Ratcheting, Competition, and the Diffusion of Technological Change: The Case of Televisions under an Energy Efficiency Program

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In differentiated goods markets with societal implications, quality standards are commonly implemented to avoid the under-provision of innovation. Firms have clear incentives to engage in strategic behavior because policymakers use market outcomes as a benchmark in designing regulation. This study examines a unique energy efficiency standard for television sets, under which future minimum efficiency standards are explicitly a function of current product offerings. The setting illustrates firms' dual incentives at work: A firm better differentiates products under a looser standard, but may want to induce a tighter standard if it can benefit from raising rivals' costs. These incentives drive firms to ratchet quality. We develop a structural model of product entry that illustrates how the regulator's standard setting rule affects a firm's product quality decision. Counterfactual simulations illustrate that ratcheting down was prevalent in this market and that incentives to ratchet up did not exist. The results suggest that in many commonly regulated markets in which firms share similar cost structures, firms are likely to experience incentives to ratchet down and delay the introduction of innovative products. The study highlights the importance of understanding supply side incentives, such as ratcheting, in designing and assessing policy.

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1   Introduction

The study of the diffusion of innovation and technological change enjoys a long tradition. From the seminal work of Griliches (1957) and Bass (1969) to more recent studies on the mechanisms that affect diffusion such as network effects and informational barriers, the empirical literature has emphasized the role of consumer adoption. Firms complement this process by choosing the extent to which they provision technological change in their product offerings. As competitive forces lead firms to differentiate, some sell less innovative products than others.

In markets with strong societal implications due to safety, health, or environmental considerations, the diffusion of less innovative products may be deemed particularly undesirable, prompting policy intervention. The adoption of hybrid vehicles, for instance, is driven by significant subsidies and standards. The FDA's list of approved drugs and food additives are frequently updated in response to developments in pharmaceutical and food research. The use of electronic health records spread rapidly among health care providers in the United States after the introduction of a series of subsidies and financial penalties.[1]

Product managers are not merely bound by such policies, however; they have the opportunity to shape them. Policymakers commonly consider the claims and actions of firms when designing regulation because firms have better knowledge about future technological advances. This information asymmetry motivates strategic behavior by firms and in turn has important consequences for the pace at which innovation reaches consumers. This study focuses on an energy efficiency standard for television sets to analyze such behavior. As a subset of regulations, efficiency standards make an ideal point of departure, since the nature of the regulation is succinctly captured by one metric, the level of the minimum efficiency standard. Under efficiency standards, firms may engage in ratcheting — i.e., manipulating the quality of their product offerings — in an attempt to influence future standards. By developing a structural model of demand and supply that endogenizes product introduction and captures regulatory constraints, we assess the forces that drive strategic behavior of ratcheting[2], as well as the implication for the diffusion of innovative products

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[1]On *automobiles*, a list of federal and state incentives for alternative fuels and advanced vehicles is available online (http://www.afdc.energy.gov/laws/state). The website lists some 80 laws and incentives in place for the State of California. See Knittel (2011) for the role that CAFE standards play in affecting vehicle characteristics, including downsizing to meet standards. Sallee (2011) shows that the incidence of tax incentives for hybrid vehicles fell on consumers. A consumer who purchased a Toyota Prius in early 2006, for example, received $3150 in tax credits. On *FDA standards*, see Cimons, Marlene "Seldane pulled for a safer allergy drug." *Los Angeles Times*. December 30, 1997. Seldane, an allergy drug, was disapproved after a safer drug Allegra was developed. The manufacturer of Seldane complied with the FDA and retracted Seldane only after two versions of the newer drug, which it also manufactures, were approved by the FDA. On *electronic health records*, see Rowland, Christopher "Hazards tied to medical records rush." *Boston Globe*. July 20, 2014. Since 2009, $30 billion in government incentives have been provided to encourage medical professional to use electronic health records. Since 2015, hospitals that had yet to transition to new systems have been penalized through reduced Medicare reimbursements.

[2]The "ratchet principle" originally refers to a central planner's tendency to use current performance in setting future

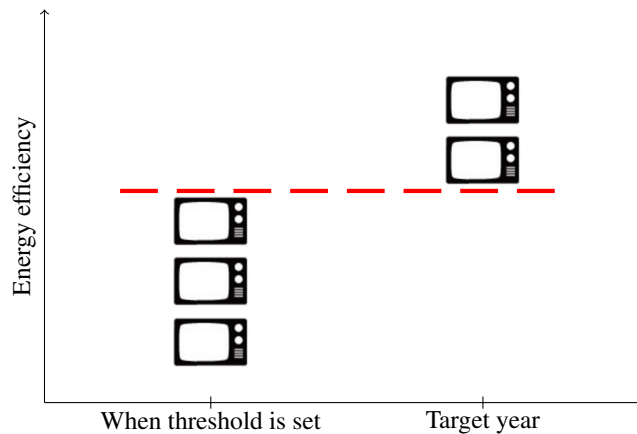Electronic copy available at: https://ssrn.com/abstract=3241157

Figure 1: Stylized illustration of the regulation: products sold during a future target year must be at least as energy efficient as the most efficient product sold in the base year.

and competitive structure.

One aspect that makes ratcheting incentives especially interesting for empirical investigation is that economic theory is ambiguous as to whether these incentives encourage firms to increase or decrease product quality in non-monopolistic, competitive environments. The well-known ratchet effect suggests that within firms, there is an incentive to keep product quality low in order to induce looser standards ("ratchet down"). With competition, however, the theoretical predictions are less clear. On the one hand, standards may encourage a firm to ratchet down even further, so that it can sell products with varying levels of quality post-regulation and differentiate its product offerings from those of its rivals. On the other hand, competition may cause firms to provision quality closer to the technological frontier, as firms attempt to subject its competitors to tighter regulation ("ratchet up"). A key contribution of this paper is to employ a structural model that allows a better understanding of the relative importance of these forces on observed outcomes in the market for televisions. To the best of our knowledge, these two forces have not been recognized empirically thus far in competitive markets, despite an abundance of theoretical work and the prevalence of standards that elicit ratcheting behavior in practice.

Two distinctive features of the energy efficiency standard in the Japanese television market make this setting an ideal testbed. First, under this particular regime, the mapping of firms' product offerings onto the eventual level of the energy efficiency standard is explicitly a function of current product offerings. In general, *products sold during a future target year must be at least as energy efficient as the most efficient product being sold in the base year,* when the regulator sets the standard (Figure 1). In contrast to typical settings in which the standard-setting procedure is noisier,[3] we directly observe the critical actions that firms took in order to influence the standard.

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goals (Weitzman, 1980).

[3]Standards levels are commonly proposed and revised repeatedly before they are implemented. During this process

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Second, the regulation is applied independently to different sub-markets based on product characteristics. We thus observe firm behavior around the time of standard-setting across regulatory sub-markets, which vary significantly in product line length, costs, and the number of active firms. This cross-sectional variation is helpful in exploring the relationship between the competitive environment and firms' incentives to engage in ratcheting, and helps us contemplate the characteristics of markets that may lead to stronger ratcheting incentives.

A simple theory of competition under endogenous standards suggest that firms' cost structures are important determinants of ratcheting behavior: when firms face similar costs, the incentives to ratchet down are more pronounced, while when firms are heterogeneous, advantageous firms may be willing to ratchet up. We find evidence consistent with this intuition, potentially leading to the conclusion that policy should have encouraged firms to compete "up" to introduce more stringent policy in markets where cost structures are known to be heterogeneous.

However, simple theoretical models cannot fully capture firms' responses to standards that might occur in practice, chiefly firms' decisions to change product line length or product attributes of multiple products. In our empirical model, firms have beliefs that are consistent with the endogenous standard-setting regime based on a set of simple heuristics. We use moment inequalities to partially identify firms' fixed-cost parameters, accounting for these beliefs. This helps to tease apart why firms might be ratcheting down; for example, we can observe whether a firm ratchets down in anticipation of changes in future profits or whether it is merely too costly for the firm to increase efficiency.

By evaluating counterfactuals to decompose strategic intra- and inter-firm incentives, we find evidence that firms generally prefer to ratchet down. No evidence is found for firms' incentives to ratchet up, regardless of the extent to which firms' costs vary across regulatory sub-markets. The policy design could not have pitted firms against one another to compete to introduce tighter standards and led to the introduction of a relatively looser policy level at significant costs and distributional effects across firms. Many markets subject to similar policy share common traits with the television market, such as the extent of concentration and the relatively similar cost structure across firms,[4] This suggests that unilateral policies, like the one introduced in the television market,

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the interests of the firms, industry groups, and regulators are deliberated. In setting appliance standards, the Department of Energy (DOE) goes through a four-phase process which typically takes three year ("Standard development and revision." U.S. Department of Energy., n.d. Web. 20 Mar. 2016. energy.gov/eere/buildings/standards-development-and-revision). It is challenging to understand firms' beliefs about how manipulating product offerings will affect the eventual levels of standards that are implemented from such negotiatoins. (The negotiations of U.S. standards typically are a trade-off between more stringent standards and more time until enforcement. Nevertheless, manufacturers have also attempted to weaken standards [Nadel, 2002]). In contrast, under the Top Runner Program, deliberations are kept to a minimum, and the future standard levels are relatively clear. (Ministry of Economy, Trade and Industry. Top Runner Program, Developing the world's best energy-efficient appliances. 2010. 6-7.)

[4]Standards are more likely to be based on firm performance when the industry is experiencing rapid technological change, making it difficult for regulators to predict future innovation levels. Because the most innovative markets

are likely to delay the introduction of the highest quality products in differentiated goods markets when firms know they may be regulated.

While this study uses data from a specific empirical context, it nonetheless addresses a common policy design in which firms are subject to unilateral standards. Firms respond strategically to opportunities to influence regulatory standards in many settings by changing product offerings. In the seventies, the introduction of emissions controls for automobiles was repeatedly delayed, due to complaints from automobile manufacturers, who claimed that the standards specified by the 1970 Clean Air Act could not be achieved (White, 1982, Yao, 1988). It "would simply not be possible," the manufacturers said, claiming that the policy would do "irreparable damage to the American economy."[5] Yet, just two months after the Environmental Protection Agency agreed to extend emission deadlines, a major manufacturer announced that it would be able to implement technology that would allow them to meet the new standards. Manufacturers presumably already had the technology to meet the standards, but their lobbying efforts would not have been convincing had firms released products that met the standards they were lobbying against. The case is just one example of a general phenomenon: in product markets, the incentives to influence standards are likely to affect both the products that are introduced to the market and the timing of the introduction. In fact, regulators are commonly mandated to receive firms' feedback when developing standards, making this phenomenon potentially widespread.[6] The finding that ratcheting down may be the dominant incentive has implications for policy design (as we discuss later, policies that directly encourage firms to introduce higher quality products are generally costly) as well as the evaluation of such a policy (a jump in quality does not necessarily imply an increase in the pace at which firms introduce innovation, despite policymakers' tendency to conclude so).

This study relates to a rich quantitative literature on the diffusion of new products and technologies. In early scholarship, beginning with Bass (1969),[7] demand was generally taken to be an exogenous process. Scholars later extended early models to take into account marketing variables

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generally tend to be more concentrated (Sutton 1998), in the very markets that are likely to be regulated, firms may realize that their current product offerings affect future regulatory standards.

[5]The first quote is from a 1970 memorandum of the Automobile Manufacturers Association. The second is of Ford's executive vice president at the time (see Weisskopf, Michael. "Auto-pollution debate has ring of the past." *The Washington Post*. March 29, 1990.). In response to emission controls, the Department of Justice also accused manufacturers of having "engaged in a combination and conspiracy to restrain competition in the development, manufacture, and installation of motor vehicle air pollution control equipment," including forming joint research ventures and agreeing to share patents. The DOJ and manufacturers eventually entered a consent decree. See Hackett (1995) and *United States v. Automobile Manufacturers Ass'n, 307 F. Supp. 617 (C.D. Cal. 1969)*.

[6]In the United States, the Administrative Procedures Act of 1946 requires regulators to give advance notice to interested parties when new regulations are drafted, and to allow them to give commentary to authorities (Lutz et al., 2000). Ratcheting forces may also arise for industry standards. A major upscale supermarket chain, Whole Foods, only carries body care products that contain organic ingredients that meet the NSF/ANSI 305 Organic Personal Care Standard, a standard that both Whole Foods and major organic product manufacturers were involved in designing.

[7]Incidentally, one of the main examples examined was the diffusion of color televisions.

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such as pricing and advertising (Kalish, 1985) and intertemporal adoption by consumers (Horsky, 1990). More recently, the literature has focused on specific mechanisms of the diffusion process, such as the role of dynamic demand in durable goods (Gordon, 2009, Nair, 2007), network effects (Dubé et al. 2010, Shriver 2015, Tucker 2008), and uncertainty and informational barriers (Bollinger, 2015). This literature is also closely tied to the empirical analysis of product introduction, positioning, and exit (Draganska et al. 2009, Eizenberg 2014, Hitsch 2006, Wollman 2014). We study the role of another mechanism — endogenous standards — that can affect product introduction and the diffusion of technology.

The paper is organized as follows. In the next section we describe the regulatory regime and the data. Section 3 lays out an empirical model, and Section 4 describes estimation and identification. Results are described in Section 5, and counterfactuals in Section 6. Section 7 concludes.

2 The energy efficiency standard and data

In 2009, televisions accounted for roughly 10% of household electricity consumption in Japan, according to a survey by the Agency for Natural Resources and Energy. The introduction of more energy-efficient, thin panel televisions became increasingly popular and affordable from the late-2000s, gradually replacing conventional cathode ray tubes (CRT) and decreasing energy usage.

The Program   The Top Runner Program was implemented in 1998 to regulate the energy usage of appliances. In general, the regulation dictates that the energy efficiency of products sold by a firm during the *target year* must be as efficient as the most efficient product, across firms, of the *base year* when the standard is set.[8]

Under the regulation, each television j belongs to a product group g that is defined by unique combinations of a vector of product characteristics, x_g. These product characteristics include key determinants of energy efficiency, such as screen size groups ($size_j \in \{(10, 19), [19, 32), [32, \infty)\}$), display speed, and whether the television is full-HD (FHD). FHD panels have more than 1080 vertical pixels and can show higher quality images. In addition to the vector x_g, energy consumption level $energycon_j$ is the major observable characteristic of a television. Energy consumption $energycon$ is measured in kwh/year and reflects the yearly energy consumption of a television under normal household usage conditions.

The regulation aims to limit $energycon$ by setting a target value for each product group. Target values generally reflect the efficiency level of the most energy efficient product in each product

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[8]Formally, the firms meet the regulation by ensuring that the quantity-sold weighted average energy efficiency exceeds standards. Throughout this study, I assume that the regulation was a de facto minimum efficiency standard. A discussion on this point, and further details of the regulation, are in the appendix.

group up to the time that the target values are set, t_{set}. Within product groups, the target values $energytarget(g, size)$ are adjusted to be a piecewise linear function of screen size. Achievement percentage, a normalized measure of energy efficiency, measures the ratio of the actual energy consumption level of a given television to the target level:

$$e_j = 100 \times energycon_j / energytarget(g_j, size_j) \ (\%)$$

In general, firms abide by the standards by selling televisions that are more efficient than the target, i.e. have e_j greater than 100%, after they go into effect.[9]

The regulation introduces three sets of time periods, which are common across product groups. In the periods leading up to t_{set}, denoted as T_{pre}, firms realize that releasing an efficient product may change the future regulation level. In the latter time periods (T_{post}), the threshold goes into effect. There is a set of periods in between, in which the threshold has been set ($T_{interim}$) but has not gone into effect. These periods are intended to allow the firm to adjust to the upcoming threshold.

We focus on the 2012 standards of the Japanese Top Runner Program for television sets. The standards were set around February 2009[10] and enforced after April 2012. This was the third "cycle" in which the program was implemented in the television market, suggesting that firms were familiar with the regulatory structure. Firms are reasonably assumed to be unconcerned about the effect of their current behavior on other regulatory standards in the near future, as this cycle was widely acknowledged to be the last one.

Consumers can easily obtain information on energy efficiency. Retailers are required to accompany televisions with a standardized label that displays annual energy consumption and electricity costs, as well as the achievement percentage. The label also shows energy efficiency on a five-star scale, determined by whether the product's achievement percentage meets cut-off values.

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[9]In theory, the regulation is met when the sales weighted energy efficiency is greater than the target. In the data, there is a marked lack of products that achieve less than 100% as the target year approaches. For tractability in my empirical model, I assume throughout this study that the Top Runner standard acts as a lower bound on the energy efficiency that firms can achieve. Under the factual Top Runner standard, firms could sell less efficient goods and still meet the standards by strategically price goods so as to affect the relative quantity of efficient televisions sold. Such "mix-shifting" has been a margin of response in the automobile industry under corporate average fuel economy (CAFE) standards. Jacobsen (2013) finds that relatively fuel efficient vehicles are priced more cheaply when manufacturers are subject to more stringent constraints, so that fleet averages can meet the CAFE standards. In the television market, the lack of products that achieve less than 100% suggests that firms did not intend to engage in such behavior. Firms may be sufficiently risk-averse in that they want to avoid any possibility of violating the regulation, or lack the ability to flexibly affect the downstream retailer's pricing.

[10]Although the standards were only officially announced in February 2010, firms generally knew when the standards were internally set. For example, the dataset that the government used to set the standards were provided by an industry group. I document supporting evidence for this claim in the appendix.

Table 1: Summary statistics by product

	Overall ($n = 854$)		2008 ($n = 145$)		2011 ($n = 184$)	
	Mean	Stdev	Mean	Stdev	Mean	Stdev
Average price	$1339	1083	$1837	1156	$964	847
Achievement percentage	102.5	34.5	74.5	16.2	140.2	26.5
Energy consumption (kWh/yr)	138.5	91.4	192.3	103	92.1	47.9
Has full-HD screen	55.2%		63.4%		56.5%	
Screen size (inches)	35.8	11.4	37.9	10.5	35	11.9
Less than 32 inches	12.3%		15.2%		9.8%	
Greater than 42 inches	55.2%		63.4%		56.5%	

Notes: An observation is a product. Second and third set of columns correspond to products introduced in 2008 and 2011, respectively. Average price is the average selling price over all months and regions that the product was sold.

Data Televisions are an ideal product to examine the changes in firm behavior under this regulation, as new products are released at an average rate of 18 models per month. We use point-of-sales (POS) data from GfK for televisions sold in Japan. The data covers all five districts of Japan, ranging in size from 5.8 million to 20.5 million households in March 2012. In the main empirical exercise, we use a dataset with 854 unique television models, starting from April 2008 and ending in March 2012, resulting in 48,199 model-month-district observations.

On the supply side, we focus on six major domestic manufacturers that were responsible for almost all (97%) of the units of televisions sold. The firms are characterized by their extensive product lines; each firm sold 34.0 unique models, including 2.1 new models, in an average month.

The rapid increase in the energy efficiency of televisions over time is suggestive of rapid technological change. Table 1 shows that the average television introduced in 2011 used 52% less energy than that the 2008 models, without controlling for the fact that televisions were generally increasing in size and number of features. This translates to an energy cost savings of roughly $300 over the life time of a television set, assuming ten years of usage. On average, the achievement percentage of new televisions improved by 21.8 percentage points every year.

The energy efficiency of products varies significantly within time periods as well. The standard deviation of achievement percentage, absorbing time-, region-, and product groups, is 18.2 percentage points, corresponding to 45.3 kwh/yr or $136 in energy cost savings over 10 years. This suggests that relative to the mean price of televisions ($1339), the choice of a television set can have non-trivial implications for private energy cost savings.

We observe multiple outcomes of the standard-setting process across product groups. For detailed analysis, we focus on four major groups which capture over 70% of total television demand. Table 2 shows that the groups vary significantly in price and market shares, as well as the number

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Table 2: Summary statistics of major product groups

| Product group | | | | | Inside | Price | Firms | Products |
	Resolution	Size	Display speed	Features	share			per firm
DG	FHD	Over 32	120fps	0	14.8%	$1473	5.7	5.8
DG1	FHD	Over 32	120fps	1	7.1%	$2136	3.3	8.6
DK	Non-FHD	19 to 32	60fps	0	24.1%	$460	11.1	3.7
DN	Non-FHD	Over 32	60fps	0	26.4%	$704	7.4	2.7
Average across all groups					3.3%	$1398	2.6	2.5

Notes: An observation is a product group. For each product group, the data was averaged across time periods, ignoring periods in which no product was released. In the average time period, there were 22 active product groups.

of firms and the number of products released by each firm. For example, there was an average of 11 active firms in group DK, a product group for budget televisions, while group DG1, a more premium group, saw three.

Understanding strategic behavior   In this subsection, we contemplate the presence of strategic behavior by looking at raw patterns in the data, as well as anecdotal institutional features. We discuss a general framework for understanding strategic behavior and motivate our empirical model by pointing out that raw patterns in the data and implications from theory are consistent, but not conclusive, with the presence of ratcheting incentives.

A first glance shows behavior consistent with firms waiting on releasing more efficient products until after the threshold is set. Figure 2 shows the transition of a normalized measure of energy efficiency of all newly released televisions over time. In February 2009, when the regulator sets the threshold (t_{set}), there is a noticeable jump in the energy efficiency of the most efficient products, consistent with the presence of ratcheting down behavior.

It is important to note that visual inspection of firms' product behavior are only indicative of the net effect of the two countervailing ratcheting up and down forces. The apparent jump may conceal the fact that firms also experienced incentives to ratchet up as well. The pattern that we observe in Figure 2 merely suggests that the incentives to ratchet up were less prevalent than the counteracting incentives to ratchet down.

The observed ratcheting pattern in Figure 2 is not robust when decomposed by sub-markets. The top panel of Figure 3 shows the trend of efficiency by whether the television has a FHD panel, i.e. those that have more than 1080 vertical pixels. The contrast of the two sets of groups is vivid around February 2009: televisions with a FHD panel exhibit the jump in energy efficiency, while the non-FHD televisions do not.[11] Across regulatory sub-markets, Figure 2 suggests that ratcheting down behavior might be less pronounced in some product groups.

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[11]These trends generally hold within individual each product groups as well, as shown in Table 2 of the appendix.
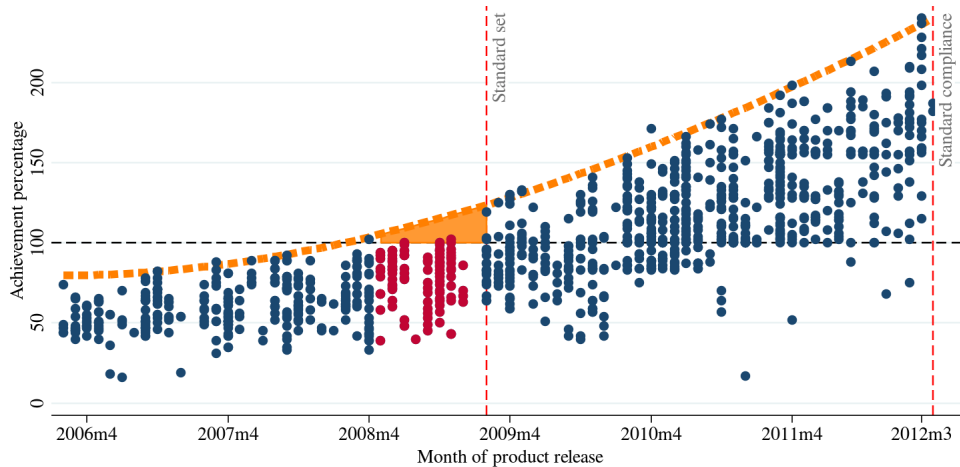
Figure 2: Energy efficiency of new models released over time. Each point represents the introduction of a unique television model. The y value of the point indicates the efficiency of the product (achievement percentage, described in Section 2). There is a jump in the trend of the most efficient goods around February 2009 (shaded triangular area). A test of structural change suggests that there was a statistically significant jump in the efficiency of the most efficient products sold, as shown in the Appendix.

What explains the difference in ratcheting across the two product groups? To answer this question, we first study the theoretical literature that examines ratcheting and minimum quality standards. On the one hand, the regulation imposes a direct effect on the incentives of the firm, as the firm that is setting the standard anticipates that the standard will increase its costs tomorrow. Under the classic ratchet effect (Freixas et al., 1985, Weitzman, 1980), a single agent ratchets down its quality today because its actions only affect its own future constraints, not any other agents'. Consistent with this intuition, a simple theoretical model can show that a single-good monopolist has the incentive to keep standard levels low if the pace of technological change is sufficiently slow such that the constraint binds in the post-regulation period. In an applied setting, keeping fixed the actions taken by competitors, a firm in a differentiated goods market has an added incentive to loosen the standard so that the firm has sufficient space to differentiate its product line in the post-regulatory period. This within-firm incentive to keep the standard level low is thus a key component of the incentive to ratchet down.

Contrast this with the indirect effect that the endogenous standards have in a competitive setting; a firm realizes that its competitors are also affected by the same standard. The thought experiment is to keep the product offerings fixed from the standard setting firm, and examine whether that firm would benefit from forcing its competitors to be subject to tighter standards. On the one hand, the cross-firm incentive may further induce the standard setting firm to ratchet down if the firm seeks to retain enough "room" in the energy efficiency space to be able to differentiate its products from its competitors. On the other hand, the standard setting firm may have an incentive to induce

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more stringent standards if competitors' higher costs sufficiently drives demand to substitute to the focal firm's products. Therefore, a pattern of ratcheting up emerges if the cross-firm incentive is strong enough to shift demand to the focal firm. A ratcheting up pattern does not emerge from within-firm incentives.

To gain intuition of the drivers of these two forces, we extend a canonical duopoly model of vertical product differentiation (Ronnen (1991)) to two time periods, a pre-regulatory and a post-regulatory period, in order to allow the regulation to be endogenous. By the structure of the theoretical model, in equilibrium one firm always sells more efficient products than the other in the pre-regulatory period, thereby setting the future minimum efficiency standard. The theoretical model suggests that the magnitude and direction of the cross-firm incentive is driven by the relative cost differentials across firms. The primary finding from the theoretical model is intuitive: the cost similarities between the two competing firms determine the extent to which the standard setting firm ratchets down. This suggests that, in a more general setting, the (dis)similarity of costs structure across firms is a key factor that determines ratcheting down (up). The model is described in detail in the Appendix.

Anecdotally, there are various reasons for why firms' costs of producing more efficient products might systematically vary. Some margins for improving energy efficiency are relatively established, such as the use of optical films that enhance the perceived brightness of the screen, and hence the costs are predictable and similar across firms. Other margins of improvements, however, particularly those that involve changes in the design of the LCD module, are closely tied to the manufacturing process and the R&D stock. Strong demand for more energy efficient models has also altered how television manufacturers manage their supply chains. Some manufacturers internalize the entire process of LCD module production, while others continue to outsource.

In particular, the cost of producing FHD televisions is known to be more homogeneous across firms than in the non-FHD market. For instance, because FHD panels are newer in technology, the number of suppliers able to manufacture these panels is limited, leading to similar cost structures.[12] This observation, combined with intuition from theory, is consistent with the top panel of Figure 3 where we see a ratcheting down pattern for FHD products.

The firms' differential product offerings also support the claim that firms were more homogeneous in the FHD groups. The bottom panel of Figure 3 shows a kernel density plot of the efficiency of televisions sold in the last six months of my dataset, immediately prior to the enforcement of the regulation. The data in this period is most indicative of the firms' behavior in the

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[12]For example, in the first half of 2006, seven suppliers manufactured non-FHD 32 inch panels; while three manufactured FHD 32 inch panels (Fuji Chimera Research Institute, 2006). The number of suppliers are limited because FHD panels require more advanced production lines which cannot be easily diverted from traditional lines. Moreover, FHD panels tend to be larger, and are costlier to manufacturer because such panels introduce unique challenges in the production and inspection procedures (Minami et al., 2007).
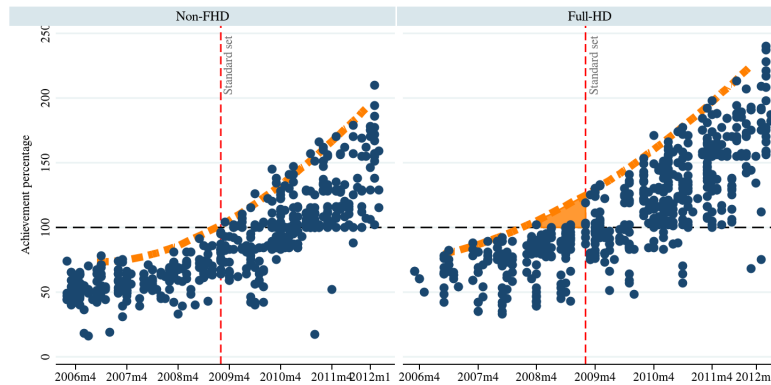
(a) Energy efficiency of new models released over time, by resolution of panel. The FHD televisions show a visible jump, while the non-FHD ones do not.
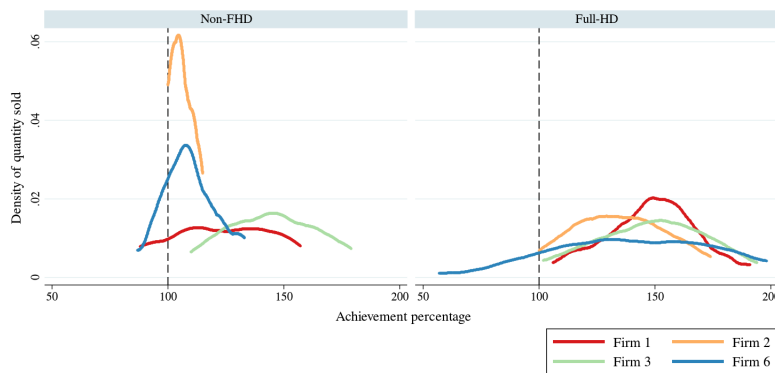
(b) Energy efficiency (achievement percentage) of televisions in last six months of data, after standards are set. The distribution of energy efficiency of the product lines, across firms, is more homogenous in the market for FHD televisions.

Figure 3: Varying behavior across non-FHD and FHD product groups.

post-regulatory regime, when the standards have already been set, and speak to the extent to which the standards were "binding" across the two set of product groups.

In these plots, the range of the efficiency of the products that were offered by each firm is represented by the horizontal span of the respective lines. The height of each line corresponds to the density of sales at a given level of efficiency for a particular firm. In the non-FHD product group, some firms release products that just meet the threshold level (firm 2), while others release products along a range of efficiency levels (firm 3). To the extent that the firms' product line decisions are suggestive of their relative cost structures, this observation is consistent with some firms having a cost advantage in manufacturing energy efficient televisions compared to others. Moreover, this is in contrast to the FHD group, where firms generally sell products that have a similar profile of efficiency – a pattern that is consistent with firms sharing a similar cost structure.

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However, while the patterns in Figure 3 are consistent with the presence of a net ratcheting down pattern in the FHD product groups, neither the figures nor the theoretical model alone can conclusively indicate that the ratcheting incentives existed. Therefore, using an empirical model, which we develop in the next section, we study counterfactual outcomes that can isolate and directly show the presence of ratcheting incentives. In particular, we run counterfactual simulations to decompose the two countervailing forces as they work in opposite directions in terms of affecting the standard levels. The decomposition is also helpful in understanding how the forces led to the overall patterns that we see in the top panel of Figure 3. Whether ratcheting plays a meaningful role in determining outcomes is relevant to understand firms' differential incentives in regulated markets, as well as the design of regulatory policies which aims to leverage these competitive forces.

3 Empirical model of product line decisions

We construct a simple empirical model of product line decisions in which firms anticipate the regulatory constraint and, in response, can change offerings. The crux is in understanding how firms' product offerings are affected when they realize that current decisions can affect profits through the regulation.

We abstract away from the dynamic product introduction decision other than through virtue of the regulation by assuming that the additional costs that firms incur to introduce new models are not sunk; the main drivers of improvement in energy efficiency are gradual decreases in marginal and fixed costs of provisioning efficiency. It is the regulation that introduces a clear motive for the firm to be forward looking in terms of how its behavior can affect future profits after the thresholds have been enforced. We expand on the simplifying assumptions after describing the base model.

3.1 Static base model

The basic building blocks of the model are individual time periods, which proceed in two stages. Within each time period, firms first decide on the set of goods J to offer, and incur a fixed cost for the set of products. Then, firms make pricing decisions and consumers make purchases. The two stages interact because in the first stage firms use backward induction to evaluate the profits that would be gained in the second stage from a given set of product offerings.

In the second stage, demand is assumed to be static. Dynamic demand would allow firms to strategically price and design products over time. Such forces are particularly important for highly differentiated goods or heterogeneous demand (Nair, 2007). For televisions, consumers often make replacement decisions when their current television reaches its end of useful life or

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when consumers move to a new house.[13] This would suggest that intertemporal dynamics are less significant in this market: Conlon (2010) estimates a dynamic demand system in the U.S. television market and finds that in response to an increase in the price of a Sony television, roughly 70% of consumers who substitute to other models do so within the same time period.[14]

The second stage Following Nevo (2001), we use a logit specification with product dummies. Consumers purchase at most one good in a given period. Each television j is manufactured by a firm f and belongs to a product group g. The utility from purchasing j at month t in region r is

$$
\begin{aligned}
u_{ijrt} + \varepsilon_{ijrt} \;=\; & d_j + \tilde{\xi}_{jrt} + \beta_{ft} + \beta_r \\
& - \exp\left(\beta_i^p\right) \cdot p_{jrt} + \beta_i^h \cdot h_j + \varepsilon_{ijrt}
\end{aligned}
\tag{1}
$$

Product dummy d_j captures the component of utility that is associated with each product. $\tilde{\xi}_{jrt}$, is a region-time specific demand shifter. β_{ft} and β_r are manufacturer-by-month and region fixed effects. h_j is an indicator variable for units that have a FHD panel. We allow for discrete heterogeneity across six income brackets on price (β^p), and the fixed effect for FHD products (β^h), corresponding to six incomes buckets in the Census that we use to construct additional moments.

Estimated product dummies d are projected onto a set of product characteristics,

$$
d_j = \beta^e \cdot e_j + \beta_f + \beta_g + \beta^{size} \cdot size_j + \beta^{size2} \cdot size_j^2 + \overline{\xi}_j
\tag{2}
$$

where e_j is achievement percentage (energy efficiency), β_g and β_f are product group and firm fixed effects, respectively. $\overline{\xi}_j$ are mean product unobservables, so that the overall demand shock can be expressed as $\xi_{jrt} = \overline{\xi}_j + \tilde{\xi}_{jrt}$. $size$ is screen size of the television. Finally, we collapse non-energy efficiency attributes in Equation 2 into a scalar, which we define as quality, $q_j = \beta_f + \beta_g + \beta^{size} \cdot size_j + \beta^{size2} \cdot size_j^2 + \overline{\xi}_j$. This allows us to characterize the key attributes of a

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[13]In Japan, March is a month of heightened demand for televisions (see trend of purchases the appendix). Because the fiscal year starts in April, people typically move to new residences in March. Such purchases are likely to be made without intertemporal considerations.

[14]Arguably, the rapid improvement in the functionalities of televisions, coupled with the decline in prices, suggests an opportunity for consumers to gain from being forward-looking. Part of the change in composition of consumers over time, driven by forward-looking behavior, will be captured by this heterogeneity, that reflects how the type of consumer (households by income brackets) purchasing televisions evolves over time.

The assumption of static demand assumes away any interaction of dynamic demand with the regulation. The provision of technology is fundamentally a dynamic question that interacts with forward-looking consumers, as firms need to decide when to eliminate older products in favor of newer ones. If a firm hopes to disregard certain technologies in the future to encourage consumers to purchase today, the regulation may help the firm commit to such a strategy. This is typically a challenge even for the durable good monopolist (Coase, 1972). In practice, however, consumers did not have an opportunity to learn about the firms' dynamic incentives because the Top Runner program was not described on standardized product labels. Firms also did not advertise the dynamic incentives that they faced under the regulation.

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television by a given firm using the vector (q_j, e_j), which signifies the quality and energy efficiency of the television.

Consumers choose at most one television from J_{tr}, the set of available products in month t in region r. By assuming that ε_{ijrt} are i.i.d. Type-I extreme value shocks and normalizing utility from the outside option to be $u_{i0rt} = 0$, the market share of a given good is

$$s_{jtr} = \sum_i w_{itr} \cdot \frac{\exp(u_{ijtr})}{1 + \sum_{m \in J_{tr}} \exp(u_{imtr})} \tag{3}$$

where w_{itr} is the weight of consumer type i.

On the supply side, prices are set conditional on product offering decisions from the first stage and with knowledge of the realization of demand shocks ξ_{jtr} and marginal cost shocks ω_{jtr} for all $j \in J_{tr}$. We assume the existence of a unique Nash-Bertrand pricing equilibrium for any possible product assortment. In estimation, the equilibrium conditions are used to back out marginal costs, mc_{jrt}.

The estimated marginal costs are projected on a set of covariates. A feature of this market is the rapid decrease in price: the quality adjusted price index, which controls for the improvement in televisions attributes over time, suggests that prices decreased by a factor of three and a half over five years. Therefore, marginal costs are allowed to flexibly fluctuate over time:

$$\log\ mc_{jrt} = \gamma_0 + \gamma_h^q \cdot q_j + \gamma_{fh}^e \cdot e_j + \gamma_g + \gamma_t + \gamma_r + \omega_{jrt} \tag{4}$$

where ω_{jrt} is a marginal cost shock; γ^q and γ^e are coefficients on quality and energy efficiency respectively, which vary based on whether the television has a FHD panel (h_j). The coefficient on e also varies by firm. γ_g, γ_t and γ_r are product group, time, and region fixed effects, respectively. Marginal costs do not exhibit returns to scale.

In summary, the second stage provides an expected variable profit function that firms use to evaluate profits from any product assortment choice J in the first stage. A product assortment choice J_{fgt} is comprised of any number of vectors (q_j, e_j) such that $q \in \mathbb{R}$, and $e \in \mathbb{N}$: $J_{fgt} = \{(q_j, e_j)\}_{j=1}^{|J_{fgt}|}$. The assortment choice is made for every product group $g \in \mathbf{G}$, where $\mathbf{G}$ is the set of all Top Runner product groups. In the first stage, assuming that firms know the distribution of these shocks, but not the realized values, the firms' expected second stage variable profits are given by

$$\pi_{ft}(J_{ft}, J_{-ft}) = \sum_r M_{rt} \cdot \int_{\xi,\omega} \sum_{j \in J_{ftr}} s_{jtr}(J_{ftr}, J_{-ftr}) \left[p_{jtr}(J_{ftr}, J_{-ftr}) - mc_{jtr} \right] dF_{(\xi,\omega)}$$

where M is the market size, $J_{ft} = \bigcup_{g \in \mathbf{G}} J_{fgt}$, and the integral is taken over the demand and

marginal cost shocks. The pricing equilibrium gives predicted market shares s from Equation (3), prices p from the pricing equilibrium, and marginal costs mc from Equation (4).

The first stage: Product introduction   In the first stage, using the expected profit function π_{ft}, firms simultaneously decide on a set of goods, J_{ft}. In this section, we describe the model in the absence of regulation. At the beginning of the first stage, firms observe realizations of fixed costs shocks ν_{jt} associated with the release of all possible products. The firms then decide on a set of products to introduce, J_{ft}. Firms incur fixed costs, which are additive in the fixed costs associated with each product. Restrictions on ν are discussed in the next section.

The function π_{ft}^F captures the total expected profits from the current period, net of fixed costs. To clarify notation, for now we assume that firms have perfect information about rivals' contemporary cost shocks and strategies when making decisions about J_{ft}.[15] Based on the assumption of static demand and no sunk costs, in the absence of regulation, each period firms simultaneously set J_{ft} so as to maximize the current total expected profits in every period

$$\max_{J_{ft}} \pi_{ft}^F\left(J_{ft}, J_{-f,t}\right) = \underbrace{\pi_{ft}\left(J_{ft}, J_{-f,t}\right)}_{\text{second-stage expected profits}} - \underbrace{\sum_{j \in J_{ft}}\left(F_{jt} + \nu_{jt}\right)}_{\text{fixed costs}} \tag{5}$$

where F_{jt} is the fixed cost of introducing product j in month t. Notice that without the regulation, the total expected profits are independent over time periods.

Remarks   In this model, technological change is exogenous. A main driver of reductions in costs in this industry is economies of scale achieved by investments in larger production lines by upstream panel manufacturers. Such roadmaps are laid out years in advance in response to the global outlook of demand and with regards to all kinds of applications for panels other than televisions, such as mobile devices. Furthermore, some innovations, such as advances in LED efficiency, are arguably exogenous to the conditions in the television market. The assumption of exogenous technological change is consistent with a model of technological change in which, similar to Moore's law in the production of integrated circuits, the pace of technological improvement in the near future is foreseeable.[16]

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[15]In the estimation procedure, I employ moment inequalities to estimate the fixed costs parameters. These inequalities rely on the logic of revealed preferences, and allows us to be agnostic about the specific equilibrium selection mechanism that lead to the observed outcomes (see Section 4).

[16]Haitz's Law suggests that the cost per lumen from LEDs decreases over time by a constant factor. Nishimura's law predicts that the production technology used for flat panel displays advances by one generation every three years. The presence of such laws suggest some predictability and stability in the path of future innovation.

This model also assumes that the costs associated with product introduction are not sunk.[17] In practice, as discussed in Section 2, some of the investments necessary for improving efficiency are sunk in nature. These include developing custom circuits to implement local dimming technologies and researching better configurations of LED backlights and optical films to enhance energy efficiency. While these costs may be sunk, because some components of thin-panel televisions are highly modular and product designs are based on common architectures, the incremental costs that firms incur to localize models to meet the demands of the Japanese market may be reasonably approximated by fixed costs.[18]

3.2   The regulation

The regulation introduces a series of restrictions on the firm's action space. In this section, I drop the subscripts related to product groups (g), because by regulation the standards plays out independently across the groups.

From the firm's perspective, the regulation changes firm incentives depending on the timing of the decisions. As the threshold values are set right after the last period of T_{pre} (denoted as t_{set}), firms have several opportunities to tighten the future standard level in the months leading up to t_{set}. I define a variable $\bar{e}_t$ to represent the maximum efficiency of products released across firms up to period t,

$$\bar{e}_t = \max_j e_j, \quad j \in \left\{ J_\tau | \tau \le t \right\}$$

where J_τ is the set of all televisions released at time τ.

The most efficient product released up to t_{set} defines the future efficiency standard, $\bar{e}_{reg} \equiv \bar{e}_{t_{set}}$. Firms are subject to this standard after the regulation goes into effect in $t \in T_{post}$:

$$\bar{e}_{reg} \le \min_{j \in J_{ft}} e_j \quad t \in T_{post}, \ \forall f \tag{6}$$

---

[17]Accounting for the sunk cost of product introduction is a challenging problem that would require the consideration of billions of states. An empirical literature that investigates such costs have been largely in markets with less differentiated goods (allowing for a smaller state space), and richer geographical variation in the firms' actions (for example, Ryan (2012)). In the Japanese TV market, six major firms release an average of 12 unique models per period and geographical variation is limited. Finally, not only is a fully dynamic specification intractable, but it also arguably deviates from manufacturers' actual business practices. For example, firms may rely on heuristics such as hurdle rates (Wollman, 2014) to evaluate dynamic payoffs.

[18]Similar to how automobiles are designed around common vehicle frames (chassis), televisions are based on common architectures, from which features are manipulated to meet design specifications (Luh et al., 2006).

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The firm's problem in T_{post} In $t \in T_{post}$, the constraints are exogenous because firms' actions cannot affect the standards. Every period, the firm's solves

$$\max_{J_{ft}} \ \pi_{ft}^F \left(J_{ft}, J_{-f,t} \right) \ \text{ s.t. } \ \overline{e}_{reg} \leq \min_{j \in J_{ft}} e_j \tag{7}$$

Firms must sell televisions that are more efficient than $\overline{e}_{reg}$.

Assuming for a moment the presence of a unique equilibrium to the firms' problem in Equation (7), we define

$$\Pi_f \left(\overline{e}_{reg} \right) \equiv \sum_{t \in T_{post}} \delta^{t - t_{post(1)}} \cdot \pi_{ft}^F \left(J_{ft}^*, J_{-f,t}^* \right) \tag{8}$$

where $\left(J_{ft}^*, J_{-f,t}^* \right)$ is the equilibrium product offerings that solves Equation (7) for all firms, and $t_{post(1)}$ refers to the first period in T_{post}. This highlights that the firm's expected profits in T_{post} are determined solely by the argument $\overline{e}$. The procedure used to empirically estimate the function $\Pi_{T_{post}}$ is described in Section 4.

The firm's problem in $T_{interim}$ During the $T_{interim}$, the future threshold level has been determined, but the regulation is not yet enforced. The regulation does not affect the firm's problem in $t \in T_{interim}$. The future regulatory level has already been set, and because by construction the base problem is static, the firm's actions in $T_{interim}$ do not influence market outcomes in T_{post}. Firms solve Equation (5) every period.

The firm's problem in T_{pre} What remains to be specified is the firm's problem for $t \in T_{pre}$. The firm's problem in T_{pre} is a finite-horizon dynamic problem: the firm's action today affects the future stream of profits in T_{post} by potentially changing the level of the standard. In order to capture the regulated firms' forward-looking incentives, we specify (1) state variables that firms know and (2) beliefs about future regulation levels and profits based on the state variables.

The state variable is $\overline{e}_{t-1}$, and is updated at the end of each period if the most efficient product released in the current period is more efficient than $\overline{e}_{t-1}$, namely $\overline{e}_t = \max \left(\overline{e}_{t-1}, \max_{j \in J_t} e_j \right)$. The state variable influences profits in T_{post} by affecting $\Pi_{f,T_{post}} \left(\overline{e}_{reg} \right)$, where $\overline{e}_{reg} \equiv \overline{e}_{t_{set}}$. Firms make product release decisions with knowledge of the realization of the state variable $\overline{e}_{t-1}$.

The firm's problem in the last month of T_{pre} illustrates the transition of the state variable. A firm maximizes the sum of its profit that can be earned in this month, and that can be made once the standard is enforced in T_{post},

$$\max_{J_{ft}} \ \underbrace{\pi_{ft}^F \left(J_{ft}, J_{-f,t} \right)}_{\text{today's profits}} + \ \underbrace{\delta^{t_{post(1)} - t} \cdot \Pi_f \left(\overline{e}_{reg} \right)}_{\text{expected total profits in } T_{post}} \ \text{ s.t. } \ \min_{j \in J_{ft}} e_j \geq \overline{e}_{t-1}$$

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where $t_{post(1)}$ refers to the first period in T_{post}. Firms know that the future standard level is either the most efficient product released up to $t-1$, or the most efficient product released today, so $\overline{e}_{reg} = \max\left(\overline{e}_{t-1}, \max_{j\in\{J_{ft}, J_{-f,t}\}} e_j\right)$.

In the more general case, when there are trailing periods in T_{pre}, firms need to have expectations about future product offerings $J_{f\tau}$, standard levels $\overline{e}_{reg}$, and demand and cost shocks based on the current state variable $\overline{e}_{t-1}$ and actions J_t. To exhibit the most general form of the firm's problem, I explicitly write out the firm's problem as a finite sum of the future stream of profits:

$$\max_{J_{ft}|\overline{e}_{t-1}} \underbrace{\pi_{ft}^F\left(J_{ft}, J_{-f,t}\right)}_{\text{today's profits}} + \underbrace{\sum_{\tau\in T_{pre}, \tau>t} \delta^{\tau-t} \cdot E\left[\pi_{f\tau}^F\left(J_{f\tau}, J_{-f,\tau}\right)\big|\,\overline{e}_t\right]}_{\text{expected total profits in subsequent periods of } T_{pre}}$$

$$+ \underbrace{\delta^{t_{post(1)}-t} \cdot E\left[\Pi_f\left(\overline{e}_{reg}\right)\big|\,\overline{e}_t\right]}_{\text{expected total profits in } T_{post}} \tag{9}$$

where $\overline{e}_t$ is endogenously determined as $\overline{e}_t = \max\left(\overline{e}_{t-1}, \max_{j\in\{J_{ft}, J_{-f,t}\}} e_j\right)$, δ is a monthly discount factor, and $t_{post(1)}$ refers to the first period in T_{post}.

In Equation (9), evaluating $\pi_{f\tau}^F\left(J_{f\tau}, J_{-f,\tau}\right)$ for each of the subsequent periods involves specifying beliefs about future product offerings $(J_{f\tau}, J_{-f,\tau})$ as a function of $\overline{e}_t$, which can be costly to evaluate. In this study, Equation (9) is simplified by making assumptions that keep the model tractable:

$$\max_{J_{ft}|\overline{e}_{t-1}} \underbrace{\pi_{ft}^F\left(J_{ft}, J_{-f,t}\right)}_{\text{today's profits}} + \underbrace{\sum_{\tau\in T_{pre}, \tau>t} \delta^{\tau-t} \cdot \left[\pi_{f\tau}\left(J_{ft}, J_{-f,t}\right) - \sum_{j\in J_{ft}} F_{j\tau}\right]}_{\text{total profits in subsequent periods of } T_{pre}}$$

$$+ \underbrace{\delta^{t_{post(1)}-t} \cdot \Pi_f\left(\overline{e}_t\right)}_{\text{total profits in } T_{post}} \tag{10}$$

where $\overline{e}_t = \max\left(\overline{e}_{t-1}, \max_{j\in\{J_{ft}, J_{-f,t}\}} e_j\right)$. The key assumptions are that firms have perfect information about $\pi_{f\tau}$ for $\tau \in T_{pre}$, $\tau > t$; and firms proxy for future product offerings by substituting them with today's, $E\left[J_\tau\right] = J_t$ for $t, \tau \in T_{pre}$, $\tau > t$. We elaborate on the assumptions that lead to the expression in Equation (10) in the remainder of this section, as well as the limitations of this approach.

Firms commonly use simplifying heuristics to solve difficult dynamic problems. The operations literature documents how firms often make future production plans, an infinite horizon problem, by solving a series of finite horizon problems to approximate the optimal solution. For in-

stance, under rolling horizon decision rules (Baker, 1977, Sethi and Sorger, 1991), every period a finite horizon period is solved, and only the first period decision is implemented. The following period's decisions are made by solving the finite horizon problem again, but with updated information from the previous period. These decision rules are practical for firms because extensive future forecasting is costly and the projections tend to be noisy.

In the context of televisions, the projections may be noisy because popular trends in functionality and designs — the consumer reception of the non-efficiency component of televisions — fluctuate rapidly. For example, 3D televisions were promoted around 2011, but quickly lost popularity after the 2012 Olympics. It may have been difficult to predict the abrupt decline in popularity of 3D televisions after the Olympics. As projections can be noisy and costly, we assume that a reasonable proxy that firms use for future product offerings is the current offering. This assumption would be less tenable if the window of projection were longer; here, because the time span of T_{pre} is at most 10 months (April 2008 through February 2009), firms make projections for up to 9 months into the future.

On the other hand, the assumption that firms know future π means that firms have foresight about how mean marginal costs and demand shocks will transition. Technological change has been assumed to be exogenous, and many of the demand shocks in this market are seasonal or known well in advance, such as end-of-the-year sales or the termination of analog broadcasting. The rolling decisions in T_{pre} are thus assumed to be made conditional on knowledge of the time varying components of demand and costs, but with a simple heuristic for future product offerings within T_{pre}. The decisions are rolling in the sense that every period the choices are made with updated information about the future minimum efficiency threshold, captured by $\overline{e}_{t-1}$.

A key implication of the assumptions is that the firm believes that the future threshold level $\overline{e}_{reg}$ is $\overline{e}_t$: $E\left[\overline{e}_{reg}|\overline{e}_t\right] = \overline{e}_t$. Figure 4 shows the trade off that a firm faces when it is deciding to release a new product. In period t, suppose that a firm releases a product with efficiency of $\overline{e}_{t-1} + \Delta e$: Δe more efficient than the most efficient product thus far. By releasing this product, the firm is able to sell products with efficiency of up to $\overline{e}_{t-1} + \Delta e$ without affecting the standard in the subsequent periods of T_{pre} (i.e. firms can sell products that fall in the shaded area (A) in Figure 4 without affecting future standards). The trade off is that because the firm has tightened the threshold value, it can no longer sell products that are less efficient than $\overline{e}_{t-1} + \Delta e$ after the enforcement (i.e. firms can no longer sell products that fall in the shaded area (B) in Figure 4).

What forces is this heuristic able to capture? Take, for example, a market in which the firms gradually increase the threshold in $t - 1$ through $t + 1$, as illustrated in Figure 5. Under the heuristic assumed in Equation (10), firms believe at time $t-1$ that the eventual minimum threshold implemented is $\overline{e}$. In other words, firms have no beliefs about how the threshold level may continue to tighten in the following time periods. A pattern of gradual increases in efficiency in data would
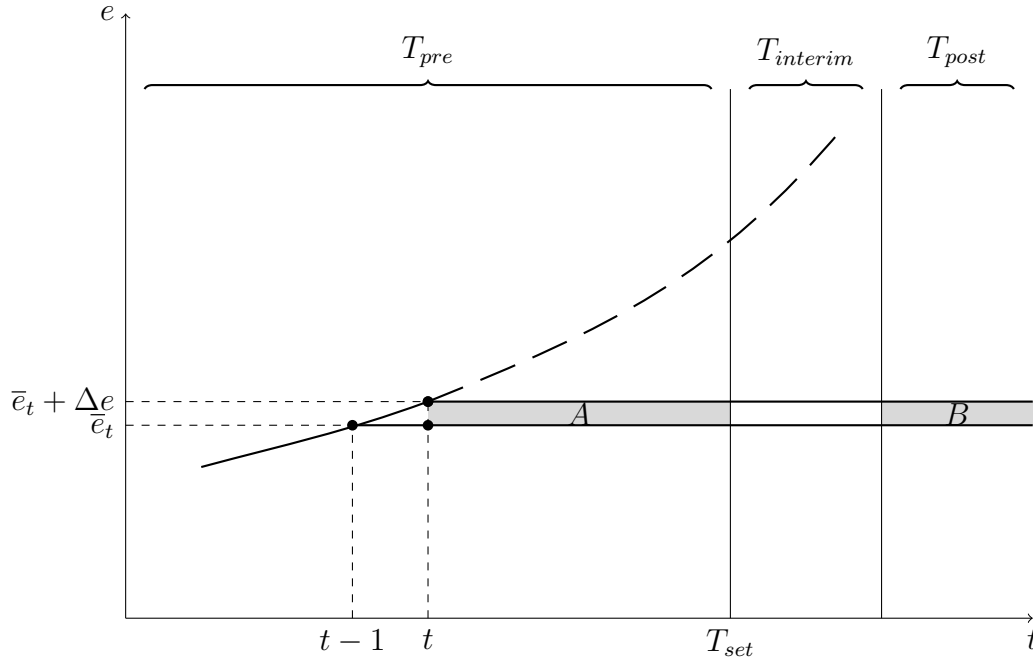
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Figure 4: The firm makes a trade off between the ability to sell more efficient products in T_{pre} (i.e. to sell products that lie in shaded area (A)), and the inability to sell products less efficient products in T_{post} (product that lie in shaded area (B)). The dotted line indicates the trend of the most efficient product that would have been sold if the regulation did not exist.
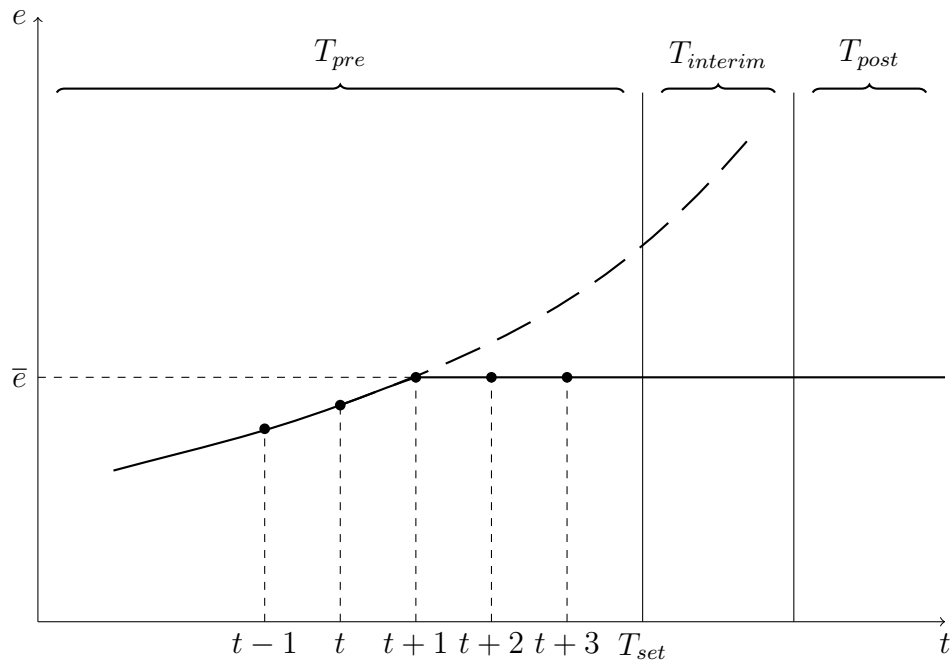

Figure 5: The firm is willing to increase the maximum efficiency of its products up to period $t + 1$. After $t + 1$, it is no longer willing to do so.

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be rationalized by the exogenous decrease in costs over time.

On the other hand, the heuristic does captures how the firm's tradeoff between T_{pre} and T_{post} changes as the number of periods remaining in T_{pre} decreases. Intuitively, the firm should be more willing to increase efficiency in T_{pre}, even if it adversely affects profits in T_{post}, when there are many periods remaining until the threshold is set. In the diagram, $\overline{e}$ settles at period $t+2$. The firm is no longer willing to increase the threshold, because the loss of profits in T_{post} becomes more significant relative to the gains in profits in T_{pre}.

A key limitation is that the heuristic does not capture the change in product offerings in the remaining periods of T_{pre}. More specifically, the heuristic does not capture rivals' responses to changes in the threshold level. Imagine that at period t, a rival firm increases the future threshold level to $\overline{e}$. In response to this, other firms are likely to re-optimize their product offerings; it is now "free" for the other firms to increase the efficiency of its products up to $\overline{e}_t$, in the sense that the firms' actions do not affect the future threshold and profits. In turn, this force may decrease the benefits of raising the threshold level in the first place. In the Appendix, we further elaborate whether the assumption $E\left[\overline{e}_{reg}\mid \overline{e}_t\right] = \overline{e}_t$ is reasonable by looking at firm behavior in T_{pre}.

4   Estimation and identification

Second stage   In the consumer's utility function, Equation (1), there are two unobservables, ε and $\tilde{\xi}$. The former is assumed i.i.d. and has the extreme value distribution, while the latter is unobserved product quality, which is both region and time period specific. We may be concerned that $\tilde{\xi}_{jrt}$ affects pricing decisions. Particular sources of concern are demand shocks that are firm specific and common across regions. For example, a firm may be a sponsor of the International Olympic Committee and hence benefit in demand during the Olympic Games. Firms also commonly market and advertise their brands, and not particular products. These firm-time specific shocks are controlled by β_{ft}. The remaining variation in $\tilde{\xi}_{jrt}$ is region- and product-specific deviations from the average firm-period demand shock. BLP instruments which help control for these shocks are discussed below.

This model assumes discrete heterogeneity, allowing for six household types that correspond to six income brackets. Data from the Japanese household expenditure survey are used to construct macro moments, akin to Petrin, 2002. The moments I match are the sales-weighted purchase price and the share of consumers who purchase any television for each income group and year. These moments are helpful in identifying heterogeneity. Within time periods, higher income households tend to purchase more televisions, and those tend to be more expensive. On average across four years, the highest income group (household income of over $100,000) purchased televisions that were 1.27 times more expensive than those purchased by the lowest income group (less than

$20,000). Over time periods, the macro data shows how the market initially attracted more high income households, and later lower income households purchased larger shares of televisions. In 2008, the highest income group purchased 27% of all televisions; in 2011 they purchased 21%. Recalling that prices decreased drastically over the data period, the macro data is able to attribute the early television purchases to those made by generally higher income households.

The macro-moments do not directly inform the type of television that was purchased. To control for endogeneity in prices and to better identify heterogeneity, a series of BLP instruments are used to form additional moments. BLP instruments reflect the number of models sold by own- and rival-firms: for all TVs; for TVs that have the same pixel density (FHD); and for TVs that are in the same TV size group, within a given period and region. The demand model is estimated with GMM.

Once the product dummies are estimated, OLS consistently estimates Equation (2), under the timing assumption that the demand shocks (ξ) and marginal cost shocks (ω) are revealed after product assortments are chosen. The timing assumption is a commonly maintained assumption for estimating models with endogenous product characteristics (e.g. Sweeting, 2013). In the current context, the coefficient β_e, which captures consumers' appreciation for energy efficiency, captures the component of quality that is correlated with energy efficiency, conditional on f and g. Manufacturers' catalogs suggest that premium models tend to be coupled with superior energy efficiency. This is consistent with accounts of technical reports that suggest that firms are typically only willing to design custom drivers that improve energy efficiency for premium models (Park, 2011). Therefore β_e is likely to be upward biased compared to consumers' true appreciation for energy efficiency per se. In this study, we assume that the relationship between e_j and unobserved quality stays the same regardless of the counterfactual level of the regulation and β_e captures the effect of efficiency as well as any associated unobserved quality shift.

First stage   A set of inequalities is constructed to back out fixed cost parameters that best rationalize the behavior observed in the data by calculating counterfactual profits that a firm would have made if another set of products were released, following the logic of revealed preferences as in Pakes et al. (2015).

Accounting for the regulation in T_{pre} helps rationalize the observed pattern of ratcheting and understand heterogeneity across firms in terms of their fixed costs. If firms are ratcheting down in T_{pre}, their product offerings will seem similar because their respective products are bunched below the standard level. If the regulation is not accounted for, the fixed cost estimates across firms will tend to look similar. Once the regulation is accounted for, firms' expected profits in T_{post} will inform how costly it was to hold back on releasing more efficient products. For instance, it may be that some firms are forgoing more profits than others by avoiding the introduction of more efficient

products.

The underlying intuition of the inequalities is straightforward. Assume for a moment that we have the true function π, and a simple additive fixed cost shock ν. If the model was limited to a single time period, the profit that a firm makes from releasing the set of products that it did in the data J_f^{Data} must be at least as large as the profit from releasing J_f^{Data} and an additional product j:

$$\pi_f\left(J_f^{Data}, J_{-f}^{Data}\right) - \sum_{k \in J_f^{Data}} (F_k + \nu_k) \geq \pi_f\left(J_f^{Data} \cup j, J_{-f}^{Data}\right) - \sum_{k \in J_f^{Data}} (F_k + \nu_k) - \underbrace{(F_j + \nu_j)}_{\text{additional fixed costs}}$$

which implies

$$F_j + \nu_j \geq \pi_f\left(J_f^{Data} \cup j, J_{-f}^{Data}\right) - \pi_f\left(J_f^{Data}, J_{-f}^{Data}\right) \tag{11}$$

That the firm released J_f^{Data} instead of $J_f^{Data} \cup j$ gives us a lower bound on the fixed cost of releasing product j: it suggests that the increase in fixed costs that would have been necessary to do so must have been larger than the additional second stage profits. Estimation amounts to making empirical analogues of the means of such inequalities to average out the error terms without causing selection. A benefit of this methodology is that an equilibrium selection mechanism need not be specified.

For operationalization, additional assumptions are necessary on the structure of the shocks. When a product is introduced, firms incur a fixed cost to release the product in that month

$$F_{jt} + \nu_{jt} = \underbrace{F_{fgt}^0 + \nu_{1,jt}^0 + \nu_{2,gt}^0}_{\text{constant}} + \underbrace{\left(F_{fgt}^e + \nu_{1,jt}^e\right) \cdot e_j}_{\text{efficiency}} + \underbrace{\left(F_{fgt}^q + \nu_{1,jt}^q\right) \cdot q_j}_{\text{quality}} \tag{12}$$

where F_{fgt}^0, F_{fgt}^e, and F_{fgt}^q are parameters to estimate. The ν shocks are decomposed into two parts. ν_2 shocks are those that firms condition on when deciding on product releases. On the other hand, ν_1 shocks are random shocks that are unknown to the firm when it is deciding on J_{ft}. They generate ex-post regret that firms seem to experience from the perspective of the econometrician. Both ν_1 and ν_2 shocks have unconditional expectations of zero over t. In practice, we constrain fixed costs parameters so that firms face the same set of fixed costs parameters during the first half (two years) of the data, as well in the latter half.

In this formulation, the structural shock that firms condition on, $\nu_{2,gt}^0$, is common across firms within a product group and time period and does not interact with energy efficiency. All else equal, this formulation means that in the earlier time periods before the threshold is set, a firm may be reluctant to release a highly efficient product because they believe that the future profit losses due to a more stringent threshold is large or because the realization of the unobservable fixed cost shock was large. Because the draw is common across firms, the assumption allows us to use information

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from other firms to infer the magnitude of the unobserved shock and to decompose the magnitude of these two forces. If these shocks were independent across firms ($\nu^0_{2,fgt}$), or if a shock pertinent to F^e existed (ν^e_2), the current set of inequalities would not be sufficient to estimate the parameters.[19]

A key element of the estimation procedure is devising informative counterfactual product offerings. If firms in a particular product group are manufacturing televisions with similar efficiency levels, we might think that these firms have similar costs structures. Using this intuition, we can make a series of inequalities in which we evaluate changes in a firm's profit from introducing a product similar to her competitors to better infer how firms' costs are similar (or dissimilar) to each other. We also consider a series of counterfactual product offerings that are informative of the restrictions imposed by the unique structure of the regulation; when considering counterfactual profits in $t \in T_{pre}$, both inequalities in which the firms' counterfactual product sets affect the future standard level, as well as those that don't affect the standard, are obtained. These help tease apart changes in firms' static, current period profits from those in T_{post}. A full listing of the moments and counterfactuals used is provided in the Appendix.

Calculating Π   As defined in Equation 8, Π returns the expected equilibrium profits in T_{post} (from solving Equation (7)) under given estimates of the fixed cost parameters F and any counterfactual values of $\overline{e}$. The challenge of estimating Π is that in response to a change in the value of $\overline{e}$, we would expect firms to reoptimize their product line, and therefore counterfactual product offerings need to be simulated.

Firstly, we approximate Equation (7) empirically based on a simplifying assumption: firms solve for future profits assuming that $J_{fg\tau} = J_{fg\tau'}$ for $\tau, \tau' \in T_{post}$. This means that firms decide on one counterfactual product offering throughout T_{post} from the perspective of T_{pre}. This significantly decreases the number of counterfactual product offerings that need to be simulated. Based on these heuristics, $\hat{\Pi}$ is defined as

$$\hat{\Pi}_{fg}\left(\overline{e}\right) = \sum_{\tau \in T_{post}} \left\{ \delta^{\tau - t_{post(1)}} \cdot \left[\pi_{f\tau}\left(J^*_{fg} \cup J^{Data}_{f,-g}, J^*_{-f,g} \cup J^{Data}_{-f,-g} \right) - \sum_{j \in J^*_{fg}} F_{j\tau} \right] \right\} \qquad (13)$$

where $J^*_g = \left\{ J^*_{f=1,g}, \cdots, J^*_{f=F,g} \right\}$ is the equilibrium product offering that satisfies

$$J^*_{fg} = \arg\max_{J_{fg}} \sum_{\tau \in T_{post}} \left\{ \delta^{\tau - t_{post(1)}} \cdot \left[\pi_{f\tau}\left(J_{fg} \cup J^{Data}_{f,-g}, J^*_{-f,g} \cup J^{Data}_{-f,-g} \right) - \sum_{j \in J_{fg}} F_{j\tau} \right] \right\} \quad \forall f$$

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[19]In practice, this assumes away selection on ν_2, because there is always at least one firm that releases a product within a (g, t) combination. In estimation, when an observation is missing, I reweight other Δr and ΔF terms in the same (g, t) combination, so that ν_2 shocks of all periods are equally weighted.

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J^* is obtained using an iterative best response logic. For every counterfactual standard level $\bar{e}$, and from an initial set of product offerings as observed in data, firms sequentially take "turns" changing optimizing its product offerings. On its turn, a firm decides on a set of products to introduce so as to maximize its expected profits in T_{post}, taking as given rivals' product offerings from the previous turns. The next firm is then allowed to take its turn, and this procedure is repeated across firms until no firm has any more profitable deviations.

The issue of multiple equilibria is well known in entry games. One solution is to explicitly consider all possible points in the state space, as considered in Eizenberg (2014) or Lee and Pakes (2009). Given the large number of firms and kinds of products that can be released, this approach is infeasible, and instead we rely on best response dynamics.[20]

5 Results

Second stage Basic logit models help understand the full demand system. Table 3 shows the results from linear regressions, as in Berry (1994). Column (1) estimates the demand specification without any instruments or product dummies. Columns (2) and (3) exhibit the role of the product dummies and BLP-style instruments. The addition of product dummies increases the magnitude of the price coefficient. While the BLP instruments are intended to help identify heterogeneity, they also contribute to higher price sensitivity and suggest that the instruments also help to control for unobservables. Finally, column (4) illustrates the decomposition of the product dummies, which is a projection of the estimated product dummies onto product characteristics. Having better controlled for price endogeneity, consumers' preferences for energy efficiency are now larger as expected.

Results from the full model are shown in Table 4. Panel (1) of the table presents the coefficients obtained from the main GMM routine, including parameters that are allowed to vary by household. We allow for six discrete household types, corresponding to six incomes brackets.[21] Higher income households (HH5, HH6) have greater appreciation for FHD televisions, while the estimates suggest that the most price-sensitive consumers are the lowest income households (HH1). The estimated product dummies have a large standard deviation, in part reflecting the vast differ-

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[20]In estimation, only relative changes in $\Pi_{T_{post}}$ ($\Delta\Pi_{f,T_{post}}$) need be evaluated to construct the inequalities (i.e. the absolute level of $\Pi_{f,T_{post}}$ ($\bar{e}_{reg}$) does not affect the estimated parameters). To the extent that local changes in $\bar{e}_{reg}$ are likely to result in product offerings that do not drastically deviate from the observed product offerings in data, it may be reasonable to use best response dynamic (which are likely to find an equilibrium that is "similar" to the one observed in data) to find counterfactuals. As a robustness test, an alternative ordering of firms in which smaller firms take turns first was considered, but did not significantly changes the equilibrium outcomes.

[21]Without any restrictions, the coefficients are allowed the vary flexibly across the six households. Due to limited data, particularly on heterogeneity on the kind of television purchased by household, the household FHD preferences ($\beta_{FHD,i}$) are assumed to be the same within households 3 and 4, as well as within 5 and 6.

Table 3: Estimates of second stage parameters using a simple logit model

	(1) $\log(s_{jrt})$ $-\log(s_{0rt})$	(2) $\log(s_{jrt})$ $-\log(s_{0rt})$	(3) $\log(s_{jrt})$ $-\log(s_{0rt})$	(4) Prd dummy from (3)
Price (p)	-0.138***	-0.968***	-2.661***	
	(0.0188)	(0.0251)	(0.149)	
Achievement percentage (e)	0.0157***			0.129***
	(0.000465)			(0.00438)
Indicator for Grp DG ($tgDG$)	0.782***			1.539
	(0.0696)			(2.604)
Indicator for Grp DK ($tgDK$)	1.010***			4.082***
	(0.125)			(1.053)
Screen size ($size$)	-0.0449***			-0.289*
	(0.00766)			(0.132)
Screen size squared ($size2$)	-0.000394***			0.00285
	(0.0000917)			(0.00148)
Pd dum	No	Yes	Yes	—
IV	No	No	BLP	—
N	46951	46951	46951	843
R^2	0.417	0.982		0.671

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Notes: Standard errors in parentheses. Standard errors in (2) and (3) not adjusted for estimation error of the product dummies. Coefficients for other product groups and fixed effects are not shown.

ences in market shares across television models. Panel (2) decomposes the product dummies. The relative magnitudes of the coefficients on energy efficiency (β_e) is about half to that in column (4) of Table 3. Panel (3) suggests that households are willing to pay between $157 to $260 for a 10 percentage-point increase in the achievement percentage of a television. A 10 percentage-point increase in achievement percentage corresponds to a $74 savings in electricity bills, assuming 30 cents per kWh and a usage of 10 years with no discounting.[22] The overvaluation of energy savings can be due to a strong preference of energy efficiency, or the unobserved characteristics correlated with efficiency, such as product design and superior features. Consistent with this, we observe that energy efficient products tend to be coupled with more premium features.

The final row of Table 4 shows the change in the total inside market share from a 1% increase in the price of all televisions. The median elasticity across all time periods and regions is -1.93. The (short-run) median elasticity is similar in order of magnitude to estimates of other durable

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[22]Absorbing month-, region-, and product group-fixed effects, a standard deviation of achievement percentage and energy costs are 18.2pp. and $135.60, respectively. Therefore, I approximate one achievement percentage to be roughly equivalent to $7.40 in energy costs.

(1) Coefficients obtained from GMM routine						
	HH1	HH2	HH3	HH4	HH5	HH6
p	-4.62***	-2.793***	-2.954***	-2.998***	-3.46***	-3.144***
	(0.382)	(0.366)	(0.364)	(0.418)	(0.314)	(0.23)
fhd	—	—	1.125***		3.076***	
			(0.025)		(0.075)	
Product dummies						
Mean			5.139			
Stdev			6.118			
(2) Projection of product dummies on characteristics						
Achievment percentage (e)			0.073*** (0.005)			
Indicator for group DG ($tgDG$)			-0.514 (0.836)			
Indicator for group DK ($tgDK$)			-0.212 (1.997)			
Size ($size$)			-0.183 (0.096)			
Size squared ($size^2$)			0.003 (0.001)			
(3) Willingness to pay						
From an average non-FHD to FHD TV						
	$160	$265	$631	$622	$1103	$1214
A 10 percentage point increase in AP						
	$157	$260	$246	$242	$210	$231
Elasticity			-1.93			

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Notes: HH1 through HH6 refer to household types, corresponding to incomes brackets ("annual income less than 20k," "between 20k-40k," "between 40k-60k," "between 60k-80k," "between 80k-100k," and "greater than 100k"). The household specific FHD coefficients are relative to that of the lowest household type. The household constants are assumed to be the same within households 3 and 4, as well as within 5 and 6.

Notes for **Willingness to pay**: Willingness to pay of non-FHD to FHD is the increase in willingness to pay from a television in Group DK (non-FHD) to DG (FHD), accounting for the accompanying increase in the average quality.

goods, such as for home personal computers (-3.6), as reported in Eizenberg (2014).

The estimates from the marginal cost equation are presented in Table 5. Due to the firm-group time trends, the marginal costs are significantly decreasing over time, which partly explains the decrease in prices over time. The estimates suggest that marginal costs for non-FHD televisions decrease at an average rate of 2.94% per month, while those for FHD televisions decrease at 2.14% per month.

The estimated costs of providing energy efficiency are more heterogeneous for non-FHD products. Table 5 shows that the coefficient of variation of the marginal costs for energy efficiency

Table 5: Estimates of marginal cost equation.

	log mc	
	Achivement percentage (e_j)	
	Non-FHD	FHD
Firm 1	0.0039587 ***	0.0157481 ***
	(0.0003193)	(0.0001854)
Firm 2	0.004741 ***	0.0191003 ***
	(0.000346)	(0.0002107)
Firm 3	0.0084906 ***	0.0158694 ***
	(0.0002796)	(0.0001992)
Firm 4	0.0075849 ***	0.0196195 ***
	(0.0003461)	(0.0002464)
Firm 5	0.0094048 ***	0.0165895 ***
	(0.0002796)	(0.0002174)
Firm 6	0.0001994	0.0147992 ***
	(0.0003486)	(0.000205)
Cf. Stdev across firms	0.003143	0.001785
cf. Coeff of variation	0.548518	0.105285
	Quality (q_j)	
	Non-FHD	FHD
(all firms)	0.1641857 ***	0.1457177 ***
	(0.001921)	(0.0011461)
N	48199	
adj. R^2	0.813	
Controls	Group, Month, Region F.E.s	
Median markup	$340	
Median $(p-mc)/p$	0.333	
Corr. of p, $mkup$	0.327	

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

is five times larger for non-FHD products than for FHD products. This is consistent with the anecdotal evidence that costs structures for FHD televisions are similar across firms as discussed in Section 2. However, whether the differences in costs are significant enough for us to account for the differential ratcheting patterns across television types, as illustrated in Figure 3, is a key question we explore in the counterfactuals.

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First stage   Table 6 presents the estimated fixed cost parameters.[23] Panel (1) of Table 6 presents the fixed cost parameters F^e, F^q and F^0, for a representative FHD (group DG) and non-FHD (group DK) product group.

Table 6: Fixed cost parameters.

(1) Fixed cost parameter estimates (unit: $1000)						
	Firm 1	Firm 2	Firm 3	Firm 4	Firm 5	Firm 6
F^e						
$grpDG$	966	1067	1420	247	1354	1928
$grpDN$	6741	13757	3853	3844	1381	5584
F^q						
$grpDG$	2142	2435	2648	328	1183	2712
$grpDN$	9013	28782	6162	4196	1303	6886
F^0						
$grpDG$	-1791	-1668	-2115	-241	-1435	-2832
$grpDN$	-5462	-24458	-5701	-2458	-1334	-5410
(2) Median fixed costs of products released in data (unit: $1000)						
$grpDG$	3354	2673	4667	647	2268	8107
$grpDN$	69834	51595	20590	23688	3020	52503
(3) Revenues and costs of average firm (unit: million USD per year)						
Revenue			506 (100%)			
Total marginal cost			235 (46%)			
Total fixed cost			175 (35%)			
Profits			96 (19%)			

Notes for **Fixed cost parameters**: In this table, fixed costs parameters are evaluated at the level of February 2009. Coefficients F^e and F^q have been scaled so that it reflects a one standard deviation increase in e and q. The standard deviation of e and q demeaning period, region, and firm-by-product group fixed effects is 16.0 and 1.3, respectively.

Notes for **Revenues and costs**: The total revenues and costs for each of the six major firms were calculated. The average across six firms is presented.

Table 6 also shows a decomposition of revenues and costs for the average firm. The estimates suggest that fixed costs are 43% of the total costs that firms incur, and 35% of total revenues. The costs associated with energy efficiency are also large, as in general, the technology for efficiency

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[23]The fixed costs parameters, albeit being estimated using inequalities, are point estimates. There are two possible reasons for this. Firstly, the functional form for fixed costs are may not be flexible enough to accommodate all of the inequalities. This is particularly true when the product attributes can take a wide range of values. For instance, a firm may simultaneously sell two products with a low and a high level of efficiency respectively, for which the marginal fixed costs vary significantly in practice but are forced to be uniform in our model. Secondly, the fixed costs may be point identified because a multitude of inequalities are used. Inequalities are random variables, and hence, the likelihood of finding a range of parameters in which all inequalities are satisfied decreases as the number of inequalities increase.

of televisions has matured, and the scope for substantial increases in efficiency was already limited by the early 2010's.

It is harder to assess the role of fixed costs differences on the perceived differential outcomes across FHD and non-FHD televisions. On the one hand, the differences of costs for energy efficiency is consistent with anecdotal evidence that they vary more in the market for non-FHD televisions. The coefficient of variation for fixed costs of energy efficiency is 0.44 in a representative FHD market (Group DG), while it is 0.67 in a representative non-FHD market (Group DN). On the other hand, if the relevant margin is the overall fixed costs of releasing a product, there is no significant difference in the coefficient of variation across product groups (0.65 for FHD televisions versus 0.62 for non-FHD televisions). In this context, the counterfactual analysis is relevant in understanding the relevant margin that drives the differential patterns seen across product groups

6 Counterfactuals

The primary intent of the counterfactual simulations is to decompose the ratcheting incentives been at play. Therefore, we focus on the post-regulatory regime and observe how both firms' profits and behavior change under counterfactual policy scenarios.

Firstly, we present results from firms' behavior under the (actual) regulation in T_{post} to further interpret the parameter estimates. The primary outcome of interest is $\Pi_{fg}(\bar{e})$, firm-by-group specific profits as a function of the standard level $\bar{e}$, as estimated at the end of Section 4. The two panels in Figure 6 illustrates the change in profits in representative non-FHD and FHD product groups, when all firms are unilaterally subject to the same counterfactual regulatory standard. The change in profit is shown relative to the profits that the firm would have made under the factual standard level, which by definition is 100% (recall that our measure of efficiency is such that 100% corresponds to the efficiency level of the most efficient product sold in data in the pre-regulatory period). Therefore, each of the lines in the panel corresponds to $\Delta\Pi_{fg}(\bar{e}) = \Pi_{fg}(\bar{e}) - \Pi_{fg}(100)$ for a firm.

Generally, these lines are monotonically decreasing, suggesting that tighter regulator levels translate to decreased profits. To interpret the magnitude of these changes in profits, it is informative to compare outcomes when the standard is set at the level observed in data (100%) to those when there is no standard in place. Because the efficiency level of the least efficient products sold in the year leading up to the post-regulatory period was roughly 80%, the outcomes under an 80% standard is roughly suggestive of outcomes when no standards did not exist or were otherwise very loose. The comparison between 100% and 80% standards are described in Table 7. As consumers strongly prefer energy efficiency, the introduction of the efficiency standards increases consumers' welfare by \$190.7 million dollars per month in the average product group. The increase in con-

Table 7: Welfare effects of efficiency standard, average across four major product groups

	Change due to introduction of standard at $\overline{e} = 100\%$
Inside share of four major product groups	+1.18%
Sales weighted ave. achievement percentage	5.03 percentage points
Firm revenue ($M per year)	$85.2
Firm profits ($M per year)	-$305
Consumer surplus ($M per year)	$190.7
Environmental benefit ($M per year)	$4.2

Notes: The non-regulation case is simulated by assuming that the lower bound on efficiency that can be introduced is 80%, roughly corresponding to the efficiency of the least efficient product that was released in data in the year leading up to the implementation of the standard. Environmental benefits are obtained by assuming that one achievement percentage in energy efficiency corresponds to $11.5 \, kwh$ savings over 10 years of usage (obtained from comparing the standard deviation of achievement percentage and energy usage within month, region, and product group); a emissions factor of $0.5 \, kg \cdot CO_2/kwh$; and social cost of carbon of $\$30/ton \cdot CO_2$.

sumer welfare is driven by the decrease in relative markups for energy efficient products; the sales weighted achievement percentage per thousand dollar increases from 152.6 to 157.60, enabling the consumer to purchase efficiency more cheaply on a per-dollar basis. The regulation forces product offerings to look more similar across firms and intensifies competition. As a result, the margins that firms can enjoy decreases. Consumers, in turn, purchase more televisions (1.18% increase in inside share). An increase in the inside market share, as well as increase in the sale weighted average achievement percentage (5.03 percentage points increase), contribute to larger consumer welfare.

On the other hand, this welfare gain is more than offset by a decrease in joint firm profits of $311.4 million dollars per year per product group. The decrease in firm profits is strongly driven by the significant increase in fixed costs ($360.2 million dollars) that the firms must now incur to be compliant with the standard. Firms respond to tighter regulations by both increasing the efficiency of existing products as well as by shrinking their product lines (the average firm decreases their product line from 4.6 to 4.1 products in each product group). Finally, the losses in firm profits are much larger than a crude estimate of the decrease in environmental externalities: the benefits from decreased CO_2 emissions due to decreased energy consumption are in the order of magnitude of $4.2 million dollars. These estimates are interpreted as short run changes in welfare, as in the longer run technological change will decrease the costs that firms must incur to comply with the standards.[24]

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[24]In the long run, because Japanese environmental standards for televisions are tighter than those introduced elsewhere, there may be environmental benefits if exported products also meet similar environmental standards. Globally,

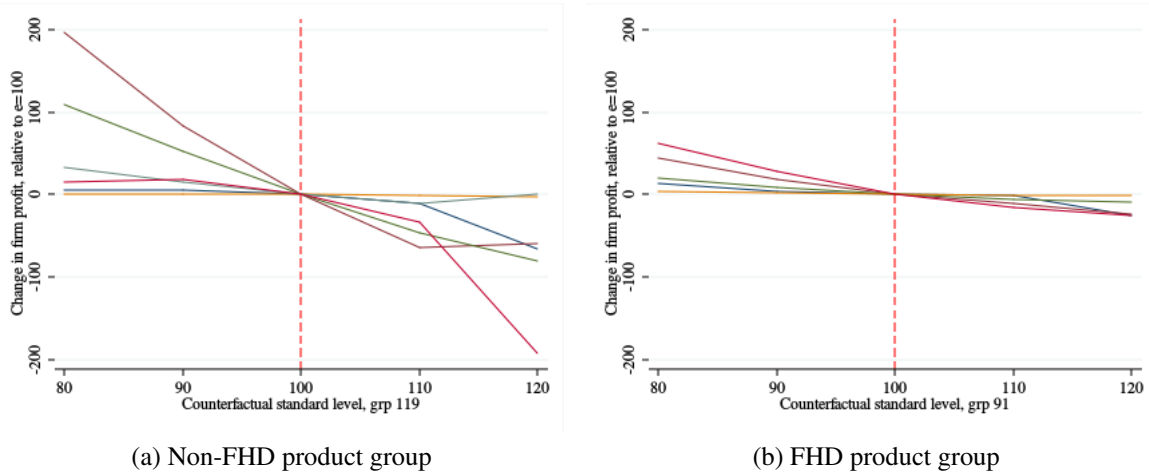| (a) Non-FHD product group | (b) FHD product group |

Figure 6: Change in yearly firm profits, in \$M, under counterfactual standard levels, across representative non-FHD and FHD product groups. Each line traces out $\Delta\Pi_{fg}^{uniform}(\overline{e}) = \Pi_{fg}^{uniform}(\overline{e}) - \Pi_{fg}^{uniform}(100\%)$ for a given firm, i.e., the change in profits for the firm under a counterfactual standard level, compared to the profits under the baseline (100%) level.

The counterfactuals are also suggestive of differential impact of the regulation across firms. For instance, the introduction of standard in the FHD product group allows one firm to gain a 21.5 percentage point increase in inside market share. Importantly, these differential effects can potentially penalize the production of energy efficient products; in the non-Full HD product group, we observe that two firms see a decrease (6.7 and 2.2 percentage points, respectively) in the sales weighted achievement percentage of their products, despite the introduction of standard which prohibits firms from selling inefficient products. These are firms that were manufacturing efficient televisions, even in the absence of the regulation. Due to the regulation, other firms that were producing less efficient products must now make televisions that look more similar to those made by firms which provided energy efficient offerings. In turn, some consumers who had previously purchased highly energy-efficient products in the absence of policy shift away to competitors. While this force is not strong enough for the two firms to stop manufacturing the highly efficient products, one can postulate that in the longer run, this may disincentivize the manufacturers of energy efficient products from developing more efficient products. The general decrease in firms' markups due to tighter standards, as well as this "punishment" that the more efficient firms receive from tighter standards, are themes that carry over to our decomposition exercise described below.

televisions consume as much as 168 TWh, corresponding to 3 to 4% of global residential electricity consumption, and about 27 megatonnes of CO2 emissions. The benefits from an global energy efficiency program for televisions may be large: Park (2011) suggests that some 70 megatonnes of CO2 emissions can be reduced during 2012 through 2030 by encouraging adoption of more efficient televisions. On the other hand, one may question whether regulations in the Japanese television market drive firms' investments in R&D. The Japanese television market is no more than a few percentage points of the world television market by share of quantity sold.

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Decomposing within- and across-firm incentives Having estimated profit changes under the unilateral standards (Π_{fg}) for both FHD and non-FHD product groups, we return to the primary exercise of decomposing the ratcheting incentives. A key question pertains to the sources of the differential outcomes across the two sets of product groups, as exhibited in Figure 3. Recall that, in FHD product groups a visual inspection of the trend suggests a jump in the most efficient products around t_{set}, but that this jump was not visible in the non-FHD product groups.

Under the uniform standard, Figure 6 highlights that firms experience (weakly) lower profits from having higher standard levels – both across FHD and non-FHD product groups. This suggests that even in non-Full HD products group in which ratcheting down behavior is not observed, firms had an (net) incentive to keep standards low to avoid future profit losses in T_{post}. Therefore, the patterns seen in Figure 3 cannot be explained by the firms' differential profits in T_{post} and must be due to differences in T_{pre}: in the FHD product groups, the firms' relatively low costs of provising energy efficiency in T_{pre} is why we observe no ratcheting down behavior. However, in the non-FHD product groups, the decrease in future profits in T_{post} from introducing a more efficient product in T_{pre} was larger than the increase in profits in T_{pre}.[25] This outcome suggests that in net, ratcheting down incentives were dominant across product groups.

It is informative to study the gross incentives, namely whether firms had any incentive to introduce more efficient products: could the regulation have introduced marginal incentives for a firm to ratchet up? This is particularly relevant in the non-FHD product group, in which no discernible pattern of ratcheting down was observed in Figure 3, and competitive forces (ratcheting up) may have played a role in determining product assortment decisions.

To build on the discussion at the end of Section 2, we consider two counterfactual regulatory regimes to separate within- and cross-firm incentives. In the classic ratchet effect (Freixas et al., 1985, Weitzman, 1980), a single agent ratchets down its quality today because its actions only affect its own future constraints, and not those of any other agents'. *Firm-by-firm constraints* simulate the magnitude of this effect by subjecting a firm in T_{post} to a regulation that affects only itself:

$$\overline{e}_f \leq \min_{j \in J_{f,T_{post}}} e_j$$

where $\overline{e}_f$ is the standard level that applies uniquely to firm f. There are no interactions between firms by virtue of the regulation, and therefore, the outcome under this regime would be suggestive

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[25] A simulation that allows for firms to reoptimize their product offerings in T_{pre} confirms this intuition. The simulation suggests that in the FHD product groups, all firms show an incentive to decrease the efficiency of their products: compared to outcomes when firms maximize pre-regulatory profits without any dynamic incentives, all firms offer less efficient products than they would have without regulatory constraints. In contrast, this behavior is not exhibited in the non-FHD product groups: in these product groups, a few (efficient) firms try to introduce products that are as efficient as possible, regardless of whether the regulation exists or not. This is consistent with the patterns illustrated across the FHD and non-FHD televisions exhibited in Figure 3.

Table 8: Change in profit for most efficient firms due to an increase in counterfactual standards from 100% to 110%, in $M per year.

	Grp DG (FHD)	Grp DN (Non FHD)
BAU ($\overline{e} = 100\%$)	-6.42	-19.06
Firm-by-firm constraints	-6.37	-18.84
Leave-own-out constraints	-0.015	-0.195
Cf. Increase in market share necessary to make leave-own-out profits exceed firm-by-firm losses	154.2%	21.5%

Notes: The table shows the average simulated profit changes for firms that sold the most efficient products under the pre-regulatory regime. The first three rows show the change in simulated profits when the standard level increases from 100% to 110% under the three counterfactual scenarios.

of the magnitude of within-firm incentives in T_{post}. To the extent that tighter $\overline{e}_f$ decreases firm f's profit in T_{post}, it would imply the existence of incentives to keep the regulatory standard looser in T_{pre}, i.e. ratchet down.

Contrast this to *leave-own-out constraints*, which are designed only to impose an cross-firm externality

$$\overline{e}_m \leq \min_{j \in J_{f,T_{post}}} e_j \ \ f \neq m$$

Under this constraint, the standard level $\overline{e}_m$ applies to all firms but firm m, the focal firm. The focal firm is not subject to the constraints. Therefore, the outcome of this regime is indicative of the magnitude of cross-firm incentives for the focal firm in T_{post}. To the extent that tighter $\overline{e}_m$ increases profits in T_{post} for firm m, it would imply the existence of incentives to introduce tighter standards in T_{pre}, i.e. ratchet up.

Outcomes from each of the counterfactuals are obtained by estimating alternative versions of the Π function. Using the iterative best response logic described at the end of Section 4 we obtain Π functions that return the firm's expected profits for each policy regime, and product group: $\Pi_{fg}^{firm-by-firm}(\overline{e}), \ \Pi_{fg}^{leave-own-out}(\overline{e})$.

The two panels of Figure 7 show how the firms' profits in a representative non-Full HD product group change under the alternative policy designs. Under firm-by-firm constraints, illustrated in the first panel, firms generally see decreased profits as the standard is tightened. The decrease in profits is 18.8 million dollars annually and explains the majority of the overall decrease in profits in this profit group (19.1 million dollars). This is consistent with the regulation binding for most firms. As with the case of overall welfare effects, the increase in firms' fixed costs are a large driver of these results.

The second panel of Figure 7 illustrates profits under the leave-own-out constraints, in which the focal firms are not subject to the regulation. In this plot, each line corresponds to the counter-
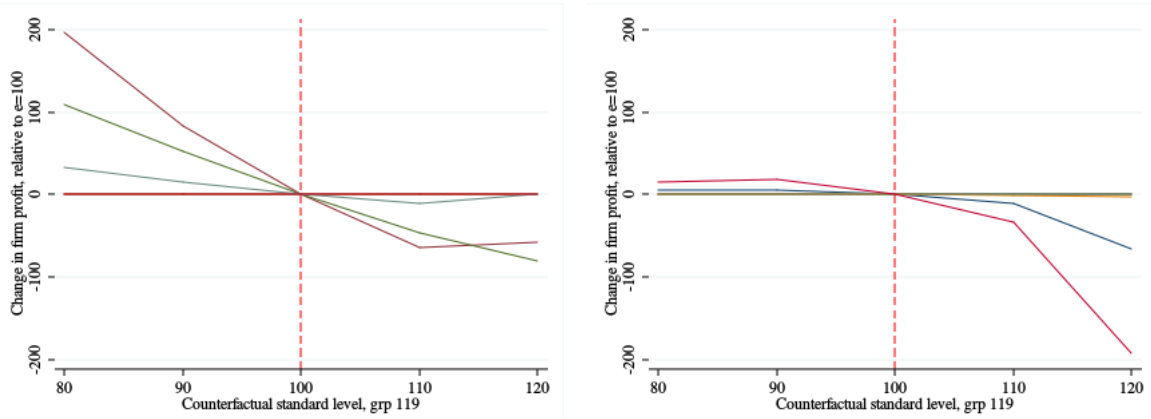
(a) Firm-by-firm constraints (each firm subject to its own efficiency standard)

(b) Leave-own-out constraints (all other firms subject to efficiency standard; focal firm is exempt)

Figure 7: Change in yearly firm profits, in \$M, in a representative non-FHD product group (group DN) under two counterfactual scenarios. Each line traces out $\Delta\Pi_{fg}^{regime}(\bar{e}) = \Pi_{fg}^{regime}(\bar{e}) - \Pi_{fg}^{regime}(100\%)$ for a firm in the non-FHD product group, where $regime \in \{firm - by - firm, leave - own - out\}$

factual profit that the focal firm would receive if every other firm was subject to the corresponding level of regulation. Across all major product groups, we find no evidence of cross-firm externalities that the regulation may have introduced. This is exhibited by the weakly downwards sloping lines suggesting that under the leave-own-out constraints, firms experience weakly decreasing counterfactual profits.

The effects under leave-own-out constraints are relevant particularly for the set of firms that could have affected the standard level, i.e. firms that were selling highly efficient products in the pre-regulatory regime. Table 8 shows that these firms see a small decrease (0.195 million dollars) in annual profits under leave-own-out constraints. On the one hand, the firm is rewarded as the margins on its own products increases slightly (0.19%), because some inefficient product offerings from its competitors are no longer available. However, this effect is offset by a larger decrease in market shares (-0.20%), as competitors are forced to introduce efficient products and do so at a relatively low price. This illustrates the strong condition that is necessary for raising rivals' costs: the marginal costs must vary significantly enough across firms, so that firms that are able to manufacture efficient products are rewarded as others are forced to make televisions at a sufficiently higher cost. In both non-FHD and FHD product group, the condition is not met.

In other words, given the sizable loss in profits under the firm-by-firm constraints, a firm must enjoy a large increase in market shares under leave-own-out constraints for the overall change in profits to be positive. Table 8 shows that a firm in the non-FHD market would need to gain a sizable 21.5% increase in market share under leave-own-out constraints for the firm to make up for the loss of profit from the firm-by-firm constraints. Consistent with the graphical analysis

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presented in Section 3, ratcheting up incentives are even weaker in the FHD market; in the FHD market, the necessary increase in market share is an even larger 154.2%.

In summary, when technology is already mature and product costs today are likely to be already low, firms may not exhibit ratcheting down because they would rather enjoy higher profits today than enjoy a relatively smaller decrease in profits in the future. On the other hand, when technology is still developing, firms realize that today's costs are likely to be higher than those in the future and, hence are willing to hold back the introduction of some technology to avoid incurring the high costs today. Regardless of the level of technology, in the market that we have analyzed, firms never find it in their interest to encourage higher levels of regulation for their direct benefit. More generally, in oligopolistic markets with developing technologies in which firms share similar cost structures, ratcheting up incentives are likely to be non-existent. In such markets, the effect of the regulation is pitted in one direction: it may encourage firms to hold back the technology, but it is unlikely to accelerator the introduction of better technology. Given that the standard significantly decreased firms' profits in the post-regulatory regime, these policies can only be justified if policy makers place a large premium on being able to increase consumer surplus in the future.

7   Conclusion

In many markets, the diffusion of innovation is heavily influenced by the presence of policy intervention. In these markets, firms have incentives to alter their product offerings because they realize their actions can influence future policy. If firms significantly hold back on quality, they and their rivals are able to continue selling less efficient products for the foreseeable future. Therefore, the firms' ratcheting incentives can have significant influence on the pace at which technological change diffuses.

Using data from the Japanese television market, which is subject to a unique regulatory regime, we show that the incentive to ratchet down energy efficiency was significant in the major regulatory submarkets. Economic theory suggests that ratcheting up is more likely to incentive firms to introduce more efficient products, when firms are dissimilar in their cost structures. For example, a firm that has an advantage in making energy efficient television sets may further benefit by inducing tighter regulatory standards. However, counterfactual analyses using empirical model developed in this paper suggest that such incentives did not exist, even in submarkets where we expected (and observed) more variation of costs across firms such as the submarket for non-FHD televisions. In other words, the cost variations were not significant enough. Ratcheting up is unlikely to be observed in concentrated markets where firms are likely to share fairly similar technological inputs and, therefore, similar cost structures.

Regulators are commonly mandated to implement unilateral policies, such as the Top Runner

Program, in which the standards firm are subject to are identical across firms. Our analysis suggest that in the presence of such unilateral standards, firms may have little incentive to ratchet-up. It can lead to firms delaying the introduction of more high quality products. This is particularly true because the structure of many such markets (such as those of durable appliances) is such that firms' cost structures are generally similar, and the exit of a given firm is very unlikely.

The lack of ratcheting-up incentives is problematic if the regulator aims to have firms reveal their ability to introduce more efficient products, because costlier policy designs may become necessary. Gersbach and Glazer (1999) theoretically show that tradable permits, combined with minimum quality standards, can mitigate firms' incentives to ratchet down. Some jurisdictions have introduced "golden carrot" schemes, in which firms that introduce the most efficient product are given substantive rewards, akin to an auction. These schemes mitigate the incentive to ratchet down by directly compensating for firms' losses, but they come at a significant cost to the policymaker.

This study also serves as a cautionary tale for assessing the benefits of standards. When evaluating unilateral policies, the fact that firms respond strategically to dynamic regulation makes clear that a simple comparison of pre-regulatory firm behavior to post-regulatory firm behavior is not sufficient. Indeed, because the Japanese efficiency standards can introduce incentives to ratchet down, a short-term comparison is likely to overstate the increase in efficiency. The UN Intergovernmental Panel on Climate Change suggests that the effectiveness of energy efficiency standards is debatable because demand side responses, such as rebound effects,[26] are far from being fully understood (Edenhofer et al., 2014). In assessing the benefits of these standards, my research suggests the need for more careful investigation of supply side behavior, such as ratcheting, as well.

In the longer run, the presence of ratcheting down is likely to slow down the pace at which newer technologies are adopted. The standards considered in this study speak to the "diffusion" stage in Schumpeter's trilogy of technological change.[27] Minimum quality standards play an important role in influencing the final stage of this linkage by preventing lower quality goods from being produced, thereby encouraging the purchase of newer technology. A looser standard means that older technology is able to linger around for a longer period of time.

Standards are commonly introduced hand-in-hand with financial incentives and informational campaigns with the intent that such policies ultimately affect the pace at which R&D in a particular

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[26]When energy efficiency policies are successful, they induce more consumption of energy services because the price (of energy services) decreases (the "rebound effect"). For instance, one may drive more as a result of buying a more fuel efficient car. See Gillingham et al. (2016).

[27]Firms' product line decisions are a key determinant of the pace of diffusion of new technologies, the final step in Schumpeter's trilogy of technological change. In Schumpeter suggests that the process of technological change involves three stages: invention (the generation of new ideas); innovation (development of new ideas into marketable products); and diffusion (adoption of products by agents). I further comment on this linkage in the conclusion.

direction is conducted (Geller and Nadel 1994). While the drivers of innovation are outside the scope of this paper, theories of innovation suggest that standards would be more likely to stimulate innovation if they were to encourage the diffusion of more efficient products (Newell et al., 1999).[28] The extent to which standards, which affect the "costs" of providing quality, play in influencing the upstream innovation process is an open question.

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[28]For example, Hick's induced innovation hypothesis suggests that innovation occurs in response to changes in the relative prices of input, so that more costly inputs are economized. Standards change the shadow price of energy (in)efficiency. Manufacturers respond by investing in R&D to improve energy efficiency, because energy inefficiency is now more costly. While the magnitude of these effects remain "uncertain" (Jaffe et al., 2003), there is some anecdotal evidence for this force. For instance, some manufacturers have stated that appliance standards have encouraged them to "develop leading edge technology for efficiency" (McInerney and Anderson, 1997).

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