Emission Control by Voluntary Agreements: Oligopoly Market with Green Consumers

Hyunseok Kim and GianCarlo Moschini *

Abstract

This paper examines the performance of voluntary agreements (VAs), relative to a tax policy and *laissez faire* (i.e., no policy), as a way to reduce environmental pollution. We find that when the market is non-competitive, the VA, relative to other policy options, improves welfare despite suffering from free-riding behavior. It is also found that, as consumers value the green good more, the VA increases the number of green firms and provides a less competitive environment for free-riders, who increase the price of conventional goods. As a result, the total market under the VA becomes less covered, at some point, than the tax policy. The potential gains from the VA are attainable provided the regulator's threat is credible and sufficiently strong. If the regulator is required to be time-consistent, it becomes infeasible to induce enough VA participants due to the weak threat. In addition, a high political cost can make the VA (or *laissez faire*) policy preferable over the tax policy despite its lower potential to affect welfare.

Key Words: green consumers, oligopolistic markets, Pigouvian tax, self-enforcing equilibrium, voluntary agreement, welfare

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1. Introduction

Environmental externalities from firms' production activities are common, and this has the potential to cause serious welfare losses in the economy. Various instruments can be used to deal with this problem, with the primary goal to reduce pollution and thereby improve welfare. With perfect information about environmental damages, Pigouvian taxes would be the most efficient way to achieve pollution abatement. Taxes leverage the incentives agents have in a decentralized economy and, along with tradable permits, offer market-based alternatives to more direct command-and-control regulation such as technology or performance standards. Voluntary approaches are also often considered as a way to reduce externalities. Although there are a variety of forms they can take, voluntary approaches in environmental policy generally rely on commitments by participants to go voluntarily beyond what would be expected of them in an unfettered equilibrium, which has the potential of cost savings on legislation and regulation (Segerson and Miceli 1998; Fleckinger and Glachant 2011).

Voluntary agreements (VAs) in an environmental context have attracted considerable interest around the world. The OECD catalogs 333 distinguishable VAs in 18 countries, mostly from European countries (http://www2.oecd.org/ecoinst/queries/Default.aspx, accessed May 2021). In the United States, after the introduction of the Environmental Protection Agency's (EPA) 33/50 program in 1991, there are a growing number of VAs initiated solely by EPA: 28 in 1996, 54 in 1999, and 87 in 2005 (Khanna and Brouhle, 2009, p. 144). According to Carmin et al. (2003), in United States there are more than 150 VAs, sponsored by the government, industries, and third parties such as non-governmental organizations (NGOs).

The motivations for firms to participate in VAs are mainly two-fold (Lyon and Maxwell 2002; Fleckinger and Glachant 2011; Kotchen and Segerson 2020): to avoid regulation and/or an alternative policy (e.g., a tax), and to improve industry reputation by appealing to consumers who value environmentally-friendly behavior (green consumers). Whereas these two motives are widely accepted as plausible, most studies have investigated each of them separately. In this paper, we consider a model that combines both motives in order to analyze the scope for a VA policy, relative to *laissez faire* (i.e., no policy) and a tax policy. To be specific, this paper adds to the literature related to multi-firm participation decisions by embedding a oligopolistic product differentiation structure in a VA context. This provides a comprehensive framework to investigate the incentives for firms' participation behavior, to characterize the feasibility of implementing a VA, and to investigate its merits relative to other policy options.

Because VAs typically pertain to industries that involve a limited number of firms, it is natural to postulate oligopolistic competition. This point has been made by David (2005), who compares tax policy and VA in an oligopolistic setting. But he leaves out the possibility of product differentiation based on consumer preference and also the possibility of firms' free-riding behavior (thereby ending up with full or zero participation). Having postulated the presence of green consumers, we assume that firms operate in an oligopolistic product differentiation setting in the manner of Bagnoli and Watts (2003). In addition, to incorporate free-riding behavior, we rely on self-enforcing equilibrium to determine the number of VA participants.[1]

To model product differentiation and the operation of a VA, we posit that firms can enhance their environmental performance by adopting a new technology. Hence, a VA aiming to reduce industry-wide emissions can simply be construed as requiring firms to use the new technology. This kind of requirement can be found, for example, in the French agreement on treatment of end-of-life vehicles (ELVs). Under this agreement, car manufacturers and insurance companies who join in the VA undertake to deal only with certified dismantlers. By considering manufacturers and dismantlers as a whole, this is a situation where participants adopt new technologies (facilities) to reduce emission. It is said that "[c]ertification of the dismantlers is a key element in the success of the EA [environmental agreement] as it provides a means of, largely, excluding free-riders" (EEA, 1998, p. 13; [ ] added). Another example is the Danish agreements on industrial energy efficiency, in which firms get a rebate on their tax payment by committing investments to enhance their energy efficiency (OECD 2000).

Lyon and Maxwell (2008) distinguish voluntary agreements and public voluntary programs, where the former is based on regulatory threat whereas the latter is not (but with in-kind subsidy), and they view US programs as broadly belonging to the latter. As in Fleckinger and Glachant (2011), the VA we model in this paper is closer to the former setting, which is more frequently used in non-US regions. In any event, the threat-based motive seems to apply to some public voluntary programs in the United States, as shown empirically by Khanna and Damon (1999) with EPA's Voluntary 33/50 Program.

[1] This equilibrium concept was introduced by d'Aspremont et al. (1983) to explain the stability of cartels. Applications to voluntary environmental agreements include Carraro and Siniscalco (1993), Barrett (1994), and Dawson and Segerson (2008).

In addition to the participants' incentive, we consider the regulator's incentive in terms of choosing policy options. We assume the regulator maximizes social welfare by choosing a policy to implement in the pursuit of an emission target. At the same time, we presume the regulator perceives a political cost associated with the use of tax policy, a cost that is avoided with a VA (or in the *laissez faire* situation). Indeed, in the real world the efficient tax policy is often not chosen (Davis and Knittel 2016), likely reflecting policymakers' unwillingness to bear the political cost associated with the use of tax instruments.[2]

Using the proposed structure, we characterize the outcome of a policy game in which the regulator chooses a policy option taking into account the equilibrium response of firms. We consider three policy alternatives: *laissez faire*, a VA policy, and a tax policy. Through numerical simulations, we find that when the market is non-competitive, the VA policy, relative to other policy options, improves welfare despite its inefficiency due to free-riding behavior. This advantage wears off as the market becomes more competitive. Our results complement the conclusion in Dawson and Segerson (2008) who, focusing on the supply side, find that a VA is less preferred than a tax policy by a welfare-maximizing regulator due to its inefficiency. The main reason for our results is that when the market is non-competitive, so that the under-production problem prevails, the VA, relative to the tax policy, induces firms to produce more (green) output. Importantly, in this setting not all consumers always welcome the VA (unlike the argument in David 2005). As the consumers value the green good more, the VA increases the number of green firms and provides a less competitive environment for free-riders, who increase the price of conventional (i.e., not environmentally friendly) goods. As a result, market coverage, at some point, is lower than under the tax policy. As to implementation, the potential payoff of the VA is attainable provided the regulator's threat is credible and sufficiently strong. Apart from this, a high political cost can make the VA (or *laissez faire*) policy preferred over the tax policy despite its lower potential to affect welfare (similar to the conclusion about non-binding VAs in Glachant 2007).

The paper is organized as follows. In Section 2, we provide a brief background about the major motives for VA participation. Section 3 develops the model for the analysis of multi-firm product differentiation. In Section 4, the equilibrium of the game is analyzed after investigating equilibria under two subgames: product differentiation under a tax policy, and product

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[2] While not explicitly modeled in this paper, the target of a VA can be the outcome of negotiation between a regulator and a group of firms. See Segerson and Miceli (1998), Glachant (2007), Fleckinger and Glachant (2011), and Langpap (2015).

differentiation under a VA. Numerical simulations are conducted in Section 5 to explore the characteristics of equilibrium. Sensitivity analysis provides a more general picture regarding possible policy implementations. Section 6 concludes.

2. Background

Lyon and Maxwell (2002) discuss the increased use of VAs and summarize three motives that corporations can have for regulating themselves: i) cost-cutting, ii) marketing to green consumers who are willing to pay extra for environmentally friendly products, and iii) pre-empting government regulation.[3] Although the case has been made in support of the first motive,[4] they note the puzzle of why cleaning up should be profitable, and suggest that there is no systematic empirical evidence for it. As to the second motive, several theoretical studies have been conducted regarding product differentiation, which give clear and coherent insights regarding corporate behavior.[5] Given that the third motive is often investigated by theoretical research, Lyon and Maxwell (2002) conclude that there is modest evidence that the threat of future regulation is a significant factor prompting firms to self-regulate. Empirically, however, Khanna and Damon (1999) find that compliance under mandatory environmental regulations provides strong incentives for participation under the 33/55 program. Fleckinger and Glachant (2011) also conclude that VA participation is mainly motivated by future threat policies and green preference of consumers, workers and shareholders.

Given that the motives arising from the threat policy and green consumers are compelling, they have been the object of considerable research (Segerson 2017). With a simple bargaining game situation of one representative firm and regulator, Segerson and Miceli (1998) show that policymakers can induce firms to engage in a VA by the threat of mandatory controls (the "stick approach") as well as by cost-sharing subsidies (the "carrot approach"). Recently, several articles have focused on the interaction among firms, rather than the interaction between one firm and the

[3] Alternatively, Croci (2005, pp. 11-20) enumerates seven specified incentives to participate in VA, including the three rationales discussed by Lyon and Maxwell (2002).

[4] For example, Smart (1992) mentions 3M's "Pollution Prevention Pays" program that achieves cost saving by reducing its total emissions. In addition, Howarth, Haddad, and Paton (2000) conduct case studies for two EPA's VAs, "Green Light" and "Energy Star Office Products," arguing that cost savings may arise from promoting the adoption of energy efficient technologies by firms.

[5] Börkey et al. (1998), for example, illustrate that the potential benefit of self-regulation is provided by product differentiation, using the example of German "Blue Angel," where products with this label command a price premium relative to non-labeled alternative goods.

government under a regulatory threat. David (2005) considers an oligopolistic market to compare tax policy and VA. In a context with only full or zero participation outcomes, he finds that a VA may be more efficient than taxation in a concentrated industry if pollution is not too damaging and if cheap and efficient abatement technology is available. Dawson and Segerson (2008) develop a multiple-firm model of pollution abatement where an entire industry is faced with possible imposition of an emissions tax if the industry level target is not met. They use the concept of "self-enforcing equilibrium" to show the existence of an equilibrium in which a VA is implemented successfully, although free-riding behavior (i.e., not joining in a VA) exists among firms under a successful VA. Similarly, Brau and Carraro (2011) examine the incentive of multiple firms to join in a VA by allowing free-riding behavior, where there are spill-over effects for participants, given a threat of nullifying the VA. McEvoy and Stranlund (2010) investigate consequences of costly enforcement on the ability of VAs in a setting very similar to that of Dawson and Segerson (2008).

Studies dealing with the motivation arising from green consumers have mostly focused on product differentiation without modeling a detailed VA structure. Based on the family of models pioneered by Gabszewicz and Thiesse (1979) and Shaked and Sutton (1982), Arora and Gangopadhyay (1995) study standard vertical product differentiation under duopoly where a firm's environmental performance is differentiated. They show why some firms voluntarily overcomply with environmental regulation. In their model, it is found that a minimum standard binding on the dirty firm has the effect of improving the performance of the greener firm. A subsidy obtains the same competitive outcome. Duopolistic vertical differentiation is also studied by Bansal and Gangopadhyay (2003), who extend the model of Arora and Gangopadhyay (1995) and derive the additional implication that a policy of discriminatory subsidy improves welfare and alleviates total pollution. Given an exogenous division of green and brown consumers, Rodríguez-Ibeas (2007) shows that an increase in the proportion of green consumers is not always good for the environment. In a more general context, García-Gallego and Georgantzís (2009) analyze the welfare effect of consumers' social consciousness by varying the shape of preference distribution and the market structure. The effect of consumers' awareness about products is also investigated by Brouhle and Khanna (2006) and Brécard (2013) in a model of duopolistic vertical differentiation. Bagnoli and Watts (2003), under a multiple-firm setting, study several vertical differentiation models where environmental friendliness is only partially internalized by consumers. They find that in some but not all cases unregulated competition for green consumers can provide the socially optimal level of the environmental public good.

Previous work has dealt with either the motive of green consumers or the motive of a threat policy, to explain the VA participation behavior, but not both motives together. When it comes to the question about the performance of a VA, however, it is hard to pull apart those two motives. Clearly, firms have many ways to differentiate their products vertically in response to green consumers. First, firms can directly put certain labels on their products. According to the Ecolabel Index (http://www.ecolabelindex.com/, accessed May 2021), for example, there are 455 ecolabels in 199 countries and 25 industry sectors, about 200 of which are present in the United States. Through VAs, furthermore, firms can label their products officially. With the Danish agreement on recycling of transport packaging, for example, public access to information is quite easy due to the well-developed 1970 Freedom of Information Act (European Environmental Agency [EEA] 1998, p. 107). In the United States, EPA's VAs—such as ENERGY STAR, WaterSense, and Design for the Environment (now, Safer Choice)—have their own labeling policy. Direct listing of participants' performance publicly as in the 33/50 program also makes consumers aware of the performance of firms, causing product differentiation. To sum up, it seems that product differentiation is possible either by a firm's own labeling or by joining in a VA.

A regulatory threat—for example, a potential tax policy—is relevant when total emissions in an industry are considered high (even with the existing environmental friendliness for labeling). Given such a threat, a VA can be initiated to further reduce aggregate emissions in the industry. To illustrate, the VA can take the form of an agreement between the regulator and a group of firms in a relevant industry with an explicit industry-wide target. Examples include the Netherland's KWS 2000 project on reduction of volatile organic compounds (Lévêque and Nadaï 2000); the French agreement on the treatment of end-of-life vehicles (ELVs) (EEA 1998; Lévêque and Nadaï 2000); and the declaration by German industry and trade on global warming prevention (EEA 1998).

All things considered, the two motives—a regulatory threat and green consumers—often coexist for firms that are potential participants in a VA. In this regard, Baron (2011) analyzes a situation where multiple firms in a voluntary organization endogenously decide the "credence" attribute of their products in the presence of consumers valuing the credence and with social pressure from NGOs. It is found that the credence standard is lower with a larger size of organization but higher under social pressure. The model, however, is restrictive in that it firms are exogenously divided into two groups, firms producing credence goods and firms producing basic goods. In addition, the former group is in the voluntary organization from the beginning, and the latter group operates in a perfectly competitive market. Baron (2011) concludes that further research is warranted on several issues, including "the formation and governance of credence organization, including the participation decision of firms" (p. 1337).

The identity of the sponsor who initiates a VA is not specified in this paper, whereas the threat of potential tax policy is coming from the regulator. In the United States, for example, VAs are sponsored by government, industries, and third parties. As noted by van't Veld and Kotchen (2011), each sponsor might have different characteristics with respect to monitoring ability, capability of using a subsidy or tax, and incentives to control the size of membership. This paper ignores such differences by focusing on the sponsors' goal to reduce industry-wide emissions through the VA. We believe this entails little loss of generality, given that one of the motivations for the formation of industry-sponsored VAs is actually to avoid, affect, or delay regulation (Carmin et al., 2003). Therefore, whether the target can be met or not is the main issue even for the industry sponsor.[6]

3. The Model

We consider an industry that consists of N ex ante identical firms, each of which produces one of two (differentiated) goods. We assume that N is large enough to have no monopolistic equilibrium in terms of the industry. In the analysis, the integer issue concerning the number of firms is often ignored for convenience. For an individual firm i producing q_i, let C_i be its total costs and E_i be its total emissions. Now, consider two possible technologies in production and abatement, namely a "new" (and clean) technology, and an "old" (and dirty) one. Let subscript n and o denote "new" and "old" technologies, respectively. We will also use these subscripts to denote the corresponding goods (firms), the environmentally friendlier "green" product from the new technology, and the "conventional" good from the old technology. For firms using the new technology, $C_{in} = c_n q_{in}$ and $E_{in} = e_n q_{in}$, while for firms using the old technology, $C_{io} = c_o q_{io}$ and $E_{io} = e_o q_{io}$, where c_n and c_o are the corresponding constant marginal production costs, and e_n and e_o are the corresponding constant marginal emission rates. We assume $c_n > c_o$ (the new technology that produces clean

[6] According to Darnall et al. (2003), among 61 VAs that responded to their survey, 42 VAs were sponsored by government, 9 VAs sponsored by industry, and 10 VAs sponsored by a third party. Thus, government-sponsored VAs may well be the majority of currently operating VAs.

goods is more costly) and $e_n < e_o$ (the new technology entails lower emission).[7] The resulting industry-level emission is $E \equiv \Sigma_{i=1}^{N} E_i$. It is assumed that product differentiation is inherently linked to which technology is used in production. Practically, as mentioned in the Introduction, such product differentiation is possible through direct production labeling or indirect information sharing under VAs.

Along with the production structure, the model incorporates green preferences of consumers who care about producers' environmental performance. To be specific, given the firm's ability to differentiate its products based on the technology used, consumers are able to distinguish the version of products (products made by firms using new technology and those made by firms using old technology). The former is considered as green good (or product made by green firms), while the latter is considered as conventional good (or product made by conventional firms). Taking into account green preferences, the channel through which firms demonstrate their environmental friendliness to green consumers is to use the new technology.

Technically, a unit mass consumers, whose type is denoted by θ, are uniformly distributed over $[\underline{\theta}, \overline{\theta}]$, where $\underline{\theta} + 1 = \overline{\theta}$. The value of θ represents the taste of individual consumers. Each consumer buys at most one unit of the product. Specifically, a consumer's utility function is written as $U = m + u(y;\theta)$, where m is the common income level, and

$$u(y;\theta) = \begin{cases} 0 & \text{if } y = 0, \\ \theta(1+s) & \text{if } y = 1 \text{ and it is made by the new technology,} \\ \theta & \text{if } y = 1 \text{ and it is made by the old technology;} \end{cases}$$

where y is the unit of consumer's purchase, and s (>0) captures the additional benefit from consuming a product made by the new technology compared to the old one. In this setting, consumers who are willing to pay more for products by the old technology are willing to pay a higher premium when those are produced by the new technology.

Based on the structure of supply and demand sides, to make the problem interesting we focus on the following parametric domain.

Assumption 1. (a) $s\overline{\theta} > c_n - c_o$ and (b) $c_n/(1+s) > c_o$.

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[7] Bagnoli and Watts (2003) considered binary cost structure regarding two versions of products in two ways: i) different marginal costs with no fixed costs, and ii) same marginal costs with different fixed costs. In our model, the former is chosen.

Assumption 1(a) means that at least for the consumer who has the highest willingness to pay for greenness, the additional benefit by purchasing the greener good exceeds the additional costs for a firm to produce it. Next, Assumption 1(b) implies that the normalized marginal production cost to provide one unit of utility for consumer θ is higher for the green good than the conventional one.

Given this basic structure, the policy game of interest can be described as follows. The baseline is the *laissez faire* situation (i.e., without any policy). The regulator may wish to reduce the industry-wide emissions up to a certain target by means of policy instruments such as a tax policy or a VA. The emission level which is regarded as appropriate by the regulator can be used as an ex ante regulatory target for a VA policy, or as the basis for setting a tax policy.[8] The regulator's payoff consists of social welfare and a fixed political cost $K\ (\geq 0)$ if a tax policy is implemented.[9] The presence of the political cost decreases the merit of a tax policy for the regulator, thereby making VA (or *laissez faire*) more attractive. The basic structure of the extensive form policy game is depicted in Figure 1. For each payoff vectors at terminal nodes, the first element pertains to the regulator and the second pertains to firms.

The whole game consists of three main subgames associated with no policy (*laissez faire*), tax policy, and VA, respectively. Consider first the tax subgame, corresponding to the regulator choosing "Tax policy" in Figure 1. Once the regulator decides to go for a tax policy, the following four-stage game is played. In Stage 1, the regulator chooses the tax rate $t\ \ (\geq 0)$ to meet the desired emission target $\overline{E}^T$ and announces the imposition of the tax rate in Stage 4. In Stage 2, firms decide which technology to use. In Stage 3, firms engage in quantity competition given the emission tax, and the aggregate emission level is determined according with constant emission rates. In Stage 4, the regulator simply levies the tax rate announced in Stage 1. We find the Nash equilibrium for Stage 3 and, in turn, Stage 2. For the quantity decision in Stage 3, we focus on symmetric outcomes, such that all green firms choose a same level of outputs, and all conventional firms choose the same level

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[8] In reality, explicit industry-wide targets are embedded for some VAs, while other VAs do not have such targets (as well as individually assigned ones). Even for the VAs with no explicit targets, however, it can be said that the initiation of them is motivated to pre-empt the regulator's threat policy which might be implemented if no further action is taken.

[9] Introducing a political cost for (tax) regulation is in the same vein as in Segerson and Miceli (1998), who posit that the VA incurs smaller costs borne by the regulator. Fleckinger and Glachant (2011) also consider that adopting a new regulation is costly for the regulator in terms of spending administrative resources.

of outputs. This tax game is also a subgame for the following VA game and its equilibrium outcome is crucial because the severity of the potential emission tax is another motive for firms to join in a VA, besides that the green consumers. Note that if the regulator chooses the *laissez faire* option, this is equivalent to the case of zero tax rate in the tax game (and $K = 0$).

Next, the case when the regulator chooses to propose the VA with a regulatory threat is describes by the subgame in the left branch of Figure 1. Again, we have a four-stage game. In Stage 1, the regulator chooses her regulatory emission target, $\overline{E}^V$. It is also announced that if enough participants adopt the new technology so that the target is achieved, the VA is implemented, otherwise the tax rate $\tau\,(>0)$ —a threat tax rate—will be imposed in Stage 4. In Stage 2, firms decide whether or not to join the VA. The participating firms in the VA commit to use the new production technology, which entails a higher marginal cost but a lower emission rate per product. In Stage 3, firms do quantity competition. In Stage 4, if the target is met with a sufficient number of participants, the regulator exempts tax making the VA successful, otherwise the treat tax rate is levied.

Note that in Stage 2 of the VA game that we investigate, there are two compelling settings in terms of the threat tax rate τ (similar to the discussion in David 2005): the pre-commitment case in which any τ is credible by firms; and, the time-consistency case in which only credible threat level is the one that the regulator would impose under the tax policy without any threatening purpose (i.e., $\tau = t$). These two cases provide implications about the credibility of the threat, which is crucial to successfully implement the VA.

Nash equilibrium applies to Stage 3 of the VA subgame, conditional on the technology choices made in Stage 2. Note that the regulator's decision regarding whether to implement the threat tax policy or not is made in Stage 4. When there are enough participants so that the emission target is met in equilibrium (and thus a zero tax is expected), therefore, firms engage in quantity competition in the same manner as in Stage 3 in the tax game, but in the absence of the emission tax. As noted earlier, we focus on symmetric equilibrium at the Cournot competition stage. Firms in Stage 2 anticipate the Cournot equilibrium outcomes of Stage 3. Implementation of the tax policy threat would have consequences for the firms' profits, and this is accounted for in Stage 2, where the self-enforcing number of participants which is stable and profitable for all firms, given the threat of tax policy, is determined.

4. Equilibrium

As a first step, we need to specify the demand functions that the two types of firms face. Let p_n and p_o represent the prices of products made by green firms (with the new technology) and by conventional firms (with the old technology), respectively. The surplus of a consumer whose individual preference is θ is as follows: $\theta + s\theta - p_n$ if she buys the green product, and $\theta - p_o$ if she buys the conventional product. Thus, the consumer type who is indifferent between purchasing a green product and a conventional product is identified by $\theta_n = (p_n - p_o)/s$, while $\theta_o = p_o$ identifies the consumer who is indifferent between purchasing a conventional product and buying nothing. We consider the case of interior solutions where $\underline{\theta} < \theta_o < \theta_n < \overline{\theta}$.

Given the assumed uniform distribution of consumer types, demands for green and conventional goods are obtained as follows.

(1) $$Q_n(p_n, p_o) = \overline{\theta} - \frac{p_n - p_o}{s};$$

(2) $$Q_o(p_n, p_o) = \frac{p_n - p_o}{s} - p_o.$$

Note that the market is uncovered as long as $p_o > \underline{\theta}$. The feature of uncovered market enables us to derive inverse demand functions and model imperfect competition à la Cournot.

4.1. Equilibrium under a Tax Policy

By backward induction, we find the equilibrium output schedules for green and conventional firms in Stage 3 under the tax rate t that will be imposed in Stage 4, and subsequently find the equilibrium number of green firms in Stage 2. When determining the equilibrium in Stage 3, the number of green firms is treated as given from Stage 2.

Considering the division of demand based on greenness of products, firms choose their technology and engage in output competition. The total number of firms in the industry is denoted by N, the number of firms using the new technology is N_n, and the number of firms using the old technology is N_o, where $N = N_n + N_o$. After N_n is determined (and N_o is determined accordingly), each of two groups engages in Cournot type competition by choosing output level. From equations (1) and (2), inverse demand functions can be derived for p_n and p_o as follows: $p_n(Q_n, Q_o) = (1+s)\overline{\theta} - (1+s)Q_n - Q_o$ and $p_o(Q_n, Q_o) = \overline{\theta} - Q_n - Q_o$.

Given an emission tax rate t, marginal costs are now $c_n + te_n$ for green firms and $c_o + te_o$ for conventional firms. The profits for green firms and conventional firms will be then $\pi_n = (p_n - c_n - te_n)q_n$ and $\pi_o = (p_o - c_o - te_o)q_o$, respectively. Again focusing on symmetric outcomes, the first order conditions for a green firm and a conventional firm require:

(3) $$0 = p_n(Q_n, Q_o) - c_n - te_n - (1+s)q_n$$

(4) $$0 = p_o(Q_n, Q_o) - c_o - te_o - q_o,$$

where $Q_n = N_n q_n$ and $Q_o = N_o q_o$. Knowing that $N = N_n + N_o$, we have following equilibrium quantities for individual green and conventional firms for given number of green firms and tax rate:

(5) $$q_n^T(N_n, t) = \frac{\left[1 + s(N - N_n + 1)\right]\overline{\theta} - (N - N_n + 1)(c_n + te_n) + (N - N_n)(c_o + te_o)}{(1+s)(N+1) + sN_n(N - N_n)};$$

(6) $$q_o^T(N_n, t) = \frac{(1+s)\overline{\theta} + N_n(c_n + te_n) - (1+s)(N_n + 1)(c_o + te_o)}{(1+s)(N+1) + sN_n(N - N_n)}.$$

where the superscript T denotes outcomes under the tax policy. For a number of firms using the new technology $N_n \in [0, N]$, and $t > 0$, we find:

Lemma 1. Under Assumption 1, equilibrium individual quantities are positive.

Proof. See Appendix A1.

The aggregate (market level) quantities are readily obtained as $Q_n^T(N_n, t) = N_n q_n^T(N_n, t)$ and $Q_o^T(N_n, t) = (N - N_n) q_o^T(N_n, t)$, and are positive by Lemma 1. Then, the industry-wide emission level under the tax policy is $E^T(N_n, t) = e_n Q_n^T(N_n, t) + e_o Q_o^T(N_n, t)$ for given N_n and t. Note that we have following feature for $N_n \in [0, N]$.

Lemma 2. For a fixed numbers of green and conventional firms, the industry-wide emission level under a tax policy decreases in the tax rate.

Proof. See Appendix A2.

The profits for green firms and conventional firms under the tax policy are

(7) $$\pi_n^T(N_n, t) = \left[\, p_n^T\left(q_n^T(N_n, t), q_o^T(N_n, t)\right) - c_n - te_n \,\right] q_n^T(N_n, t);$$

(8) $$\pi_o^T(N_n, t) = \left[\, p_o^T\left(q_n^T(N_n, t), q_o^T(N_n, t)\right) - c_o - te_o \,\right] q_o^T(N_n, t).$$

Meanwhile, from equations (3) and (4), we get $q_n = (p_n - c_n - te_n)/(1+s)$ and $q_o = p_o - c_o - te_o$. Hence, equations (7) and (8) can be alternatively expressed as:

(9) $$\pi_n^T(N_n,t) = \frac{\left[q_n^T(N_n,t)\right]^2}{1+s};$$

(10) $$\pi_o^T(N_n,t) = \left[q_o^T(N_n,t)\right]^2.$$

Firms' technology decisions in Stage 2 can now be characterized with the foregoing equilibrium profits. First of all, under Assumption 1, $q_n^T(N_n,t)$ and $q_o^T(N_n,t)$ are strictly convex for all N_n (Appendix A3), and so are the profits $\pi_n^T(N_n,t)$ and $\pi_o^T(N_n,t)$ (they are convex monotonic increasing transformations of $q_n^T(N_n,t)$ and $q_o^T(N_n,t)$ as in equations (9) and (10). Note that Cournot competition entails the so-called business-stealing effect (Mankiw and Whinston 1986). Hence, an increase in the number of firms for one group reduces the relative merit of belonging to that group compared to belonging to the other group. Then there is at most one intersection between the two equilibrium profit schedules (ignoring the integer issue on the number of firms). Consider two extreme cases which have no intersection: for given t, if $\pi_n^T(N,t) > \pi_o^T(N,t)$, every firm produces green goods of $q_n^T(N,t)$; if $\pi_n^T(0,t) < \pi_o^T(0,t)$, every firm produces conventional goods of $q_o^T(0,t)$. For the interior case ($\pi_n^T(N,t) \le \pi_o^T(N,t)$ and $\pi_n^T(0,t) \ge \pi_o^T(0,t)$), the unique equilibrium number of green firms satisfies the following condition, as in Bagnoli and Watts (2003):

(11) $$\pi_n^T(N_n^T,t) = \pi_o^T(N_n^T,t).$$

This condition means there is no incentive for firms to deviate from their current technology decision.[10] From equation (11), the equilibrium number of green firms $N_n^T(t)$ is a function of the tax rate announced in Stage 1 (and imposed in Stage 4).

Remarkably, we can obtain closed-form solutions for the interior case outcome at the equilibrium of this game, which are functions of t such as $N_n^T(t)$, $q_\ell^T(t) \equiv q_\ell^T(N_n^T(t),t)$,

[10] Note that the equality in the condition is guaranteed by ignoring the integer issue in regards to the number of firms. The equilibrium condition, when considering the integer issue, is that i) no green firm has an incentive to be conventional unilaterally, i.e., $\pi_n^T(N_n^T,t) \ge \pi_o^T(N_n^T-1,t)$, and ii) no conventional firm has an incentive to be green unilaterally, i.e., $\pi_o^T(N_n^T,t) \ge \pi_n^T(N_n^T+1,t)$.

$Q_\ell^T(t) \equiv Q_\ell^T(N_n^T(t),t)$, $\pi_\ell^T(t) \equiv \pi_\ell^T(N_n^T(t),t)$ and $E^T(t) \equiv E^T(N_n^T(t),t)$ for $\ell = n,o$. First, we have expressions for aggregate quantities of green and conventional goods in the demand side as equations (1) and (2), while Cournot competition yields expressions for aggregate quantities of green and conventional goods in the supply side as above. In addition, equation (11) gives us an extra condition so that we can derive explicit solutions for equilibrium outcomes with exogenous parameters (see Appendix A4 for the detailed derivation). Specifically, the explicit expression for the equilibrium number of green firms is:

(12) $$N_n^T(t) = \frac{\bar{\theta}\left[(1+s)-(1+s)^{0.5}+sN\right]-(1+N)(c_n+te_n)+\left[(1+s)^{0.5}+N\right](c_o+te_o)}{s\bar{\theta}-\left[1-(1+s)^{-0.5}\right](c_n+te_n)-\left[(1+s)^{0.5}-1\right](c_o+te_o)}.$$

With the obtained solutions, furthermore, comparative statics can be conducted as follows.

Lemma 3. At the interior equilibrium in Stage 2 of the tax game, the following comparative statics hold:

- the quantity of individual green firm decreases in the tax rate;
- the quantity of individual conventional firm decreases in the tax rate;
- the profits of individual green firm decrease in the tax rate;
- the profits of individual conventional firm decrease in the tax rate;
- the aggregate quantity of green firms increases in the tax rate;
- the aggregate quantity of conventional firms decrease in the tax rate;
- the number of green (conventional) firms increases (decreases) in the tax rate;
- the industry-wide emission level decreases in the tax rate.

Proof. See Appendix A5.

The above results are intuitive in that, for example, if a higher tax rate is levied, the industry-wide emission level will decrease at equilibrium with a larger number of green firms resulting in an increased aggregate level of green products. Importantly, Lemma 3 holds for tax rates that yield the interior solution for the Stage 2 equilibrium. Regarding boundary cases, we have Lemma 4.

Lemma 4. Given that all firms are conventional ($N_n^T = 0$) or given that all firms are green ($N_n^T = N$) in Stage 2 of the tax game, the individual quantity, individual profit, aggregate quantity and resulting industry-wide emission level of firms decrease in the tax rate.

Proof. See Appendix 5.

By Lemmas 3 and 4 we conclude that for any level of emission target, which is smaller than the given *laissez faire* emission level, there will be a tax rate which achieves the target. We now define the full range of applicable tax rates as $t \in [0, t_{\max}]$, where $q_n^T(N, t_{\max}) = 0$.

In Stage 1 the regulator imposes a specific level of t. To achieve the target, she sets $t = \bar{t}$ that satisfies $E^T(\bar{t}) = \bar{E}^T$, where the social welfare is maximized. Based on one-to-one relationship implied by Lemma 3 and Lemma 4, one can find a tax rate that leads to the corresponding target. Actually, the set of feasible emission levels is $E^T \in [0, E^L]$ where $E^T(t_{\max}) = 0$ and $E^L \equiv E^T(0)$. We consider E^L as the baseline level of total emissions in the *laissez faire* case, and N_n^L $(\equiv N_n^T(0))$ as the baseline number of green firms.

The equilibrium in the tax game is summarized in Proposition 1.

Proposition 1. At the equilibrium under tax policy, for the target $\bar{E}^T \in [0, E^L]$,

(i) the regulator imposes tax rate as $t = \bar{t}$;

(ii) the number of green firms and conventional firms are, respectively,

$$N_n^T = \begin{cases} 0 & \text{if } \pi_n^T(0,\bar{t}) < \pi_o^T(0,\bar{t}) \\ N & \text{if } \pi_n^T(N,\bar{t}) > \pi_o^T(N,\bar{t}) \\ N_n^T(\bar{t}) & \text{otherwise} \end{cases}, \qquad N_o^T = \begin{cases} N & \text{if } \pi_n^T(0,\bar{t}) < \pi_o^T(0,\bar{t}) \\ 0 & \text{if } \pi_n^T(N,\bar{t}) > \pi_o^T(N,\bar{t}) \\ N - N_n^T(\bar{t}) & \text{otherwise} \end{cases};$$

(iii) green firms and conventional firms exactly meet the target by producing, respectively

$$Q_n^T = \begin{cases} 0 & \text{if } \pi_n^T(0,\bar{t}) < \pi_o^T(0,\bar{t}) \\ Q_n^T(N,\bar{t}) & \text{if } \pi_n^T(N,\bar{t}) > \pi_o^T(N,\bar{t}) \\ Q_n^T(\bar{t}) & \text{otherwise} \end{cases}, \qquad Q_o^T = \begin{cases} Q_o^T(0,\bar{t}) & \text{if } \pi_n^T(0,\bar{t}) < \pi_o^T(0,\bar{t}) \\ 0 & \text{if } \pi_n^T(N,\bar{t}) > \pi_o^T(N,\bar{t}) \\ Q_o^T(\bar{t}) & \text{otherwise} \end{cases},$$

4.2. Equilibrium under a Voluntary Agreement

Next, consider the VA subgame (the left branch of Figure 1). Let superscript V represent equilibrium outcome under the VA. The equilibrium is solved for by backward induction. Conditional on the number of new technology adopters in Stage 2 (i.e., the number of green firms), firms anticipate whether the treat tax rate is levied or not in Stage 4, and behave accordingly in their Stage 3 Cournot competition. If the VA is successful, this output competition yields exactly the same equilibrium quantities as in the tax game with a zero tax rate. Thus, we define equilibrium outputs, profits and aggregate emissions in Stage 3 of the VA subgame as follows: $q_\ell^V(N_n) \equiv q_\ell^T(N_n, t=0)$, $Q_\ell^V(N_n) \equiv Q_\ell^T(N_n, 0)$, $\pi_\ell^V(N_n) \equiv \pi_\ell^T(N_n, 0)$ for $\ell = n, o$, and $E^V(N_n) \equiv E^T(N_n, 0)$ for $\ell = n, o$. Noted that, unlike the tax policy, equilibrium outcomes under the VA are unchanged with different target levels, given the maintained absence of emission tax.

The implementation of a VA, of course, is of interest only when N_n^L is smaller than N. In other words, if all firms are already using the new technology in the *laissez faire* situation, there is no reason to initiate the VA. Under Assumption 1, for the given equilibrium total emissions, we then have following Lemma.

Lemma 5. Under a successfully implemented VA based on a threat policy and green consumers, the total emissions of the oligopolistic industry decrease in the number of participants (i.e., green firms) for $N_n \in [N_n^L, N]$.

Proof. See Appendix A6.

Lemma 5 holds in that the increase in the total output of green goods leads to a reduction in total industry emissions. This result is actually not obvious, given the feature of Cournot competition that as the number of participants increases the number of non-participants decreases with a higher level of individual output. By Lemma 5, the target $\bar{E} \in [E^V(N), E^L]$ can be met by increasing the number of participants $N_n \in [N_n^L, N]$. Under the VA, therefore, the number of participants—i.e., green firms—directly plays the key role for meeting the target emission level (while in the tax policy the tax rate determines the number of green firms and in turn the total emissions). Note that, as the number of participants increases, the profits of a green firm get smaller than those of a conventional firm, given the nature of Cournot competition. Thus, increasing the number of participants reduces the relative attractiveness of being a participant compared to being a non-participant, and vice versa.

In Stage 2, given the threatened tax rate τ, the number of participants is determined. Suppose that the target emission level is feasible, and let $\tilde{N}_n$ (>0) denote the minimum number of participants needed to achieve the emission target under the VA. In Stage 2 firms know that in Stage 4the regulator exempts tax when the target is going to be met, i.e., $N_n \geq \tilde{N}_n$. If $N_n < \tilde{N}_n$, however, the announced τ is imposed, resulting in the tax game outcome ($N_n = N_n^T(\tau)$). For the latter situation, we can think that the number of VA participants becomes zero. As a results, possible equilibrium numbers of participants in Stage 2 lie in $N_n \in \left\{0,[\tilde{N}_n, N]\right\}$.

Now we consider the "self-enforcing equilibrium" number of participants in Stage 2. Following the discussion in Dawson and Segerson (2008), two conditions should be satisfied: the "profitability condition" and the "stability condition." For profitability, it needs to be guaranteed that participants enjoy a level of profits no less than that which would occur if the VA fails (i.e., the threat tax is imposed). The participating firms consist of two types: i) firms who would produce green good even under the tax policy, and ii) firms who would choose old technology absent the VA. If the profit level for green firms under the threat tax is higher than that under the VA, the number of firms in the second group becomes insufficient and the threat tax is implemented in Stage 4. That the non-participants are always better off compared to the tax outcome makes the profit level of individual green firm pivotal for the VA to proceed to the end of the game, i.e., "successfully implemented." We assume that the VA which is successful is preferred by firms to tax policy when both give same profits. Next, the number of participants is stable if there is no incentive to deviate unilaterally for each group of firms, i.e., no participants want to be a non-participant and no non-participants want to be a participant.

Depending on the threat level—i.e., profit level when the announced threat tax rate is imposed—the set of N_n that satisfies the profitability condition can be null or not. Figure 2 describes the possible situations with different threats (but the same target), where the bold line and dots indicate the relevant payoff for a green firm by taking the threatened profit level and possible values of N_n into account. First, in the panel (a), for $\tau = \tau'$ there is no N_n at which individual green firm is at least as well off as under the tax policy, within $[\tilde{N}_n, N]$. In this case there is no participation and the VA threat tax is imposed. In panel (b) we consider a more severe tax threat $\tau'' > \tau'$. Here there is a range of N_n, from $\tilde{N}_n$ to N_n at which $\pi_n^V(N_n) = \pi_n^T(\tau'')$, satisfying the profitability condition.

Given the situation of panel (b) in Figure 2, what remains to be checked is the stability condition for the values within $\tilde{N}_n$ to N_n at which $\pi_n^V(N_n) = \pi_n^T(\tau'')$. Note that only $N_n = \tilde{N}_n$ satisfies the stability condition in the sense that, at $N_n = \tilde{N}_n$, i) no non-participant (conventional firm) has an incentive to change their technology to sell green products (because that would cause a lower level of profits), and ii) no participant (green firm) has an incentive to convert the current technology to the old one (which would make the target unmet and thereby trigger the tax policy). For any number of green firms greater than the minimum requirement, participants are still be able to enjoy a higher profit by becoming a non-participant, hence stability does not hold.

To summarize, the equilibrium number of participants is as follows.

$$N_n^V = \begin{cases} \tilde{N}_n & \text{if } \pi_n^V(\tilde{N}_n) \geq \pi_n^T(\tau) \\ 0 & \text{if } \pi_n^V(\tilde{N}_n) < \pi_n^T(\tau) \end{cases}$$

where the positive N_n^V satisfies

(13) $$E^V(N_n^V) = \bar{E}^V .$$

By Lemma 5 we can obtain the unique positive $N_n^V(\bar{E}^V)$ that satisfies equation (13). To be specific, the nonlinear relationship between positive N_n^V and $\bar{E}^V$ is as follows:

(14) $$\left[N_n^V + \frac{1+s}{s}\frac{\phi-1}{\phi}\right]\left[\frac{\psi + c_n - (1+s)c_o}{s(N-N_n^V)+1+s-\varphi}\right] + \frac{\psi}{\phi}N_n^V = \frac{1+s}{s\phi}(s\bar{\theta} - c_n + c_o - \psi),$$

where $\phi = \left[e_n + (1+s)e_o\right]/(e_n + e_o)$ and $\psi = (\bar{E}^V - e_n\bar{\theta})s\big/(e_n + e_s) + \phi c_o - c_n$ (See Appendix A7 for the derivation of equation (14)).

4.2.1. Commitment Case

In Stage 1, the regulator proposes the target emission level together with the threat tax rate. Here we first consider the case in which the regulator has "commitment power" by assuming that the announced threat is credible regardless of its value. Consider the lowest effective threat $\bar{\tau}$ that preserves the profitability and stability for the equilibrium number of participants. Such threat would make both the VA and tax policy equally profitable for the green firm.

(15) $$\pi_n^V(N_n^V(\bar{E}^V)) = \pi_n^T(\bar{\tau}).$$

Equation (15) describes the relationship between the target and the lowest effective threat under the VA. For given target any potential tax rate higher than or equal to $\bar{\tau}$ yields the same outcome by resulting in no higher threat profits than those under the VA (recall Lemma 3). We simply assume that the regulator announces $\bar{\tau}$ as the potential tax rate in Stage 1.

Now we need to look at the feasibility issue of the target across VA and tax policy. Directly from Lemma 2, if an emission target is attainable via the VA, it could be also met under the tax policy with an appropriate tax rate, but the converse does not necessarily hold. To obtain the feasible set, based on Lemma 5 we define $E^V_{\min} = E^V(N)$, the lower limit of total emissions under the VA. As in the tax game, the upper bound of total emissions is given by the case of *laissez faire*. Then the set of feasible emission targets under the VA is $\bar{E} \in [E^V_{\min}, E^L]$. Figure 3 depicts the relationship of feasible sets under the *laissez faire*, VA and tax policy. Once we delimit the feasible target under the VA, we have Lemma 6 regarding the existence of $\bar{\tau}$.

Lemma 6. There is always a tax rate that makes the VA with a feasible target ($\bar{E} \in [E^V_{\min}, E^L]$) more profitable for all firms than the tax outcome.

Lemma 6 is followed by Lemmas 1 and 4. Specifically, under the VA for a feasible target the equilibrium profits for a green firm are always positive (by Lemma 1 and equation (9)), while under the tax policy we can find a tax rate that makes the profits equal to zero (by Lemma 4). Thus we can always find $\bar{\tau}$. Now the equilibrium of the VA subgame, given that the regulator has commitment power, can be summarized as follows.

Proposition 2. At the equilibrium under the VA when the regulator has commitment power:

(i) the regulator announces the target $\bar{E}^V \in [E^V_{\min}, E^L]$ with the threat tax rate $\tau = \bar{\tau}$;

(ii) the equilibrium number of participants is $N^V_n(\bar{E}^V)$ (that of non-participants is $N - N^V_n(\bar{E}^V)$), and the VA is successfully implemented;

(iii) participants sell green products of $Q^V_n(\bar{E}^V)$, while non-participants sell conventional products of $Q^V_o(\bar{E}^V)$ by having the target exactly met ($E^V(\bar{E}^V) = \bar{E}^V$).

4.2.2. Time Consistency Case

The foregoing has assumed that the regulator can commit to any arbitrary tax threat for the purpose of enticing firms to join in a VA. Indeed, Stage 4 of the VA policy subgame in Figure 1 simply envisions the application of a rule on the part of the regulator, to decide whether or not the threat tax τ is to be imposed. This, of course, is a questionable assumption. As we know since the seminal paper of Kydland and Prescott (1977), the incentive to keep a commitment may well differ from the incentive to (try to) make the commitment. Because agents (firms in our case) know that, the initial tax threat level may therefore not be credible and the announced policy may be time inconsistent.

To analyze the case when the initial policy threat is required to be "credible," such that the VA policy is time consistent, suppose that, in Stage 4 of the VA subgame, the regulator does not simply follow the binary rule of Figure 1, but instead retains the discretion to choose the tax rate it prefers. Such a tax rate may well differ from the pre-announced threat. In the context of this model, in fact, it is apparent that the only credible threat is the tax level that would be imposed under the tax policy, that is $\overline{\tau} = \overline{t}$, while still pursuing $\overline{E}^V$. Whereas in principle we have the same set of feasible target under the VA as in Figure 3 (meaning the target could be met with a suitable number of VA participants), the crucial issue of whether the VA can be successful. If the credible threat is not sufficiently strong, firms will simply accept the tax and the stated emission goal of the VA will not be achieved. The resulting equilibrium is summarized as follows.

Proposition 3. At the equilibrium under the VA with time consistency,

(i) the regulator announces the target $\overline{E}^V \in [E^V_{\min}, E^L)$ with the potential tax rate $\overline{\tau} = \overline{t}$;

(ii) the equilibrium number of participants is $N^V_n(\overline{E}^V)$ (that of non-participants is $N - N^V_n(\overline{E}^V)$), and the VA is successfully implemented, provided joining in the VA is profitable; otherwise, the tax game outcome is obtained;

(iii) if VA is successful, participants sell green products of $Q^V_n(\overline{E}^V)$, while non-participants sell conventional products of $Q^V_o(\overline{E}^V)$ by having the target exactly met ($E^V(\overline{E}^V) = \overline{E}^V$).

4.3. Equilibrium of the Policy Game

For a given set of primitive parameter values, the regulator chooses one of the three policy options—*laissez faire*, VA, and tax policy—to maximize his objective function (i.e., the social welfare net of political cost). We sum up the equilibrium of the game in Proposition 4. When welfare levels are equal, assume that *laissez faire*, VA and tax policy are preferred in order.

Proposition 4. There are three potential equilibria based on eleven possible situations for given welfare W^j for $j = L$ (*laissez faire*), V (VA) and T (tax policy) and political cost K:

EQ 1. No policy is implemented (*laissez faire* situation)

if (a) $W^L \geq W^V \geq W^T$, (b) $W^L \geq W^T > W^V$, (c) $W^V > W^L \geq W^T$ with weak threat, (d) $W^T > W^L \geq W^V$ with large K, or (e) $W^V \geq W^T > W^L$ with weak threat and large K;

EQ 2. Tax policy is implemented

if (a) $W^T > W^L \geq W^V$ with small K, (b) $W^T > W^V > W^L$ with small K, or (c) $W^V \geq W^T > W^L$ with weak threat and small K;

EQ 3. VA is implemented

if (a) $W^V > W^L \geq W^T$ with sufficient threat, (b) $W^V \geq W^T > W^L$ with sufficient threat, or (c) $W^T > W^V > W^L$ with large K;

where in the pre-commitment case the situations of EQ 1(c) and EQ 2(c) would not occur.

5. Numerical Simulation and Welfare Analysis

The foregoing has shown that, under certain conditions, two alternative instruments, tax policy and VA, are able to achieve the targeted emission level in the industry. Unfortunately, we are unable to provide analytical results to characterize equilibrium outcomes for the VA scenario. Hence, we resort to numerical simulations to explore the equilibrium characteristics of the two regulatory instruments, including their impacts on social welfare.

5.1. Illustration of Equilibrium

Consistent with our partial equilibrium framework, social welfare (W) is defined as the sum of producer surplus (PS) and consumer surplus (CS) net of the environmental externality (EX), whereas tax revenue (RV) is added to them for the case of a tax policy. Alternatively, W can be calculated by integrating under the demand functions, while netting out all social costs (production and externality costs). Recall that the market is uncovered with two threshold values, $\theta_n = (p_n - p_o)/s$ for green goods and $\theta_o = p_o$ for conventional goods. Then, aggregate welfare is computed as:

(16) $$W = \int_{\theta_n}^{\overline{\theta}} (1+s)\theta d\theta + \int_{\theta_o}^{\theta_n} \theta d\theta - (c_n Q_n + c_o Q_o) - x(e_n Q_n + e_o Q_o),$$

where $Q_n = \overline{\theta} - \theta_n$, $Q_o = \theta_n - \theta_o$, and x is the (constant) marginal externality costs from one unit of emission.

In order to illustrate possible equilibrium outcomes including social welfare, specific values of parameters are chosen as in Table 1 by preserving internal coherence within the model. First of all, $\overline{\theta}$ is normalized to 1 and thereby $\underline{\theta} = 0$ (to determine the degree of heterogeneity between consumers and ensure that the market is uncovered). c_o is set by 0.1 which is consistent with Assumption 1. e_o is normalized to 1 so that producing one unit of conventional good causes one unit of emission. For features of green goods, c_n is 20 % higher than c_o and e_n is 20 % lower than e_o, reflecting a situation that green goods are less cost-effective but more emission-effective. x is set to 0.02, that is 20% of marginal cost of conventional good. Note that the difference in production costs between green and conventional good, $c_n - c_o$, is 0.02. Then s is chosen by 0.03 which is 1.5 time of the cost difference, thereby satisfying the Assumption 1.[11] As for concentration in the oligopolistic market, in the baseline we set $N = 20$. Based on the assumed parameters and welfare function, we can obtain the following welfare-maximizing targets: $\overline{E}^T$ that maximizes the welfare under the tax policy and $\overline{E}^V$ that maximizes the welfare under the VA, where each maximum level is unique (as either interior or corner solution). For the time being, assume no political cost ($K = 0$).

Table 2 describes the outcomes of all terminal nodes in Figure 1, based on the assumed parameters in Table 1, where only columns (1) to (3) can happen in equilibrium. For display purposes, the equilibrium number of green firms (or participants under the VA) are rounded to the nearest integer. First, the resulting industry-wide emissions are lowest under the VA. The social welfare is highest under the VA, followed by the tax policy and the *Laissez faire* case. In the case of pre-commitment, thus, a VA is implementable based on the minimum feasible threat that makes the equilibrium profits for a green firm to be the same under the VA (column 3) as under the threat policy (column 4) (EQ 3(a) in Proposition 4). In the case of time consistency, however, the VA is not implementable because the threat is too weak to make the VA profitable (column 2). Then, if the political cost is insignificant (K <0.000018), the tax policy would be implemented (EQ 2(c) in Proposition 4); if large (K ≥0.000018), the *laissez faire* situation would occur (EQ 1(e)).

Other features between tax policy (column 2) and VA (column 3) from Table 2 are as follows. In terms of total production costs TC, the VA is less efficient than the tax policy in maximizing welfare. This is because under the VA more firms are forced to use the new technology with a higher marginal cost. For CS and PS, the VA generates more surplus than the tax policy.

[11] When defining marginal social costs as $c_n + xe_n$ and $c_o + xe_o$, the difference $c_n - c_o + x(e_n - e_o)$ is smaller than $c_n - c_o$ given that $e_n < e_o$ and $x > 0$. Therefore, under Assumption 1 the additional social costs of the green good is also covered by the consumer of highest willingness-to-pay.

Given the non-competitive situation (N=20), the main reason for the higher CS is that there is more total output in the market under the VA than under the tax policy. Relative to the tax policy, under the VA the segment of the covered market expands for green goods and in turn for total goods (recall that the market coverages for two goods are measured by $Q_n = \bar{\theta} - \theta_n$ and $Q_o = \theta_n - \theta_o$, respectively). Also, the tax exemption under the VA makes PS greater despite of the decrease in prices of both goods. Overall, even after taking tax revenue RV into account, net social welfare W is higher under the VA than under the tax policy, provided the VA is successfully implemented.

5.2. Comparative Analysis of Welfare Levels

Considering the baseline results in Table 2 as a snapshot, further scrutiny is needed for a more general assessment of equilibrium characteristics. In this section we thus conduct comparative analysis. To look at how the maximized welfare behaves, we plot the maximized welfare level when changing one parameter at a time (See Figure A1). We also plot the market output and price as well as consumer surplus with respect to changes in the additional benefit from purchasing a green good (s) (See Figures A2). For this comparative analysis, the following ranges are considered: $c_o \in$[0.095, 0.105], $c_n \in$[0.115, 0.125], $e_o \in$[0.95, 1.05], $e_n \in$[0.75, 0.85], $s \in$[0.02, 0.04],[12] $x \in$[0.015, 0.025], and $N \in$[5, 150]. The range of N is set to cover both more and less competitive situations, while other ranges are set to have the assumed values in Table 1 as their mean. $\bar{\theta}$ is still set to 1, and K is ignored which is irrelevant to welfare. Whenever changing a parameter, the welfare-maximizing target and tax rate are recalculated and applied for the outcomes.

It turns out that for both VA and tax policy, the maximized welfare level decreases in c_o, c_n, e_o, e_n, and x.[13] Also, it is increasing in s, as expected. The comparative analysis shows that the VA, if it is successful, yields higher welfare than the tax policy with small N, while this is reversed as N becomes large. The reason for this feature is as follows. For a given N, the exemption of the

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[12] Based on the assumed ranges, the highest difference in social costs between green and conventional goods is 0.0285, while the lowest is 0.0025. We set the lower bound of s as 0.02, while setting the upper bound by 0.04 to have the mean as 0.03. This range brings in cases that s is small to cover the gap of social costs between two goods as well as the opposite cases.

[13] In particular, for x we have $\partial W/\partial x = -E$ from equation (16), meaning that the welfare decreases in x and the decrease becomes larger when total emissions are heavier.

emission tax under the VA has two effects in general: i) in the absence of the tax burden, firms produce more outputs in total than the tax policy, yielding higher aggregate CS and PS, and ii) the regulator loses a method to make up the social costs of externality (i.e., no tax revenue). When N is small, the first effect overwhelms the second effect resulting in a higher social welfare under the VA. But as N increases, the market becomes more competitive with more total output. Then the total externality becomes more important than the under-production issue, thereby tax policy performs better in maximizing welfare.

Given that the VA improves welfare partially by increasing overall consumer surplus (in a non-competitive situation), not all consumers always gain from it. Based on more green firms, the welfare-maximizing VA results in more green goods and less conventional goods than the welfare-maximizing tax policy. As a result, the total market can be either more covered or less covered (the former happens in the illustration of Table 2). As the consumer's additional benefit (s) increases, however, the welfare-maximizing VA reduces the total output, while the tax policy increases it. As a result, when s is sufficiently large, the total market is less covered and the price of conventional goods is higher under the VA than under the tax policy. This is mainly because when maximizing welfare for a higher s, the tax policy lowers the tax burden for all firms in the industry, while the VA directly increases the number of green firms, which exploits the increased willingness-to-pay, while letting free-riders (i.e., non-participants) enjoy the reduced competition with a higher price.

5.3. Sensitivity Analysis

To gain further insights into the equilibria that arise in this model, and what instrument is implemented in order to enhance the social welfare, here we conduct a sensitivity analysis that explores the parameter space as follows. Each parameter is randomly drawn from a uniform distribution 10,000 times. Keeping $\bar{\theta} = 1$, the aforementioned ranges of six parameters in the comparative analysis, c_o, e_o, c_n, e_n, s, and x, are considered where their mean values are the assumed values in Table 1. For N, we focused on two scenarios: a less-competitive situation with $N \in [5, 35]$; and the more-competitive situation of $N \in [75, 125]$. We assume the political cost is zero during the simulation ($K = 0$). To illustrate the procedure, for each simulation, s is randomly drawn from uniformly distributed range [0.01, 0.05], c_o is drawn from [0.095, 0.105], and so on for remaining parameters. For each vector consisting of drawn values for seven parameters, we check whether the set of drawn values satisfies Assumption 1. If it does not, we consider the drawn vector as an invalid situation. Only for valid cases, we calculate the equilibrium outcomes including the social welfare. Then for each simulation we check which equilibrium occurs under what circumstance.

Table 3 reports simulation results. Out of 100,000 simulations, 8,723 cases (about 10%) are sorted into invalid cases (which do not depend on the level of N, so the same number of invalid cases applies for both ranges of N). For valid cases (about 90% of 100,000 cases), there are eight possible situations ending up with one of three possible equilibria. (Given that $K = 0$, EQ 1(d), EQ 1(e) and EQ 3(c) in Proposition 4 are excluded). We first look at the case of $N \in [5, 35]$. In the pre-commitment case the VA is the only policy implemented because it yields highest welfare for all valid cases. Within them, for more than 70% of cases the tax policy yields second highest welfare level (which is the case for the results of Table 2). But as long as it is implementable via a credible commitment, the VA will be chosen. Next, if the regulator has no commitment power, such that only the time-consistent threat level is effective, the VA becomes far from an implementable option: only 0.1% of valid cases end up with successful VAs. Instead, for three-fourths of valid cases the tax policy is implemented, and for a fourth no policy is implemented. Thus, even though the VA yields highest welfare in an oligopolistic situation, a strong threat is essential to actually implement it. When examining more competitive situations by $N \in [75, 125]$, the same feature is found. One difference is that there are more cases in which the tax policy yields highest welfare. As noted in the foregoing comparative analysis, this is mainly because in a more competitive market there would be more outputs produced (thereby the merit of the VA decreases) and in turn more emissions, which increases the need for correcting the externality (thereby the *laissez faire* becomes less desirable).

In addition, we can think about the role of the political cost K. To be specific, for the cases of EQ 2(c), in which the tax policy is implemented due to the weak threat under the VA, the number will decrease as K increases, yielding more cases with the *laissez faire* (i.e., the cases move from EQ 2(c) to EQ 1(e)). Then, actually the lowest welfare level among three possible outcomes is achieved. For the cases of EQ 2(b), in which the tax policy is implemented to achieve highest welfare, the number will decrease as K increases and there will be more cases of the VA implemented if the threat is working (i.e., the cases move from EQ 2(b) to EQ 3(c)) or there will be more cases of the *laissez faire* if the treat under the VA is not sufficiently strong (i.e., the cases move from EQ 2(b) to EQ 1(d)). Then, for the pre-commitment case, the VA is going to be the second best option for the regulator who wants to avoid the political cost and has the power to commit. For the time-consistency case, on the other hand, it would be highly likely ending up with the *laissez faire* situation and thereby the industry face with the lowest welfare level among three options.

6. Conclusion

This paper analyzes the incentives for firms to participate in a voluntary agreement in the presence of two compelling motives—green consumers and a potential regulatory threat. A voluntary agreement in this paper refers to an environmental agreement initiated to reduce industry-wide emissions through the promotion of an environmentally friendly technology. Firms have a binary choice for technology: an old (dirty) technology, and a new (clean) one. The voluntary agreement requires member firms to use the new (greener) technology. In this setting, choosing the new technology enables firms to differentiate their products as well as to join in the voluntary agreement. Therefore, participation in a VA can be motivated in terms of appealing to green consumers as well as avoiding the potential tax policy.

Throughout the analysis, we find that a VA can improve welfare over the tax policy in a non-competitive market. This result buttresses the use of VAs in oligopolistic situations, where firms find that being a participant in a VA is another channel to appeal to consumers via product differentiation. But we also find that, because of free-riding behavior, the VA can hurt consumers who have lower willingness-to-pay for green products by leaving them to non-participants firms. In particular, as consumers' common valuation for the green good rises, the VA, relative to the tax policy, generates more green firms, yielding a less competitive market for free-riders. Hence, the overall coverage of the market could be lower under the VA, although the equilibrium outcome still gives higher overall consumer surplus.

Whereas VAs have clear potential as instruments for emission reduction, implementation issues remain. The major obstacle concerns the question of whether the regulatory threat—a critical component of a VA policy—is credible and strong enough to encourage the participation. We find that, if the regulator's commitment is credible regardless of its severity, the VA can be successful whenever it guarantees higher welfare than other policy options. In particular, the existence of political costs of regulation would tilt policy preference towards the VA, relative to a Pigouvian tax. The crucial issue, however, concerns the credibility of the threat required to ensure firms' participation in the VA. We find that if the policy is required to be time-consistent, the threat is considerably weakened, and it is almost infeasible to ensure the VA success, despite the fact that, in our context, consumers' green preferences provide an additional incentive for emission reduction.

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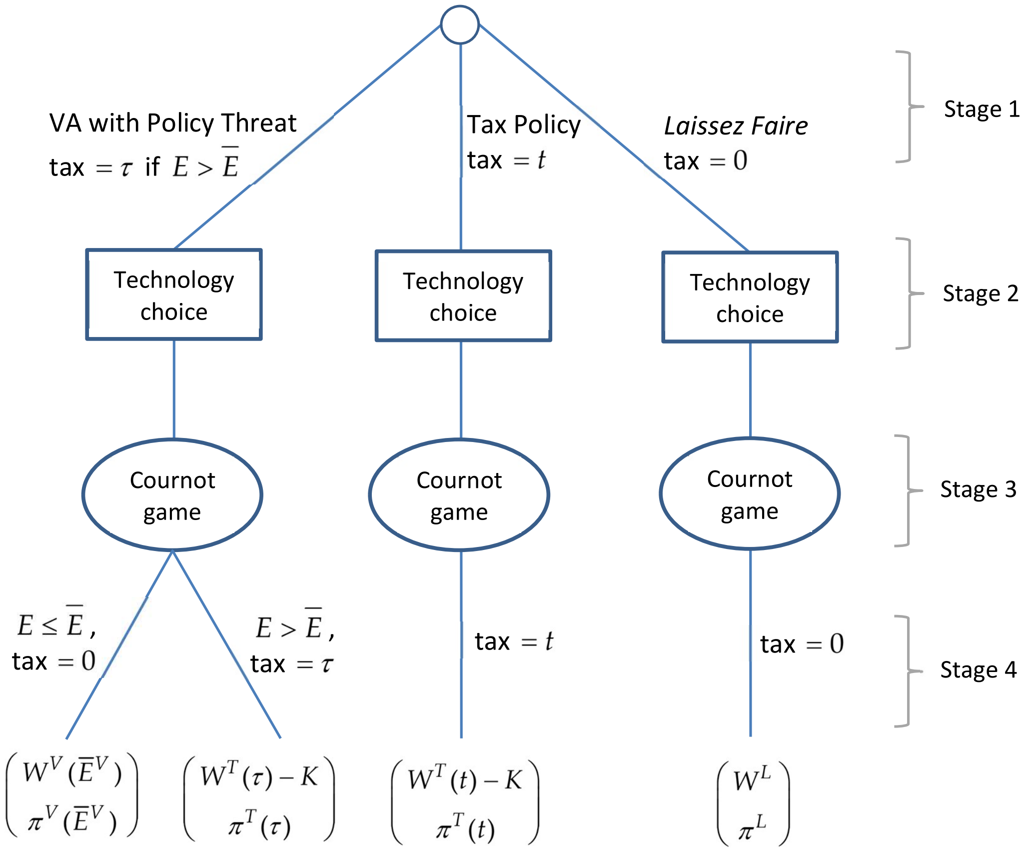
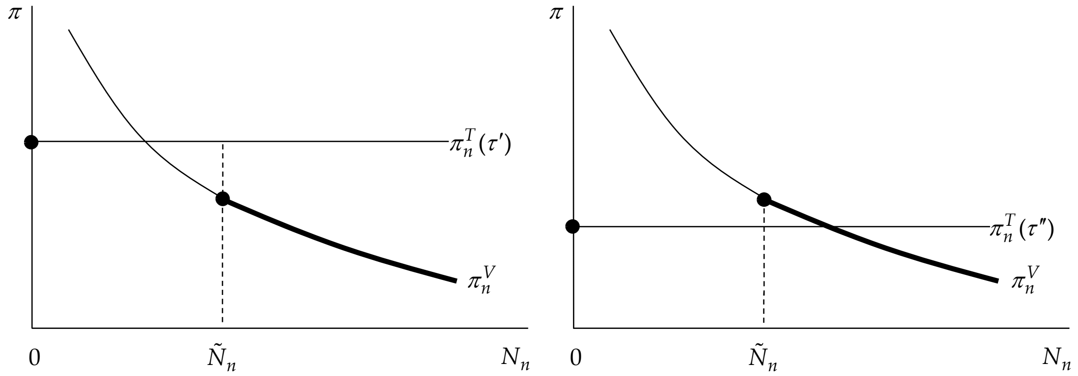
Figure 1. Policy Game



Note: This figure illustrates the structure of the policy game. The conventional moves first by choosing one of three policy options. Firms' have two sequential choices. First, they choose a technology: new (clean) or old (dirty). Second, given their technology, they compete a la Cournot (marginal costs are different). For the VA policy branch, if the industry emission constraint is not met, the "threat" tax $= \tau$ is imposed. Terminal nodes report the payoffs to regulator and firms, respectively.

Figure 2. Profits for an Individual Green Firm under the VA Tax Threat



(a) VA participation is not profitable (b) VA is profitable for a range of N_n

Figure 3. Set of Feasible Targets under the VA and the Tax Policy

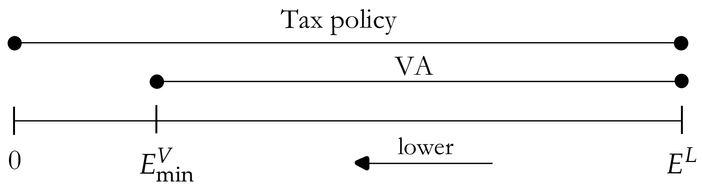


Table 1. Selected Values for Parameters

Parameter	Description	Value
$\overline{\theta}$	Upper bound of uniformly distributed preference ($\underline{\theta} = \overline{\theta} - 1$)	1.00
s	Additional benefit for consuming a green good	0.03
c_o	Marginal cost per conventional good	0.10
c_n	Marginal cost per green good	0.12
e_o	Marginal emission per conventional good	1.00
e_n	Marginal emission per green good	0.80
x	Marginal externality costs per unit of emission	0.02
$\overline{E}$	Emission target	$\overline{E}^V$ or $\overline{E}^T$
N	Total number of firms in the industry	20

Note: Given the parameters, E^V_{min} =0.6740< $\overline{E}^V$ =0.7650< $\overline{E}^T$ =0.7854< E^L =0.7945.

Table 2. Representative Terminal Node Outcomes

	Laissez faire (1)	Tax policy (2)	VA (3)	VA failure (threat is imposed) (4)
N_n	7	8	11	14
q_n	0.0424	0.0423	0.0406	0.0406
q_o	0.0431	0.0429	0.0453	0.0412
Q_n	0.3120	0.3387	0.4484	0.5982
Q_o	0.5450	0.5144	0.4062	0.2178
Q	0.8569	0.8531	0.8547	0.8160
p_n	0.1637	0.1667	0.1619	0.1961
p_o	0.1431	0.1469	0.1453	0.1840
π_n	0.0019	0.0018	0.0017	0.0017
π_o	0.0019	0.0018	0.0021	0.0017
E	0.7945	0.7854	0.7650	0.6963
RV		0.0031		0.0298
EX	0.0159	0.0157	0.0153	0.0139
TC	0.0919	0.0921	0.0944	0.0936
CS	0.3686	0.3656	0.3683	0.3383
PS	0.0371	0.0368	0.0372	0.0340
W	0.3898	0.3899	0.3901	0.3882

Note: For tax policy $\overline{t}$ =0.0040, while the minimum effective threat for VA is $\overline{\tau}$ =0.0428.

Table 3. Simulation Results (100,000 draws; 8,273 invalid cases violating Assumption 1)

		$N \in$ [5, 35]		$N \in$ [75, 125]	
	Implemented Policy	Pre-commitment	Time consistency	Pre-commitment	Time consistency
EQ 1(a)	*Laissez faire*	-	-	-	-
EQ 1(b)	*Laissez faire*	-	-	-	-
EQ 1(c)	*Laissez faire*	-	23,588	-	-
EQ 2(a)	Tax policy	-	-	-	-
EQ 2(b)	Tax policy	-	-	55,200	55,200
EQ 2(c)	Tax policy	-	68,013	-	36,479
EQ 3(a)	VA	23,588	-	-	-
EQ 3(b)	VA	68,139	126	36,527	48
Total valid cases		91,727	91,727	91,727	91,727

Note: Parameters are drawn from following ranges: $\bar{\theta} = 1$, $s \in$ [0.02, 0.04], $c_o \in$ [0.095, 0.105], $e_o \in$ [0.95, 1.05], $c_n \in$ [0.115, 0.125], $e_n \in$ [0.75, 0.85], $x \in$ [0.015, 0.025]. K is assumed to be zero.

Figure A1. Effects of Parameter Changes on Maximized Welfare

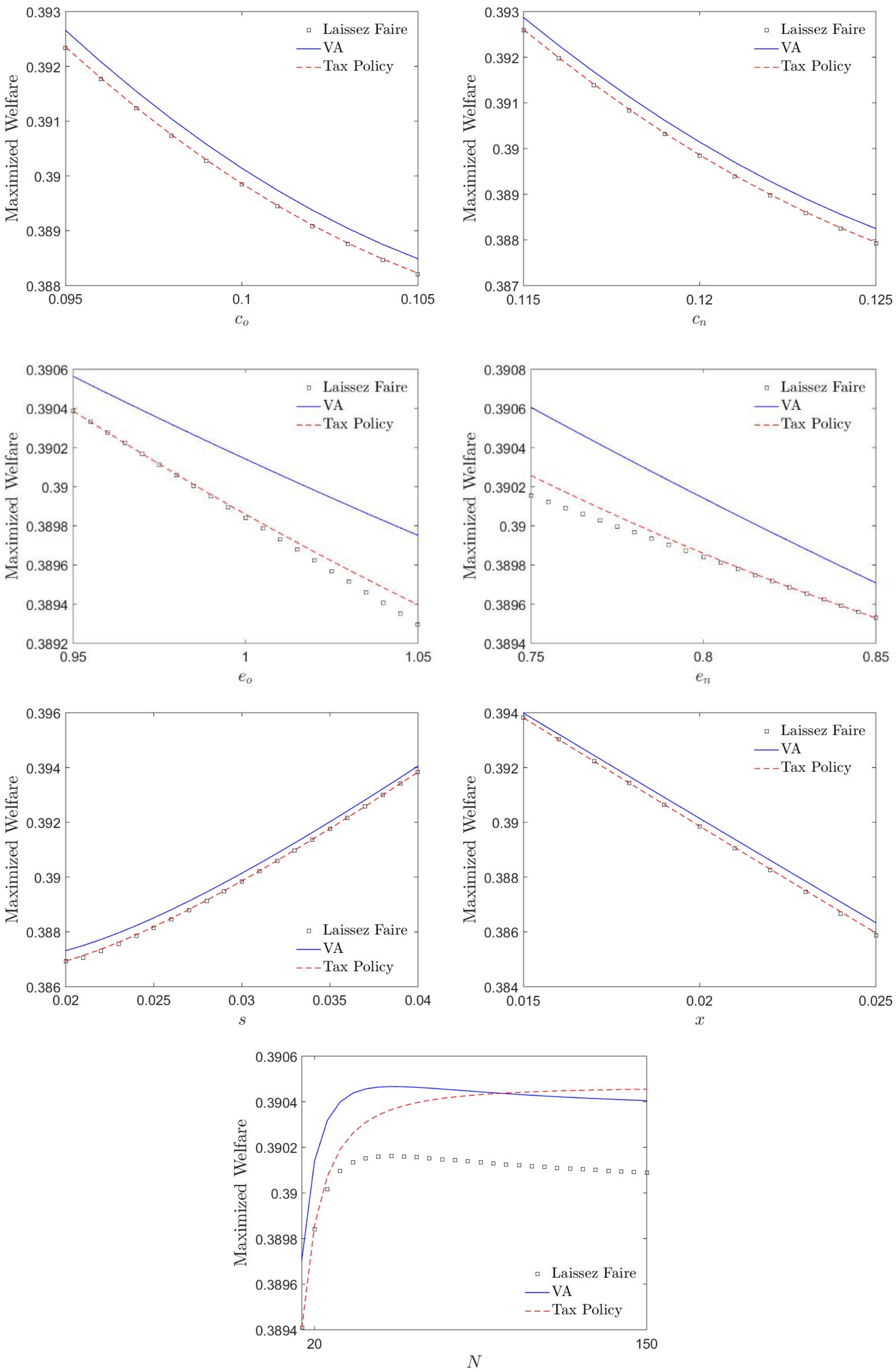
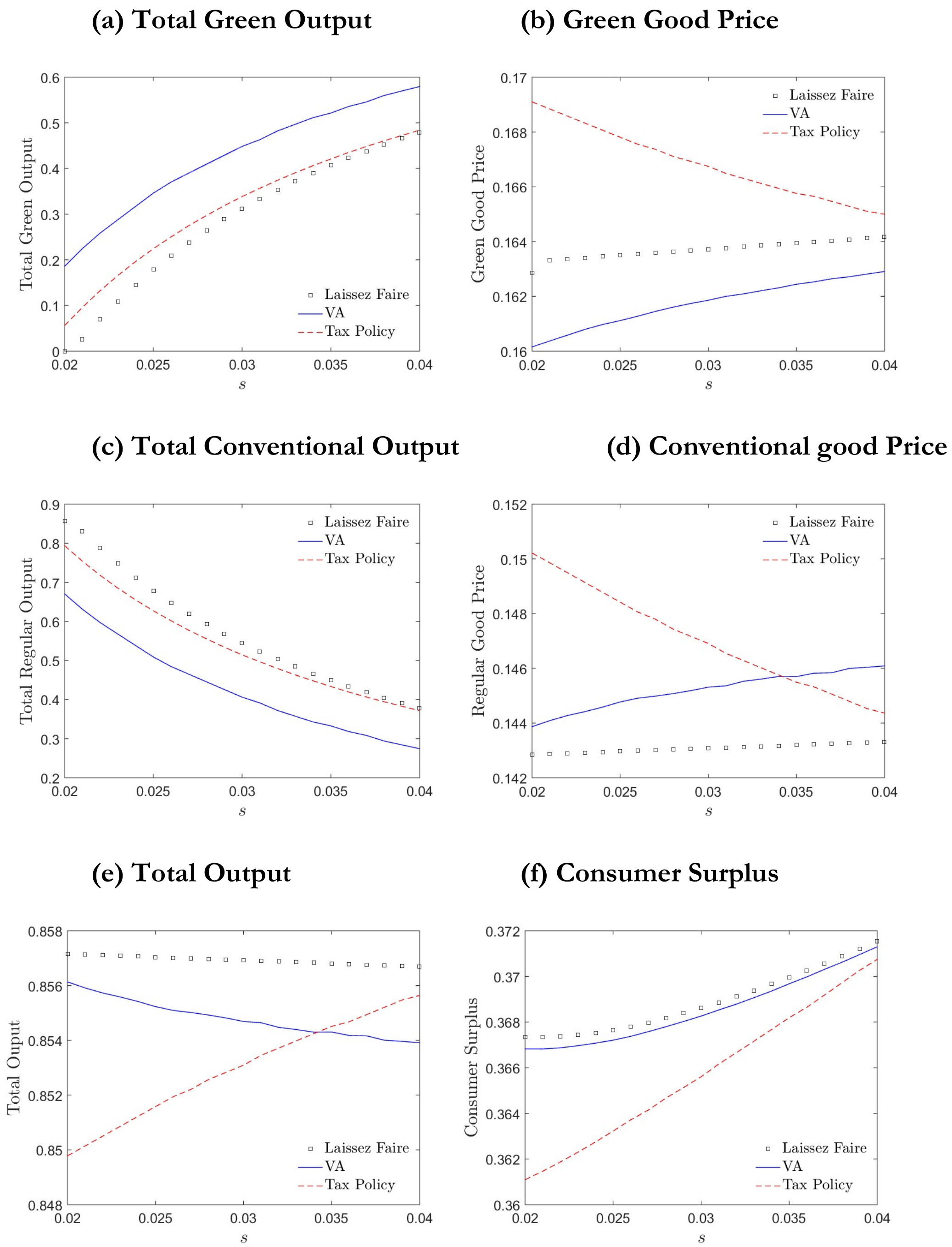


Figure A2. Effects of Changes in Consumers' Additional Benefit from a Green Good (s) on Markets



Appendix – Proofs

… To be added.