On dynamic standards for energy efficiency in differentiated duopoly

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08.10.2015

Abstract. We consider a two-periods-model of differentiated duopoly. Firms produce an energy consuming household durable differentiated by its energy efficiency. Consumers differ by the weight they apply to their future energy costs when deciding which product to buy. In line with the Japanese Top Runner Program, the regulator introduces a minimum efficiency standard in period t=2 which is fixed according to the efficiency of the product supplied by the high efficiency firm in t=1. We show that in t=1 both firms supply lower efficiency products and the high efficiency firm gains in market share and profits. In t=2 these effects are reversed. Calculated over both periods, total energy consumption does not change. Although there is no ecological effect, total welfare increases because price competition becomes tighter and the cost savings accruing to the consumers exceed the firms' losses in profits.

Keywords: energy efficiency standards, product differentiation, duopoly, regulation

JEL Classification: L13, Q48, Q58

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1. Introduction

Concerns about environmental degradation due to climate change and dwindling reserves of fossil fuels generated an ongoing debate about efficient and effective ways to save energy. In addition to putting a price tag on emissions from burning fossil fuels and promoting renewable energies, enhancing energy end-use efficiency of durables is a major policy goal in e.g. the European Union (EU 2006, EU 2009), several states in the USA (EPA 2006) and Japan (METI 2010). Besides building codes, efficiency standards concerning the specific energy consumption[1] of household durables are widely used. There are (at least) three reasons leading to the presumption that the specific energy consumption of such durables is too high from the viewpoint of the social optimum (for a more throughout discussion of this topic see, e.g., Schipper and Hawk 1991):

1) Energy prices may be too low compared to the social optimum due to negative externalities.

2) Consumers may be subject to information asymmetries concerning the specific energy consumption of the durables.

3) Consumers may behave myopic when deciding which appliance to purchase. This might lead to unduly high discount rates or even full neglect of the energy costs accruing over the useful life of a durable.[2]

Of course, the first two reasons do not necessarily require the introduction of standards for energy efficiency since external costs can be captured by an emission tax and information asymmetries may be corrected with the help of labeling obligations.[3] However, myopic behavior by consumers might not be adequately met with those policies. Consequently, energy efficiency standards are an appropriate instrument in the policy maker's toolbox for enhancing energy end-use efficiency.

An advancement of this policy approach are dynamic energy efficiency standards which incorporate the actual levels of the durables' energy efficiency. Such dynamic standards tighten the mandatory efficiency level over time based on a benchmarking approach by determining a feasible or the most efficient appliance in each line of product per period. Next the regulator sets this efficiency level for all producers.

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[1] The term "specific energy consumption" refers to the energy consumption per unit of service.

[2] For example, from purchasing patterns for a standard and an energy-efficient refrigerator, Meier and Whittier have estimated the following distribution of implied consumer discount rates: "*Roughly 2/5 of the consumers behaved as if they had real discount rates above 60 %, 1/5 between 35 and 60 %, and 2/5 less than 35 %*" (Meier and Whittier, 1983, p. 957).

[3] Concerning the impact of eco-labelling on consumer behaviour see, e.g., Sammer and Wüstenhagen (2006).

An example for such dynamic standards is the European Ecodesign Directive (EU 2005, EU 2009). Although it offers the possibility of voluntary agreements by industry it also enables mandatory energy efficiency targets accompanied by product labeling obligations. These targets are revised in regular intervals and may therefore be subject to continuous tightening. However, a more prominent example for dynamic energy efficiency standards is the Japanese Top Runner Program which started in 1998 with 9 products and by 2012 covers 23 products (Osamu 2012). The core of the Top Runner Program is that it obliges producers to establish the currently highest efficiency level for the respective durable by a certain target year. Although this policy approach is considered to have performed well,[4] a dynamic standard for energy efficiency gives rise to strategic decision making. Especially a producer of high efficiency durables can influence the future standard by his efficiency choice today. This incentive might therefore affect environment and energy related policy goals counterproductively, if the high efficiency producer chooses to understate his actual capabilities. Examples from products regulated by the Japanese Top Runner Program like fluorescent lighting and liquid crystalline show that the efficiency targets were met much earlier than required by the program (Osamu 2012). This observation supports the presumption that dynamic standards for energy efficiency may prompt producers to refrain from implementing the actual potential for efficiency improvements.

To the best of our knowledge, the economic incentives caused by dynamic standards for energy efficiency as described above have not been considered in the literature so far. However, our work is closely related to the literature on the effects of a minimum quality standard (MQS) because energy efficiency can be interpreted as a special type of quality. The respective literature traces back to the seminal papers of Leland (1979) and Shaphiro (1983) who demonstrate that an MQS can increase welfare in the case of asymmetric information about product quality when firms have no market power. Ronnen (1991) was the first to analyze the welfare effects of an MQS using a standard set up of vertically differentiated duopoly. In his model, the demand side is given by a continuum of consumers who are differentiated by the value that they place on quality. The supply side is described by two identical firms each offering one single quality, where costs only consist of quality dependent fixed costs. Assuming quality competition on the first and Bertrand competition on the second stage, Ronnen shows that introducing an appropriately chosen MQS can increase welfare even in the absence of information asymmetries. The reason is that the positive effect on consumers' surplus, which

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[4] See Nordqvist (2006) and Osamu (2012). Moreover, the Japanese Top Runner Programme has been celebrated by political scientists to be "the most advanced and sophisticated approach to 'ecological modernisation'" (Jänicke, 2006, p. 17).

is caused by limiting product differentiation and intensifying price competition, dominates the negative effect on the firms' profits. Subsequently, the approach of Ronnen (1991) has been modified and extended in several ways. For example, Crampes and Hollander (1995) introduce unit costs that increase in quality and Valetti (2000) considers the case of Cournot instead of Bertrand competition in the second stage of the game. Both papers show that Ronnen's optimistic results concerning the welfare effects of an MQS can not always be sustained and depend on the set up of the model.

Moreover, since the mid nineties, the issues dealt with in the literature on minimum quality standards have become increasingly diversified. For example, Häckner (1994), Ecchia and Lambertini (1997) as well as Napel and Oldehaver (2011) analyze the impact of minimum quality standards on the incentives for collusion; Lehmann-Grube (1997) and Kuhn (2006) assess the advantages and disadvantages to be the high or the low quality firm, respectively; Maxwell (1998), Puller (2006) and Garella (2006) evaluate the effects on the incentive to innovate; Boom (1995) and Lutz and Baliamoune-Lutz (2003) consider the role of minimum quality standards in international trade models; Lee and Phuyal (2013) study strategic entry deterrence by an incumbent under a MQS regime; and Cellini and Lamantia (2013) analyze the joint effects of minimum quality standards and price regulations within a dynamic framework.

In contrast to the more recent literature cited above we are not concerned with advanced topics like, e.g., collusion or the incentive to innovate. Instead, our work is in the spirit of the earlier contributions to the literature as we explore the more fundamental question whether or not a dynamic standard according to the Japanese Top Runner Program is an appropriate instrument at all when the regulator aims at increasing energy efficiency or total welfare. The remainder of our paper is organized as follows. In Section 2, we introduce the model and in Section 3, we calculate the unregulated equilibrium as our reference case. In Section 4, we derive the regulated equilibrium and in Section 5, we compare our results concerning energy consumption and welfare obtained for the regulated case with those for the unregulated one. Finally, in Section 6, we summarize our main conclusions and identify some topics for future research.

2. The Model

We employ a modified dynamic version of the model on MQS in differentiated duopoly presented by Crampes and Hollander (1995). The time horizon comprises two periods t=1,2, where the length of each period equals the useful life of the durables under consideration. There are two firms j=H,L each producing a single variant differentiated by the energy con-

sumption $\varepsilon_{jt}>0$ which is calculated over the durables' complete useful life.[5] In line with the literature and without loss in generality we assume $\varepsilon_{Lt}>\varepsilon_{Ht}$,[6] i.e., the role of each firm as high- or low-efficiency producer, respectively, is considered as given. The price of variant j in period t is denoted by p_{jt}.

The demand side is given by a unit mass of consumers indexed by i, each buying exactly one unit per period (this assumption will be discussed in Section 6). When deciding which variant to buy, the consumers compare the sum of purchase price p_{jt} and perceived energy costs. The latter are given by $\alpha_i \cdot w \cdot \varepsilon_{jt}$, where w indicates the energy price and α_i, which is distributed uniformly on the interval [a,b] with $0<a<1$ and $b=1+a$, is the individual weight assigned to energy costs by consumer i. Interpreting the different values of α_i is straightforward: A consumer with $\alpha_i<1$ can be characterized as "myopic" since he underestimates future energy costs, whereas a consumer with $\alpha_i>1$ can be characterized as "green" since he accounts not only for total energy costs but also for environmental damage costs caused by energy consumption. Solving the equation $p_{Ht}+\alpha_i w\varepsilon_{Ht}=p_{Lt}+\alpha_i w\varepsilon_{Lt}$ for α_i yields the position of the indifferent consumer in period t: $\hat{\alpha}_t=[p_{Ht}-p_{Lt}]/[w(\varepsilon_{Lt}-\varepsilon_{Ht})]$.

As mentioned above, our approach is closely related to the literature on minimum quality standards. However, quality is a positive characteristic, whereas energy consumption is a negative one. In order to ensure comparability of our results with the literature on MQS, we transform energy consumption ε_{jt} into the positive characteristic "energy efficiency" e_{jt} using the definition $e_{jt} \equiv e^{max}-\varepsilon_{jt} \geq 0$.[7] With this transformation, the position of the indifferent consumer can be re-written as:

$$\hat{\alpha}_t = \frac{p_{Ht}-p_{Lt}}{w[e_{Ht}-e_{Lt}]}.$$ (1)

Consequently, in period t, all consumers with $\alpha_i<\hat{\alpha}_t$ choose variant L, whereas all consumers with $\alpha_i>\hat{\alpha}_t$ choose variant H. The resulting market shares in period t are $s_{Lt}=\hat{\alpha}_t-a$ for firm L and $s_{Ht}=a+1-\hat{\alpha}_t$ for firm H. Moreover, from $e_{jt}=e^{max}-\varepsilon_{jt}$ and $\varepsilon_{Lt}>\varepsilon_{Ht}$ we obtain $e_{Lt}<e_{Ht}$, i.e., L is the low efficiency supplier and H is the high efficiency supplier. Both firms share the same technology, and production costs per unit are assumed to be independent of

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[5] This way of modelling energy consumption implies that all consumers apply the same rate of utilization (for example, four washes per week in the case of a washing machine).

[6] The case $\varepsilon_{Lt}=\varepsilon_{Ht}$ can be ruled out a priori because Bertrand competition would eliminate all profits.

[7] The term e^{max} is an arbitrarily chosen but sufficiently large constant which cancels out in all of our calculations.

quantity but increasing in energy efficiency.[8] In line with several other studies on MQS in differentiated duopoly (e.g., Motta 1993, Ecchia and Lambertini 1997, Napel and Oldehaver 2011) we use a quadratic unit cost function $c(e_{jt}) = \gamma e_{jt}^2$ with $\gamma > 0$.

In both periods, firms compete in two stages: In stage one, firms choose the level of energy efficieny e_{jt},[9] and in stage two they simultaneously choose prices p_{jt}. Finally, the regulation constitutes the link between the two periods: In period t=1 there is no regulation, whereas in period t=2 a minimum standard concerning energy efficiency denoted by $\bar{e}$ is introduced. In line with the Japanese Top Runner Program we assume that $\bar{e}$ is fixed according to the energy efficiency chosen by the high efficiency firm in period t=1: $\bar{e} = e_{H1}$. Consequently, in period t=2 the firms have to comply with the restriction $e_{j2} \geq e_{H1}$. The solution concept we employ is subgame perfect equilibrium, i.e., we solve the model backwards.

3. Unregulated Equilibrium[10]

Without regulation, there is no link between the two periods, and the equilibria in both periods will be identical. Hence, it suffices to calculate the equilibrium for a representative period t.[11] In the price game in the second stage, energy efficiency e_{jt} is already fixed, and the firms' profits are given by $\pi_{jt} = s_{jt}[p_{jt} - \gamma e_{jt}^2]$. Inserting $s_{Lt} = \hat{\alpha}_t - a$ as well as $s_{Ht} = a + 1 - \hat{\alpha}_t$ and accounting for (1) leads to:

$$\pi_{Lt}(p_{Ht}, p_{Lt}) = [p_{Lt} - \gamma e_{Lt}^2]\left[\frac{p_{Ht} - p_{Lt} - w\,a(e_{Ht} - e_{Lt})}{w(e_{Ht} - e_{Lt})}\right], \tag{2a}$$

$$\pi_{Ht}(p_{Ht}, p_{Lt}) = [p_{Ht} - \gamma e_{Ht}^2]\left[\frac{p_{Lt} - p_{Ht} + w(1 + a)(e_{Ht} - e_{Lt})}{w(e_{Ht} - e_{Lt})]}\right]. \tag{2b}$$

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[8] Our assumption of variable costs increasing in energy efficiency implies that a higher degree of efficiency requires more expensive inputs like, e.g., skilled labour and raw materials. An alternative way of modelling would be to assume fixed costs increasing in energy efficiency; in this case the main burden of efficiency improvements is caused by R&D activities (see Motta 1993). However, in our model we focus on improvements in energy efficiency stemming from incremental innovations which usually entail increases in variable costs.

[9] In the reference case without regulation in Section 3 firms *simultaneously* decide on efficiency as usual in most models on MQS. In contrast, under the dynamic standard in Section 4 firm H attains the role of a leader in the efficiency game.

[10] For the unregulated (i.e., static) case, apart from differences in notation and the use of a quadratic instead of a general cost function, the formal structure of our model is almost completely identical with Crampes and Hollander (1995, pp.73-75).

[11] In principle, due to the static nature of the unregulated case, the time index "t" could be suppressed in this Section. However, since we need some of the following equations also in the dynamic analysis in Section 4, we refrain from suppressing t.

From the first order conditions $\partial \pi_{jt} / \partial p_{jt} = 0$ we obtain the respective reaction functions which can be solved for the optimal prices depending on e_{jt}:

$$p_{Lt}(e_{Lt}, e_{Ht}) = \frac{1}{3}[w(1-a)(e_{Ht} - e_{Lt}) + \gamma(2e_{Lt}^2 + e_{Ht}^2)], \tag{3a}$$

$$p_{Ht}(e_{Lt}, e_{Ht}) = \frac{1}{3}[w(2+a)(e_{Ht} - e_{Lt}) + \gamma(e_{Lt}^2 + 2e_{Ht}^2)]. \tag{3b}$$

Inserting (3a) and (3b) into (2a) and (2b) yields the reduced profit functions to be used in the efficiency game in the first stage:

$$\pi_{Lt}(e_{Lt}, e_{Ht}) = \frac{(e_{Ht} - e_{Lt})[w(1-a) + \gamma(e_{Ht} + e_{Lt})]^2}{9w}, \tag{4a}$$

$$\pi_{Ht}(e_{Lt}, e_{Ht}) = \frac{(e_{Ht} - e_{Lt})[w(2+a) - \gamma(e_{Ht} + e_{Lt})]^2}{9w}. \tag{4b}$$

The first order conditions $\partial \pi_{jt}(e_{Lt}, e_{Ht}) / \partial e_{jt} = 0$ lead to the following reaction functions:[12]

$$e_{Lt}(e_{Ht}) = \frac{w(a-1) + \gamma e_{Ht}}{3\gamma}, \tag{5a}$$

$$e_{Ht}(e_{Lt}) = \frac{w(2+a) + \gamma e_{Lt}}{3\gamma}. \tag{5b}$$

Solving these reaction functions results in the optimal levels of the durables' energy efficiency:[13] $e_{Lt}^o = (w/8\gamma) \cdot (4a - 1)$ and $e_{Ht}^o = (w/8\gamma) \cdot (4a + 5)$.[14] The implications of this result are obvious: Everything else equal the energy efficiency is the higher, 1) the higher the energy price w is, 2) the lower the cost parameter γ is, and 3) the higher the average weight that consumers assign to energy costs is (given by a+1/2).

However, since negative values for energy efficiency are ruled out,[15] e_{Lt}^o and e_{Ht}^o represent the equilibrium only under the assumption $a \geq 0.25$ which guarantees an interior solution. In contrast, for $a < 0.25$ our model leads to a corner solution where firm L always chooses $\tilde{e}_{Lt}^o = 0$ and firm H chooses $\tilde{e}_{Ht}^o = (w/3\gamma) \cdot (2+a)$ according to (5b).

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[12] For both firms there exists a second solution to $\partial \pi_{jt}(e_{Lt}, e_{Ht}) / \partial e_{jt} = 0$ which, however, is irrelevant because it leads to zero profits.

[13] In the following, we indicate the unregulated equilibrium by the superscript „o" and the regulated equilibrium in Section 4 by the superscript „*".

[14] Inserting e_{Lt}^o and e_{Ht}^o into the second derivatives $\partial^2 \pi_{jt}(e_{Lt}, e_{Ht}) / \partial e_{jt}^2$ proofs that the second order conditions are satisfied. Moreover, in the Appendix we show that leapfrogging can be ruled out.

[15] Due to the quadratic unit cost function, cost would be decreasing in energy efficiency for $e_{jt} < 0$ which makes no sense. For a similar argument relating to negative quality levels and quadratic unit cost functions see Cremer and Thisse (1994, p.616).

In the following we concentrate on the more interesting case of an interior solution, with $a \geq 0.25$. Inserting e_{jt}^o into (3a) and (3b) yields the corresponding prices in equilibrium: $p_{Lt}^o = (w^2 / 64\gamma) \cdot [25 + 8a(2a - 1)]$ and $p_{Ht}^o = (w^2 / 64\gamma) \cdot [49 + 8a(2a + 5)]$. In the next step, inserting e_{jt}^o and p_{jt}^o into (1) yields the position of the indifferent consumer, $\hat{\alpha}_t^o = a + 0.5$, and the accompanying market shares are $s_{Lt}^o = s_{Ht}^o = 1/2$. Finally, inserting e_{jt}^o into (4a) and (4b) yields the profits in equilibrium: $\pi_{Lt}^o = \pi_{Ht}^o = 3w^2 / 16\gamma$.

Concerning the latter result, it might seem paradoxical that increasing energy prices lead to increasing profits of firms that produce energy consuming durables. However, within the framework of our model, the economic explanation is straight forward: A higher energy price accelerates the importance of differences in energy efficiency from the viewpoint of consumers. This effect relaxes price competition between the firms and increases profits (see, e.g., Shaked and Sutton, 1982).[16]

4. Regulated Equilibrium

In the following, we solve the model backwards starting with period t=2. In the price game in the second stage, energy efficiencies e_{j2} are already given. Consequently there is no difference compared to the unregulated case analyzed above and we can employ the reduced profit functions (4a) and (4b) for t=2:

$$\pi_{L2}(e_{L2}, e_{H2}) = \frac{(e_{H2} - e_{L2})[w(1 - a) + \gamma(e_{H2} + e_{L2})]^2}{9w}, \tag{6a}$$

$$\pi_{H2}(e_{L2}, e_{H2}) = \frac{(e_{H2} - e_{L2})[w(2 + a) - \gamma(e_{H2} + e_{L2})]^2}{9w}. \tag{6b}$$

However, in the efficiency game in stage one, the firms have to comply with the standard $e_{j2} \geq \overline{e} = e_{H1}$. Since the latter is a binding restriction for the low efficiency producer, we obtain $e_{L2}^* = e_{H1}$. Consequently, introducing the dynamic standard is equivalent to granting firm H quality leadership. Inserting $e_{L2}^* = e_{H1}$ into firm H's reaction function (5b) for t=2 yields:

$$e_{H2}^* = \frac{w(2 + a) + \gamma e_{H1}}{3\gamma}. \tag{7}$$

Hence, firm H's optimal choice of energy efficiency in period t=2 solely depends on the efficiency chosen in t=1. Next, from inserting $e_{L2}^* = e_{H1}$ as well as (7) into the reduced profit functions (6a) and (6b) we obtain equilibrium profits in period t=2 as a function of firm H's decision in t=1:

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[16] Of course, the above result concerning profits also depends on the assumption of inelastic demand, i.e., each consumer buys exactly one unit per period irrespective of the energy prices given. See Section 6 for a discussion of this assumption.

$$\pi^*_{L2}(e_{H1}) = \frac{[w(2+a) - 2\gamma e_{H1}][w(2a-5) - 4\gamma e_{H1}]^2}{243w\gamma} \ , \tag{8a}$$

$$\pi^*_{H2}(e_{H1}) = \frac{4[w(2+a) - 2\gamma e_{H1}]^3}{243w\gamma} \ . \tag{8b}$$

It is easy to show that $\partial\pi^*_{H2}(e_{H1})/\partial e_{H1} < 0$. Consequently, firm H faces a trade-off: The higher the efficiency chosen in period t=1, the lower will be the profit in t=2. The economic reason is straightforward: Increasing e_{H1} leads to a more severe efficiency standard in t=2 thereby lowering the scope for product differentiation and intensifying price competition.

We now turn to the firms' decisions in period t=1. The reduced profit functions for this period are given by (4a) and (4b) for t=1:

$$\pi^*_{L1}(e_{L1}, e_{H1}) = \frac{(e_{H1} - e_{L1})[w(1-a) + \gamma(e_{H1} + e_{L1})]^2}{9w} \ , \tag{9a}$$

$$\pi^*_{H1}(e_{L1}, e_{H1}) = \frac{(e_{H1} - e_{L1})[w(2+a) - \gamma(e_{H1} + e_{L1})]^2}{9w} \ . \tag{9b}$$

With their decision in period t=1, both firms aim at maximizing total profits which are given by $\Pi^*_j(e_{L1}, e_{H1}) := \pi^*_{j1}(e_{L1}, e_{H1}) + \pi^*_{j2}(e_{H1})$. Discounting is neglected for simplicity. The first order conditions $\partial\Pi^*_j(e_{L1}, e_{H1})/\partial e_{j1} = 0$ lead to the following reaction functions:

$$e_{L1}(e_{H1}) = \frac{w(a-1) + \gamma e_{H1}}{3\gamma} \ , \tag{10a}$$

$$e_{H1}(e_{L1}) = \frac{w(2+a) + 3\gamma e_{L1}}{5\gamma} \ . \tag{10b}$$

For the low efficiency firm we obtain the same reaction function as in the unregulated case analyzed in Section 3 because firm L is not able to influence the second period outcome via the choice of e_{L1} (see also equation 8a). In contrast, due to the effect of e_{H1} on the standard fixed in period t=2, the reaction function of the high efficiency firm is steeper compared to the unregulated case. Solving the reaction functions yields the durables' energy efficiency in the regulated equilibrium in t=1 for the case of an interior solution with a≥0.5: $e^*_{L1} = (w/4\gamma)\cdot(2a-1)$ and $e^*_{H1} = (w/4\gamma)\cdot(2a+1)$.[17] In contrast, for a<0.5 we obtain a corner solution with $\tilde{e}^*_{L1} = 0$ and $\tilde{e}^*_{H1} = (w/5\gamma)\cdot(2+a)$.

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[17] Inserting e^*_{L1} and e^*_{H1} into the second derivatives $\partial^2\Pi^*_j(e_{L1}, e_{H1})/\partial e^2_{j1}$ proofs that the second order conditions are satisfied. Moreover, in the Appendix we show that leapfrogging can be ruled out for both firms and both periods if leapfrogging is associated with positive but arbitrarily small costs (which seems to be pretty reasonable).

In the following, we again concentrate on the more interesting case of an interior solution and assume a>0.5. From inserting e^*_{j1} into (3a) and (3b) for t=1 we obtain the equilibrium prices $p^*_{L1} = (w^2 / 48\gamma) \cdot [11 + 12a(a - 1)]$ and $p^*_{H1} = (w^2 / 48\gamma) \cdot [19 + 12a(a + 1)]$. Moreover, inserting e^*_{j1} and p^*_{j1} into (1) yields the position of the indifferent consumer, $\hat{\alpha}^*_1 = (1/3) + a$, which leads to market shares of $s^*_{L1} = 1/3$ und $s^*_{H1} = 2/3$. Finally, from inserting e^*_{j1} into [9a] and [9b] we obtain the accompanying profits $\pi^*_{L1} = w^2 / 18\gamma$ and $\pi^*_{H1} = 2w^2 / 9\gamma$.

We now turn to period t=2. Inserting e^*_{H1} into $e^*_{L2} = e_{H1}$ as well as into (7) yields the energy efficiency of the durables supplied: $e^*_{L2} = (w / 4\gamma) \cdot (2a + 1)$ and $e^*_{H2} = (w / 4\gamma) \cdot (2a + 3)$. Moreover, following our approach for the first period we obtain equilibrium prices p^*_{j2} of $p^*_{L2} = (w^2 / 48\gamma) \cdot [19 + 12a(a + 1)]$ and $p^*_{H2} = (w^2 / 48\gamma) \cdot [35 + 12a(a + 3)]$, the position of the indifferent consumer at $\hat{\alpha}^*_2 = (2/3) + a$, market shares of $s^*_{L2} = 2/3$ and $s^*_{H2} = 1/3$, and profits of $\pi^*_{L2} = 2w^2 / 9\gamma$ and $\pi^*_{H2} = w^2 / 18\gamma$.

5. Comparison of Results

Table 1 compares the results of Section 4 with those calculated for the unregulated equilibrium in Section 3. As can easily be verified, in period t=1 energy efficiency and prices of both product variants are lower compared to the unregulated case. Moreover, firm H gains in market share and profits, whereas firm L looses. In period t=2, these results are reversed: energy efficiency and prices of both product variants are higher compared to the unregulated case, firm L gains and firm H looses.

The economic reasons leading to the changes in energy efficiency described above are obvious: In the first period, firm H reduces energy efficiency because of the detrimental effect on its second period profits caused by the standard provoked due to $\bar{e} = e_{H1}$. This decrease in e_{H1} induces firm L also to reduce energy efficiency since both levels of efficiency are strategic complements. In the second period, firm L is forced to increase energy efficiency e_{L2} due to the standard applied, and this in turn induces firm H also to increase e_{H2}.

The changes in market shares and profits caused by the standard can also readily be explained: In period t=1 firm H gains due to its leadership. In period t=2 firm L gains because setting a standard has the same effect as granting firm L the ability to commit to a higher level of efficiency (see also Crampes and Hollander, 1995, p. 76).

	Unregulated Equilibrium Periods t=1,2	Regulated Equilibrium Period t=1	Regulated Equilibrium Period t=2
Energy efficiency e_{jt}	$e_{Lt}^o = \dfrac{w(4a-1)}{8\gamma}$ $e_{Ht}^o = \dfrac{w(4a+5)}{8\gamma}$	$e_{L1}^* = \dfrac{w(2a-1)}{4\gamma} < e_{L1}^o$ $e_{H1}^* = \dfrac{w(2a+1)}{4\gamma} < e_{H1}^o$	$e_{L2}^* = \dfrac{w(2a+1)}{4\gamma} > e_{L2}^o$ $e_{H2}^* = \dfrac{w(2a+3)}{4\gamma} > e_{H2}^o$
Prices p_{jt}	$p_{Lt}^o = \dfrac{w^2[25+8a(2a-1)]}{64\gamma}$ $p_{Ht}^o = \dfrac{w^2(49+8a(2a+5)]}{64\gamma}$	$p_{L1}^* = \dfrac{w^2[11+12a(a-1)]}{48\gamma} < p_{L1}^o$ $p_{H1}^* = \dfrac{w^2(19+12a(a+1)]}{48\gamma} < p_{H1}^o$	$p_{L2}^* = \dfrac{w^2[19+12a(a+1)]}{48\gamma} > p_{L2}^o$ $p_{H2}^* = \dfrac{w^2(35+12a(a+3)]}{48\gamma} > p_{H2}^o$
Market shares s_{jt}	$s_{Lt}^o = 1/2$ $s_{Ht}^o = 1/2$	$s_{L1}^* = 1/3 < s_{L1}^o$ $s_{H1}^* = 2/3 > s_{H1}^o$	$s_{L2}^* = 2/3 > s_{L2}^o$ $s_{H2}^* = 1/3 < s_{L2}^o$
Profits π_{jt}	$\pi_{Lt}^o = \dfrac{3w^2}{16\gamma}$ $\pi_{Ht}^o = \dfrac{3w^2}{16\gamma}$	$\pi_{L1}^* = \dfrac{w^2}{18\gamma} < \pi_{L1}^o$ $\pi_{H1}^* = \dfrac{2w^2}{9\gamma} > \pi_{H1}^o$	$\pi_{L2}^* = \dfrac{2w^2}{9\gamma} > \pi_{L2}^o$ $\pi_{H2}^* = \dfrac{w^2}{18\gamma} < \pi_{H2}^o$

Table 1: Comparison of results (interior solution).

In the following, we are interested in the total effects calculated over both periods. Let us denote the average degree of the durables' energy efficiency weighted by periods and market shares as $\hat{e}$, i.e.:

$$\hat{e} = \frac{1}{2}\sum_{t=1}^{2}(s_{Ht}e_{Ht} + s_{Lt}e_{Lt}).\qquad(11)$$

Applying the results summarized in Table 1, we obtain $\hat{e}^o = (w/4\gamma)\cdot(2a+1)$ for the unregulated case and the same for the regulated case: $\hat{e}^* = (w/4\gamma)\cdot(2a+1) = \hat{e}^o$. Due to the linear relationship between energy efficiency and energy consumption (see Section 2), this implies that calculated over both periods total energy consumption caused by the durables sold in the market does not change. Consequently, within the framework of our model, a dynamic standard for energy efficiency according to the Japanese Top Runner Program has no ecological effect at all.

Moreover, aggregated over both periods, firm L as well as firm H are worse off under the standard because the degree of product differentiation decreases in each period and price competition becomes tighter.[18] Profits aggregated over both periods are $\Pi_L^o = \Pi_H^o = 3w^2/8\gamma$ in the unregulated case and $\Pi_L^* = \Pi_H^* = 5w^2/18\gamma < \Pi_j^o$ in the regulated case, respectively. Hence, from an overall perspective of welfare, the total losses in firms' profits are $\Delta\Pi = 2(\Pi_j^o - \Pi_j^*) = 7w^2/36\gamma$.

	Group G_1	Group G_2	Group G_3	Group G_4
Position	$\alpha_i < 0.\overline{3}+a$	$0.\overline{3}+a < \alpha_i < 0.5+a$	$0.5+a < \alpha_i < 0.\overline{6}+a$	$\alpha_i > 0.\overline{6}+a$
Unregulated (t=1,2)	Variant L	Variant L	Variant H	Variant H
Regulated (t=1)	Variant L	Variant H	Variant H	Variant H
Regulated (t=2)	Variant L	Variant L	Variant L	Variant H
Cost Difference ΔC_k	$\dfrac{(13-8a)w^2}{32\gamma}$	$\dfrac{(71-72a)w^2}{96\gamma}$	$\dfrac{(72a-1)w^2}{96\gamma}$	$\dfrac{(8a+5)w^2}{32\gamma}$

Table 2: Consumers' buying decisions.

Next, we consider how consumers are affected. As shown in Table 2, consumers can be divided into four different groups G_k (k=1:4) according to their buying decision. The interpre-

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[18] From the results in Table 1 it is easy to calculate that the degree of product differentiation amounts to $e_{Ht}^o - e_{Lt}^o = 3w/4\gamma$ in the unregulated case and to $e_{Ht}^* - e_{Lt}^* = w/2\gamma$ in the regulated case.

tation is straightforward: For example, consumers belonging to G_2, who are characterised by the position $0.\bar{3}+a < \alpha_i < 0.5+a$, always choose variant L in the unregulated case whereas in the regulated case they choose variant H in period t=1 and variant L in period t=2. Now, let us denote the actual monetary costs caused by the purchase and the use of a durable of variant j in period t by $\varphi_{jt} = p_{jt} + w\varepsilon_{jt}$.[19] From this we can calculate total cost summed up over both periods for a representative consumer of each group denoted by C_k. For example, concerning a consumer in group G_2 we obtain for the unregulated case $C_2^o = 2\varphi_{Lt}^o$ since she chooses variant L in both periods, whereas the regulated case implies $C_2^* = \varphi_{H1}^* + \varphi_{L2}^*$ since she chooses variant H in period t=1 and variant L in t=2. In the last step, we calculate the difference in cost between the regulated and the unregulated regime: $\Delta C_k = C_k^o - C_k^*$. The results of this calculation are shown in the last row of Table 2. A positive difference $\Delta C_k > 0$ indicates that the consumer under consideration is better off in the regulated case because his actual costs are smaller compared to the unregulated case. A negative difference $\Delta C_k < 0$ indicates the opposite.

As shown in the last row of Table 2, consumers belonging to G_1 and G_2, that apply a weight below average to energy costs when deciding which durable to buy, will win or loose in terms of their actual cost burden depending on the magnitude of the parameter a. In contrast, consumers belonging to G_3 and G_4 that apply a weight above average will always be better of in the regulated case.[20]

Finally, we consider the net effect on welfare aggregated over both periods. Since total energy consumption does not change, it suffices to compare the firms' total changes in profits, $\Delta\Pi$, with consumers' total changes in actual costs, denoted by ΔC. The latter can be obtained by weighting ΔC_k with the different groups' shares on the total unit mass of consumers: $\Delta C = (1/3) \cdot (C_1 + C_4) + (1/6) \cdot (C_2 + C_3)$. Applying the results in the last row of Table 2 leads to $\Delta C = 89w^2/288\gamma$. Comparing with $\Delta\Pi = 7w^2/36\gamma$ reveals $\Delta C > \Delta\Pi$ such that consumers' cost savings exceed the firms' losses in profits and total welfare increases. Consequently, dynamic standards for energy efficiency according to the Japanese Top Runner Program do not necessarily contribute to energy savings but nevertheless they can be viewed as a possible measure to increase total welfare.

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[19] Note that from an overall welfare perspective, actual accruing energy costs $w\varepsilon_{jt}$ are relevant and not energy costs individually perceived at the stage of buying decision, $\alpha_i w\varepsilon_{jt}$.

[20] Remember that we have assumed a>0.5 in order to guarantee an interior solution.

6. Summary and Conclusions

We analyzed a simple model of dynamic energy efficiency standards in a differentiated duopoly with two firms producing a durable which varies in its level of energy efficiency. Demand is assumed to be inelastic and consumers weigh energy costs individually in the sense that "myopic" consumers underestimate future energy costs and "green" consumers additionally account for environmental damages caused by energy consumption. We found that compared to the unregulated scenario the high efficiency firm has an incentive to set a lower level of energy efficiency in the first period in order to relax the standard to be introduced in the second period. This induces its competitor also to reduce the energy efficiency of the durable because both levels of efficiency are strategic complements. In the second period, the standard applied constitutes a binding restriction for the low efficiency firm and the energy efficiency of the durables supplied by both firms increases compared to the scenario without regulation. However, in total, energy consumption calculated over both periods does not change. Consequently, under the assumptions of our model, dynamic standards for energy efficiency have no ecological effect at all.

Concerning the economic effects of such standards we found that the degree of product differentiation decreases in both periods and price competition becomes tighter. As a consequence, the firms' profits calculated over both periods are also decreasing. However, consumers are better of in terms of their cost burden (purchase price plus actual energy costs) and total welfare increases because the consumers' cost savings exceed the firms' losses in profit. Hence, within the framework of our model, dynamic energy efficiency standards do not contribute to energy savings but they weaken the negative impacts of imperfect competition on consumers' surplus and welfare.

Of course, a possible shortcoming of our analysis is the assumption of inelastic demand, i.e., each consumer buys exactly one unit per period irrespective of the purchase price and energy costs given. To what extend this assumption is realistic depends on the specific durable under consideration. Concerning durables that are essential in the sense that they are absolutely necessary for a vast majority of consumers (like, e.g., refrigerators or heating appliances), the assumption of inelastic demand seems to be justifiable on the whole. In contrast, for non-essential durables (like, e.g., freezer chests or mobile air conditionings) it would be more realistic to assume an elastic demand such that increasing costs cause consumers with a comparatively high weight factor α_i to refrain from buying at all. In this case, it is not guaranteed that consumers' surplus will increase due to the regulation of energy efficiency. Consequently, it cannot be ruled out that total welfare will decrease (although everything else equal

a smaller number of durables sold in the market as well implies less energy consumption and thereby decreasing environmental costs). However, the analytical complications associated with incorporating the possibility of an uncovered market would go well beyond the scope of our paper and are therefore left to future research.

Appendix

We start with leapfrogging in the unregulated case calculated in Section 3. In order to rule out leapfrogging by firm H we have to show, that choosing an efficiency level with $e_{Ht} < e_{Lt}$ does not pay for firm H if firm L adheres to its initial position $e_{Lt}^o = (w/8\gamma)\cdot(4a-1)$. For $e_{Ht} < e_{Lt}$ the reduced profit function of firm H is given by:

$$\pi_{Ht}(e_{Lt}, e_{Ht}) = \frac{(e_{Lt} - e_{Ht})[w(1-a) + \gamma(e_{Ht} + e_{Lt})]^2}{9w}. \tag{A.1}$$

Inserting $e_{Lt}^o = (w/8\gamma)\cdot(4a-1)$ into (A.1) yields the leapfrogging-profits of firm H solely as a function of its decision on e_{Ht}:

$$\hat{\pi}_{Ht}(e_{Ht}) = \frac{[w(4a-1) - 8\gamma e_{Ht}][w(4a-7) - 8\gamma e_{Ht}]^2}{4608w\gamma}. \tag{A.2}$$

From the first order condition $\partial\hat{\pi}_{Ht}(e_{Ht})/\partial e_{Ht} = 0$ we obtain the optimal leapfrogging-strategy of firm H in the unregulated case: $\hat{e}_{Ht}^o = (w/8\gamma)\cdot(4a-3)$. Inserting $\hat{e}_{Ht}^o$ into (A.2) yields the accompanying leapfrogging-profit $\hat{\pi}_{Ht}^o = w^2/144\gamma$. Comparing this with the equilibrium-profit calculated in Section 3, $\pi_{Ht}^o = 3w^2/16\gamma$, reveals $\hat{\pi}_{Ht}^o < \pi_{Ht}^o$. Consequently, leapfrogging does not pay for firm H.[21] Due to symmetry, calculating along the same lines for leapfrogging by firm L yields $\hat{\pi}_{Lt}^o = w^2/144\gamma < \pi_{Lt}^o = 3w^2/16\gamma$. Hence, leapfrogging by firm L can also be ruled out.

We now turn to the regulated case calculated in Section 4 where leapfrogging has to be considered for both periods explicitly. With leapfrogging by firm H in the first period we obtain the reduced profit function $\pi_{H1}(e_{L1}, e_{H1})$ by inserting the time index t=1 into (A.1). In the next step we replace e_{L1} by firm L's initial position $e_{L1}^* = (w/4\gamma)\cdot(2a-1)$ which leads to:

$$\hat{\pi}_{H1}(e_{H1}) = \frac{[w(2a-1) - 4\gamma e_{H1}][w(2a-3) - 4\gamma e_{H1}]^2}{576w\gamma}. \tag{A.3}$$

The first order condition $\partial\hat{\pi}_{H1}(e_{H1})/\partial e_{H1} = 0$ yields the optimal leapfrogging-strategy of firm H in period t=1: $\hat{e}_{H1}^* = (w/12\gamma)\cdot(6a-5)$. Inserting into (A.3) leads to the accompanying leapfrogging-profit $\hat{\pi}_{H1}^* = w^2/486\gamma < \pi_{H1}^* = 2w^2/9\gamma$. Hence, leapfrogging by firm H in period t=1 can be ruled out. Moreover, leapfrogging by H in period t=2 can also be ruled out because the standard $e_{j2} \geq \bar{e}$ is already binding for firm L such that $e_{H2} < e_{L2}$ is not possible.

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[21] The case of a corner solution for a<3/4 does not need to be analyzed in detail since it is obvious that if leapfrogging does not pay for firm H in the case of an interior solution it would put firm H in an worse position in case of a corner solution. This is due to firm H's loss in flexibility in a corner solution. The same argument holds for leapfrogging leading to corner solutions in the regulated case to be considered below.

Next, we consider leapfrogging by firm L. In period t=1, firm L's reduced profit function for the case $e_{L1} > e_{H1}$ is given by:

$$\pi_{L1}(e_{L1}, e_{H1}) = \frac{(e_{L1} - e_{H1})[w(2+a) + \gamma(e_{H1} + e_{L1})]^2}{9w} \ . \tag{A.4}$$

Replacing e_{H1} by firm H's initial position $e_{H1}^* = (w/4\gamma) \cdot (2a+1)$ yields the leapfrogging-profits of firm L depending on its decision on e_{L1}:

$$\hat{\pi}_{L1}(e_{L1}) = \frac{[4\gamma e_{L1} - w(2a+1)][w(7+2a) - 4\gamma e_{L1}]^2}{576w\gamma} \ . \tag{A.5}$$

From the first order condition $\partial \hat{\pi}_{L1}(e_{L1}) / \partial e_{L1} = 0$ we obtain the optimal leapfrogging-strategy of firm L in period t=1 with $\hat{e}_{L1}^* = (w/4\gamma) \cdot (2a+3)$. Inserting this result into (A.5) yields the profit $\hat{\pi}_{L1}^* = w^2/486\gamma = \pi_{L1}^*$. Consequently, in period t=1 firm L would earn the same profit with leapfrogging as well as without it. However, this calculation does not account for possible costs associated with leapfrogging by firm L: If a firm hitherto known as a cheap low efficiency producer tries to penetrate the high efficiency segment of the market, it will most likely be forced to change its marketing strategies and distribution channels. Hence, it seems reasonable to assume that leapfrogging by Firm L will lead to additional fixed costs. Although we are not able to quantify these costs, from it $\hat{\pi}_{L1}^* = \pi_{L1}^*$ is obvious that even assuming an arbitrarily small amount of additional costs suffices to rule leapfrogging by firm L in period t=1.

Finally, we consider leapfrogging by firm L in period t=2. For this case, the reduced profit function $\pi_{L2}(e_{L2}, e_{H2})$ can easily be obtained by changing the time index in (A.4) from t=1 to t=2. Next, replacing e_{H2} by $e_{H2}^* = (w/4\gamma) \cdot (2a+3)$ yields:

$$\hat{\pi}_{L2}(e_{L2}) = \frac{[4\gamma e_{L2} - w(2a+3)][w(5+2a) - 4\gamma e_{L2}]^2}{576w\gamma} \ . \tag{A.6}$$

The first order condition $\partial \hat{\pi}_{L2}(e_{L2}) / \partial e_{L2} = 0$ yields $\hat{e}_{L2}^* = (w/12\gamma) \cdot (6a+11)$. Inserting $\hat{e}_{L2}^*$ into (A.6) leads to $\hat{\pi}_{L2}^* = w^2/486\gamma < \pi_{L2}^* = 2w^2/9\gamma$. Consequently, leapfrogging by firm L in period t=2 can also be ruled out.

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