Impact of regulatory intervention and consumer environmental concern on product introduction

ABSTRACT

To meet consumer expectations for greener and better quality products and to ensure effective compliance with emissions regulations, firms have begun investing in improving the quality and greenness (low carbon level) of existing products. Emissions regulations currently restrict carbon emissions from product manufacturing rather than the emissions from the use of sold products. However, a large amount of carbon may be emitted from the use of products. Motivated by these issues, we analytically investigate the impact of environmental concern and the policies of regulators, and consumer environmental concern on product introduction. Our results show that (i) whether emissions trading regulations benefit firms depends on the quality improvement capability, and the interaction between emissions price and allowed emissions cap; (ii) the environmental concern of consumers helps firms obtain higher profits when quality improvement capability is relatively high, and always benefits environmental performance; and (iii) relatively low environmental concern set by regulators is detrimental to the maximization of social welfare, whereas high regulator environmental concern helps to maximize social welfare but at the expense of reducing firms' profits.

Keywords: Product introduction; Social welfare; Emissions cap; Quality improvement capability; Environmental concern.

1. Introduction

Concerns over global warming and air pollution have resulted in more and more countries and regions introducing and implementing emissions regulations to restrict firms' carbon emissions. We focus on two emissions regulations, namely strict emissions cap and emissions trading regulations. A strict emissions cap effectively regulates the emissions from firms when they manufacture products, which is currently receiving significant attention by environmentalists and environmental protection organizations. China has implemented carbon cap policy (Ghosh et al., 2017). In addition, firms have begun using eco-labels, which can be deemed a voluntary emissions cap (Murali et al., 2019). Moreover, in a recent poll conducted by Yale University, more than 64% of respondents supported imposing strict carbon cap (Ghosh et al., 2017). Meanwhile, market-based emissions trading regulations (i.e., cap-and-trade) that allow firms to buy or sell allowances in compliance with regulations are the foremost concern of economists. For example, China's recent initiatives to control carbon emissions deploy an emissions trading regulation (Anand and Giraud-Carrier, 2020). In addition, the Australian government has employed an emissions trading regulation since 2015 (Zakeri et al., 2015). Furthermore, several bills in the US Congress have proposed emissions trading regulations (Drake et al., 2016).

Aside from ensuring effective compliance with emissions regulations, many firms also hopefully are able to meet consumer expectations for greener and better quality products by improving existing products to increase market share and enhance profitability. For many electronic products (e.g., PCs), firms frequently introduce improved products, providing consumers with an opportunity to use better and improved products (Agrawal and Ülkü., 2013). For example, Apple continues to launch more advanced iPhones.

All of the abovementioned regulations and practices have a profound impact on the green operation and long-term profitability of firms, especially those that manufacture and sell energy using products.

For energy using products such as network equipment, household appliances, and electric vehicles, one source of environmental impact comes from the carbon emissions when using these products. According to an EPA report, private cars emit approximately 25.35% of the total carbon emissions because of consuming gasoline (EPA, 2011). Furthermore, a survey from China Science Daily reveals that a large proportion of emissions come from a combination of car battery chargers and from the driving mileage of electric cars (China Science Daily, 2019). In addition, a report from Walmart shows that when refrigeration equipment is used in retail stores, those emissions are much higher than what are generated in manufacturing processes (Chen et al., 2013). Toshiba also stated in its 2012 annual report that the use of its electronic products after sale accounted for 88% of its carbon emissions

(Toshiba, 2012). In addition, another major source of environmental impact is the carbon emissions from product manufacturing. For example, more than 68% of Nokia N8's carbon emissions are released during the manufacturing stage (Nokia, 2012).

From a practical perspective, emissions regulations currently tend to restrict carbon emissions from product manufacturing, but rarely restrict emissions from product use. However, as discussed above, a large amount of carbon may be emitted from the use of products. Consequently, the general environmental impact of emissions regulations is not readily apparent. In other words, urging firms to emphasize reducing carbon emissions during the use stage when introducing upgraded products is very important for improving environmental performance (i.e., lowering carbon emissions) and even social welfare. To accommodate this possibility, we explore two sources of environmental concern, one is consumer environmental concern and the other is regulator environmental concern. For example, a survey conducted by Nielsen in 2015 revealed that 51% of consumers were willing to pay more for green products (Hafezi and Zolfagharinia, 2018). In practice, environmentally concerned consumers are not only concerned about green product improvement (e.g., improving energy use efficiency), but are also willing to pay higher prices for low carbon manufacturing improvements (Deltas et al., 2013). Clearly, the presence of environmentally concerned consumers focusing on carbon emissions from their use of products affects product introduction and profitability of firms. Furthermore, governments that indirectly set the level of environmental concern urge firms to introduce upgraded products effectively to maximize social welfare. Indeed, there seems to be an unclear understanding of how the environmental concern of consumers and regulators affects product introduction. Generally speaking, regulatory intervention is more universal than consumer environmental concern in influencing carbon emissions. In addition, consumers have great differences in the carbon emissions from product manufacturing and the use of products. Moreover, the environmental concern of consumers is relatively more difficult to quantify accurately. Considering this discussion, persuading and educating consumers to be more environmentally concerned may be not the focal discussion. From a theoretical perspective, few studies have explored the fundamental interaction between product introduction, carbon emissions regulations and product carbon emissions characteristics. Thus, balancing all of these factors is the focus of this paper.

Overall, our analysis will be of significant theoretical and practical support for both firms that manufacture and sell energy using products and regulators that are facing the challenge of maximizing social welfare. First, compared with having no regulatory intervention, whether emissions trading regulations that employ a more flexible incentive mechanism benefit firms depends on the quality improvement capability, as well as the interaction between the emissions price and emissions cap. Second, the environmental concern of consumers has a farther reaching impact on product introduction than regulator environmental concern because attracting consumers is an appealing incentive to firms while adhering to regulations to avoid punitive measures is a negative incentive.

The remainder of this paper is organized as follows. We provide a review of related literature in Section 2. We present the basic model in Section 3. We then study effect of carbon regulations on product introduction in Section 4. In Section 5 and Section 6, we examine impact of consumer environmental concern and regulator environmental concern on product introduction, respectively. Managerial implications for practice and for research are explored in Section 7. In Section 8, we provide concluding remarks.

2. Literature review

Our paper draws on the following research streams: emissions regulations, product introduction, and environmental concern. The first related stream of research examines emissions regulations. Research on emissions trading regulations include Kuiti et al. (2020), who study a manufacturer-retailer channel selling complementary green products under the emissions trading regulation and analyse strategic decisions in various settings. Anand and Giraud-Carrier (2020) show that cap-and-trade can improve firm's profits, consumer surplus, and welfare. In addition, Chai et al. (2018) explore the possibility of a monopolistic manufacturer involved in both manufacturing and remanufacturing to profit under emissions trading mechanism. Moreover, Yuan et al. (2018) examine how to deal with the interaction between volatile emission price and stochastic demand under emissions trading regulation. Sabzevar et al. (2017) study the impact of emissions trading regulations and price sensitive demand on the profitability of competitive firms. While Ji et al. (2017) examine the optimal emissions reduction strategy of O2O retail supply chain members under emissions trading regulations. Furthermore, Hong et al. (2017) investigate a policy-making problem for a local government to implement an emissions trading regulation. They reveal that governments should set emissions reduction targets appropriately. In addition, Subramanian et al. (2007) characterize the trade-offs among firms' compliance strategies in a market-based program where a regulator interested in controlling emissions from a given set of sources auctions off a fixed number of emissions permits. Zakeri et al. (2015) compare the supply chain performance under carbon tax and emissions trading regulation. Benjaafar et al. (2013) examine how concern about carbon emission could be integrated into operational decision-making. Drake et al. (2016) compare the impact of emissions tax and emissions trading regulation on a firm's technology choice and capacity decisions. These studies do not include product introduction decision as we do. Moreover, concerning research on strict cap regulations, Qi et al. (2017) examine the pricing decision based on a two-stage supply chain under strict cap regulation. Ghosh et al. (2017) study the optimal batch size under emission cap regulation and stochastic demand. In addition, Hammami et al. (2015) examine the production and inventory modelling of multi-level supply chain under emission cap. While Chen et al. (2013) examine conditions under which the relative reduction in emissions is greater than the relative increase in cost. These studies do not consider the effect of emission cap on product introduction. In addition, there is also a growing body of literature on how regulation maximizes social welfare. A closely related paper is that by Murali et al. (2019), who examine the impact of voluntary eco-labels and mandatory regulation on green product development among competing firms, but do not compare emissions regulations or consider consumer environmental concern whereas our work focuses on these two aspects. Krass et al. (2013) find that when the regulator is moderately concerned with environmental impacts, the tax level that maximizes social welfare can motivate the choice of clean technology. In contrast to these studies that account for the impact of emissions regulations on operation and supply chain management, we examine how emissions regulations affect product introduction.

The second related stream of research examines product introduction. For example, Liang et al. (2014) examine the interaction between product rollover strategies and strategic consumer purchasing behavior. They do not consider emissions regulations. Agrawal and Ülkü (2013) investigate when modular upgradability leads to lower environmental impact and higher profits, and do not deal with the emissions regulations whereas we complement this literature by analytically examining the impact of emissions regulations on product introduction. Plambeck and Wang (2009) investigate the impact of e-waste regulation on new product introduction. The focus of our research is different, we study emissions regulations. Tseng et al. (2016) study sustainability innovations on firms and government regulations. Tan et al. (2017) find that harvesting big data can help to deliver better fact-based decisions aimed at improving product quality. Tseng et al. (2018b) draw conclusions that firms should maintain operations and aim for business synergy in self-generated innovative products along with high-quality products, and product innovations. Furthermore, Krishnan and Ramachandran (2011) find that design inconsistency of modular upgradablity lowers consumer surplus and results in environmental waste. Unlike these studies focusing on e-waste regulation or modular upgrade decisions, we focus on the impact of emissions regulatory intervention on product introduction.

Third, our work is closely related to environmental concern. Liu et al. (2012) examine the impact of consumers' environmental concern on the coordination of key supply chain players, players, where consumer environmental concern can be explained as consumers that are willing to pay higher prices for more eco-friendly products. Furthermore, Servaes and Tamayo (2013) conclude that corporate social responsibility and firm value are positively related for firms with high consumer concern, and Deltas et al. (2013) study the consumers' concern about a product's greenness and how duopoly firms selling horizontally differentiated products select green products to comply with environmental regulation. However, these studies do not discuss emissions regulations. Attari et al. (2010) show well-designed efforts to improve the public's understanding of how energy use and savings could improve consumer environmental concern. Agrawal et al. (2012) explore the effect consumer environmental concern on the environmental performance of leasing. Tseng et al. (2018a) evaluate sustainable service supply chain management based on environmentally concerned design and environmental service operation design. In addition to consumer environmental concern, we focus on the environmental concern of the regulator.

To summarize the contribution of our work relative to existing literature, there has been no research that specifically focuses on supplementing product introduction, regulatory intervention, and emissions characteristics of products; our work incorporates all these aspects.

3. The model

Consider a firm (manufacturer) introducing original (existing) product 1V in period 1 and upgrading it to version 2V in period 2. We assume market demand as a mass of infinitesimal consumers, and each consumer has the most unit demand. The number of consumers N is fixed and does not change with time as in Agrawal and Ülkü (2013), which shows that the number of consumers is the same in period 1 and period 2. Similar to Plambeck and Wang (2009), we assume that consumers dispose of 1V after purchasing 2V.

The firm improves the quality and greenness of existing products. Concerning product quality, in period 1, the quality of the original product is ρ_1. A consumer's willingness to pay for 1V (i.e., the highest price she is willing to pay) is given by $WTP_1 = v\rho_1$, which is also the highest price that the firm can charge. Note that v denotes the consumer's marginal willingness to pay. First, the incremental quality (i.e., the level of quality improvement) is $\Delta\rho = \tau\lambda$, depending both on the introduction time of 2V (i.e., the usage time of 1V) τ ($\tau \in (0, \bar{\tau}]$) and the quality improvement capability λ of the firm (Agrawal and Ülkü, 2013; Plambeck and Wang, 2009). It is assumed that improving the level of product quality $\Delta\rho$ incurs a quadratic cost of $h(\Delta\rho)^2$, where h is an investment parameter, implying that higher levels of quality improvement require more investment as well as diminishing returns from quality improvement investments. In general, the quadratic function is used to describe the cost related to quality improvement. In period 2, the quality of 2V is represented as $\rho_2 = \rho_1 + \Delta\rho$. A consumer replaces 1V with 2V and obtains an incremental utility of $\beta v(\rho_2 - \rho_1) = \beta v\lambda\tau$, where β captures the depreciation in value due to the loss of utility in period 1 (Liang et al., 2014). A consumer's willingness to pay for 2V is given by $WTP_2 = \beta v\lambda\tau$, which is the highest sales price the firm is able to charge for 2V. At the end of period 2, 2V will be discarded. The unit production cost of 1V and 2V is equal to c.

Furthermore, to ensure effective compliance with regulations, green manufacturing improvement (also known as low carbon manufacturing), such as equipment upgrading and replacement (Muthulingam et al., 2013) and the design of more energy-efficient new materials (Deltas et al., 2013), could be implemented to reduce carbon emissions in the manufacturing process. Through green manufacturing improvement, the carbon emissions of 2V are $e_1 - \varepsilon_1\tau$, where e_1 denotes initial carbon emissions from manufacturing 1V, and $\varepsilon_1\tau$ is the emissions reduction during the manufacturing stage, depending on both introduction time τ of 2V and green manufacturing improvement capacity ε_1 of the firm. Thus, the total emissions from manufacturing 1V and 2V are $2e_1 - \varepsilon_1\tau$. Similarly, we assume that the costs of green improvement are given by $\xi_1(\varepsilon_1\tau)^2$, where ξ_1 is a green investment constant (see Liu et al., 2012).

We start by considering the basic case of neither regulatory intervention nor consumer environmental concern. Regarding the basic case, the firm's profits are denoted as

$$\Pi_B(\tau) = Nv\rho_1 + N\beta v\lambda\tau - h(\lambda\tau)^2 - 2cN \,. \tag{1}$$

Solving this optimization problem allows us to get the optimal introduction time of 2V $\tau^* = N\beta v/(2h\lambda)$, and the resulting optimal profit $\Pi_B^* = Nv\rho_1 + \frac{(N\beta v)^2}{4h} - 2cN$.

Proposition 1. *The optimal introduction time of 2V is decreasing in quality improvement capability. The optimal profit* Π_B^* *does not depend on* λ.

Proposition 1 reveals that as λ increases, the optimal introduction time of 2V decreases, implying that the firm changes from delaying introducing 2V to speeding up 2V introduction. Furthermore, the level of quality improvement ($\Delta\rho_B = \lambda\tau^* = \frac{N\beta v}{2h}$) does not depend on λ, meaning that even if λ increases, the firm's profit remains unchanged.

4. Emissions regulations

In this section, we account for the firm deciding on the introduction time of 2V under emissions regulations. As mentioned before, regulators largely restrict emissions generated by firms but rarely regulate the emissions from the use of products. Thus, firms have no incentive to reduce the emissions from the use of products.

4.1. Strict emissions cap regulation

To begin with, we focus our analysis on a strict cap regulation that imposes emissions cap B on firms, which is the maximum amount that firms can emit. Following convention (e.g., Zhu et al., 2017), we assume that the firm can bank any unused emissions allowance in period 1 for period 2, or borrow on the allowance of period 2 for period 1. In other words, as long as the firm's cumulative emissions within the entire sales horizon do not exceed B, it is free to store (or borrow) the emissions allowance over time. Under such a regulation, the optimization model of the firm is as follows:

Maximize $\Pi_C(\tau) = Nv\rho_1 + N\beta v\lambda\tau - h(\lambda\tau)^2 - \xi_1(\varepsilon_1\tau)^2 - 2cN$ (2)

Subject to: $(2e_1 - \varepsilon_1\tau)N \le B$ (3)

In Equation (2), the first item represents the revenue from the sale of 1V, the second item captures the revenue from the sale of 2V, the third item represents the costs of quality improvement, the fourth item represents green manufacturing improvement costs, and the last item is production costs of products. The constraint $(2e_1 - \varepsilon_1\tau)N \le B$ implies that the cap on carbon emissions is not exceeded.

Based on the optimization model, we obtain Lemma 1.

Lemma 1. *Under an emissions cap regulation, there exists a threshold* $B_1 = N[2e_1 - \frac{\varepsilon_1 N\beta v\lambda}{2(h\lambda^2 + \xi_1\varepsilon_1^2)}]$ *such that* (i) *if* $B \le B_1$, *then the optimal launch time of 2V is* $\tau_C = \tau_2 = \frac{1}{\varepsilon_1}(2e_1 - \frac{B}{N})$, τ_C *is decreasing in B but does not depend on λ.* (ii) *If* $B > B_1$, *then* $\tau_C = \tau_1 = \frac{N\beta v\lambda}{2(h\lambda^2 + \xi_1\varepsilon_1^2)}$, τ_C *does not depend on B; in addition, there exists a threshold* $\lambda_c = \varepsilon_1\sqrt{\xi_1 / h}$ *such that if* $\lambda < \lambda_c$, *then* $d\tau_C / d\lambda > 0$; *if* $\lambda \ge \lambda_c$, *then* $d\tau_C / d\lambda \le 0$.

See the Appendix for the proof.

Lemma 1 characterizes that when emissions cap *B* is less than B_1 ($B \le B_1$), a strict cap regulation has a strongly rigid constraining effect. Thus, the firm must slow down 2V introduction to reduce emissions in accordance with the emissions cap (i.e., the total emissions equal *B*) because the introduction time of 2V τ_2 only depends on *B*. In addition, as *B* increases, τ_2 gradually decreases. In contrast, when the emissions cap is greater than B_1, the strict cap regulation is no longer a stringent intervention and can be understood to have a weakly flexible constraining effect (i.e., the total emissions from product manufacturing are generally less than *B*); in light of this, τ_1 depends on λ instead of *B*. Specifically, when λ is relatively low ($\lambda < \lambda_c$), the firm slows down 2V introduction, which greatly reduces the emissions from manufacturing 2V but increases the costs of green manufacturing improvement. When λ is high ($\lambda > \lambda_c$), the firm is able to speed up 2V introduction, which slightly reduces the emissions of 2V and results in lower costs of green improvement.

Proposition 2. (i) Π_C^* *is increasing and then decreasing in λ; that is, there exists a threshold* $\lambda_C = \frac{N^2 \beta v \varepsilon_1}{2h(2e_1 N - B)}$ *such that if* $\lambda < \lambda_C$, *then* $\frac{d\Pi_C^*}{d\lambda} > 0$; *if* $\lambda > \lambda_C$, *then* $\frac{d\Pi_C^*}{d\lambda} < 0$.

(ii) *If* $B \le B_1$, Π_C^* *is increasing in B; if* $B > B_1$, Π_C^* *does not depend on B.*

See the Appendix for the proof.

Proposition 2 shows that, (i) an increase in quality improvement capability increases and then decreases a firm's profits. The reason for this is as follows: As λ increases, the firm changes from slowing down 2V introduction to speeding up 2V introduction, and this in turn gradually increases emissions from manufacturing 2V and reduces green manufacturing costs. Furthermore, increasing the level of quality improvement ($\Delta\rho_C=\lambda\tau_C$) leads to an increase in both the revenue from the sale of 2V and the cost of quality improvement. Taken together, when λ is less than λ_C, the increased revenue from the sale of 2V can compensate for the increased quality and green improvement costs, which enable the firm to gain higher profits. The opposite will hold for quality improvement capability that is above λ_C. Thus, when λ equals λ_C, accounting for the trade-off between the revenue from the sale of products, the costs of quality improvement and green manufacturing improvement effectively enables the firm to obtain the maximum profits.

(ii) With an increase in emission cap *B*, the firm's profits first increase, and then remain stable. This can be explained as follows: If *B* is less than B_1, this illustrates that a strict cap regulation applies stringent restrictions, so the firm must delay introduction of 2V. This in turn greatly invests in green manufacturing improvement to reduce emissions. However, increasing *B* continues to decrease penalties from the regulation, which prompts firms to invest in quality improvement rather than green improvement, thereby substantially increasing profits from the sale of products. In contrast, when *B* is greater than B_1, the strict cap regulation is no longer a stringent intervention (i.e., intervention remains stable). This leads to the investment in green improvement remaining unchanged. Thus, even if *B* is sufficiently greater than B_1, the firm's profits remain unchanged.

Proposition 3. *The firm's profit under a strict cap regulation is less than that without regulation, i.e.,* $\Pi_C^* < \Pi_B^*$.

See the Appendix for the proof.

Proposition 3 indicates that the profits gained by a firm under a strict cap regulation are lower than what can be achieved in the basic case. To understand this result, recall from the proof of Proposition 2 that $\Pi_C^*(\lambda_C) = \Pi_B^* - \xi_1(2e_1 - B/N)^2$, when λ = λ_C, the firm can earn the maximum profits of $\Pi_C^*(\lambda_C)$ being less than Π_B^*. This is because the level of quality improvement ($\Delta\rho_C = \lambda_C \tau_C$) and the resulting profit from selling both 1V and 2V are the same as those of the basic case. However, investing in green improvement reduces the total profit and makes it lower than what can be achieved in the basic case. Furthermore, as noted in the discussion of Proposition 2, when λ is greater than or less than λ_C, the firm's profits are lower than the maximum profits when λ=λ_C. As a result, the firm's profits under a strict cap regulation are generally less than what they are without regulation.

4.2. Emissions trading regulation

Regarding an emissions trading regulation, the regulator first sets the emissions allowance cap *B*, followed by firms ensuring effective compliance with the emission cap by buying or selling an emissions allowance. Specifically, if firm's carbon emissions are less than *B*, it can sell surplus allowances at the cost of emissions *P*. In contrast, if the firm emits more emissions than *B*, it needs to buy additional emissions allowances for *P*. Two key constraining parameters of this regulation are emissions price *P* and allocated allowances cap *B*. In practice, no firm under emissions trading regulation can substantially influence the emissions price through its own behavior regarding the reduction of carbon emissions, thus implying that both *P* and *B* are exogenous for firms (see Subramanian et al., 2007; Drake et al., 2016).

Similarly, consistent with the existing practice, emissions trading regulation mainly intervenes to reduce carbon emissions emitted during the manufacturing phase.

The firm's profits are therefore denoted as

$$\Pi_T(\tau) = Nv\rho_1 + N\beta v\lambda\tau - h(\lambda\tau)^2 - \xi_1(\varepsilon_1\tau)^2 - 2cN + P[B - (2e_1 - \varepsilon_1\tau)N]. \quad (4)$$

In Equation (4), the first two items represent the revenue the firm is capable of earning from selling 1V and 2V, respectively, the third item represents quality improvement cost, the fourth item captures green improvement costs, the fifth item denotes production cost, and the last item captures the revenue from trading emissions allowances.

Following the same logic as in Proposition 1, we obtain Proposition 4.

Proposition 4. *Under an emissions trading regulation,* (i) *the optimal launch time of 2V is* $\tau_T = \frac{N(\beta v\lambda + P\varepsilon_1)}{2(h\lambda^2 + \xi_1{\varepsilon_1}^2)}$. *Furthermore, there exists a threshold* $\lambda_t = \varepsilon_1[\sqrt{\frac{\xi_1}{h} + (\frac{P}{\beta v})^2} - \frac{P}{\beta v}]$ *such that if* $\lambda < \lambda_t$, *τ_T increases in λ; if* $\lambda > \lambda_t$, *τ_T decreases in λ.* (ii) *If* $\lambda < \lambda_T$, *then* Π_T^* *is increasing in λ; if* $\lambda > \lambda_T$, *then* Π_T^* *decreases in λ, where* $\lambda_T = \frac{\beta v\xi_1\varepsilon_1}{hP}$, *and* $\lambda_t < \lambda_T$.

Proposition 4 suggests that an increase in quality improvement capability increases and then decreases the optimal launch time of 2V, so the firm shifts from delaying sale of 2V to speeding up 2V introduction. This in turn leads to increasing *λ* increasing and then decreasing the firm's profits. Following the same logic as in Proposition 2, when *λ* equals λ_T, the firm earns the maximum profit of $\Pi_T^*(\lambda_T)$.

Concerning the interaction between *P* and *B*, we make the following simplifying assumptions. (i) *P* is independent of *B*. For example, a closely related paper is that by Benjaafar et al. (2013), who assume that an emissions price is exogenous to decisions made by a typical firm. They also suggest that the firm can employ financial options to guarantee a fixed emissions price. (ii) *P* decreases in *B*. First, based on the data of the second column (emissions cap) and the third column (emissions price) (Zakeri et al., 2015, p.202), we use the polynomial curve fitting method to fit the interaction between *P* and *B* as P = 12178.8-4595.1B +583.8B^2-24.8B^3, which fully reflects that the emissions price decreases in an emissions cap. Second, both Benjaafar et al. (2013) and Subramanian et al. (2007) examine the interaction between *P* and *B* by considering a simple linear carbon pricing model, thus implying that a higher emissions cap leads to lower emissions costs.

Based on the above simplifying assumptions, we have Proposition 5 that highlights the impact of emissions trading regulation on a firm's profits.

Proposition 5. (i) *If P is independent of B, (a) when* $P < P_1$, *then* Π_T^* *decreases in P; when* $P > P_1$, *then* Π_T^* *increases in P, where* $P_1 = \frac{1}{\varepsilon_1}[\frac{2(h\lambda^2 + \xi_1{\varepsilon_1}^2)(2e_1N - B)}{\varepsilon_1 N^2} - \beta v\lambda]$; *(b) there exists a threshold* $B_\Theta = N(2e_1 - \frac{PN}{4\xi_1})$ *such that if* $B \le B_\Theta$, *then* $\Pi_T^* \le \Pi_B^*$; *if* $B > B_\Theta$, *there exist two thresholds* λ_1 *and* λ_2 ($\lambda_1 < \lambda_2$) *such that if* $\lambda \le \lambda_1$ *or* $\lambda \ge \lambda_2$, *then* $\Pi_T^* \le \Pi_B^*$; *if* $\lambda_1 < \lambda < \lambda_2$, *then* $\Pi_T^* > \Pi_B^*$.

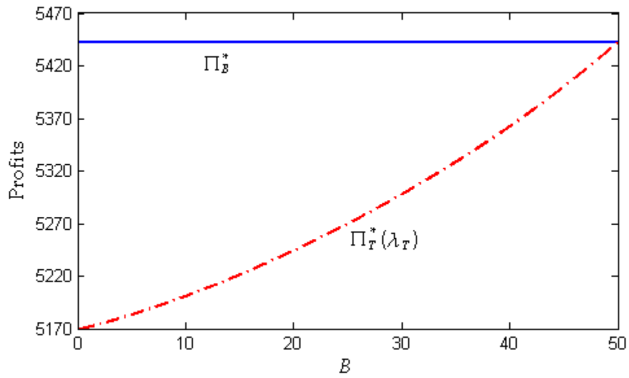
(ii) *If P decreases linearly in B, specifying* $P = a - bB$*, then* $\Pi_T^* \le \Pi_B^*$.

See the Appendix for the proof.

The condition $P = a - bB$ in Proposition 5 is sufficient but not necessary, where $a > 0$ denotes the emissions cost upper bound, and $b > 0$ indicates the level of cap sensitivity. In addition, in Fig.1 below, we also consider that *P* decreases nonlinearly in *B*. Specifically, let $P = a - bB^2$.

Proposition 5 reveals that, (i) if the price of carbon *P* and emissions cap *B* are independent, emissions trading regulations can be deemed an emissions tax levied by the regulators, where *PB* represent the value of free emissions allowances owned by the firm. By comparing Π_T^* and Π_B^*, we note that when $\lambda = \lambda_T$, the firm earns the maximum profit $\Pi_T^*(\lambda_T)$ under an emissions trading regulation. Because the level of quality improvement ($\Delta\rho_T(\lambda_T) = \frac{N\beta v}{2h}$) and the resulting profit from selling products are the same as the basic case, whether $\Pi_T^*(\lambda_T)$ is greater than Π_B^* depends on the revenue from trading emissions allowances. Specifically, if *B* is greater than B_Θ (i.e., the regulator's intervention is relatively low), the firm can get the revenue from selling its surplus emissions allowance at *P* because of green improvement. This results in its maximum profits being higher than what can be achieved in the basic case. In addition, as discussed before, increasing λ increases and then reduces the firm's revenue. In light of this discussion, when λ is relatively low ($\lambda \le \lambda_1$) or high ($\lambda \ge \lambda_2$), the profits of the firm under an emissions trading regulation is less than that of the basic case. For the intermediate value of λ ($\lambda_1 < \lambda < \lambda_2$), the firm's profit under an emissions trading regulation is higher than that of basic case. Conversely, if *B* is lower than B_Θ (i.e., the regulator's intervention is high), the firm will shift from selling its surplus emissions allowance to purchasing additional emissions allowances, which makes its profits lower than what can be achieved without regulations.

(ii) If *P* decreases in *B*, the firm's profits under an emissions trading regulation are less than what can be achieved in the basic case. This follows from that the firm's maximum profit $\Pi_T^*(\lambda_T)$ being not greater than Π_B^*. The logic of this is as follows: First, an extremely low *B* not only reduces the firm's free emissions allowances, but also increases the emissions price significantly. Thus, firms must incur higher emissions costs, implying that the revenue of green manufacturing improvement tends to be negative. Second, although a sufficiently high B increases the free emissions allowances endowed by the firm, it heavily reduces the emissions price and even tends to be zero; therefore, the firm still cannot obtain revenue from green improvement (i.e., the green revenue tends to 0). Third, increasing B increases the revenue of green improvement for the firm. Clearly, the profits from green manufacturing improvement are generally negative. This, together with the same profits obtained from selling products as the basic case, leads to lower total profits compared with having no regulatory intervention.



Note. $N = 70$, $v = 3$, $\rho_1 = 3$, $\beta = 1$, $h = 2$, $\xi_1 = 100$, $\varepsilon_1 = 0.05$, $c = 5$, $e_1 = 1$, a=2.5, b =0.001.

Fig.1. Effect of B on the firm's profits.

4.3 *Comparing carbon emissions*

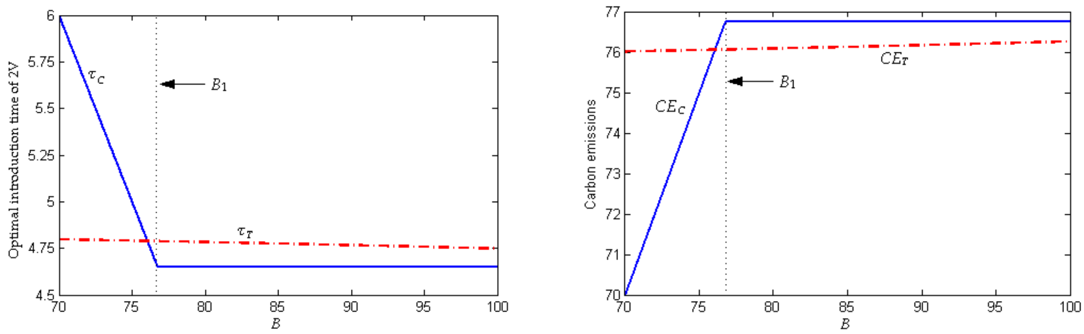
Proposition 6 compares the effects of the two regulations on carbon emissions emitted by firms in the manufacturing phase.

Proposition 6. (i) *If $B \le B_1$, and supposing that P does not depend on B, there exists a threshold $P^* = \frac{1}{\varepsilon_1}[\frac{2(h\lambda^2 + \xi_1\varepsilon_1^2)(2e_1N - B)}{N^2\varepsilon_1} - \beta v\lambda]$ such that if $P < P^*$, then $\tau_T < \tau_C$ and the total emissions under an emissions trading regulation is greater than that under a strict cap regulation (i.e., $CE_T > CE_C$); if $P \ge P^*$, then $\tau_T \ge \tau_C$, and $CE_T \le CE_C$.*

(ii) *If $B > B_1$, then $\tau_T \ge \tau_C$, and $CE_T \le CE_C$.*

Proposition 6 reveals that an emissions trading regulation is not necessarily conducive to improving environmental performance (i.e., leading to lower total carbon emissions) than a strict cap regulation, and this can be explained by comparing the introduction time of 2V in that the total emissions *CE* mainly depend on the introduction time of 2V. To further illustrate this, in Fig.2, we look at how a change in B affects both the introduction time of 2V and the total emissions under both regulations when P decreases in B. Obviously, increasing τ results in an increase in the level of green manufacturing improvement (i.e., higher $\varepsilon_1\tau$), thus reducing the carbon emissions from manufacturing 2V and total emissions.

(i) If B is less than B_1 (B_1=76.744 in Fig. 2), a strict cap regulation has a rigid constraining effect on the carbon emissions. In addition, for P less than P^*, emissions trading regulation weakly restricts carbon emissions. Taken together, a further delayed introduction of 2V significantly reduces emissions in the manufacturing stages in accordance with a strict cap regulation, thus leading to the carbon emissions under an emissions trading regulation being higher than under a strict cap regulation, even if an emissions trading regulation provides flexible intervention. In contrast, if P is above P^*, an emissions trading regulation has a stronger regulatory effect on carbon emissions. Under such a situation, the introduction of 2V is delayed longer than under an emissions cap regulation, so the total emissions are also lower.



(a) (b)

Note. N = 50, v = 3, ρ_1 = 3, β = 1, h = 2, ξ_1 = 100, ε_1 = 0.1, c = 5, e_1 = 1, λ=8, P =10-0.0005B^2.

Fig.2. Effects of B on optimal introduction time of 2V and carbon emissions.

(ii) When B is greater than B_1, an emissions cap regulation is no longer a more stringent intervention (i.e., intervention remains unchanged). In this respect, both the introduction time of 2V and investing in green improvement are independent of B. However, an emissions trading regulation can help firms obtain emissions reduction benefits by selling surplus emissions allowances rather than purchasing additional emissions allowances. This leads to further delayed introduction of 2V and reduces the carbon emissions of 2V. Considering this discussion, an emissions trading regulation benefits the environmental performance.

5. Consumer environmental concern

Our analysis so far has assumed that firms are reluctant to invest in green use improvement, and we now examine the effect of the environmental concern of consumers on product introduction. More specifically, as discussed before, we focus on environmentally concerned consumers being not only concerned about the emissions reduction from the use of products, but also being willing to pay higher prices for firms to reduce the manufacturing stage emissions. In practice, consumers are willing to pay higher prices for low carbon products and manufacturing processes, which are mostly reflected in the social responsibility of consumers. For example, Liu et al. (2012) examine consumers who are willing to pay higher prices for eco-friendly production. In addition, Raz et al. (2013) focus on green use improvement that reduces use stage energy consumption and increases consumer willingness to pay. Furthermore, Deltas et al. (2013) examine that consumers are willing to pay higher prices for both green use and manufacturing improvement. Similarly, the total emissions of energy using products are the sum of both the firm's and consumers' emissions. For simplicity, let e_2 and $e_2 - \varepsilon_2\tau$ be carbon emissions from the use of 1V and 2V, respectively, where $\xi_2\tau$ denotes the emissions reduction during the use stage. Likewise, the costs of green use improvement the firm incurs are denoted by $\xi_2(\varepsilon_2\tau)^2$, where ξ_2 is the green use investment constant, specifying that a higher level of green use improvement requires more investment. The marginal willingness to pay of environmentally concerned consumers is given by $v_e = v[1+k(\varepsilon_1+\varepsilon_2)\tau]$, which urges firms to consider emissions reductions in both stages. Note that $k > 0$ measures the level of consumer environmental concern and can be deemed the consumer's sensitivity to carbon emissions. The firm's optimization model remains the same as in the base model. The only change is v being modified to v_e. The firm's profit is therefore as follows

$$\Pi_E(\tau) = N(\rho_1 + \beta\lambda\tau)v[1+k(\varepsilon_1+\varepsilon_2)\tau] - h(\lambda\tau)^2 - \xi_1(\varepsilon_1\tau)^2 - \xi_2(\varepsilon_2\tau)^2 - 2cN\,. \quad (5)$$

Following the same logic as in Proposition 1, we obtain Lemma 2.

Lemma 2. *With environmentally concerned consumers,* (i) *there exists a threshold* k^* *such that if* $k < k^*$*, the optimal introduction time of 2V is* $\tau_E = \frac{Nv[\beta\lambda + \rho_1 k(\varepsilon_1 + \varepsilon_2)]}{2[h\lambda^2 + \xi_1\varepsilon_1^{\ 2} + \xi_2\varepsilon_2^{\ 2} - Nv\beta\lambda k(\varepsilon_1 + \varepsilon_2)]}$*; in addition, if* $\lambda < \lambda_e$*, then* τ_E *increases in* λ*; if* $\lambda > \lambda_e$*, then* τ_E *decreases in* λ*, where* $\lambda_e = \sqrt{\frac{\xi_1\varepsilon_1^{\ 2} + \xi_2\varepsilon_2^{\ 2} + Nv\rho_1 k^2(\varepsilon_1 + \varepsilon_2)^2}{h} + z^2} - z$ *and* $z = \frac{\rho_1 k(\varepsilon_1 + \varepsilon_2)}{\beta}$*;* (ii) *if* $k \geq k^*$*, then* $\tau_E = \bar{\tau}$*, where* $\bar{\tau}$ is the upper bound of τ, $k^* = \frac{h\lambda^2 + \xi_1\varepsilon_1^{\ 2} + \xi_2\varepsilon_2^{\ 2}}{Nv\beta\lambda(\varepsilon_1 + \varepsilon_2)}$.

From Lemma 2, we observe that, (i) if consumer environmental concern k is less than k^*, the firm introduces both 1V and 2V. In addition, the optimal 2V introduction time τ_E depends on the quality improvement capability of the firm λ. Specifically, as λ increases, τ_E first increases and then decreases, implying that the firm will change from slowing down 2V introduction to speeding up 2V introduction. (ii) If k is greater than k^*, the introduction time of 2Vτ_E becomes $\bar{\tau}$, which is independent of the quality improvement capability.

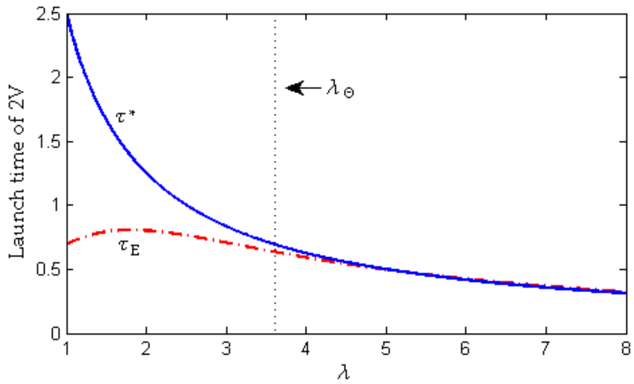
To make the conclusion more meaningful, we next restrict ourselves to the $k < k^*$ case.

Proposition 7. (i) *The firm's profit increases and then decreases in* λ*; that is, there exists a threshold* $\lambda_E = \frac{2\beta(\xi_1\varepsilon_1^{\ 2} + \xi_2\varepsilon_2^{\ 2}) + N\rho_1\beta v k^2(\varepsilon_1 + \varepsilon_2)^2}{k(\varepsilon_1 + \varepsilon_2)(2h\rho_1 + N\beta^2 v)}$ *such that if* $\lambda < \lambda_E$*, then* $\frac{d\Pi_E^*}{d\lambda} > 0$*; if* $\lambda > \lambda_E$*, then* $\frac{d\Pi_E^*}{d\lambda} < 0$. (ii) *The firm's profit increases in k.*

Proposition 7 illustrates that an increase in quality improvement capability λ increases and then decreases the firm's profit. The reason for this is as follows: A relatively low λ ($\lambda < \lambda_E$) reduces the revenue from the sale of 2V, but a high λ ($\lambda > \lambda_E$) increases the revenue from selling 2V and requires the firm to heavily invest in quality improvement. Therefore, when λ equals λ_E, the seller obtains the maximum profit by appropriately balancing revenue of the sale of products and the costs of quality and green improvement. In addition, as consumers become more environmentally concerned (higher k), the firm's profit increases. This occurs because increasing k results in an increase in the marginal revenue of products, which encourages the firm to invest in green improvement to increase v_e, greatly increasing the firm's profit.

Proposition 8 *There exists a threshold* λ_Θ *(* $\lambda_\Theta \le \lambda_E$ *) such that if* $\lambda < \lambda_\Theta$*, then* $\Pi_E^* < \Pi_B^*$*; if* $\lambda \ge \lambda_\Theta$*, then* $\Pi_E^* \ge \Pi_B^*$*, where* $\lambda_\Theta = \dfrac{\beta^2(\xi_1\varepsilon_1{}^2 + \xi_2\varepsilon_2{}^2) - h[\rho_1 k(\varepsilon_1+\varepsilon_2)]^2}{\beta k(\varepsilon_1+\varepsilon_2)(2h\rho_1 + \beta^2 N v)}$.

See the Appendix for the proof.



Note. $N = 50$, $v = 3$, $\rho_1 = 3$, $\beta = 1$, h=30, $\xi_1 = \xi_2 = 250$, $\varepsilon_1 = \varepsilon_2 = 0.5$, $e_1 = e_2 = 0.5$, $c = 5$, k=0.1.

Fig.3. Impact of λ on launch time of 2V.

Contrasting Proposition 8 with Proposition 1 reveals that whether the environmental concern of consumers helps the firm earn a higher profit depends on the quality improvement capability. This follows from comparing introduction time of 2V with and without consumer environmental concern. First, if λ is lower than λ_Θ ($\lambda_\Theta = 3.706$ in Fig. 3), the presence of environmentally concerned consumers induces the firm to introduce 2V more quickly (see Fig. 3), which (i) leads to incremental quality ($\Delta\rho_E = \lambda\tau_E$) and the resulting revenue from the sale of the products being lower than that which can be achieved without consumer environmental concern, and (ii) results in a relatively low green manufacturing and use improvement, slightly increasing consumer's marginal willingness to pay. Thus, the firm's profits are generally lower in the presence of environmentally concerned consumers than without them. Second, when λ is greater than λ_Θ, there is little difference in the introduction time of 2V with and without consumer environmental concern. This, together with green manufacturing and use improvement that increase v_e, leads to the revenue from the sale of the products being higher than that which can be achieved without consumer environmental concern. Consequently, the environmental concern of consumers unequivocally benefits the firm. In light of this, the firm can achieve higher economic performance and environmental performance (i.e. lower total emissions from product manufacturing and use) by educating consumers to become more environmentally concerned.

6. Maximizing social welfare

Maximizing social welfare has always been the ultimate objective for governments. Because imposing a carbon cap does not effectively regulate the emissions from the use of sold products, a more effective measure for the regulator is to set the level of environmental concern, urging firms to invest in green use improvement when introducing 2V. To a certain extent, the level of environmental concern can be deemed a carbon tax levied by the regulator on various emissions sources, such as electricity and gasoline, used by firms and consumers. Similar to Krass et al. (2013), we assume that social welfare W consists of three components: the firm's profit Π, the surplus of consumers using products CS, and the environmental impact ϖ measured by total emissions from both manufacturing and using products. It is worth noting, however, that the highest price the firm can charge is equal to a consumer's willingness to pay for it, which leads to $CS = 0$, thus social welfare degenerates into two parts: the firm's profits and the total carbon emissions.

Likewise, the firm faces a conflict between maximizing profits and minimizing carbon emissions. In other words, the introduction time of 2V, which generates higher profits for the firm, may lead to higher carbon emissions. Let $\theta > 0$ be the level of environmental concern of the regulator (Krass et al., 2013; Cohen et al., 2016). Note that a higher θ means that the carbon emissions will result in higher social welfare losses. A closely related paper is that by Krass et al. (2013), who only focus on imposing a tax per unit of pollutant emitted during the manufacturing phase. Hence, social welfare becomes $\mathrm{W}(\tau) = \Pi - \theta\omega$, where $\omega = N(2e_1 - \varepsilon_1\tau + 2e_2 - \varepsilon_2\tau)$ and $\theta\omega$ denote the total emissions and environmental losses, respectively.

Social welfare is given by

$$W(\tau) = Nv\rho_1 + N\beta v\lambda\tau - h(\lambda\tau)^2 - [\xi_1(\varepsilon_1\tau)^2 + \xi_2(\varepsilon_2\tau)^2] - 2cN - \theta N(2e_1 + 2e_2 - \varepsilon_1\tau - \varepsilon_2\tau) . \qquad (6)$$

By solving social welfare optimization problem, we get Lemma 3.

Lemma 3. *With the regulator's environmental concern, the optimal introduction time of 2V is* $\tau_W = \dfrac{N[\beta v\lambda + \theta(\varepsilon_1+\varepsilon_2)]}{2(h\lambda^2 + \xi_1\varepsilon_1{}^2 + \xi_2\varepsilon_2{}^2)}$. *Moreover, if* $\lambda \le \lambda_w$, *then* τ_W *increases in* λ; *if* $\lambda > \lambda_w$, *then* τ_W *decreases in* λ, *where* $\lambda_w = \sqrt{\dfrac{(\xi_1\varepsilon_1{}^2 + \xi_2\varepsilon_2{}^2)}{h} + [\dfrac{\theta(\varepsilon_1+\varepsilon_2)}{\beta v}]^2} - \dfrac{\theta(\varepsilon_1+\varepsilon_2)}{\beta v}$.

Lemma 3 reveals that as λ increases, τ_W increases and then decreases, implying that the firm changes from slowing down 2V introduction to speeding up 2V introduction.

Proposition 9. (i) *If* $\lambda < \lambda_W$, *the optimal social welfare* W^* *increases in* λ; *if* $\lambda \ge \lambda_W$, W^* *decreases in* λ, *where* $\lambda_W = \beta v(\xi_1\varepsilon_1{}^2 + \xi_2\varepsilon_2{}^2)/[h\theta(\varepsilon_1+\varepsilon_2)]$. (ii) W^* *decreases in* θ.

Proposition 9 reveals that, (i) as λ increases, social welfare W^* increases and then decreases. In other words, a relatively low λ ($\lambda < \lambda_W$), which reduces the revenue from the sale of the products, and a high λ ($\lambda > \lambda_W$), which increases the revenue from selling 2V but requires the firm to greatly invest in quality and green improvement, cannot help to maximize social welfare. Thus, when λ equals λ_W, social welfare is maximized by effectively balancing the sale of the products, the cost of quality and green improvement, and environmental damage in monetary terms. (ii) As θ increases, this illustrates that the regulator's punishment for environmental damage caused by carbon emissions increases, so the firm will delay 2V introduction to reduce emissions in the manufacturing and use stages. This increases investment in green manufacturing and use improvement. In addition, the sale of the products is less able to compensate the firm for the increase in the investment. Hence, the optimal social welfare is reduced.

Proposition 10 below compares the firm's profits as well as social welfare with and without regulator environmental concern.

Proposition 10. (i) *The firm's profits* Π_W^* *are less than that when there is no regulatory intervention* Π_B^*; *i.e.,* $\Pi_W^* < \Pi_B^*$.

(ii) *There exists a threshold* λ_{BW} ($\lambda_{BW} < \lambda_W$) *such that if* $\lambda < \lambda_{BW}$, *then* $W^* < W_B$; *if* $\lambda \ge \lambda_{BW}$, *then* $W^* \ge W_B$, *where* $\lambda_{BW} = \dfrac{(\beta v)^2(\xi_1\varepsilon_1{}^2 + \xi_2\varepsilon_2{}^2) - h[\theta(\varepsilon_1+\varepsilon_2)]^2}{2h\beta v\theta(\varepsilon_1+\varepsilon_2)}$.

(iii) *If* $\theta < \theta_{BW}$ *, then* $W^* < W_B$ *; if* $\theta \geq \theta_{BW}$ *, then* $W^* \geq W_B$ *, where* $\theta_{BW} = \frac{\beta v}{\varepsilon_1 + \varepsilon_2}(\sqrt{\frac{\xi_1 \varepsilon_1^2 + \xi_2 \varepsilon_2^2}{h} + \lambda^2} - \lambda)$.

See the Appendix for the proof.

Proposition 10 proves a meaningful connection among the firm's profits, social welfare, and the regulator's environmental concern. (i) In the presence of the regulator's environmental concern, the firm's profits are lower than when there is no environmental concern from the regulator. This is due to the fact that although investing in green improvement reduces carbon emissions from both manufacturing and using products, it greatly lowers the firm's profits. As a result, the presence of the regulator's environmental concern leads to a lower profit for the firm. (ii) Regarding social welfare, whether the regulator's environmental concern is an effective measure for maximizing social welfare depends on the quality improvement capability. This follows from comparing τ_W and τ^*. If $\lambda \leq \lambda_W$, then $\tau_W \leq \tau^*$; if $\lambda > \lambda_W$, then $\tau_W > \tau^*$. First, when λ is less than λ_{BW}, note that λ_{BW} is also below λ_W, and the presence of the regulator's environmental concern induces the firm to make a rapid 2V introduction. This results in the level of quality improvement and revenue from the sale of the products being substantially less than what it would be without the regulator's environmental concern, and lowers the level of green manufacturing and use improvement. Thus, the environmental concern of regulators is detrimental to social welfare. Second, for $\lambda \in [\lambda_{BW}, \lambda_W)$, there is little difference in the introduction time of 2V with and without the regulator's environmental concern. Furthermore, increased green manufacturing and use improvement reduces carbon emissions. If carbon emissions are charged as θ of the levy of the emissions tax, then the regulator's environmental concern will unequivocally benefit social welfare. Third, if λ is great than λ_W, in the presence of the regulator's environmental concern, delaying introducing 2V (a) leads to incremental quality and revenue from the sale of the products being significantly greater than what it would be without the regulator's environmental concern; and (b) increases green manufacturing and use improvement, which greatly reduce carbon emissions. Likewise, if carbon emissions are also charged as θ, the regulator's environmental concern will be helpful in improving social welfare. In light of this discussion, we caution the regulator that achieving its ultimate objective of maximizing social welfare is at the expense of the firm's profits.

(iii) Concerning the interaction between θ and social welfare, it can be seen from the proof of Proposition 10 that θ less than (greater than) θ_{BW} is equivalent to λ less than (greater than) λ_{BW}. If θ is lower than θ_{BW}, this illustrates that the regulator has a relatively low constraining effect on carbon emissions from manufacturing and using products, thus the firm introduces 2V more rapidly and reduces investment in green manufacturing and use improvement. This makes the firm's revenue from the sale of products lower than those that can be achieved without the regulator's environmental concern. In light of this, the presence of such concern is greatly detrimental to social welfare. In contrast, if θ is greater than θ_{BW}, this shows that the regulator has a relatively strict intervention, so the firm introduces 2V more slowly. This in turn leads to an increase in investment in green manufacturing and use improvement. In addition, increasing θ significantly leads to an increase in environmental loss in the absence of the regulator's environmental concern. Consequently, social welfare with the regulator's environmental concern is higher than what can be achieved without such concern.

7. Managerial implications

7.1. Implications for practice

From the perspective of emissions regulations, theoretically, an emissions trading regulation can be better than a strict cap regulation in encouraging firms to reduce emissions because it employs a more flexible incentive mechanism. However, as highlighted in Proposition 6, such a regulation with a low emissions cap and a high emissions price may result in higher emissions in the manufacturing phase than what would occur with an emissions cap regulation. In addition, although the essence of emissions trading regulation is still to set emissions caps, an emissions trading regulation is more complicated because it is not only affected by the same influences as a strict cap regulation, but is also affected by the dynamics and volatility of the emissions trading market.

There are two points worth illustrating regarding environmental concern. Clearly, both kinds of environmental concern not only affect the carbon emissions from product manufacturing, but also affect the carbon emissions from the use of products. First, consumer environmental concern tends to be more of an incentive, which (i) always helps to improve environmental performance (reduce carbon emissions), and (ii) enables firms to obtain profits that may be higher than those in the absence of such concern (see Proposition 8). Second, the regulator's environmental concern is mostly punitive and can be deemed a tax levied on firms for causing environmental damage. As noted in the discussion of Proposition 10, relatively low environmental concern set by regulators is not only detrimental to the maximization of social welfare, but also makes the firm's profits lower than when there is no regulatory intervention. However, if the regulator's environmental concern is relatively high, maximizing social welfare is often at the expense of the firm's profits. Collectively, we expect that consumer environmental concern has a more profound impact on product introduction than regulator environmental concern. In practice, various measures for enhancing the environmental concern of consumers can be taken, including: (i) adopting active marketing strategies such as a trade in program; (ii) educating consumers about energy consumption and saving potential; and (iii) conveying carbon emissions information from manufacturing and using products via carbon labels for consumers. In this way, economic performance (higher profits) and environmental performance (lower carbon emissions) can be achieved. From a practical perspective, it is more difficult to measure the implementation effectiveness of educating consumers to be more environmentally concerned; in contrast, the level of environmental concern of regulator can be deemed a carbon tax levied on various emissions sources, which can be easier to implement.

From the product introduction perspective, first, in the absence of regulatory intervention, introducing upgraded products is only affected by the quality improvement capability. Second, under emissions regulations, introducing upgraded products needs to be balanced between the quality improvement capability and the regulatory intervention in carbon emissions from product manufacturing. Third, in the presence of environmentally concerned consumers, introducing upgraded products requires balancing the quality improvement capability with regulatory intervention in carbon emissions from both manufacturing and using products. Last, in the presence of the regulator's environmental concern, introducing upgraded products is basically driven by the maximization of social welfare rather than the maximization of firm's profits.

7.2. Implications for research

Implications for our study are to incorporate three existing areas: product introduction, green (low carbon) innovation, and emissions regulation. By doing so, we hopefully provide a new vision for interdisciplinary integration. Moreover, our work complements existing literature by analytically examining how the environmental concern of consumers and regulators urges firms to reduce carbon emissions from both manufacturing and using products. In addition, we also analytically compare an emissions trading regulation with a strict cap regulation.

8. Conclusion

It is commonly believed that carbon emissions are one of the main contributing factors to global warming and widespread environmental degradation. Low carbon development has become a foremost concern of governments, firms and environmental protection organizations. This has prompted more and more countries and governments to introduce and implement more restrictive emissions regulations to restrict the adverse effects of firms. In addition, to meet consumers' expectations for greener and better quality products, firms also need to improve the quality of existing products. In general, the introduction time of upgraded products has significant differences in meeting consumer requirements and emissions regulations. This not only affects the profits from the sale of products, but also affects the carbon emissions from manufacturing and using products. To achieve the comprehensive goal of uncovering the influence of regulatory intervention and consumer environmental concern, we first study the impact of a strict cap regulation and an emissions trading regulation on product introduction. We then account for consumer environmental concern and explore its impact on introducing upgraded products. In addition, we also examine the impact of regulator environmental concern on product introduction, the firm's profits and social welfare.

Overall, several valuable results are obtained. First, compared with having no regulatory intervention, a strict cap regulation results in lowering the firm's profits; whether an emissions trading regulation benefits firms depends on the quality improvement capability and the interaction between the emissions cap and emissions price. In addition, if the quality improvement capability of firms turns out to be poor, the presence of environmentally concerned consumers is not conducive to creating higher profits for firms. The opposite will hold for the quality improvement capability that is relatively high. Second, the emissions emitted by the firm under an emissions trading regulation may be higher than those under a strict cap regulation. Last, when the environmental concern of regulators is relatively low, it is not conducive to the maximization of social welfare; in contrast, a relatively high regulator's environmental concern can maximize social welfare but at the expense of the firms' profits.

Clearly, educating consumers to be environmental concerned is better than depending on the regulator's environmental concern for encouraging firms to account for the carbon emissions from the use of products when upgraded products are introduced. Satisfying environmentally concerned consumers is an incentive while adhering to the regulator's environmental concern is more punitive. Consequently, firms can improve consumer environmental concern through the analysis and use of the trends in energy prices, the use of active marketing strategies such as a trade in program, and by education on energy consumption and saving potential. In addition, firms can also include a carbon label (showing the product's carbon emissions during its life cycle) on their products to show consumers how environmentally friendly the products are, and to enhance the firms' environmental protection reputation. This can also increase consumer attention and recognition of social benefits (positive environmental externalities).

This analysis can be extended in several ways. First, our research mainly accounts for the emissions price that does not depend on or decreases in the emissions cap. However, in practice, the emissions price is widely affected by the supply and demand of the emissions allowance; thus, exploring the impact of the uncertainty and volatility of an emissions trading regulation on product introduction will further reveal the interaction between regulatory intervention and product introduction. Second, our work studies how emissions regulations affect product introduction. Further research can study how emissions and waste recycling regulations such as WEEE affect product introduction. Third, our work could be extended from a single firm to supply chain that introduces improved products under emissions regulations. Last, a large amount of direct investment is needed to reduce emissions, hence, government subsidies (indirect subsidies to consumers to buy energy saving products and direct subsidies to firms for investment in energy saving and emissions reduction) also influence product introduction. Further research should examine the impact of supplementing maximizing social welfare with a subsidy mechanism on product introduction.

In addition, further research could be extended to include economic and suasive intervention on product introduction.

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Appendix

Proof of Lemma 1

(i)Taking the derivative of Π_C with respect to τ, we obtain

$\frac{d\Pi_C}{d\tau} = N\beta v\lambda - 2(h\lambda^2 + \xi_1{\varepsilon_1}^2)\tau$, and $\frac{d^2\Pi_C}{d\tau^2} = -2(h\lambda^2 + \xi_1{\varepsilon_1}^2) < 0$.

Noted that $\left.\frac{d\Pi_C}{d\tau}\right|_{\tau=0} = N\beta v\lambda > 0$, and $\left.\frac{d\Pi_C}{d\tau}\right|_{\tau=\bar{\tau}} < 0$.

The first-order condition $\frac{d\Pi_C}{d\tau} = 0$ yields $\tau_1 = \frac{N\beta v\lambda}{2(h\lambda^2 + \xi_1{\varepsilon_1}^2)}$.

From Constraint (3), we get $\tau \geq \tau_2 = \frac{1}{\varepsilon_1}(2e_1 - \frac{B}{N})$.

By comparing τ_1 and τ_2, we obtain immediately that if $B \geq B_1 = N[2e_1 - \frac{\varepsilon_1 N\beta v\lambda}{2(h\lambda^2 + \xi_1\varepsilon_1^2)}]$, then $\tau_1 > \tau_2$, and $\tau_C = \max(\tau_1, \tau_2) = \tau_1$; if $B \leq B_1$, then $\tau_1 \leq \tau_2$, and $\tau_C = \tau_2$.

(ii)When $B \geq B_1$, differentiating τ_1 with respect to λ allows us to obtain that there exists a threshold $\lambda_c = \varepsilon_1\sqrt{\xi_1 / h}$ such that if $\lambda < \lambda_c$, then $d\tau_C / d\lambda > 0$; if $\lambda \geq \lambda_c$, then $d\tau_C / d\lambda \leq 0$.

Proof of Proposition 2

Applying the Envelope Theorem gives $\frac{d\Pi_C^*}{d\lambda} = \tau_C(N\beta v - 2h\lambda\tau_C)$. When $B \leq B_1$, then $\tau_C = \tau_2$, and $\frac{d\Pi_C^*}{d\lambda} = \tau_2(N\beta v - 2h\lambda\tau_2)$. Solving $\frac{d\Pi_C^*}{d\lambda} = 0$ yields $\lambda_C = \frac{N^2\beta v\varepsilon_1}{2h(2e_1 N - B)}$ such that if $\lambda < \lambda_C$, then $\frac{d\Pi_C^*}{d\lambda} > 0$; if $\lambda \geq \lambda_C$, then $\frac{d\Pi_C^*}{d\lambda} \leq 0$. Note that $B \leq B_1$. Based on $B = B_1$, we get two solutions: $\lambda_1 = \varepsilon_1[\frac{N\beta v}{4zh} - \sqrt{(\frac{N\beta v}{4zh})^2 - \frac{\xi_1}{h}}]$ and $\lambda_2 = \varepsilon_1[\frac{N\beta v}{4zh} + \sqrt{(\frac{N\beta v}{4zh})^2 - \frac{\xi_1}{h}}]$, where $z = 2e_1 - \frac{B}{N}$. If $\lambda \leq \lambda_1$ or $\lambda \geq \lambda_2$, then $B \leq B_1$; if $\lambda_1 < \lambda < \lambda_2$, then $B > B_1$.

By comparing λ_2 and λ_C, we obtain $\lambda_1 < \lambda_2 < \lambda_C$. Hence, (a) if $\lambda \leq \lambda_1$, then $B \leq B_1$, combined with $\lambda < \lambda_C$, we obtain $d\Pi_C^* / d\lambda > 0$; (b) if $\lambda \in [\lambda_2, \lambda_C)$, then $B \leq B_1$, which together with $\lambda < \lambda_C$ leads to $d\Pi_C^* / d\lambda > 0$; (c) if $\lambda \in (\lambda_1, \lambda_2)$, then $B > B_1$, in this case, note that $\tau_C = \tau_1$, so $\frac{d\Pi_C^*}{d\lambda} = \frac{N\beta v\xi_1\varepsilon_1^2\tau_1}{h\lambda^2 + \xi_1\varepsilon_1^2} > 0$; (d) if $\lambda \geq \lambda_C$, then $B \leq B_1$, and $d\Pi_C^* / d\lambda \leq 0$. Therefore, if $\lambda \leq \lambda_C$, then Π_C^* is increasing in λ; if $\lambda > \lambda_C$, then Π_C^* is decreasing in λ.

(ii) Repeating above arguments, there are consequently two cases: if $B \leq B_1$, then $\frac{d\Pi_C^*}{dB} = \frac{1}{N\varepsilon_1}[\frac{2(h\lambda^2 + \xi_1\varepsilon_1^2)}{\varepsilon_1}(2e_1 - \frac{B}{N}) - N\beta v\lambda]$, and $\frac{d^2\Pi_C^*}{dB^2} = -\frac{2(h\lambda^2 + \xi_1\varepsilon_1^2)}{N^2\varepsilon_1^2} < 0$. By noting that $(d\Pi_C^* / dB)\big|_{B=B_1} = 0$, we get immediately $d\Pi_C^* / dB > 0$. Alternatively, if $B > B_1$, we have $\Pi_C^* = \Pi_C\big|_{\tau_C=\tau_1}$, and $d\Pi_C^* / dB = 0$.

Proof of Proposition 3

Note from the proof of Lemma 1 that $\tau_C = \tau_2 = \frac{1}{\varepsilon_1}(2e_1 - \frac{B}{N})$ when $\lambda = \lambda_C$. After calculation, we get $\tau_C \lambda_C = \frac{N\beta v}{2h}$, $\Pi_C^*\big|_{\lambda=\lambda_C} = \Pi_B^* - \xi_1[(2e_1 - \frac{B}{N})]^2$ and $\Pi_C^*\big|_{\lambda=\lambda_C} < \Pi_B^*$. Combined with $\Pi_C^* < \Pi_C^*\big|_{\lambda=\lambda_C}$, we have $\Pi_C^* < \Pi_B^*$.

Proof of Proposition 5

After calculation, we get $\lambda_T \tau_T = \frac{N\beta v}{2h}$, and $\Pi_T^*\big|_{\lambda=\lambda_T} = \Pi_B^* + \Delta\Pi^*$, where $\Delta\Pi^* = P(B - 2e_1 N + \frac{PN^2}{4\xi_1})$.

(i) If P does not depend on B, differentiating $\Delta\Pi^*$ w.r.t. P, we obtain

$$\frac{d\Delta\Pi^*}{dP} = B - [2e_1 - \varepsilon_1 \frac{N(\beta v\lambda + P\varepsilon_1)}{2(h\lambda^2 + \xi_1\varepsilon_1^2)}]N.$$

From $\frac{d\Delta\Pi^*}{dP} = 0$, we get $P_1 = \frac{1}{\varepsilon_1}[\frac{2(h\lambda^2 + \xi_1\varepsilon_1^2)(2e_1N - B)}{N^2\varepsilon_1} - \beta v\lambda]$ such that if $P > P_1$, then $\frac{d\Delta\Pi^*}{dP} > 0$; if $P < P_1$, then $\frac{d\Delta\Pi^*}{dP} < 0$. From $\Delta\Pi^* = 0$, we obtain $B_\Theta = N(2e_1 - \frac{PN}{4\xi_1})$ such that (a) if $B \le B_\Theta$, then $\Pi_T^*\big|_{\lambda=\lambda_T} \le \Pi_B^*$, and $\Pi_T^* \le \Pi_B^*$; (b) if $B > B_\Theta$, then $\Pi_T^*\big|_{\lambda=\lambda_T} > \Pi_B^*$, let $\lambda_1 < \lambda_2$ be the two solutions to $\Pi_T^* = \Pi_B^*$. If $\lambda \le \lambda_1$ or $\lambda \ge \lambda_2$, then $\Pi_T^* \le \Pi_B^*$; if $\lambda_1 < \lambda < \lambda_2$, then $\Pi_T^* > \Pi_B^*$.

(ii) Suppose $P = a - bB$, calculating boundary conditions yields $\Delta\Pi^*\big|_{B=0} = -aN(2e_1 - \frac{aN}{4\xi_1})$, and $\Delta\Pi^*\big|_{B=\bar{B}} = 0$, where $\bar{B} = a/b$. Note that maximum emissions reduction from product manufacturing should not exceed initial carbon emissions. In other words, $e_1 - \varepsilon_1\tau_T\big|_{\lambda=\lambda_T} \ge 0$ need to be satisfied. Substituting λ_T into this inequality, we get $2e_1 \ge NP/\xi_1$. Combined with $2e_1 - \frac{aN}{4\xi_1} > 2e_1 - \frac{aN}{\xi_1} \ge 0$, we further get $\Delta\Pi^*\big|_{B=0} < 0$.

Differentiating $\Delta\Pi^*$ w.r.t. B, we can get

$$\frac{d\Delta\Pi^*}{dB} = -b(B - 2e_1N + \frac{PN^2}{2\xi_1}) + P, \text{ and } \frac{d^2\Delta\Pi^*}{dB^2} = -b(2 - \frac{bN^2}{2\xi_1}).$$

Calculating the first-order boundary conditions:

$$\frac{d\Delta\Pi^*}{dB}\bigg|_{B=0} = bN(2e_1 - \frac{aN}{2\xi_1}) + a > 0, \quad \frac{d\Delta\Pi^*}{dB}\bigg|_{B=\bar{B}} = bN(2e_1 - \frac{\bar{B}}{N}) > 0.$$

Regarding $\frac{d^2\Delta\Pi^*}{dB^2}$, if $\xi_1 > \frac{bN^2}{4}$, then $\frac{d^2\Delta\Pi^*}{dB^2} < 0$. This, together with boundary conditions, leads to $\Delta\Pi^*$ being increasing concavely in *B*. If $\xi_1 = \frac{bN^2}{4}$, then $\frac{d^2\Delta\Pi^*}{dB^2} = 0$. Combined with boundary conditions, $\Delta\Pi^*$ increases linearly in *B*. Similarly, If $\xi_1 < \frac{bN^2}{4}$, then $\frac{d^2\Delta\Pi^*}{dB^2} > 0$, and $\Delta\Pi^*$ being increasing convexly in *B*. Taken together, $\Delta\Pi^*$ is increasing in *B*.

Therefore, we further obtain $\Delta\Pi^* \le 0$, $\Pi_T^*\big|_{\lambda=\lambda_T} \le \Pi_B^*$, and $\Pi_T^* \le \Pi_T^*\big|_{\lambda=\lambda_T} \le \Pi_B^*$.

Proof of Proposition 8

After calculation, we get $\Pi_E^* = Nv\rho_1 - 2cN + \frac{(Nv)^2}{4}\frac{[\beta\lambda + \rho_1 k(\varepsilon_1+\varepsilon_2)]^2}{(h\lambda^2 + \xi_1{\varepsilon_1}^2 + \xi_2{\varepsilon_2}^2) - Nv\beta\lambda k(\varepsilon_1+\varepsilon_2)}$. Note that $\Pi_B^* = Nv\rho_1 - 2cN + \frac{(Nv)^2}{4}\frac{\beta^2}{h}$.

Solving $\Pi_E^* = \Pi_B^*$ allows us to get $\lambda_\Theta = \frac{\beta^2(\xi_1{\varepsilon_1}^2 + \xi_2{\varepsilon_2}^2) - h[\rho_1 k(\varepsilon_1+\varepsilon_2)]^2}{\beta k(\varepsilon_1+\varepsilon_2)(2h\rho_1 + \beta^2 Nv)}$. By further comparing λ_E and λ_Θ, we get $\lambda_\Theta < \lambda_E$. Thus, if $\lambda < \lambda_\Theta$, then $\Pi_E^* < \Pi_B^*$; if $\lambda \ge \lambda_\Theta$, then $\Pi_E^* \ge \Pi_B^*$.

Proof of Proposition 10

(i) Comparison of the firm's profits. After calculation, we get

$$\Pi_W^* = Nv\rho_1 - 2cN + \frac{N^2}{4}\frac{(\beta v\lambda)^2 - \theta^2(\varepsilon_1+\varepsilon_2)^2}{h\lambda^2 + \xi_1{\varepsilon_1}^2 + \xi_2{\varepsilon_2}^2}.$$

By comparing Π_W^* and Π_B^*, we obtain immediately $\Pi_W^* < \Pi_B^*$.

(ii) Comparison of social welfare.

After some algebraic manipulation, we get

$$W^* = Nv\rho_1 - 2cN - 2\theta N(e_1+e_2) + \frac{N^2}{4}\frac{[\beta v\lambda + \theta(\varepsilon_1+\varepsilon_2)]^2}{h\lambda^2 + \xi_1{\varepsilon_1}^2 + \xi_2{\varepsilon_2}^2},$$

$$W_B = Nv\rho_1 - 2cN - 2\theta N(e_1+e_2) + \frac{N^2}{4}\frac{(\beta v)^2}{h}.$$

Solving $W^* = W_B$ allows us to get $\lambda_{BW} = \frac{(\beta v)^2(\xi_1{\varepsilon_1}^2 + \xi_2{\varepsilon_2}^2) - h[\theta(\varepsilon_1+\varepsilon_2)]^2}{2h\beta v\theta(\varepsilon_1+\varepsilon_2)}$. Comparing λ_{BW} and λ_W allows us to get $\lambda_{BW} < \lambda_W$. Therefore, if $\lambda < \lambda_{BW}$ ($\lambda_{BW} < \lambda_W$), then $W^* < W_B$; if $\lambda \ge \lambda_{BW}$, then $W^* \ge W_B$.

(iii) Repeating above arguments, we obtain that if $\theta < \theta_{BW}$, then $W^* < W_B$; if $\theta \geq \theta_{BW}$, then $W^* \geq W_B$, where $\theta_{BW} = \frac{\beta v}{\varepsilon_1 + \varepsilon_2}(\sqrt{\frac{\xi_1 {\varepsilon_1}^2 + \xi_2 {\varepsilon_2}^2}{h} + \lambda^2} - \lambda)$.