Environmental taxes, consumer awareness and the relative efficiency of the output vs emissions tax base

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Abstract

In this work, we employ the model in Martis (2022) (Model B), and we compare their results to those of Constantatos et al. (2021) (Model A) in order to see whether committing to a tax rate or not yields better environmental conditions and social welfare. We find that under both models, the abatement has the same path, however, in Model B the abatement under both taxes lies higher than that of Model B, due to tax manipulation efforts. Consequently, output tax net emissions lie lower that all other tax plans under both committed and time consistent regulator, and quickly becomes zero. This is not true in the case of the emissions tax, where the time-consistent regulator generates higher abatement but also higher quantity than the committed one. Therefore, net emissions in the case of the time-consistent regulator lies higher from both committed regulator net emissions and the first-best case. Finally, due to over-abatement, the output-tax social welfare in Model B monotonically decreases, however, it lies higher than that of Model A for low levels of ϕ. In the case of emissions tax, social welfare generated by the committed regulator lies lower than the one generated by the time-consistent one. As for the robustness of the model, k raises some robustness issues. The most interesting one is that of the social welfare function. For low levels of ϕ, the social welfare function becomes positive-sloped due to cost rationalization reaches first-best and after that it decreases.

Keywords: Commitment, Green consumers, Output tax, Emissions tax, Monopoly, Social Responsibility.

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1 Introduction

Consumers' awareness over environmental issues has been substantially raised over the past few decades, causing firms to modify their behavior in order to have better performance towards the environment and therefore have increased demand. However, this incentive may not suffice and therefore, government intervention is needed. In this work, two types of taxes are used, an emissions tax and an output tax. We employ the results of Constantatos et al. (2021) (hereafter CPS) and Martis (2022) and compare them in order to see the relative efficiency of the two tax bases under a time-consistent and a committed regulator. The comparison between these two types of the regulator, has been analyzed in the literature in extend (see Literature Review).

The comparison between output and emissions taxes with endogenous abatement decisions has also been object of CPS. While analysis in Martis (2022) follows closely the modeling principles of that paper, the results when altering the order of the game are substantially different. In CPS, the regulator decides at the first stage not only the tax type but also the tax rate. Consequently, the monopolist takes the tax-rate as given and adjusts its decisions accordingly, whereas in Martis (2022) work part of the abatement decisions aims at manipulating the ensuing tax-rate decision. The two games can be interpreted as an Stackelberg game, in which the player who does the first move is way off her reaction function. We refer to the two-stage game in CPS as model A and to Martis (2022) model as model B. Several interesting observations follow from comparing the two formulations. When the monopolist plays first, she promises better performance, gets lower tax and sells more, only to generate higher net emissions! However, model B still prevails to model A in terms of social welfare. Under the output tax regime, once again when the monopolist plays first, the abatement level is very high which leads to a much lower tax and an exponential-like increase in quantity. The better performance yields better environmental conditions. Nevertheless, model B is better than model A in terms of social welfare only if the environmental consciousness of the consumers stays at low levels, otherwise model A dominates.

After completing the comparison between the time-consistent and the committed regulator, we examine the robustness of the time-consistent model (presented in Martis (2022)). The cost parameter raises robustness issues and therefore, we attempt to track the changes that arise in our variables of interest due to changes in that parameter. When the latter increases, the level of abatement in the case of the output tax for every level of ϕ decreases, without changes in the slope. As a result, for low levels of awareness, it lies below the emissions-tax abatement level. Consequently, the output-tax rate increases and thus for low levels of environmental consciousness it is above the emissions-tax rate, while both keep their slope. The output-tax quantity has similar behavior to the abatement level which yields higher net emissions than both the first-best and the emissions-tax net emissions. Finally, there is a change in the behavior of the social welfare in case of an output tax, which initially increases, reaches a maximum value and after that point decreases. For increases of k, the analysis was focused on the output-tax policy rather than the emissions tax, because there is not a significant change in the conclusions derived from the emissions-tax policy functions. In other words, the results derived in the case of the emissions tax are robust.

The rest of the work is as follows: Section 2 contains the Literature Review, in Section 3 we present the model, as well as the equilibrium values from Martis (2022) and the first-best expressions, in Section 4 we compare the CPS model with the one presented in Martis (2022), in Section 5 we present the robustness of the model and in Section 6 we conclude.

2 Literature Review

The existence of negative externalities[1] leads to the Pigouvian tax which may be either on output or emissions, when assuming that those taxes are equivalent. The latter is based on the assumption that the firm cannot engage in abatement, i.e., the amount of emission produced per unit of output is immutable. Therefore, by letting the firm do abatement, the equivalence of output and emission taxes breaks up. There is an extensive literature examining the optimal choice of environmental tax instrument under different settings. Schmutzler & Goulder (1997) compare two types of taxes, an emissions and an output tax, under a partial equilibrium framework and in the presence of imperfect monitoring of emissions, whereas in Fullerton et al. (2001) and Cremer & Gahvari (2001) general equilibrium is used. Aoyama & Delfino Silva (2016) compare the output and emission tax in terms of effectiveness in promoting the adoption of advanced abatement technology without considering environmentally conscious consumers. Closest to this work, Constantatos et al. (2021) compare the two tax bases in terms of welfare when consumers are environmentally aware, yet they only examine the case where the social planner commits to a tax rate.

Green consumerism changes the traditional environmental taxation patterns and therefore raises questions about their appropriate adjustments and furthermore initiates a discussion regarding the effectiveness of information campaigns and advertising, aiming to increase environmental awareness, as an additional policy instrument (see for example Petrakis et al. (2005), Nyborg et al. (2006), Brouhle & Khanna (2007) and Sartzetakis et al. (2012)). The literature has approached the emergence of green consumers using different frameworks. In most of the models there is the assumption that green consumers differentiate products according to their environmental attributes motivating firms to produce a "greener" type of the product. This has been examined mainly under the framework of vertical differentiation (Bansal & Gangopadhyay (2003), García-Gallego & Georgantzís (2009), Bansal (2008), Deltas et al. (2013) and Doni & Ricchiuti (2013)), and less within a framework of horizontal differentiation (Conrad (2005)). Alternatively, Gil-Moltó & Varvarigos (2013) examine the case in which environmental consciousness leads consumers to devote resources to

[1]"When the actions of one agent directly affect the environment of another agent, we will say that there is externality. In a consumption externality the utility of one consumer is directly affected by the actions of another consumer. [...]. In a production externality the production set of one firm is directly affected by the actions of another agent"(Varian (1992)). There are two types of externalities, the positive and negative ones. The latter describes a situation in which an action of an agent has negative consequences in a society, for example the environmental pollution. On the other hand, positive externality is the case where an agent's actions benefit others in a society (for example education)

reduce pollution (participation in carbon offsetting schemes, donations to NGOs, etc).

Analyses for the regulator's ability to commit can be found, among others, in J. Poyago-Theotoky & Teerasuwannajak (2002), Requate (2005), and J. A. Poyago-Theotoky (2007). The first paper examines the impact of taxation on product differentiation while the remaining two deal with the impact that the taxation has on the environmental R&D in presence of R&D spillovers.

3 The Model, First Best case and Equilibrium values

Following the model of Constantatos et al. (2021), assume a monopolistic firm which produces Q units of a good X. The marginal cost of the production is assumed to be constant and equal to zero. The production process causes emissions which the firm wants to reduce. In order to do so, it uses end-of-pipe abating technology. In this case, the main importance in given to the fixed costs and therefore the cost function is:

$$C = kv^2, \quad k \geq 1 \tag{1}$$

where v is the level of abatement and k shows the degree of convexity of the cost function. We set $k = 1$ in order to simplify our calculations. When the firm invests in abatement, it generates the following net emissions:

$$e = \delta Q - v, \quad \delta > 0, \tag{2}$$

where δ is the units of harmful pollutant that the productions process releases to the environment. The abatement is restricted to the $[0,\ \delta Q]$ interval in order to ensure non-negative net emissions. The resulting environmental damage is:

$$D = ze^2, \quad z > 1, \tag{3}$$

where z indicates the transformation of net emissions into environmental damage. From the consumption side, assume that there are $n \geq 1$ consumers with individual utility:

$$U = aq - \frac{1}{2}q^2 + M, \;\; \alpha > 0, \tag{4}$$

where $q \geq 0$ shows the individual consumption of the product and M is the numéraire good. We assume that M is sufficiently large as to exclude corner solutions. In this work, we allow the consumers not only to care about their consumption, as in (4) but to also detest emissions. Consumers in this case *act consciously* and voluntarily decrease their consumption. Therefore, the utility of the conscious consumers:

$$\tilde{U}(q;\phi) = \begin{cases} (\alpha - \phi e)q - \frac{1}{2}q^2, & e > 0 \\ U(q), & e \leq 0 \end{cases} \tag{5}$$

This utility function designates the Social Responsibility approach, in the sense that the consumers do not devalue their consumption, rather that they voluntarily decrease their quantity consumed. In fact, they maximize (5) but value their consumption according to (4). We assume that $\phi \leq z$ in order to avoid over-internalization of the externality. When $\phi = 0$, the consumers do not care about the environment and therefore they maximize (4). As ϕ becomes positive the consumer internalizes part of the externality caused by emissions and behaves according to (5). By taking the derivative of (5) with respect to q, substitute (2) and multiply by n, we take the total demand function:

$$Q(p; n, \delta, \phi, v) = \frac{n(\alpha + \phi v)}{\phi n \delta + 1} - \frac{n}{\phi n \delta + 1} p$$

In this work, we assume a representative consumer ($n = 1$) and for simplicity we set $\delta = \alpha = 1$. Setting $\alpha = 1$ is a mere normalization in the sense that it does not alter the results. The resulting demand function is:

$$p(q; n, \delta, \phi, v) = \begin{cases} (\alpha + \phi v) - (1 + \phi)q, & \text{if } q > v \\ \\ \alpha - q & otherwise \end{cases}, \tag{6}$$

As a last ingredient to the analysis, we introduce the social welfare function:

$$W = \sum_{i=1}^{n} u_i - (D + C) \tag{7}$$

This function is consisted of the sum of n individual utilities, minus the social cost, i.e., the environmental damage and the cost of abatement. While it is obvious that we will substitute the cost of abatement and the damage function with (1) and (3) respectively, the individual utility will be substituted by that dictated in (4). By doing this, we show that the social welfare does not include the environmental consciousness due to the fact that the regulator does not take into consideration any voluntary decrease in consumption by the consumers. In other words, there is no *double accounting* in the sense that no psychological damage is taken into consideration due to environmental degradation. By substituting (1), (3) and (4) into (7), we obtain the social welfare function as a function of q and v:

$$W = q - \frac{1}{2}q^2 - z(q - v) - v^2$$

We assume that $z \leq \alpha (= 1)$ in order to ensure that the environmental damage is at least of equal importance as consumption. In what follows, we use the first-best values and the equilibrium values of $v_i,\ t_i,\ q_i,\ ne_i,\ sw_i,\ i = O,\ E$, as presented in Martis (2022). In all of the expressions, we use the simplifying assumptions of $k = \delta = n = \alpha = 1$.

The expressions for the first-best case are shown below:

$$\begin{aligned} v^* &= \frac{z}{3z + 1} \\ q^* &= \frac{z + 1}{3z + 1} \\ ne^* &= \frac{1}{3z + 1} \\ sw^* &= \frac{z + 1}{6z + 2} \end{aligned} \tag{8}$$

Even though we compare the results of Model A and Model B, here we are going to present only the expressions of Model B, since later on we check for robustness issues in Model B. Therefore, the expressions for abatement are:

$$\begin{aligned} v_O &= -\frac{2z(\phi+1)}{4z(z\phi-1)-1} \\ v_E &= \frac{4z(z+1)-2\phi-1}{16z(z+1)-2\phi+2} \end{aligned} \tag{9}$$

The v_O expression is positive for values of $z > 2$ and for $0 \leq \phi \leq \dfrac{1+4z}{4z^2}$, while v_E is always positive. As shown in Martis (2022), the output-tax abatement is an increasing function of ϕ, while emissions-tax abatement decreases as the environmental consciousness increases. The tax expressions are:

$$\begin{aligned} t_O &= \frac{2\phi\left(2z^2-z\phi+z+1\right)+1}{4z(z\phi-1)-1} \\ t_E &= \frac{-4z(z+4)\phi+4z(2z-1)+2\phi^2-3\phi-2}{16z(z+1)-2\phi+2} \end{aligned} \tag{10}$$

These expressions are decreasing in ϕ with the former being always negative (a subsidy) while the latter has to remain non-negative, since we require that the emissions tax must not be negative. The expressions for the quantity are given below:

$$\begin{aligned} q_O &= \frac{2z+1}{-4z^2\phi+4z+1} \\ q_E &= 1-\frac{3z(2z+1)}{8z(z+1)-\phi+1} \end{aligned} \tag{11}$$

The expressions above follow the same path as the abatement, i.e., q_O increases in ϕ while q_E decreases. The positivity constraint remains the same for q_O as it is for v_O. Below, we present the equilibrium expressions for net emissions:

$$\begin{aligned} ne_O &= \frac{1-2z\phi}{-4z^2\phi+4z+1} \\ ne_E &= \frac{6z+3}{16z(z+1)-2\phi+2} \end{aligned} \tag{12}$$

Output-tax net emissions remain positive for $0 \leq \phi \leq \dfrac{4z+1}{4z^2}$, $z > 2$ while emissions-tax net emissions are always positive. Here, we have a difference in the behavior of the functions as well. Since v_O increases in ϕ, net emissions sharply decreases, while v_E mildly increases. Finally, the social welfare functions are:

$$\begin{aligned} sw_O &= \frac{2z(-4(z+1)z\phi(\phi+2)+2z+3)+1}{2\left(-4z^2\phi+4z+1\right)^2} \\ sw_E &= \frac{z\left(2z\left(20z^2+58z+49\right)+31\right)-16z(z+1)\phi-2\phi^2-8\phi+1}{4(-8z(z+1)+\phi-1)^2} \end{aligned} \tag{13}$$

Since it is not easy to see the behavior of the functions, we use the results of Martis (2022). Both social welfare functions decrease, however, the output-tax social welfare drops sharply and becomes equal to zero very quickly. The emissions-tax social welfare, even though it decreases, it remains very close to the first-best case.

4 The Order of Moves

In this section, we are going to compare the results of Martis (2022) to those of Constantatos et al. (2021). CPS performs an exercise similar to that of the present work with as only difference the order of moves. Instead of a three-stage game, there is a two-stage game, where the regulator plays in the first stage by choosing the optimal output/emissions tax rate, followed by the monopolist who chooses the optimal abatement and quantity levels simultaneously in the second stage[2]. Hereafter, we are going to refer to the CPS model as Model A, while the model in Martis (2022) is going to be named as Model B. In the rest of the section, we are going to compare our variables of interest between the two models in order to examine the potential difference that exists between them.

4.1 Abatement

Hereafter, a subscript will be added to the usual notation in order to indicate the model to which the equilibrium variable belongs. For instance, v_{OB} and v_{EB} indicate equilibrium values in Model B, while v_{OA} and v_{EA} denote equilibrium abatement in the CPS model (model A) in the case of output and emissions tax, respectively. The first-best abatement level, v^* remains the same both in Models A and B. The gray and black dashed lines depict the limitations to the admissible interval of values. Concerning graphical illustrations, in all Figures the blue and red colors are used for equilibrium variables in Model A under output and emissions tax, respectively; as before, cyan and magenta illustrate equilibrium values under output and emissions tax in Model B. Starting with abatement, Figure 1 illustrates the abatement in the two models under both tax plans.

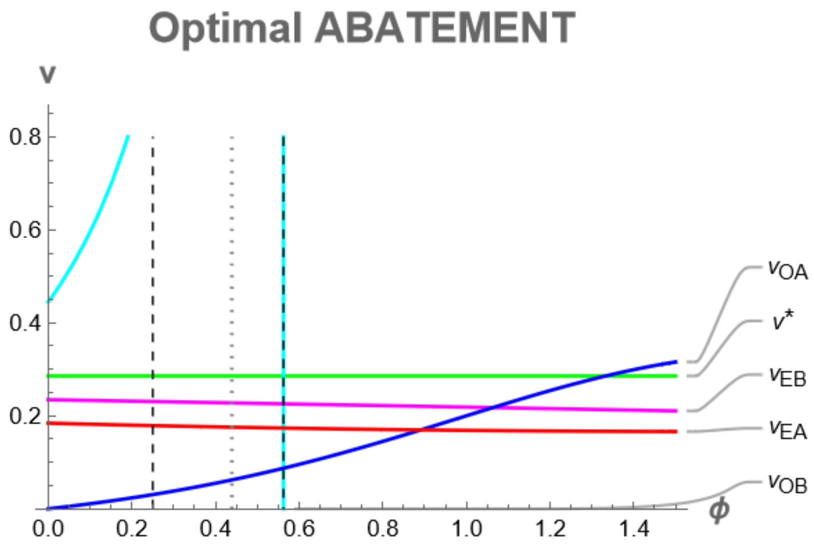


Figure 1: ABATEMENT COMPARISON

The figure illustrates with cyan (blue) the output-tax abatement in Model B (Model A), where as with magenta (red) the emissions-tax abatement in Model B (Model A). The black dashed line represents the critical level of ϕ (ϕ_e) under which output-tax net emissions are positive, whereas the gray-dotted line shows the critical level

[2]See Constantatos et al. (2021) for their results

of ϕ (ϕ_t) under which the emissions-tax rate remains non-negative. We see that for $\phi \in [0, \phi_e]$, both v_{OB} and v_{OA} increase with respect to ϕ, but at markedly different rates: when the monopolist can choose abatement before the regulator chooses the output tax rate, the abatement level is extremely sensitive to increases in consumers' consciousness whereas for given output-tax rates the monopolist responds positively but very mildly to such increases. Given also the fact that for $\phi = 0$, $v_{OB} > v_{OA}$, we conclude that for every admissible values of the firms engages in much higher abatement when it acts in anticipation of the tax rate.
Abatement under emissions tax is also higher in model B, but the difference is now less pronounced. As in both cases, the abatement under an emissions tax is a declining function of ϕ, as increases the importance of the order of moves in equilibrium abatement value under an emissions tax vanishes.

4.2 Tax Rates

Figure 2 illustrates the difference in tax/subsidy rates between the two models. As in the previous figure, output and emissions tax rates of model A are named as t_{OA} and t_{EA} respectively. The optimal output and emissions tax rates of model B follow the same rule and therefore are named as t_{OB} and t_{OA}.

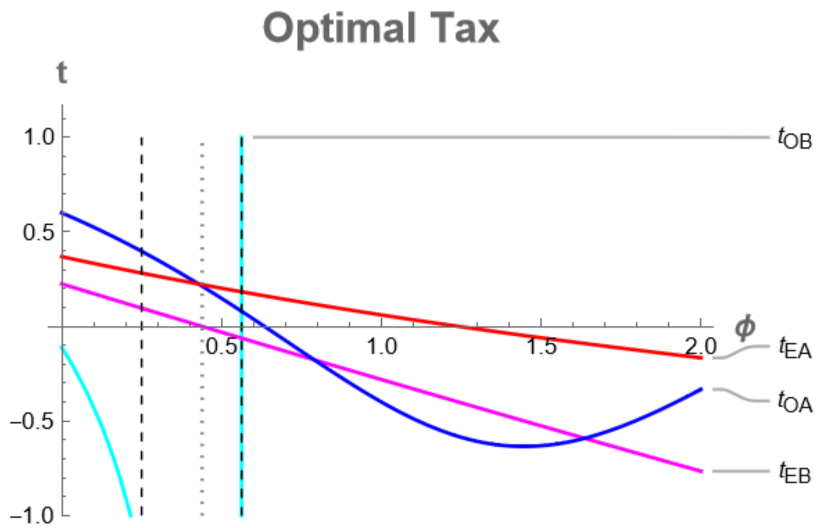


Figure 2: Tax Rate Comparison

In order to avoid any misunderstanding, the vertical cyan line is a vertical asymptote which is out of the bound determined by the black dotted line and therefore it is not to be considered. When the regulator plays first (model A), the optimal output tax is not always a subsidy. Low levels of environmental consciousness induce the regulator to punish the monopolist for her low abatement performance (see Figure 1). Anticipating the regulator's incentive the monopolist in model B starts with relatively high levels of abatement even when $\phi = 0$. When the monopolist has the first move, her already chosen high abatement level is rewarded by a subsidy. Thus, while in model A at low levels of output tax can be positive, this is not the case in model B.

Some kind of tax manipulation happens in case of the emissions tax as well. In both models the tax decreases with respect to the environmental consciousness. The abatement level in model A lies lower than that of model B, due to the fact that in the former, the tax rate has already been set. Therefore, by knowing the optimal tax rate, the monopolist behaves accordingly. From the regulator's point of view, when she plays in the first stage, she sets the tax rate in such a level, in order to prevent any quality under-provision. In model B though, since the monopolist plays in the first stage, she predicts the optimal tax rate, and therefore she has to increase the optimal abatement level in order to get lower tax. Thus, the analysis above leads us to the conclusion that the tax in model A is greater than the tax in model B.

4.3 Quantity

Figure 3 illustrates the gap that exists between the quantity produced in model A and in model B. Since the change in the order of moves creates quality differences of the product, we are actually talking about two separate products. Therefore, another way to describe the content of the plot below is that it shows the differences in consumers' preferences according to how much cleaner the good is. The colors of the functions are the same as it was in the previous plots.

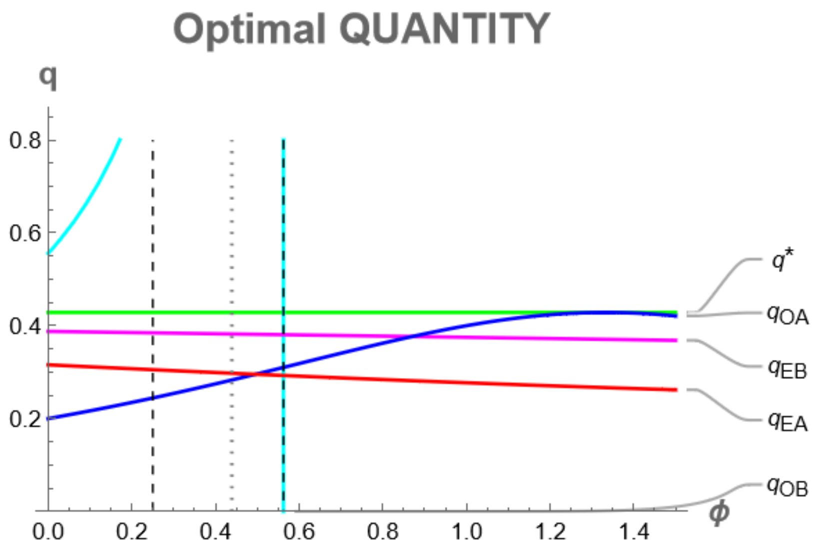


Figure 3: Quantity Comparison

Let us begin the analysis of the plot from the quantities under the output tax regime (blue and cyan curves). Both quantities increase with respect to the environmental consciousness, due to increasing abatement level at initial levels of ϕ. However, q_{OB} is greater than q_{OA}. This happens because in model B, the monopolist uses a higher than needed, in terms of cost, abatement level, making the regulator to apply a subsidy in order to give a reward to the monopolist. The latter gives the incentive to the monopolist to increase the abatement level as well as the quantity produced. From the demand side, the consumers, as they become more environmentally conscious and by observing the raised abatement level of the firm, want to consume more of the product. Similarly, in model A, the regulator, at initial levels of sets a tax, in order to make the monopolist to do abatement. As the environmental consciousness increases, the regulator lowers the tax and the abatement level of the firm raises. However, the abatement level of model A is lower than that of model B, meaning that there is a quality difference of the product, thus separating the one good into two, according to their quality attributes. The consumers will choose to consume more of the cleaner good, which derives from model B, and at a faster rate, making the firm to produce more of that product. Nevertheless, since the abatement level increases and the tax decreases in model A, the producer will agree to produce more and the consumers will purchase more of the product, just at a smaller rate.

The analysis in case of an emissions tax is almost the same. In this case, in model B, the monopolist reduces the abatement level as the environmental consciousness increases. As a result the regulator imposes a tax to the monopolist, which decreases with respect to ϕ, predicting that the consumers will "punish" the firm by purchasing less of the good. However, when the regulator plays first, the abatement level lies lower than that of model B, meaning that the tax will be greater and the quantity produced will be less than the respective variables of model B.

4.4 Net Emissions

The environmental consciousness of the consumers, the choices of the monopolist as well as the order with which the players do their move, as it is obvious, have an impact on the net emissions. Figure 4 displays the equilibrium environmental condition in all examined situations.

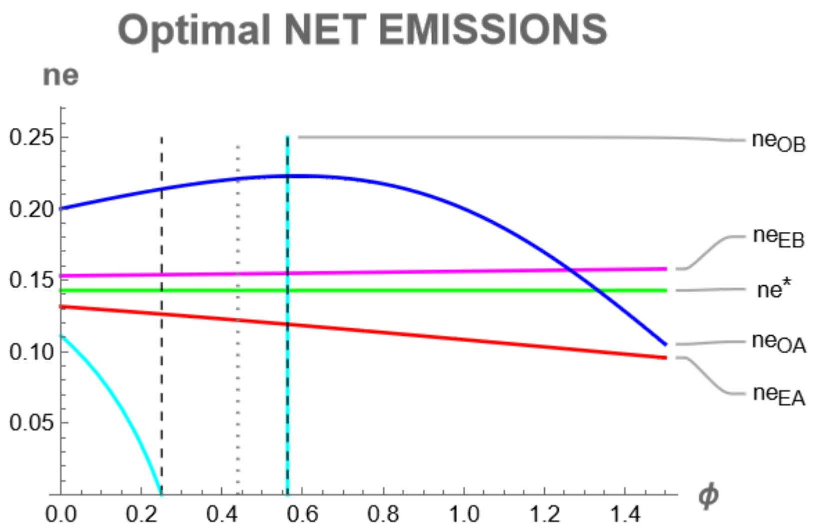


Figure 4: Net Emissions Comparison

Despite yielding higher equilibrium quantity, an output tax in model B produces the best environmental condition compared to all other situations, including first-best. However, by observing the plot and the analysis made by Constantatos et al. (2021), in the case of the output tax, net emissions are over the first-best level and increase at initial levels of ϕ. Only after the consumers develop a significant "amount" of environmental consciousness net emissions start to drop. Thus, net emissions generated in model B are less than net emissions of model A. In other words, in terms of environmental condition, model B is superior to model A, when the regulator sets an output tax. The main result here is that when the monopolist plays first, the credible promise of a better performance combined with a subsidy given by the regulator create better environmental conditions.

In case of the emissions tax, there is a rather interesting result. We can see that

ne_{EB} lies higher than both the first-best net emissions and ne_{EA}. Net emissions of model B tend to increase as the consumers become more environmentally aware. In model A, however, net emissions have a negative slope meaning that the environment becomes clearer when the consumers understand and internalize more of the externality. It is worth mentioning that, while in model A net emissions are already lower than the first-best outcome and diverge from the latter as ϕ increases, in model B net emissions are higher than the first-best and keep increasing with respect to ϕ. Therefore, ne_{EA} are less than ne_{EB}. This is a rather interesting result since it shows that the monopolist's leadership leads to some sort of greenwashing: By credibly promising better performance, the monopolist tries to manipulate the regulator in order to avoid higher tax levels.

4.5 Social Welfare

In this part of the current section, we are going to compare the optimal social welfare in both models. Figure 5 shows the difference in the optimal social welfare under the two policies in both models.

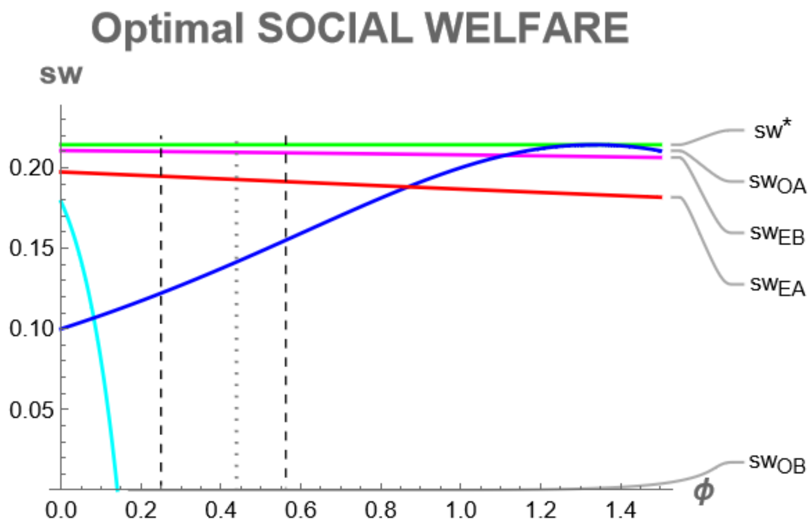


Figure 5: Social Welfare Comparison

Once again, let us begin our analysis by discussing the optimal social welfare of both models under the assumption of a tax on output. In model B, despite the sharp increases in both consumption and the environmental condition, the optimal social welfare decreases with ϕ and sharply so. On the contrary, when the regulator makes his decision without taking the abatement as given, the output-tax complements harmoniously increases in social consciousness[3]. However, in a society with low levels of social consciousness, the monopolist anticipating the tax rate may yield higher welfare. This is so because at low levels of social consciousness the abatement incentive of the monopolist coming from her desire to increase her product's demand is weak. Contrary to model A (CPS) where this is only incentive for abatement, in model B (Martis (2022)) the monopolist has a second incentive, namely to affect the tax/ subsidy rate. This additional incentive makes the output tax much more effective when it is mostly needed, i.e., in situations where ϕ is low. As ϕ rises, the tax-manipulations

[3]The point where touches is out of the allowed bounds of ϕ

incentive becomes a curse for social welfare. Thus, in a society where the consumers do not care as much for the environment and the regulator uses output taxes, it is better if the regulator let the monopolist adopt her abatement under the warning of a potential high tax rate (or low subsidy) for insufficient abatement choices.

In case of an emissions tax, both optimal social welfare functions have a negative slope, meaning that when consumer become more aware of the potential environmental hazards of the product, welfare drops. However, model B is very close to the first-best outcome, especially in our interval of interest. The above statement means that when an emissions tax is imposed, model B is always socially preferable than model A. The basic conclusion of the analysis above, is that we are dealing with a Stackelberg leadership changing hands from the regulator to the monopolist. Either way, the player who does the first move is well off her reaction function.

5 Robustness

In this part of the thesis, we are going to examine the robustness of Model B by changing the simplifying assumptions of the parameters $n,\ \delta,\ k,\ \alpha$. Initially, we have set those parameters equal to one, i.e., $n = \delta = k = \alpha = 1$. Those assumptions were made in order to simplify our calculations and to extract useful conclusions in the simplest possible way, as well as to enhance comparability with CPS, where the same assumptions are made.
To begin with the analysis, first we show the initial first-best abatement level, quantity, net emissions and social welfare:

$$v_R^* = \frac{\delta n z}{2\delta^2 knz + k + z},$$
$$q_R^* = \frac{n(k+z)}{2\delta^2 knz + k + z},$$
$$ne_R^* = \frac{\delta k n}{2\delta^2 knz + k + z},$$
$$sw_R^* = \frac{n(k+z)}{2\left(2\delta^2 knz + k + z\right)}$$

The subscript R denotes the robustness chapter. When we use the initial assumptions made, i.e., $n = \delta = k = \alpha = 1$, (9), (10), (11), (12) and (13) arise. The general expression of the abatement, tax, quantity, net emissions functions in equilibrium are the following:
Abatement:

$$v_{OB} = \frac{2\delta nz(\delta n\phi + 1)}{k\left(2\delta^2 nz + 1\right)^2 - 4\delta^2 nz^2(\delta n\phi + 1)}$$

$$v_{EB} = \frac{2\delta n\left(2\delta z\left(\delta^2 nz + 1\right) - \phi\right) - 1}{2\delta k\left(2\delta^2 nz + 1\right)^2 + 8\delta z\left(\delta^2 nz + 1\right) - 2\phi}$$

Tax:

$$t_{OB} = \frac{k\left(2\delta^2 nz+1\right)\left(2\delta n(\delta z-\phi)-1\right)-2\delta nz(\delta n\phi+1)(2\delta z-\phi)}{k\left(2\delta^2 nz+1\right)^2-4\delta^2 nz^2(\delta n\phi+1)},$$

$$t_{EB} = \frac{2\delta\left(4\delta^4 kn^2z^2-2\delta n\phi\left(\delta^2 nz(2k+z)+k+2z\right)-k+n\phi^2-2z\right)+\phi}{2\delta\left(\delta k\left(2\delta^2 nz+1\right)^2+4\delta z\left(\delta^2 nz+1\right)-\phi\right)}$$

Quantity:

$$q_{OB} = \frac{n\left(2\delta^2 knz+k\right)}{k\left(2\delta^2 nz+1\right)^2-4\delta^2 nz^2(\delta n\phi+1)}$$

$$q_{EB} = \frac{n\left(\delta\left(2\delta^2 nz(k+z)+k+3z\right)-\phi\right)}{\delta k\left(2\delta^2 nz+1\right)^2+4\delta z\left(\delta^2 nz+1\right)-\phi}$$

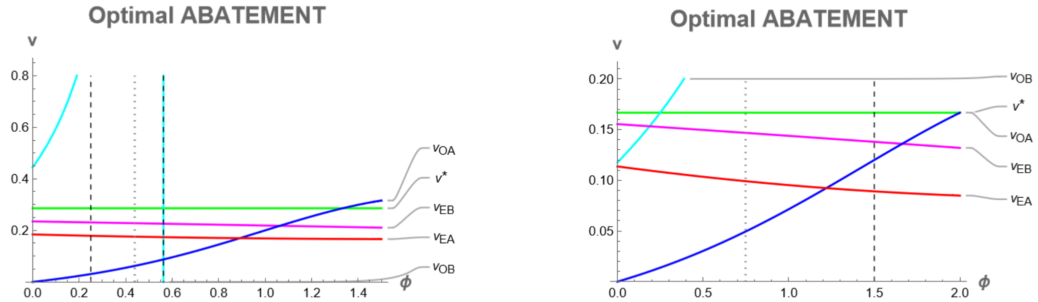
Net Emissions:

$$ne_{OB} = \frac{\delta n\left(2\delta^2 knz+k-2(\delta nz\phi+z)\right)}{k\left(2\delta^2 nz+1\right)^2-4\delta^2 nz^2(\delta n\phi+1)}$$

$$ne_{EB} = \frac{\left(2\delta^2 kn+1\right)\left(2\delta^2 nz+1\right)}{2\delta k\left(2\delta^2 nz+1\right)^2+8\delta z\left(\delta^2 nz+1\right)-2\phi}$$

Due to increased complexity, no social-welfare expression is presented here (they can be found in the Appendix). Furthermore, as in Constantatos et al. (2021), $\alpha = 1$ is a mere normalization since changes in do not change significantly the results in Model B. Therefore, for the rest of the section, we set it equal to one. The other parameters have a much more important role in the examination of the robustness of Model B. By relaxing the initial assumptions on basic parameters and analyzing the results one can show that only the assumptions on δ and k can raise robustness issues. The n parameter, which represents the number of identical consumers in the market, changes the order of the variables in the equilibrium. For example, when we increase n, for relatively low levels of ϕ, the optimal abatement level in case of an emissions tax is greater than the optimal abatement level in case of an output tax. This is due to the fact that any change in the number of consumers do not affect the cost of abatement. Since the consumers care less for the environment, the monopolist prefers to keep the equilibrium output-tax abatement in low levels in order to reduce the cost. As a result, the regulator imposes a higher commodity tax rate, such that for low levels of ϕ, the tax rate is positive. Consequently, the quantity produced is reduced. Nevertheless, the output-tax abatement level, tax rate and quantity produced keep their slope shown in the proposition in the rest of the paper. As a result, the equilibrium output-tax net emissions are greater than the equilibrium emissions-tax net emissions and the first-best outcome. The cost rationalization caused by the increment of the parameter makes the equilibrium social welfare to increase up to a point. However, the increased net emissions and the reduced utility function make the social welfare to lie at a lower level than sw_O. We mainly focus on the robustness issues generated by k. Figure 13 shows all our variables of interest. The left side illustrates our variables when $k = 2$ and right side when $k = 1$.

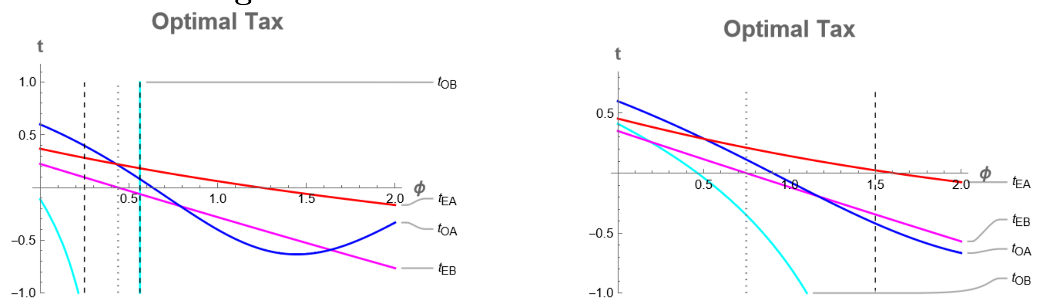
Figure 6: Abatement with $k = 1$ and $k = 2$



Panel A:
Abatement with $k = 1$

Panel B:
Abatement with $k = 2$

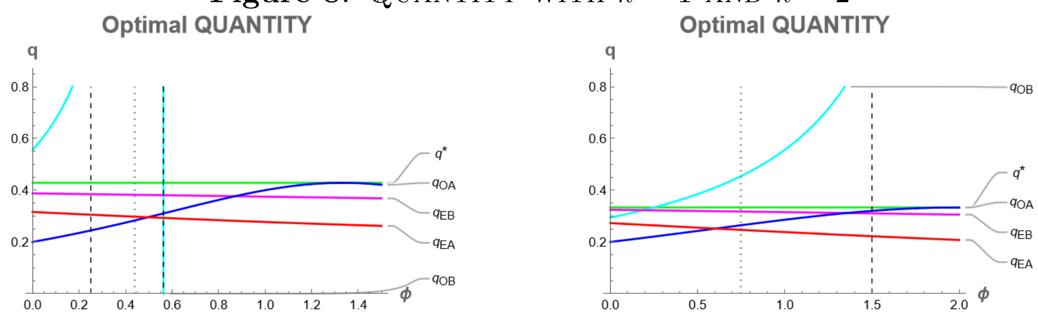
Figure 7: Tax Rates with $k = 1$ and $k = 2$



Panel A:
Tax Rates with $k = 1$

Panel B:
Tax Rates with $k = 2$

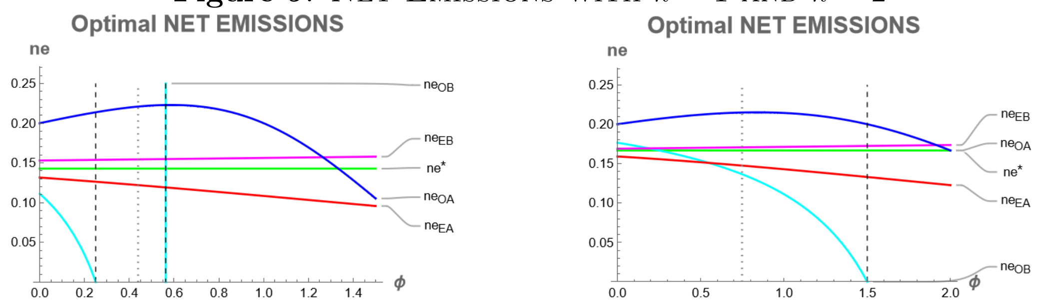
Figure 8: Quantity with $k = 1$ and $k = 2$



Panel A:
Quantity with $k = 1$

Panel B:
Quantity with $k = 2$

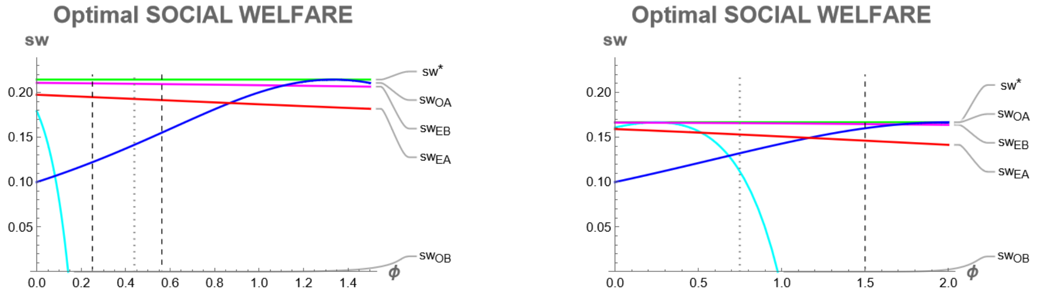
Figure 9: Net Emissions with $k = 1$ and $k = 2$



Panel A:
Net Emissions with $k = 1$

Panel B:
Net Emissions with $k = 2$

Figure 10: Social Welfare with $k = 1$ and $k = 2$



Panel A: Social Welfare with $k = 1$

Panel B: Social Welfare with $k = 2$

Ceteris paribus, increases in k tend to change the behavior of the functions. The first plot illustrates the abatement level. It shows that for low levels of environmental consciousness, the abatement level in case of an output tax is less than not only the first-best outcome, but also than the abatement level in case of an emissions tax. However, v_{OB} and v_{EB} keep their slopes, which are positive and negative respectively. In accordance to the above, the regulator sets a tax on output which is greater than the emissions-tax rate for low levels of ϕ in order to punish the monopolist for her bad performance. However, since increases of environmental consciousness increase the abatement level, the tax is reduced. Moreover, both tax rates keep their negative slope. The quantity functions seem to have similar behavior to the abatement level. At low levels of ϕ, since v_{OB} is the lowest among all of the function depicted in the plot, followed by a higher tax rate, it is only reasonable that the producer would produce less and the responsible consumers will not prefer to purchase much of that good. Of course, since the abatement level in case of the output tax increases and the output-tax rate decreases, the quantity produced and consumed will increase as well. The lower abatement and quantity levels has an effect on the net emissions in case of the output as well. Remember that the optimal net emissions in case of an output tax policy was less than both ne^* and ne^{EB}, meaning that the over-provision of quality generates better environmental conditions. When the parameter of the cost function increases, making the abatement more expensive, it is only logical for the firm to generate more emissions for relatively low levels of ϕ. As ϕ increases, the net emissions in case of the output tax reduce, thus creating better environmental conditions. An increase in the environmental consciousness counterbalances the negative effect than k creates. Last but certainly not least, for relatively low levels of ϕ, sw_{OB} increases, because of the cost rationalization the k parameter creates. After a certain point of ϕ, however, the excessive abatement accompanied with the increased subsidy and quantity produced generates decreases in social welfare. All of the analysis above was focused on the optimal output-tax function, due to the fact that there is no significant change in the emissions-tax policy functions. In general, increases in k shift the abatement, the quantity and the social welfare levels down, while shifting the tax and net emissions up (under both tax regimes). Moreover, it is worth mentioning that the analysis in the previous paragraph remains true $\forall\ k \geq 2$.

6 Conclusions

This work presents the effects of letting the regulator commit or not to a tax rate, when the choice of abatement is an endogenous variable under a monopolistic framework as well as the robustness issues that may arise. By comparing model A, which is introduced by Constantatos et al. (2021), and model B, presented in Martis (2022), some interesting results arise. In case of the output tax, the monopolist chooses higher abatement level in model B in order to manipulate the regulator's choice of optimal tax rate. Therefore, the tax rate in model A is greater than that of model B. All of the above makes the consumers to choose the cleaner than the less clean good, which makes the monopolist in model B to produce more than in model A. Thus, the environmental condition in model B is better than in model A. When it comes to social welfare, model B prevails over model A for relatively low levels of environmental consciousness, whereas in relatively higher levels of ϕ model A yields higher social welfare. Under an emissions tax regime, the monopolist leads to some sort of "*greenwashing*": She promises higher abatement levels to get lower tax by the regulator and to sell more of her product only to generate higher levels of net emissions. In terms of social welfare, in the case of the emissions tax, model B is more preferable than model A since it generates higher social welfare, however when the tax is on output, then the level of environmental consciousness is crucial. For low levels of ϕ, it is socially more preferable for a regulator to commit to a tax schedule. On the other hand, for high levels of ϕ, Model A prevails due to the over-abatement effect.

Finally, the model in Martis (2022) is sensitive to changes in k. When the latter increases, the level of abatement in the case of the output tax decreases, though keeping the positive slope. For relatively low levels of environmental awareness, it is below the emissions-tax abatement level. As a result, the output-tax rate increases and for a relatively low levels of environmental consciousness it lies above the emissions-tax rate, while both are keeping their negative slope. The output-tax quantity has a similar behavior to the abatement level, thus generating higher net emissions than both the first-best and the emissions-tax net emissions. Lastly, there is a change in the optimal social welfare in case of an output tax, which initially increases, reaches a maximum value and starts to decrease. We have to mention that for increases of k, the analysis was focused on the output-tax policy rather than the emissions tax, because there is not a significant change in the conclusions derived from the emissions-tax policy functions.

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A Appendix

A.1 Expressions of social welfare functions

The social welfare function under the output tax:

$$sw_{OB} = \frac{n\left(k^2\left(2\delta^2 nz+1\right)^3 - 8\delta^2 knz^2(\delta n\phi+1)^2 - 8\delta^2 nz^3(\delta n\phi+1)^2\right)}{2\left(k\left(2\delta^2 nz+1\right)^2 - 4\delta^2 nz^2(\delta n\phi+1)\right)^2}$$

The social welfare function under the emissions tax:

$$sw_{EB} = \frac{\Gamma+\Delta+\Theta-z}{4\left(\delta k\left(2\delta^2 nz+1\right)^2 + 4\delta z\left(\delta^2 nz+1\right)-\phi\right)^2}$$

where $\Gamma = 2\delta^2 k^2 n\left(2\delta^2 nz+1\right)^3$,
$\Delta = k\left(4\delta n\left(\delta(-n)\phi^2 + \delta z\left(4\delta^2 nz\left(\delta^2 nz\left(\delta^2 nz+3\right)+3\right)+5\right)-2\phi\right)-1\right)$
$\Theta = 2n\left(\delta^2 z^2\left(2\delta^2 nz\left(6\delta^2 nz+13\right)+13\right) - 8\delta z\phi\left(\delta^2 nz+1\right)+\phi^2\right)$