Title
Trends in the cost of efficiency for appliances and consumer electronics

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Abstract

There exists significant historical evidence that production costs and consumer prices of residential appliances and consumer electronics have decreased in real terms over the last several decades. Such declines in cost likely result from increased production efficiency gained with cumulative experience on the part of manufacturers. This process is typically modelled by an empirical experience curve. One implication of such historical trends is that increased production costs of more efficient appliances and consumer electronics are likely to diminish relative to baseline costs over time. In this paper, we present price trends in the U.S. for several residential appliances and consumer electronics, from a variety of data sources. We also examine the results of including price trend effects in economic impact modelling of more efficient products. Our results highlight the importance of including such effects in order to obtain more representative results consistent with historical trends. This is true regardless of the policy that is being modelled, whether a minimum efficiency standard, an energy use label, a financial incentive, or other policy. The omission of such cost and price dynamics would likely overestimate the consumer cost associated with an increasing market share of more efficient appliances and consumer electronics.

1. Introduction

Many residential energy efficiency programs around the world focus on consumer goods such as appliances, HVAC (heating, ventilation, and air conditioning) equipment, and electronic equipment, as these represent the vast majority of the energy end-use in a typical household. Such programs include mandatory minimum efficiency performance standards (MEPS), voluntary efficiency standards (e.g., ENERGY STAR), and/or labelling requirements (e.g., EU energy label). Many analyses have shown the cost-effectiveness to consumers of purchasing newer and more efficient appliances. One key input to such analyses, however, is the incremental cost of more efficient products. Such costs are often difficult to estimate, especially if the design option under consideration is not an actual commercial product yet. To estimate these costs, *ex ante* tear-down engineering costs are developed based on the costs of individual components, as well as modelling investments in new capital equipment that may be required for production. These analyses are the best available for products not yet commercialized.

There exists, however, considerable historical evidence that production costs and consumer prices of residential appliances and consumer electronics have decreased in real terms over the last several decades. There is also a broad literature examining how real costs decline with cumulative production, for a variety of products. This market dynamic is often underestimated in analyses looking at the impact of energy efficient products. In some cases, prices are assumed to be fixed in the analysis, because there exist insufficient data to estimate future price dynamics. Nevertheless, the ubiquity of this dynamic suggests that assuming constant prices, even in cases with little data, potentially leads to an underestimate of the consumer benefits related to more efficient appliances.

In this paper, we review some recent work related to price trends for appliances, as developed for MEPS in the U.S. In particular, we focus on the total net consumer impacts of energy efficiency policies, both with and without price trends in the analysis. This helps to quantify how omitting price trends underestimates consumer benefits.

2. Methods and Data Sources

Many prior studies have noted how production costs tend to decline relatively predictably with increased cumulative production. This dynamic is often referred to as experience, and is empirically modelled by an experience curve (for a thorough review of the experience curve literature, see for example Yelle 1979, Dutton & Thomas 1984, Argote & Epple 1990, McDonald & Schrattenholzer 2001, and Weiss et al. 2010). Experience typically includes factors such as labor and management efficiency, standardization, capital investments, automation, and distribution improvements. Experience is an industry-wide phenomenon, as opposed to learning which is typically used to describe a more narrow and localized process (e.g., manufacturing of a product at a single plant). The conventional functional relationship for experience is given by

$$P = P_o n^{-b},$$

where P_o is the price of the first unit of production, n is the cumulative volume of product, and b is a constant known as the experience rate parameter. The experience curve is an empirical formulation. It is a proxy measure for all of the underlying casual factors. It is also well supported by historical data for many different industries, however, and as such is readily used in the literature. In cases where the cumulative volume of production is difficult to estimate, one can assume that production grows approximately exponentially with time. In that special case, the experience curve simplifies to an exponential model given by

$$P = P_o n^{-b} = P_o\,(n_o e^{ct})^{-b} = P'_o e^{-at},$$

where t is time (usually expressed in years after a certain date), P'_o is the price at time zero, and a is a constant known as the exponential model parameter. In the analyses described below, we primarily utilized experience curves, but also considered a variety of sensitivity scenarios, including those with the exponential model as an alternative model.

The U.S. Department of Energy (DOE) performs detailed and rigorous analyses looking at the impacts of potential MEPS. One of the main models developed is a 30-year cumulative national impacts analysis (NIA). The NIA models aggregate national energy savings and consumer benefits and costs, and includes projections of annual shipments, product lifetimes, electricity prices, energy usage, prices, and efficiency distributions. The analysis considers various discrete trial standard levels (TSLs) above the baseline (i.e., a set of potential new MEPS targets). A key output of the NIA is the discounted consumer net present value (NPV) of all benefits and costs over 30 years at each TSL. Those analyses published since 2011 include discussions of price trends, and where appropriate, utilize experience curves to estimate future prices of products.[1] Appliances included here are refrigerators & freezers, furnaces, central air conditioners and heat pumps, room air conditioners, clothes dryers, clothes washers, dishwashers, and microwave ovens (US DOE 2011a-d, 2012a-b).

Data from the U.S. Bureau of Labor Statistics (BLS) were used to develop price trends for individual appliances in the U.S. market. The BLS publishes a Producer Price Index (PPI) [2] for many individual industries, including manufacturers of household appliances. The PPI is quality-adjusted, so that changes in producer prices are meant to reflect real changes in production costs, as opposed to changes driven by evolving product features and characteristics.[3] Table 1 lists all the indices from the BLS used to develop price trends for U.S. appliances. The PPI is a nominal index, and so was deflated to a real price index using either the All Items Consumer Price Index (CPI) from the BLS, or the Chained GDP Price Index from the U.S. Bureau of Economic Analysis (the current methodology uses the GDP Index). To then develop an experience curve, historical shipment data were used to construct a cumulative shipment history. Historical U.S. shipments are usually obtained as part of the MEPS development process, and used to calibrate future shipment projections in the NIA. Figure 1 shows the historical real price indices based on the PPI, and the projected trends based on the experience curve fits, for several major appliance categories.

Table 1: Producer Price Indices from the U.S. Bureau of Labor Statistics.

Appliance	Series Name	Price Index Series ID
Refrigerators and Freezers	Household refrigerator and home freezer manufacturing	PCU335222335222
	Refrigerators and home freezers[a]	MWUR0000SE3001
Room Air Conditioners	Room air-conditioners and dehumidifiers, except portable dehumidifiers	PCU3334153334156
Furnaces	Warm air furnaces, incl. duct furnaces and humidifiers, and electric comfort heating	PCU333415333415C
Central Air Conditioners	Unitary air-conditioners, except air source heat pumps	PCU333415333415E
Clothes Washers and Dryers	Household laundry equipment manufacturing - primary products	PCU335224335224P
Microwave Ovens	Household cooking appliance manufacturing: Electric (including microwave) household ranges, ovens, surface cooking units, and equipment)	PCU3352213352211Y
Dishwashers	All Other Miscellaneous Household Appliances and Parts for Appliances	PCU3352283352285

[a] The refrigerator and freezer price trend was extended using a discontinued series from the Consumer Price Index - Urban Wage Earners and Clerical Workers.

[1] For a more complete description of the various analyses, see the specific DOE Technical Support Documents.
[2] http://www.bls.gov/ppi/
[3] For a detailed description of how the BLS performs this quality adjustment, see the BLS Handbook of Methods, Chapter14. http://www.bls.gov/opub/hom/homch14.htm

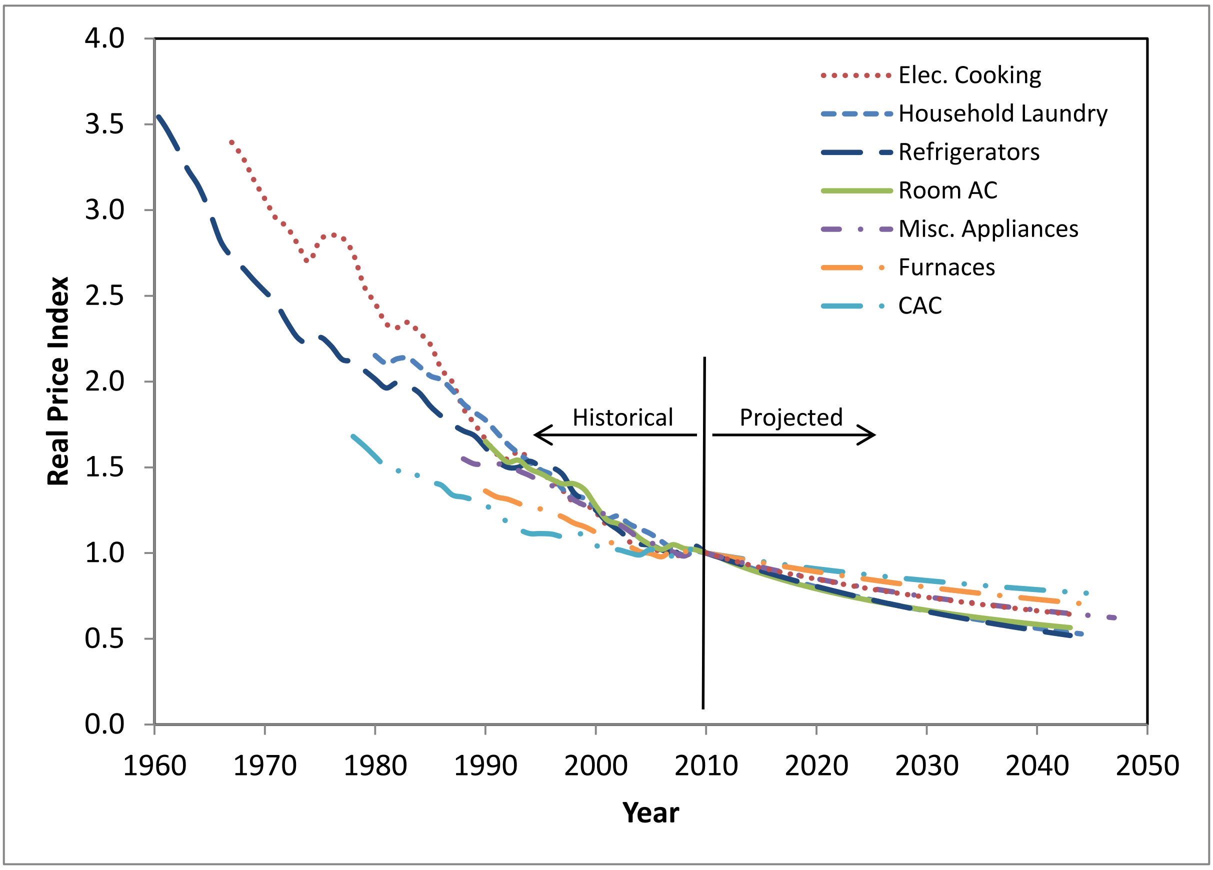

Figure 1: Historical and projected real price indices for major appliance categories in the U.S. Historical trends based on the PPI published by the U.S. Bureau of Labor Statistics. Projected trends are experience curve fits to the historical data.

The experience curve fits use simple least-squares fitting. As the BLS does not publish any uncertainty estimates for their indices, all data points are weighted equally in the fitting. Due to the uncertain nature of projecting price trends, however, several sensitivity scenarios were developed to characterize the impact of such uncertainty on the final NPV. These sensitivity scenarios included alternate data sources (e.g., Annual Energy Outlook), different models (e.g., experience curve vs. exponential model), and fitting to only a subset of the time series data. The latter explores the possibility of structural changes in certain markets, so that the experience curve parameters might change with time. Out of all these scenarios, the full range of sensitivity was considered to represent the uncertainty on the default price trend projection. The resulting experience curve parameters were then applied to the incremental cost of efficiency.

It is important to emphasize that the above analyses used an average shipment-weighted price trend (derived from PPI data) to estimate changes in the incremental cost of efficiency. This was a necessary approximation due to data limitations. Price trends were not available for individual design options or components. The same relative price trend was applied to all TSLs, representing both more mature and newer efficient technologies. In reality, various technologies to improve efficiency are likely to experience different price trends, as discussed below.

3. Results

The appliances examined include refrigerators, room air conditioners, furnaces, central air conditioners, clothes dryers, clothes washers, microwave ovens, and dishwashers. Figure 2 shows the impact of including price trends in cost-benefit analyses of efficient appliances (US DOE 2011a-d, 2012a-b). For furnaces and central air conditioners, the results are aggregated into HVAC (heating, ventillation, and air conditioning) equipment. In all cases, the consumer benefits, as measured by a positive NPV, are significantly greater when incorporating price trends. In some cases, the NPV actually changes sign, so that a previously uneconomical efficiency level becomes economical when assuming that the incremental price of efficiency will decline over the 30-year period.

The effect on NPV is also greatest for the highest efficiency levels. This is because the incremental cost of efficiency is largest for very high-efficiency products. The price trend utilized is a relative trend, therefore in absolute terms the highest efficiency levels experience the biggest cost difference when incorporating price trends. This is representative of real market behavior. The higher effciency levels represent more specialized, higher technology designs that can often carry large cost premiums when first introduced, but then quickly decline as market penetrations increase beyond just niche products.

The range of sensitivity scenarios also illustrate that the increase in NPV is relatively robust across multiple products and efficiency levels. In only a few specific cases, the impact of price trends on consumer NPV is less certain. These cases tend to be for high-efficiency designs only, where the impact of price trends is largest. For the other cases, including price trends leads to an average increase in NPV ranging from only a few percent for microwave ovens and dishwashers, to between 30-40% for HVAC equipment, clothes washers and dryers, and room air conditions, and finally to over 60% for refrigerators. Omitting price trends therefore results in a considerable underestimate of consumer benefits of using more efficient appliances. This work highlights the need to accurately reflect representative market dynamics (well supported by historical data) when assessing the impact of efficiency programs.

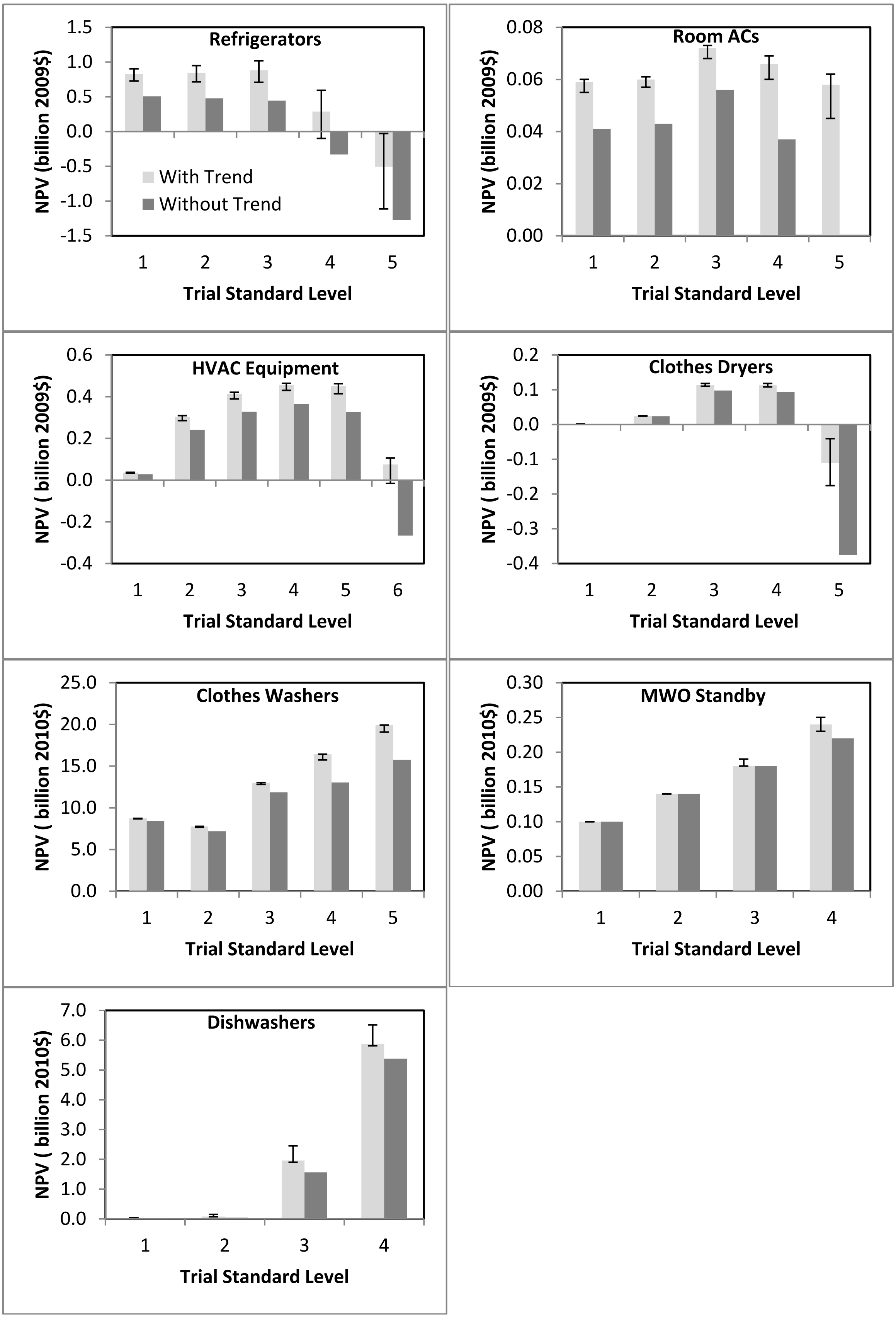

Figure 2: The net present value (in $US) of potential MEPS in the U.S., with and without price trends. Error bars indicate the full range of results from a sensitivity analysis. The analysis period is 30 years, and the discount rate is 7%.

4. Discussion

Detailed historical price data are often very difficult to obtain, especially over very long time frames. The PPI published by the BLS is a very convenient public data source, but it is not without potential issues. It is an index, not raw data. It represents producer prices, not consumer prices or manufacturing costs. And it includes only U.S. manufacturers. Despite these limitations, however, we believe the trend in the PPI is representative of actual consumer prices for all products sold in the U.S. Furthermore, the trends based on the PPI are likely to be conservative.

As shown in Desroches et al. (2013), the PPI trends match those obtained with alternate data sources, such as point-of-sale market research data, and data obtained from consumer magazines such as *Consumer Reports*. These latter sources represent direct consumer prices for a broad range of products (and not just U.S.-produced). The agreement between all these independent data sources suggests that using PPI data does not introduce any obvious systematic biases into the analysis, at least not for residential appliances. Additionally, Gordon (1990) demonstrated that the PPI is consistent with several other price trends determined from alternate data sources. These include the CPI specific to individual appliances, *Consumer Reports,* and prices listed in the *Sears* catalogue. Figure 3 shows these trends for refrigerators (the only major appliance with a significant CPI time series). Because the PPI is quality adjusted, the price trend derived from *Sears* data uses a hedonic model to account for changing product features. The CPI and Consumer Reports price trends both use pair-wise comparisons from year to year, to compare price changes of similar products. They are therefore quality adjusted. The refrigerator example further justifies the use of the PPI as a market price indicator, and if anything suggests that using the PPI results in a conservative price trend.

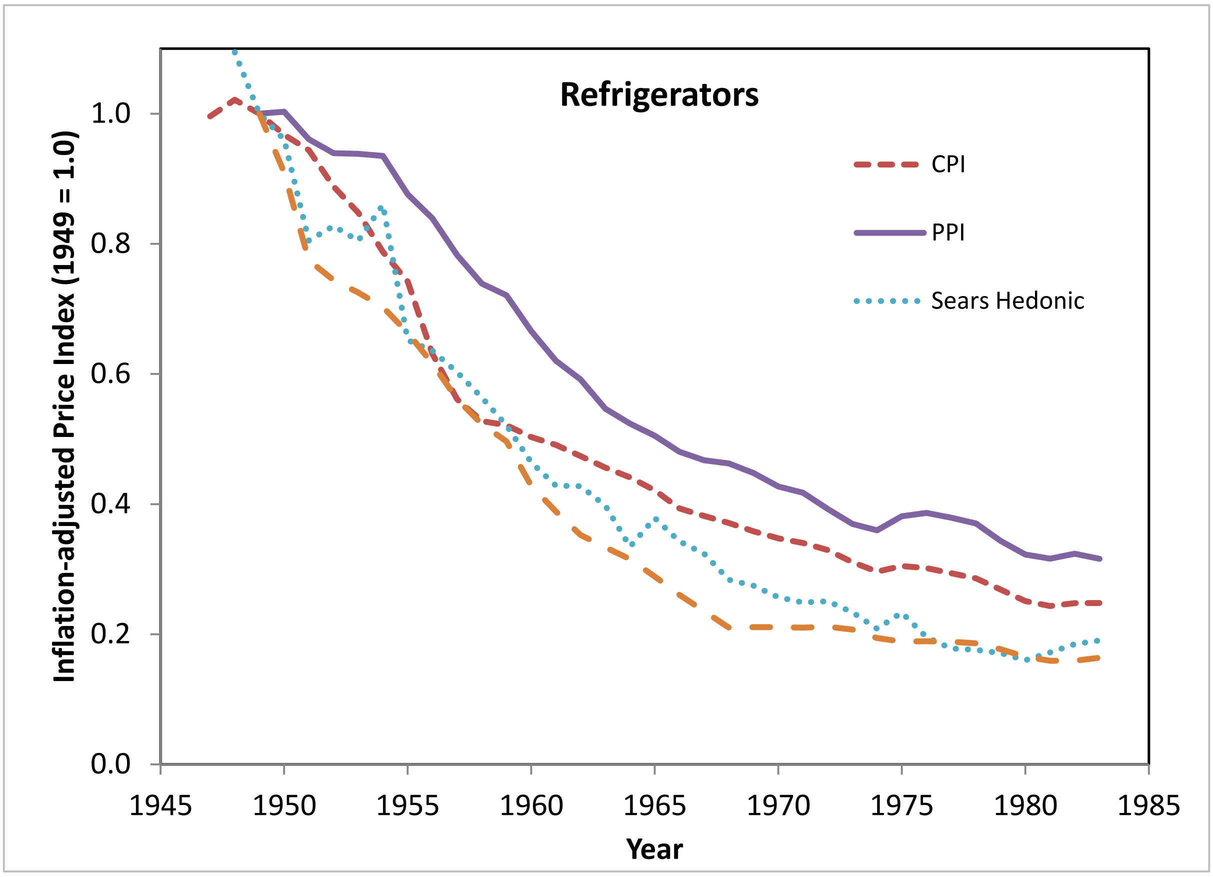

Figure 3: Comparison of various historical price trends for refrigerators sold in the U.S. All price trends are quality-adjusted. Data from Gordon (1990).

Price trends determined from PPI data cannot distinguish between more mature technologies and newer high-efficiency technologies, because the index is a shipment-weighted average over all products in a given category. Newer technology is likely to experience faster price changes than more mature technology, and thus applying the relative PPI trend to the incremental cost for all efficiency levels likely underestimates the change in the incremental price of efficiency. This can be seen qualitatively by comparing *ex ante* engineering estimates of the cost of efficiency for several appliances. Shown in Figure 4 are examples of cost-efficiency curves estimated for top-mounted refrigerators, room ACs, furnaces, and blower-coil split ACs for the U.S. market (US DOE 1995, 1997, 1999, 2007, 2011a-c). For each appliance, there are two sets of curves: an older estimate and a more recent estimate (naturally, the more recent estimates include more efficient design options). Dishwashers and microwave ovens are not included because they do not have older cost-efficiency curves to compare with. Clothes washers are not included because the most recent cost-efficiency curves do not overlap prior cost-efficiency curves (a testament to how quickly the efficiency of clothes washers is improving). The curves in Figure 4 are normalized such that the cost and energy use equal 1 for the baseline design option in the older engineering analysis. In all cases, it is very clear that the estimated cost of a given design option (i.e., at a given energy use) declines very rapidly in a short amount of time, in several cases by more than 50%. This change is much faster than the equivalent changes in the PPI trends, highlighting the difference between an average trend, and a technology-specific trend. As a result of this exercise, it is clear that the additional consumer benefits calculated using PPI price trends are, in fact, likely conservative. In reality, the incremental cost of efficiency for more efficient products likely declines faster than the average cost, leading to an even greater consumer NPV.

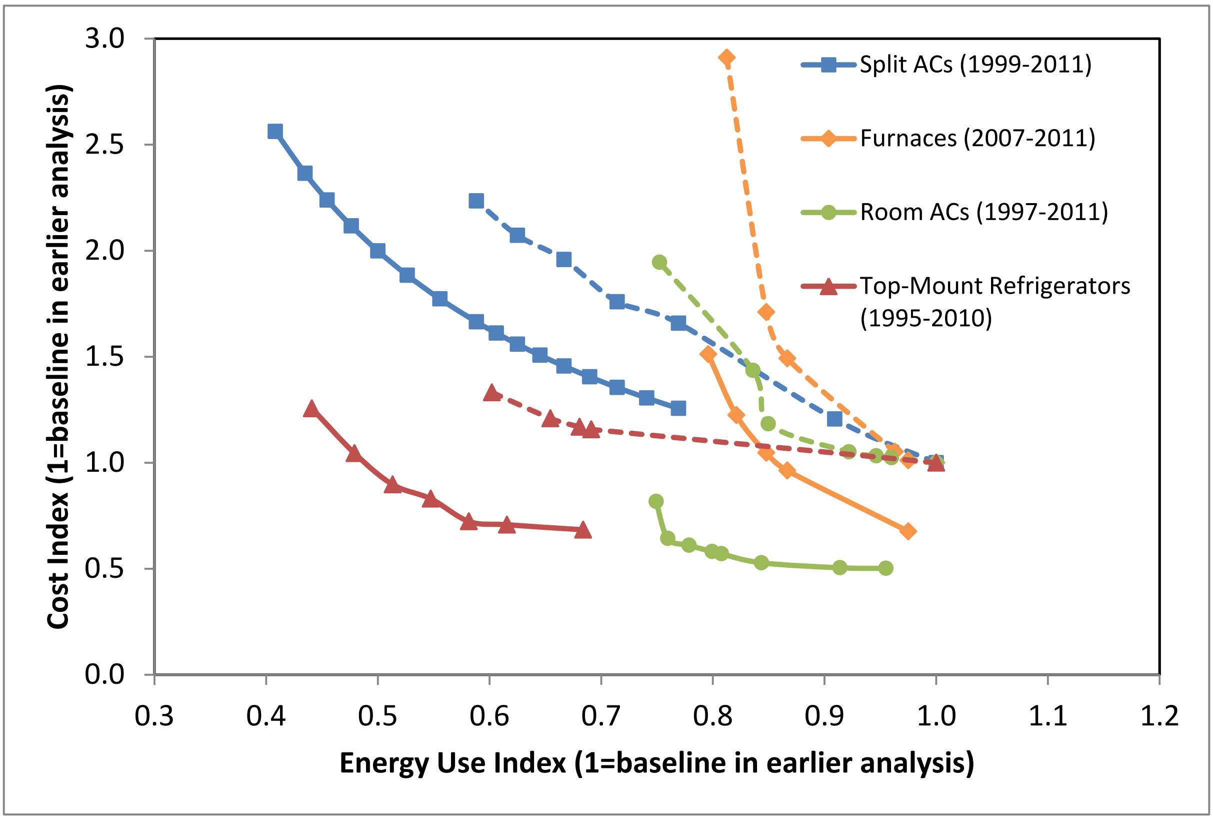

Figure 4: Ex ante estimated cost-efficiency curves for U.S. appliances. Each appliance has two sets of curves, one developed recently (solid line) and another developed several years prior (dashed line).

Unfortunately, technology-specific (or efficiency-specific) price data of such high quality are very difficult to obtain, and for many markets are likely impossible to gather. It is for this reason that the PPI trends are used in this instance. In a market such as the European Union, with a decade or so of mandatory energy labelling with several efficiency categories, it becomes possible to do a more sophisticated analysis of the evolution of price-efficiency relationships (Van Buskirk, 2013). When doing so, the incremental cost of efficiency for the most efficiency products appears to decline much faster than the average cost, perhaps by even an order of magnitude, consistent with the qualitative discussion above.

As an example of this phenomenon, we consider the television market in the U.S. Televisions offer a unique opportunity to study the dynamics of the cost of efficiency, due to the very rapid evolution of consumer electronics. Indeed, annual sales of televisions easily surpass those of any major appliance, and a relatively low product lifetime ensures that stock turnover occurs fairly quickly as compared to traditional household appliances. We use data from market research firm DisplaySearch[4], which develops a pricing model for individual television technologies and sets of features. In particular we consider CCFL LCD televisions (cold cathode fluorescent lamp liquid crystal display), which are inexpensive to manufacture,

[4] http://www.displaysearch.com

and LED edge-lit LCD televisions (light emitting diode liquid crystal display), which are more efficient and more expensive to produce. Figure 5 illustrates the historical and projected average selling prices of 32" televisions (a very popular size), both medium and high resolution, with 60 Hz refresh rates. Experience curves are also fit to each time series. Given that all other features are the same, we can approximate the price premium for LED televisions as the incremental cost of efficiency. That incremental cost is clearly declining very rapidly. In just a few short years the incremental cost will be essentially negligible.

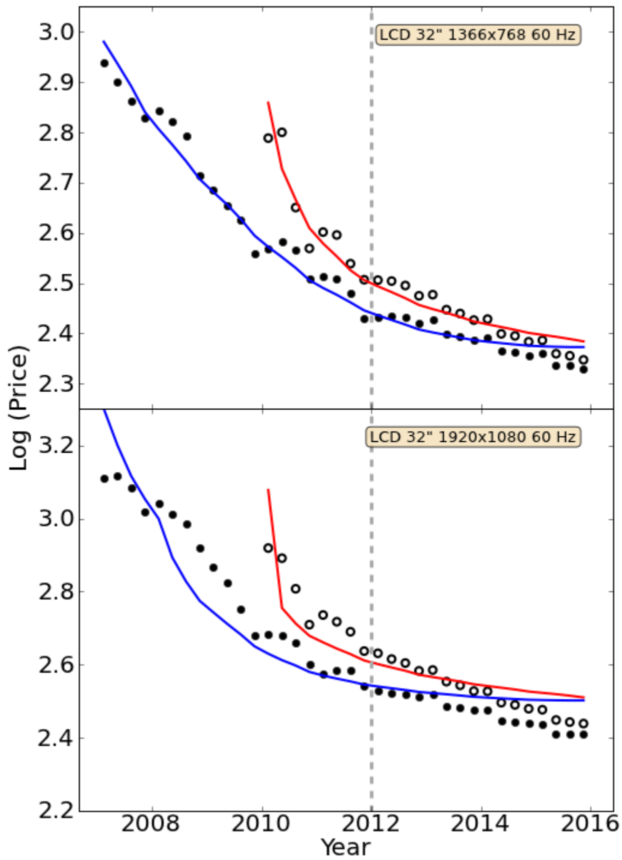

Figure 5: The declining incremental cost of efficiency in televisions. Shown are modelled average selling prices from DisplaySearch for CCFL LCD televisions (solid circles) and LED edge-lit LCD televisions (open circles). Top panel is for 1366x768 resolution televisions, and the bottom panel is for 1920x1080 resolution televisions. Data prior to 2012 are historical estimates, and data after 2012 are projections. Experience curve fits (lines) are also shown.

This is further illustrated using television point-of-sale data from market research firm NPD[5]. The point-of-sale data offer the added benefit of separating according to ENERGY STAR qualification. Looking at just 32" CCFL LCD televisions, we consider the average historical selling price of ENERGY STAR and non-ENERGY STAR CCFL televisions, as show in Figure 6. The incremental cost of efficiency again declines relatively quickly, so that the price premium for more efficient products becomes insignificant in a short amount of time. We

[5] http://www.npd.com

note that the ENERGY STAR specifications were updated several times between 2007-2011, so televisions before and after a specification revision cannot be compared directly.

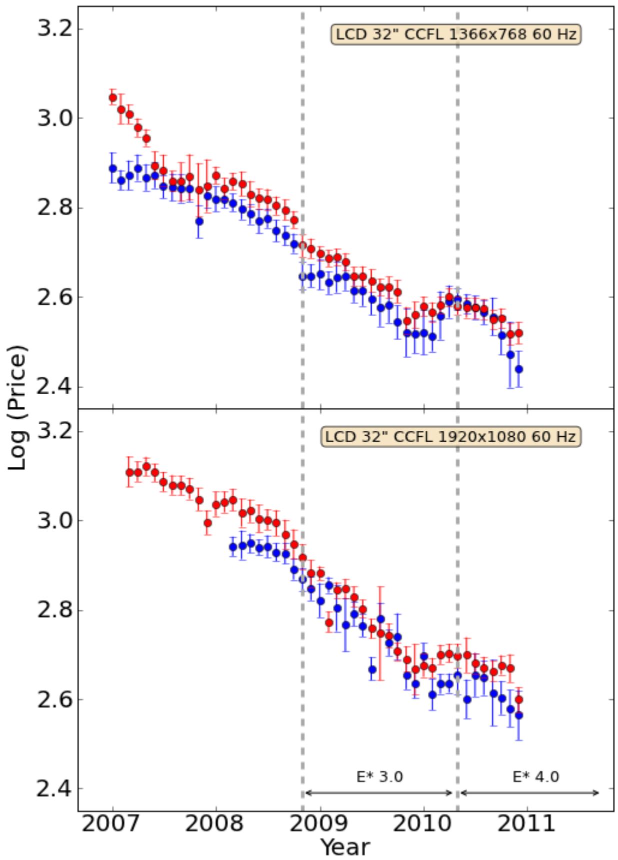

Figure 6: The declining incremental cost of efficiency in televisions, continued. Shown are the shipment-weighted average selling prices from point-of-sale data from NPD, for 32" ENERGY STAR-qualified CCFL televisions (upper circles) and non-ENERGY STAR-qualified CCFL televisions (lower circles). Top panel is for 1366x768 resolution televisions, and the bottom panel is for 1920x1080 resolution televisions. The effective dates for ENERGY STAR specification revisions are also shown.

5. Conclusions

Using historical price trends for several appliance categories in the U.S., we developed experience curves to more accurately represent price dynamics in economic impact modelling of more efficient appliances. When including these trends in the economic impact modelling, the estimated consumer benefits (in the form of a positive net present value) are larger by up to 60%. This suggests that omitting such price trends probably undervalues consumer benefits of using efficient appliances. Furthermore, the projected price trends developed are likely to be conservative, and the actual consumer benefits may in fact be significantly larger.

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