The benefits of energy efficiency standards and how policies may accelerate declines in appliance costs

R D Van Buskirk[1], C L S Kantner[1], B F Gerke[1], L-B Desroches[1] and S Chu[2]

[1] Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California, U.S.A. 94720-8136
[2] Department of Physics and Department of Molecular and Cellular Physiology, Varian Bldg., Room 252, Stanford University, Stanford, CA, U.S.A. 94305-4060

E-mail: RDVanBuskirk@lbl.gov

Abstract. We perform a retrospective analysis of multi-decade trends in price and life-cycle cost for home appliances in periods with and without energy-efficiency standards. In contrast to the classical picture of the impact of efficiency standards, the introduction and updating of appliance standards is not associated with a long-term increase in purchase price; rather, quality-adjusted prices undergo a continued or accelerated long-term decline. We also show that the incremental price of efficiency improvements has declined much faster than the baseline product price. Both observations are consistent with an alternative picture of energy efficiency standards in which such policies increase long term rates of learning-by-doing for both price and life-cycle cost.

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1. Introduction

Energy efficiency (EE) standards are widely viewed as a key policy tool for reducing energy consumption, saving money, and mitigating climate change [1]. There has been substantial debate, however, in both the academic literature and the political discourse regarding the impact of standards on both the life-cycle cost of ownership (LCC) and on the purchase price of home appliances. Many studies argue that appliance standards achieve a net neutral or beneficial economic impact by decreasing the operating energy costs more than the increase in purchase price expected to result from compliance with the standard [2, 3, 4, 5, 6]. Other papers assert that such mandates as EE standards are inefficient and costly means of decreasing CO_2 emissions based on assumed parameters [7] or are likely to lead to expensive products that may force budget-constrained consumers to choose products of lower quality or reduced features [8]. There also exists a fairly extensive literature on innovation that may be induced by regulation. This literature discusses a diverse range of cases where regulation may have caused private firms to create innovations that would not have occurred in the absence of regulation [9].

Over the past quarter century, the academic debate on the costs and benefits of EE standards has been based on short-term snapshots of appliance market conditions and has not addressed the impacts of EE standards on innovation. From this short-term perspective—which assumes that innovation effects are not significant—the primary problems addressed by the regulation are market failures associated with environmental externalities, imperfect information, principal-agent issues, liquidity constraints, or behavioral anomalies [10]. Energy policies, such as minimum EE standards and labeling policies (e.g., ENERGY STAR Program), are devised to address these market failures and informational problems that lead to socially suboptimal outcomes. In the classical regulatory impact analysis picture, labels and mandates bring the market to a new equilibrium where appliances have higher prices and lower operating costs. The lower operating costs and internalized market externalities of the more efficient appliances are thought to justify the higher purchase prices paid by consumers.

Recent empirical work with appliance market data suggests that price-efficiency relationships observed in appliance markets may be far from static [11]. Some studies argue that the prices decline faster than forecast in regulatory analyses due to technological innovation [12]. Additionally, a recent study of the 2004 and 2007 US EE standards for clothes washers finds that the rate of decline in appliance prices appears to have accelerated after the EE standards came into effect [13]. This observation is largely inconsistent with the static picture of EE standards impact that is traditionally used in policy analysis which would have predicted a price increase. As a growing number of observers examine the retrospective data on appliance price changes associated with EE standards, there appears to be an expanding body of evidence suggesting that the traditional static picture of EE standards impacts on costs may be inconsistent with observed market behavior [14].

In this paper, we investigate long-term trends in appliance prices and energy use in an effort to better understand interactions between policy and rates of change in appliance markets. Specifically, we examine the long-term dynamics of markets for efficient products and estimate long-term rates of change of appliance first costs and operating costs for periods both with no EE policy and with active EE standards and labeling programs. Our analysis considers mandatory EE standards, but the results may also be applicable to EE labeling programs that allow consumers to make cost-effective trade-offs between the price of efficiency and energy-cost savings [15].

The discussion of market failures in the literature with regard to EE technology has largely focused on factors that hinder consumers' choice of efficient technologies that are cost-effective on a life-cycle-coast basis—the so-called energy-efficiency gap. From the long-term-dynamics perspective, an economically inefficient market equilibrium at a particular point in time may not be the only market failure addressed by regulation. Another market failure that regulation may potentially address is the well-known market failure regarding underinvestment in research, development and innovation [16, 17, 18]. In particular, the structure of the supply markets for appliances may lead to underinvestment in innovation, thus hindering EE in the menu of products offered to consumers. There is evidence that the supply markets for appliances are not perfectly competitive and there are varying levels of industry concentration, which can lead to price discrimination and under-investment in EE by manufacturers [19]. In a theoretical model [20], Fischer demonstrated that when suppliers discriminate on price, they will offer less efficient products to the low-income consumers and extract their entire economic surplus, while charging high-income consumers more for the higher efficiency appliances than in a perfectly competitive market. In this situation, minimum EE standards will increase consumer welfare. This study examines new economic evidence regarding rates of change in quality-adjusted product prices and EE, which may indicate that changes in consumer costs and welfare over the long term are driven by changes in EE policy.

2. Life-cycle cost

EE standards effectively mandate the manufacturing of appliances and equipment that may have a higher first cost but which have lower operating costs. The total consumer impacts of EE standards are estimated by calculating the energy-related[*] LCC of an appliance, which is a sum of the purchase price P_A and the energy-related operating costs over time, $OC(t)$. LCC includes a discounted sum of operating costs, because money spent on operating costs y years in the future is worth less than the same amount of money in the present which could be invested at some interest rate.[†] Assuming a yearly compound interest rate i, the present value of an expense y years in the future is discounted to $OC(y)/(1+i)^y$, so that the total present value of operating costs over the appliance lifetime of L-years is given by

$$PVOC_L = \sum_{y=1}^{L} \frac{OC(y)}{(1+i)^y} \tag{1}$$

The sum of price and present value of operating costs then provides an estimate of the LCC of that appliance:

$$LCC = P_A + PVOC_L \tag{2}$$

[*] This analysis assumes that non energy-related operating costs (e.g., maintenance and repair costs) are independent of EE and therefore irrelevant to the effect of EE policy on LCC.

[†] If operating cost is measured in inflation-adjusted dollars, the inflation-adjusted interest rate is used. We assume operating costs and interest are charged at the end of the year in which they occur.

3. Experience curve calculations

Experience curves (also called learning curves) can be used to describe price trends for many technologies[‡] by modeling price P as a power-law function of the total cumulative quantity Q of units deployed: $P = P_o Q^{-b}$ where P_o and b are empirically determined parameters [21, 22, 23]. Q is the observable variable used as proxy for cumulative manufacturing experience [24]. The parameter b is a parameter that describes the relation between fractional increases in experience and fractional declines in price. The experience curve concept is based on the empirical observation that people and organizations complete tasks more efficiently as they accumulate experience, thus reducing the marginal cost of production. However, there are other mechanisms that could also yield a correlation between price and cumulative experience (e.g., changes in pricing strategies or globalization of manufacturing operations and supply chains). In this study, we will use the phrase *experience curve* as shorthand to refer to any empirical correlation between price and cumulative experience, without necessarily linking observed trends to learning-by-doing processes.

To calculate the experience curves, we estimate inflation- and quality-adjusted prices over time by projecting current prices into the past using product-specific price indices. Price indices provide a method of accounting for changes in the mix of products offered in the market, as well as the quality and features of those products. For example, the refrigerators that were available for sale in the 1960s are no longer available today, and the technologies, features and configurations of refrigerators today did not exist in the 1960s. Any measurement of long term price trends needs to account for these gradual but significant changes.

For US data, we use price indices published by the Bureau of Labor Statistics (BLS) and the Bureau of Economic Analysis. [See the Supplemental Information (SI) for additional detail regarding price indices and the calculation of experience curves.] The BLS provides both consumer price indices for retail purchase prices and producer price indices for the prices received by producers for their products. We use the all-items consumer price index (CPI) to adjust for inflation in our analysis. In some cases our CPI data is sourced indirectly from the BLS using tables published by Gordon [25].

In the LCC calculations, to estimate an average price in a recent year, we use the shipment-weighted average price obtained from the LCC spreadsheets associated with the Department of Energy's (DOE) most recent rulemaking or notice of proposed rulemaking for a particular appliance. These spreadsheets are available on the DOE's Appliance Standards website as part of technical support documents created for each rulemaking. We obtain the historical inflation- and quality-adjusted prices by multiplying this recent shipment-weighted price by the appropriate inflation- and quality-adjusted price index.

We obtained data to estimate historical average energy use from a variety of different sources, including the Association of Home Appliance Manufacturers (AHAM), recent DOE rulemakings, DOE's Energy Information Administration's (EIA) Residential Energy Consumption Surveys [26], and the published literature [27]. For periods with missing or incomplete data, we interpolate from the historical trends. In the case of clothes washers, we also consider water usage and water efficiency when calculating operating costs. Water usage data were obtained from recent DOE rulemakings.

[‡] The experience curve literature focuses on product cost rather than price. Although price often deviates from the cost of production, we assume that on average the price trend is a good approximation of the cost trend.

We use historical average retail prices of electricity for residential consumers from the Annual Energy Review published by EIA [28]. For years prior to 1960, we extrapolate the retail price of electricity using the CPI for electricity [29]. In the case of water, the average retail price in 2008 was obtained from a recent DOE rulemaking analysis, and extrapolated to prior years using the CPI for water and sewage maintenance.

Cumulative unit shipments to the US market for each product are estimated using annual shipment data from recent DOE rulemaking analyses. Other inputs to the LCC calculation, such as the appliance lifetime and discount rate, are similarly estimated using data from these DOE analyses. We follow DOE's practice of using a weighted-average consumer cost of capital from a variety of debt and asset classes to represent the discount rate, because that average represents the financial cost of money to a consumer. For a review and discussion of the issues surrounding discount rates and the energy efficiency gap, we recommend Jaffe and Stavins [30]. Depending on the rulemaking, the average discount rate for each appliance type was found to be 5.0 ±0.5%. For simplicity, we use an average real discount rate of 5.0% in the LCC calculations for all appliances.

For refrigerators in the Netherlands, we obtained price and energy use data from Weiss et.al. [31] and from the German market research firm The GfK Group. These refrigerator price data are not quality-adjusted. We calculate the inflation adjustment using the Harmonized Index of Consumer Prices (HICP) from Eurostat [32]. We obtained nominal pre-tax electricity prices from Eurostat [33], and estimate post-tax electricity prices using tax rates from the U.K. Department of Energy and Climate Change [34]. We use the average tax rate for 2008 and 2009 as the assumed tax rate for the analysis period. Historic shipments were obtained from an Ecocold report [35]. Shipments to the EU-15 nations were used as the basis for experience, since manufacturers tend to sell products across the European market. The lifetime and discount rates are assumed to be constant in time and the same as those of US refrigerators.

The ultimate product of this data collection, processing, and integration is a set of yearly time series for cumulative shipments, prices, and LCCs, for four US appliances and for refrigerators in the Netherlands. Shipments data refer only to the US market (or the EU market for Netherlands refrigerators). Global shipments would be a closer indicator of cumulative experience, but provided that manufacturers' global shipments grow consistently with their US/EU shipments, power-law experience curves can be accurately fitted using the more limited data set. We combine the price and LCC data with the shipments data to obtain experience curves, $P(Q)$ and $LCC(Q)$.

4. Efficiency policy and changes in long term trends

Figure 1 shows the results of fitting experience curves to price and LCC for four major US appliances (refrigerators, clothes washers, room air conditioners and central air conditioners) and for refrigerators in the Netherlands. These products were chosen because multi-decadal information was available both before and after the establishment of standards ("pre-standards" and "post-standards," respectively). In all cases, the price and LCC generally decline with time, and a significant transition can be seen in the LCC decline rate parameter near the initiation of standards. A distinct acceleration of the price decline can also be seen for clothes washers, room air conditioners, central air conditioners, and refrigerators in the Netherlands.

We consider the post-standards period to begin after the issuance of the first standard likely to affect the market under consideration. In most cases, the first standard corresponds to a federal standard, or to a European Union standard in the case of refrigerators in the Netherlands. We also consider California standards given that California is the most populous US State and therefore constitutes a significant fraction of the US appliance market. In some cases, California efficiency standards may have been effectively treated as a national standard by manufacturers.

We fit the data with a simple mathematical model that includes two power-law experience curves with different decline-rate parameters *b*, corresponding to the periods before and after a transition year. The decline rates, transition year, and overall normalization are treated as free parameters, allowing us to calculate the transition year within a 95% confidence interval using standard maximum-likelihood techniques. [See the SI for further details. The SI also evaluates the sensitivity of results to variations in model formulation.] Table 1 provides the resulting transition years and confidence intervals of these experience-curve fits for US refrigerators, clothes washers, room air conditioners, central air conditioners, and Netherlands refrigerators, and compares them to the first year of efficiency standards for these products.

Table 1. Results for least-squares, two-slope experience curve model fit of price and LCC for the appliances considered in this study; 95% confidence intervals were calculated from the appropriate χ^2 distribution. For reference, the year of the first efficiency standard implementation is also shown for each appliance.

		Transition Year		**Pre-Transition Decline Rate *b***		**Post-Transition Decline Rate *b***	
Appliance	**First Efficiency Standard Year**	**LCC**	**Price**	**LCC**	**Price**	**LCC**	**Price**
Refrigerators (US)	1977	$1977.2^{+2.3}_{-3.2}$	$1995.0^{+3.7}_{-8.0}$	$0.36^{+0.01}_{-0.08}$	$0.84^{+0.05}_{-0.00}$	$1.25^{+0.00}_{-0.05}$	$1.51^{+0.04}_{-0.14}$
Clothes Washers (US)	1988	$1989.8^{+1.9}_{-1.2}$	$1986.9^{+1.3}_{-1.5}$	$0.12^{+0.04}_{-0.00}$	$0.45^{+0.03}_{-0.03}$	$1.20^{+0.01}_{-0.10}$	$0.98^{+0.00}_{-0.03}$
Room Air Conditioners (US)	1979	$1976.3^{+1.8}_{-2.8}$	$1972.8^{+1.3}_{-1.6}$	$0.16^{+0.04}_{-0.01}$	$0.27^{+0.01}_{-0.04}$	$0.76^{+0.00}_{-0.04}$	$0.75^{+0.01}_{-0.04}$
Central Air Conditioners (US)	1979	$1975.5^{+4.0}_{-0.9}$	$1973.9^{+3.1}_{-2.3}$	$0.01^{+0.03}_{-0.00}$	$0.07^{+0.03}_{-0.03}$	$0.39^{+0.02}_{-0.03}$	$0.28^{+0.00}_{-0.03}$
Refrigerators (Netherlands)	1999	2000^{+4}_{-26}	2001^{+2}_{-14}	$0.45^{+0.14}_{-0.15}$	$0.25^{+0.32}_{-0.14}$	$1.08^{+0.11}_{-0.11}$	$0.80^{+0.12}_{-0.12}$

The correspondence between calculated transition year and first efficiency standard year can be seen in figure 2 with 95% confidence intervals shown as error bars. In almost all cases, the data yield a transition year that is close to the onset of standards, with the exception of US refrigerator purchase price. The confidence intervals for the Netherlands refrigerator case are relatively large because of the larger variance in the available price and efficiency data.

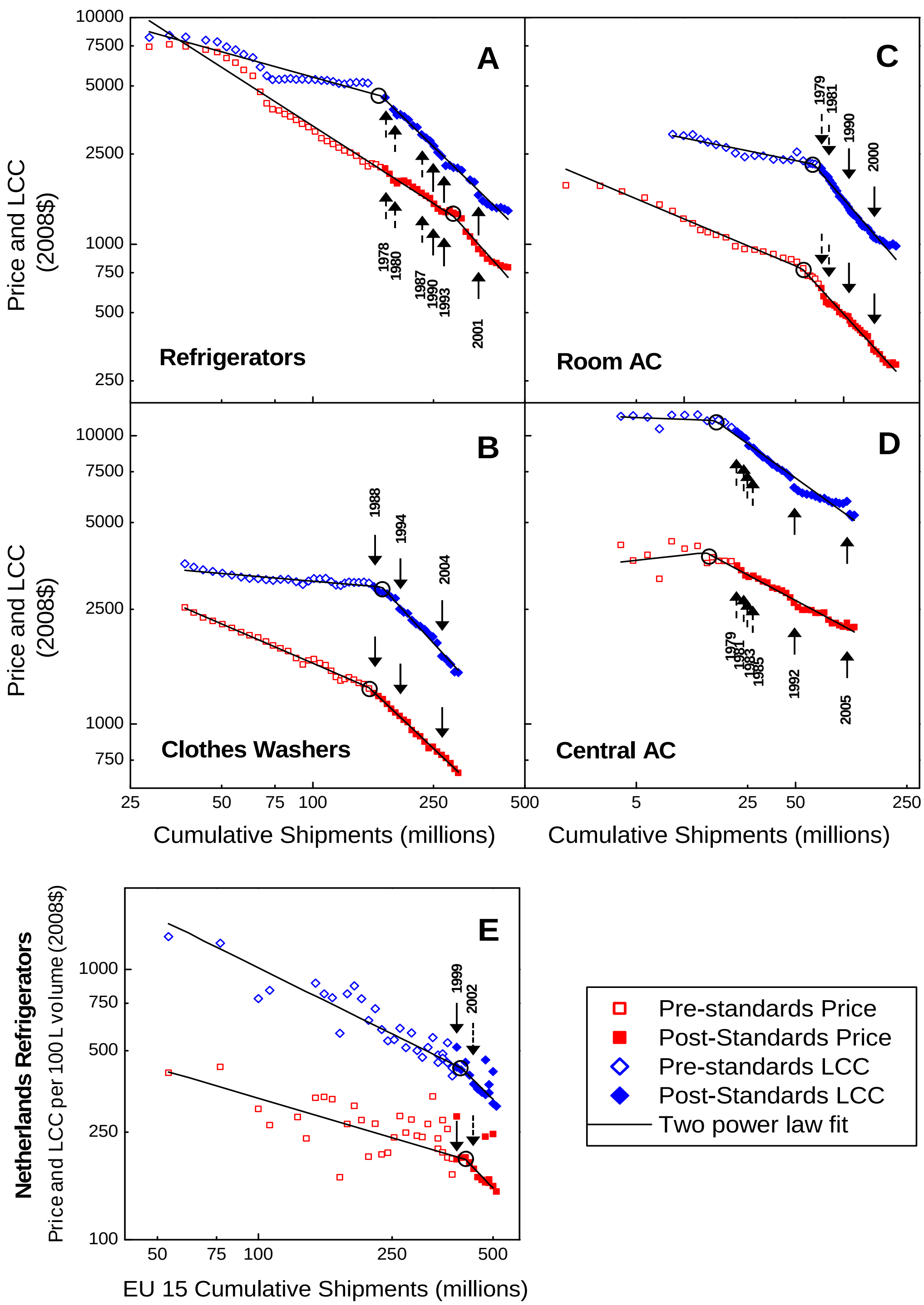

Figure 1. Price and LCC trends for appliances pre-standards and post-standards. Unfilled symbols indicate pre-standards data, while solid symbols indicate the post-standards era. Lines indicate best-fit experience curves from the two-trend model. Circles indicate transition points in the decline rates. Data are shown for United States (*A*) refrigerators, (*B*) clothes washers, (*C*) room air conditioners, and (*D*) central air conditioners, as well as for (*E*) Netherlands refrigerators. Netherlands refrigerator price and LCC are shown per 100 liters of volume, and cumulative shipments are for the EU. In figures 1(*A) – (D)*,

the dashed and solid arrows represent California and Federal standards, respectively. In figure 1(*E*), the dashed arrows indicate a voluntary agreement with manufacturers, and solid arrows indicate mandatory standards.

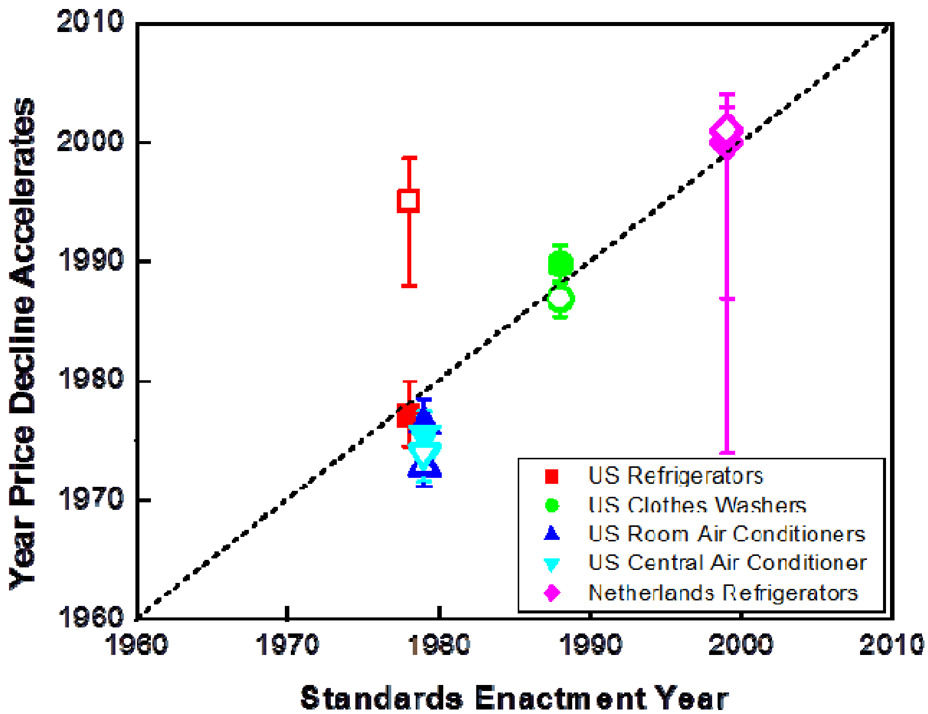

Figure 2. The calculated year of transition to an accelerated price or LCC decline, as a function of the year standards are first enacted. Open symbols correspond to price transition year, closed symbols to LCC transition year. If the change in slope of the experience curves in figure 1 occurred at the time the standard was introduced, the data points would lie on the dashed line.

5. Trends in the incremental price of efficiency: the case of US refrigerators

The price and LCC trends observed in figure 1 clearly diverge from historical, pre-2011 US regulatory forecasts, which assumed no future price declines in the absence of new standards, and which projected an increase in appliance price following the introduction and subsequent updates of standards. We compiled historical, engineering-based estimates of the relationship between appliance price and efficiency that were developed in DOE regulatory analyses accompanying the consideration of new or updated efficiency standards for refrigerators. For refrigerators, new mandatory Federal EE standards had initial compliance dates of 1990, 1993, 2001 and 2014, with supporting analyses performed in 1982, 1987, 1989, 1995, and 2010. At the time each analysis was done, the incremental cost of higher efficiency was based on the current market costs of introducing technologies to achieve a given efficiency. The full historical sequence of price-efficiency estimates for 17- to 18-cubic-foot refrigerators with top-mount freezers and automatic defrost is shown in figure 3*(A)*. Note that the most energy-efficient refrigerator considered in 1989 had higher energy use than the least efficient refrigerator considered in 2010, and the estimated price of achieving that efficiency was roughly twice the price estimate of the least efficient

2010 refrigerator. Over the period considered, the efficiency of the least efficient refrigerator on the market improved at an average rate of 4% per year while its price dropped 2.5% per year.

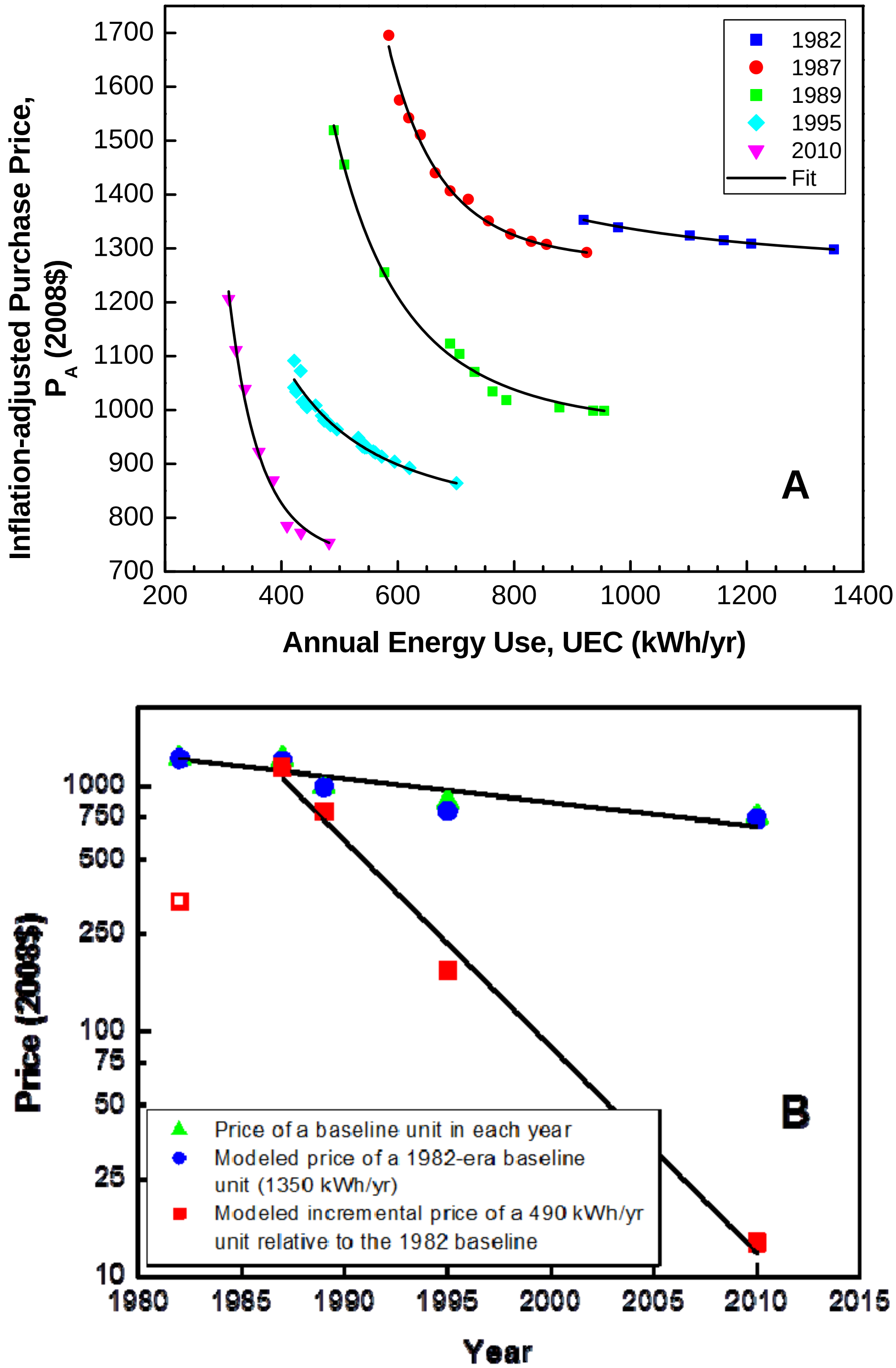

Figure 3. Modeling of energy use vs. price. (*A*) Engineering-based estimated purchase price of US 17- to 18-cubic-foot top-mounted refrigerator-freezers as a function of annual energy. Solid lines show the fit to the data using equation (2). (*B*) Evolution in the modeled price of the baseline, least efficient refrigerator

on the US market in each year (green points); a refrigerator with a fixed efficiency of a 1982-era baseline unit (blue points); and the incremental price associated with a fixed efficiency increase relative to the 1982 baseline (red points). Solid lines show the exponential fit of (4) to the red and blue points. The incremental price for 1982 (hollow symbol) is excluded from the fit because 490 kilowatt-hours per year (kWh/yr) is well outside the estimated price-efficiency range for that year, so this point is derived from an extreme extrapolation.

We mathematically characterize the price-efficiency relation as a baseline price P_{min} plus a power-law relation between unit energy consumption (UEC) and the additional price of achieving that efficiency level:

$$P_A(UEC) = P_{min} + P_{UEC}\left(\frac{UEC}{UEC_0}\right)^{-\varepsilon} \tag{3}$$

Here, P_{min} is the minimum price of an appliance, P_{UEC} is the additional price required to purchase an appliance whose energy consumption takes a reference value UEC_0 (which we are free to choose), and ε is the power law exponent, which, in economic terms, represents the elasticity of the energy-related price component with respect to efficiency. Figure 3*(A)* illustrates a reasonably good fit to the engineering-based price-efficiency estimates using this simple functional form, where we have fit the model in (3) to each of the five price-efficiency estimates separately, yielding five sets of fit parameters (see Table 2).

Table 2. Results of fitting engineering-based price-efficiency estimates for refrigerators with a power-law model (3).

Year	P_{min}	P_{UEC}	UEC_0	ε	R^2
1982	1260	38.1	1350	2.32	0.995
1987	1270	20.7	925	6.47	0.991
1989	961	37.6	955	4.07	0.995
1995	796	67.9	700	2.65	0.993
2010	717	36.8	482	5.90	0.991

From these fits we can estimate the evolution of the price of a refrigerator with fixed efficiency and of the incremental price of a fixed increase in efficiency. For each of the five fits shown in figure 3*(A)*, figure 3*(B)* shows the actual baseline price, the modeled price of a 1982-era baseline unit, and the modeled price increase required to improve the 1982 baseline unit to a reference energy consumption of 490 kWh/yr, a value chosen since it lies in or near the range of UEC values covered by most of the engineering estimates after 1982.

The evolution of our fit parameters over time demonstrates that the price of efficiency declines at a much faster rate than the price of the baseline appliance. We can quantify this by fitting our price measurements to a Moore's-law type model in which price declines exponentially with time:

$$P_X = P_{X0}e^{-\alpha_X(t-t_0)} \tag{4}$$

where X represents either the 1982-baseline-efficiency unit or a unit with a UEC of 490 kWh/yr **(**see the SI for more detailed discussion of Moore's-law type price trends). If the price of refrigerator efficiency mirrored the overall trend in refrigerator price, we might expect the incremental price of a fixed increase in efficiency to decrease at the same rate as the quality-adjusted price: 2.5% per year. This assumption has been used in recent appliance standards rulemakings that have incorporated experience curves [36]. Instead, the data presented here show that while the price of a fixed, low-efficiency refrigerator declines at that rate, $\alpha_{min} = 0.025$, the incremental price of improving that efficiency by a fixed amount drops much more quickly: $\alpha_{UEC} = 0.19$, or a rate of price decline of roughly 19% per year between 1987 and 2010 (see figure 3*(B)*)

This rapid drop in the price of efficiency may be what allowed the price of refrigerators to continue to decline even as efficiency has improved at 4% per year. The incremental price increase of a given efficiency improvement rapidly became negligible compared to the more slowly declining baseline price.

6. Price-efficiency trends for European Union refrigerators

While the results for US refrigerators give some indication that the price of efficiency may have rapidly decreased over time, engineering curves are estimates, not observed prices. Aggregated European refrigerator sales data from ten European countries (Austria, Belgium, Great Britain, Italy, the Netherlands, Germany, Spain, and France, Sweden and Portugal) enable us to model the observed efficiency-categorized price over time directly.[§] Equivalent data are not available for the US because the US does not have labeling requirements with multiple EE categories.

[§] Europe uses a substantially different refrigerator test procedure than does the US; energy use figures are not directly comparable.

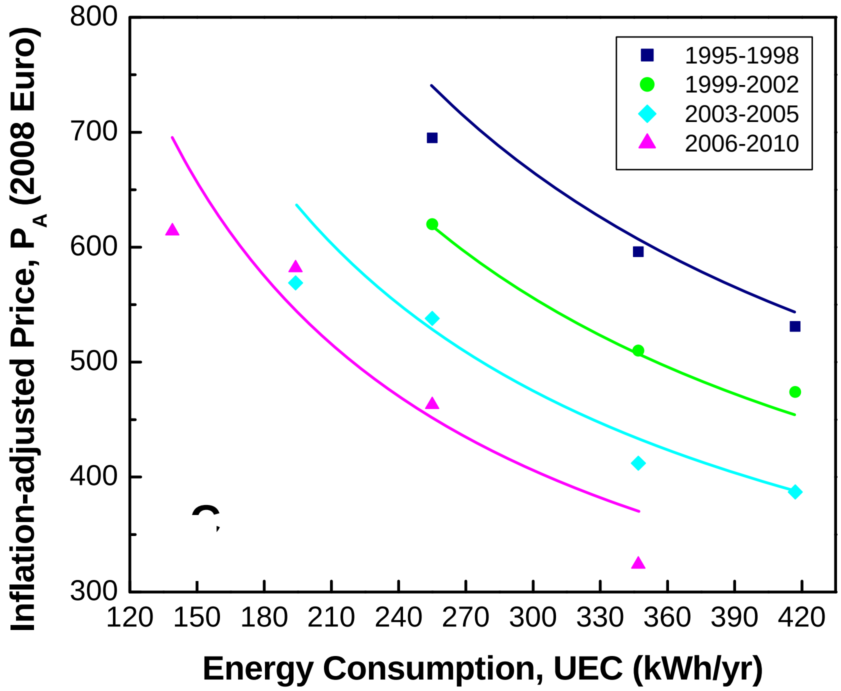

Figure 4. Market-based price-efficiency estimates for European refrigerators illustrating the evolution over time. Points correspond to categorical averages over several years. Solid curves show the fit to these categorical averages using (5).

As with the Netherlands data, we use sales-weighted averages of retail prices (not quality-adjusted) obtained from The GfK Group. We adjusted prices for both inflation and consumer purchasing power differences between countries [37] and converted all prices into 2008 Austrian purchasing power parity (PPP) Euros. We obtained comparative price indices for purchasing power parity adjustments between countries from table 1357 of the 2012 US Statistical Abstract [38].

We obtained refrigerator price data binned according to EE grade, which range from A++ to G for each country in the sample. The grades correspond to an energy efficiency index (EEI), which is defined as a unit's energy consumption divided by the consumption of an average model (based on all models on the market from 1990–1992) for units of the same adjusted volume. The European Commission adopted the grades in 1992 (92/75/EC). The grades were implemented into national ordinances between 1994 and 1998. The A+ and A++ grades were introduced in 2003 (2003/66/EC) and began being implemented in 2004. To scale the EEI to the energy use of a refrigerator, we set an EEI of 100% at 463 kWh/yr, the value the European Commission cited in its COLD II report [39]. Refrigerator volume was approximated as constant during 1995–2009.

Similar to the Netherlands refrigerator analysis, European electricity prices are estimated using data from Eurostat [40] and UK Department of Energy and Climate Change [41]. We use the same lifetime and discount rate assumptions as those for US refrigerators: 17.1 years and 5.0% per year, respectively.

We perform a simplified fit to the European data using (5) and assuming an exponential dependence of price on time (i.e. a form of Moore's law: see SI for details):

$$P_{UEC}(UEC,t) = P_{UEC0}e^{-\alpha(t-t_0)}(UEC/UEC_0)^{-\varepsilon} \tag{5}$$

where P_{UEC_0} is a reference price at a particular reference annual energy use UEC_0 and reference time t_0.

Figure 4 shows the fit to the European market data, which describes the data reasonably well (see SI for additional details). Within a category corresponding to an EE grade, the average inflation-adjusted price declined by 4.5% per year between 1995 and 2009, while the average shipment-weighted inflation-adjusted price computed across all efficiency categories declined by approximately 1.3% per year. The market average estimated UEC simultaneously decreased by 4.2% per year. As in the US, European refrigerator prices have declined even as efficiency policies have increased the average efficiency on the market.

7. Life-cycle cost optimization

By analyzing price trends for baseline prices and for the incremental price of efficiency, it may be possible to generate more accurate price-efficiency forecasts and thereby devise more optimally beneficial policies. We can combine (2) and (3) above to obtain an equation for LCC as a function of UEC. Minimizing this equation with respect to UEC then yields the following optimization condition (see the SI for a detailed derivation):

$$LCC_{\min} = P_A + \varepsilon P_{UEC} \,. \tag{6}$$

Inserting the Moore's-Law model for the time evolution of price from (4) gives an equation for the time evolution of the minimum LCC:

$$LCC(t) = P_A e^{-\alpha_{min}(t-t_0)} + \varepsilon P_{UEC0}\left(\frac{PVOC_L(UEC_0)}{\varepsilon P_{UEC0}}\right)^{\frac{\varepsilon}{1+\varepsilon}} e^{-\alpha_{UEC}(t-t_0)/(1+\varepsilon)} \,, \tag{7}$$

where $PVOC_L(UEC_0)$ is the present value of the operating costs for an appliance with lifetime L whose UEC is equal to UEC_0. Equations similar to this one could be used to derive more accurate forecasts of the LCC-minimizing UEC value, thus enabling EE policies that more precisely maximize the economic benefit to consumers.

Figure 5 illustrates using these equations to forecast the UEC that minimizes refrigerator LCC in 2020, based on the 2010 price-efficiency relation shown in figure 3*(A)*. If the price of all refrigerators is predicted to decline by 2.5% per year regardless of efficiency level, the LCC-minimizing UEC is expected to decline from 410 kWh/yr in 2010 to 400 kWh/yr in 2020. This is the approach to price trends that is currently used in DOE EE standards analysis, and which was first utilized in support of the refrigerator standard issued in 2011 [36, 42]. If, instead, the incremental price of efficiency is forecast to decline at 19% per year (while P_{min} continues to decline at 2.5% per year), the LCC minimum point is expected to decrease an additional 17.5% to 330 kWh/yr, yielding an additional LCC reduction of $97 for each of the estimated 13 million refrigerators sold in the US in 2020 [42]. If all the refrigerators purchased in 2020 saved the additional 70 kWh/yr enabled by the faster incremental price decline, they would save a cumulative 15 TWh of electricity over their 17-year lifetime, which corresponds to approximately 9 million metric tons/yr of avoided CO_2 emissions with present-day electricity generation. Determining price trends at the required level of granularity for such a forecast is challenging, and it may not always be possible to produce forecasts with sufficient certainty for use in a regulatory analysis. In this case, given the potentially rapid price evolution of efficient technologies, regular regulatory updates are especially important to maintaining EE policies that are close to the social optimum.

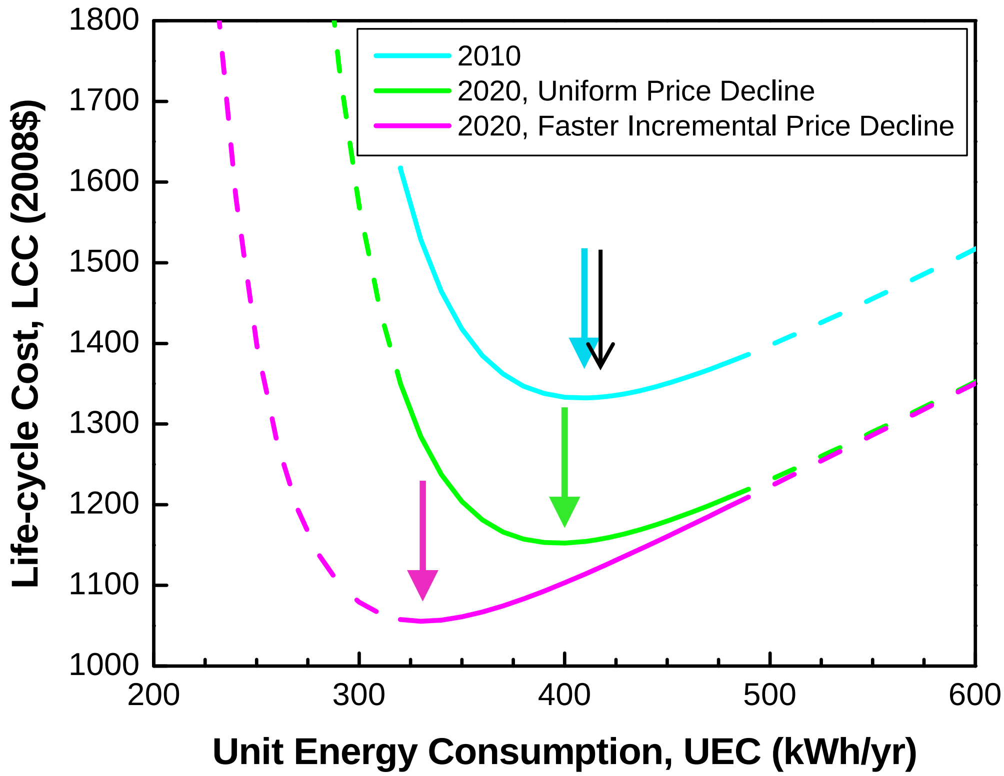

Figure 5. Dependence of LCC on baseline and incremental price declines. The blue curve shows the dependence of refrigerator LCC on UEC in 2010 according to the model in figure 3*(A)* (the LCC rises at high UEC because increased energy costs outweigh decreased first cost). The solid portion of the line indicates the range of efficiencies considered in the refrigerator rule published in 2011. The green curve shows how the LCC may change in 2020 if both the baseline and incremental price of efficiency decrease at 2.5% per year. The magenta curve illustrates how the LCC in 2020 may change more rapidly if the incremental price decreases at 19% per year instead. The arrows with corresponding color indicate the LCC minima. The black arrow indicates the minimum efficiency performance standard that was determined in 2011 and will go into effect in 2014.

8. Conclusion

By examining the 35-year history of appliance standards, we observe an accelerated decline in appliance LCC post-standards in all cases studied and an accelerated decline in appliance price in most cases. We also find that the incremental price of efficiency generally decreases faster than the baseline price of appliances, which may help explain the sustained long-term price decline under standards.

Since 1978, the US Department of Energy has analyzed energy-efficiency standards for a growing number of residential appliances and devices using a standard-setting process that is governed by a number of procedural and technical requirements. The regulatory analysis of each standard includes a "bottom-up" engineering estimate for the incremental cost of achieving higher efficiency. Prior to 2011, declines in cost described by learning curve trends were not included in this analysis. Since 2011, learning-curve trends have been used in the determination of US appliance efficiency standards. The regulatory analysis currently uses only the learning trends of the base price and assumes no additional innovation induced by EE standards. The present analysis suggests that this approach is likely to be conservative.

Our analysis indicates that the rate of price decline for the incremental price of efficiency may be as much as an order of magnitude faster than for the baseline price. If this observation is correct, better modeling of the potentially much faster price decline for efficient technologies may produce more accurate forecasts of cost-effective energy savings. Future research could help determine how to model dynamic market reactions to regulation and the potentially complex time dependence of market distributions for regulated products.

Some of the possibilities for future research may be indicated by some of the new models of price dynamics in regulated appliance markets have been explored by very recent work undertaken by Spurlock [13] and Van Buskirk [11].

Spurlock evaluated a model of second-degree price discrimination in a quality-differentiated market for household durables based on the classic work by Mussa and Rosen [43] for US clothes washer standards in 2004 and 2007. Spurlock found that "along with a level drop in prices at the time the new standard went into effect, price trends broke downward, particularly following the 2007 standard change. The within-model downward trend in prices was particularly pronounced in the higher efficiency categories."

In a similar exploration of a differentiated market, Van Buskirk explored a different style of model for the dynamics of the European refrigerator market where learning-by-doing occurred at different rates for different efficiency categories of refrigerators. Because cumulative experience scaled up more rapidly on a per-category basis as higher efficiency refrigerators were adopted by the market, this model reproduced the observation of a rapidly changing incremental cost of efficiency that is noted by the present study.

Alternatively, some of the observations of the accelerated decline of appliance purchase price under standards may also be explained as a spillover effect [44] of improved efficiency technology. That is, learning -curve-driven productivity improvements in the manufacture of high-efficiency products could spillover and potentially yield productivity improvements for baseline products.

Substantial research into multiple potential modeling approaches will likely be required to settle on new modeling techniques that can reliably produce forecasts consistent with the empirical observations of this study. But if such new models can be developed, they may improve the dynamic forecasting of the interplay between innovation and regulatory impacts. Such improved forecast methods are likely to aid in the development of more optimal energy-efficiency policies that could provide additional economic benefits for consumers and climate mitigation efforts.

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