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Energy efficiency subsidies with price-quality discrimination

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We compare various kinds of energy efficiency subsidies in a market subject to both energy-use externalities and price-quality discrimination by a monopolist. We find that differentiated subsidies can establish the social optimum. Unlike per-quality schedules, ad valorem schedules generate downstream interferences: Subsidization of the high-end good leads the monopolist to cut the quality of the low-end good. For this reason, ad valorem differentiated rates should always be decreasing in energy efficiency, a result seemingly at odds with actual practice. In contrast, with per-quality differentiated subsidies, the rates can be increasing if the externality is large enough relative to the market share of low-type consumers. Contrary to differentiated subsidies, what we shall call single-instrument subsidies only achieve second-best outcomes. A uniform ad valorem subsidy should have a rate higher than that needed to specifically internalize energy-use externalities. Lastly, if, as is often observed in practice, only the high-end good is to be incentivized, a per-quality schedule should be preferred over an ad valorem one. An ad valorem tax on the high-end good may even be preferred over an ad valorem subsidy if the externality is small enough and low-end consumers dominate the market.

Nous comparons plusieurs types de subventions destinées à améliorer l'efficacité énergétique dans un contexte où coexistent des externalités dues à la consommation d'énergie et une discrimination prix-qualité. L'optimum social peut être atteint avec des subventions différenciées. Si ces subventions sont ad valorem, la subvention en faveur du bien le plus efficace conduit le monopoleur à réduire l'efficacité de l'autre bien. Pour cette raison, les taux optimaux de la subvention ad valorem doivent toujours diminuer avec l'efficacité énergétique, à l'opposé de ce que l'on observe en pratique. Des subventions proportionnelles à l'efficacité énergétique n'entraînent pas de telles interférences et les taux peuvent augmenter avec l'efficacité énergétique si l'externalité est assez grande et si les consommateurs préférant le bien le plus efficace sont assez nombreux. Des subventions non différenciées ne permettent d'atteindre qu'un optimum de second rang. Si une subvention ad valorem uniforme est retenue, elle doit être supérieure à la subvention qui serait nécessaire pour internaliser spécifiquement l'externalité. Enfin, si, comme cela est souvent observé dans la pratique, seul le bien le plus efficace est subventionné, mieux vaut une subvention proportionnelle à l'efficacité énergétique plutôt qu'ad valorem. Une taxe ad valorem sur ce bien peut même être préférée à une subvention ad valorem si l'externalité est assez faible et si les consommateurs préférant le bien le moins efficace sont assez nombreux.

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1 Introduction

Energy efficiency has become a popular theme in the policy arena. The enthusiasm is sustained by engineering studies claiming that energy efficiency is the most cost-effective way to save energy, hence internalize the multiple externalities associated with energy use.[4] Such externalities include carbon dioxide emissions at the source of the climate change problem, local pollution, risks related to nuclear safety and domestic concerns about the security of energy supply. They motivate implementation of various types of energy efficiency policies across the world.[5]

Within the panoply of energy efficiency policies, subsidies are probably the most widespread instrument. Energy efficiency subsidies come in a variety of forms. In the US, under the State Energy Efficient Appliance Rebate Program (SEEARP), States used Federal funds in 2009-2010 to subsidize efficient refrigerators, dishwashers and clothes washers (Houde and Aldy, 2014). The rebates were on average 12-15% of sale prices. While most states offered fixed rebate amounts, Florida, Illinois, North Carolina, and Oregon offered ad valorem rebates. In China, a one-year subsidy program for energy-efficient home appliances was implemented in 2012-2013. The program consisted of offering cash rebates ranging from about 100 to 400 RMB Yuan (16 to 64 US dollars) per appliance (Yao et al., 2014). In France, since 2005, improvements to building energy efficiency are eligible to ad valorem tax credits (Nauleau, 2014). The subsidy rates, initially increasing in energy efficiency (e.g. 15% of the price of low-temperature boilers and 25% of the price of more efficient condensing boilers), are now restricted to the most efficient options. Meanwhile, since 2014, all energy efficient options are eligible to a uniform value-added tax reduction.

In parallel to the importance of subsidies, another regularity with energy efficiency policies is the high concentration of the markets they are devised in. In the US, Fischer (2005) documents high concentration levels in appliance manufacturing, as measured by Herfindhal-Hirschman indexes (HHI) and the market shares of the top four firms, which systematically exceed 50%. In France, HHI indexes are also substantially higher in the appliance and energy retrofit industries than in other industries (Carbonnier, 2008). The French Anti-trust authority has pointed to high levels of concentration in the heating, air conditioning and hot water industries, both at the manufacturing and retail levels, raising suspicion over collusive practices (Conseil de la concurrence, 2006).[6]

Such an imperfect competition context is conducive to price-quality discrimination. The problem, first studied by Mussa and Rosen (1978) in a monopoly setting and recast by Cremer and Thisse (1994) in an oligopoly setting, goes as follows. A dominant firm facing consumers with heterogeneous tastes for quality can find it optimal to restrict the provision of quality at the low-end of the product line while at the same time increasing the price charged for high-end products. As shown by Fischer (2005), this general economic problem can provide a supply-side explanation as to why energy efficiency levels are

[4] For instance Mc Kinsey & Co. (2009), to name only the most impactful.

[5] Just for the European Union, 550 energy efficiency policies are referenced in the MURE database(http://www.measures-odyssee-mure.eu/)

[6] The five largest firms have a 59% market share in the floor boilers sector, the three largest firms have a 80% market share in the mural boilers sector and the four largest firms have a 90% market share in the electric heating systems sector.

too low in the economy, a phenomenon known as the energy efficiency gap (Jaffe and Stavins, 1994).[7] More recently, Houde (2013) and Spurlock (2013) in the US and Cohen et al.(2014) in the UK found empirical evidence that appliance industries do respond to economic and regulatory signals in a way consistent with price-quality discrimination.

Despite the practical relevance of the issue, little is known about the properties of energy efficiency subsidies in imperfect competition contexts.[8] Most of the discussion on the interaction between environmental policy and price-quality discrimination has focused on quality standards, pollution charges, and combinations thereof (Plourde and Bardis, 1999; Fischer, 2005, 2011). While some authors have considered tax/subsidy incentives (Lombardini-Riipinen, 2005; Bansal, 2008), attention has remained confined to single ad valorem instruments. As illustrated above, energy efficiency subsidies take a wider variety of forms in practice, with at least two unexplored consequences. First, according to the Tinbergen rule (Tinbergen, 1952), jointly addressing energy-use externalities and imperfect competition requires two instruments. Therefore, what we shall call single-instrument subsidies can only generate second-best outcomes – unless they are combined with pollution charges, a much less common instrument. In contrast, differentiated subsidies, while overlooked in the literature, offer more flexibility to address both market failures.[9] Second, ad valorem subsidies have not yet been compared to specific ones related to the quality of the good. Such a comparison can uncover interesting effects, as the taxation literature suggests (Keen, 1998).

Against this background, we examine the following questions: What are the normative and positive effects of energy efficiency subsidies in a market subject to both energy-use externalities and price-quality discrimination? How do differentiated subsidy rates compare to uniform rates? How do ad valorem rates compare to per-quality rates? We provide some answers using the model of Fischer (2005) featuring a multiproduct monopolist and two consumer types with fixed market shares. We extend the set-up by explicitly taking into account energy-use externalities and accommodating energy efficiency subsidies.

We find that in an economy subject to both energy-use externalities and price-quality discrimination, differentiated subsidies can establish the first-best solution. Unlike per-quality schedules, ad valorem schedules generate downstream interferences: Subsidization of the high-end good leads the monopolist to cut the quality of the low-end good. For this reason, ad valorem differentiated rates should always be

[7] Supply-side explanations for the energy efficiency gap are little studied. The existing literature on the topic tends to focus more on demand-side explanations. For comprehensive reviews, see Sorrell (2004), Gillingham et al. (2009) and Allcott and Greenstone (2012).

[8] The existing literature on energy efficiency subsidies is mostly empirical and concerned with estimating the effectiveness of and windfall gains from subsidies (Hassett and Metcalf, 1995; Grösche and Vance, 2009; Boomhower and Davis, 2014; Nauleau, 2014; Houde and Aldy, 2014).

[9] Energy efficiency subsidies can be used to address either market failure in isolation. Subsidies are a conceptually valid tool to address output contraction due to market power. Yet such an intervention increases the profits of dominant firms and thus faces political hurdles. Moreover, it is only a substitute for anti-trust regulation. Subsidies can also directly address energy-use externalities. However, they may generate a rebound effect, hence save energy less cost-effectively than externality taxation (Giraudet and Quirion, 2008). Note that subsidies can also be used to internalize technology spillovers, a market failure not considered in the model but discussed in Section 5.

decreasing in energy efficiency, a result seemingly at odds with actual practice. In contrast, with per-quality differentiated subsidies, the rates can be increasing if the externality is large enough relative to the market share of low-type consumers. Contrary to differentiated subsidies, single-instrument subsidies only achieve second-best outcomes. A uniform ad valorem subsidy should have a rate higher than that needed to specifically internalize energy-use externalities. Lastly, if, as is often observed in practice, only the high-end good is to be incentivized, a per-quality schedule should be preferred over an ad valorem one. An ad valorem tax on the high-end good may even be preferred over an ad valorem subsidy if the externality is small enough and low-end consumers dominate the market. In the Appendices, we use the model to provide new results on energy taxes and minimum energy efficiency standards. We find that a second-best energy tax should be set above the marginal external cost. A second-best minimum quality standard may be set at the high-end of the product line if consumers are not too dissimilar, otherwise it should only target the low-end good.

The paper is organized as follows. Section 2 introduces the model and the market environments considered. Section 3 examines first-best, differentiated subsidies. Section 4 examines second-best, single-instrument subsidies. The results are discussed in Section 5. Section 6 concludes.

2 Set-up

Model notations are outlined in Table 1, equilibrium notations are outlined in Table 2 and illustrative equilibrium outcomes are summarized in Figure 1.

2.1 Consumer demand for energy efficiency

We build on the model of Fischer (2005) and extend it to account for energy-use externalities and energy efficiency subsidies. Consumers purchase goods which, combined with energy, provide energy services such as light and heat. The energy-related goods considered can be appliances, light bulbs, heating systems, improvements to building envelopes (wall insulation, double glazing windows), vehicles, etc. They are characterized by their energy intensity $\phi_j > 0$, bounded from above by Φ, the energy intensity that would be offered if energy were costless. Energy intensity is the energy input per unit of energy service, hence the inverse of energy efficiency.

Energy efficiency is the only dimension of quality in the model. That is, quality is negatively correlated with energy intensity. We abstract from ancillary attributes of the goods, such as capacity for appliances, aesthetics for light bulbs or safety for cars. This assumption is relevant to most choices within a capacity segment, e.g., a standard boiler versus a more efficient one of the same size, or a standard car versus a hybrid car with similar characteristics. It is less relevant to choices between capacity segments, e.g., a large boiler or car versus a smaller option with similar energy requirements per unit of capacity.[10]

We consider two levels of energy efficiency, high (*h*) and low (*l*), with corresponding energy intensities $0 < \phi_h < \phi_l < \Phi$. For consumers *I*, the net surplus of purchasing and using good *j* is

[10] Plourde and Bardis (1999) study the opposite model in which quality is positively correlated with energy intensity, assuming that the safety attribute associated with larger cars is the main driver of choice. Unsurprisingly, they find opposite results to those of Fischer (2005).

$$CS_{ij} \equiv \beta_i(v - g\,\phi_j) - p_j \qquad (1)$$

$v > 0$ is the annual gross utility of the energy service. It is produced with a combination of energy, purchased at a constant price $g > 0$, and the durable good j, purchased at price $p_j > 0$.

We assume heterogeneity across the population in the valuation of energy services. This is reflected by parameter β_i, the cumulative discount factor for the net utility flow over the lifetime of the good. Heterogeneity stems from either preferences or financial constraints. It materializes through differences across consumers in their willingness to invest in energy efficiency and their frequency of utilization of the goods after investment. For instance, a homeowner sensitive to the cold will be likely to upgrade his or her heating system and set the thermostat at a high temperature. Both margins are in fact identified into β_i.[11] For simplicity, we assume that consumers are of two types, high (*h*) and low (*l*), with $\beta_h > \beta_l$.

The two types of consumers cover the market in fixed proportions $n_h$and n_l, with $n_h + n_l = 1$. Through this assumption, we confine our attention to the intensive margin of investment. Therefore, our model is more relevant to capital maintenance investment (e.g., replacement of broken appliances or light bulbs) than to capital enhancement investment (e.g., improvements to the building envelope).

2.2 The firm

Energy efficiency is supplied at a convex increasing cost. In other words, the cost of energy intensity $c(\phi_j)$ is decreasing: $c' < 0$ and $c'' > 0$.

We assume that the firm is a monopolist. This is admittedly an extreme case of imperfect competition. As discussed in Section 5, qualitative insights would be similar in a more general (though less tractable) oligopoly setting.

Table 1.Model notations

Variable	Definition	Illustrative unit
p_h,p_l	Price of durable good	€ per durable good
v	Gross utility of energy service	€ per unit of energy service
Φ, ϕ_h, ϕ_l	Energy intensity (inverse of energy efficiency)	kWh per unit of energy service
g	Energy price	€per kWh
γ	external cost	€ per kWh
β_h, β_l	Flow of energy service, discounted over the lifetime of the durable good	Discounted years
n_h, n_l	Share of consumers of each type ($n_h + n_l = 1$)	Percentage

[11] As discussed by Fischer, the willingness to invest v_i and the discounted frequency of utilization $u_i$could be determined endogenously through the following net utility: $v_i(u_i) - u_i g\,\phi_j - p_j$. Yet thanks to the Envelope theorem, the impact of small changes of$u_i$on utility would be second-order compared to those of ϕ_j. As we are primarily interested here in how firms set ϕ_j, we follow Fischer and keep utilization exogenous through β_i. For a model with endogenous frequency of utilization, see Giraudet and Houde (2014).

Table 2.Equilibrium notations

	Superscript	Associated equilibrium
Market structures	*	Social optimum
	M	Monopoly equilibrium
	E	Competitive equilibrium with energy-use externalities
	ME	Laissez-faire equilibrium (monopoly + energy-use externalities)
First-best policies	AA	Differentiated ad valorem subsidy
	PP	Differentiated per-quality subsidy
Second-best policies	A	Uniform ad valorem subsidy
	P	Uniform per-quality subsidy
	H	Subsidy restricted to good *h*
	T	Energy tax (see Appendix 1)
	S	Minimum energy efficiency standard (see Appendix 2)

2.3 Social optimum

Let $\gamma \geq 0$ be the constant marginal external cost of energy use. External costs may arise from environmental pollution or energy security concerns. A benevolent social planner would maximize total surplus TS, defined as the difference between the gross consumer surplus and the three types of costs: the production cost, the energy cost and the external cost.

$$\underset{\phi_h,\phi_l}{\text{Maximize}}\, TS = n_h(\beta_h(v-(g+\gamma)\phi_h)-c(\phi_h))+n_l(\beta_l(v-(g+\gamma)\phi_l)-c(\phi_l))$$

The first-order conditions for total surplus maximization are (equilibrium outcomes are denoted with superscript *):

$$\forall \mathrm{i}\quad \frac{\partial \mathrm{TS}}{\partial \phi_i}=0 \Leftrightarrow -c'(\phi_i^*)=\beta_i(g+\gamma) \Leftrightarrow \phi_i^* = -c'^{-1}\big(\beta_i(g+\gamma)\big) \qquad (2)$$

The social planner would separate the two markets and allocate good *i* to consumer *i*. Optimal energy efficiency levels would be set so that marginal production costs equate the discounted social value of energy savings to the targeted consumer.[12]

If energy-use externalities are not internalized, energy efficiency levels are set at lower values (denoted with superscript *E*): $\forall i\;\; \phi_i^E = -c'^{-1}(\beta_i g) > \phi_i^*$.

2.4 Monopoly

To isolate the discrimination problem from energy-use externalities, we first suppose that the latter are internalized by the regulator through a Pigouvian tax. Consumers thus face social energy cost $g+\gamma$ and enjoy surplus $CS_{ij}^* \equiv \beta_i(v-(g+\gamma)\,\phi_j)-p_j$.

In Section 2.5, we will study how the two market failures interfere.[13]

[12] Throughout, we assume that $-c'(\Phi) < g\beta_l$, which guarantees separating equilibria with interior solutions. If $g\beta_l \leq -c'(\Phi) < g\beta_h$ then in the equilibria studied hereafter ϕ_h will be interior and ϕ_l will be a corner solution. If $-c'(\Phi) \geq g\beta_h$ there will be a pooling equilibrium at the corner solution.

2.4.1 Perfectly discriminating monopolist

A perfectly discriminating monopolist would maximize the following profit function:

$$\underset{\phi_h,\phi_l,p_h,p_l}{\text{Maximize}}\ \pi = n_h(p_h - c(\phi_h)) + n_l(p_l - c(\phi_h))$$

subject to individual rationality constraints (IR^M): $CS_{ij}^* \geq 0$. The resulting energy efficiency levels would be similar to those set by the social planner. Moreover, prices would be set so as to extract all consumer surplus: $p_j = \beta_j(v - (g+\gamma)\phi_j)$.

2.4.2 The screening problem

More realistically, the monopolist knows the distribution of consumer types but cannot prevent consumers *h* from buying the goods targeting consumers *l*, or cannot prevent arbitrage. A screening problem arises. If the monopolist sets prices and energy efficiency levels as above, then consumers *h* will purchase good *l*. By doing so, consumers *h* will enjoy a positive surplus $CS_{hl}^* = (\beta_h - \beta_l)(v - (g+\gamma)\phi_l^*)$, instead of zero surplus by consuming good *h*.

2.4.3 Imperfectly discriminating monopolist

As demonstrated first by Mussa and Rosen (1978), to prevent consumers *h* from purchasing good *l*, the imperfectly discriminating monopolist does two things: reduce the price of good *h* and cut the quality of good *l,* as compared to their perfect discrimination levels. The latter diminishes the surplus to consumers *h* from buying good *l*, hence allows the monopolist to make consumers *h* indifferent between buying either good without reducing the price of good *h* too much. The monopolist cannot deteriorate good *l* too much, though, otherwise the profit loss from producing a low-end good is no longer compensated by the surplus extracted from consumers *h*.

Formally, such equilibrium requires the monopolist to endogenize Incentive Compatibility constraints (IC) in addition to IR constraints to ensure that consumers self-select into the good they are targeted for. The monopolist maximizes profit subject to (superscript *M* denotes monopoly outcomes):

$$IR_l^M: \beta_l(v - (g+\gamma)\phi_l) \geq p_l$$

$$IR_h^M: \beta_h(v - (g+\gamma)\phi_h) \geq p_h$$

$$IC_l^M: \beta_l(v - (g+\gamma)\phi_l) - p_l \geq \beta_l(v - (g+\gamma)\phi_h) - p_h$$

$$IC_h^M: \beta_h(v - (g+\gamma)\phi_h) - p_h \geq \beta_h(v - (g+\gamma)\phi_l) - p_l$$

It can be shown that only IR_l and IC_h constraints will bind (Mahenc and Podesta, 2012). That is, consumer *l* is left with no surplus and consumer *h* is indifferent between purchasing either good

[13] In fact, there are three market failures in the model: energy-use externalities, imperfect competition and imperfect information. In our unit purchase set-up with no extensive margin, imperfect competition alone changes surplus distribution but not Pareto-efficient allocations. It is the very interaction between imperfect competition and imperfect information that deteriorates social welfare. Therefore, in the model, we view the combination of the two as a single market failure.

In equilibrium, the quality of good *h* will still be defined by Equation (2), so that

$$\phi_h^* = \phi_h^M.$$

In contrast, the quality of good *l* will be determined by the following first-order condition:

$$-c'\left(\phi_l^M\right) = (g+\gamma)\left(\beta_l - \frac{n_h}{n_l}(\beta_h - \beta_l)\right) \tag{3}$$

For ϕ_l^M to be interior, the right-hand side must be positive, hence:

$$\frac{\beta_l}{\beta_h} > \frac{n_h}{n_h + n_l} = n_h \tag{4}$$

The inequality $-c'\left(\phi_l^{\mathrm{M}}\right) \leq -c'(\phi_l^*)$ leads to

$$\phi_l^M > \phi_l^*.$$

In words, imperfect discrimination generates a suboptimal level of energy efficiency at the low-end of the product line, even if energy-use externalities are fully internalized. This can be a rational explanation for the energy efficiency gap, that is, the apparently low levels of energy efficiency in the economy (Jaffe and Stavins, 1994).

The price of good *l* leaves no surplus to low-end consumers:

$$p_l^M = \beta_l(v - (g+\gamma)\phi_l^M)$$

In contrast, some surplus is left to the high-end consumers:

$$p_h^M = v\beta_l - (g+\gamma)\beta_h\phi_h^M + (g+\gamma)(\beta_h - \beta_l)\phi_l^M$$

The distortions on the price of good *h* and the quality of good *l* interfere. The lower the quality offered to low-end consumers, the smaller the surplus left to high-end consumers:

$$\mathrm{d}\, p_h^M / \mathrm{d}\, \phi_l^M = (g+\gamma)(\beta_h - \beta_l) > 0$$

2.5 Monopoly with energy-use externalities

If, in addition to monopoly distortions, energy-use externalities are not internalized, a new equilibrium is established. Equilibrium outcomes (denoted with superscript *ME*) can easily be visualized by setting $\gamma = 0$ in Equations (2) and (3). Energy efficiency is undersupplied at the high-end of the product line:

$$\phi_h^{ME} = \phi_h^E > \phi_h^* = \phi_h^M$$

The same effect occurs at the low-end of the product line, where the two market failures reinforce each other:

$$\phi_l^{ME} > \phi_l^E > \phi_l^* \text{ and } \phi_l^{ME} > \phi_l^M > \phi_l^*$$

Which stand-alone market failure has the largest effect on the degradation of good *l* is ambiguous. Discrimination has a larger impact if and only if:

$$\phi_l^M > \phi_l^E \Leftrightarrow \frac{\beta_l}{\beta_h} < n_h \left(1 + \frac{gn_l}{\gamma + gn_h}\right) \quad (5)$$

Quite intuitively, the inequality is likely to hold when γ is small. Since the discrimination problem has no impact on the level of good h, the inequality is also a sufficient condition for the discrimination problem to generate a smaller deadweight loss than the externality problem.

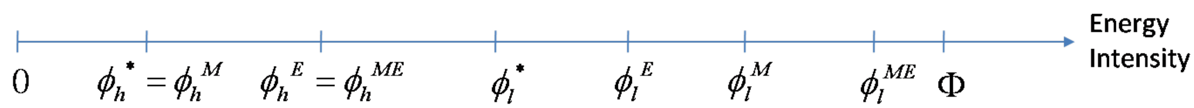

Figure 1: Illustrative quality levels under different market structures (**,E,M,ME*). Energy intensity increases rightward and energy efficiency increases leftward. Note that ϕ_l^E needs not be more energy-efficient than ϕ_l^M; it depends on Condition (5). Likewise, ϕ_h^{ME} needs not be more energy-efficient than ϕ_l^*; it depends on Condition (19).

3 First-best, differentiated subsidies

We now consider an institution in charge of regulating the imperfectly discriminating monopolist, subject to energy-use externalities. The monopolist and the regulator are assumed to share the same level of information. The regulator, unable to implement anti-trust regulation, seeks to decentralize the energy efficiency pair from its laissez-faire level $(\phi_h^{ME}, \phi_l^{ME})$ to its socially optimal one (ϕ_h^*, ϕ_l^*).

After the Tinbergen rule, the regulator should employ two policy instruments to address the two market failures. This can be done in many different ways. The regulator can combine what we shall call single instruments, that is, policies with only one instrument variable. Perhaps the most intuitive intervention is to combine a minimum quality standard equal to ϕ_l^* to address the discrimination problem and an energy tax equal to γ to address the externality problem.

Alternatively, the regulator can use differentiated instruments, that is, policies that accommodate several instrument variables. In the context of the model, where energy efficiency is undersupplied, this can be achieved through differentiated subsidies.

In this section, we compare per-quality and ad valorem subsidy designs. As in the rest of the paper, we consider a partial equilibrium framework in which subsidies are received by the consumers and funded by lump-sum taxes. In this setting, the results would be the same if the subsidies were received by the firm. We discuss government budget constraints in Section 5.

3.1 Per-quality subsidies

The regulator can offer subsidy payments that depend on the energy efficiency level of the energy-related good purchased by the consumer, as for instance in the US (Houde and Aldy, 2014) and China (Yao et al., 2014).

Such an incentive can be modeled as a two-stage game played by a principal, the regulator, and an agent, the monopolist. In the second stage of the game, the monopolist takes policy parameters as given and sets price and energy efficiency levels so as to maximize profit under the consumers' individual rationality and incentive compatibility constraints. Using backward induction, resolution of the second stage gives equilibrium outcomes as functions of the policy parameters. In the first stage of the game, the regulator sets policy parameters so as to maximize total surplus.

3.1.1 Second stage: monopolist's response to the instruments

Consumers receive a payment $(z_i - \phi_i)\sigma_i$ for purchasing good *i*, with σ_i the per-quality subsidy rate. The z_i are arbitrary energy-intensity reference levels below which consumers receive the payment. The monopolist maximizes profit subject to (equilibrium outcomes are denoted with superscript *PP*):

$$\mathrm{IR_l}^{\mathrm{PP}}\!: \beta_l(v - g\phi_l) + (\phi_l - z_l)\sigma_l \geq p_l$$

$$\mathrm{IR_h}^{\mathrm{PP}}\!: \beta_h(v - g\phi_h) + (\phi_h - z_h)\sigma_h \geq p_h$$

$$\mathrm{IC_l}^{\mathrm{PP}}\!: \beta_l(v - g\phi_l) + (\phi_l - z_l)\sigma_l - p_l \geq \beta_l(v - g\phi_h) + (\phi_h - z_h)\sigma_h - p_h$$

$$\mathrm{IC_h}^{\mathrm{PP}}\!: \beta_h(v - g\phi_h) + (\phi_h - z_h)\sigma_h - p_h \geq \beta_h(v - g\phi_l) + (\phi_l - z_l)\sigma_l - p_l$$

With binding $\mathrm{IR_l}^{\mathrm{PP}}$ and $\mathrm{IC_h}^{\mathrm{PP}}$ constraints, equilibrium efficiency levels are determined by the following first-order conditions:

$$-c'(\phi_h^{PP}) = \sigma_h + g\beta_h \tag{6}$$

$$-c'(\phi_l^{PP}) = g\left(\beta_l - \frac{n_h}{n_l}(\beta_h - \beta_l)\right) + \sigma_l \tag{7}$$

Per-quality subsidies raise both the energy efficiency ($\mathrm{d}\phi_i^{PP}/\mathrm{d}\sigma_i = -1/c''\left(\phi_i^{PP}\right) < 0$) and price ($\mathrm{d}p_i^{PP}/\mathrm{d}\sigma_i = g\beta_i > 0$) levels of the good they specifically target. While a subsidy on good *h* does not change the price of good *l* ($\mathrm{d}p_l^{PP}/\mathrm{d}\sigma_h = 0$), a subsidy on good *l* reduces the price of good *h*:

$$\frac{\mathrm{d}p_h^{PP}}{\mathrm{d}\sigma_l} = -g(\beta_h - \beta_l) < 0$$

This is because with σ_l, good *l* becomes more efficient and would provide consumer *h* with a higher surplus, would this consumer buy that good. The monopolist thus responds by lowering the price of *h* to keep consumer *h* indifferent between buying either good. In contrast, as $\mathrm{IC_l}$ does not bind, the choice of consumer *l* is not affected by σ_h, so the monopolist does not need to change the price of good *l*.

3.1.2 First stage: Regulator's intervention.

The regulator seeks the subsidy rates that maximize total surplus, taking into account energy-use externalities. This leads to the same first-order conditions for both goods:

$$\forall i \;\; n_i\left[-(g+\gamma)\beta_i - c'\left(\phi_i^{PP}\right)\right]\frac{\mathrm{d}\phi_i^{PP}}{\mathrm{d}\sigma_i} = 0 \tag{8}$$

Since $\mathrm{d}\phi_i^{PP}/\mathrm{d}\sigma_i < 0$, both subsidies will implement the socially optimal energy efficiency levels:

$$\forall i \quad -c'\left(\phi_i^{PP}\right) = (g+\gamma)\beta_i \tag{9}$$

By matching the right-hand side of Equation (9) with that of Equation (6), we derive the optimal subsidy rate on good *h* to correct the two market failures:

$$\sigma_h^{PP} = \beta_h \gamma$$

By matching the right-hand side of Equation (9) with that of Equation (7), we obtain the optimal subsidy rate on good *l*:

$$\sigma_l^{PP} = \beta_l \gamma + g \frac{n_h}{n_l}(\beta_h - \beta_l)$$

3.1.3 Comments

Subsidy rates σ_h^{PP} and σ_l^{PP} can be decomposed into two additive components. The $\beta_i \gamma$ terms are the components needed to internalize the energy-use externality. The second term – zero for σ_h^{PP} and $g(\beta_h - \beta_l)\, n_h/n_l$ for σ_l^{PP} – is the one needed to address the discrimination problem.

Which subsidy rate should be higher is not straight forward. It relies on the following condition:

$$\sigma_h^{PP} > \sigma_l^{PP} \Leftrightarrow \frac{\gamma}{g} > \frac{n_h}{n_l}$$

The externality must be large and/or the market share of the high-end consumers must be small for the subsidy rates to be increasing in energy efficiency. To put this condition in perspective, current estimates of the implicit carbon price in OECD countries typically range in the 10% of domestic energy price, hence$\gamma/g \approx 0.1$. In such a market environment, the market share of the high-end consumers should be no larger than 11% for the optimal subsidy schedule to be increasing in energy efficiency.

3.2 Ad valorem subsidies

An alternative to relating subsidy rates to the quality of the goods is to link them to their price. This is the prevailing subsidization schedule in many countries. Besides the French example mentioned in the introduction, in Germany, the KFW Bank offers price cuts for residential building retrofitting equal to 10% if the project exceeds building code requirements by 15% and 25% if the Passivhaus standard is met (Rüdinger, 2013). Such an instrument is modeled here in the same principal-agent framework as before.

3.2.1 Second stage: monopolist's response to the instruments

Let $\epsilon_i$be the ad valorem subsidy rate to good *i*. p_i denotes producer prices while $p_i(1-\epsilon_i)$ denotes consumer prices. The monopolist maximizes profit subject to

$$\mathrm{IR}_l^{AA}: \beta_l(v - g\phi_l) \geq p_l(1-\epsilon_l)$$

$$\mathrm{IR}_h^{AA}: \beta_h(v - g\phi_h) \geq p_h(1-\epsilon_h)$$

$$\mathrm{IC}_l^{AA}: \beta_l(v - g\phi_l) - p_l(1-\epsilon_l) \geq \beta_l(v - g\phi_h) - p_h(1-\epsilon_h)$$

IC_h^{AA}: $\beta_h(v - g\phi_h) - p_h(1-\epsilon_h) \geq \beta_h(v - g\phi_l) - p_l(1-\epsilon_l)$

Under binding IR_l^{AA} and IC_h^{AA} constraints, profit maximization leads to the following energy efficiency levels:

$$-c'(\phi_h^{AA}) = g\,\frac{\beta_h}{1-\epsilon_h} \tag{10}$$

$$-c'(\phi_l^{AA}) = g\left(\frac{\beta_l}{1-\epsilon_l} - \frac{n_h}{n_l}\frac{\beta_h-\beta_l}{1-\epsilon_h}\right) \tag{11}$$

Like per-quality subsidies, ad valorem subsidies increase the energy efficiency of the good they specifically target:

$$\forall i \quad \frac{\mathrm{d}\phi_i^{AA}}{\mathrm{d}\epsilon_i} = \frac{-g\beta_i}{(1-\epsilon_i)^2 c''[\phi_i^{AA}]} < 0 \tag{12}$$

Yet unlike per-quality subsidies, ad valorem subsidies entail some interference. The subsidy on good *h* indeed deteriorates the quality of good *l*:

$$\frac{\mathrm{d}\phi_l^{AA}}{\mathrm{d}\epsilon_h} = \frac{n_h}{n_l}\frac{g(\beta_h-\beta_l)}{c''[\phi_l^{AA}](1-\epsilon_h)^2} > 0 \tag{13}$$

This is because of the two channels that can be used by the monopolist to maximize profit, namely cut ϕ_l or increase p_h, an ad valorem subsidy makes the latter costlier. The monopolist therefore harnesses the former.

Using the binding constraints, equilibrium prices before subsidies are:

$$p_l^{AA} = \frac{\beta_l\left(v - g\phi_l^{AA}\right)}{1-\epsilon_l}$$

$$p_h^{AA} = \frac{g\beta_h\left(\varphi_l^{AA} - \phi_h^{AA}\right) - \beta_l\left(v - g\phi_l^{AA}\right)}{1-\epsilon_h}$$

The effect of ad valorem subsidies on the prices of the durable goods is more subtle than that of per-quality subsidies. Both subsidies have an opposite effect on the price of good *l*, which reflects their opposite effect on the quality of that good:

$$\frac{\mathrm{d}p_l^{AA}}{\mathrm{d}\epsilon_l} = \frac{1}{1-\epsilon_l}\left(p_l^{AA} - g\beta_l\frac{\mathrm{d}\phi_l^{AA}}{\mathrm{d}\epsilon_l}\right) > 0$$

$$\frac{\mathrm{d}p_l^{AA}}{\mathrm{d}\epsilon_h} = \frac{-g\beta_l}{1-\epsilon_h}\frac{\mathrm{d}\phi_l^{AA}}{\mathrm{d}\epsilon_h} < 0$$

The price of good *h* increases with ϵ_h and decreases with ϵ_l:

$$\frac{\mathrm{d}p_h^{AA}}{\mathrm{d}\epsilon_h} = \frac{1}{1-\epsilon_h}\left(p_h^{AA} - g\beta_h \frac{\mathrm{d}\phi_h^{AA}}{\mathrm{d}\epsilon_h} + g(\beta_h + \beta_l)\frac{\mathrm{d}\phi_l^{AA}}{\mathrm{d}\epsilon_h}\right) > 0$$

$$\frac{\mathrm{d}p_h^{AA}}{\mathrm{d}\epsilon_l} = \frac{g(\beta_h + \beta_l)}{1-\epsilon_h}\frac{\mathrm{d}\phi_l^{AA}}{\mathrm{d}\epsilon_l} < 0$$

3.2.2 First stage: Regulator's intervention.

The regulator seeks the subsidy levels that maximize total surplus, taking into account energy-use externalities. The first-order conditions for maximization are:

$$n_h\left[-(g+\gamma)\beta_h - c'\left(\phi_h^{AA}\right)\right]\frac{\mathrm{d}\phi_h^{AA}}{\mathrm{d}\epsilon_h} + n_l\left[-(g+\gamma)\beta_l - c'\left(\phi_l^{AA}\right)\right]\frac{\mathrm{d}\phi_l^{AA}}{\mathrm{d}\epsilon_h} = 0 \qquad (14)$$

$$n_l\left[-(g+\gamma)\beta_l - c'\left(\phi_l^{AA}\right)\right]\frac{\mathrm{d}\phi_l^{AA}}{\mathrm{d}\epsilon_l} = 0 \qquad (15)$$

Since $\mathrm{d}\phi_l^{AA}/\mathrm{d}\epsilon_l > 0$, Equation (15) simplifies to:

$$-c'\left(\phi_l^{AA}\right) = (g+\gamma)\beta_l \qquad (16)$$

This implies that the efficiency of good *l* will be set at its optimal level. This result, introduced in Equation (14) and combined with the fact that $\mathrm{d}\phi_h^{AA}/\mathrm{d}\epsilon_h < 0$ implies that good *h* will also be set at its optimal level:

$$-c'\left(\phi_h^{AA}\right) = (g+\gamma)\beta_h \qquad (17)$$

By matching the right-hand side of Equation (17) with that of Equation (10), we derive the optimal subsidy rate on good *h* to correct the two market failures:

$$\epsilon_h^{AA} = \frac{\gamma}{g+\gamma}$$

Using this and matching the right-hand side of Equation (16) with that of Equation (11), we derive the optimal subsidy rate on good *l*:

$$\epsilon_l^{\mathrm{AA}} = \frac{n_h(\beta_h - \beta_l) + \frac{\gamma}{g+\gamma} n_l\beta_l}{n_h(\beta_h - \beta_l) + n_l\beta_l}$$

3.2.3 Comments

Ad valorem subsidies differ from per-quality subsidies in two ways. First, they cannot systematically be decomposed into two additive components meant to specifically address one market failure. If discrimination were the only market failure to address ($\gamma = 0$), the subsidy rate would be nil on good *h* ($\epsilon_h^M = 0$) and equal to $\epsilon_l^M = n_h(\beta_h - \beta_l)/[n_h(\beta_h - \beta_l) + n_l\beta_l]$ on good *l*.[14] Reciprocally, if energy-use externalities were the only market failure to internalize, energy efficiency levels would be set so that

[14] The intuition that the larger distortion at the bottom of the product line warrants decreasing subsidization schedules is alluded to, though not formally discussed, by Besanko et al. (1988).

equilibrium levels with the subsidy (defined by$-c' = g\beta_i/(1-\epsilon_i)$) match the socially optimal ones (defined by $-c' = (g+\gamma)\beta_i$). Hence, both goods would need to be subsidized at the same uniform rate $\epsilon^E = \gamma/[\gamma + g]$. With the orders of magnitude discussed in Section 3.1.3, this rate is typically equal to 9%.

With these definitions, $\epsilon_h^{AA} = \epsilon^E + \epsilon_h^M$ and:

$$\epsilon_l^{AA} = \epsilon^E + \epsilon_l^M - \epsilon_l^M\epsilon^E = \epsilon^E + \epsilon_l^M(1-\epsilon^E)$$

In other words, if the two market failures are to be jointly corrected, the subsidy rates specifically needed for each market failure are additive on good *h* but sub-additive on good *l*.

A second difference between ad valorem subsidies and per-quality ones it that with the former, subsidy rates should always be larger on good *l* than on good *h*: $\epsilon_h^{AA} < \epsilon_l^{AA}$. An intuition for this result is that the efficiency of good *h* must increase only to internalize the externality, while the efficiency of good *l* must increase to also correct the distortion due to imperfect discrimination. Of course, though, subsidy amounts $p_h^{AA}\epsilon_h^{AA}$need not be lower than $p_l^{AA}\epsilon_l^{AA}$. In practice, as the French and German examples illustrate, subsidy rates tend to be increasing in energy efficiency.

4 Second-best, single-instrument subsidies

In practice, the Tinbergen rule is rarely satisfied. For a variety of informational, institutional or political reasons, there are seldom as many policy instruments as there are market failures to correct.[15] In the context we are interested in, for instance, implementing differentiated subsidy rates would open room for lobbying by dominant firms.

In this section, we therefore take a more positive view and examine how single-instrument subsidies perform in the context of two market failures. Overall, six types of single-instrument subsidies can be thought of. Subsidy rates can uniformly target both goods, or specifically target either of the two goods. In each case, the rates can be ad valorem or per-quality.

Much of the analysis carried out in Section 3 carries over to the second-best analysis. The monopolist's responses to each of these instruments have already been analyzed in the second stages of the principal-agent games. The difference in the second-best setting is that in the first stage of the games, the regulator maximizes total surplus with respect to one instrument variable only.

For subsidies specifically targeting the low-end good (either ad valorem or per-quality) and per-quality subsidies targeting the high-end good, the analysis directly derives from Section 3. Recall from the second stages of the games that these subsidies do not interfere with the good they are not targeted for. Therefore, in a second-best setting, the best the regulator can do is to set their rates at their socially optimal level.

[15] To quote Tinbergen himself, "Economists or economic politicians holding the opinion that there is such a one-by-one correspondence between targets and instruments evidently assume a very special structure." (Tinbergen, 1952, note 1, p. 31).

More analysis is needed for uniform subsidies (either ad valorem or per-quality) and ad valorem subsidies on the high-end good, which is the object of the present section.

4.1 Uniform subsidies

4.1.1 Ad valorem schedule

In France, home energy retrofits benefit from a reduced value-added tax rate (5% against a normal rate of 20%). Various technologies of different energy efficiency levels are indistinctly eligible.

The monopolist's response to such a uniform ad valorem subsidy rate is directly given by Equations (10) and (11), with $\epsilon_h = \epsilon_l \equiv \epsilon$. The comparative statics of equilibrium efficiencies is (superscript A denotes equilibrium outcomes):

$$\frac{\mathrm{d}\phi_h^A}{\mathrm{d}\epsilon} = \frac{-g\beta_h}{c''(\phi_h^A)(1-\epsilon)^2} < 0$$

$$\frac{\mathrm{d}\phi_l^A}{\mathrm{d}\epsilon} = \frac{-g}{c''(\phi_l^A)(1-\epsilon)^2}\left(\beta_l - \frac{n_h}{n_l}(\beta_h - \beta_l)\right) < 0$$

The comparative statics of price established in 3.2.1 suggest that the effect of a uniform ad valorem subsidy on product prices will be ambiguous.

In the first stage of the game, the regulator solves Program (14) with $\epsilon_h \equiv \epsilon$. Identifying the $c'(\phi_i)$ in the resulting first-order conditions with the right-hand sides in Equations (10) and (11), we end up with the following equality (A denotes equilibrium outcomes):

$$\epsilon^A = \epsilon^E + (1-\epsilon^E)\frac{n_h(\beta_h - \beta_l)\,\mathrm{d}\phi_l^A/\mathrm{d}\epsilon}{n_h\beta_h\mathrm{d}\phi_h^A/\mathrm{d}\epsilon + n_l\beta_l\,\mathrm{d}\phi_l^A/\mathrm{d}\epsilon}$$

The second-best uniform rate is larger than that needed to specifically internalize energy-use externalities. As a result, the quality of the high-end good will be higher than the socially optimal one.

How the uniform subsidy rate compares to ϵ_l^{AA} depends on how the fraction in the right-hand side of the above equality compares to ϵ_l^M. The comparison leads to the following equivalence:

$$\epsilon^A < \epsilon_l^{AA} \Leftrightarrow 1 - \frac{\beta_l}{\beta_h} < \frac{\mathrm{d}\phi_h^A/\mathrm{d}\epsilon}{\mathrm{d}\phi_l^A/\mathrm{d}\epsilon} = \frac{\beta_h}{\beta_l - (\beta_h - \beta_l)n_h/n_l}\frac{c''\left(\phi_l^A\right)}{c''\left(\phi_h^A\right)}$$

The conditions under which the inequality holds are ambiguous. With a quadratic cost function, $c''\left(\phi_h^A\right)/c''\left(\phi_h^A\right)$ would be equal to 1. The right-hand side of the inequality would be larger than 1 and, since the left-hand side is lower than 1, the inequality would always hold. The uniform subsidy rate would be lower than the first-best rate on the low-end good. As a result, the quality of the low-end good would be lower than the socially optimal one.

4.1.2 Per-quality schedule

The monopolist's response to such a subsidy is the same as the one described in Section 3.1.1. By the same reasoning as before, the regulator will set the uniform per-quality subsidy at the following level (P denotes equilibrium outcomes):

$$\sigma^P = \frac{\sigma_h^{PP}}{1+\frac{n_l}{n_h}\frac{\mathrm{d}\phi_l^P/\mathrm{d}\sigma}{\mathrm{d}\phi_h^P/\mathrm{d}\sigma}} + \frac{\sigma_l^{PP}}{1+\frac{n_h}{n_l}\frac{\mathrm{d}\phi_h^P/\mathrm{d}\sigma}{\mathrm{d}\phi_l^P/\mathrm{d}\sigma}} < \sigma_h^{PP} + \sigma_l^{PP}$$

The payment to consumers will be lower than that the sum of the two differentiated per-quality subsidies ($\sigma_h^{PP} + \sigma_l^{PP}$).

4.2 Subsidies restricted to the high-end good

4.2.1 Ad valorem schedule

The recent evolution of the French tax credit program resembles such an instrument. Only the best available technologies are incentivized (e.g. condensing boilers, etc.) with a 30% price cut.

Recall from Section 3.2.1 that an ad valorem subsidy on good *h* deteriorates the quality of good *l* ($\mathrm{d}\phi_l^H/\mathrm{d}\epsilon_h > 0$, where superscript *H* here denotes equilibrium outcomes). Therefore, here, in equilibrium the quality of good *h* will be below its socially optimal level $\phi_h^*$and the quality of good *l* will be even below its laissez-faire level ϕ_l^{ME}.

In the first stage of the game the regulator sets the ad valorem incentive at the following rate:

$$\epsilon_h^H = \frac{\gamma n_h \beta_h \, d\phi_h^H/d\epsilon_h + (\gamma n_l \beta_l + g n_h(\beta_h - \beta_l))\, d\phi_l^H/d\epsilon_h}{(\gamma + g) n_h \beta_h \, d\phi_h^H/d\epsilon_h + (\gamma n_l \beta_l + g n_h(\beta_h - \beta_l))\, d\phi_l^H/d\epsilon_h}$$

Since the $\mathrm{d}\phi_i^H/\mathrm{d}\epsilon_h$ have opposite signs, the sign of this expression is ambiguous. If it is negative, the second-best incentive on good *h* shifts from a subsidy to a tax. This occurs if and only if the numerator and the denominator have opposite signs. Since the denominator is smaller than the numerator, this condition is equivalent to having a positive numerator and a negative denominator. Therefore:

$$\epsilon_h^H < 0 \Leftrightarrow 0 < \gamma n_h \beta_h \frac{\mathrm{d}\phi_h^H}{\mathrm{d}\epsilon_h} + \left(\gamma n_l \beta_l + g n_h(\beta_h - \beta_l)\right)\frac{\mathrm{d}\phi_l^H}{\mathrm{d}\epsilon_h} < -g n_h \beta_h \frac{\mathrm{d}\phi_h^H}{\mathrm{d}\epsilon_h} \tag{22}$$

This condition is likely to hold ifγ is small enough and type *l* consumers dominate the market. To see this, assume γ is negligible. The condition boils down to:

$$0 < 1 - \frac{\beta_l}{\beta_h} < -\frac{\mathrm{d}\phi_h^H/\mathrm{d}\epsilon_h}{\mathrm{d}\phi_l^H/\mathrm{d}\epsilon_h} = \frac{n_l}{n_h}\frac{\beta_h}{\beta_h - \beta_l}\frac{c''(\phi_l^H)}{c''(\phi_h^H)}$$

We know from Equations (10) and (11) that $\phi_l^H > \phi_h^H$, but without further assumptions on $c'''(.)$, we do not know how $c''(\phi_l^H)/c''(\phi_h^H)$ compares to 1. Still, if n_l is sufficiently larger than n_h, the right-hand side of the inequality will be larger than 1 and the inequality will be satisfied.

This outcome can be rationalized as follows. If the externality is very small, then the high-end good is very close to its socially optimal level, while the low-end good is far from its socially optimal level. Therefore, the tax has a first-order effect on good *l* but only a second-order effect on good *h*. In other words, with the tax, the marginal welfare gain from improving good *l* is larger than the marginal welfare loss from deteriorating good *h*. The fact that n_l is larger than n_h only amplifies this effect.

It should be kept in mind though that having a small γ and a large n_l is neither a necessary nor a sufficient condition for the optimal incentive to be a tax. Clearer conditions can be derived using a more restrictive quadratic cost assumption. Hence, the second derivative of cost is constant. The last fraction drops from the inequality, which becomes:

$$\left[\left(1-\frac{\beta_l}{\beta_h}\right)^2+\frac{\beta_l}{\beta_h}\right]<\frac{g}{\gamma}\frac{n_h}{n_l}\left(1-\frac{\beta_l}{\beta_h}\right)^2<\left[\left(1-\frac{\beta_l}{\beta_h}\right)^2+\frac{\beta_l}{\beta_h}\right]+\frac{g}{\gamma}$$

The interior condition $\beta_l/\beta_h \geq n_h$ implies $n_l \geq n_h(1-\beta_l/\beta_h)^2$, hence the right inequality. Therefore, with quadratic costs, the left inequality above is sufficient for the incentive to be a tax.

4.2.2 Per-quality schedule

In France, a 1,350€ subsidy on energy efficiency investment was introduced in 2014 for middle- and low-income households undergoing home energy retrofit works. The program has similar eligibility requirements as the most recent version of the tax credit program. It can be seen as a per-quality subsidy on the most energy efficient goods.

With a per-quality subsidy on good *h*, the quality of good *h* will be socially optimal (ϕ_h^*) and the quality of good *l* will be unchanged (ϕ_l^{ME}). This instrument therefore strictly dominates the second-best ad valorem subsidy on good *h*, which brings both goods to lower quality levels. Yet if the ad valorem subsidy turns out to be a tax (under Condition (22)), the comparison with the per-quality subsidy is no longer obvious. According to the comparative statics of quality levels with respect to ϵ_h (Equations (12) and (13)), the tax will push the quality of good *h* away from its socially optimal level (which is worse than the per-quality equivalent) but bring the quality of good *l* closer to its socially optimal level (which is better than the per-quality equivalent).

5 Discussion

In this section, we reexamine how the main assumptions of our model affect the results. Recall first that we model only two types of consumers and two goods. In general, the finding of no distortion at the top of the product line is robust to extensions to more than two consumers or a continuum thereof (Mussa and Rosen, 1978).

We focus on the intensive margin of investment and consider energy efficiency as the only dimension of quality. These assumptions are well suited to product replacement within a capacity segment. This is most relevant to operations on heating systems, which we used as our leading example. Introducing other dimensions of quality would reinforce the superiority of per-quality subsidies over ad valorem ones, when only good *h* is subsidized. Indeed, ad valorem subsidies would reduce the marginal cost of increasing the qualities unrelated to energy efficiency. This would not occur with per-quality subsidies, which can be targeted at only one dimension of quality (energy efficiency). As a result, ad valorem subsidies on good *h* would generate an overprovision of these other dimensions of quality.

A strong assumption of the model is the monopoly setting. In a more general oligopoly setting where firms specialize in one quality, all firms would contribute to market segmentation. As a result, the quality of the high-end good too would be distorted – actually it would be too high (Cremer and Thisse, 1994). This would partly compensate any underprovision of quality induced by energy-use externalities, while at the low-end of the product line, the two market failures reinforce each other, just like in the monopoly setting. At some point, if the externality is low enough, the quality of the high-end good under the two market failures may be above its socially optimal level, thus warranting a tax on the low-end good. More generally, an oligopoly setting would make the conditions for the optimal incentive on the high-end good to be a tax less restrictive.

We assumed away the opportunity cost of public funds. If the Government faced budget constraints, the efficiency of those interventions involving large transfers would be lower. This would narrow the welfare gap between single-instrument subsidies and differentiated subsidies, which involve larger subsidy amounts. Moreover, the public cost of per-quality subsidies can be limited by setting a relatively high reference level z_i. It can even be nullified or become negative by taxing the goods whose efficiency is below the reference level – as in the feebate system currently implemented in the automobile sector in various countries.[16] This policy variable is not available with ad valorem subsidies. Hence, introducing an opportunity cost of public funds would also reinforce the superiority of per-quality subsidies over ad valorem ones.

Lastly, an important result of our analysis is the higher first-best ad valorem subsidy rate on the low-end good, as compared to the high-end good. This result is very specific to the market failures taken into account. Technology spillovers would be another relevant market failure to consider. It is plausible to suppose that more energy-efficient products are less mature than less energy-efficient ones, hence generate larger spillovers. In this perspective, the subsidies needed to internalize technology spillovers would be larger on high-end goods, thus countervailing the effects studied in the analysis.

6 Conclusion

Energy efficiency markets are commonly subject to both energy-use externalities and price-quality discrimination. They are also the realm of various types of subsidies, the properties of which have been little studied. To address this knowledge gap, we have used and extended the model of Fischer (2005) to examine a variety of first-best and second-best energy efficiency subsidies in the presence of the two market failures. We have considered two types of consumers, a multiproduct monopolist which can imperfectly price discriminate and two levels of energy efficiency which are positively correlated with quality.

[16] The feebate system, implemented e.g. in France, Canada, the Netherlands and Norway, combines taxes and subsidies, the amount of which depends on the energy efficiency level of the car purchased, regardless of its price (d'Haultfoeuille et al., 2013).

From a normative perspective, the two levels of energy efficiency are undersupplied in laissez-faire. This so-called energy efficiency gap can be addressed with energy efficiency subsidies, the rate of which is differentiated across energy efficiency levels. Subsidy schedules can be either per-quality or ad valorem, with different consequences. We find that with ad valorem subsidies, the rate on the more energy efficient goods interferes with the provision of less energy efficient goods. The rates should always be decreasing in energy efficiency, a result seemingly at odds with actual practice. With per-quality subsidies, there are no such interferences and the rates can be increasing if the marginal external cost of energy use is large enough relative to the market share of low-type consumers.

From a positive perspective, for a variety of informational, institutional or political reasons, single instruments are more likely to be implemented. We find that a uniform ad valorem subsidy should be set above the subsidy that would be needed to specifically internalize energy-use externalities. Lastly, if, as is often observed in practice, only the high-end good is to be incentivized, a per-quality schedule should be preferred over an ad valorem one. An ad valorem tax may even be preferred over an ad valorem subsidy if the externality is small enough and low-end consumers dominate the market.

APPENDIX 1: Energy tax

Most European countries, Japan and a few other countries have implemented important fuel taxes in the transport sector. These taxes were found to efficiently restrain fuel demand (Sterner 2007).

Energy taxes here are assumed to be funded by lump-sum subsidies.

Second stage: Monopolist's response

A tax on energy at rate *t* would lead to the following first-order conditions (superscript *T* denotes equilibrium outcomes):

$$-c'\left(\phi_h^T\right) = (g+t)\beta_h \tag{20}$$

$$-c'\left(\phi_l^T\right) = (g+t)\left(\beta_l - \frac{n_h}{n_l}(\beta_h - \beta_l)\right) \tag{21}$$

The tax would increase the energy efficiency of the two goods:

$$\frac{\mathrm{d}\phi_h^T}{\mathrm{d}t} = \frac{-\beta_h}{c''(\phi_h^T)} < 0$$

$$\frac{\mathrm{d}\phi_l^T}{\mathrm{d}t} = \frac{-1}{c''(\phi_l^T)}\left(\beta_l - \frac{n_h}{n_l}(\beta_h - \beta_l)\right) < 0$$

The effect of the tax on the price of good *l* is ambiguous. Recall that $p_l^T = \beta_l\left(v - (g+t)\phi_l^T(t)\right)$. Differentiating, we obtain:

$$\frac{\mathrm{d}p_l^T}{\mathrm{d}t} = -\beta_l\phi_l^T(1+\mu_l) \text{ with } \mu_l = \frac{\mathrm{d}\phi_l^T}{\mathrm{d}t}\frac{t}{\phi_l^T}$$

Variable μ_l is the elasticity of the supply of energy efficiency with respect to the price of energy. If $-1 < \mu_l < 0$, a "normal" rebound effect occurs. If $\mu_l \geq 0$, a "backfire" rebound effect occurs. Recall that $\mathrm{d}\phi_l^T/\mathrm{d}t$ is negative, hence so is μ_l. Therefore, $\mathrm{d}\phi_l^T/\mathrm{d}t$ is negative if there is a "normal" rebound effect and positive if there is no rebound effect ($\mu_l \leq -1$).

The price of good *h* will vary with even more ambiguity. Recall that

$$p_h^T = p_l^T + \beta_h(g+t)\left(\phi_l^T(t) - \phi_h^T(t)\right).$$

Differentiating and using the same elasticity formulas as before, we obtain:

$$\frac{\mathrm{d}p_h^T}{\mathrm{d}t} = -(\beta_h - \beta_l)\phi_l^T(1+\mu_l) - \beta_h\phi_h^T(1+\mu_h)$$

First stage: Regulator's intervention

The optimal tax rate to address the two market failures is the one that maximizes social welfare, including energy-use externalities. This leads to the following first-order condition:

$$n_h\left[-(g+\gamma)\beta_h - c'\left(\phi_h^T\right)\right]\frac{\mathrm{d}\phi_h^T}{\mathrm{d}t} + n_l\left[-(g+\gamma)\beta_l - c'\left(\phi_l^T\right)\right]\frac{\mathrm{d}\phi_l^T}{\mathrm{d}t} = 0$$

Identifying the $c'\left(\phi_i^T\right)$ with the right-hand sides in Equations (20) and (21), we end-up with the following equality:

$$t = \gamma + \frac{(g+\gamma)n_h(\beta_h - \beta_l)\,\mathrm{d}\phi_l^T/\mathrm{d}t}{n_h\beta_h \mathrm{d}\phi_h^T/\mathrm{d}t + \left(n_l\beta_l - n_h(\beta_h - \beta_l)\right)\mathrm{d}\phi_l^T/\mathrm{d}t} > \gamma$$

Unless the two consumers are identical ($\beta_h = \beta_l$), the optimal tax rate is larger thanγ. If it were equal to γ, external costs would be internalized but there would still remain some deadweight loss from price-quality discrimination. Further energy taxation could reduce the deadweight loss on the quality of good *l*, up to the point that the marginal welfare gains are offset by the marginal welfare loss of an inefficiently high quality of good *h*.

This result contrasts with the classical one in the environmental economics literature that under imperfect competition, the second-best tax rate needed to compensate the over-supply of a polluting good should be smaller than the Pigouvian rate, so as to balance the output contraction effect of market power (Baumol 1988). The difference comes from the fact that energy efficiency can be seen as a cleaning technology. In this context, instead of being mutually compensating, the two market failures are mutually reinforcing. They both contribute to an underprovision of the cleaning technology (Mahenc and Podesta, 2011).

Lastly, note that this result would be different in an oligopoly setting, where market power distorts the quality of the high-end too (Lombardini-Riipinen, 2005).

APPENDIX 2: Minimum Energy Efficiency Standard

Most European countries and some US states have implemented minimum quality standards for new buildings after the oil shocks of the 1970s, and have strengthened them since then. Now such standards exist in all developed countries and in many developing countries. The main appliances, as well as electric motors and lighting equipment are also covered by energy efficiency standards in most of the developed and transition countries.

Let us consider the effect of a standard (denoted *S*) on each good *i*, independently of the other good. The deadweight loss of a standard ϕ^Son good *l* is:

$$DWL_i = n_i[(g+\gamma)\beta_i(\phi^S - \phi_i^*) + c(\phi^S) - c(\phi_i^*)]$$

It varies with ϕ^S in an ambiguous manner:

$$\frac{\mathrm{d}DWL_i}{\mathrm{d}\phi^S} = n_i[(g+\gamma)\beta_i + c'(\phi^S)]\begin{cases} < 0 \text{ if} \phi_i^* < \phi^S \leq \Phi \\ = 0 \text{ if} \phi^S = \phi_i^* \\ > 0 \text{ if } 0 \leq \phi^S < \phi_i^* \end{cases} \tag{18}$$

That is, tightening the standard is welfare-improving, up to the point that the socially optimal value of the good is reached. Beyond that point, further tightening the standard is socially detrimental. The question of interest now is: should the standard constrain the efficiency of both goods (pooling standard) or that of good *l* only (separating standard)?

A necessary and sufficient condition for a pooling standard

An optimal pooling standard would minimize the sum of the deadweight losses on each of the two goods. This leads to the following first-order condition:

$$-c'(\phi^S) = (n_h\beta_h + n_l\beta_l)(g+\gamma)$$

The pooling standard would be optimal to a consumer of average type $n_h\beta_h + n_l\beta_l$. To be effective, such a standard should be more stringent than the monopolist's supply of good *h*: $\phi^S \leq \phi_h^{ME}$. This is true if and only if $c'^{-1}\big(-(g+\gamma)(n_h\beta_h + n_l\beta_l)\big) \leq c'^{-1}(-g\beta_h)$, that is:

$$\frac{\beta_h}{n_h\beta_h + n_l\beta_l} \leq 1 + \frac{\gamma}{g} \tag{19}$$

A sufficient condition for a pooling standard

If the externality is so large that $\phi_h^{ME} \geq \phi_l^*$ then the standard, at least equal to ϕ_l^*, is necessarily more stringent than $\phi_h^{ME} \geq \phi_l^*$. This occurs when $c'^{-1}(-(g+\gamma)\beta_l) \leq c'^{-1}(-g\beta_h)$, which leads to the sufficient condition for a pooling standard:

$$\frac{\beta_h}{\beta_l} \leq 1 + \frac{\gamma}{g}$$

Obviously, this condition implies Condition (19).

Separating standard

If Condition (19) is not satisfied, $\phi^S > \phi_h^{ME}$. It is not optimal for the monopolist to supply only one good of efficiency ϕ^S. The monopolist could increase the profit earned from consumers *h* by extending its product line to includeϕ_h^{ME}. With this new constraint, the only way to minimize the total deadweight loss is to eliminate the deadweight loss from good *l*. After Equation (18), this can only be done by setting the standard at ϕ_l^*.

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