in hot, dry climates	19,867	145	441	385	$5.05	20	No	No	No	No
C: Use multiple-small plate (MSP) technology to dehumidify	32%	Yes		$0.50	per square foot	C: Cooling in hot, humid climates	30,772	286	873	254	$2.97	20	No	No	No	Yes
C: Use spray-cooled evaporators for packaged A/C	14%	Yes		$0.53	per square foot; 1 ton per 280 sq. ft.	C: Rooftop/ resi style A/C's	37,350	242	738	79.2	$14.25	20	No	No	No	No
C: Used sprayed mesh to improve A/C efficiency	18%	Yes		$3.28	per square foot; 1 ton per 280 sq. ft.	C: Rooftop/ resi style A/C's	37,350	242	738	125	$42.15	20	No	No	No	No
R: Add whole house fan to replace A/C use when appropriate in existing homes	25%	Yes		$692	per home; 3 ton cooling	R: Central cooling in coldest 3 climates, single family existing homes	42.7	171	522	50.9	$13.70	40	No	No	No	No
R: Add whole house fan to replace A/C use when appropriate in new homes	25%	Yes		$392	per unit	R: Central cooling in coldest 3 climates, new homes	17.1	55.3	169	37.5	$11.10	40	No	No	No	No
R: Charge A/C refrigerant to improve efficiency (applied in all climates)	5%	Yes		$128	per unit	R: Coils (A/C and HP) - heating and cooling	103	977	2,982	104	$5.29	20	No	No	Yes	Yes
R: Clean A/C coils to improve cooling efficiency	6%	Yes		$10	per unit	R: Coils (A/C and HP) - heating and cooling	103	977	2,982	180	$1.48	1	Yes	Yes	No	Yes
R: Develop air-conditioning systems customized for hot-dry climates	20%	Yes		$200	per home	R: Cooling in hot, dry climates	12.5	119	364	65.8	$1.92	20	No	No	No	Yes
R: Incorporate awnings in home to shade windows	20%	Yes		$600	per home; six awnings/home	R: Central Cooling in hot climates	66.6	577	1,761	302	$5.72	20	No	No	Yes	Yes
R: Incorporate natural ventilation systems into homes in temperate climates	46%	Yes		-$3,000	per home, 3 ton equivalent cooling	R: Central cooling in new homes in temperate climates	8.5	29.2	89.2	41.0	-$32.21	80	Yes	Yes	Yes	Yes
R: Increase ceiling fan use (in lieu of A/C)	9%	Yes		$420	per home with 2.8 fans/home	R: Heating and cooling in homes w/o ceiling fans	49.3	1,941	2,835	188	$4.55	20	Yes	Yes	Yes	Yes
R: Increase efficiency of room A/C to 10.7 EER	21%	Yes		$132.60	per unit; 12 kBTU/hr for 1,000 sq. ft.	R: Room A/C	52.6	89.3	272	47.6	$8.08	20	No	No	No	No
R: Increase use of central A/C with 21 SEER	42%	Yes		$1,800	per home; 3 ton cooling	R: Central A/C	83.9	634	1,933	813	$10.19	20	No	No	No	No
R: Install night economizers	10%	Yes		$780	per home	R: Single family central cooling	64.9	497	1,517	107	$18.98	20	No	No	Yes	Yes
R: Plant shade trees to provide cooling in hot climates	12%	Yes		$900	per home; 3 trees/home	R: Central Cooling in hot climates	66.6	577	1,761	178	$14.36	20	No	No	No	Yes
R: R&D to decrease cost of central A/C with 24 SEER	49%	Yes		$710	per home; 3 ton cooling	R: Central A/C	83.9	634	1,933	816	$3.50	20	No	No	No	Yes
R: R&D to decrease cost of room A/C with 13 EER	35%	Yes		$325.10	per unit; 12 kBTU/hr for 1,000 sq. ft.	R: Room A/C	52.6	89.3	272	94.1	$8.55	20	No	No	No	Yes
R: Replace A/C with fan for existing homes in cooler climates	81%			-$511	per home; 1 fan plus one room A/C vs. 21 kBTU/hr CAC cost	R: Central cooling in coldest 2 climates, existing homes	21.0	58.8	179	180	-$3.06	20	No	No	No	No
R: Replace A/C with fan for new homes in cooler climates	81%			-$1,141	per home; 1 fan plus one room A/C vs. 21 kBTU/hr CAC cost	R: Central cooling in coldest 2 climates, new homes	5.6	22.0	67.3	58.8	-$6.21	20	No	No	No	No

Primary sources used	Data used and/or methodology	Other supporting sources
Kozubal, E.; Woods, J.; Judkoff, R.; "Development and Analysis of Desiccant Enhanced Evaporative Air Conditioner Prototype"; NREL, 2012. Kozubal, E. et. al.; "Desiccant Enhanced Evaporative Air-Conditioning (DEVap): Evaluation of a New Concept in Ultra Efficient Air Conditioning"; NREL, 2011	"Modeling at NREL has shown that the yearly combined source energy for the thermal and electrical energy required to operate DEVap is expected to be 30%–90% less than state-of-the-art direct expansion cooling (depending on whether it is applied in a humid or a dry climate)", NREL research team performed climate and sector specific calculations	
Sachs, H..; Lin, W.; Lowenberger, A.; "Emerging Energy Savings HVAC Technologies and Practices for the Buildings Sector"; ACEEE, 2009. DuCool Case Studies, Advantix Company presentations (publicly available, 2011)	Percent savings 66% elec; 85% gas (ACEEE). DuCool observed savings 35%-70% depending on configuration. Most comparable case study to hot-humid climate suggests 40% savings. Cost given DuCool payback times	Choi-Granade et. Al.; "Unlocking Energy Efficiency in the U.S. Economy"; McKinsey & Company (2009)
U.S. Department of Energy. 2007. Coolerado Cooler Helps to Save Cooling Energy and Dollars. FEMP Technology Installation Review DOE/GO-102007-2325. http://www1.eere.energy.gov/femp/pdfs/tir_coolerado.pdf. Coolerado website. http://www.coolerado.com/	DOE: Energy savings of 30% estimated based on Table 1 compared to a typical EER of 10 for a standard air conditioner. "Installed cost per ton $900–$1,100/ton." NREL: Typical A/C is $3960 for a 3-ton system ($110/kBtu/hr)	
Coolerado technical manuals, Desroches, L.-B. et al. Max Tech and Beyond. 60 (2011)	"Utilizing the Maisotsenko cycle, indirect evaporative coolers can provide approximately 80% energy savings compared to standard vapor-compression air conditioners.", cost and savings taken from manufacturer's website and documentation	
MSP Technology, "Dehumidification Equipment for Recirculated Air and Dedicated Outside Air Systems (DOAS)." Desroches, L.-B. et al. Max Tech and Beyond (2011)	Savings taken from page 7 of MSP manual; supported by nautica claims (used manufacturer estimate)	
Acul, H. Air Cooled Condensers And Their Effect On Energy. 1-13 (2008)	Impacts estimated from table on page 11. Decrease fan use from 4.68 to 1.12 kW/h	
Acul, H. Air Cooled Condensers And Their Effect On Energy. 1-13 (2008)	Impacts estimated from table on page 4, Increase COP from 3.03 to 3.71	Choi-Granade et. Al.; "Unlocking Energy Efficiency in the U.S. Economy"; McKinsey & Company (2009)
Southface Energy Institute & Oak Ridge National Laboratory FEMP Technology Fact Sheet: Whole House Fan. (1999)	Calculations based on information on page 1 of fact sheet, assumes reduction of A/C use at night estimated at 25% of total annual load	
Southface Energy Institute & Oak Ridge National Laboratory FEMP Technology Fact Sheet: Whole House Fan. (1999)	Calculations based on information on page 1 of fact sheet, assumes reduction of A/C use at night estimated at 25% of total annual load	
Goswami et. al.; "Effect of refrigerant charge on the performance of air conditioning systems"; Int. J. Energy Res. 2001; 25:741}750	"experimental results show that if a system is undercharged to 90% a 2 per cent increase in the (COP); The maintenance costs included 2 h of labour at $60/h and one pound of refrigerant charge at $8/lb," assumed typical charge level of 85-90% and $150 labor and material cost given expert interviews	Choi-Granade et. Al.; "Unlocking Energy Efficiency in the U.S. Economy"; McKinsey & Company (2009)
Choi-Granade et. al.; "Unlocking Energy Efficiency in the U.S. Economy"; McKinsey & Company (2009)	Savings and cost estimates derived from Exhibits 7, 13 and personal communication	
Desroches, L.-B. et al. Max Tech and Beyond (2011)	Pg 22: Such regionally appropriate designs could save 20% to 25% (Used lower end of range provided)	
First principles: window shading. Performed HES Pro analysis for each of 5 climate zones. Cost from web-search	20% average savings, $100/awning cost	Choi-Granade et. Al.; "Unlocking Energy Efficiency in the U.S. Economy"; McKinsey & Company (2009)
Cardinale, N., Micucci, M. & Ruggiero, F. Analysis of energy saving using natural ventilation in a traditional Italian building. Energy and Buildings 35, (2003). Walker, A (2010). "Natural Ventilation". Whole Building Design Guide (http://www.wbdg.org/resources/naturalventilation.php). Price: Windowmaster/ Aarhus Engineering College websites	Replace A/C with automated ventilation system in temperate climates: no ducting cost or HVAC. Cardinale: Simulations (Italina homes) showed savings of 41%, 46%, and 52%; using average of 46%. New home installed cost of $3,000 vs. $6,000 for conventional	Choi-Granade et. Al.; "Unlocking Energy Efficiency in the U.S. Economy"; McKinsey & Company (2009)
Aens, E; Turner, S; Zhang, H; Paliaga, G. "Moving Air for Comfort". ASHRAE Journal, May 2009, pp 8–18. Aynsley, R. "Circulating Fans for Summer and Winter Comfort and Indoor Energy Efficiency". Environment Design Guide, Nov. 2007	Citation 1, Figure 5 indicates 3-6 degree F increase in temperature with air movement admits same comfort; estimates of cooling savings ~3-4%/F. Citation 2 suggests upper heating benefit limit of 10% for homes. Cost from google search for fans; savings weighted average of 20% cooling, 5% heating	
Savings: First principles. Cost: NREL retrofit measure database		
Savings: first principles. Cost: NREL retrofit measure database		
Itron Inc., Kema, Inc. "*California Energy Efficiency Potential Study*" Pacific Gas & Electric (2008)	A-10: "The assumed savings for night economizer was 20% of the RASS household UEC for coastal regions and 10% of the UEC for inland regions." (Used 10% as majority of country is best represented as "inland" in this dataset). Price taken from web search	
Energy and Buildings Volume 25, Issue 2, 1997, Pages 139–148; Atmospheric Environment Volume 32, Issue 1, January 1998, Pages 69–74; Improved estimates of tree-shade effects on residential energy use Energy and Buildings, Volume 34, Issue 10, November 2002, Pages 1067-1076	Analysis of examples provided suggests 12 +/- 3% savings from existing "planting practices" (analysis included in tool). Cost from web-search for 3 medium-sized trees installed	
Savings: first principles. Cost: Navigant Consulting, personal communication		
Savings: First principles. Cost: DOE published target for funded research		
Southface Energy Institute & Oak Ridge National Laboratory FEMP Technology Fact Sheet: Whole House Fan. (1999)	Calculations based on information on page 1 of fact sheet, Calculated from average cost to operate reduction from 11 to 2.1 cents/hour	Choi-Granade et. Al.; "Unlocking Energy Efficiency in the U.S. Economy"; McKinsey & Company (2009)
Southface Energy Institute & Oak Ridge National Laboratory FEMP Technology Fact Sheet: Whole House Fan. (1999)	Calculations based on information on page 1 of fact sheet, Calculated from average cost to operate reduction from 11 to 2.1 cents/hour	Choi-Granade et. Al.; "Unlocking Energy Efficiency in the U.S. Economy"; McKinsey & Company (2009)

1. Description of the measure	2. Energy savings			3. Price	4. Units & capacity	5. Market description	6. Market size, 2030	7. Site use	8. Source use	9. Max adopt	10. CCE	11. Life	12. Used in scenario?			
	Percent	SD?	Fuel switch?										McK	NAS	Emerg	Tech
R: Right-size A/C in new buildings	13%	Yes		-$180	per home, 3 tons of cooling	R: All Cooling, other than room A/C	134	880	2,684	266	-$6.33	20	Yes	Yes	No	Yes
R: Use desiccant wheels in hot-humid climates	13%	Yes		$720	per home; assume 0.3 ACH, 1800 sq. ft.	R: Cooling in hot, humid climates	16.8	192	586	75.9	$8.46	20	No	No	No	No
R: Use desiccant-enhanced evaporative cooling (e.g., DeVAP) in humid climates	2%	Yes	FS	$1,770	per home, 3 ton unit	R: Central cooling in humid climates	52.7	531	1,621	725	$5.17	20	No	No	No	Yes
R: Use desiccant-enhanced evaporative cooling (e.g., DeVAP) in dry climates	82%	Yes	FS	$2,804	per home; 3 ton	R: Central cooling in dry climates	52.2	338	1,032	656	$8.97	20	No	No	No	Yes
R: Use liquid desiccant air conditioning in humid climates	40%	Yes		$1,100	per home; 3 ton	R: Central cooling in humid climates	52.7	531	1,621	603	$6.44	20	No	No	No	Yes
R: Use Maisotsenko cycle cooling (e.g., Coolerado) in cold- and mixed-dry climates	30%	Yes		$5,270	per home; 3 ton	R: Cooling in cold and mixed dry climates	27.1	124	380	114	$68.01	20	No	No	No	No
R: Use Maisotsenko cycle cooling (e.g., Coolerado) in hot-dry climates	88%	Yes		$2,685	per home; 5 ton	R: Cooling in hot, dry climates	12.5	119	364	321	$5.73	20	No	No	No	No
R: Used sprayed mesh to improve A/C efficiency	18%	Yes		$273.44	per home; 3 tons of cooling	R: All Cooling, other than room A/C	134	880	2,684	363	$4.19	20	No	No	No	No
R: Deploy reverse-cycle chillers to capture A/C waste heat for water heating	22%	Yes		$600	per home; family of 4: 3 ton A/C; 70 gal/day hot H_2O	R: Single family cooling and water heating	101	2,380	4,747	853	$3.75	20	No	No	No	No
C: Develop integrated heat pumps (i.e., heating, cooling, and hot water) (FS only)	43%	Yes	FS	$0.79	per square foot	C: Non-electric space heating, proportion of cooling and hot water	87,841	2,721	3,823	-438.2	$4.27	20	No	No	No	No
C: Develop integrated heat pumps (i.e., heating, cooling, and hot water) (no FS)	50%	Yes		$1.05	per square foot	C: Electric space heating, proportion of cooling and hot water	5,709	513	1,307	414	$0.67	20	No	No	Yes	Yes
C: Reduce cost of ground source heat pumps (FS only)	81%	Yes	FS	$7.38	per square foot; 1 ton per 280 sq. ft.	C: Non-electric space heating, proportion of cooling and hot water	87,841	2,721	3,823	2,191	$16.38	20	No	No	Yes	Yes
C: Reduce cost of ground source heat pumps (no FS)	65%	Yes	FS	$8.38	per square foot; 1 ton per 280 sq. ft.	C: Electric space heating, proportion of cooling and hot water	5,709	513	1,307	760	$3.82	20	No	No	Yes	Yes
R: Develop integrated heat pumps (i.e., heating, cooling, and hot water) (FS only)	43%	Yes	FS	$4,265	per home; 3 ton	R: All non-electric heating and water heating plus central air conditioner	83.4	5,576	6,719	-1,208.7	$12.55	20	No	No	No	No
R: Develop integrated heat pumps (i.e., heating, cooling, and hot water) (no FS)	50%	Yes		$3,864	per home; 3 ton	R: All electric heating & hot water; proportion of cooling	47.0	1,112	3,392	1,057.4	$6.71	20	No	No	No	Yes

Primary sources used	Data used and/or methodology	Other supporting sources
Djunaedy, E., Van Den Wymelenberg, K., Acker, B., Thimmana, H. (n.d.). "Oversizing of HVAC System: Signatures and Penalties. Energy and Buildings" Energy and Buildings, In Press. Florida Solar Energy Center, "Right-Size Heating and Cooling Equipment", Department of Energy (2002). NREL Measure Database (for cost per unit capacity)"	Pg. 6: "estimated an energy savings of 0.2% for every 1% reduction in oversizing." Pg 1: "One Florida study showed a typical 9 percent increase in annual space cooling electricity usage for units that were oversized by 50 percent or more;nearly 40 percent of contractors indicated that they purposefully oversized equipment",assume 50% oversizing on average for cooling, 25% for heating	Choi-Granade et. Al.; "Unlocking Energy Efficiency in the U.S. Economy"; McKinsey & Company (2009)
S.J. Slayzak and J.P. Ryan; Desiccant Dehumidification Wheel Test Guide (2000). Desroches, L.-B. et al. Max Tech and Beyond (2011)	"energy savings on building cooling systems are estimated to be approximately 25%." Adjusted 25% to 12.5% to incorporate baseline improvement in A/C since publication of original source	
Kozubal, E.; Woods, J.; Judkoff, R.; "Development and Analysis of Desiccant Enhanced Evaporative Air Conditioner Prototype"; NREL, 2012. Kozubal, E. et. al.; "Desiccant Enhanced Evaporative Air-Conditioning (DEVap): Evaluation of a New Concept in Ultra Efficient Air Conditioning"; NREL, 2011	"Modeling at NREL has shown that the yearly combined source energy for the thermal and electrical energy required to operate DEVap is expected to be 30%–90% less than state-of-the-art direct expansion cooling (depending on whether it is applied in a humid or a dry climate)". NREL research team performed climate and sector specific calculations	
Eric Kozubal, Jason Woods, Jay Burch, Aaron Boranian, and Tim Merrigan. Desiccant Enhanced Evaporative Air-Conditioning (DEVap): Evaluation of a New Concept in Ultra Efficient Air Conditioning. http://www.nrel.gov/docs/fy11osti/49722.pdf. NREL Residential Efficiency Measures Database. http://www.nrel.gov/ap/retrofits/measures.cfm?gId=2&ctId=16	Kozubal: $7484 for 3-ton DeVap (uninstalled). Plus $2080 for installation. Same energy savings as Measure 678.	
Sachs, H..; Lin, W.; Lowenberger, A.; "Emerging Energy Savings HVAC Technologies and Practices for the Buildings Sector"; ACEEE, 2009. DuCool Case Studies, Advantix Company presentations (publicly available, 2011)	Percent savings 66% elec; 85% gas (ACEEE). DuCool observed savings 35%-70% depending on configuration. Most comparable case study to hot-humid climate suggests 40% savings. Cost given DuCool payback times	Choi-Granade et. Al.; "Unlocking Energy Efficiency in the U.S. Economy"; McKinsey & Company (2009)
U.S. Department of Energy. 2007. Coolerado Cooler Helps to Save Cooling Energy and Dollars. FEMP Technology Installation Review DOE/GO-102007-2325. http://www1.eere.energy.gov/femp/pdfs/tir_coolerado.pdf. NREL Residential Efficiency Measures Database. http://www.nrel.gov/ap/retrofits/measures.cfm?gId=2&ctId=16	DOE: Energy savings of 30% estimated based on Table 1 compared to a typical EER of 10 for a standard air conditioner. "Installed cost per ton $900–$1,100/ton." NREL: Typical A/C is $3960 for a 3-ton system ($110/kBtu/hr)	
Coolerado technical manuals, Desroches, L.-B. et al. Max Tech and Beyond. 60 (2011)	"Utilizing the Maisotsenko cycle, indirect evaporative coolers can provide approximately 80% energy savings compared to standard vapor-compression air conditioners.", cost and savings taken from manufacturer's website and documentation.	
Acul, H. Air Cooled Condensers And Their Effect On Energy. 1-13 (2008)	Impacts estimated from table on page 4, Increase COP from 3.03 to 3.71	Choi-Granade et. Al.; "Unlocking Energy Efficiency in the U.S. Economy"; McKinsey & Company (2009)
Heller, J. & Cejudo, C. Reverse Cycle Chillers for Multifamily Buildings in the Pacific Northwest: Phase I Final Report. Bonneville Power Administration (2009)		Choi-Granade et. Al.; "Unlocking Energy Efficiency in the U.S. Economy"; McKinsey & Company (2009)
Navigant Consulting. (2009). Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances. Washington, D.C.: Building Technology Program, Department of Energy., http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 6-11: Summary of Primary Energy Savings Potential of all Water Heating Technology Options. Percent savings and cost changed to reflect site energy baseline of non-electric heating -> 43% savings	"Murphy,R; Rice, C; Baxter, V; Craddick, W. "Air-Source Integrated Heat Pump for Net Zero-Energy Houses: Technology Status Report". Oak Ridge National Laboratory ORNL/TM-2007/112. Baxter, V.; Murphy, R; Rice, K; Craddick, B; "Development of a Small Integrated Heat Pump (IHP) for Net Zero Energy Homes" 9th International IEA Heat Pump Conference (2008)"
Navigant Consulting. (2009). Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances. Washington, D.C.: Building Technology Program, Department of Energy., http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 6-11: Summary of Primary Energy Savings Potential of all Water Heating Technology Options	
Liu, X. Assessment of National Benefits from Retrofitting Existing Single-Family Homes with Ground Source Heat Pump Systems. Oak Ridge National Laboratory (2010). Hughes, P.J. Geothermal (Ground-Source) Heat Pumps: Market Status, Barriers to Adoption, and Actions to Overcome Barriers. Oak Ridge National Laboratory (2008)	savings of [4.2 quads primary energy], a 45% reduction associated with SH–SC–WH in existing U.S. single-family homes. Worked with author to disaggregate into fuel-switching and non-fuel-switching opportunities. DoD, perhaps the largest single customer for GHP retrofit projects, reports that in 2006 dollars housing and commercial retrofits cost $4600 and $7000 per ton respectively	"Office of the Deputy Under Secretary of Defense Report to Congress: Ground-Source Heat Pumps at Department of Defense Facilities. (2007). Hughes, P.J. & Shonder, J.A. The Evaluation of a 4000-Home Geothermal Heat Pump Retrofit at Fort Polk , Louisiana: Final Report. Oak Ridge National Laboratory (1998)"
Liu, X. Assessment of National Benefits from Retrofitting Existing Single-Family Homes with Ground Source Heat Pump Systems. Oak Ridge National Laboratory (2010). Hughes, P.J. Geothermal (Ground-Source) Heat Pumps: Market Status, Barriers to Adoption, and Actions to Overcome Barriers. Oak Ridge National Laboratory (2008)	savings of [4.2 quads primary energy], a 45% reduction associated with SH–SC–WH in existing U.S. single-family homes. Worked with author to disaggregate into fuel-switching and non-fuel-switching opportunities. DoD, perhaps the largest single customer for GHP retrofit projects, reports that in 2006 dollars housing and commercial retrofits cost $4600 and $7000 per ton respectively	"Office of the Deputy Under Secretary of Defense Report to Congress: Ground-Source Heat Pumps at Department of Defense Facilities. (2007). Hughes, P.J. & Shonder, J.A. The Evaluation of a 4000-Home Geothermal Heat Pump Retrofit at Fort Polk , Louisiana: Final Report. Oak Ridge National Laboratory (1998)"
Navigant Consulting. (2009). Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances. Washington, D.C.: Building Technology Program, Department of Energy., http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 6-11: Summary of Primary Energy Savings Potential of all Water Heating Technology Options. Percent savings and cost changed to reflect site energy baseline of non-electric heating -> 43% savings	
Baxter, V.; Murphy, R; Rice, K; Craddick, B; "Development of a Small Integrated Heat Pump (IHP) for Net Zero Energy Homes" 9th International IEA Heat Pump Conference (2008)	"For the air-source IHP version, the simulation results showed ~46-67% energy savings depending upon location. For the ground-source IHP version, the simulation showed over 50% savings in all locations" Used 50% as conservative estimate within 46-67% range	

1. Description of the measure	2. Energy savings			3. Price	4. Units & capacity	5. Market description	6. Market size, 2030	7. Site use	8. Source use	9. Max adopt	10. CCE	11. Life	12. Used in scenario?			
	Percent	SD?	Fuel switch?										McK	NAS	Emerg	Tech
R: Install ground-source heat-pumps (GSHP) in single family homes (FS only)	81%	Yes	FS	$14,400	per home; 3 ton	R: All non-electric heating and water heating plus central air conditioner	83.4	5,576	6,719	1,881	$19.58	40	No	No	No	Yes
R: Install ground-source heat-pumps (GSHP) in single family homes (no FS)	65%	Yes		$14,400	per home; 3 ton	R: All electric heating & hot water; proportion of cooling	47.0	1,112	3,392	1,262	$18	40	No	No	Yes	Yes
C: Change inside temp 1° F	5%	Yes		$0	per square foot	C: Commercial HVAC	103,945	3,192	4,924	242	$0	1	No	No	No	Yes
C: Close blinds to reduce solar heat gain	16%	Yes		$0.14	per square foot; one unit per 6x6 window on south face	C: Windows that can benefit from attachments	51,972	501	767	105	$4.11	10	No	No	No	Yes
R: Change inside temp 1° F	5%	Yes		$0	per home	R: Heating and cooling	160	5,568	8,290	417	$0	1	No	No	No	Yes
R: Close blinds to reduce solar heat gain	16%	Yes		$440	per home; 8 south facing blinds	R: Windows that can benefit from attachments	70.7	918	1,361	186	$9.19	10	No	No	No	Yes
R: Develop air-source heat pumps for cold climates (FS only)	76%	Yes		$3,000	per home; 3 ton	R: Non-electric heating, proportion of cooling in coldest 2 climates	37.0	2,041	2,348	1,781	$3.13	20	No	No	No	Yes
C: Increase efficiency of circulator pumps	60%			$0.05	per unit; Assumed 1 per 1500 sq. ft.	C: Circulator pumps	32,769	43.7	133	80.5	$1.07	20	Yes	Yes	Yes	Yes
C: Install demand ventilation (e.g., CO_2 sensing)	20%	Yes		$0.54	per square foot; $800/zone	C: Commercial HVAC	103,945	3,192	6,017	924	$3.20	10	Yes	Yes	Yes	Yes
C: Switch ventilation from CAV to VAV	25%			$0	per unit	C: CAV ventilation	49,917	316	963	225	$0	20	No	No	Yes	Yes
C: Use VAV insulation instead of CAV	25%			$0	per unit	C: CAV ventilation	49,917	316	963	225	$0	20	No	No	Yes	Yes
R: Switch to variable speed motors in furnace fans for home ventilation	51%			$296	per unit	R: Furnace Fans Total	88.1	186	567	378	$3.67	20	Yes	Yes	Yes	Yes
R: Use most efficient circulator pumps for multi-family buildings	60%			$75	per unit	R: Heating systems pumps (all radiative and heat pumps)	48.2	49.3	150	90.9	$1.91	20	Yes	Yes	Yes	Yes
C/I/O: Eliminate constant electrode heating in rapid start ballasts	5%			$20.30	per unit	C/IRapid-Start/ Dimming Ballasts/ Industrial	223	75.6	231	0	$7,319.24	5	No	No	No	No
C/I/O: Improve efficiency of HID dimmable ballasts	15%			$125	per ballast	C/IHIDs and Fluorescents - Dimmable Ballasts (Comm/ Indust/Outd)	1,944	1,044	3,184	0	$258.06	5	No	No	No	No
C/I/O: Improve high-intensity discharge lamps for use in low CRI applications	75%			$42	per lamp	C/IMV and MH (C,I,O)	89.3	188	573	618	$0.74	3	No	No	Yes	Yes
C/I/O: Increase use of low-CRI high-intensity discharge lamps	63%			$62.96	per lamp	C/IIncandescent (Comm), MV and MH (Comm/Indust/Outd)	793	228	694	103	$37.63	1	No	No	Yes	Yes
C/I/O: Research and develop multi-photon phosphors for fluorescent lights	63%			$6	per lamp	C/IHIDs and Fluorescents (C/I/O)	3,056	1,641	5,007	2,554	$0.80	7	No	No	No	No
C/I: Develop dimmable instant-start ballasts	15%	Yes		$20.30	per ballast	C/IFluorescent Dimming Instant-Start Ballasts/Industrial	2,437	682	2,080	155	$22.96	5	No	No	No	No
C/I: Develop general-use organic light emitting diode (OLED)	62%			$0.03	per lamp	C/IAll commercial Lighting	2,889	1,249	3,811	2,181	$0	5	No	No	No	No

Primary sources used	Data used and/or methodology	Other supporting sources
Liu, X. Assessment of National Benefits from Retrofitting Existing Single-Family Homes with Ground Source Heat Pump Systems. Oak Ridge National Laboratory (2010). Hughes, P.J. Geothermal (Ground-Source) Heat Pumps: Market Status, Barriers to Adoption, and Actions to Overcome Barriers. Oak Ridge National Laboratory (2008)	savings of [4.2 quads primary energy], a 45% reduction associated with SH–SC–WH in existing U.S. single-family homes. Worked with author to disaggregate into fuel-switching and non-fuel-switching opportunities. DoD, perhaps the largest single customer for GHP retrofit projects, reports that in 2006 dollars housing and commercial retrofits cost $4600 and $7000 per ton respectively	"Office of the Deputy Under Secretary of Defense Report to Congress: Ground-Source Heat Pumps at Department of Defense Facilities. (2007). Hughes, P.J. & Shonder, J.A. The Evaluation of a 4000-Home Geothermal Heat Pump Retrofit at Fort Polk , Louisiana: Final Report. Oak Ridge National Laboratory (1998)"
Liu, X. Assessment of National Benefits from Retrofitting Existing Single-Family Homes with Ground Source Heat Pump Systems. Oak Ridge National Laboratory (2010). Hughes, P.J. Geothermal (Ground-Source) Heat Pumps: Market Status, Barriers to Adoption, and Actions to Overcome Barriers. Oak Ridge National Laboratory (2008)	savings of [4.2 quads primary energy], a 45% reduction associated with SH–SC–WH in existing U.S. single-family homes. Worked with author to disaggregate into fuel-switching and non-fuel-switching opportunities. DoD, perhaps the largest single customer for GHP retrofit projects, reports that in 2006 dollars housing and commercial retrofits cost $4600 and $7000 per ton respectively	"Office of the Deputy Under Secretary of Defense Report to Congress: Ground-Source Heat Pumps at Department of Defense Facilities. (2007). Hughes, P.J. & Shonder, J.A. The Evaluation of a 4000-Home Geothermal Heat Pump Retrofit at Fort Polk , Louisiana: Final Report. Oak Ridge National Laboratory (1998)"
Berry, C; Swenson, A; "Winter Energy Savings from Lower Thermostat Settings", EIA Brief (2000)	Natural Gas. Households whose main space-heating fuel was natural gas would have consumed 5 percent less natural gas for space heating and would have spent $22 less (for the entire year of 1997) if they had set their thermostat 1° F lower	
Cho, S.-hwan, Shin, K.-S. & Zaheer-Uddin, M. The Effect of Slat Angle of Windows With Venetian Blinds on Heating and Cooling Loads in South Korea. Energy 20, 1225-1236 (1995)	Results show that the use of windows with Venetian blinds can reduce the building heating load by about 5% and cooling loads by as much as 30% Used conservative weighted average of savings range	
Berry, C; Swenson, A; "Winter Energy Savings from Lower Thermostat Settings", EIA Brief (2000)	Natural Gas. Households whose main space-heating fuel was natural gas would have consumed 5 percent less natural gas for space heating and would have spent $22 less (for the entire year of 1997) if they had set their thermostat 1° F lower	
Cho, S.-hwan, Shin, K.-S. & Zaheer-Uddin, M. The Effect of Slat Angle of Windows With Venetian Blinds on Heating and Cooling Loads in South Korea. Energy 20, 1225-1236 (1995)	Results show that the use of windows with Venetian blinds can reduce the building heating load by about 5% and cooling loads by as much as 30%." Used conservative weighted average of savings range	
Sachs et al, 2009, "Emerging Energy-Saving HVAC Technologies and Practices for the Buildings Sector." Hallowell International; Personal communication: Bouza, DOE	Energy savings equivalent to no-fuel-switching measure but measured against oil and natural gas market	
Waide, P. & Brunner, C. Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems. International Energy Agency (2011).	Page 58: An exemplary study of two optimal pump systems demonstrates that if all available state-of-the-art efficiency measures of a pump system are systematically applied, energy-efficiency savings of 80% to 90%	Byrne, Jeanne, "Motors Matter". Home Energy Magazine Online 1-7 (2000)
Goetzler, W., Zogg, R., Burgos, J., Hiraiwa, H. & Young, J. Energy Savings Potential and RD & D Opportunities for Commercial Building HVAC Systems. Navigant Consulting (2011)	Page 16: "These savings are equivalent to a 10% reduction in total energy costs." Page 11: "For a new system to be installed will generally cost $600-$700 per zone; retrofit at $700-$900/zone." Used 10% total energy savings -> 20% HVAC savings; using average retrofit cost as that is the majority of the opportunity	
Directly calculated from NEMS detailed data tables	Directly calculated from NEMS detailed data tables	
EPA, (2012) "IAQ Building Education and Assessment Model"		
Murray, M. & Fitzpatrick, S. Residential HVAC Electronically Commutated Motor Retrofit Report Table of Contents. Advanced Energy (2012)	"ECM motors represent a 51 percent full-load efficiency improvement over permanent split-capacitor (PSC) motors." "The three ECMs used in this study cost, on average, $296. The average motor installation cost was approximately $547.50." Only retrofit is cost effective, so using 51% savings, $296 cost"	Franco, V., Lutz, J., Lekov, A. & Gu, L. Furnace Blower Electricity: National and Regional Savings Potential. Florida Solar Energy Center(2008)
Waide, P. & Brunner, C. Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems. International Energy Agency (2011).	Figure 27 and table 23 show savings of 55-63% improvement of existing system with new, optimized pump. Cost from google search	
Navigant Consulting U.S. Lighting Market Characterization Volume II: Energy Efficient Lighting Technology Options. Energy II, 286 (2005).	Page 38: "With the elimination of constant electrode heating, these values would decline to 37 watts and 38 watts, respectively, correlating to a 5% decrease in energy consumption. A 5% decrease in energy consumption would result in energy savings of 0.01 quad per year." and Table 3-16: Ballast Price, by Type	
Navigant Consulting U.S. Lighting Market Characterization Volume II: Energy Efficient Lighting Technology Options. Energy II, 286 (2005).	Table 3-45: Technical Potential Energy Savings of HID Dimmable Ballasts and page 84: "A cost estimates for a 400-watt electronic ballast is $223, approximately $125 more than a 400-watt CWA ballast (Advance Transformer, 2003)."	
Navigant Consulting U.S. Lighting Market Characterization Volume II: Energy Efficient Lighting Technology Options. Energy II, 286 (2005).	Assumes 10,000 hr life, 10 incandescent as standard cost	
Navigant Consulting U.S. Lighting Market Characterization Volume II: Energy Efficient Lighting Technology Options. Energy II, 286 (2005).	Table 3-34: Technical Potential Energy Savings of Ceramic Metal Halide	Cost data are from google searches of commercially available appliances
Navigant Consulting U.S. Lighting Market Characterization Volume II: Energy Efficient Lighting Technology Options. Energy II, 286 (2005).	Table 3-17: Technical Potential Energy Savings of Multi-photon Phosphors	Cost data are from google searches of commercially available appliances
Navigant Consulting U.S. Lighting Market Characterization Volume II: Energy Efficient Lighting Technology Options. Energy II, 286 (2005).	Table 3-13: Technical Potential Energy Savings of Dimmable Instant-Start Ballasts and Table 3-14: Ballast Price, by Type	
Navigant Consulting U.S. Lighting Market Characterization Volume II: Energy Efficient Lighting Technology Options. Energy II, 286 (2005).	Table 3-50: Potential Energy Savings of OLED Technology	

1. Description of the measure	2. Energy savings			3. Price	4. Units & capacity	5. Market description	6. Market size, 2030	7. Site use	8. Source use	9. Max adopt	10. CCE	11. Life	12. Used in scenario?			
	Percent	SD?	Fuel switch?										McK	NAS	Emerg	Tech
C/R: Develop high-CRI, low-wattage high-intensity discharge lamps	71%			$5.87	per lamp	C/RResi and Comm Incandescents	6,695	296	904	579	$18.94	1	No	No	No	Yes
C/R: Implement the recent electronic ballast standard	7%	Yes		$0.13	per ballast; 2 lamps in stock per ballast	C/RResi and Comm Fluorescents	3,304	1,294	3,949	183	$0.16	20	Yes	Yes	Yes	Yes
C/R: Raise ballast standard to higher efficiency level	11%			$9	per ballast	C/RResi and Comm Fluorescents	3,304	1,294	3,949	186	$10.10	20	No	No	No	Yes
C: Add skylights for daylighting in new buildings	8%	Yes		$1.37	per square foot; 45,000 ft² ave. grocery store	C: All fluorescents, new commercial	50,966	582	1,777	133	$35.12	20	No	No	No	No
C: Develop advanced general use LED lighting (i.e., DOE roadmap)	72%			-$0.77	per lamp	C: All commercial Lighting	2,889	1,249	3,811	2,674	-$0.04	40	No	No	Yes	Yes
C: Develop low-CRI sulfur lights to replace fluorescent	35%			$436.14	per lamp	C: Fluorescents Commercial/Industrial (for sulfur lamps)	1,056	368	1,123	237	$172.40	5	No	No	No	No
C: Develop low-CRI sulfur lights to replace HID	30%			$414	per lamp	C: All HID (C/I/O)	161	353	1,075	95.9	$50.66	2	No	No	No	No
C: Increase use of CFLs as incandescent replacement	63%			-$1.81	per lamp	C: Incandescent	703	39.8	121	4.61	-$6.12	1	Yes	Yes	Yes	Yes
C: Increase use of solid-state lighting for signage	89%			-$1,854.86	per sign	C: Commercial Signs	25.3	31.0	94.6	103	-$28.42	11	Yes	Yes	Yes	Yes
C: Install hard-wired lighting occupancy sensors	13%	Yes		$0.34	per square foot	C: All commercial lighting, per square foot stock	103,945	1,249	3,811	431	$7.88	4	No	No	No	No
C: Install wireless lighting occupancy sensors for lighting	13%	Yes		$0.05	per square foot; one controller per 4 luminaires	C: All commercial lighting, per square foot stock	103,945	1,249	3,811	347	$1.02	20	No	No	Yes	Yes
C: Optimize windows for daylighting, new	8%	Yes		$0.15	per square foot; 200,000 ft² ave. building	C: All fluorescents, new commercial	50,966	582	1,777	123	$4.64	40	No	No	Yes	Yes
C: Parking lot LED w/controls	50%			$140	per luminaire	C: Parking lot lighting	46.7	113	345	0	$5.92	10	No	No	Yes	Yes
C: Perimeter zone day lighting	40%	Yes		$184.93	per square foot	C: Perimeter zone fluorescent	481	223	682	185	$16.18	40	No	No	Yes	Yes
C: Task lighting	50%			$1.96	per square foot	C: Task lighting	12,473	143	435	219	$5.52	20	No	No	No	Yes
C: TDDs and controls, existing	21%	Yes		$8.50	per square foot; 210,800 ft² school	C: All fluorescents, existing commercial	52,979	605	1,847	378	$67.97	20	No	No	Yes	Yes
C: Troffer specification: 1x4 without controls improvement	23%	Yes		$58	per luminaire	C: Lighting: 1x4 troffers	38.1	20.9	63.7	12.4	$11.92	10	No	No	Yes	Yes
C: Troffer specification: 2x2 without controls improvement	21%	Yes		$58	per luminaire	C: Lighting: 2x2 troffers	76.2	41.7	127	21.9	$13.41	10	No	No	Yes	Yes
C: Troffer specification: 2x4 with controls improvement	51%	Yes		$291	per luminaire	C: Lighting: 2x4 troffers benefitting from controls	217	119	363	178	$23.27	10	No	No	Yes	Yes

Primary sources used	Data used and/or methodology	Other supporting sources
Navigant Consulting U.S. Lighting Market Characterization Volume II: Energy Efficient Lighting Technology Options. Energy II, 286 (2005).	Table 3-26: Technical Potential Energy Savings of Low-Wattage MH Lamps. "The GE ceramic MH lamp has an efficacy of 85 lm/W, and would replace a miniature halogen lamp that has an efficacy of 21 lm/W"	Cost data are from google searches of commercially available appliances
Navigant Consulting & Pacific Northwest National Laboratory Final Rule Technical Support Document Energy Conservation Program for Consumer Products and Certain Commercial And Industrial Equipment: Fluorescent Lamp Ballasts. Department of Energy (2011)	In depth analysis based on technical data included in tool	
Universal Lighting Technologies, "Triad High Efficiency System". Manufacturer (2011)	Difference between Triad and standard electric ballast averaged between 0.78 and 0.88 ballast factors	
Leach, M., Hale, E., Hirsch, A. & Tocellini, P. Grocery Store 50 % Energy Savings Technical Support Document Grocery Store (2009). http://www.nrel.gov/docs/fy09osti/46101.pdf	3% of roof area for 45,000 ft^2 grocery store @ $45.8/$ft^2$. $1.37/$ft^2$ = 0.03%*$45.8/$ft^2$. Energy savings assumes skylights contribute 50% of total daylighting energy savings. Average of Miami, Chicago, and Seattle.	
Bardsley Consulting et. al. "Solid-State Lighting Research and Development: Multi-Year Program Plan". Department of Energy 2012	Represents cost and performance goals for LED lighting measured against today's installed base	"Navigant Consulting. "2010 U.S. Lighting Market Characterization". Department of Energy (2005). Navigant Consulting U.S. Lighting Market Characterization Volume II: Energy Efficient Lighting Technology Options. Department of Energy (2005)."
Navigant Consulting U.S. Lighting Market Characterization Volume II: Energy Efficient Lighting Technology Options. Energy II, 286 (2005).	Table 3-48: Technical Potential Energy Savings of Molecular Discharge Lamps	Cost data are from google searches of commercially available appliances
Navigant Consulting U.S. Lighting Market Characterization Volume II: Energy Efficient Lighting Technology Options. Energy II, 286 (2005).	Table 3-48: Technical Potential Energy Savings of Molecular Discharge Lamps	Cost data are from google searches of commercially available appliances
ENERGY STAR (n.d.). Savings Calculator for ENERGY STAR Qualified Lighting. Retrieved from: http://www.energystar.gov/ia/business/bulk_purchasing/bpsavings_calc/LightingCalculator.xlsx?94b4-cb27&94b4-cb27	Cost per unit comes from the savings calculator	ENERGY STAR (n.d.). Light Bulbs for Consumers. Retrieved from: http://www.energystar.gov/index.cfm?fuseaction=find_a_product.showProductGroup&pgw_code=LB
Navigant Consulting U.S. Lighting Market Characterization Volume II: Energy Efficient Lighting Technology Options. Energy II, 286 (2005).	Table 6-6: Summary Table for Utilization: Fixtures, "Monochromatic LEDs exhibit 80-90% energy savings over neon in signage fixtures.	
Leach, M., Hale, E., Hirsch, A. & Tocellini, P. Grocery Store 50 % Energy Savings Technical Support Document Grocery Store 50% Energy Savings Technical Support Document. 174 (2009).	Energy savings assumed the same as Measure 206. Cost of $0.36/$ft^2$ based the Grocery Store TSD.	Brambley, M. et al. Advanced sensors and controls for building applications: Market assessment and potential R&D pathways. Pacific Northwest National Laboratory (2005).
Navigant Consulting U.S. Lighting Market Characterization Volume II: Energy Efficient Lighting Technology Options. Energy II, 286 (2005). NREL. 2011. Advanced Energy Retrofit Guide for K-12 Schools (Draft). EERE Report DOE/GO-102011-3467. Project Lead: Robert Hendron	Energy savings based on the average of the K-12 schools AERG (11%) and the Navigant Lighting Study (15%). From Navigant, the incremental cost of $24/controller translates to about $0.014/$ft^2$ (assuming 126 controllers per 210,000 ft^2 based on the K-12 AERG). The K-12 AERG suggests a cost of about $0.08/$ft^2$. The difference was split and $0.05/$ft^2$ was used.	Brambley, M. et al. Advanced sensors and controls for building applications: Market assessment and potential R&D pathways. Pacific Northwest National Laboratory (2005).
Hendron, R. Senior Engineer - National Renewable Energy Laboratory Commercial Buildings Group. Personal communications.		
Department of Energy, "CBEA High-Efficiency Troffer Lighting Specification" (2012). Myer, personal communication		"Navigant Consulting Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications. 116 (2008). Navigant Consulting U.S. Lighting Market Characterization Volume I: National Lighting Inventory and Energy Consumption Estimate. Renewable Energy I, 120 (2002)."
Brambley, M. et al. Advanced sensors and controls for building applications: Market assessment and potential R&D pathways. Energy 156 (2005).at <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.111.8772&rep=rep1&type=pdf>	PNNL page 2.23: "A report by the EPA (2001) suggests that daylit offices can achieve up to 35%-40% savings, and that other daylit spaces (classrooms, grocery stores, and retail outlets) can achieve 40%-60% savings." and used $1.60 per sq-ft for 80 billion square feet	
California Lighting Technology Center. (n.d.). Integrated Office Lighting System (IOLS). Retrieved from Demonstration: http://cltc.ucdavis.edu/content/view/673/359/	"Energy savings: 50% annual energy savings; over 15 years, one system can yield savings of 7,500 kWh"	Heschong Mahone Group, Inc. (2009). Small Office ("Encon" Building) Site Report. Pacific Gas and Electric Company.
NREL. 2011. Advanced Energy Retrofit Guide for K-12 Schools (Draft). EERE Report DOE/GO-102011-3467. Project Lead: Robert Hendron	$1.79 million for TDDS, controls, and dimming ballasts. Analysis based on a typical 210,800 ft^2 high school.	
Department of Energy, "CBEA High-Efficiency Troffer Lighting Specification" (2012). Myer, personal communication	1'x 4' : 1.6 TWh (site) – 23% savings against incumbent technology	"Navigant Consulting Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications. 116 (2008). Navigant Consulting U.S. Lighting Market Characterization Volume I: National Lighting Inventory and Energy Consumption Estimate. Renewable Energy I, 120 (2002)."
Department of Energy, "CBEA High-Efficiency Troffer Lighting Specification" (2012). Myer, personal communication	2' x 2' : 2.6 TWh (site) – 21% savings against incumbent technology	"Navigant Consulting Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications. 116 (2008). Navigant Consulting U.S. Lighting Market Characterization Volume I: National Lighting Inventory and Energy Consumption Estimate. Renewable Energy I, 120 (2002)."
Department of Energy, "CBEA High-Efficiency Troffer Lighting Specification" (2012). Myer, personal communication	Including controls in "1-to-1" replacement measure increases savings to 51% and cost to $291/luminaire; applicable to approximately 50% of fixtures	"Navigant Consulting Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications. 116 (2008). Navigant Consulting U.S. Lighting Market Characterization Volume I: National Lighting Inventory and Energy Consumption Estimate. Renewable Energy I, 120 (2002)."

1. Description of the measure	2. Energy savings			3. Price	4. Units & capacity	5. Market description	6. Market size, 2030	7. Site use	8. Source use	9. Max adopt	10. CCE	11. Life	12. Used in scenario?			
	Percent	SD?	Fuel switch?										McK	NAS	Emerg	Tech
C: Troffer specification: 2x4 without controls improvement	35%	Yes		$116	per luminaire	C: Lighting: 2x4 troffers	362	198	605	191	$14.64	10	No	No	Yes	Yes
C: Use spectrally enhanced lighting	17%	Yes		$1.95	per lamp	C: fluorescent	2,406	1,188	3,624	539	$0.77	5	No	No	No	Yes
O: Install off-grid solar-powered outdoor lighting	100%			$80.03	per luminaire	O: All lighting, Outdoor	120	256	782	835	$1.85	2	No	No	No	No
R/C/I/O: Develop LED lighting to replace incandescent PAR	79%			$39.29	per lamp	R/CR/C/I/O Reflector lamps	785	62.7	191	91.3	$16.83	10	No	No	No	Yes
R: Develop advanced general use LED lighting (i.e., DOE roadmap)	90%			-$23.10	per home; 30 lamps replaced/home	R: Lighting, all (by home)	141	441	1,346	1,208	-$0.11	68	Yes	Yes	Yes	Yes
R: Increase use of CFLs	63%			-$1.81	per lamp	R: Resi incandescents	5,992	257	783	115	-$8.33	1	Yes	Yes	Yes	Yes
R: Replace incandescent decorative strings with LEDs	70%			$15.49	per unit	R: Decorative Light Strings	195	34.8	106	123	$2.22	3	Yes	Yes	No	Yes
R: Use occupancy sensor for lighting control in homes	15%	Yes		$5.43	per sensor; one unit per 8 bulbs	R: Lighting, all (by home)	141	441	1,346	165	$0.19	20	No	No	Yes	Yes
C/R: Develop advanced display power management systems	20%			$0.80	per unit	C/RComputers and TVs for power management and Resi	297	507	1,548	329	$0.08	4	No	No	Yes	Yes
C/R: Develop and use interdevice power control for audio-visual equipment	10%	Yes		$0.10	per unit	C/RAudio/video power control, Resi	357	129	395	26.1	$0.11	7	No	No	Yes	Yes
C/R: Develop cholesteric liquid-crystal displays (LCDs) for monitors and TVs	50%			$150	per unit	C/RMonitors Resi + Comm	474	36.1	110	55.7	$130.20	4	No	No	No	Yes
C/R: Increase use of network presence proxy for PC power management	30%	Yes		$0	per unit	C/RResi and Comm Standby Power	89.5	285	868	262	$0	4	No	No	Yes	Yes
C/R: Switch from desktop to notebook PCs	80%			$100	per unit	C/RResi and Comm Desktop PCs	44.2	182	555	305	$2.25	4	No	No	No	Yes
C/R: Use more efficient (i.e., level of proposed standards) small motors in miscellaneous devices	21%			$41	per unit	C/RSmall motors (covered in recent rulemaking)	29.2	192	586	109	$0.69	12	Yes	Yes	Yes	Yes
C/R: Use most efficient (i.e., max-tech) small motors in miscellaneous devices	33%			$159	per unit	C/RSmall motors (not in other analyzed products)	108	619	1,890	599	$2.67	5	No	No	Yes	Yes
C/R: Deploy energy efficient ethernet protocols (i.e., 802.3az)	5%	Yes		$0.03	per unit	C/REnergy efficient ethernet and Resi	239	379	1,158	31.9	$0.02	4	Yes	Yes	Yes	Yes
C/R: Develop an LCD monitor standard	40%			$75	per unit	C/RMonitors Resi + Comm	474	36.1	110	56.5	$38.47	8	No	No	Yes	Yes
C/R: Increase use of desktop computer power management	44%	Yes		$0	per unit	C/RAll desktop PCs	44.2	182	555	161	$0	4	No	No	Yes	Yes
C/R: Increase use of laptop computer power management	28%	Yes		$0	per unit	C/RResi and Comm Notebook PCs	420	48.8	149	35.2	$0	4	Yes	Yes	Yes	Yes
C/R: Increase use of most efficient (i.e., max-tech) desktop computers	80%			$392.63	per unit	C/RResi and Comm Desktop PCs	44.2	182	555	508	$6.38	4	Yes	Yes	Yes	Yes
C: Controllable power outlets, new	19%	Yes		$1.75	per square foot; 50,000 ft^2 retail store	C: All plug loads in new commercial buildings	50,966	999	3,047	514	$12.96	20	No	No	No	No
C: Dry distribution transformers, High	69%			$0	per unit	C: Dry Distribution Transformers	0.86	123	375	170	$0	32	No	No	Yes	Yes

Primary sources used	Data used and/or methodology	Other supporting sources
Department of Energy, "CBEA High-Efficiency Troffer Lighting Specification" (2012). Myer, personal communication	2' x 4' : 16.4 TWh (site) – 35% savings against incumbent technology	"Navigant Consulting Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications. 116 (2008). Navigant Consulting U.S. Lighting Market Characterization Volume I: National Lighting Inventory and Energy Consumption Estimate. Renewable Energy I, 120 (2002)."
Navigant Consulting U.S. Lighting Market Characterization Volume II: Energy Efficient Lighting Technology Options. Energy II, 286 (2005).	Table 5-3: Price of Lamps, Spectrally Enhanced vs. Non-Spectrally Enhanced	
Navigant Consulting U.S. Lighting Market Characterization Volume II: Energy Efficient Lighting Technology Options. Energy II, 286 (2005).	Page 193: "Off-grid luminaires would affect energy consumption in the outdoor stationary sector, essentially taking it 100% off grid, reducing energy used from 0.6 quad (NCI, 2002) to 0 quad (technical potential energy savings, primary energy)."	Cost data are from google searches of commercially available appliances
Navigant Consulting. "Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications". Department of Energy (2011).	Savings: Page 14, table 2.4. Cost: Page 59: "LED MR16 and PAR30 lamps cost nearly eight times more than the conventional halogen lamps they replaced", supported by google search	
Bardsley Consulting et. al. "Solid-State Lighting Research and Development: Multi-Year Program Plan". Department of Energy (2012).	Represents cost and performance goals for LED lighting measured against today's installed base	"Navigant Consulting. "2010 U.S. Lighting Market Characterization". Department of Energy (2005). Navigant Consulting U.S. Lighting Market Characterization Volume II: Energy Efficient Lighting Technology Options. Department of Energy (2005)."
ENERGY STAR (n.d.). Savings Calculator for ENERGY STAR Qualified Lighting. Retrieved from: http://www.energystar.gov/ia/business/bulk_purchasing/bpsavings_calc/LightingCalculator.xlsx?94b4-cb27&94b4-cb27	Cost per unit comes from the savings calculator	
ENERGY STAR (n.d.).Decorative Light Strings for Consumers. Retrieved from: http://www.energystar.gov/index.cfm?fuseaction=find_a_product.showProductGroup&pgw_code=DS	"ENERGY STAR Qualified Decorative Light Strings consume 70% less energy than conventional incandescent lights strands."	Cost data are from google searches of commercially available appliances
Navigant Consulting U.S. Lighting Market Characterization Volume II: Energy Efficient Lighting Technology Options. Energy II, 286 (2005).	Page 108: "Typical LED drive electronics operate at efficiencies in the range of 75% to 85%. For comparison, the most efficient ballasts for fluorescent lamps operate at a little better than 90% efficiency, with single digit losses (Lightfair, 2003)."	Cost data are from google searches of commercially available appliances
Personal communication: Nordman, LBNL (12/2010)	20% savings, very low costs relative to savings, usually several orders of magnitude difference (using benefit/cost ratio of 100)	
Personal communication: Nordman, LBNL (12/2010)	10% savings, very low costs relative to savings, usually several orders of magnitude difference (using benefit/cost ratio of 100)	
Roth, K.W., Larocque, G.R., Kleinman, J. & Doe, B.C. Energy Consumption by Office and Telecommunications Equipment in Commercial Buildings Volume II?: Energy Savings Potential. Engineering II, 201 (2004).	Page 4-13, Table 4-9	Cost data are from google searches of commercially available appliances
Personal communication with Nordman on Dec. 15, 2010	30% savings, very low costs relative to savings, usually several orders of magnitude difference (using benefit/cost ratio of 100)	
Roth, K.W., Mckenney, K., Ponoum, R. & Paetsch, C. Residential Miscellaneous Electric Loads: Energy Consumption Characterization and Savings Potential. Energy 197 (2007).	Page 4-33: Specifically, a desktop PC plus a monitor has a UEC about five times greater than a notebook PC.	Cost data are from google searches of commercially available appliances
Department of Energy, Small Electric Motors Final Rule Technical Support Document (2010). Desroches, L.-B. et al. Max Tech and Beyond (2011)	Efficiency level 5 from chapter 5 of 2010 TSD (and MTAB pg. 44 Fig. 2)	
Department of Energy, Small Electric Motors Final Rule Technical Support Document (2010). Desroches, L.-B. et al. Max Tech and Beyond (2011)	Highest efficiency level in 2010 TSD (and MTAB pg. 44 Fig. 2) represents increasing small motor efficiency from 62% (ave. installed base" to best available (92%)	
Personal communication with Nordman on Dec. 15, 2010	5% savings, very low costs relative to savings, usually several orders of magnitude difference (using benefit/cost ratio of 100)	
Roth, K.W., Mckenney, K., Ponoum, R. & Paetsch, C. Residential Miscellaneous Electric Loads: Energy Consumption Characterization and Savings Potential. Energy 197 (2007).	Page 4-46: On average, a 17-inch LCD monitors draws about 40% less power than CRT monitors in active mode…."	Cost data are from google searches of commercially available appliances
Roth, K.W., Mckenney, K., Ponoum, R. & Paetsch, C. Residential Miscellaneous Electric Loads: Energy Consumption Characterization and Savings Potential. Energy 197 (2007).	Page 4-31, last sentence.	Cost data are from google searches of commercially available appliances
Roth, K.W., Mckenney, K., Ponoum, R. & Paetsch, C. Residential Miscellaneous Electric Loads: Energy Consumption Characterization and Savings Potential. Energy 197 (2007).	Page 4-31, last sentence.	Cost data are from google searches of commercially available appliances
Roth, K.W., Mckenney, K., Ponoum, R. & Paetsch, C. Residential Miscellaneous Electric Loads: Energy Consumption Characterization and Savings Potential. Energy 197 (2007).	Table 4-20: Personal Computers Summary	Cost data are from google searches of commercially available appliances
E.T. Hale, D.L. Macumber, N.L. Long, B.T. Griffith, K.S. Benne, S.D. Pless, and P.A. Torcellini. 2008. Technical Support Document: Development of the Advanced Energy Design Guide for Medium Box Retail—50% Energy Savings. (http://www.nrel.gov/docs/fy08osti/42828.pdf)	Energy savings and cost from Hale et al. \$87,500 for a 50,000 ft^2 retail store. Assumes reduction from 40% to 15% MELs operation during unoccupied hours	
TSD supporting spreadsheets: http://www1.eere.energy.gov/buildings/appliance_standards/docs/dt_nopr_tools_nia_ria.zip	This data came from a complex calculation/manipulation of the TSD supporting spreadsheets that is included in the tool	

1. Description of the measure	2. Energy savings			3. Price	4. Units & capacity	5. Market description	6. Market size, 2030	7. Site use	8. Source use	9. Max adopt	10. CCE	11. Life	12. Used in scenario?			
	Percent	SD?	Fuel switch?										McK	NAS	Emerg	Tech
C: Improve data center energy management (e.g., CADE)	70%			-$14k	per data center	C: Data Centers	0.02	551	1,682	1,688	-$13.10	4	Yes	Yes	Yes	Yes
C: Increase fume hood efficiency	50%			-$500	per unit	C: Fume Hoods	0.99	67.5	206	104	-$0.32	10	Yes	Yes	Yes	Yes
C: Reduce standby power of miscellaneous equipment to 1W	67%			$0	per unit	C: Commercial Standby Power	163	137	418	305	$0	5	Yes	Yes	Yes	Yes
C: Use more efficient (i.e., proposed standard) liquid distribution transformers	10%			$0	per unit	C: Liquid Distribution Transformers	2.1	199	607	63.6	$0	32	No	No	No	No
C: Use most efficient (i.e., max-tech) liquid distribution transformers	50%			$0	per unit	C: Liquid Distribution Transformers	2.1	199	607	202	$0	32	No	No	Yes	Yes
C: Use most efficient fitness equipment	50%			$4,500	per unit	C: Fitness equipment	1.1	5.40	16.5	9.47	$38.73	7	No	No	Yes	No
C: Use regenerative technology for geared elevators	31%			$10,000	per unit	C: Regenerative geared elevators in mid-rise commercial buildings	0.12	1.97	6.01	1.38	$40.51	25	No	No	Yes	Yes
R: Decrease set-top box power use	25%			$0.50	per unit	R: Set-top boxes, Resi	118	87.2	266	77.7	$0.07	5	Yes	Yes	Yes	Yes
R: Develop an active-power draw TV standard	50%			$10	per unit	R: TV Total	530	471	1,438	761	$0.47	10	Yes	Yes	Yes	Yes
R: Develop OLED monitors	75%			$140.63	per unit	R: Resi TVs and Resi and Comm PC monitors	742	541	1,651	1,210	$6.90	8	No	No	No	Yes
R: Incorporate power management into video game consoles	72%			$0	per unit	R: Video game consoles	98.0	18.6	56.7	59.0	$0	5	Yes	Yes	Yes	Yes
R: Increase insulation on coffee maker carafes	26%			$41	per unit	R: Coffee Maker Total	85.1	17.5	53.2	15.0	$28.23	3	No	No	Yes	Yes
R: Reduce standby power of miscellaneous equipment to 1W	67%			$0	per unit	R: Residential standby power	182	152	465	339	$0	5	Yes	Yes	Yes	Yes
R: Reducing spa standby temperature (2-4°F)	6%	Yes		$0	per unit	R: Spas Total	5.1	40.7	124	6.13	$0	15	No	No	Yes	No
R: Replace remaining CRT monitors with LCD monitors	40%			$150	per unit	R: Resi TVs and Resi and Comm PC monitors	742	541	1,651	667	$12.42	8	No	No	No	Yes
R: Use more efficient motors in ceiling fans	63%			$86	per unit	R: Ceiling Fan Total	306	72.8	222	131	$12.42	13	No	No	Yes	Yes
R: Use most efficient (i.e., ENERGY STAR) packaged dehumidifiers	15%			$0	per unit; 70 pint/day capacity	R: Residential Dehumidifier	17.5	229	700	79.3	$0	12	Yes	Yes	Yes	Yes
R: Use most efficient hydraulic elevator	21%			$10,000	per unit	R: Efficient Hydraulic elevators in low-rise residential buildings	0.62	10.5	32.0	5.77	$43.75	25	No	No	Yes	Yes
R: Use most efficient vacuum cleaner	50%			$0	per unit	R: Vacuums	176	24.9	76.1	38.6	$0	7	Yes	Yes	Yes	Yes
R: Use regenerative technology for geared elevators	30%			$9,000	per unit	R: Regenerative elevators in high-rise residential buildings	0.04	0.66	2	0.51	$27.79	25	No	No	Yes	Yes
R: Use techniques from California pool pump standard nationally	63%			$79	per unit	R: Pool Pumps	10.3	53.0	162	102	$0.56	10	Yes	Yes	Yes	Yes
C: Add doors to supermarket display cases	30%	Yes		$160	per unit	C: All Reach-Ins	2.5	46.5	142	41.2	$0.60	10	No	No	Yes	Yes
C: Increase ice machine wall insulation	3%	Yes		$77	per unit	C: Ice Machines	1.4	37.0	113	2.52	$2.77	9	No	No	No	No
C: Optimize air jets for reduced energy use in open display cases	20%	Yes		$160	per unit	C: All Reach-Ins	2.5	46.5	142	26.7	$1.04	10	Yes	Yes	Yes	Yes

Primary sources used	Data used and/or methodology	Other supporting sources
Zogg, R. et al. Energy Savings Potential and RD & D Opportunities for Commercial Building Appliances Department of Energy (2009). Kaplan, J.M., Forrest, W. & Kindler, N. Revolutionizing Data Center Energy Efficiency. McKinsey & Company (2008)	Combination of virtualization, power management, and CADE-related utilization management measures: 70% with a resultant decrease in IT infrastructure and maintenance personnel cost	
Mckenney, K., Guernsey, M., Ponoum, R. & Rosenfeld, J. Commercial Miscellaneous Electric Loads: Energy Consumption Characterization and Savings Potential in 2008 by Building Type. Energy 244 (2010).	Page 5-45: Table 9	Cost data are from google searches of commercially available appliances
Choi-Granade, C. e. (2009). Unlocking Energy Efficiency in the U.S. Economy. McKinsey & Company.	Page 49: "A standby standard could reduce standby consumption by roughly two-thirds, yielding 90 - 110 TWh in savings."	
TSD supporting spreadsheets: http://www1.eere.energy.gov/buildings/appliance_standards/docs/dt_nopr_tools_nia_ria.zip	This data came from a complex calculation/manipulation of the TSD supporting spreadsheets that is included in the tool	
TSD supporting spreadsheets: http://www1.eere.energy.gov/buildings/appliance_standards/docs/dt_nopr_tools_nia_ria.zip	This data came from a complex calculation/manipulation of the TSD supporting spreadsheets that is included in the tool	
Mckenney, K., Guernsey, M., Ponoum, R. & Rosenfeld, J. Commercial Miscellaneous Electric Loads: Energy Consumption Characterization and Savings Potential in 2008 by Building Type. Energy 244 (2010).	Page 5-42, Table 8.	Cost data are from google searches of commercially available appliances
E Source. (n.d.). Elevators. Retrieved from Business Energy Advisor: http://www.esource.com/escrc/0013000000DP22YAAT/BEA1/PA/PA_ElevatorsEscalators/PA-57	Table 2: Elevator payback period	
Personal communication: Nordman, LBNL (12/2010)	25% savings, very low costs relative to savings, usually several orders of magnitude difference (using benefit/cost ratio of 100)	
Roth, K.W., Mckenney, K., Ponoum, R. & Paetsch, C. Residential Miscellaneous Electric Loads: Energy Consumption Characterization and Savings Potential. Energy 197 (2007).	Page 4-100, last sentence and Table 4-96	Cost data are from google searches of commercially available appliances
Roth, K.W., Mckenney, K., Ponoum, R. & Paetsch, C. Residential Miscellaneous Electric Loads: Energy Consumption Characterization and Savings Potential. Energy 197 (2007).	Page 4-48, Table 4-43 and page 4-47, "Organic light-emitting diodes (OLED)-based monitors potentially could offer energy savings of 50% over LCD monitors"	Cost data are from google searches of commercially available appliances
Desroches, L.B., & Garbesi, K. (2011). Max Tech and Beyond. Lawrence Berkeley National Laboratory.	Page 20, Table 3	
Roth, K.W., Mckenney, K., Ponoum, R. & Paetsch, C. Residential Miscellaneous Electric Loads: Energy Consumption Characterization and Savings Potential. Energy 197 (2007).	Page 4-23, Table 4-16: Coffee Makers Summary	Cost data are from google searches of commercially available appliances
Choi-Granade, C. e. (2009). Unlocking Energy Efficiency in the U.S. Economy. McKinsey & Company.	Page 49: "A standby standard could reduce standby consumption by roughly two-thirds, yielding 90 - 110 TWh in savings."	
Roth, K.W., Mckenney, K., Ponoum, R. & Paetsch, C. Residential Miscellaneous Electric Loads: Energy Consumption Characterization and Savings Potential. Energy 197 (2007).	Page 5-24: "the ADL model indicates reducing the set point by 2 to 4 F can reduce the idle power draw by approximately three to eight percent (ADL 2004)"	
Roth, K.W., Mckenney, K., Ponoum, R. & Paetsch, C. Residential Miscellaneous Electric Loads: Energy Consumption Characterization and Savings Potential. Energy 197 (2007).	Page 4-46: On average, a 17-inch LCD monitors draws about 40% less power than CRT monitors in active mode...."	Cost data are from google searches of commercially available appliances
Environmental Protection Agency, "ENERGY STAR Ceiling Fan Product List", 2012	Represents second fastest of six speeds from one of the most efficient manufacturers using a DC motor at 280 CFM/W Installed base estimated at typical 100 CFM/W 63% reduction possible at $86 premium	
ENERGY STAR. (n.d.). Dehumidifiers for Consumers. Retrieved from Products: http://www.energystar.gov/index.cfm?fuseaction=find_a_product.showProductGroup&pgw_code=DE	"Dehumidifiers that have earned the ENERGY STAR are 15% more efficient than non-qualified models." and cost is from the savings calculator	
E Source. (n.d.). Elevators. Retrieved from Business Energy Advisor: http://www.esource.com/escrc/0013000000DP22YAAT/BEA1/PA/PA_ElevatorsEscalators/PA-57	Table 2: Elevator payback period	
Roth, K.W., Mckenney, K., Ponoum, R. & Paetsch, C. Residential Miscellaneous Electric Loads: Energy Consumption Characterization and Savings Potential. Energy 197 (2007).	Page 5-32: "If the high end of the Captive Air-Flow Cleaner tested power draw is used as the average power draw of vacuum cleaners, the active mode power draw and, hence, UEC of vacuum cleaners would decrease by almost 50% relative to the current estimate"	
E Source. (n.d.). Elevators. Retrieved from Business Energy Advisor: http://www.esource.com/escrc/0013000000DP22YAAT/BEA1/PA/PA_ElevatorsEscalators/PA-57	Table 2: Elevator payback period	
Pacific Gas & Electric, Sempra Energy; "Codes and Standards Enhancement Initiative: Draft Report Residential Swimming Pools", (2007)	Table 23 (savings), Table 25 (cost, but designs 2 to 1 only), using 63% savings, $79 extra cost	Roth, K.W., Mckenney, K., Ponoum, R. & Paetsch, C. Residential Miscellaneous Electric Loads: Energy Consumption Characterization and Savings Potential. Tiax (2007)
Garry, M; "New Tests Support Doors on Cases", Supermarket News 10/4/2010. Garry, M; "Fresh & Easy Installs Case Doors in 35 Stores" Supermarket News 9/20/2011	Multiple examples cited indicating (+/-) small change in sales, ~30% energy savings, ~3-5 year paybacks quoted. Using 30% savings and ~ 4 year payback and no statistically significant proof of sales impact	
DOE/Navigant (2009), Energy Savings Potential and R&D Opportunities for Commercial Refrigeration Equipment (http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_refrig_report_10-09.pdf)	Table 5-24, page 152, line 1, "Thicker Insulation"	Department of Energy, "Energy Conservation Program: Energy Conservation Standards for Residential Refrigerators, Refrigerator-Freezers, and Freezers" Federal Register (9/2010) and supporting documentation
Amin, Mazyar; Dabiri, Dana; Navaz, Homayun K., "Comprehensive study on the effects of fluid dynamics of air curtain and geometry, on infiltration rate of open refrigerated cavities"; Applied Thermal Engineering Volume 31, Issues 14–15, October 2011, Pages 3055–3065	Used geometric mean of min and maximum values in table 2; assumed similar cost to adding doors as labor should dominate retrofit cost	

1. Description of the measure	2. Energy savings			3. Price	4. Units & capacity	5. Market description	6. Market size, 2030	7. Site use	8. Source use	9. Max adopt	10. CCE	11. Life	12. Used in scenario?			
	Percent	SD?	Fuel switch?										McK	NAS	Emerg	Tech
C: Reduce evaporator thermal cycling in ice machine	5%			$25	per unit	C: Ice Machines	1.4	37.0	113	14.0	$0.17	8	No	No	No	No
C: Reduced meltage during harvest in ice machine	4%	Yes		$110	per unit	C: Ice Machines	1.4	37.0	113	3.43	$3.06	8	No	No	No	No
C: Retrofit lighting in refrigerated displays to LEDs	74%			$975	per unit	C: WI Coolers, BM, VM, Display Cases	6.7	210	641	421	$0.90	13	No	No	No	Yes
C: Use brushless DC motors in compressors	9%			$63	per unit	C: Compressors-DC	8.2	155	472	173	$0.19	11	No	No	No	Yes
C: Use brushless DC motors in refrigerator-freezer evaporator fans	17%			$98	per unit	C: Evaporator Fans	9.9	346	1,054	249	$0.23	12	No	No	No	Yes
C: Use central fiber-optic lighting system in supermarket refrigeration systems	25%			$1,607.14	per unit	C: WI Coolers, BM, VM, Display Cases	6.7	210	641	176	$3.60	13	No	No	No	No
C: Use more efficient (i.e., currently available) ice machines	15%			$140	per unit; 706 lbs/day	C: Ice Machines	1.4	37.0	113	24.8	$0.48	10	Yes	Yes	Yes	Yes
C: Use most efficient (i.e., max-tech) ice machines	23%			$334	per unit	C: Ice Machines	1.4	37.0	113	35.3	$0.88	9	Yes	Yes	Yes	Yes
C: Use most efficient (i.e., max-tech) supermarket refrigeration systems	28%			$228,536	per unit	C: Rfrg System, Supermarkets	0.03	286	873	264	$1.67	12	Yes	Yes	Yes	Yes
C: Use most efficient (i.e., max-tech) vending machine	33%			$296	per unit	C: Vending Machines	3.5	43.5	133	82.3	$0.73	12	Yes	Yes	Yes	Yes
C: Use variable-speed compressors for refrigeration	20%			$86	per unit	C: Compressors-DC	8.2	155	472	224	$0.19	10	No	No	No	Yes
R: Use LED lighting in refrigerators	1%	Yes		$7.99	per unit; 25 Lumens	R: Standard Size Refrigerators	153	410	1,250	3.99	$13.22	15	No	No	No	No
R: Add fans to upright freezers	8%	Yes		$1.45	per unit	R: Upright Freezers	20.0	35.3	108	8.63	$0.19	15	No	No	Yes	No
R: Decrease refrigerator size	6%	Yes		-$90	per unit	R: Standard Size Refrigerators	153	410	1,250	43.6	-$16.88	15	No	No	No	No
R: Develop thermo-accoustic refrigerators	15%			$1,549.75	per unit	R: All Refrigerators and Freezers	229	502	1,532	94.4	$147.66	15	No	No	No	No
R: Develop thermo-tunneling refrigerators	63%			$1,549.75	per unit	R: All Refrigerators and Freezers	229	502	1,532	638	$21.42	15	No	No	No	Yes
R: Eliminate icemaker parasitic energy use (i.e., hot-wire used for cube separation)	14%	Yes		-$110	per unit	R: Primary Refrigerators with Icemakers	108	325	991	100	-$7.14	15	No	No	Yes	Yes
R: Implement refridge standard (i.e., final rule 9/2011)	25%			$1.45	per unit	R: All Refrigerators and Freezers	229	502	1,532	313	$0.06	15	Yes	Yes	Yes	Yes
R: Increase freezer insulation	2%	Yes		$28.44	per unit; 25 ft^3	R: Freezers and Compact Refrigerators	75.9	92.3	282	2.29	$59.53	15	No	No	Yes	No
R: Increase use of adaptive defrost in home refrigerator-freezers	4%	Yes		$8	per unit	R: All Refrigerators and Freezers	229	502	1,532	19.3	$4.39	15	No	No	Yes	No

Primary sources used	Data used and/or methodology	Other supporting sources
DOE/Navigant (2009), Energy Savings Potential and R&D Opportunities for Commercial Refrigeration Equipment (http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_refrig_report_10-09.pdf)	Table 5-24, page 152, line 6, "Reduced Evaporator Thermal Cycling	Department of Energy, "Energy Conservation Program: Energy Conservation Standards for Residential Refrigerators, Refrigerator-Freezers, and Freezers" Federal Register (9/2010) and supporting documentation
DOE/Navigant (2009), Energy Savings Potential and R&D Opportunities for Commercial Refrigeration Equipment (http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_refrig_report_10-09.pdf)	Table 5-24, page 152, line 5, "Reduced Meltage During Harvest"	Department of Energy, "Energy Conservation Program: Energy Conservation Standards for Residential Refrigerators, Refrigerator-Freezers, and Freezers" Federal Register (9/2010) and supporting documentation
DOE/Navigant (2009), Energy Savings Potential and R&D Opportunities for Commercial Refrigeration Equipment (http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_refrig_report_10-09.pdf)	Page 125: "An estimated potential energy savings of 74% could be achieved through the use of LED lighting."	
DOE/Navigant (2009), Energy Savings Potential and R&D Opportunities for Commercial Refrigeration Equipment (http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_refrig_report_10-09.pdf)	Average of energy savings and installed cost premium of high efficiency compressors from tables 5-17, 5-19, 5-20, 5-22, 5-26, 5-27	Department of Energy, "Energy Conservation Program: Energy Conservation Standards for Residential Refrigerators, Refrigerator-Freezers, and Freezers" Federal Register (9/2010) and supporting documentation
Navigant Consulting Energy Savings Potential and R&D Opportunities for Commercial Refrigeration Final Report. Department of Energy (2009)	Tables 5-8, 13, 14, 17, 19, 20, 22, 26, 27 Averaged cost and savings over equipment in indicated tables	
DOE/Navigant (2009), Energy Savings Potential and R&D Opportunities for Commercial Refrigeration Equipment (http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_refrig_report_10-09.pdf)	Table 6-1, page 157 for energy savings. For cost assumes $30,000 measure cost for 14 cases rather than $7,500 for 14 cases of lighting. Resultant per-case incremental cose: ($30,000-$7,500)=$1607	Department of Energy, "Energy Conservation Program: Energy Conservation Standards for Residential Refrigerators, Refrigerator-Freezers, and Freezers" Federal Register (9/2010) and supporting documentation
Consortium for Energy Efficiency (2007), "Commercial Ice Makers" (http://www.cee1.org/resrc/facts/com-ice-fx.pdf)	The average annual energy use of a 500 lb./day air-cooled ice-maker is 5,000 kWh with a potential increase in efficiency of 15 percent (less than a two-year payback).	ENERGY STAR, "Commercial Ice Machines", http://www.energystar.gov/index.cfm?fuseaction=find_a_product.showProductGroup&pgw_code=CIM
DOE/Navigant (2009), Energy Savings Potential and R&D Opportunities for Commercial Refrigeration Equipment (http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_refrig_report_10-09.pdf)	Table 5-24, line 8, page 152	Department of Energy, "Energy Conservation Program: Energy Conservation Standards for Residential Refrigerators, Refrigerator-Freezers, and Freezers" Federal Register (9/2010) and supporting documentation
DOE/Navigant (2009), Energy Savings Potential and R&D Opportunities for Commercial Refrigeration Equipment (http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_refrig_report_10-09.pdf)	Cost is sum of compressor racks, condensers, sprmkt walk-ins, and 60x display cases, all max tech options; savings are reduced to account for load reduction (derived from Table 5-12)	
DOE/Navigant (2009), Energy Savings Potential and R&D Opportunities for Commercial Refrigeration Equipment (http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_refrig_report_10-09.pdf)	Table 5-27, Page 154, see "max tech"	
Department of Energy, "Energy Conservation Program: Energy Conservation Standards for Residential Refrigerators, Refrigerator-Freezers, and Freezers" Federal Register (9/2010) and supporting documentation	Arthur D. Little reported savings of approximately 25 % compared to single-speed motor systems in 1999; Tecumseh Products Company demonstrated that energy savings of 15%. An average of the estimates of this cost increase provided by the manufacturers weighted by manufacturer market share is near $56; an additional $30 for addition of an electronic control system Using average of two studies: 20% at $86 cost	
LEDLight.com, "Standard Appliance LED Light Bulb", http://www.ledlight.com/standard-appliance-led-light.aspx	Plastic assembly so it is more durable than a regular light bulb and it only consumes 1/10 the power so it is more energy efficient" and current price is listed at $7.99 each. 90% reduction applied to refrigerator lighting load: -1%	
Department of Energy, "Energy Conservation Program: Energy Conservation Standards for Residential Refrigerators, Refrigerator-Freezers, and Freezers" Federal Register (9/2010) and supporting documentation	All data taken from TSD and supporting engineering and national impact estimates	
Department of Energy, "Energy Conservation Program: Energy Conservation Standards for Residential Refrigerators, Refrigerator-Freezers, and Freezers" Federal Register (9/2010) and supporting documentation	Represents 1 step down in fridge size for equipment classes 3 & 5 (as per equations 5.4.12). Change in cost captured from Kenmore ENERGY STAR 21 vs. 18.2 sq. ft. top-mounted freezer price difference 6/12	
Navigant Consulting Energy Savings Potential and R&D Opportunities for Commercial Refrigeration Final Report. Department of Energy (2009)	Performance average of table 6-1, cost	
Brown, D., Dirks, J., Fernandez, N., & Stout, T. (2010). The Prospects of Alternatives to Vapor Compression Technology for Space Cooling and Food Refrigeration Applications. Pacific Northwest National Laboratory	"The theoretical performance of thermotunneling devices operating near room temperature has been estimated by GE, Borealis, and Tempronics to be in the range of 50% to 80% of Carnot (COP ~3-5)." Represents max-tech improvements to refrigerator but compressor (COP 2.2) replaced with technology limit for themotunneling (COP 3.0)"	
Meier, A. Martinex, M; "Energy Use of Icemaking in Domestic Refrigerators", LBNL-39183 (1996)	"The refrigerators' gross electricity use increased about IO%, or 100 kWh/yr, due to operation of the automatic icemaker...The net energy difference, i.e., after subtracting the energy needed to make ice manually, is roughly 55 kWh/yr." 55 kWh/year corresponds to ~ 9.5% of today's typical refrigerator of 585 kWh/year; current Kenmore icemaker kit priced at $110 (6/12)	
Department of Energy, "Energy Conservation Program: Energy Conservation Standards for Residential Refrigerators, Refrigerator-Freezers, and Freezers" Federal Register (9/2010) and supporting documentation	All data taken from TSD and supporting engineering and national impact estimates	
Department of Energy, "Energy Conservation Program: Energy Conservation Standards for Residential Refrigerators, Refrigerator-Freezers, and Freezers" Federal Register (9/2010) and supporting documentation	Table 5-A.3.10, 11, 13, 14 Averaged data to get 10% savings improvement, $37 cost	
Department of Energy, "Energy Conservation Program: Energy Conservation Standards for Residential Refrigerators, Refrigerator-Freezers, and Freezers" Federal Register (9/2010) and supporting documentation	"energy consumption can be reduced by three to four percent with adaptive defrost." "DOE used an incremental cost of $8 in the energy analysis for adaptive defrost ($0 if electronics onboard)." Used $8 controller cost, average of 3-4% savings range provided"	

1. Description of the measure	2. Energy savings			3. Price	4. Units & capacity	5. Market description	6. Market size, 2030	7. Site use	8. Source use	9. Max adopt	10. CCE	11. Life	12. Used in scenario?			
	Percent	SD?	Fuel switch?										McK	NAS	Emerg	Tech
R: Minimize cold loss upon refrigerator door opening	16%	Yes		$0	per unit	R: Refrigerator Total	178	412	1,256	215	$0	1	No	No	Yes	No
R: Perform routine dusting of refrigerator heat exchanger coils	3%	Yes		$10	per unit	R: All Refrigerators and Freezers	229	502	1,532	33.7	$3.72	15	Yes	Yes	Yes	Yes
R: Remove replaced refrigera-tors (rather than using as back-up refrigerator)	38%	Yes		$79.53	per unit	R: Refrigerators as Second Units	42.7	5.78	17.6	6.99	$28.58	15	No	No	No	No
R: Retire pre-2010 fridges on accelerated schedule	63%	Yes		$81	per unit	R: Refrigerators Eligible for Early Retirement	0.89	2.68	8.16	-146.9	$1.22	100	No	No	No	No
R: Use linear compressor in refrigerator-freezers	15%			$50	per unit; net of space savings value	R: All Refrigerators and Freezers	229	502	1,532	154	$4.44	15	No	No	No	No
R: Use more efficient (i.e., cur-rently available) compressors	14%			$14.02	per unit	R: All Refrigerators and Freezers	229	502	1,532	140	$1.43	15	No	No	No	No
R: Use most efficient (i.e., max-tech) refrigerators	55%			$116.21	per unit	R: Refrigerator Total	178	412	1,256	669	$1.71	15	Yes	Yes	Yes	Yes
C: Use most efficient high-temperature conveyor-style dish washer	30%			$3,500	per unit	C: Conveyor High Temp Dishwashers	0.20	44.3	96.0	29.0	$1.20	20	No	No	Yes	Yes
C: Use most efficient high-temperature door-style dish washer	33%			$2,100	per unit	C: Door Type High Temp DW	0.03	5.60	11.1	3.71	$1.02	15	No	No	Yes	Yes
C: Use most efficient low-temperature conveyor-style dish washer	30%			$3,500	per unit	C: Conveyor Low Temp Dishwashers	0.20	29.1	47.5	14.3	$2.44	20	No	No	Yes	Yes
C: Use most efficient low-temperature door-style dish washer	36%			$2,000	per unit	C: Door Type Low Temp DW	0.08	10.9	16.4	5.97	$1.41	15	No	No	Yes	Yes
C: Develop condensing single load clothes dryers	14%	Yes		$896.53	per unit	C: Single-Load Coin Op Dryers	0.07	4.74	7.30	1.02	$3.59	11	No	No	Yes	Yes
C: Develop condensing tumble clothes dryers	14%	Yes		$217.77	per unit	C: Tumble Dryers	2.7	58.5	70.5	9.82	$3.60	11	No	No	Yes	Yes
C: Develop dryer exhaust heat recovery for clothes dryers	45%	Yes		$200	per unit	C: Single-Load Coin Op Dryers	0.07	4.74	7.30	3.42	$0.98	1	No	No	No	Yes
C: Develop heat pump clothes dryers	50%			$0	per unit	C: Single-Load Coin Op Dryers	0.07	4.74	4.74	2.32	$0	11	No	No	Yes	Yes
C: Develop microwave clothes dryers	25%			$295	per unit	C: Single-Load Coin Op Dryers	0.07	4.74	7.30	1.60	$0.80	11	No	No	No	Yes
C: Develop nylon bead clothes washers	94%			-$6,000	per unit	C: Comm. Washers and Dryers	6.2	469	526	495	-$4.21	15	No	No	Yes	Yes
C: Increase motor efficiency in single-load clothes washer	10%	Yes		$0	per unit	C: Machine Energy for Single Load Coin Op Washers	0.57	0.39	1.18	0.10	$0	7	No	No	Yes	Yes
C: Recycling waste-water in commercial washers (multi-load and tunnel)	53%	Yes		-$20,803.75	per unit; 20 GPM over 4 machines	C: Hot Water for Both Tunnel Washers and Multi-Load Washers	0.17	237	237	128	-$1.53	15	No	No	No	Yes
C: Switch from multi-load to tunnel	82%			-$121,250	per unit	C: Hot Water for Multi-Load Washers	0.17	233	257	238	-$4.49	15	No	No	No	Yes
C: Use advanced agitation ap-proaches in clothes washer	15%	Yes		$0	per unit	C: Hot Water for Top Loading Coin Op Washers	0.46	3.27	4.16	0.62	$0	7	No	No	No	Yes
C: Use advanced ozone systems for multi-load clothes washers	89%			$7,500	per unit	C: Hot Water for Multi-Load Washers	0.17	233	297	266	$0.26	15	No	No	Yes	Yes
C: Use auto sprayer shutoff in dishwashers	50%	Yes		$4,000	per unit	C: Conveyor Type Dishwashers	0.40	73.4	147	73.7	$1.09	20	Yes	Yes	Yes	Yes
C: Use automatic fill control in clothes washers	15%	Yes		$20	per unit	C: Hot Water for Top Loading Coin Op Washers	0.46	3.27	4.16	0.62	$1.13	7	No	No	No	Yes

Primary sources used	Data used and/or methodology	Other supporting sources
Saidur, R., Masjuki, H. H., Choudhry, I.A. (2000). "Role of Ambient Temperature, Door Opening, Thermostat Setting Position and Their Combined Effect on Refrigerator-Freezer Energy Consumption." *Energy Conservation and Management*, 43(6), 845-854. (http://www.sciencedirect.com/science/article/pii/S0196890401000693)	Annual energy use reduced in test from 2,290 kWh/year to 1,930 kWh/year representing a 16% savings	Department of Energy, "Energy Conservation Program: Energy Conservation Standards for Residential Refrigerators, Refrigerator-Freezers, and Freezers" Federal Register (9/2010) and supporting documentation
Meier, A. Martinex, M; "Energy Use of Icemaking in Domestic Refrigerators", LBNL-39183 (1996)	"None of these studies obtained more than a 6% reduction in energy use." Used average of 0% and 6% as min/max savings estimated; $10 for brush cost from websearch (5/11)	
Department of Energy, "New Opportunities Multiply Savings: Refrigerator Market Report, 2009", 2009	By 2005 22% of homes had a second refrigerator; 10% of new purchases keep their old refrigerators as second units. Supporting calculations in tool	
Department of Energy, "New Opportunities Multiply Savings: Refrigerator Market Report, 2009", 2009	730 kWh of savings off a base of 1165 kWh (i.e., 63%) $134 of economic costs of early retirement	
Department of Energy, "Energy Conservation Program: Energy Conservation Standards for Residential Refrigerators, Refrigerator-Freezers, and Freezers" Federal Register (9/2010) and supporting documentation	EER 7.5 from table 3.3.10; cost estimated form web search for existing products with value added for internal refrigerator space	
Department of Energy, "Energy Conservation Program: Energy Conservation Standards for Residential Refrigerators, Refrigerator-Freezers, and Freezers" Federal Register (9/2010) and supporting documentation	Tables 5-A.3.2 (and .4, .6) (and also p.5-46) Averaged maximum compressor improvements over all refrigerator types	
Department of Energy, "Energy Conservation Program: Energy Conservation Standards for Residential Refrigerators, Refrigerator-Freezers, and Freezers" Federal Register (9/2010) and supporting documentation	All measure tables drawn from engineering and national impact analysis from TSD and supporting material	
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 4-22, page 104, see "Conveyor HT	
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 4-22, page 104, see "Door-Type HT"	
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 4-22, page 104, see "Conveyor LT"	
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 4-22, page 104, see "Door-Type LT"	
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 8-36, page 272, see "inlet air preheat, condensing mode"	Cost assumes 5-year payback based on annual savings of $172.51
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 8-37, page 273, see "inlet air preheat, condensing mode"	Cost assumes 5-year payback based on annual savings of $41.73
Navigant Consulting; "Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances" (2009)	Tables 8-32 & 8-36	
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 8-36, page 272, see "heat pump". Cost estimated from average of prices in table 8-33, converted to US dollars.	
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 8-36, page 272, see "microwave"	
"Misra, A., Pimphalkhute, H., Murthi, S. & Kamdar, T. Pricing strategy: Waterless Washing Machine (2010). Xeros website. Desroches, L.-B. et al. Max Tech and Beyond (2011)"	"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." Used Weighted average of savings for full cycle	
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 8-23, page 257, see "increased motor efficiency"	
Savings: Navigant Consulting; "Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances" (2009). Cost: RMC Water and Environment; Integrated Water Resources Program Report, Appendix H (12/2007)	Table 8-24 & 8-25	
Goetzler, W., Zogg, R., Burgos, J., Hiraiwa, H. & Young, J. Energy Savings Potential and RD & D Opportunities for Commercial Building HVAC Systems. Navigant Consulting (2011). Garbarine, R. Commercial Property / New Jersey ; In Piscataway, a Central Laundry for Region Hiltons. New York Times 5 (1999)	Savings from Goetzler: Tables 8-24, 8-25 Cost from New York Times payback calculation 82% savings, $120,000 savings per establishment	
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 8-23, page 257, see "advanced agitation"	
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 8-25, page 258, see "advanced ozone system"	"An Introduction to the Use of Ozone in the Laundry Industry", http://www.cwtozone.com/uploads/SalesDocs/Markets/Laundry/EcoTex/Sales%20Sheets-individual/Intro%20to%20EcoTex%20RR%20032808.pdf
Hobart Cle Warewasher Opti-Rinse, http://www.hobartcorp.com/products/warewashing/conveyor-type/cle-warewasher/	"Exclusive Opti-Rinse™ technology for 50% less energy and water usage than comparable models"	
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 8-23, page 257, see "automatic fill control"	Control is available in residential units; approximate cost based on replacement of water level control sensor for *residential* unit

1. Description of the measure	2. Energy savings			3. Price	4. Units & capacity	5. Market description	6. Market size, 2030	7. Site use	8. Source use	9. Max adopt	10. CCE	11. Life	12. Used in scenario?			
	Percent	SD?	Fuel switch?										McK	NAS	Emerg	Tech
C: Use direct-drive motors in single load clothes washers	60%			$132	per unit	C: Hot Water for Top Loading Coin Op Washers	0.46	3.27	4.16	2.45	$1.90	7	No	No	No	No
C: Use improved cycle termination in clothes dyers	15%	Yes		$21	per unit	C: Single-Load Coin Op Dryers	0.07	4.74	7.30	1.09	$0.08	11	No	No	Yes	Yes
C: Use improved drum design in clothes washer	20%	Yes		$768.45	per unit	C: Single-Load Coin Op Dryers	0.07	4.74	7.30	1.46	$2.64	7	No	No	Yes	Yes
C: Use improved water extraction in clothes washer	25%	Yes		$960.57	per unit	C: Single-Load Coin Op Dryers	0.07	4.74	7.30	1.82	$2.64	7	No	No	Yes	Yes
C: Use low-temperature detergent in multi-load clothes washers	20%	Yes		$996.86	per unit	C: Hot Water for Multi-Load Washers	0.17	233	297	63.3	$0.65	1	No	No	No	Yes
C: Use low-temperature detergent in single load clothes washers	20%	Yes		$94.60	per unit	C: Hot Water for Single Load Coin Op Washers	0.57	3.50	4.46	0.95	$13.94	1	No	No	No	Yes
C: Use more efficient (i.e., currently available) tunnel washers	60%			$1,200,000	per unit	C: Tunnel Washers	0	3.41	3.41	2.05	$9.93	11	No	No	Yes	Yes
C: Use petroleum-based dry cleaning	58%			$52,500	per unit	C: Dry Cleaning	0.05	49.3	53.7	36.8	$4.23	15	Yes	Yes	Yes	Yes
C: Use spray-rinse in top-loading washers	50%			$182.06	per unit	C: Hot Water for Single Load Coin Op Washers	0.57	3.50	3.50	1.73	$4.47	7	No	No	No	Yes
C: Use soil sensors in clothes washers	10%	Yes		$100	per unit; 3.8 ft^3 capacity	C: Hot Water for Single Load Coin Op Washers	0.57	3.50	4.46	0.44	$9.85	7	No	No	Yes	Yes
R: Advanced washer-dryer pair	40%	Yes		$1,800	per pair	R: Clothes Washing, Drying, and Water Heating	120	620	1,064	426	$34.11	10	No	No	Yes	Yes
R: Develop condensing clothes dryers	14%	Yes		$73.24	per unit	R: Gas dryer	24.4	82.6	216	30.3	$3.46	12	No	No	Yes	No
R: Develop dryer exhaust heat recovery for clothes dryers	45%	Yes		$200	per unit	R: Dryer Total	120	391	1,019	583	$10	1	No	No	Yes	Yes
R: Develop heat pump clothes dryers (no FS)	50%			$731	per unit	R: Electric dryer	95.2	309	942	416	$11.45	12	No	No	Yes	Yes
R: Develop microwave clothes dryers	25%			$295	per unit	R: Electric dryer	95.2	309	808	129	$15.47	12	No	No	No	No
R: Develop modulating gas clothes dryers	15%			$31.86	per unit	R: Dryer Total	120	391	391	23.5	$10.08	12	No	No	Yes	Yes
R: Develop nylon-bead clothes washers	83%			$558.25	per unit	R: Clothes Washing, Drying, and Water Heating	120	620	1,348	998	$3.68	12	No	No	No	Yes
R: Develop zeolithic dishwashers	39%			$486	per unit	R: Dishwash Total	98.5	111	340	114	$26.73	13	No	No	Yes	Yes
R: Eliminate heated dry in dishwashers	7%	Yes		$0	per unit	R: Dishwash Total	98.5	111	340	24.6	$0	1	Yes	Yes	Yes	Yes
R: hang-dry laundry	100%	Yes		$0	per unit	R: Dryer Total	120	391	1,019	1,040	$0	12	No	No	No	No
R: Use high-speed water extractor in clothes washers	25%	Yes		$79.01	per unit	R: Dryer Total	120	391	1,025	222	$2.58	12	Yes	Yes	Yes	Yes
R: Use improved cycle termination in clothes dyers	15%	Yes	FS	$21	per unit	R: Dryer Total	120	391	1,025	159	$0.99	12	Yes	Yes	Yes	Yes
R: Use improved hydraulic efficiency in dishwasher	25%	Yes		$0	per unit	R: Dishwash Total	98.5	111	340	69.5	$0	12	Yes	Yes	Yes	Yes
R: Use low-temperature detergent in clothes washers	20%	Yes		$10.80	per unit	R: Hot Water for Clothes Washing	120	200	326	73.7	$4.31	1	No	No	No	Yes
R: Use low-temperature detergent in dish washers	20%	Yes		$10.80	per unit	R: Hot Water for Dishwashing	98.5	127	196	28.9	$10.04	1	No	No	No	Yes
R: Use more efficient (i.e., currently available) front load clothes washer	43%			$0	per unit	R: Front Loading Washers	18.1	15.1	46.0	21.5	$0	11	Yes	Yes	Yes	Yes

Primary sources used	Data used and/or methodology	Other supporting sources
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 8-23, page 257, see "direct drive motor"	
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 8-36, page 272, see "improved cycle termination"	Cost estimated from part currently in use in residential units.
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 8-23, page 257, see "improved drum design"	Cost assumes 3-year payback from annual savings of $246
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 8-23, page 257, see "improved water extraction"	Cost assumes 3-year payback based on annual savings of $308.06
Navigant Consulting; "Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances" (2009)	Table 8-24 & 8-25	Chemical and Engineering News, Vol. 85 #5, Jan. 2007
Navigant Consulting; "Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances" (2009)	Table 8-24 & 8-25	Chemical and Engineering News, Vol. 85 #5, Jan. 2007
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 8-27, page 259, see "advanced tunnel washer"	
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Figure 8-33, page 281. Energy savings is percent difference between PCI and Petroleum	EPA, "Case Study: Liquid Carbon Dioxide (CO_2) Surfactant System For Garment Care", http://www.epa.gov/dfe/pubs/garment/lcds/micell.htm
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 8-23, page 257, see "spray rinse technology"	Cost assumes 5-year payback based on annual savings of $34.81
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 8-23, page 257, see "adaptive control system"	
Personal communication: Bouza, DOE (1/2012)		
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 8-36, page 272, see "inlet air preheat, condensing mode"	Cost assumes 5-year payback based on annual savings of $14.29
Navigant Consulting; "Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances" (2009)	Tables 8-32 & 8-36	
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 8-36, page 272, see "heat pump". Cost estimated from average of prices in table 8-33, converted to US dollars.	
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 8-36, page 272, see "microwave"	
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 8-36, page 272, see "modulating gas burner"	Cost assumes 5-year payback of savings of $6.09 per year
Desroches, L. et al. (2011). MaxTech and Beyond, Maximizing Appliance and Equipment Efficiency by Design, http://efficiency.lbl.gov/drupal.files/ees/MTAB%20Final%20LBNL%20Report.pdf	Page 19, Table 3	
Siemens product description (available in the UK)	Siemens: 0.83 kWh/cycle. AHAM blog: in 1991 the average dishwasher consumed 2.67 kilowatts (kWh) per cycle and by 2010 it was only 1.37 kWh/ cycle	
ACEEE, "Dishwashing", http://www.aceee.org/consumer/dishwashing	"An electric heating element is generally used to dry dishes at the end of the final rinse cycle, consuming about 7% of dishwasher energy use."	
First principles: 100% savings at zero marginal cost (assuming same time invest to hang & fold as dry & fold)		
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 8-23, page 257, see "improved water extraction"	Cost assumes 3-year payback based on annual savings of $25.69
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 8-36, page 272, see "improved cycle termination"	Cost is approx. price of replacement temperature sensor
Dries, John, (2008), "Improving Dishwasher Efficiency", http://www.appliancemagazine.com/editorial.php?article=1978	"Assuming that the upper and lower spray-arms operate the same amount of time, the average power consumption of this wash system went from 208 to 155 W, a reduction in overall power consumption of 25%, while improving the hydraulic washing power of the dishwasher—all without any increase to product cost or complexity."	
Navigant Consulting; "Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances" (2009)	Table 8-24 & 8-25	Chemical and Engineering News, Vol. 85 #5, Jan. 2007
Navigant Consulting; "Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances" (2009)	Table 8-24 & 8-25	Chemical and Engineering News, Vol. 85 #5, Jan. 2007
Energy Efficient and Smart Appliance Agreement of 2010, AHAM power point	Savings listed in agreement	

1. Description of the measure	2. Energy savings			3. Price	4. Units & capacity	5. Market description	6. Market size, 2030	7. Site use	8. Source use	9. Max adopt	10. CCE	11. Life	12. Used in scenario?			
	Percent	SD?	Fuel switch?										McK	NAS	Emerg	Tech
R: Use more efficient (i.e., currently available) top load clothes washer	37%			$0	per unit	R: Top Loading Washers	102	13.2	40.4	0	$0	11	Yes	Yes	Yes	Yes
R: Use more efficient (i.e., currently available) vented electric clothes dryer	5%			$0	per unit	R: DV Total	95.2	309	942	0	$0	12	No	No	Yes	Yes
R: Use more efficient (i.e., currently available) vented gas clothes dryer	5%			$0	per unit	R: DS_WASH	24.4	82.6	82.6	0.22	$0	12	No	No	Yes	Yes
R: Use soil sensors in dishwashers	25%	Yes		$30	per unit	R: Dishwash Total	98.5	111	340	73.8	$2.62	11	Yes	Yes	No	Yes
R: Use soil sensors in clothes washers	10%	Yes		$100	per unit; 3.8 ft^3 capacity	R: Hot Water for Clothes Washing	120	200	326	13.5	$37.71	11	No	No	Yes	Yes
C: Adapt current generation (EF 2.2) heat-pump water heaters (HPWH) to commercial uses (FS only)	64%			$1,075	per unit; 120 gallons	C: Small WH Needs (Electric)	1.3	57.7	176	74.0	$0.82	30	No	No	Yes	Yes
C: Adapt current generation (EF 2.2) heat-pump water heaters (HPWH) to commercial uses (no FS)	50%			$3,000	per unit	C: All Comm Elec Storage WH	1.7	46.6	142	56.6	$5.63	16	No	No	Yes	Yes
C: Advance air-source heat-pump water-heater (ASHPWH) to its technology limit (FS only)	83%		FS	$5,698	per unit	C: All Comm Gas Storage WH	1.9	294	294	138	$5.55	10	No	No	No	No
C: Advance air-source heat-pump water-heater (ASHPWH) to its technology limit (no FS)	79%			$7,505	per unit	C: All Comm Elec Storage WH	1.7	46.6	142	101	$10.07	10	No	No	No	Yes
C: Advance gas-driven HPWH to its tech limit (FS only)	45%		FS	$32,781.95	per unit	C: All Comm Elec Storage WH	1.7	46.6	142	107	$40.63	10	No	No	No	No
C: Advance gas-driven HPWH to its tech limit (no FS)	64%			$30,974.95	per unit	C: All Comm Gas Storage WH	1.9	294	294	185	$22.19	10	No	No	No	Yes
C: Advance Solar-assisted air-source heat-pump water-heaters to their technology limit (FS only)	88%		FS	$31,477	per unit	C: All Comm Gas Storage WH	1.9	294	294	181	$29.78	10	No	No	No	Yes
C: Advance Solar-assisted air-source heat-pump water-heaters to their technology limit (no FS)	81%			$33,284	per unit	C: All Comm Elec Storage WH	1.7	46.6	142	106	$51.67	10	No	No	No	Yes
C: Develop advanced HPWH (COP 5.1, EF 4.4) (no FS)	72%			$28,031	per unit	C: All Comm Elec Storage WH	1.7	46.6	142	47.3	$34.85	30	No	No	Yes	Yes
C: Develop gas absorption heat-pump water heaters	40%			$13,500	per unit	C: All Comm Gas Storage WH	1.9	294	294	115	$15.05	11	No	No	No	Yes
C: Employ drain-water waste-heat recovery	30%	Yes		$8,000	per unit	C: All Comm Storage WH	3.8	358	456	125	$19.20	12	No	No	Yes	Yes
C: Recover waste heat from air conditioning for water heating	11%	Yes		$3,320	per unit	C: Water Heating in Hottest Two Climates	3.1	295	375	23.4	$25.35	16	No	No	No	No
C: Reduce installed cost of solar water heating systems-indirect active, elec. BU (no FS)	61%	Yes		$51,805	per unit; 1000 square feet absorber	C: All Comm Elec Storage WH	1.7	46.6	142	83.1	$68.80	10	No	No	No	Yes
C: Reduce installed cost of solar water heating systems-indirect active, gas BU (FS only)	61%	Yes	FS	$51,805	per unit; 1000 square feet absorber	C: All Comm Elec Storage WH	1.7	46.6	142	122	$46.17	12	No	No	No	No
C: Reduce installed cost of solar water heating systems-indirect active, gas BU (no FS)	61%	Yes	FS	$16,059.55	per unit; 310 square feet absorber	C: All Comm Gas Storage WH	1.9	294	294	165	$11.78	12	No	No	Yes	Yes
C: Use condensing gas water heaters	22%			$3,285	per unit	C: All Comm Gas Storage WH	1.9	294	294	87.2	$5.78	11	No	Yes	Yes	Yes
C: Use heat pump water heaters in commercial kitchens (i.e., for hot water and cooling)	45%			$3,500	per unit	C: Commercial Kitchens	0.42	119	216	92.5	$0.96	15	No	No	No	Yes

Primary sources used	Data used and/or methodology	Other supporting sources
Energy Efficient and Smart Appliance Agreement of 2010, AHAM power point	Savings listed in agreement	
Energy Efficient and Smart Appliance Agreement of 2010, AHAM power point	Savings listed in agreement	
Energy Efficient and Smart Appliance Agreement of 2010, AHAM power point	Savings listed in agreement	
ACEEE, "Dishwashing", http://www.aceee.org/consumer/dishwashing		
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 8-23, page 257, see "adaptive control system"	
U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE). (2011, March 30). Residential Heating Products Final Rule Analytical Tools. Retrieved from Appliance & Equipment Standards: http://www1.eere.energy.gov/buildings/appliance_standards/residential/heating_products_fr_spreadsheets.html	DOE 2011: Used 120 gal HPWH at 2.27 EF. $1022 used for price of baseline electric, and $2097 used for price of best 120 gallon HPWH, based on scaling 50-gallon. Assumed 1.5 water heaters per building.	
Goetzler, W., Zogg, R., Burgos, J., Hiraiwa, H. & Young, J. Energy Savings Potential and RD & D Opportunities for Commercial Building HVAC Systems. Navigant Consulting (2011). Tables 6-11, 6-24	Cost taken from google shopping search, average of 12 venders (installed); scaled to commercial capacity; EF 2.38 50% savings, $2,700 incremental to tank cost	Navigant Consulting Research and Development Roadmap for Water Heating. Department of Energy (2011).
Zhang, J., Wang, R.Z. & Wu, J.Y. System optimization and experimental research on air source heat pump water heater. Applied Thermal Engineering 27, 1029-1035 (2007).	Table 3 yields seasonally averaged COP of ~4.8, Cost from 80%/20% ratio of investment cost/energy cost	Xu, G., Zhang, X. & Deng, S. A simulation study on the operating performance of a solar–air source heat pump water heater. Applied Thermal Engineering 26, 1257-1265 (2006).
Zhang, J., Wang, R.Z. & Wu, J.Y. System optimization and experimental research on air source heat pump water heater. Applied Thermal Engineering 27, 1029-1035 (2007).	Table 3 yields seasonally averaged COP of ~4.8, Cost from 80%/20% ratio of investment cost/energy cost	Xu, G., Zhang, X. & Deng, S. A simulation study on the operating performance of a solar–air source heat pump water heater. Applied Thermal Engineering 26, 1257-1265 (2006).
Zhang et. al. "Analysis on the heating performance of a gas engine driven air to water heat pump based on a steady-state model", Energy Conversion and Management 46 (2005) 1714–1730	Figure 5 shows the PER: "The primary energy ratio (PER) is defined as the heat gained divided by the input energy." Cost taken as 64% "investment" cost, 36% operating at 6 MMBTU/year + $50 service biannually. Implies: $2,880 cost improvement from COP 0.59 to 1.67	Hepbasli, A. & Kalinci, Y. A review of heat pump water heating systems. Renewable and Sustainable Energy Reviews 13, 1211-1229 (2009).
Zhang et. al. "Analysis on the heating performance of a gas engine driven air to water heat pump based on a steady-state model", Energy Conversion and Management 46 (2005) 1714–1730	Figure 5 shows the PER: "The primary energy ratio (PER) is defined as the heat gained divided by the input energy." Cost taken as 64% "investment" cost, 36% operating at 6 MMBTU/year + $50 service biannually. Implies: $2,880 cost improvement from COP 0.59 to 1.67	Hepbasli, A. & Kalinci, Y. A review of heat pump water heating systems. Renewable and Sustainable Energy Reviews 13, 1211-1229 (2009).
Li. Et.al, "Experimental performance analysis on a direct-expansion solar-assisted heat pump water heater"; Applied Thermal Engineering 27 (2007) 2858–2868	The seasonal average value of the COP and the collector efficiency was measured as 5.25 and 1.08, respectively. Used COP provided for performance; estimated cost using capital/operating cost target provided	Guoying, X; Ziaosong, Z; Lei, Y; Shiming, D.; "Performance of a solar-air source heat pump system for water heating on different weather conditions" IEEE (2009)
Li. Et.al, "Experimental performance analysis on a direct-expansion solar-assisted heat pump water heater"; Applied Thermal Engineering 27 (2007) 2858–2868	The seasonal average value of the COP and the collector efficiency was measured as 5.25 and 1.08, respectively. Used COP provided for performance; estimated cost using capital/operating cost target provided	Guoying, X; Ziaosong, Z; Lei, Y; Shiming, D.; "Performance of a solar-air source heat pump system for water heating on different weather conditions" IEEE (2009)
r744.com, "Eco Cute Update: new line-up with 5.1 COP by Panasonic, upgrades by Hitachi and domestic statistics in Japan" (2011) Zogg, Robert, et al. "CO_2 Heat pump water heaters." ASHRAE Journal (Nov, 2007)	"achieve a COP of 5.1"; The current retail price of this Eco Cute is 814,653 Yen (~€7,940.12)	Navigant Consulting Research and Development Roadmap for Water Heating. Department of Energy (2011).
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Table 6-11, page 183, see "heat pump water heater" and Table 6-21, page 209. See "heat pump water heater" for cost and use midpoint of range given	
Goetzler, W., Zogg, R., Burgos, J., Hiraiwa, H. & Young, J. Energy Savings Potential and RD & D Opportunities for Commercial Building HVAC Systems. Navigant Consulting (2011)	Tables 6-11, 6-20, 30% savings at a cost of $300-$500/4 gpm, assume ~15-20 drains per water heater to capture benefits	GFX case studies
Navigant Consulting. (2009). Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances. Washington, D.C.: Building Technology Program, Department of Energy. http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Energy savings and cost estimates from Navigant Tables 6-11 and 6-19, respectively.	
Itron, Inc.; "California Center for Sustainable Energy Solar Water Heating Pilot Program" (3/2011). Federal Energy Management Program, "Solar Water Heating with Low-Cost Plastic Systems" (1/2012)	Thorough analysis of multiple sources; represents aggregate savings net of parasitic loads. Costs represent program targets informed by roadmap (in preparation)	Hudon, Burch "Solar Water Heating Roadmap" (in preparation)
Itron, Inc.; "California Center for Sustainable Energy Solar Water Heating Pilot Program" (3/2011). Federal Energy Management Program, "Solar Water Heating with Low-Cost Plastic Systems" (1/2012)	Thorough analysis of multiple sources; represents aggregate savings net of parasitic loads. Costs represent program targets informed by roadmap (in preparation)	Hudon, Burch "Solar Water Heating Roadmap" (in preparation)
Itron, Inc.; "California Center for Sustainable Energy Solar Water Heating Pilot Program" (3/2011). Federal Energy Management Program, "Solar Water Heating with Low-Cost Plastic Systems" (1/2012)	Thorough analysis of multiple sources; represents aggregate savings net of parasitic loads. Costs represent program targets informed by roadmap (in preparation)	Hudon, Burch "Solar Water Heating Roadmap" (in preparation)
Navigant/DOE (2009): Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances, http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf	Energy savings comes from average of Tables 6-11 and 6-21. Cost comes from Table 6-21: max cost of $8,300 minus $5015 of standard commercial gas storage water heater	
Washington State University (2005), "Energy Efficiency Fact Sheet: Commercial Water Heaters"		Estimated new unit cost is $5,000, $3,500 more than a traditional water heater

1. Description of the measure	2. Energy savings			3. Price	4. Units & capacity	5. Market description	6. Market size, 2030	7. Site use	8. Source use	9. Max adopt	10. CCE	11. Life	12. Used in scenario?			
	Percent	SD?	Fuel switch?										McK	NAS	Emerg	Tech
C: Use most efficient (i.e., max-tech) tankless gas water heats for buildings with small water heating loads	15%			$1,895	per unit	C: Small WH Needs	0.66	219	279	61.8	$1.55	12	No	No	No	Yes
C: Use residential heat pump water heaters for buildings with larger hot water demand (FS only)	71%		FS	$1,090.58	per unit	C: All Comm Gas Storage WH	1.9	294	294	136	$1.02	11	No	No	No	No
C: Use residential heat pump water heaters for buildings with low hot water demand (FS only)	74%		FS	-$425	per unit; 120 gallons	C: Small WH Needs (Gas)	1.4	156	156	41.6	-$0.93	11	No	No	No	No
C: Wrap water heaters with insulation blankets	40%	Yes		$20	per unit	C: Commercial Water Heater Standby Losses	3.8	10.7	13.7	5.40	$0.75	12	No	No	No	Yes
R: Advance air-source heat-pump water-heater (ASHPWH) to its technology limit (FS only)	86%		FS	$9,331.67	per unit	R: Gas water heating	72.7	1,399	1,399	728	$69.38	10	No	No	No	No
R: Advance air-source heat-pump water-heater (ASHPWH) to its technology limit (no FS)	79%			$9,858.67	per unit	R: Electric water heating	63.2	535	1,631	1,173	$67.47	10	No	No	No	Yes
R: Advance gas-driven heat-pump water-hears to their technology limit (FS only)	45%		FS	$2,328	per unit; 50 gallon capacity	R: Electric water heating	63.2	535	1,631	1,203	$9.81	10	No	No	No	No
R: Advance gas-driven heat-pump water-hears to their technology limit (no FS)	64%			$1,801	per unit; 50 gallon capacity	R: Gas water heating	72.7	1,399	1,399	813	$13.40	10	No	No	No	Yes
R: Advance Solar-assisted air-source heat-pump water-heaters to their technology limit (FS only)	88%		FS	$3,303	per unit	R: Gas water heating	72.7	1,399	1,399	761	$33	10	No	No	No	Yes
R: Advance Solar-assisted air-source heat-pump water-heaters to their technology limit (no FS)	81%			$3,830	per unit	R: Electric water heating	63.2	535	1,631	1,189	$24.09	10	No	No	No	Yes
R: Develop advanced HPWH (COP 5.1, EF 4.4) (no FS)	74%			$9,948	per unit	R: Electric water heating	63.2	535	1,631	1,094	$38.68	13	No	No	Yes	Yes
R: Develop reverse-cycles chillers for commercial buildings	63%			$0.94	per square foot	R: Waterheating with tanks	103,945	692	881	484	$10.45	20	No	No	No	No
R: Develop reverse-cycles chillers for multi family homes	63%			$677	per unit; 20 tons per building	R: Multi family hot water	32.0	328	527	291	$4.82	15	No	No	No	No
R: Develop gas-powered heat pump water heaters (e.g., absorption, gas-engine) (no FS)	61%			$1,436	per unit	R: Gas water heating	72.7	1,399	1,399	707	$11.22	11	No	No	No	Yes
R: Increase insulation in oil-fueled water heaters	15%	Yes		$53	per unit	R: LPG and Distillate hot water	4.4	88.9	89.8	11.7	$1.30	12	No	No	Yes	No
R: Install drain-water heat-recovery in bathrooms	35%	Yes		$1,165	per unit	R: HW in Bathrooms	141	907	1,399	426	$23.35	12	No	No	No	Yes
R: Install drain-water heat-recovery in clothes washers	35%	Yes		$1,265	per unit	R: Hot Water for Laundry	141	414	638	208	$62.55	12	No	No	Yes	Yes

Primary sources used	Data used and/or methodology	Other supporting sources
Navigant Consulting. (2009). Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances. Washington, D.C.: Building Technology Program, Department of Energy. http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE). (2011, March 30). Residential Heating Products Final Rule Analytical Tools. Retrieved from Appliance & Equipment Standards: http://www1.eere.energy.gov/buildings/appliance_standards/residential/heating_products_fr_spreadsheets.html	Energy savings from Navigant. Table 6-21. Cost from DOE 2011: Large (>55 gal) storage. Does not include gas access and plumbing costs.	
Goetzler, W., Zogg, R., Burgos, J., Hiraiwa, H. & Young, J. Energy Savings Potential and RD & D Opportunities for Commercial Building HVAC Systems. Navigant Consulting (2011). Tables 6-11, 6-24	Cost taken from google shopping search, average of 12 venders (installed); scaled to commercial capacity, EF 2.38 Implies: 70% savings, $2,700 incremental to tank cost	Navigant Consulting Research and Development Roadmap for Water Heating. Department of Energy (2011).
U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE). (2011). Water Heater Final Rule Analytical Tools. Retrieved from Appliance & Equipment Standards: http://www1.eere.energy.gov/buildings/appliance	Assumed two large water heaters for baseline; energy savings based on residential EF correct for small commercial	
Navigant Consulting. (2009). Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances. Washington, D.C.: Building Technology Program, Department of Energy. http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_appliances_report_12-09.pdf. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE). (2011, March 30). Residential Heating Products Final Rule Analytical Tools. Retrieved from Appliance & Equipment Standards: http://www1.eere.energy.gov/buildings/appliance_standards/residential/heating_products_fr_spreadsheets.html	Energy savings of 40% from Tables 6-11 in the Navigant reference. Cost from DOE 2011.	
Zhang, J., Wang, R.Z. & Wu, J.Y. System optimization and experimental research on air source heat pump water heater. Applied Thermal Engineering 27, 1029-1035 (2007).	Table 3 yields seasonally averaged COP of ~4.8, Cost from 80%/20% ratio of investment cost/energy cost	Xu, G., Zhang, X. & Deng, S. A simulation study on the operating performance of a solar–air source heat pump water heater. Applied Thermal Engineering 26, 1257-1265 (2006).
Zhang, J., Wang, R.Z. & Wu, J.Y. System optimization and experimental research on air source heat pump water heater. Applied Thermal Engineering 27, 1029-1035 (2007).	Table 3 yields seasonally averaged COP of ~4.8, Cost from 80%/20% ratio of investment cost/energy cost	Xu, G., Zhang, X. & Deng, S. A simulation study on the operating performance of a solar–air source heat pump water heater. Applied Thermal Engineering 26, 1257-1265 (2006).
Zhang et. al. "Analysis on the heating performance of a gas engine driven air to water heat pump based on a steady-state model", Energy Conversion and Management 46 (2005) 1714–1730	Figure 5 shows the PER: "The primary energy ratio (PER) is defined as the heat gained divided by the input energy." Cost taken as 64% "investment" cost, 36% operating at 6 MMBTU/year + $50 service biannually. Implies: $2,880 cost improvement from COP 0.59 to 1.67	Hepbasli, A. & Kalinci, Y. A review of heat pump water heating systems. Renewable and Sustainable Energy Reviews 13, 1211-1229 (2009).
Zhang et. al. "Analysis on the heating performance of a gas engine driven air to water heat pump based on a steady-state model", Energy Conversion and Management 46 (2005) 1714–1730	Figure 5 shows the PER: "The primary energy ratio (PER) is defined as the heat gained divided by the input energy." Cost taken as 64% "investment" cost, 36% operating at 6 MMBTU/year + $50 service biannually. Implies: $2,880 cost improvement from COP 0.59 to 1.67	Hepbasli, A. & Kalinci, Y. A review of heat pump water heating systems. Renewable and Sustainable Energy Reviews 13, 1211-1229 (2009).
Li. Et.al, "Experimental performance analysis on a direct-expansion solar-assisted heat pump water heater"; Applied Thermal Engineering 27 (2007) 2858–2868	The seasonal average value of the COP and the collector efficiency was measured as 5.25 and 1.08, respectively." Used COP provided for performance; estimated cost using capital/operating cost target provided	Guoying, X; Ziaosong, Z; Lei, Y; Shiming, D.; "Performance of a solar-air source heat pump system for water heating on different weather conditions" IEEE (2009)
Li. Et.al, "Experimental performance analysis on a direct-expansion solar-assisted heat pump water heater"; Applied Thermal Engineering 27 (2007) 2858–2868	The seasonal average value of the COP and the collector efficiency was measured as 5.25 and 1.08, respectively." Used COP provided for performance; estimated cost using capital/operating cost target provided	Guoying, X; Ziaosong, Z; Lei, Y; Shiming, D.; "Performance of a solar-air source heat pump system for water heating on different weather conditions" IEEE (2009)
r744.com, "Eco Cute Update: new line-up with 5.1 COP by Panasonic, upgrades by Hitachi and domestic statistics in Japan" (2011). Zogg, Robert, et al. "CO_2 Heat pump water heaters." ASHRAE Journal (Nov, 2007)	"achieve a COP of 5.1"; The current retail price of this Eco Cute is 814,653 Yen (~€7,940.12). EF 3.56 (converted from COP 5.1); using provided cost assuming 1-to-1 drop in for resi unit	Navigant Consulting Research and Development Roadmap for Water Heating. Department of Energy (2011).
Heller, J. & Cejudo, C. Reverse Cycle Chillers for Multifamily Buildings in the Pacific Northwest : Phase I Final Report. Bonneville Power Administration (2009)	Used same percent savings and cost as multi-family measure	
Heller, J. & Cejudo, C. Reverse Cycle Chillers for Multifamily Buildings in the Pacific Northwest : Phase I Final Report. Bonneville Power Administration (2009)	The savings from this alternative design are about 1,700 kWh/yr per unit with an expected measure life of 15 years. This represents a simple payback of about 4.4 years at a retail electricity cost of $0.09/kWh. Reducing kWh/unit from 2,700 to 1,000 with indicated payback	
Navigant Consulting Research and Development Roadmap for Water Heating. Department of Energy (2011).	Performance target from Roadmap; Robur price list for air-water gas absorption heat pump (40 kW) indicates 11,480 euros ($14,586) (www.lhprotrade.com/getcatfile.php?w=18). Scaling linearly with capacity gives: a 4.5 kW unit cost of $1641. Adding median installation cost of a condensing boiler ($874) gives a total cost: $2515. 51% savings (0.59 -> 1.2 EF)	
U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE). (2011, March 30). Residential Heating Products Final Rule Analytical Tools. Retrieved from Appliance & Equipment Standards: http://www1.eere.energy.gov/buildings/appliance_standards/residential/heating_products_fr_spreadsheets.html	Cost and energy savings from DOE 2011, Level 0 to Level 5. EF improved from 0.53 to 0.62 (15% savings).	
Home Depot Canada. Accessed January 2012. http://www.homedepot.ca/catalog/drain-water-heat-recovery/173006. CADDET. 1997. Residential waste water heat-recovery. System: GFX. CADDET Newsletter. http://www.gfxtechnology.com/CADDET.pdf.	Cost and energy savings are same as Measure 551.	
Home Depot Canada. Accessed January 2012. http://www.homedepot.ca/catalog/drain-water-heat-recovery/173006. CADDET. 1997. Residential waste water heat-recovery. System: GFX. CADDET Newsletter. http://www.gfxtechnology.com/CADDET.pdf.	Cost and energy savings are same as Measure 551, plus $100 for storage capability	

1. Description of the measure	2. Energy savings			3. Price	4. Units & capacity	5. Market description	6. Market size, 2030	7. Site use	8. Source use	9. Max adopt	10. CCE	11. Life	12. Used in scenario?			
	Percent	SD?	Fuel switch?										McK	NAS	Emerg	Tech
R: Install drain-water heat-recovery in kitchens	35%	Yes		$500	per unit	R: Hot Water for Kitchens	141	571	880	266	$16	12	No	No	Yes	Yes
R: Install night time timers on water heaters	3%	Yes		$40	per unit	R: Hot Water Total	141	2,027	3,127	80.5	$3.84	12	No	No	No	No
R: Lower water heater thermo-stat setting	4%	Yes		$0	per unit; decrease by 15 degrees	R: Hot Water Total	141	2,027	3,127	94.1	$0	12	No	No	Yes	No
R: Reduce installed cost of solar water heating systems-elec. BU - indirect active (no FS)	61%	Yes		$2,900	per home; 48.3 sq. ft. absorber	R: Electric water heating	63.2	535	1,631	920	$12.58	13	No	No	Yes	Yes
R: Reduce installed cost of solar water heating systems-elec. BU - indirect passive (no FS)	45%	Yes		$2,030	per home; 48.3 sq. ft. absorber	R: Electric water heating	63.2	535	1,631	644	$13.92	12	No	No	No	No
R: Reduce installed cost of solar water heating systems-gas BU - indirect active (FS only)	61%	Yes	FS	$2,900	per home; 48.3 sq. ft. absorber	R: Electric water heating	63.2	535	1,631	1,307	$8.59	15	No	No	No	No
R: Reduce installed cost of solar water heating systems-gas BU - indirect active (no FS)	61%	Yes	FS	$2,900	per home; 48.3 sq. ft. absorber	R: Gas water heating	72.7	1,399	1,399	773	$17.66	11	No	No	Yes	Yes
R: Reduce installed cost of solar water heating systems-gas BU - indirect passive (FS only)	44%	Yes	FS	$2,030	per home; 48.3 sq. ft. absorber	R: Electric water heating	63.2	535	1,631	1,186	$6.77	15	No	No	No	No
R: Reduce installed cost of solar water heating systems-gas BU - indirect passive (no FS)	44%	Yes	FS	$2,030	per home; 48.3 sq. ft. absorber	R: Gas water heating	72.7	1,399	1,399	510	$16.03	16	No	No	No	No
R: Use condensing gas water heaters	23%			$814	per unit	R: Gas water heating	72.7	1,399	1,399	192	$19.80	11	No	No	Yes	Yes
R: Use current generation (EF 2.2) HPWH (FS only)	70%		FS	$892	per unit	R: Gas water heating	72.7	1,399	1,399	77.0	$37.05	30	No	No	No	No
R: Use current generation (EF 2.2) HPWH (no FS)	55%			$892	per unit	R: Electric water heating	63.2	535	1,631	974	$3.94	13	No	Yes	Yes	Yes
R: Use drain-water heat recov-ery in showers	35%	Yes		$1,165	per unit	R: Hot Water for Showers	141	509	785	255	$46.79	12	No	No	Yes	Yes
R: Use electric ignition in gas water heaters	8%			$444	per unit	R: Gas water heaters with pilot lights	63.0	1,212	1,212	11.7	$65.98	11	No	No	Yes	No
R: Use electric, faucet-based tankless water heaters	23%			$175	per unit	R: Hot Water for Showers and Faucets	141	1,695	2,540	134	$6.83	12	No	No	No	Yes
R: Use gas-driven heat pump water heaters (FS only)	23%		FS	$1,963	per unit	R: Electric storage water heaters with gas availability	13.0	111	338	131	$12.49	12	No	No	No	No
R: Use low-flow faucets	71%	Yes		-$409.15	per unit	R: High flow water heating for showers/ faucets	84.4	570	879	773	-$1.85	15	No	No	Yes	Yes
R: Use most efficient available oil water heater	22%			$160	per unit	R: LPG and Distillate hot water	4.4	88.9	89.8	0.0	$6.55	12	No	No	Yes	No
R: Use most efficient tankless gas water heater (FS only)	0%	Yes	FS	$2,332	per unit; 199,000 BTU/hr capacity	R: Electric storage water heaters with gas availability	13.0	111	338	203	$9.44	12	No	No	No	Yes

Primary sources used	Data used and/or methodology	Other supporting sources
Home Depot Canada. Accessed January 2012. http://www.homedepot.ca/catalog/drain-water-heat-recovery/173006. CADDET. 1997. Residential waste water heat-recovery. System: GFX. CADDET Newsletter. http://www.gfxtechnology.com/CADDET.pdf.	Cost and energy savings are same as Measure 551, plus $100 for storage capability	
Water heater energy use—and how to save on it" (http://michaelbluejay.com/electricity/waterheaters.html)	"A timer for an old (pre-1998) electric heater costs around $40 and saves about 25kWh/mo. for a family of two using 40 gallons a day with the heater off four to six hours a day, but only 14kWh/mo. for a family of four using 80 gallons a day."	
http://www.aceee.org/consumer/water-heating	All households down 15-deg F; Each 10-deg F reduction in thermostat setting saves 3-5% in WH energy costs. Using average of range (4%) at zero cost	
Itron, Inc.; "California Center for Sustainable Energy Solar Water Heating Pilot Program" (3/2011). Federal Energy Management Program, "Solar Water Heating with Low-Cost Plastic Systems" (1/2012)	Thorough analysis of multiple sources; represents aggregate savings net of parasitic loads. Costs represent program targets informed by roadmap (in preparation)	Hudon, Burch "Solar Water Heating Road-map" (in preparation)
Itron, Inc.; "California Center for Sustainable Energy Solar Water Heating Pilot Program" (3/2011). Federal Energy Management Program, "Solar Water Heating with Low-Cost Plastic Systems" (1/2012)	Thorough analysis of multiple sources; represents aggregate savings net of parasitic loads. Costs represent program targets informed by roadmap (in preparation)	Hudon, Burch "Solar Water Heating Road-map" (in preparation)
Itron, Inc.; "California Center for Sustainable Energy Solar Water Heating Pilot Program" (3/2011). Federal Energy Management Program, "Solar Water Heating with Low-Cost Plastic Systems" (1/2012)	Thorough analysis of multiple sources; represents aggregate savings net of parasitic loads. Costs represent program targets informed by roadmap (in preparation	Hudon, Burch "Solar Water Heating Road-map" (in preparation)
Itron, Inc.; "California Center for Sustainable Energy Solar Water Heating Pilot Program" (3/2011). Federal Energy Management Program, "Solar Water Heating with Low-Cost Plastic Systems" (1/2012)	Thorough analysis of multiple sources; represents aggregate savings net of parasitic loads. Costs represent program targets informed by roadmap (in preparation)	Hudon, Burch "Solar Water Heating Road-map" (in preparation)
Itron, Inc.; "California Center for Sustainable Energy Solar Water Heating Pilot Program" (3/2011). Federal Energy Management Program, "Solar Water Heating with Low-Cost Plastic Systems" (1/2012)	Thorough analysis of multiple sources; represents aggregate savings net of parasitic loads. Costs represent program targets informed by roadmap (in preparation)	Hudon, Burch "Solar Water Heating Road-map" (in preparation)
Itron, Inc.; "California Center for Sustainable Energy Solar Water Heating Pilot Program" (3/2011). Federal Energy Management Program, "Solar Water Heating with Low-Cost Plastic Systems" (1/2012)	Thorough analysis of multiple sources; represents aggregate savings net of parasitic loads. Costs represent program targets informed by roadmap (in preparation)	Hudon, Burch "Solar Water Heating Road-map" (in preparation)
Water Resources Engineering, I. Water Conservation Market Penetration Study. East Bay Municipal Utility District (2002)	Tables 4-7 and 4-9 represents installed faucet aerator base; used to scale nationally; fixture cost ($90 for 5 per home)provided by web search and is net of water savings valued at $8/1000 gallons	
Fitzpatrick, S, Murray, M; "GE Heat Pump Water Heater Report", Advanced Energy (2011)	Cost taken from google shopping search, average of 12 venders (installed), EF 2.38. EF 3.56 (converted from COP 5.1); using provided cost assuming 1-to-1 drop in for resi unit	Navigant Consulting Research and Develop-ment Roadmap for Water Heating. Depart-ment of Energy (2011).
Fitzpatrick, S, Murray, M; "GE Heat Pump Water Heater Report", Advanced Energy (2011)	Cost taken from google shopping search, average of 12 venders (installed) 62% savings, (EF 0.89 -> 2.38), cost $1438 (average installed). EF 2.38	Navigant Consulting Research and Develop-ment Roadmap for Water Heating. Depart-ment of Energy (2011).
Home Depot Canada. Accessed January 2012. http://www.homedepot.ca/catalog/drain-water-heat-recovery/173006. CADDET. 1997. Residential waste water heat-recovery. System: GFX. CADDET Newsletter. http://www.gfxtechnology.com/CADDET.pdf.	Home Depot Canada: Purchase costs of $500-$1600 for Power Pipe ($480-$1550 US $). $150 installation assumed. Estimated cost is $1015 equipment + $150 installation ($1165 total), for existing buildings. CADDET: Improvement in EF from 0.84 to 1.29 (35% energy savings).	
U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE). (2011, March 30). Residential Heating Products Final Rule Analytical Tools. Retrieved from Appliance & Equipment Standards: http://www1.eere.energy.gov/buildings/appliance_standards/residential/heat-ing_products_fr_spreadsheets.html	DOE 2011 for efficiency improvement and cost. Savings based on moving EF from 0.59 to 0.64.	
Web search of available products. U.S. Department of Energy, Office of En-ergy Efficiency and Renewable Energy (EERE). (2011, March 30). Residential Heating Products Final Rule Analytical Tools. Retrieved from Appliance & Equipment Standards: http://www1.eere.energy.gov/buildings/appli-ance_standards/residential/heating_products_fr_spreadsheets.html. Robert Hendron, Jay Burch, Marc Hoeschele, Leo Rainer. "Potential for Energy Savings Through Residential Hot Water Distribution System Improvements". ASME 2009 3rd International Conference on Energy Sustainability col-located with the Heat Transfer and InterPACK09 Conferences (ES2009). July 19–23, 2009, San Francisco, California, USA	Cost for Bosch 1000P NG (2-3.5 gpm) based on web search of prices; $376-461 for each of three 3.5 gal unit ($418 each on average). Incremental cost calculated relative to standard gas ($1079 from DOE 2011): $176=3*418-1079. Does not include gas access and plumbing costs. Wasted hot water (23%) calculated based on Hendron 2009. Possible savings due to lower hot water set points or better efficiency were neglected.	
Navigant Consulting Research and Development Roadmap for Water Heat-ing. Department of Energy (2011).	Performance target from Roadmap; Robur price list for air-water gas absorption heat pump (40 kW) indicates 11,480 euros ($14,586) (www.lhprotrade.com/getcatfile.php?w=18). Scaling linearly with capacity gives: a 4.5 kW unit cost of $1641. Adding median installation cost of a condensing boiler ($874) gives a total cost: $2515. 51% savings (0.59 -> 1.2 EF)	
Water Resources Engineering, I. Water Conservation Market Penetration Study. East Bay Municipal Utility District (2002)	Tables 4-7 and 4-9 represents installed faucet aerator base (used to scale nationally); fixture cost ($90 for 5 per home)provided by web search (3/2012) net of water savings valued at $8/1000 gallons. Results in $409 cost savings per home, 71% reduction moving to 2 gpm faucets	McMordie-Stoughton, K.L., Elliott, D., Parker, G., Solana, A. & Sullivan, G. Update of Market Assessment for Capturing Water Conservation Opportunities in the Federal Sector. Pacific North West National Labora-tory (2005).
U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE). (2011, March 30). Residential Heating Products Final Rule Analytical Tools. Retrieved from Appliance & Equipment Standards: http://www1.eere.energy.gov/buildings/appliance_standards/residential/heat-ing_products_fr_spreadsheets.html	Efficiency and cost from DOE 2011, Efficiency Level 7. Baseline efficiency and cost is for standard electric storage. Does not include gas access and plumbing costs.	
U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE). (2011, March 30). Residential Heating Products Final Rule Analytical Tools. Retrieved from Appliance & Equipment Standards: http://www1.eere.energy.gov/buildings/appliance_standards/residential/heat-ing_products_fr_spreadsheets.html	Efficiency and cost from DOE 2011, Efficiency Level 7. Baseline efficiency and cost is for standard electric storage. Does not include gas access and plumbing costs.	

1. Description of the measure	2. Energy savings			3. Price	4. Units & capacity	5. Market description	6. Market size, 2030	7. Site use	8. Source use	9. Max adopt	10. CCE	11. Life	12. Used in scenario?			
	Percent	SD?	Fuel switch?										McK	NAS	Emerg	Tech
R: Use most efficient tankless gas water heater (no FS)	33%	Yes		$1,805	per unit; 199,000 BTU/hr capacity	R: Gas water heating	72.7	1,399	1,399	448	$22.28	11	No	No	No	Yes
R: Water heater off when away	1%	Yes		$0	per home	R: Water heater tank losses	139	239	730	6.72	$0	1	No	No	Yes	Yes
R: Wrap water heaters with insulation blankets	50%	Yes		$20	per unit	R: Water heater tank losses	139	239	369	183	$1.07	12	Yes	Yes	Yes	Yes
C: Add heat transfer fins to stock pots	5%	Yes		$0	per unit	C: Natural Gas Griddles	0.37	12.9	12.9	0.51	$0	10	No	No	Yes	Yes
C: Develop electric ignition for commercial gas cooking	4%			$100	per unit	C: Natural Gas All Cooking	4.1	224	224	1.91	$9.15	10	No	No	No	No
C: Develop heat pipe griddles	4%			$0	per unit	C: Electric and Gas Griddles, Comm	1	15.5	47.4	0	$0	4	No	No	Yes	Yes
C: Improve insulation on fryers	7%	Yes		$0	per unit	C: Electric and Gas Fryers, Comm	1.5	37.3	98.6	2.66	$0	12	No	No	Yes	No
C: Improve insulation on griddles	7%	Yes		$0	per unit	C: Electric and Gas Griddles	0.73	15.5	41.0	1.25	$0	10	No	No	Yes	No
C: Improvements in food preparation equipment motors	2%			$0	per unit	C: Food Preparation Appliances	3.7	7.09	21.6	0	$0	12	No	No	Yes	Yes
C: Incorporate infrared burners into broilers	37%			$1,750	per unit	C: Natural Gas Broilers	0.24	25.2	25.2	11.5	$2.87	10	Yes	Yes	Yes	Yes
C: Incorporate infrared burners into fryers	30%			$750	per unit	C: Natural Gas Fryers	0.86	33.5	33.5	12.3	$4.14	12	No	No	Yes	Yes
C: Incorporate infrared burners into gas ovens	30%			$1,000	per unit	C: Natural Gas Ovens	1.3	70.1	70.1	25.5	$4.27	10	No	No	Yes	Yes
C: Incorporate infrared burners into gas ranges	39%			$1,700	per unit	C: Natural Gas Ranges	0.99	66.2	66.2	31.9	$4.07	10	Yes	Yes	Yes	Yes
C: Incorporate power burners into gas fryers	31%	Yes		$500	per unit	C: Natural Gas Fryers	0.86	33.5	33.5	9.70	$3.62	12	Yes	Yes	Yes	Yes
C: Incorporate power burners into gas ranges	34%			$3,000	per unit	C: Natural Gas Ranges	0.99	66.2	66.2	25.0	$8.01	10	No	No	Yes	Yes
C: Reduce broiler idle energy	26%	Yes		$0	per unit	C: Natural Gas Broilers	0.24	25.2	25.2	6.13	$0	10	No	No	Yes	Yes
C: Use more efficient (i.e., currently available) electric broiler	9.0%			$1,696	per unit	C: Electric Broilers	0.02	0.50	1.52	0	$202.15	10	No	No	Yes	Yes
C: Use more efficient (i.e., currently available) electric fryer	6%			$275	per unit	C: Electric Fryers	0.62	3.80	11.6	0	$234.16	12	No	No	Yes	Yes
C: Use more efficient (i.e., currently available) electric griddle	11%			$800	per unit	C: Electric Griddles	0.37	2.58	7.86	0	$181.60	10	No	No	Yes	Yes
C: Use more efficient (i.e., currently available) electric oven	39%			$3,825	per unit	C: Electric Ovens	1.1	9.23	28.2	5.57	$49.46	10	No	No	Yes	Yes
C: Use more efficient (i.e., currently available) electric range	24%			$3,400	per unit	C: Electric Ranges	0.10	1.12	3.42	0	$86.61	10	No	No	Yes	Yes
C: Use more efficient (i.e., currently available) electric steamer	57%			$0	per unit	C: Electric Steamers	0.53	5.26	16.0	7.01	$0	10	Yes	Yes	Yes	No
C: Use more efficient (i.e., currently available) gas broiler	12.5%			$1,223	per unit	C: Natural Gas Broilers	0.24	25.2	25.2	3.44	$8.01	10	No	No	Yes	Yes
C: Use more efficient (i.e., currently available) gas fryer	31%			$1,219	per unit	C: Natural Gas Fryers	0.86	33.5	33.5	12.8	$6.46	12	No	No	Yes	Yes

Primary sources used	Data used and/or methodology	Other supporting sources
U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE). (2011, March 30). Residential Heating Products Final Rule Analytical Tools. Retrieved from Appliance & Equipment Standards: http://www1.eere.energy.gov/buildings/appliance_standards/residential/heating_products_fr_spreadsheets.html	Efficiency and cost from DOE 2011, Efficiency Level 7. Baseline efficiency and cost is weighted average of standard gas storage/tankless. Does not include gas access and plumbing costs.	
Calculated from first principles	Tank with 40 sq. ft. surface area, typical R-30, dT=60F	http://www.aceee.org/consumer/water-heating
U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE). (2011, March 30). Residential Heating Products Final Rule Analytical Tools. Retrieved from Appliance & Equipment Standards: http://www1.eere.energy.gov/buildings/appliance_standards/residential/heating_products_fr_spreadsheets.html	Cost from DOE 2011. Insulating blankets designed to reduce tank losses by roughly 50%.	
Navigant Consulting. (2009). Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances. Washington, D.C.: Building Technology Program, Department of Energy.	Page 56: Table 2-48	
Navigant Consulting. (2009). Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances. Washington, D.C.: Building Technology Program, Department of Energy.	Page 53, Table 2-46 and Page 54, Table 2-47	
Navigant Consulting. (2009). Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances. Washington, D.C.: Building Technology Program, Department of Energy.	Page 377, Table A-20	
Navigant Consulting. (2009). Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances. Washington, D.C.: Building Technology Program, Department of Energy.	Page 51, Table 2-42	Cost data are from google searches of commercially available appliances
Navigant Consulting. (2009). Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances. Washington, D.C.: Building Technology Program, Department of Energy.	Page 51, Table 2-42	
Navigant Consulting. (2009). Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances. Washington, D.C.: Building Technology Program, Department of Energy.	Page 78, Table 3-9	
Navigant Consulting. (2009). Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances. Washington, D.C.: Building Technology Program, Department of Energy.	Page 48, Table 2-33 and Page 49, Table 2-35	
Navigant Consulting. (2009). Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances. Washington, D.C.: Building Technology Program, Department of Energy.	Page 48, Table 2-33 and Page 49, Table 2-35	
Navigant Consulting. (2009). Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances. Washington, D.C.: Building Technology Program, Department of Energy.	Page 48, Table 2-33 and Page 49, Table 2-35	
Navigant Consulting. (2009). Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances. Washington, D.C.: Building Technology Program, Department of Energy.	Page 48, Table 2-33 and Page 49, Table 2-35	
Navigant Consulting. (2009). Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances. Washington, D.C.: Building Technology Program, Department of Energy.	Page 49, Table 2-36 and Page 50, Table 2-38	
Navigant Consulting. (2009). Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances. Washington, D.C.: Building Technology Program, Department of Energy.	Page 49, Table 2-36 and Page 50, Table 2-38	
Navigant Consulting. (2009). Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances. Washington, D.C.: Building Technology Program, Department of Energy.	Page 56, Table 2-48	
Navigant Consulting. (2009). Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances. Washington, D.C.: Building Technology Program, Department of Energy.	Page 45, Table 2-31	Cost data are from google searches of commercially available appliances
ENERGY STAR (n.d.). Savings Calculator for ENERGY STAR Qualified Commercial Kitchen Equipment. Retrieved from: http://www.energystar.gov/ia/business/bulk_purchasing/bpsavings_calc/commercial_kitchen_equipment_calculator.xls?ba38-b08e	Using indicated spreadsheet Enter "1" for gas oven: "results summary" tab shows energy savings and cost	
ENERGY STAR (n.d.). Savings Calculator for ENERGY STAR Qualified Commercial Kitchen Equipment. Retrieved from: http://www.energystar.gov/ia/business/bulk_purchasing/bpsavings_calc/commercial_kitchen_equipment_calculator.xls?ba38-b08e	Enter "1" for electric Griddle and tab over to the "results summary" tab for the energy savings and cost	
ENERGY STAR (n.d.). Savings Calculator for ENERGY STAR Qualified Commercial Kitchen Equipment. Retrieved from: http://www.energystar.gov/ia/business/bulk_purchasing/bpsavings_calc/commercial_kitchen_equipment_calculator.xls?ba38-b08e	Enter "1" for electric oven and tab over to the "results summary" tab for the energy savings and cost	
Brown, R., Borgeson, S., Koomey, J. & Biermayer, P. U.S. Building-Sector Energy Efficiency Potential. Environmental Protection 33 (2008).	Page 8, Table 5. Cost is \$7,400 - \$4,000 = \$3,400	
Brown, R., Borgeson, S., Koomey, J. & Biermayer, P. U.S. Building-Sector Energy Efficiency Potential. Environmental Protection 33 (2008).	Page 8, Table 5	
Navigant Consulting. (2009). Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances. Washington, D.C.: Building Technology Program, Department of Energy.	Page 45, Table 2-31	Cost data are from google searches of commercially available appliances
Navigant Consulting. (2009). Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances. Washington, D.C.: Building Technology Program, Department of Energy.	Page 376, Table A-17 and A-18	Cost data are from google searches of commercially available appliances

1. Description of the measure	2. Energy savings			3. Price	4. Units & capacity	5. Market description	6. Market size, 2030	7. Site use	8. Source use	9. Max adopt	10. CCE	11. Life	12. Used in scenario?			
	Percent	SD?	Fuel switch?										McK	NAS	Emerg	Tech
C: Use more efficient (i.e., currently available) gas griddle	12%			$800	per unit	C: Natural Gas Griddles	0.37	12.9	12.9	1.59	$16.98	10	No	No	Yes	Yes
C: Use more efficient (i.e., currently available) gas oven	29%			$0	per unit	C: Natural Gas Ovens	1.3	70.1	70.1	103.8	$31.39	10	Yes	Yes	Yes	Yes
C: Use more efficient (i.e., currently available) gas range	25%			$1,830	per unit	C: Natural Gas Ranges	0.99	66.2	66.2	699.2	$3.94	10	No	No	Yes	Yes
C: Use more efficient (i.e., currently available) gas steamer	43%			$0	per unit	C: Natural Gas Steamers	0.26	16.4	16.4	656.40	$8.97	10	Yes	Yes	Yes	No
C: Use most efficient (i.e., max-tech) electric steamer	73%			$2,500	per unit	C: Electric Steamers	0.53	5.26	16.0	931.4	$52.72	10	Yes	Yes	Yes	Yes
C: Use most efficient (i.e., max-tech) gas steamer	73%			$3,700	per unit	C: Natural Gas Steamers	0.26	16.4	16.4	15.0	$4.28	10	Yes	Yes	Yes	Yes
C: Use pulse combustion burners in gas fryers & griddles	31%			$760	per unit	C: Gas Fryers and Griddles	1.2	46.5	46.5	13.4	$4.84	11	No	No	Yes	Yes
R: Energy-consumption indicators on cooking devices	12%	Yes		$35	per unit	R: Cooking (including microwaves)	267	458	784	81.6	$7.46	10	No	No	Yes	Yes
R: Incorporate all microwave improvements (i.e., "max-tech")	20%			$55	per unit	R: Microwave Total	127	55.3	169	35.5	$12.62	10	Yes	Yes	Yes	Yes
R: Microwave use instead of oven/stove	12.5%	Yes	FS	$0	per unit	R: Cooking - microwave to replace oven/stove	135	113	199	-83.4	$0	10	No	No	No	No
R: Replace electric with induction cook top	20%			$550	per unit	R: Electric cooktops	90.6	140	426	84.0	$39.25	10	No	No	Yes	No
R: Replace gas with induction cook top	70%		FS	$800	per unit	R: Gas cooktops	44.8	237	237	169	$13.26	10	No	No	Yes	No

Primary sources used	Data used and/or methodology	Other supporting sources
ENERGY STAR (n.d.). Savings Calculator for ENERGY STAR Qualified Commercial Kitchen Equipment. Retrieved from: http://www.energystar.gov/ia/business/bulk_purchasing/bpsavings_calc/commercial_kitchen_equipment_calculator.xls?ba38-b08e	Enter "1" for Gas Griddle and tab over to the "results summary" tab for the energy savings and cost	
ENERGY STAR (n.d.). Savings Calculator for ENERGY STAR Qualified Commercial Kitchen Equipment. Retrieved from: http://www.energystar.gov/ia/business/bulk_purchasing/bpsavings_calc/commercial_kitchen_equipment_calculator.xls?ba38-b08e	Using indicated spreadsheet Enter "1" for gas oven: "results summary" tab shows energy savings and cost	
Navigant Consulting. (2009). Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances. Washington, D.C.: Building Technology Program, Department of Energy.	Page 51: "Insulation at major heat loss locations in cooking appliances can reduce standby heat loses by 25% in both electric and gas powered models"	Cost data are from google searches of commercially available appliances
Brown, R., Borgeson, S., Koomey, J. & Biermayer, P. U.S. Building-Sector Energy Efficiency Potential. Environmental Protection 33 (2008).	Page 11, Table 6	
Navigant Consulting. (2009). Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances. Washington, D.C.: Building Technology Program, Department of Energy.	Page 56: Table 2-48 and Page 56: Table 2-49	
Navigant Consulting. (2009). Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances. Washington, D.C.: Building Technology Program, Department of Energy.	Page 56: Table 2-48 and Page 56: Table 2-49	
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Electrolux. (n.d.). 30" Induction Cooktop. Retrieved from http://www.electroluxappliances.com/kitchen-appliances/cooktops/induction/ew30ic60is	"Cooking with induction is...20% more efficient than electric." and MSRP of induction stove is $2,000	
Electrolux. (n.d.). 30" Induction Cooktop. Retrieved from http://www.electroluxappliances.com/kitchen-appliances/cooktops/induction/ew30ic60is	"Cooking with induction is 70% more efficient than gas..." and MSRP of induction stove is $2,000	

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