# Energy Efficiency is a Renewable Resource

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## ABSTRACT

Sequential estimates of efficiency potential for ex ante analysis of appliance standards underestimate long-term potential, which continues to evolve over time. Technologies that provide the same service while using less energy are more energy efficient. Engineering-economic studies of energy efficient technologies for a large set of residential services have been conducted since the 1970s. Designs have changed, and energy efficient products have been successfully manufactured, sold and utilized, in part owing to energy performance labels and standards. Examination of several generations of technologies and standards reveals that energy efficiencies and potentials continue to increase. Comparing a series of ex ante estimates of possible design changes and costs shows that the horizon of possible improvements continues to advance. Over time, as designs change to achieve increasing energy efficiency in products sold, additional efficiency opportunities are identified beyond those originally envisioned. This paper provides quantitative examples for residential appliances and equipment where the maximum efficiency achievable with mass production continues to increase. Consumer life cycle costs, including purchase and lifetime operating costs, for some energy-service products have declined over time, while efficiencies have increased. The major conclusions are that: (1) energy efficiency is a renewable resource, in that with each design change, new opportunities become available for further increasing the energy efficiency in the next generation of products. The compound annual growth rate in efficiency of maximum technologically feasible levels ranges from -0.2 to +9.9% (median 1.5%); and (2) consumer life cycle costs are declining over time while energy efficiencies continue to increase.

## Introduction

Appliance standards that are technologically feasible and economically justified have been established repeatedly since the 1970s. For household refrigerators, refrigerator-freezers and freezers since 1974, mandatory energy performance standards were established in California four times (the 1992 California standards were pre-empted by 1993 U.S. standards and are not shown), and for the United States four times. Figure 1 shows that average annual energy consumption per new U.S. residential refrigerator or refrigerator-freezer by year sold has declined 74% in 2009 and is expected to decline by 80% by 2014, compared to 1972. These changes include increases in size and changes in market share (e.g., between top-freezer, side-by-side, and bottom-freezer refrigerator-freezers).

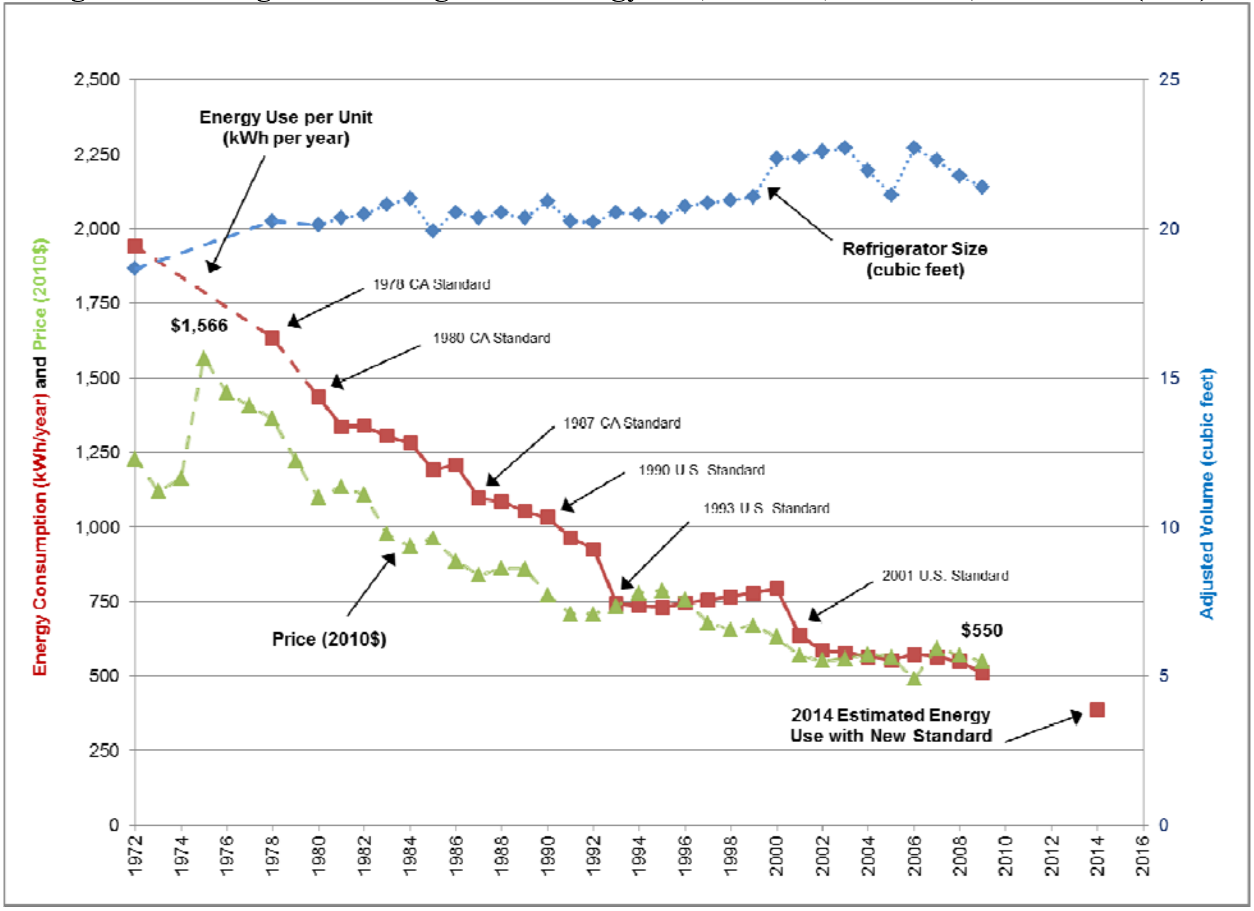
Technology and production changes have shifted the range of energy consumption consistently lower while meeting regulatory targets. The highest efficiency levels that were commercially available, and even the levels that were envisioned as the maximum technology feasible in earlier analysis, have now been achieved or exceeded in practice. As a consequence, consumers are experiencing comparable or higher levels of service at lower operating costs than envisioned 20-25 years ago.

During this same period, the real (corrected for inflation) retail price of refrigerator-freezers has declined (Dale 2009, DOE 2011b). The consumer life-cycle cost is the sum of the retail purchase price and the operating expense. Since both retail price and operating expense have, on average, declined, consumers now receive household refrigeration services at both lower lifetime operating cost and lower life cycle cost.

## Data Sources and Engineering-Economic Analysis

This paper relies upon public government documents and industry market surveys. Since 1979, the U.S. Department of Energy (DOE) has conducted extensive research as part of developing mandatory energy performance standards. Engineering and economic analysis specific to each product type was conducted to identify the design options and energy efficiency levels that are potentially available for mass production in the next few years. DOE estimated the expected retail prices by efficiency level, lifetime energy consumption and operating costs, and life cycle costs; and published the analysis results in Technical Support Documents. DOE conducted public meetings and workshops over a period of years for each rulemaking, and elicited review and comment. This process involved input from not only academic and national laboratory technical experts under contract to DOE, and also from manufacturers and others.

**Figure 1. Average New Refrigerator Energy Use, Volume, and Price, 1972-2009 (U.S.)**



Source: Appliance Standards Awareness Project 2011.

Figure 1 shows the trend in average unit energy consumption for new US refrigerators and refrigerator-freezers by year sold, and the trends in size (adjusted volume) and price. The average annual energy consumption for new US refrigerators or refrigerator-freezers declined from 1941 kWh/yr in 1972 to 587 kWh/yr in 2002 (including Energy Standard Adjustment Factor based on new test procedure). The compliance dates when three California standards (1978, 1980 and 1987) and four US standards (1990, 1993, 2001 and 2014) took (or will take) effect are shown. The annual energy consumption for new refrigerators and refrigerator-freezers in 2014 is projected to average 389 kWh/yr.

## Commercially Available and Maximum Technologically Feasible Levels

The DOE analysis that provided the basis for US standards was conducted in 1989 (for the 1993 standard), 1995 (for the 2001 standard) and 2010 (for the 2014 standard) (DOE 1989, 1995, 2011a). The maximum technologically feasible level for a typical-size top-mount refrigerator-freezer was estimated to be 551 kWh/yr in 1989, 474 in 1995, and 370 in 2010.[1] The maximum technologically feasible level represents a product having a combination of efficient components that could potentially be mass produced in time for the implementation date of the next standard, typically more than three years after the analysis. Measures are excluded from the analysis if they meet any of four criteria: is not technologically feasible; is impractical to manufacture, install, and service; would adversely affect product utility or product availability; or would have adverse impacts on health and safety.

Figure 2 shows the range of unit energy consumption for one class, automatic-defrost top-freezer refrigerator-freezer models, available for sale in California for selected years, from the most energy-consumptive ("Highest") at the top of the range to the least energy consumptive commercially available ("Best Available").[2] In addition, the U.S. average energy consumption for all new refrigerators and refrigerator-freezers (data from Figure 1) is shown. The three lines have similar characteristics and similar cumulative changes. Expressed as average annual percent change from 1978 to 2010, the highest consumption values have decreased 3.74% per year, average values decreased 3.67% per year, and best available decreased 3.94% per year.

Three estimates of maximum technology feasible (1989, 1995, 2010) are shown from three analyses: 1989 (for the 1993 standard), 1995 (for the 2001 standard) and 2010 (for the 2014 standard). The maximum energy level allowed in the standard for 2001 (540 kWh/yr) is approximately the maximum technology feasible level from 1989 (551 kWh/yr), after adjusting both by the Energy Standard Adjustment Factor, 1.124. In other words, all products commercially manufactured or imported in 2001 were more efficient than what was viewed as the maximum technologically feasible (and not economically justified) in 1989. Similarly, due to the updated standard to take effect in 2014, all products manufactured from that date forward will consume less electricity than the maximum technology feasible level from 1995 (474 kWh/yr). From 1989 to 2010, the annual percent change in maximum technology feasible level has been 1.88%/year. The improvements in the market are approaching a moving horizon characterizing what is possible.

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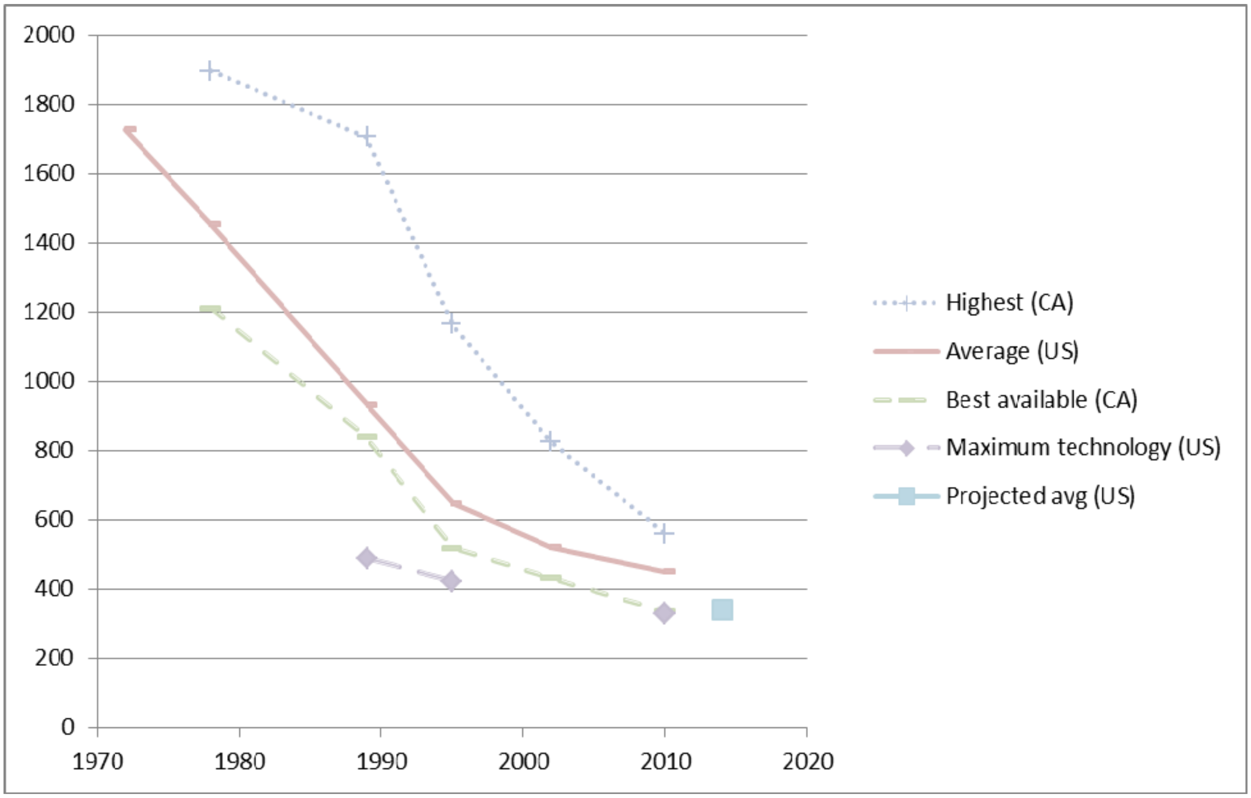
[1] The original estimates were 490 kWh/yr in 1989 and 422 kWy/yr in 1995. For consistency with changes to the test procedure in the 2010 analysis that lead to higher energy consumption estimates, the older estimates have been multiplied by the Energy Standard Adjustment Factor for Class 3, namely, 1.124.

[2] All data in this figure are based on the older DOE test procedure, so energy consumption estimates from the California and US data have not been multiplied by the Energy Standard Adjustment Factor for Class 3, 1.124.

**Figure 2. Highest, Average, Lowest and Maximum Technology Feasible Energy Consumption in kWh Per Year for New California and U.S. Refrigerator-Freezers, 1972-2014**[3]



For comparison, the standard levels changed from 1068 kWh/yr in 1990, to 773 kWh/yr in 1993, to 540 kWh/yr in 2001, and to 403 kWh/yr in 2014. Expressed as average annual percent change, this is equivalent to 3.98% from 1990 to 2014. The average annual percent changes from one standard to the next are 10.2% (1990 to 1993), 4.40% (1993 to 2001) and 2.22% (from 2001 to 2014).

Table 1 shows changes in maximum technology feasible levels from DOE analysis from 1997 to 2011 for a range of product types. The maximum efficiency considered for room air conditioners decreased from 1997 to 2011. At the other extreme, in the case of electric water heaters, the most efficient technology considered changed from electric resistance to electric heat pump water heaters, more than doubling the top efficiency considered. This is a one-time event and does not represent a trend that can be projected into the future, although it is possible that heat pump efficiencies will improve. For most products, the annual percent change in maximum technology feasible levels was 0.7-2.0%. Further improvements are possible in future until a thermodynamic limit is reached.

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[3] Source: California Energy Commission 1978-2012.

**Table 1. Trends in Maximum Technologically Feasible Efficiency Levels for U.S. Residential Products, 1989-2011**

| PRODUCT | METRIC | Efficiency (Year Analyzed) | Average Annual Percent Change (%) | Notes |
|---|---|---|---|---|
| Room air conditioner | EER | 12.39 (1997),<br>12.0 (2011) | -0.2% | 8,000-13,999 Btu with louvers. EER = energy efficiency ratio |
| Water heater, gas | EF | 0.71 (2000),<br>0.77 (2010) | 0.7% | EF = energy factor |
| Heat pump | HSPF | 8.8 (2001),<br>9.9 (2011) | 1.2% | Split, three ton. HSPF = heating season performance factor |
| Heat pump | SEER | 18 (2001),<br>21 (2011) | 1.5% | Split, three ton. SEER = seasonal energy efficiency ratio |
| Refrigerator-freezer, class 3 | kWh/yr | 551 (1989),<br>370 (2010) | 1.9% | Automatic defrost, top freezer, without through-the-door services |
| Central air conditioner | SEER | 18 (2001),<br>22 (2011) | 2.0% | Split, three ton. Comparing coil only (2001) to blower coil (2011) |
| Water heater, electric | EF | 0.91 (2000),<br>2.35 (2010) | 9.9% | Heat pump option in 2010 |

## Consumer Retail Prices, Operating Costs, and Life Cycle Costs

In the DOE analyses to date, manufacturer costs for increased energy efficiency are calculated relative to a baseline design. The baseline design typically has unit energy consumption at or near the standard level at that time. Energy efficiency levels are composed of incremental changes to the baseline design, such as more efficient compressors or lower conductivity insulation for refrigerators.

The 2011 DOE analysis for three classes of refrigerator-freezers is shown in Table 2. The last efficiency level is the maximum technologically feasible level.

As part of the economic analysis, DOE calculated the consumer life cycle cost for each efficiency level. The life cycle cost is the sum of purchase price and operating expenses over the product's lifetime, where future operating costs are discounted to year of purchase. The median lifetime is 16.2 years, with a broad range from under 5 years to more than 20 years.

**Table 2. Unit energy consumption and installed cost by efficiency level**

| CLASS | **Top-Mount Auto Defrost Refrigerator-Freezer** | | **Bottom-Mount Refrigerator-Freezer** | | **Side-by-Side Refrigerator-Freezer** | |
|---|---|---|---|---|---|---|
| Market share, 2007 | 53.9% | | 13.6% | | 32.4% | |
| Efficiency Level | kWh/yr | Price 2009$ | kWh/yr | Price 2009$ | kWh/yr | Price 2009$ |
| Baseline | 574 | 491 | 716 | 858 | 881 | 1040 |
| 1 | 517 | 501 | 645 | 860 | 793 | 1043 |
| 2 | 488 | 508 | 609 | 861 | 749 | 1048 |
| 3 | 460 | 564 | 573 | 867 | 705 | 1064 |
| 4 | 431 | 602 | 537 | 926 | 661 | 1123 |
| 5 | 402 | 686 | 501 | 1023 | 617 | 1251 |
| 6 | 370 | 806 | 457 | 1157 | 590 | 1351 |

Source: U.S. Department of Energy, 2011

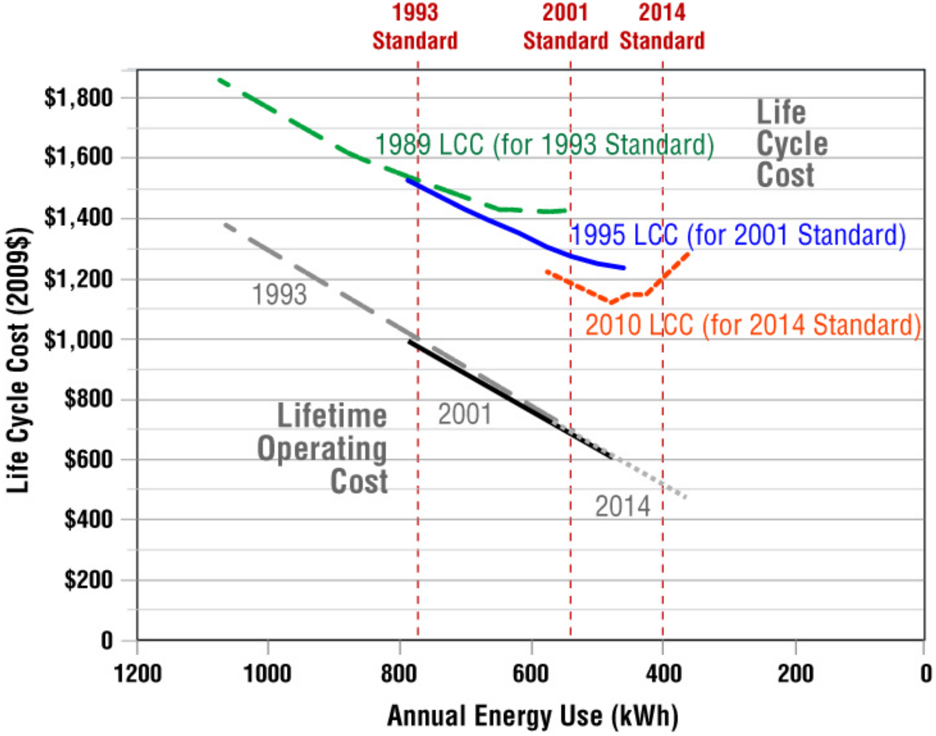
Using a similar approach, Figure 3 shows the expected consumer life cycle cost (LCC) and lifetime operating costs for new US top-mount refrigerator-freezers of a typical size, as a function of energy efficiency level from three analyses, 1989, 1995, and 2010. In order to make estimates from different years comparable, the purchase prices have been adjusted to 2009$ by the producer price index (Bureau of Labor Statistics, 2012), and a single time series of expected electricity prices has been used (EIA, 2010). Each data point on each LCC curve represents an incremental design change, such as a more efficient compressor or better insulation. The maximum technologically feasible level changed to lower energy consumption in each subsequent analysis.

Projections are shown from three analysis periods, 1989, 1995, and 2010. The maximum technology feasible efficiency level is the right-most (lowest kWh/yr on the x-axis) point on each curve. Comparing the first two analyses, the estimate of maximum technologically feasible annual energy decreased 14%, from 551 kWh/yr in 1989 to 474 kWh/yr in 1995. The third analysis produced a maximum technology feasible level of 370 kWh/year, 33% lower than the 1989 analysis and 22% lower than the 1995 analysis. Expressed as an annual average percent change, the maximum technologically feasible annual energy consumption decreased 2.46% from 1989 to 1995, 1.64% from 1995 to 2010, for an overall change of 1.88% from 1989 to 2010.

The 1989 LCC (for the 1993 standard) begins with a baseline at 1073 kWh/yr, shows decreasing LCC to a minimum at 571 kWh/yr, then increasing LCC. Decreasing LCC means that the increased purchase price to pay for higher efficiency levels is more than compensated by lifetime savings in energy bills. Increasing LCC occurs when the value of lifetime energy bill savings is less than the increased purchase price. The 1993 standard (maximum electricity consumption for this size top-mount refrigerator-freezer) was set at 773 kWh/yr.

The 1995 LCC (for the 2001 standard) begins with a baseline at 788 kWh/yr, approximately corresponding to the 1993 standard level. Unlike the 1989 LCC, the 1995 LCC decreases until about 479 kWh/yr, then flattens. This reflects an expanded set of efficiency levels and revised estimates for the manufacturing or retail costs of these efficiency levels, lower than estimated in 1989. The 2010 LCC (for the 2014 standard) begins with a baseline at 574 kWh/yr, near the 2001 standard level of 540 kWh/yr, declines for the next two efficiency levels to 488 kWh/yr, then increases. Again, the range of efficiency levels expanded and estimates of manufacturing or retail costs of these efficiency levels are lower than previous estimates.

**Figure 3. Life Cycle & Operating Costs vs Annual Energy Use (Automatic-defrost top-freezer refrigerator-freezer without through-the-door features, 20.8 cubic foot adjusted volume)**



At the bottom of Figure 3, three lifetime operating cost curves are shown, corresponding to calculations using data from three analysis periods, applied from the implementation date of the resulting standard (e.g, 1993, 2001, 2014). Annual operating cost declines in proportion to annual energy consumption, and increases or decreases as a function of changing energy prices. A single time series of annual average US residential electricity prices was used here for all three curves. The differences are mostly in the set of efficiency levels considered. In addition, the energy prices in the 2000s were lower than in the 1990s or in the projections after 2010, causing the estimate of 2001 operating costs at any annual energy use to be lower than the other two analysis periods.

Major observations are that: i) the range of efficiency levels considered possible, including “maximum technology feasible”, changed to lower energy consumption from 1989 to 1995 to 2010; ii) the expected manufacturer cost and corresponding consumer retail price at higher efficiency levels declined over time; and iii) minimum LCC moved to lower energy consumption per unit with each analysis. These results may be useful to climate change policy.

## Limitations and Future Analysis

Efficiency and annual energy consumption in these studies are based on engineering calculations consistent with the existing DOE laboratory test procedure, adjusted to reflect actual consumption in the field. Empirical studies to measure the energy consumption of refrigerator-freezers during actual usage are summarized in DOE 2011. Similar studies could serve to validate or adjust the ex-ante estimates of energy savings from the appliance standards program for other products.

In Figure 1, average annual energy consumption for residential refrigeration services includes changes in service, both larger volumes and changing market shares among classes (e.g., top-freezer, side-by-side, and bottom-mount refrigerator-freezers). In the rest of this analysis, the level of service (class and volume of refrigerator-freezer) was held constant. In reality, the mix of products (e.g., side-by-side or top-freezer) changed over time. To the extent that sizes of refrigerators increased, one could suggest that the service provided was increased, while operating and lifecycle costs declined. This research could be expanded to account for other classes of refrigerators, and the overall impact, accounting for both the increased refrigeration service provided and changes in retail price and operating expenses. A retrospective hedonic analysis has been published after the 1990 and 1993 refrigerator standards (Greening, 1997).

This analysis considered trends in maximum technologies feasible for seven products (Table 1) and for refrigerator-freezers in detail. Analysis could be expanded to other products to see if these trends occur more broadly in association with technological changes to achieve higher energy efficiency over time. For some products, standard levels were set by legislation; in some of these cases, insufficient analysis was done or technical support documents are not available to document the maximum technologically feasible level at that time.

## Conclusions

Sequential estimates of efficiency potentials for ex ante analysis of appliance standards underestimate the long-term efficiency potential, which continues to evolve over time. A review of several generations of technologies and standards reveals that the range of possible higher energy efficiencies continues to increase. Over time, as designs change to achieve increasing energy efficiency in products sold, additional efficiency opportunities are identified beyond those originally envisioned. Seven residential products were studied - room air conditioners, gas water heaters, heat pumps (both for heating and cooling efficiency), refrigerator-freezers, central air conditioners, and electric water heaters - and this trend was observed for six (not room air conditioners). Expressed as average annual percent change, the maximum technologically feasible efficiency level changed in the range of -0.2 to +9.9% per year. Excluding the two most extreme values, the range is +0.7-2.0%/yr, with a median of 1.5%/yr. The efficiency potential estimates served as a basis for policies in the next few years. For longer term studies, such as climate change policies, the trends in maximum technologically feasible efficiency levels merit consideration.

The case of refrigerator-freezers was examined in detail. Average annual energy consumption per new U.S. refrigerator or refrigerator-freezer by year sold has declined 74% in 2009 and is expected to decline by 80% by 2014, compared to 1972, and average size has increased. The highest efficiency levels that were commercially available, and even the levels that were envisioned as the maximum technology feasible in earlier analysis, have now been exceeded in general practice. As a consequence, consumers are experiencing comparable or higher levels of service at lower operating costs than envisioned 20-25 years ago. Sequential estimates of manufacturer, retail and installed costs have declined over time. Since both retail price and operating expense have, on average, declined, consumers now receive household refrigeration services at both lower lifetime operating cost and lower life cycle cost.

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