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Energy efficiency policy with price-quality discrimination

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1 Introduction

Energy efficiency has become a popular theme in the policy arena. The enthusiasm is sustained by engineering studies (for instance Mc Kinsey & Co. (2009), to name only the most impactful) claiming that energy efficiency is the most cost-effective way to save energy, hence internalize the multiple externalities associated with energy use. Such externalities include carbon dioxide emissions at the source of the climate change problem, local pollution, risks related to nuclear energy and national concerns about the security of energy supply. They motivate implementation of numerous energy efficiency standards, labels and subsidies across the world.[4]

These policies are commonly devised in highly concentrated market environments. In the US, Fisher (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).[5]

Such an imperfect competition context is conducive to price-quality discrimination. The problem, first studied by Mussa and Rosen (1978), 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 Fisher (2005), this general economic problem can provide a supply-side explanation as to why energy efficiency levels are too low in the economy, a phenomenon known as the energy efficiency gap (Jaffe and Stavins, 1994).[6] More recently, Houde (2013) and Spurlock (2013) in the US and Cohen et al. (2014) in the UK found empirical evidence that appliance industries actually do discriminate among consumers along the price and energy efficiency dimensions.

Against this background, we are interested in the following question: How do various policy instruments compare in a market for energy efficiency subject to both energy-use externalities and price-quality discrimination? From a normative perspective, after the Tinbergen rule, the existence of two market failures calls for a combination of two policy instruments (Tinbergen, 1952). Interestingly, the tools usually warranted to internalize energy-use externalities, namely energy taxes, energy efficiency subsidies and standards, can in some ways also be used to address market power. How market failure

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

[5] 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.

[6] This is one of the few supply-side explanations. The existing literature on the energy efficiency gap tends to focus more on demand-side explanations. For comprehensive reviews, see Sorrell (2004), Gillingham et al. (2009) and Allcott and Greenstone (2012).

interference change the design and merit order of these instruments is an open question. From a positive perspective, it is also questionable how second-best policy can be designed when, due to political constraints, only one instrument can be implemented.

Partial answers to the question can be found in the literature. A first set of papers focuses on the instruments specifically needed to address price-quality discrimination, without consideration for energy-use externalities. Following Mussa and Rosen (1978), Besanko et al. (1988) show in a monopoly setting that the deadweight loss can be eliminated by ad valorem subsidies, the rate of which should be decreasing in the quality of the product. Fischer (2005) studies the same problem in a more specific energy efficiency context and pays specific attention to various forms of quality standards. In a subsequent paper, the author extends her analysis to a Bertrand price and quality competition framework (2011). Another set of papers, in line with Cremer and Thisse (1994), discuss instrument combinations in an oligopoly setting where price-quality discrimination coexists with energy-use externalities. Lombardini-Riipinen (2005) finds that the social optimum can be achieved by a combination of a uniform ad valorem tax on the durable good coupled with either an emission tax or a subsidy proportional to the environmental quality of the good. Bansal (2008) studies second-best policy and finds that the second-best ad valorem incentive should be a subsidy if environmental damages are high, and a tax otherwise.[7]

In this paper, we compare a wide range of first-best and second-best energy efficiency policies. We integrate in a unified framework energy efficiency subsidies, minimum efficiency standards and energy taxes. We build on the model of Fischer (2005), which features a monopoly and two consumer types with fixed market shares.[8]

Our main contribution is to pay specific attention to a variety of subsidy designs. Indeed, little is known about the properties of energy efficiency subsidies in an imperfect competition context.[9] This is at odds with the importance of the instrument in practice, perhaps the most widespread of all energy efficiency policies. For instance in France, a tax credit has been implemented in 2005 in the residential building sector. The program can be seen as a differentiated ad valorem subsidy. The subsidy rates, frequently updated, were initially increasing in energy efficiency. Until recently, the subsidy rate was 15% of the price for low-temperature boilers and 25% for more efficient condensing boilers, while the least-efficient boilers were not eligible (Nauleau, 2014). Since 2014, only the best available technologies are eligible to

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[7] Product differentiation has different causes in monopoly and oligopoly settings (Champsaur and Rochet, 1986). In an oligopoly structure *à la* Cremer and Thisse, it results from quality-specific fixed costs which compel firms to specialize into one single quality. In Mussa and Rosen's monopoly model, there are no such fixed costs and product differentiation only results from a strategy consisting in creating variety to discriminate.

[8] We do not analyse energy efficiency labels because they are usually warranted to address information asymmetries (not considered here) rather than energy-use externalities. For an analysis of energy efficiency labels in an imperfect competition context, see Houde (2013) and Spurlock (2013). The authors model labels by supposing that information provision change the preferences over energy efficiency for a fringe of consumers.

[9] 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). The few existing theoretical works assume perfect competition (Giraudet and Quirion, 2008).

a 30% subsidy rate. This can be seen as an ad valorem subsidy restricted to high-end goods. In parallel, since 2014, all building energy efficiency measures are eligible to a reduced VAT rate, irrespective of the energy efficiency level achieved. This program can be seen as a uniform ad valorem subsidy.

We find that in an economy subject to both energy-use externalities and price-quality discrimination, the social optimum can be achieved with differentiated subsidies. With ad valorem subsidies, the subsidization of the high-end good leads the monopolist to cut the quality of the low-end good. The rates should always be decreasing in energy efficiency. With per-quality subsidies, there are no such interference and the rates can be increasing if the externality is large enough relative to the market share of low-type consumers. Stand-alone instruments only achieve second-best outcomes. A 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. An energy tax should be set above the marginal external cost. Likewise, 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 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.

The paper is organized as follows. Section 2 introduces the model and the different market environments. Section 3 discusses first-best policy interventions, focusing on ad valorem and per-quality subsidies with differentiated rates. Section 4 discusses second-best policy interventions, involving minimum quality standards, energy taxes and various single-instrument subsidies. Section 5 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). Consumers purchase durable goods which, combined with energy, provide energy services such as light and heat. The durable goods considered here can be appliances, light bulbs, heating systems, improvements to building envelopes (wall insulation, double glazing windows), vehicles, etc. The goods are characterized by their energy intensity $\phi_j > 0$, bounded from above byΦ, the energy intensity that would be chosen if energy were costless. Energy intensity is the energy use 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).[10] We abstract from ancillary attributes of the goods, such as noise for appliances, aesthetics for light bulbs or safety for cars. There are two levels of energy efficiency, high (h) and low (l), with $0 < \phi_h < \phi_l < \Phi$.

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[10] Plourde and Bardis (1999) study the opposite model in which quality is positively correlated with energy intensity. This is supposed to mimic the fact that for safety reasons, consumers may have a higher preference for large, inefficient cars than for small, efficient cars. Unsurprisingly, they find opposite results to those of Fischer (2005).

For consumer *i*, the net surplus of purchasing and using good *j* is

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

$v > 0$ 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 durable 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 her heating system and set her 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 in durable goods. 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$-c'(\Phi) < g\beta_l$, which guarantees separating equilibria with interior solutions.[12]

We assume that the firm supplying the durable good is a monopolist. This is admittedly an extreme case of imperfect competition. However, qualitative insights would be similar in a more general (though less tractable) oligopoly setting, as the two approaches of Fischer (2005, 2011) illustrate.

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[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).

[12] If $g\beta_l \leq -c'(\Phi) < g\beta_h$ then in the equilibria studied hereafter $\phi_h$will be interior and ϕ_l will be a corner solution. If $-c'(\Phi) \geq g\beta_h$ there will be a pooling equilibrium with two corner solutions.

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

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	S	Minimum quality standard
	T	Energy tax
	A	Uniform ad valorem subsidy
	P	Uniform per-quality subsidy
	H	Ad valorem subsidy restricted to good h
	Q	Per-quality subsidy restricted to good h

2.3 Social optimum

Let $\gamma \geq 0$ be the constant marginal external cost of energy use. This may include 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 energy cost, the external cost and the production cost of the durable good.

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

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

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

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.

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

2.4 Monopoly

To isolate the discrimination problem from energy-use externalities, we first suppose that the latter are internalized. Consumers thus face social energy cost $g+\gamma$ and enjoy surplus $CS_{ij}^* \equiv \beta_\mathrm{i}(v-(g+\gamma)\,\phi_j)-p_j$.In Section 2.5, we will study how the two market failures interfere.

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$^{\mathrm{M}}$): $CS_{ij}^* \geq 0$. The resulting energy efficiency levels would be similar to those set by the social planner. Moreover, the prices of the durable goods would be set so as to extract all consumer surplus: $p_j = \beta_j(v-(g+\gamma)\phi_\mathrm{j})$.

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 set price and energy efficiency levels as above, then consumers *h* will purchase good *l*. By doing so, consumers *h* will enjoy a positive surplus $\mathrm{CS}_{\mathrm{hl}} * = (\beta_h-\beta_l)(v-(g+\gamma)\phi_l^*)$, instead of zero surplusby consuming good *h*.

2.4.3 Imperfectly discriminating monopolist

As demonstrated first byMussa and Rosen (1978), to prevent consumers *h* from purchasing good *l*, the imperfectly discriminating monopolist cuts the quality of good *l*. This diminishes the surplus from buying good *l* to consumers *h*, hence allows the monopolist to raise the price of good *h* to make consumers indifferent between buying either good. 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 an equilibrium requires the monopolist to endogenize Incentive Compatibility constraints (IC) in addition to IR to ensure that consumers self-select into the good they are targeted for. The monopolist maximizes profit subject to (superscript M denotes monopoly outcomes):

$$\mathrm{IR}_{\mathrm{l}}^{\mathrm{M}}\!:\beta_l(v-(g+\gamma)\phi_l) \geq \mathrm{p}_l$$

$$\mathrm{IR}_{\mathrm{h}}^{\mathrm{M}}\!: \beta_h(v-(g+\gamma)\phi_h) \geq \mathrm{p}_h$$

$$\mathrm{IC}_{\mathrm{l}}^{\mathrm{M}}\!: \beta_l(v-(g+\gamma)\phi_l) - \mathrm{p}_l \geq \beta_l(v-(g+\gamma)\phi_h) - \mathrm{p}_h$$

$$\mathrm{IC}_{\mathrm{h}}^{\mathrm{M}}\!: \beta_h(v-(g+\gamma)\phi_h) - \mathrm{p}_h \geq \beta_h(v-(g+\gamma)\phi_l) - \mathrm{p}_l$$

It can be shown that only IR_l and IC_h will bind. That is, consumer *l* is left with no surplus and consumer *h* is indifferent between purchasing either good (see Spurlock (2013) for a formal demonstration).

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:

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

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

$$\frac{\beta_l}{\beta_h} > \frac{\mathrm{n}_h}{\mathrm{n}_h + \mathrm{n}_l} = \mathrm{n}_h \tag{4}$$

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, 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 the low-end consumer:

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

In contrast, some surplus is left to the consumer h:

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

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

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

2.5 Monopoly with energy-use externalities

If, in addition to monopoly distortions, energy-use externalities are not internalized, a new equilibrium is reached. Equilibrium outcomes (denoted with superscript ME) can easily be visualized by setting γ=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 smaller impact if and only if:

$$\phi_l^M > \phi_l^E \Leftrightarrow \frac{\mathrm{\beta}_l}{\mathrm{\beta}_h} > \mathrm{n}_h\left(1+\frac{g\mathrm{n}_l}{\gamma+g\mathrm{n}_h}\right) \tag{5}$$

Since the discrimination problem has no impact on the level of good h, this condition is also a sufficient one for the discrimination problem to generate a smaller deadweight loss than the externality problem. Note that the right-hand side is greater than n_h. That is, Condition (5) is more restrictive than Condition (4) in that it requires less heterogeneity across consumers.

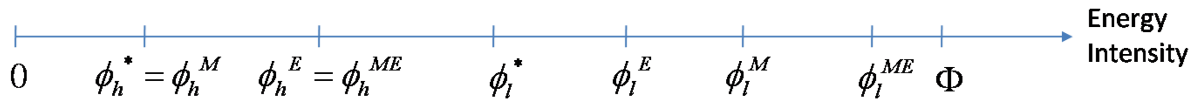

Figure 1: Illustrative quality levels under different market structures. Energy intensity increases rightward and energy efficiency increases leftward. Note that ϕ_l^E needs not be more energy-efficient than ϕ_l^M; this depends on Condition (5). Likewise, ϕ_h^{ME} needs not be more energy-efficient than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

3 First-best policies with two instruments

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 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 “pure instruments,” that is, policies with only one instrument variable. Such instruments include quality standards (e.g. minimum or average), energy taxes, or uniform energy efficiency subsidies. Perhaps the most intuitive intervention is to combine a minimum quality standard equal to ϕ_l^* (meant to address the discrimination problem) and an energy tax equal to γ (meant 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.[13]

In this section, we focus on two main types of subsidy design: per-quality and ad valorem. Throughout, we consider a partial equilibrium setting in which subsidies are funded by lump-sum taxes. We assume that the subsidies are received by the consumers, but the results would be the same if they were received by the firm.

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[13] Note that there could be other justifications for subsidy implementation than the two market failures considered here. Subsidies may for instance be warranted if the adoption of energy efficient technologies generates positive externalities.

3.1 Per-quality subsidies

The regulator can offer subsidy payments that depend on the energy efficiency level of the durable good purchased by the consumer.[14] 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 policy

Consumers are offered a payment $(z_i - \phi_i)\sigma_i$ for purchasing good i, with σ_i the per-quality subsidyrate. $z_i > \phi_i$ is an energy-intensity reference level, higher than the market equilibria, below which consumers receive the payment. It disappears in the first-order conditions so it does not change the product prices and efficiencies. The monopolist maximizes profit subject to (equilibrium outcomes are denoted with superscript PP):

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

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

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

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

With binding IR_l^{PP} and IC_h^{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 ($d\phi_i^{PP}/d\sigma_i = -1/c'' < 0$) and price ($dp_i^{PP}/d\sigma_i = g\beta_i > 0$) levels of the good they specifically target. While a subsidy on good *h* does not change the price of good *l* ($dp_l^{PP}/d\sigma_h = 0$), a subsidy on good *l* reduces the price of good *h*:

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

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[14] The closest practical experience we can think of is the feebate system currently implemented in the automobile sector in various countries (e.g. France, Canada, the Netherlands and Norway). The feebate system 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).

This is because with σ_l, the more efficient good *l* would provide consumer *h* with a higher surplus, would this consumer buy that good. The monopolist thus responds by lowering the price of *l* to keep consumer *h* indifferent between buying either good. In contrast, the provision of good *l* is not affected by σ_l, 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:

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

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

$$\forall \mathrm{i}\ \ -\mathrm{c}'\left(\phi_\mathrm{i}^\mathrm{PP}\right) = (\mathrm{g}+\gamma)\beta_\mathrm{i} \tag{9}$$

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:

$$\sigma_\mathrm{h}^\mathrm{PP} = \beta_\mathrm{h}\,\gamma$$

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

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

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 in each subsidy formula (zero for σ_h^PP and $\mathrm{g}(\beta_h - \beta_l)\,n_h/n_l$ in σ_l^{PP}) is the one needed to address the discrimination problem.

Which subsidy rate should be higher is not straightforward. It depends on:

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

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 $\gamma/\mathrm{g} \approx 0.1$. 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. In practice, the subsidy schedules tend to be increasing in energy efficiency (e.g. the French tax credit program until 2013).

3.2 Ad valorem subsidies

An alternative to relating subsidy rates to the quality of the durable goods is to link them to the price of the goods. Such a subsidization schedule prevails in many countries (e.g. the French tax credit program introduced above). For instance in Germany, the KFW subsidization program for residential building retrofitting offers a 10% price cut if the retrofitted building reaches 115% of the standard energy needs for new constructions, and a 25% price cut if it meets the Passivhaus standard (Rüdinger, 2013). Again, such an instrument is modeled here within a principal-agent framework.

3.2.1 Second stage: monopolist's response to the policy

We consider ad valorem subsidies of rate ϵ_i to good i. p_i denotes producer prices while $\mathrm{p}_i(1-\epsilon_i)$ denotes consumer prices. The monopolist maximizes profit subject to

$$\mathrm{IR_l}^{\mathrm{AA}}\!:\beta_l(v-g\phi_l) \geq \mathrm{p}_l(1-\epsilon_l)$$

$$\mathrm{IR_h}^{\mathrm{AA}}\!:\ \beta_h(v-g\phi_h) \geq \mathrm{p}_h(1-\epsilon_h)$$

$$\mathrm{IC_l}^{\mathrm{AA}}\!:\ \beta_l(v-g\phi_l)-\mathrm{p}_l(1-\epsilon_l) \geq \beta_l(v-g\phi_h)-\mathrm{p}_h(1-\epsilon_h)$$

$$\mathrm{IC_h}^{\mathrm{AA}}\!:\ \beta_h(v-g\phi_h)-\mathrm{p}_h(1-\epsilon_h) \geq \beta_h(v-g\phi_l)-\mathrm{p}_l(1-\epsilon_l)$$

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

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

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

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

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

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

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

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.

The effect of ad valorem subsidies on the prices of the durable goods is more subtle than that of per-quality subsidies. This is detailed in Appendix 1.

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:

$$\mathrm{n_h}\left[-(\mathrm{g}+\gamma)\beta_{\mathrm{h}} - \mathrm{c}'\left(\phi_{\mathrm{h}}^{\mathrm{AA}}\right)\right]\frac{\mathrm{d}\phi_{\mathrm{h}}^{\mathrm{AA}}}{\mathrm{d}\epsilon_{\mathrm{h}}} + \mathrm{n_l}\left[-(\mathrm{g}+\gamma)\beta_{\mathrm{l}} - \mathrm{c}'\left(\phi_{\mathrm{l}}^{\mathrm{AA}}\right)\right]\frac{\mathrm{d}\phi_{\mathrm{l}}^{\mathrm{AA}}}{\mathrm{d}\epsilon_{\mathrm{h}}} = 0 \tag{14}$$

$$\mathrm{n_l}\left[-(\mathrm{g}+\gamma)\beta_{\mathrm{l}} - \mathrm{c}'\left(\phi_{\mathrm{l}}^{\mathrm{AA}}\right)\right]\frac{\mathrm{d}\phi_{\mathrm{l}}^{\mathrm{AA}}}{\mathrm{d}\epsilon_{\mathrm{l}}} = 0 \tag{15}$$

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

$$-\mathrm{c}'\left(\phi_{\mathrm{l}}^{\mathrm{AA}}\right) = (\mathrm{g}+\gamma)\beta_{\mathrm{l}} \tag{16}$$

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 $d\phi_h^{\mathrm{AA}}/d\epsilon_h < 0$ implies that good h will also be set at its optimal level:

$$-\mathrm{c}'\left(\phi_{\mathrm{h}}^{\mathrm{AA}}\right) = (\mathrm{g}+\gamma)\beta_{\mathrm{h}} \tag{17}$$

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* ($\epsilon_h^{\mathrm{M}} = 0$) and equal to $\epsilon_l^{\mathrm{M}} = n_h(\beta_h - \beta_l)/[n_h(\beta_h - \beta_l) + n_l\beta_l]$ on good *l*. Reciprocally, if energy-use externalities were the only market failure to internalize, energy efficiency levels would be set so that equilibrium levels with the subsidy (defined by $-c' = \mathrm{g}\beta_{\mathrm{i}}/(1-\epsilon_{\mathrm{i}})$) match the socially optimal ones (defined by $-c' = (\mathrm{g}+\gamma)\beta_{\mathrm{i}}$). Hence, both goods would need to be subsidized at the same uniform rate$\epsilon = \gamma/[\gamma+g]$. With these definitions, $\epsilon_h^{\mathrm{AA}} = \epsilon^E + \epsilon_h^{\mathrm{M}}$ and:

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

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. Indeed, since the subsidy on good h deteriorates the efficiency of good l, the subsidy on good l needs to be higher.

A second difference between ad valorem subsidies and per-quality ones it that with the former, subsidy rates should always be larger on good than on good *h*: $\epsilon_h^{\mathrm{AA}} < \epsilon_l^{\mathrm{AA}}$. An intuition for this result is that 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. Yet the fact that subsidy *rates* should always be larger on good *l* does not mean that good *l* necessarily receives a larger *amount* of subsidies per unit sold, since it is cheaper than good *h* and subsidies are ad valorem. In other words, $p_h^{\mathrm{AA}}\epsilon_h^{\mathrm{AA}}$ may be higher or lower than $p_l^{\mathrm{AA}}\epsilon_l^{\mathrm{AA}}$.

4 Second-best policies with one instrument

In practice, the Tinbergen rule is rarely applied. 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 from industrial firms.

In this section, we therefore take a more positive view and examine how single instruments perform in the context of two market failures. In addition to classical minimum quality standards and energy tax, we examine several forms of single-instrument energy efficiency subsidies.

4.1 Minimum quality standard

This instrument is widely applied worldwide. 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. 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^S on good *i* 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:

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

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)?

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[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).

4.1.1 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:

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

4.1.2 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).

4.1.3 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^*.

4.2 Energy tax

This instrument is also widely applied. Most European countries, Japan and a few other countries have implemented 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.

4.2.1 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):

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

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

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

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

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

As discussed in Appendix 2, the tax has an ambiguous effect on product prices.

4.2.2 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:

$$\mathrm{n_h}\left[-(\mathrm{g}+\gamma)\beta_\mathrm{h} - \mathrm{c}'\left(\phi_\mathrm{h}^\mathrm{T}\right)\right]\frac{\mathrm{d}\phi_\mathrm{h}^\mathrm{T}}{\mathrm{dt}} + \mathrm{n_l}\left[-(\mathrm{g}+\gamma)\beta_\mathrm{l} - \mathrm{c}'\left(\phi_\mathrm{l}^\mathrm{T}\right)\right]\frac{\mathrm{d}\phi_\mathrm{l}^\mathrm{T}}{\mathrm{dt}} = 0$$

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:

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

Unless the two consumers are identical ($\beta_\mathrm{h} = \beta_\mathrm{l}$), the optimal tax rate is larger than γ. 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 differs from Lombardini-Riipinen (2005) who finds a second-best tax equal to the social valuation of the externality γ. Besides, both results differ from the classical one in the environmental economics literature that under full information, homogeneous goods and oligopolies with symmetric firms, the second-best tax should be smaller than the externality so as to balance the output contraction effect of the tax (Baumol 1988). However, such an effect could not occur in our model, which does not accommodate the extensive margin of investment.

4.3 Subsidies

Overall, six types of single-instrument subsidies can be thought of. Subsidy rates can target uniformly both goods or specifically 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 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.

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.

4.3.1 Uniform ad valorem subsidies

Such a policy is perhaps the most widespread. For instance in France, home energy retrofits benefit from a reduced VAT rate (5% against a normal rate of 20%), irrespective of the level of energy savings achieved.

The monopolist's response to a uniform ad valorem subsidy rate ϵ 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):

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

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

In the first stage of the game, by the same type of reasoning as for the tax, the regulator will set the subsidy at a larger rate than the one needed to specifically internalize energy-use externalities:

$$\epsilon = \frac{\gamma}{g+\gamma}\left(1 + \frac{g}{\gamma}\frac{n_h(\beta_h - \beta_l)\, d\phi_l^A/d\epsilon}{n_h\beta_h d\phi_h^A/d\epsilon + n_l\beta_l\, d\phi_l^A/d\epsilon}\right) > \frac{\gamma}{g+\gamma}$$

It can be shown that with a more restrictive quadratic cost assumption, both this subsidy and the energy tax lead to the same equilibrium outcome. Consumer *h*'s surplus and profits are then higher with this subsidy than with the energy tax.

4.3.2 Ad valorem subsidy on the high-end good

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* ($d\phi_l^H/d\epsilon_h > 0$, where superscript H denotes equilibrium outcomes). Therefore, here, in equilibrium the quality of good *h* will be below its socially optimal level ϕ_h^* and the quality of good *l* will be even below its laissez-faire level ϕ_l^{ME}.

With the same type of reasoning as with the tax, 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 $d\phi_i^H/d\epsilon_h$have opposite signs, the sign of this expression is ambiguous. If it is negative, a tax on good *h* would be preferred over a subsidy. 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:

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

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

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

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 very 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 so the last fraction drops from the inequality, which becomes:

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

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

4.3.3 Per-quality subsidy on the high-end good

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). In Appendix 3, we confine our attention to quadratic costs and further discuss the conditions under which one instrument dominates the other. Overall, this result contributes to the literature comparing ad valorem and per-quality instrument (Keen 1998).

4.3.4 Uniform per-quality subsidies

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 tax at the following level:

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

The payment to consumers is lower than the one that would be needed to address the two externalities ($\sigma_h^{PP} + \sigma_l^{PP}$).

5 Conclusions

Energy efficiency markets are commonly subject to both energy-use externalities and price-quality discrimination. How do energy efficiency policy instruments compare in such a market environment? To answer this question, we have examined a broad set of first-best and second-best policy interventions in a unified framework. We have paid particular attention to energy efficiency subsidies, an instrument frequently encountered in practice but, by contrast, little studied in the market environment considered here. We have built on the model of Fischer (2005), which features two types of consumers, a monopolist which can imperfectly price discriminate and two levels of energy efficiency which are positively correlated with quality.

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 efficient goods. 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. 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. This is at odds with actual practice in which differentiated subsidies tend to be ad valorem with increasing rates.

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 minimum quality standard may be set at the high-end of the product line if consumers are not too dissimilar. An energy tax on energy should be set above the marginal external cost of energy use. Similarly, 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: Effect of ad valorem subsidies on product prices

Equilibrium prices are:

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

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

Comparative statics of the price of good l is as follows:

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

$$\frac{dp_l^{AA}}{d\epsilon_h} = \frac{-g\beta_l}{1 - \epsilon_h}\frac{d\varphi_l^{AA}}{d\epsilon_h} < 0$$

Both subsidies have an opposite effect on the price of good l, which reflects their opposite effect on the quality of good l.

The price of good h increases with φ_h^{AA}:

$$\frac{dp_h^{AA}}{d\epsilon_h} = \frac{1}{1 - \epsilon_h}\left(p_h^{AA} - g\beta_h \frac{d\varphi_h^{AA}}{d\epsilon_h} + g(\beta_h + \beta_l)\frac{d\varphi_l^{AA}}{d\epsilon_h}\right) > 0$$

It is decreasing with φ_l^{AA}:

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

APPENDIX 2: Effect of an energy tax on product prices

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

$$\frac{dp_l^T}{dt} = -\beta_l\varphi_l^T(1+\mu_l) \text{ with } \mu_l = \frac{d\varphi_l^T}{dt}\frac{t}{\varphi_l^T}$$

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 $d\varphi_l^T/dt$ is negative, hence so is μ_l. Therefore, $d\varphi_l^T/dt$ is negative if there is a "normal" rebound effect and positive if there is no rebound effect ($\mu_l \leq -1$).

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

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

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

$$\frac{dp_h^T}{dt} = -(\beta_h - \beta_l)\varphi_l^T(1+\mu_l) - \beta_h\varphi_h^T(1+\mu_h)$$

APPENDIX 3: Ad valorem versus per-quality high-end subsidy with quadratic cost

Here we assume that:

$$c(\phi_j) = \frac{(\Phi - \phi_j)^2}{2}$$

The value of the externality above which the ad valorem incentive on good h would be a subsidy is noted $\gamma 1$:

$$\gamma 1 \equiv g \frac{n_h(\beta_h - \beta_l)^2}{n_l(\beta_h^2 - \beta_h\beta_l + \beta_l^2)}$$

Recall that the per-quality subsidy on good h improves the efficiency of good h without changing that of good l. A natural question is how this kind of subsidy, independent from the price of the subsidized good, compares to the ad valorem subsidy when both subsidy rates are set at their optimal level. This question is related to the debate between specific and ad valorem taxes which has generated numerous contributions (see Keen (1998) for a review).

In our model, the optimal per-quality subsidy rate is simply $\gamma\beta_h$. The difference between the ad valorem and the per-quality subsidy on good h can be written as a two degrees polynomial of γ:

$$\begin{aligned}\Delta_{AH-SH} = {} & \frac{g^2 n_h^3(\beta_h - \beta_l)^4}{2n_l(n_l\beta_h^2 + n_h(\beta_h - \beta_l)^2)} - \gamma \frac{g n_h^2(\beta_h - \beta_l)^2(\beta_h^2 - \beta_h\beta_l + \beta_l^2)}{n_l\beta_h^2 + n_h(\beta_h - \beta_l)^2} \\ & - \gamma^2 \frac{n_h(\beta_h - \beta_l)(n_h\beta_h^2(\beta_h - \beta_l) + n_l\beta_l(2\beta_h^2 - \beta_h\beta_l + \beta_l^2))}{2(n_l\beta_h^2 + n_h(\beta_h - \beta_l)^2)}\end{aligned}$$

Without externality ($\gamma = 0$), Δ_{AH-SH} is positive, but it decreases with γ. The positive root of this polynomial, above whichΔ_{AH-SH} is negative i.e. the per-quality subsidy performs better, is:

$$\gamma 2 = \frac{g^2 n_h^2(\beta_h - \beta_l)^3}{\sqrt{g^2 n_h^2 n_l \beta_h^2(n_l\beta_h^2 + n_h(\beta_h - \beta_l)^2)(\beta_h - \beta_l)^2} + g n_h n_l(\beta_h - \beta_l)(\beta_h^2 - \beta_h\beta_l + \beta_l^2)}$$

It can be shown that $\gamma 1 > \gamma 2$, so if γ is high enough for $\epsilon_h^{\mathrm{AH}} > 0$ i.e. it is a subsidy, then this subsidy is always dominated, in welfare terms, by a per-quality subsidy.

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